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Historical and Modern Conservation Methods of a Crack in Stained Glass. Practical Case Study of Five Selected Methods

Bachelor thesis

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1. Introduction

What is stained glass? Stained glass, also known as “*vitrage*” in French and in other languages that have borrowed (German, Dutch) or customised (*vitraaž* – Estonian) the word. Although in this thesis, the English term “stained glass” shall be used in place of the word *vitrage*.

The International Committee of the *Corpus Vitrearum* for the Conservation of Stained Glass in association with the Stained Glass Committee of ICOMOS, in guidelines from article 1.4. from 2004 state that: “the term "stained glass" covers painted and/or stained glass as well as plain leaded lights, copper-foiled glass, *dalle de verre* and other types of architectural glass, whether in situ or after removal to a museum or private collection.”

This work is partly based on personal experience from my internship in glass conservation in the University of Antwerp and partly a practical case study of a selection of five historic and modern conservation methods that will be showcased on a stained glass panel created for the thesis. The five methods were chosen on the basis of: frequency of usage in the past, the complexity of the technique, availability of the products and my personal experience using them. The theoretical part consists of a historical overview, physical and chemical properties, introduction to different types of glass and damages and their causes and definitions to common terminology, with Estonian translations.

The information presented in this thesis is mostly compiled of scientific research and publishings form conservators specialised in glass. Articles from various sources, mostly history based websites, were consulted to give the most accurate overview for the historic chapters. For the information on crack patterns, most of it is compiled from forensic articles and publishings.

Although Estonia has stained glass artists like Rait Prääts (Stained glass in St. Nicholas Church (Niguliste kirik)), Dolores Hoffman (Stained glass in Tallinn’s St. John’s Church (Tallinna Jaani kirik)), Andrei Lobanov, Riho Hütt, Eva Jänes, Urmo Raus etc. however, to my knowledge, based on the small number of papers by Estonian authors, the different conservation methods and the science of stained glass has not been researched thoroughly in Estonia. There are a few exceptions like Eve Koha, who was also consulted for the chapter “Terms and definitions”, for the Estonian translations.

The aim of this bachelor thesis is to explore glass conservation methods in case of a crack, a as that is the most noticeable damage to the naked eye, to cultivate more information based on my studies abroad and interest in the world of glass conservation in Estonia. All of this, so I could document

the knowledge to conserve and maintain our national heritage and the works of stained glass artists. I would like to thank my supervisors Monique de Caluwé and Merike Kallas. In addition, everyone else who helped tremendously: Riin Alatalu, Eve Koha, Triin Reidla, Anneli Randla.

2. Brief historical overview

Since the ancient times glass has been used for various purposes. Archaeological findings in Egypt and Eastern Mesopotamia indicate that the first manufactured glass dates back to 3000 BC. As glassmaking was a very lengthy and expensive process it was considered a luxury to own glass objects.[1]

First known civilization to make glass were the ancient Egyptians. Most commonly they fused[2] beads and then slumped[3] that or used the core-forming technique[4] to make small vessels.[5]

During the 1st century *Anno Domini* glass blowing was discovered thanks to the Syrian craftsmen in the Roman Empire. This was one of the first, but definitely not the last, revolutionary discovery in glass making throughout history. However the tools and techniques in traditional glass blowing have changed little over time. Glass blowing made glass widely available for people of a lower status and thus helped the spread of glass across Western Europe and the Mediterranean.[6]

With the rise of popularity of glass, glassware itself became common for the wealthy in Rome and was considered a sign of relatively low status. The upper class opted to use gold and silver vessels instead.[7]

The Romans were the first who began to use glass for architectural purposes like windows after the discovery of "clear" glass in Alexandria around the year 100 AD[8].

They mostly used two different methods for making glass windows. The first method, which has not been 100% confirmed because of the loss of information due to the fall of Roman empire, was used to produced cast glass[9]. Although the technique of how it was precisely made is up to debate. The sheets were uneven in thickness, with one side glossy, due to the fire polishing, and the other matte[10].

The other, better known, technique was used to produce cylinder glass which was of more even thickness and glossy on both sides. It is made by blowing a glass cylinder (fig. 1), cutting it laterally

1 The History of Glass Making, History of Glass, http://www.historyofglass.com/glass-history/glass-making/ (Accessed 07.XI 2021).
2 **Fusing** – taking many separate pieces of glass, placing them side by side and heating them- as the pieces cool the edges of the glass pieces stick together and fuse to a single object.
3 **Slumping** – placing a piece of glass in/over mould. As the glass is heated it slumps over/into the mould taking the shape of the mould.
4 **Core forming** – The technique of forming a vessel by gathering molten glass around a core supported by a rod. After forming, the object is removed from the rod and annealed. After annealing, the core is removed by scraping.
5 The Origins of Glassmaking, Corning Museum of Glass, 01.XII.2011, https://www.cmog.org/article/origins-glassmaking (Accessed 10.XI 2021).
6 The history of glass making.
7 D. Quick, Roman Window Glass, Liss Archeology – Community archeology in Hampshire, UK; 07.V 2019, Updated: 21.VIII. 2021, https://www.lissarchaeology.uk/post/windowglass (Accessed 05.XI 2021).
8 The History of Glass Making.
9 **Cast glass** – Molten glass was poured into a mould in much the same way metals are cast.
10 M. Taylor, No Pane, No Gain! - Roman window glass, Roman Glassmakers, 2000, Updated: 2003, http://www.theglassmakers.co.uk/archiveromanglassmakers/articles.htm#No (Accessed 12.XI 2021).

and flattening it out[11]. This method was one of the most popular techniques for producing large sheets of glass until the 17th century.

Fig. 20. — Fabrication des manchons de verre destinés à former des carreaux de vitres. Vue prise dans une des fabriques d'Aniche (Nord).

Figure 1: Manufacturing of glass cylinders which will be used to make window panes. View taken at a factory in Aniche (France). Illustration by P. Broux, published in "Les merveilles de l'industrie, vol. 1" by Louis Figuier in 1873.

European glass is a legacy of Roman glassmaking[12]. By the late 13th century glass production had moved to Venice and was the city's number one industry. Venetian glass reached the peak of its popularity in the 15th and 16th centuries. That was due to the fact that in the 15th century, Angelo Barovier discovered the process for producing *cristallo*[13] which allowed Murano glassmakers to become the only producers of mirrors in Europe[14]. Glassmaking became important in more northern European countries by the late 15th century and early 16th century[15]. By the 17th century Venice was losing its monopoly on the glass world, as new factories emerged in England and France[16]. This

11 R. J. Forbes, Studies in Ancient Technology volume V, Editors: Leiden, Brill, University of Michigan, 1966, p 180.
12 A. Polak, Glass: Its Traditions and its Makers. G.P. Putnam's Sons, New York, 1975, p 37.
13 **Cristallo** – Italian, "crystal". Term used in Venice in the 14th century to describe glass that resembles colourless rock crystal.
14 History of Murano Glass, Glass of Venice, https://www.glassofvenice.com/murano_glass_history.php(Accessed 14.X 2021).
15 The History of Glass Making.
16 History of Murano Glass.

change of power was confirmed when in 1674 George Ravenscroft (1618–1681), an English glassmaker, invented[17] lead glass[18]. In 1688 a method of making plate-glass[19] was perfected by Louis Lucas de Nehou and Abraham Thevart in France[20]. The polishing process was industrialized around 1800s with the adoption of a steam engine to carry out the grinding and polishing of the cast glass.

In 1871, a machine that allowed larger sheets of glass to be made, was invented by William Pilkington[21]. By the early 20th century most glass was manufactured using the plate glass method, where a ribbon of molten glass was drawn between cooled rollers[22].
The glass manufacturing underwent another huge revolution when Alistair Pilkington invented the float glass process in 1959. In the float glass process, the molten glass flows into the float tank onto a shallow pool of liquid metal, usually tin. There, surface tension and gravity make the molten glass into a flat ribbon shape[23]. Glass is much less expensive to produce via the flat process than any other type of process. Today more than 90 percent of the world's flat glass is made via the float process[24].

2.1. Stained glass

It is though that the English term "stained glass" comes from silver stain[25], that turns the glass a yellow colour when fired[26].
One of the theories of the beginnings of stained glass is that it developed from a method called cloisonné[27] enamel, as they are both techniques where material is held together by strips of metal[28]. The spread of Christianity throughout Europe is directly related to the popularity of stained glass in the new millennium[29]. That was mostly because the illustrations used were based on the

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17 The history of glass making.
18 **Lead glass** – Glass that contains a high percentage of lead oxide (at least 20 percent of the batch).
19 **Plate glass** – Flat glass of high quality, formed by rolling molten glass on a metal plate and later grinding and polishing it until the surfaces are parallel and completely smooth.
20 Encyclopaedia Britannica 11th edition (1911).
21 L. Hill, What is Glass?, Glass.com: The Glass Experts, 15. VIII 2016, https://info.glass.com/what-is-glass/ (Accessed 20.X 2021).
22 The History of Glass Making.
23 On a Pool of Tin: Float Glass, Corning Museum of Glass, 24. X 2011, https://www.cmog.org/article/pool-tin-float-glass?search=all_about_glass%3Ae7e9a5ccfafce970af3774afddb03792&p=8 (Accessed 20.X 2021).
24 The History of Glass Making.
25 **Silver stain** – Yellow stain made by painting the surface of the glass with silver nitrate or similar compounds and firing it.
26 A Short History of Stained Glass, The Stained Leaded Glass Company, https://www.stainedleadedglass.co.uk/the-history-of-stained-glass.html (Accessed 17.XI 2021).
27 **Cloisonné** – An enameling technique which consists of soldering to a metal surface metal strips bent to the outline of a design and filling the resulting cellular spaces, called cloisons (French: "compartments"), with vitreous enamel paste.
28 P. S. Casciani, The Technique of Decorative Stained Glass, London, Batsford, 1996, p 104.
29 The History of Stained Glass, History of Glass, http://www.historyofglass.com/glass-history/stained-glass-history/ (Accessed 10.XI 2021).

stories from the Bible. Through the symbolism and pictures of stained glass the illiterate viewer had a way to familiarise themselves with the religious tellings.

By the 7th century, glassworkers started to become interested in windows as well, rather than just glassware. The stained glass windows were most commonly used in religious buildings like abbeys, convents and monasteries. St. Paul's Monastery in Jarrow, England is one of the earliest known examples. The stained glass windows were created when the building was founded in 686 AD. Pieces of the stained glass windows were excavated by archaeologist Rosemary Cramp in 1973[30].

The original composition of the window is unknown, so R. Cramp made different compositions with the pieces to showcase the shards (fig. 2; 3).

Figure 2: Stained glass window in St. Paul's Church. Picture by Stephen Liddell, 2018.

Figure 3: Static window cling of the stained glass window in St.Paul's church by Winged Heart Stained Glass Static Window clings.

30 K. Richman-Abdou, Stained Glass: The Splendid History of an Ancient Art Form That Still Dazzles Today, My Modern MET, 28. IV 2019, https://mymodernmet.com/stained-glass-history/ (Accessed 10.XI 2021).

The oldest complete European windows are thought to be five relatively sophisticated figures (fig. 4) in Augsburg Cathedral in Bavaria from the second half of the 11th century[31].

Figure 4: Stained glass windows in Augsburg Cathedral, Bavaria. Picture by Hans Bernhard (Schnobby)/Wikimedia Commons/CC BY 3.0.

During the Middle Ages, glasshouses were typically in isolated forests due to the need of potash[32] or in coastal settings where there were marine plants that could be used to produce[33] soda ash[34].

The main methods of making glass during the medieval times was the, before mentioned, cylinder method and a newer crown glass[35] method. For the crown glass method (fig. 5) the glass was blown into a bubble, transferred from the blowpipe to the pontil[36], held in front of the mouth of the furnace and rapidly spun. The centrifugal force from spinning made the hot glass take on a round disc shape[37]. After the disc cooled there was an option to cut squares or rectangles from the edges. The edges were often preferred because in the middle of the disc the glass was thicker where the pontil mark was. It is known that the leftover centre pieces of the crown glass with the pontil mark were used as window panes by themselves.

31 M. Faith, The History of the World's Oldest Antique Stained Glass Windows, Scottish Stained Glass, https://www.scottishstainedglass.com/religious-stained-glass/the-history-of-the-worlds-oldest-antique-stained-glass-windows/ (Accessed 04.XII 2021).

32 **Potash** – Potassium carbonate. It is an alternative to soda as a source of alkali in the manufacture of glass.

33 G. McKearin, H. McKearin, American Glass, Crown Publishers, New York, 1941, p 3.

34 **Soda ash** – Sodium carbonate. Soda is commonly used as the alkali ingredient of glass. It serves as a flux to reduce the fusion point of the silica when the batch is melted.

35 **Crown glass** – Sheet glass made by blowing a parison, cutting it open, and rotating it rapidly, with repeated reheating, until the centrifugal force has caused it to become a flat disk.

36 **Pontil** – The pontil, or punty, is a solid metal rod that is usually tipped with a wad of hot glass, then applied to the base of a vessel to hold it during manufacture.

37 P. S. Casciani, The Technique of Decorative Stained Glass, p 105.

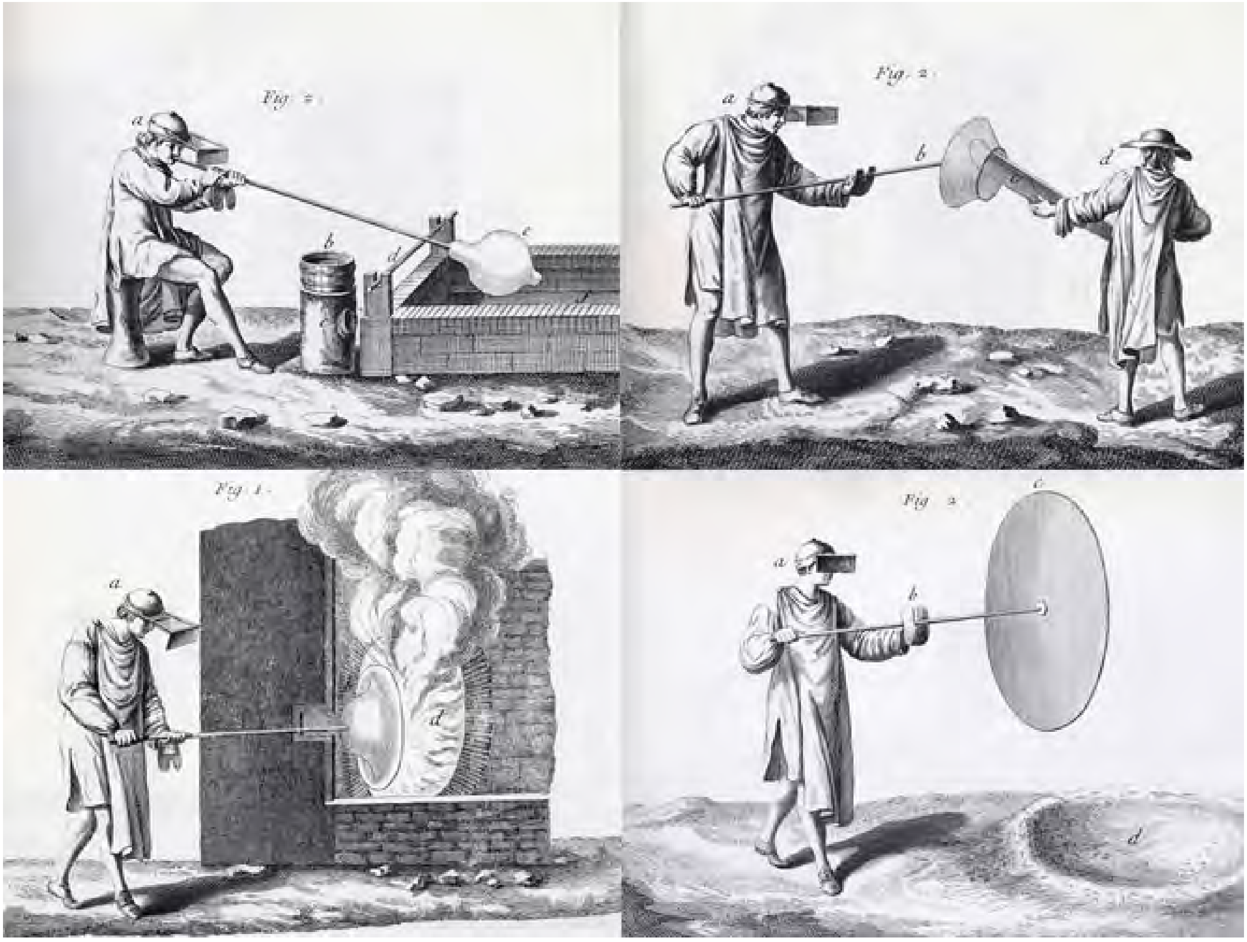

Figure 5: Engraving of crown glass making (Verrerie en bois) by Robert Bénard from D. Diderot and d'Alembert's Encyclopédie (1772).

During the Romanesque period (9th–10th century) the buildings were getting taller and lighter than ever before. In the 12th century the Romanesque style was followed by the Gothic period (13th–14th century), churches and cathedrals built in this style show an interest in height and light.[38]

The development of medieval stained glass can be directly connected to the developments in Gothic architecture. The windows became larger due to the use of pillars as support for the roof. Previously the roof's weight rested almost solely on the walls. The larger the window arches became the more stained glass was needed to fill them. A single holy figure in a decorated canopy became one of the most popular ways to fill the space on the glass with.[39] Thus the stained glass windows took centre stage in elaborate and monumental cathedral designs.

In the Gothic era the stained glass was mostly made of many smaller pieces of coloured glass that were joined together by lead to create complex patterns. The stained glass windows were illustrated with the stories of the bible and the lives of saints (fig. 7).

38 Stained Glass: The Splendid History of an Ancient Art Form That Still Dazzles Today.
39 P. S. Casciani, The Technique of Decorative Stained Glass, p 106.

As with other art forms of the period, the stained glass artists were not interested in the realism of the designs but more in the ideas (fig. 9).[40]
All of this is reflected on the windows of the time.

Gothic windows typically come in two designs: the lancet windows[41] and the rose windows[42] (fig. 6; 8) Both of these window styles are often made in a huge scale with the glass supported and window decorated by tracery[43].[44]

Figure 6: Detail of the Rose window "The Dean's Eye" (1235) in Lincoln Cathedral. Top left: A Funeral or Translation of a Saint. The others show Blessed souls in Heaven. Photo by Tilman2007/Wikimedia Commons/CC BY 3.0.

Figure 7: Detail from the Great East Window, "Adam and Eve, the Fall from Grace" (1405-1408) in York Minster picture by John Thornthon.

40 A Short History of Stained Glass.
41 **Lancet window** – A narrow window with a sharp pointed arc.
42 **Rose Window** – A round window divided into segments by stone mullions and tracery that imitate a multi-petalled rose.
43 **Tracery** – A pattern of interlacing lines, esp. one in a stained glass window, often made of wood, stone or cast iron.
44 Stained Glass: The Splendid History of an Ancient Art Form That Still Dazzles Today.

Figure 8: Rose window "The Dean's Eye" (1235) in Lincoln Cathedral. Photo by Tilman2007/Wikimedia Commons/CC BY 3.0.

Figure 9: Detail of upper royal chapel, "Devil kidnapping a woman" (1248) in Sainte-Chapelle. Picture by Clio20 assumed (based on copyright claims), CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=560880

In the 15th century the way that stained glass was made and viewed gradually changed.

The Gothic style, with its strong dark lines and figures was gradually replaced by the new Classical style, which was inspired by the new realism style in Renaissance paintings[45].

With the new style, the stained glass was treated more like a translucent painting – the colours became paler and the figures larger (fig. 10), the lead lines, which in the Gothic style were very much a part of the design were viewed as a disturbance (fig. 11). As the Classical style evolved, eventually most of the stained glass was just made from white panels that were heavily painted. The depictions also changed, as the stories told through stained glass started to lose a lot of their previous symbolism.

Figure 10: Stained Glass Panel with the Visitation from Carmelite church (1444). Picture by the Metropolitan Museum of Art.

Figure 11: The Mater Dolorosa from the cathedral of Constance Peter by Hemmel von Andlau (Strassburger Werkstattgemeinschaft) (1480). Picture by the Metropolitan Museum of Art.

However, in this era the stained glass moved from religious buildings to also decorating public buildings and houses of the wealthy. The Classical style lasted about 300 years[46].

45 The History of Stained Glass.
46 A Short History of Stained Glass.

Until the 16th century, stained glass was primarily a Catholic art form in England. A lot of the stained glass windows depicting saints were destroyed during the 1600's when King Henry VIII broke apart from the Catholic Church. Beside religious unrest in England, the decrease of popularity of stained glass was caused by the Baroque period (17–18th century)[47].

Although in the late 16th century and early 17th century in Switzerland, Low Countries and Germany there was a rise of the portable glass heraldic panels (fig. 12), that were usually hung from the home windows of the families. The use of these panels was not enough to keep stained glass popular in the countries overall. Usually the panels were maximum 60 cm in height[48].

Figure 12: Heraldic panel from Germany (16th century). Picture by the Metropolitan Museum of Art.

47 The History of Stained Glass.

48 R. W. Sowers, Stained Glass, Periods and Centres of Activity, 17th and 18th Centuries, Encyclopaedia Britannica, https://www.britannica.com/art/stained-glass/17th-and-18th-centuries (Accessed 19.XII 2021).

Unfortunately, the dramatic lighting and illusions of movement in Baroque art could just not be reciprocated in the art of stained glass. Instead, artists realised that they could just use glass as an opaque canvas, without the need to incorporate lead as a part of the design. After that, lead was purely used to just hold the painted glass physically together (fig. 13; 14). The aforementioned reasons had a direct impact on the decline of stained glass[49].

Figure 13: Judith onthoofdt Holofernes in Sint Janskerk, Gouda by Dirck Crabeth (1571). Picture by Frans Holtkamp, 2015.

Figure 14: Jonah and the City of Nineveh by Abraham van Linge in Christ Church Cathedral, Oxford (1630). Picture by Dominic Price, 2019.

49 Periods and Centres of Activity, 17th and 18th Centuries.

During the 18th century the removal of medieval stained glass was commonplace, the windows were destroyed and replaced with painted glass. In the late 18th and early 19th century the Gothic revival made an appearance. This was caused partly because of the revival of the Catholic church in England and partly to counteract the Baroque movement. With the revival of the Catholic church, a lot of new churches and cathedrals were built and old religious buildings restored[50].

With this focus on the Gothic era, the interest in both the technique and history of medieval stained glass returned. The stained glass itself was a combination of the old Gothic style and the Romantic style (fig. 15), but also many new styles were developed[51].

In the first half of the 19th century the attempt to mimic the early Gothic period was made, but unfortunately there was a lack of appreciation of the medieval aesthetic. A lot of the stained glass was mass-produced, often in Germany, and varied a lot in quality. The pioneers in the Gothic revival of the stained glass field were E. Viollet-Le-Duc in France and Charles Winston in England. Winston wrote the first exhaustive study about stained glass as a medium in 1847 and by experimenting improved the quality of coloured glass itself. Thanks to these experiments W. E. Chance produced antique quality glass in 1863. In the second half of the 19th century the lead lines in the windows were seen as a part of the design again, and not a disturbance like previously[52].

In America, the first glasshouse was built in Jamestown, Virginia during the 17th century for the purpose of manufacturing glass beads and bottles[53]. English immigrant William Jay Bolton was the first to establish a stained glass studio in America in 1842. He made Gothic style figural stained glass, which was the norm until the American style stained glass emerged. Joseph and Richard Lamb established their studio "J&R Lamb Studios" in 1857, which turned out to be the longest run decorative arts company in America[54].

50 A Short History of Stained Glass.
51 The History of Stained Glass.
52 Periods and Centres of Activity, 17th and 18th Centuries.
53 G. McKearin, H. McKearin, American Glass, p 75.
54 A Short History of Stained Glass.

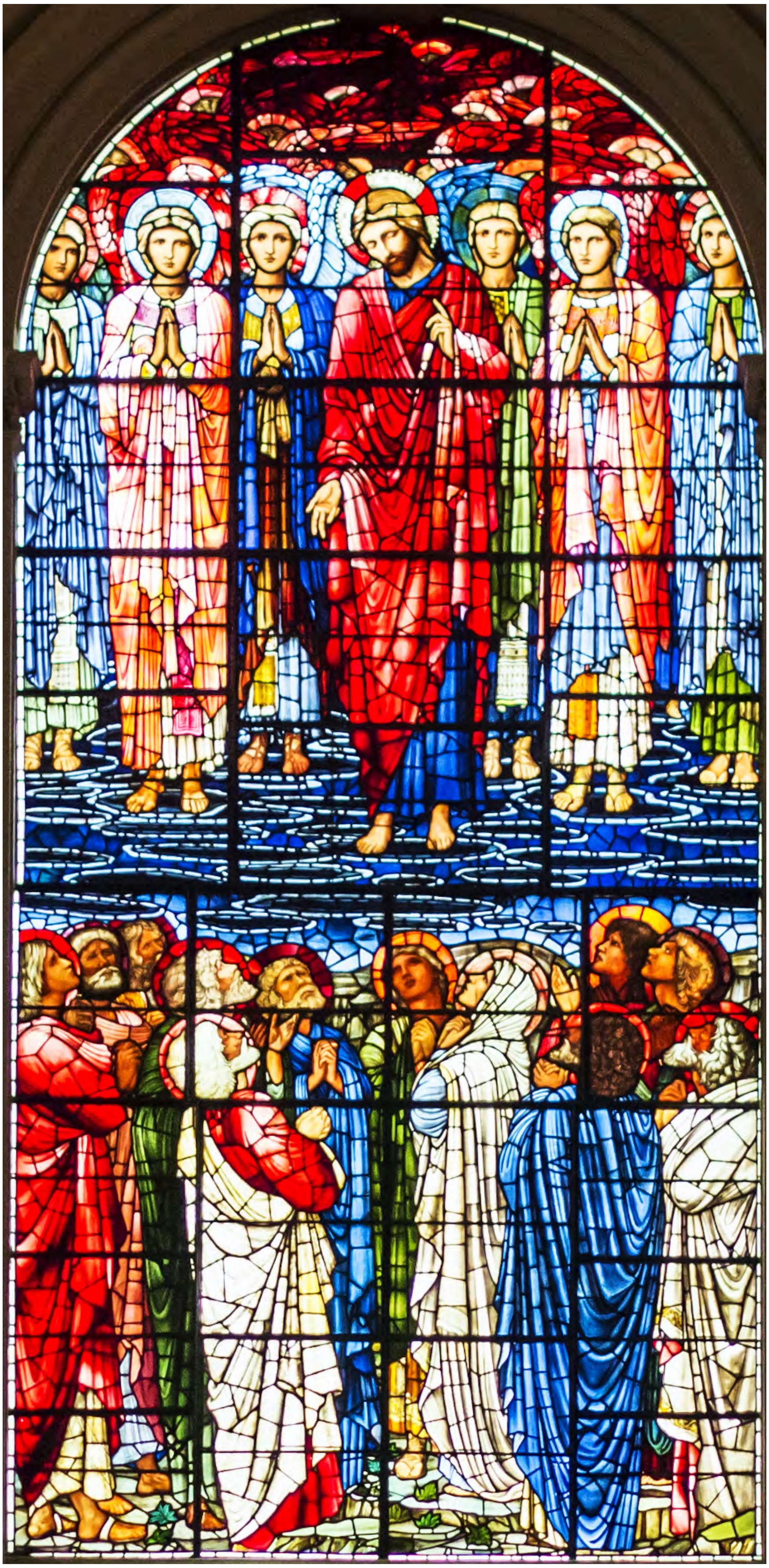

Figure 15: Stained glass in St. Philip's Cathedral, Birmingham by Edward Burne-Jones (1897). Picture by Raheel Shahid - Flickr: St phillips cathedral, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=33243644.

At the end of the 19th century John LaFarge and Louis Comfort Tiffany created opalescent glass[55]. This invention meant that the effects of paint could be made with glass itself[56]. Tiffany was also the one that popularised, and possibly invented, the copper foil method[57] which he used in a multitude of ways – from lampshades to windows. The Tiffany style was widely imitated and remained popular until the death of Tiffany (1933), when opalescent glass started to lose its esteem[58].

Parallel to the invention of opalescent glass, a new style of architecture and interior architecture, including stained glass, emerged from America. The new style was called the Prairie School movement and one of its pioneers was Frank Lloyd Wright. This style was mostly inspired by nature and the art of craftsmanship and, although strictly ornamental, established the beginning of modern stained glass (fig. 16).[59]

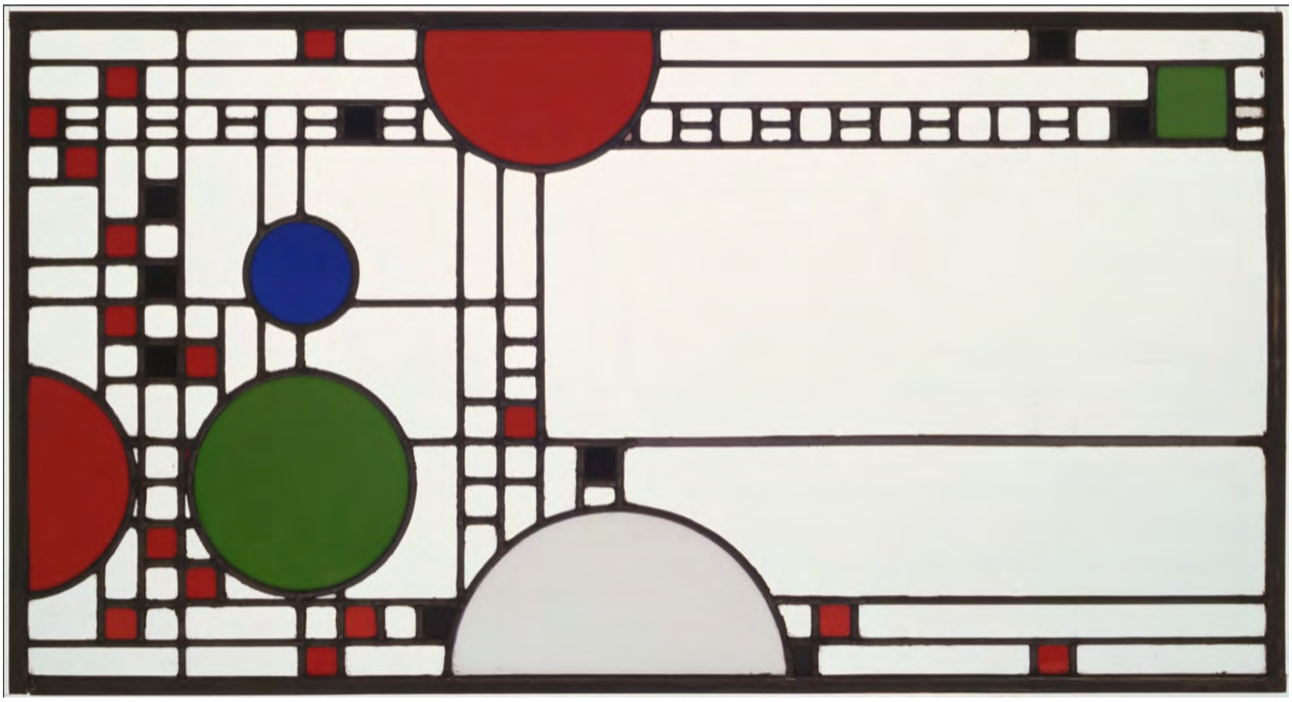

Figure 16: Clerestory windows from the Avery Coonley Playhouse, Illinois by Frank Lloyd Wright (1912). Picture by The Museum of Modern Art.

With the exception of the stained glass in churches, for example in Notre-Dame du Raincy by Maurice Denis during 1922–1923 and in St. Georg's Church, Cologne by Johan Thorn Prikker in 1930, the overall popularity of stained glass was in decline until the end of WWII (1945)[60].

55 **Opalescent glass** – A type of late 19th-century Art Glass, made by covering a gather of coloured glass with a layer of colourless glass containing bone ash and arsenic or minerals.
56 Periods and Centres of Activity, 17th and 18th Centuries.
57 **Copper-foil method** – In the copper foil technique, edges of glass are wrapped in thin copper foil. The foil covers the entire edge of the glass and about one-sixteenth of the front and back sides.
58 A Short History of Stained Glass.
59 Stained Glass: The Splendid History of an Ancient Art Form That Still Dazzles Today.
60 A Short History of Stained Glass.

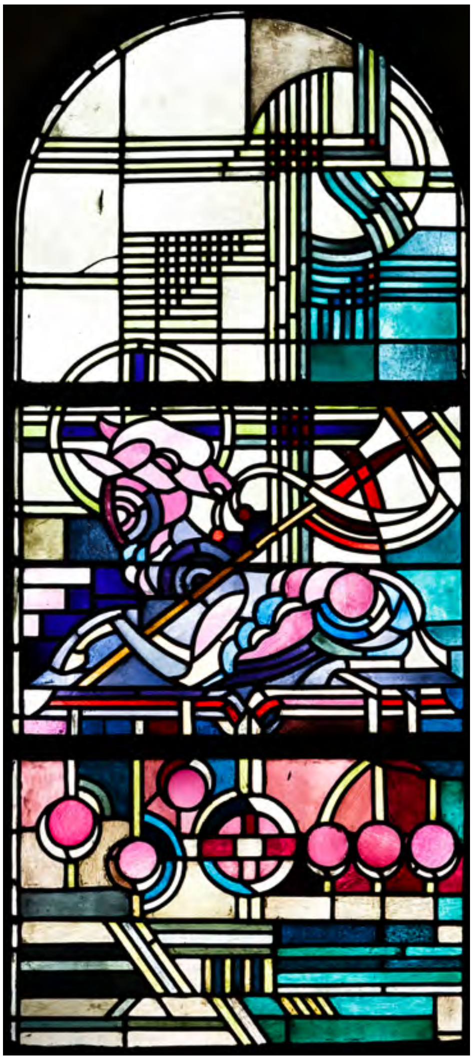

Figure 17: Stained glass windows in St. Georg, Cologne by Johan Thorn Prikker (1930). Photo by © CEphoto, Uwe Aranas, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=47222274.

After 1946 stained glass started to suddenly gain popularity[61]. The expressionist movement inspired artists to experiment with different mediums, this included glass and the art of stained glass[62]. Artists, including Henri Matisse, Georges Braque and Fernand Léger (fig. 18), started the new era of stained glass. The designs became abstract (fig. 17) and took more of the form of decorative art[63]. The expressionist artists, and the ones after them, have continued to explore the world of stained glass through the different properties of opalescent and textured glass and the incorporation of the lead line as a more organic part of the stained glass[64]. These experiments have encouraged artists from all around the world to start creating their own works of glass art[65]. This in turn has popularised stained glass as a hobby – becoming more accessible and creating new and original styles from combining existing styles[66].

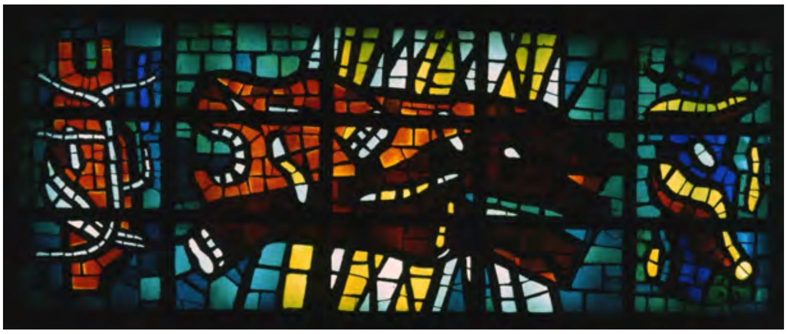

Figure 18: "La Sainte Tunique" in Sacré-Cœur at Audincourt by Fernand Léger (1951). Picture by The Vatican Museum.

61 R. W. Sowers, Stained Glass, Periods and Centres of Activity, 20th Century, Encyclopaedia Britannica, https://www.britannica.com/art/stained-glass/20th-century (Accessed 19.XII 2021).
62 A Short History of Stained Glass.
63 The History of Stained Glass.
64 Periods and Centres of Activity, 20th Century.
65 The History of Stained Glass.
66 A Short History of Stained Glass.

3. Glass as a material

In a very broad definition, glass can be defined as a homogeneous material with a noncrystalline molecular structure[67] or more specifically as silicone dioxide (SiO_2), flux and stabiliser melted together and then cooled. With sand being mostly silicone dioxide, flux as any substance (most commonly soda ash or potash (K_2CO_3) made from the ashes of marine plant or burned trees respectively) that lowers the melting point of a solid and the stabiliser as a substance that prevents glass from dissolving or crumbling (breaking down), commonly calcium oxide (CaO)[68].

It should be mentioned that before glass was man made, it occurred in nature due to magmas (silicate melts) coming into contact with ice, water or atmosphere and as a result promptly cooling down[69]. When looking at the durability of glass from the so-called beginning, it must be said that generally Roman glasses, which are very sodium rich, are fairly stable[70].

The Romans used natron ($Na_2CO_3 \cdot 10H_2O$) as soda, which was also supplied to northern Europe by the Roman trade routes. After it became difficult to obtain it was replaced by potash (K_2CO_3) (burnt tree ashes) in northern Europe as a fluxing agent. This caused a huge shift in chemical composition, as soda-lime silicate glasses were replaced by potash-lime silicate glasses. The impact of this change will be explained in finer detail in the following sub chapters. The potassium-rich medieval glasses are very sensitive to water, which is the main culprit of corrosion. With glasses having lost up to ⅓ of their original thickness due to corrosion[71].

Even though medieval glasses are more sensitive, all glasses have water as the main aggressive agent, being generally the most influential of the environmental factors[72]. Firstly there is a formation of a gel or hydrated layer that after a certain thickness is covered in a craquelure pattern[73]. The soda-lime silicate glasses of the 19th century are much more durable compared to the medieval windows[74]. Glass, no matter if coloured, textured or clear, produced from the 19th century onwards has retained the basic composition quite consistently and with a consistent composition the response to outside factors has remained consistent as well[75]. Even though the basic composition of the soda-

67 Glass, Glass Dictionary, Corning Museum of Glass, https://www.cmog.org/content/glass-8 (Accessed 12.I 2022).
68 G. Gronniger, Break it Down: Analyzing Glass Fracture Patterns, Missouri State University Sociology and Anthropology Department ANT 650, 2013, p 3.
69 H. Römich, Chapter 7: Glass and Ceramics, Conservation Science, Heritage Materials, Edited by Eric May; Mark Jones, RSC Publishing, The Royal Society of Chemistry, 2006, p 161.
70 Ibid, p 168.
71 Ibid, p 167.
72 Ibid, p 172.
73 Ibid, p 166.
74 Iibid, p 167.
75 S. Hardingham, An Analysis of Stained Glass Fabric Specific to Conservation Assessment, Master of Heritage Conservation, the Faculty of Architecture, Design and Planning, University of Sydney, June, 2013, p 7.

lime silicate glasses are comparable to modern glasses, there is a key difference concerning the quality of the glass. The ancient glasses[76] contain large amounts of impurities coming from the impure raw materials[77].

3.1. Chemical composition

Most of the early stained glass windows are made of potash-lime-silica glass. Still there are huge differences in the composition, likely from being made of different batch materials. Some examples of the differences can be: different types of plant ashes (used as alkali), where the silica came from, how the batch was purified/prepared, adding lime or bone ash, the size of the portions of the materials when mixed together and the percent of ferric oxide present[78].

Besides the complex compositions the differences of chemical durability in glasses come from aspects like the roughness of the surface and production process, including the thermal history[79]. Usually potash glasses with high lime and low alkali concentration are less affected by the outside conditions than potash glasses with high potash levels[80].

Generally the higher the concentration of silica and sodium in glass, the more thermally and chemically stable it is. That is due to the ion bonds, sodium ions have stronger bonds than potassium ions, meaning generally sodium silicate glasses are much more durable than potassium-rich glasses. For most ancient glasses sand (SiO_2) is the main component with the additives to lessen the melting temperature like lime ($CaCO_3$) or magnesium carbonate ($MgCO_3$) and soda (Na_2CO_3) or potash (K_2CO_3)[81]. The addition of lime also makes the glass more water-proof, as the soda-silica glasses alone are generally more sensitive to water than soda-lime-silica glasses, but still less sensitive than just potassium rich glasses[82]. The aforementioned elements make up more than 90% of the composition of soda- or potash-lime silicate glasses. Still, as mentioned before, most ancient glasses are made of up to 30 different components, most showing up as only the trace amount. Besides SiO_2 there are other inorganic oxides that can be network formers (they form cross-linked network of chemical bonds), for example phosphorus oxide (P_4O_{10}). Alkaline earth oxides, like calcium oxide (CaO), can also be used with silica to form glass, although the reaction is very different than with inorganic oxides. With alkaline oxides the silicon-oxygen bond is broken

76 **Ancient glass** – A term frequently used to mean all pre-Roman and ancient Roman glass.
77 R. H. Brill, A Note on the Scientist's Definition of Glass, The Journal of Glass Studies vol. 4, 1962, p 134.
78 R. H. Brill, P. Pongracz., Stained Glass from Saint-Jean-des-Vignes (Soissons) and Comparisons with Glass from Other Medieval Sites, The Journal of Glass Studies vol. 46, 2004, p 121.
79 H. Römich, Chapter 7: Glass and Ceramics, p 165.
80 Stained Glass from Saint-Jean-des-Vignes (Soissons) and Comparisons with Glass from Other Medieval Sites, p 122.
81 H. Römich, Chapter 7: Glass and Ceramics, p 163.
82 R. H. Brill, A Note on the Scientist's Definition of Glass, p 134.

up, that means that the ionic bonds between the network modifier (cations) and NBO (non-bridging oxygen; anions) are not as strong as the links within the network. This means that the cations, like calcium ions, have the possibility to migrate in the structure, therefore impacting the chemical durability of the glass. There is also a third group of oxides like lead, magnesium and aluminium, that can work in the glass structure as either a network modifier or a former[83].

One of the most important chemical properties of glass is the chemical durability of it, which also holds the key to its degradation[84]. The chemical degradation starts with water on the surface of the glass. Although the degradation rate itself depends on the pH of the liquid. When water is acidic it migrates into the glass with hydronium ions (H_3O) and replaces the alkaline/alkaline earth elements positively-charged ions, which then are leached out of the glass. Meaning, the hydroxide ions attack the SiOSi bonds leading to the disintegration of the network. The result is the creation of the gel layer (a hydrated layer) which has a very different composition compared to the rest of the glass[85].

3.2. Physical properties

There isn't any sole substance that is used in the definition of glass. It should be used as an umbrella term for the different compositions of materials[86]. Since technically, glass can not be defined by its chemical composition due to the variety of chemical compositions that can be made into glass, it must be defined by the atomic arrangements and physical structure[87]. All matter consists of molecules that are constantly in motion. The molecules are made up of atoms that are chemically bonded together. The relative balance between kinetic energy and attractive forces regulates the physical state of the matter[88]. The attractive forces holding iron oxide and silica together are very strong, that is why the melting/boiling points are very high. The stronger the bonds the more thermal energy is needed to break them. There are three recognised states of matter: liquid, gas and solid. Glasses do not fit within these three categories. They have the mechanical rigidity of crystals (fig. 19) but the structure is disordered (fig. 20) like with liquids[89]. Although the network of the structure in glasses is not like the structure in conventional liquids, where the molecular units are much smaller than in glasses[90].

83 H. Römich, Chapter 7: Glass and Ceramics, p 163.
84 Ibid, p 168.
85 Ibid, p 164.
86 R. H. Brill, A Note on the Scientist's Definition of Glass, p 131.
87 Ibid, p 127.
88 Ibid, p 128.
89 Ibid, p 129.
90 Ibid, p 132.

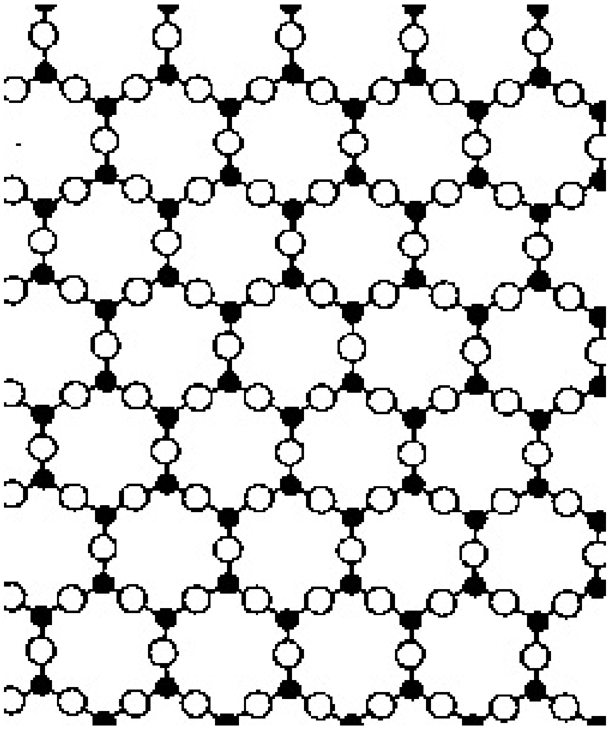

Figure 19: The molecular arrangement in a crystal. Image from "Is glass a liquid or solid?" by Philip Gibbs, The Physics and Relativity FAQ (1996)

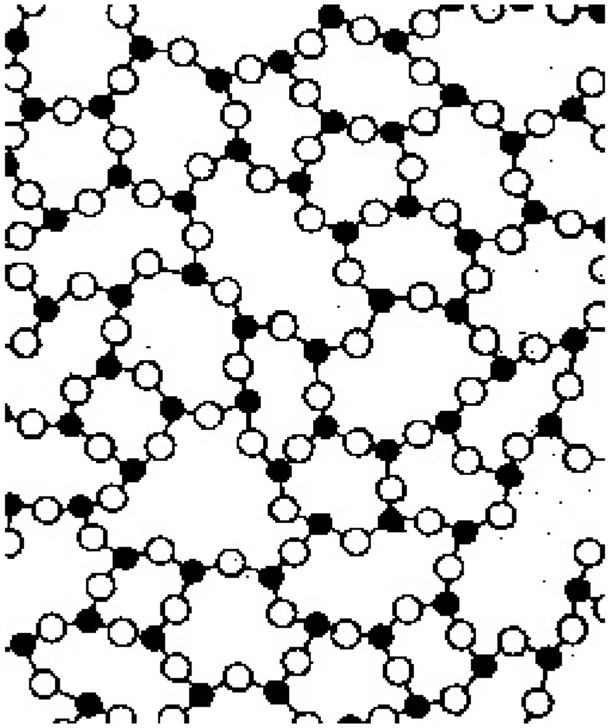

Figure 20: The molecular arrangement in a fused silica glass. Image from "Is glass a liquid or solid?" by Philip Gibbs, The Physics and Relativity FAQ (1996)

That is why there is a term called the “vitreous state”, where the molecular units are disordered, but there is still enough cohesion to produce mechanical rigidity[91]. It is the so-called fourth state of matter. The vitreous state may also be categorised as a different case of the polymerized state where the molecules combine with each other to create the chainlike networks with great rigidity[92]. A difference between glasses and crystals, that must be noted, is that the melting point of a crystal is very sharp, meaning that the crystalline material remains solid until it hits the precise melting temperature and then suddenly liquifies. The reason for this is because the chemical bonds in the crystal break at the same time because they are all identical[93].

However, the chemical bonds in glass are not in the stable geometric form, so the different bonds break at different temperatures, because each bond has its own degree of strain and thus its own melting point. As a rule, the bigger the strain is the weaker the bond. This is the reason why unlike crystals, glasses melt slowly. As the temperature rises the weaker bonds start to break, until the temperature becomes high enough that all the bonds have broken and the glass has therefore become fluid[94].

91 R. H. Brill, A Note on the Scientist’s Definition of Glass, p 129.
92 Ibid, p 132.
93 Ibid, p 134.
94 Ibid, p 136.

Due to this physical structure the rigidity of the glass changes dramatically based on the temperature and thus it is fitting to describe this aspect in terms of viscosities[95]. Even though, technically, the term itself is used in context of liquids and measures the flow rate (the higher the viscosity the slower the flow rate). The unit of viscosity is called poise, water at room temperature is .010 poise, but the viscosity of most glasses at room temperature is about 10^{19}–10^{22} poises (almost the highest of viscosity measurable). As the temperature rises the viscosity drops, at 10^{3-4} poises the glass can be blown/moulded (about anything above 540 Celsius[96]). Usually, at the softening point, the viscosity of glass is $10^{7.65}$ poises and, depending on the composition of glass, the temperature is around 450 Celsius when glass reaches that point. When heated to a very high temperature the glass can have a low viscosity as well. Between the two ends of a viscosity spectrum, although there is no clear transition, the state of glass might change from vitreous to a true liquid (molecular units being small and glass itself flowing with ease). Still, this is why some might say that glasses are just supercooled liquids, being extremely viscous at room temperature[97].

A list of physical properties can be attributed to glasses in general: the viscosity determines the working range, visual properties connected to the refractive index characterise the transparency and of course most physical properties of glasses can be characterised by hardness, brittleness and density[98].

95 R. H. Brill, A Note on the Scientist's Definition of Glass, p 138.
96 P. Beveridge, I. Domenech, E.Pascual, Warm Glass, New York, Lark Books, 2005, p 62.
97 A Note on the Scientist's Definition of Glass, p 136.
98 H. Römich, Chapter 7: Glass and Ceramics, p 168.

4. Different types of glass

Sheet glass is often categorised based on the appearance and the technique that it was made. The following sub-chapters will give a short description of the most common glasses used for making works of stained glass. It should be mentioned before that not all of these categories are exclusive and often overlap with each other. Meaning that glass can have characteristics of two categories at the same time.

For the stained glass panel displaying the different conservation techniques three different types of glass were used: light blue coloured cathedral, blue coloured, dark purple cathedral and light pink coloured.

4.1. Opalescent

As written previously, opalescent glass was developed by John La Farge and Louis C. Tiffany at the end of the 19th century. The glass was named after opal stones, because of its iridescent look. With the characteristics of appearance being varying degrees of opaqueness from lightly translucent to almost fully opaque and generally milky appearance with a mix of streaks of two or more colours, although one coloured versions exist as well[99]. The glass usually is made by swirling two to four colours together by adding particles of pigments to the glass, unless, only one colour is needed[100].

4.2. Flashed

Flashed glass is essentially two layers of different coloured glass made into one sheet of glass. Technically, there can be a variety of colours flashed on top of another, but most common is any intense colour flashed on top of white (colourless) glass[101]. The technique of making flashed glass was discovered in the 13th century by trying to find an alternative to red glass, as it was often dense, thus hard to cut, due to the gold salts or colloidal gold used to produce the colour and also expensive to make. Therefore, flashed ruby was invented by fusing only a layer of the red glass onto a clear base glass. Besides being easier to cut, flashed glass also has the ability to be abraded, so the

99 Opalescent Stained Glass ("American glass"), Illustrated Architecture Dictionary, Buffalo as an Architectural Museum, https://buffaloah.com/a/DCTNRY/stained/opa/opa.html (Accessed 20.IX 2021).
100 B. Lerew, Getting to Know the Different Types of Stained Glass, Cumberland Stained Glass INC, 18.V 2020, https://www.cumberlandstainedglass.com/getting-to-know-the-different-types-of-stained-glass/ (Accessed 23.X 2021).
101 Flashed Glass, Illustrated Architecture Dictionary, Buffalo as an Architectural Museum, https://buffaloah.com/a/DCTNRY/stained/dcty/dcty.html#Flashed (Accessed 20.IX 2021).

part of the red glass can be removed to show the white underneath[102]. Often the removal is done by etching the glass with hydrogen fluoride (HF) or sandblasting. The glass itself is made by dipping a ball of hot white glass into molten coloured glass, which then was blown and flattened. The coloured layer will be less intense than it would be with full coloured glass, because it is white on one side[103].

4.3. Coloured

Coloured glass is a unicoloured sheet of glass throughout. The glass gets its colour from either the impurities present in the basic batch ingredients or by purposeful colouring. For that there are three main methods. Either using a powdered metal oxide in the batch to get uniform colour throughout, with the formation of colloidal metallic/non metallic nanoparticles in the glass by for example dipping hot glass in pulverised particles[104]. Although it must be mentioned that the colour itself depends on the oxidation state, which can be regulated by the temperature in the furnace of the metal and not only the amount that is present[105].

Table 1: A table about Metallic oxides and their corresponding glass colours[106].

Metal oxides	*Colour*
Gold Chloride	*Red*
Selenium Oxide	*Red*
Manganese Dioxide	*Purple*
Nickel Oxide	*Violet*
Cobalt Oxide	*Blue-Violet*
Copper Compounds	*Blue, Green, Red*
Chromic Oxide	*Emerald Green*
Iron Oxide	*Green, Brown*
Carbon Oxides	*Amber-Brown*
Sulphur	*Yellow-Amber*
Uranium Oxide	*Fluorescent Wellow, Green*
Lead Compounds	*Yellow*
Cadmium Sulphide	*Yellow*
Tin Compounds	*White*
Antimony Oxides	*White*

102 P. S. Casciani, The Technique of Decorative Stained Glass, p 106.
103 Flashing, Glass Dictionary, Corning Museum of Glass, https://www.cmog.org/glass-dictionary/flashing (Accessed 23.X 2021).
104 Colored Glass, Glass Dictionary, Corning Museum of Glass, https://www.cmog.org/glass-dictionary/colored-glass (Accessed 23.X 2021).
105 H. Römich, Chapter 7: Glass and Ceramics, p 163.
106 H. M. King, Elements of Color in Stained and Colored Glass; Cobalt, Gold, Lead, Copper and Uranium Have Been Used to Color Glass, Geology.com, https://geology.com/articles/color-in-glass.shtml (Accessed 30.III 2021).

4.4. Cathedral

Cathedral glass is an umbrella term for any glass that has texture on one side. Usually the glass is transparent and in single colour. It can be either machine made or poured, where in either case the molten glass takes the shape of the textured tabletop mould beneath[107]. The name comes from the similarity of the windows used in medieval European cathedrals[108]

4.5. Antique

Antique glass usually refers to glass made with traditional methods like the blown cylinder method[109]. Since antique glass is handmade, it has certain "imperfections" like air bubbles (called seeds), draw lines and striation (lines that appear like cracks on the surface of the glass). The reason that antique glass is still so desired, despite the aforementioned, is because the glass usually accepts glass paint and stains more consistently throughout[110].

107 Getting to Know the Different Types of Stained Glass.
108 Cathedral Glass, Illustrated Architecture Dictionary, Buffalo as an Architectural Museum, https://buffaloah.com/a/DCTNRY/stained/dcty/dcty.html#Cathedral (Accessed 23. X 2021).
109 Getting to Know the Different Types of Stained Glass.
110 S. Hardingham, An Analysis of Stained Glass Fabric Specific to Conservation Assessment, p 16.

5. In depth about a fracture and other common damages

Typical stained glass reacts to extreme heat, cold and mechanical damage in a certain pattern. That is why determining the type of the damage helps to determine the correlating cause of the damage itself[111]. Although cracks have different causes and appearances, generally they will follow the line of applied stress or start at the point of applied stress and follow the internal stress points of the glass[112]. There is a theory, that internal fractures in glass always begin from pre-existing flaws (Griffith Flaws)[113].

When a crack in the stained glass window is not stabilised, the edges of the break will grind against each other due to thermal movement, vibrations or other outside movements, leading it to enlarge over time. That is why the sooner the crack is discovered, the better it is to repair it, while the edges of the break remain sharp and the break is “clean”[114].

Besides the fracture, there are also other damages that occur in flat and three-dimensional glass. For example, the aforementioned water damage can cause weathering (fig. 22) and crizzling (fig. 23).

Weathering is a form of glass corrosion that causes changes on the surface of glass by chemical reaction with the environment. Usually involving the leaching of alkali from the glass by water, leaving behind siliceous weathering products[115].

Crizzling is the result of chemical instability in glass caused by an imbalance in the ingredients of the batch, particularly an excess of alkali or a deficiency of stabilizer (usually lime). The instability of the glass results in an attack by atmospheric moisture, which produces a network of fine cracks in the surface that may feel damp or oily. There are five stages of severity of crizzling: initial stage, incipient crizzling, full-blown crizzling, advanced crizzling, fragmentation stage. Crizzling can be slowed, but not yet reversed. Crizzled glass is sometimes described as “sick” or “weeping.”[116] The extreme form of crizzling is sometimes called sugaring[117].

111 S. Hardingham, An Analysis of Stained Glass Fabric Specific to Conservation Assessment, p 7.
112 Ibid, p 8.
113 A. A. Griffith, The Phenomena of Rupture and Flow in Solids. Philosophical Transactions. Royal Society of London Series A 221, 1920, p 582.
114 N. A. Vogel, R. Achilles, The Restoration and Repair of Historic Stained and Leaded Glass, Old House Journal, https://www.oldhouseonline.com/repairs-and-how-to/restoration-repair-historic-stained-leaded-glass/ (Accessed 07.IV 2022).
115 Weathering, Glass Dictionary, Corning Museum of Glass, https://www.cmog.org/glass-dictionary/weathering (Accessed 14.V 2022).
116 Crizzling, Glass Dictionary, Corning Museum of Glass, https://www.cmog.org/glass-dictionary/crizzling (Accessed 14.V 2022).
117 K. Wittstadt, G. Maas-Diegeler, P. Bellendorf, C. Dirsch, A Special Kind of Crack Pattern on Historic Glass – Exploring the Causes of ‘Sugaring’, Recent Advances in Glass, 2013, p 21.

Figure 21: Glass statuette of Venus with very thick weathering layers which have been lost in some areas.When it was new, the object was yellowish green colour. (1st or 2nd century). Image by Corning Museum of Glass, "Statuette of Venus", accession number: 55.1.84.

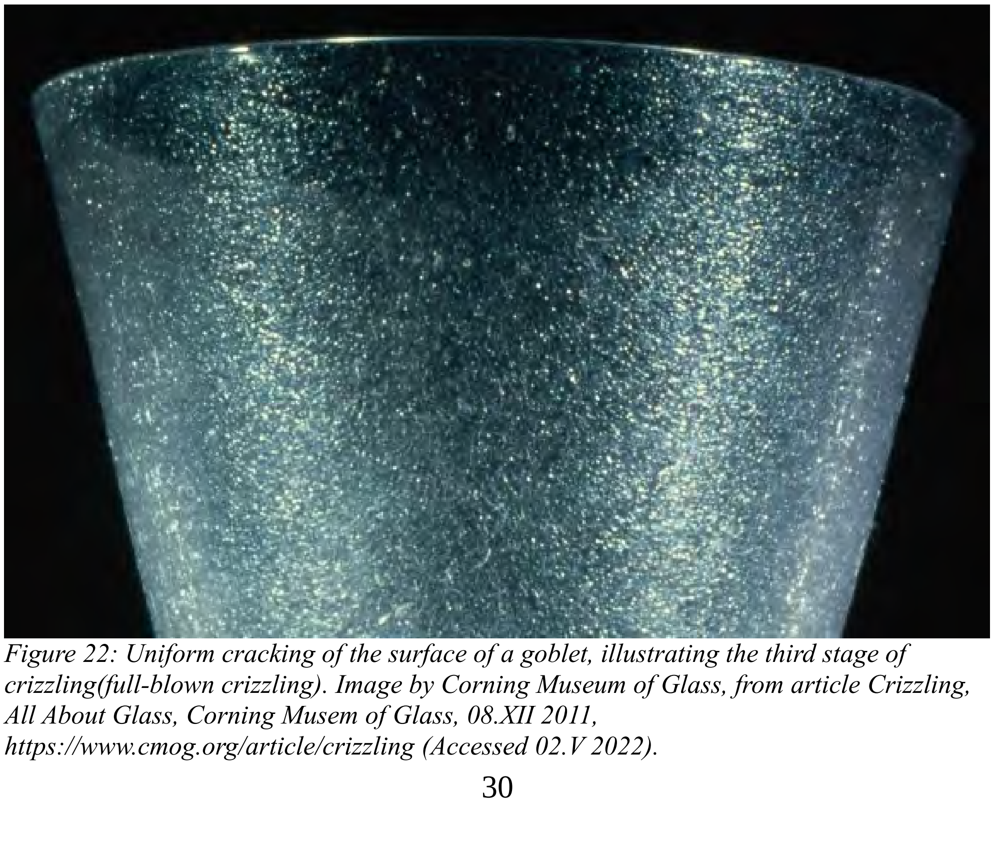

Figure 22: Uniform cracking of the surface of a goblet, illustrating the third stage of crizzling(full-blown crizzling). Image by Corning Museum of Glass, from article Crizzling, All About Glass, Corning Musem of Glass, 08.XII 2011, https://www.cmog.org/article/crizzling (Accessed 02.V 2022).

5.1. Different types and causes

It is inevitable that the process of making glass and the composition of glass itself leaves it with microscopical imperfections. Therefore fractures and breaks are very common in all types of glass objects and can happen from a lot of external factors like thermal and physical stress on the object. Fractures can occur more often on two dimensional large objects as there is more surface area and mass, so their potential energy can break the bonds easier[118].

For the practical part of the thesis a panel will be constructed showcasing the different crack patterns and the five different conservation methods that will be used on them. The panel itself will be made with a pattern called boxed diamond, that was popular in the Tudor era (16th century) and the Tudor revival era (19th century).

For the panel, mostly a combination of stress cracks from different origins were used.

5.1.1. Stress crack

Stress cracks are formed from external pressures like thermal expansion, climatic changes and outside movement that manifest after there has been a change in conditions[119]. Most commonly, stress cracks start as small fractures near the edge of the glass and slowly spread across the glass[120]. Stress cracks caused by heat will usually travel an irregular path and with the fracture suddenly changing direction, as it spread across the glass[121].

118 L. Ristal, Internship report: Glass, University of Antwerp, Faculty of Design Sciences, 2021, p 6.
119 S. Hardingham, An Analysis of Stained Glass Fabric Specific to Conservation Assessment, p 9.
120 The 3 Types of Glass Cracks and How to Prevent Them from Spreading, Charles Window & Door Company, https://www.charleswindows.com/the-3-types-of-glass-cracks-and-how-to-prevent-them-from-spreading/ (Accessed 07.IV 2022).
121 N. A. Vogel, R. Achilles, The Restoration and Repair of Historic Stained and Leaded Glass.


Figure 23: Stress crack made by making a small crack and applying pressure with glass pliers. Image by L.Ristal, 2022.


Figure 24: Variety of stress cracks from an unknown cause, from glass at the edges of a panel. Image by L.Ristal, 2021.

5.1.2. Incomplete crack – vent

Stabilised cracks, also known as vents[122], are incomplete breaks at the edges of the glass. With additional pressure/stress the vent will form a full crack from one edge to another, breaking the glass[123]. This kind of crack is hard to re-create and thus will not be used as an example of fracture patterns in the panel.

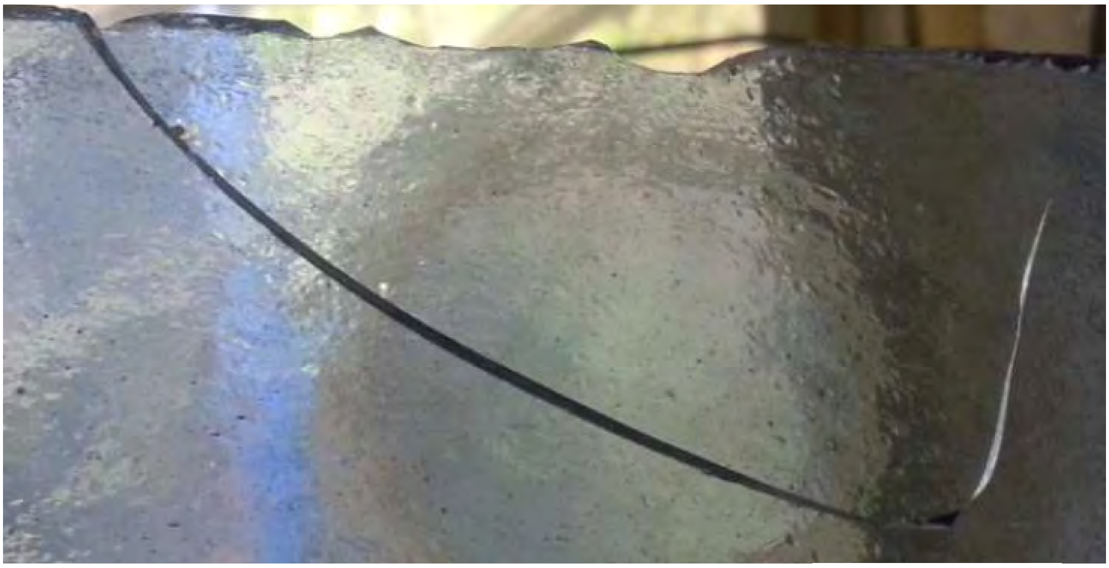

Figure 25: An incomplete crack. Image by Sean Hardigan, May 2013, from An Analysis of Stained Glass Fabric Specific to Conservation Assessment, p 8.

5.1.3. Mechanical break – impact crack

Impact crack is caused by something hitting the glass at high speed. It is easily recognised because of the point of contact[124]. Although when the panel is placed in a moving frame like a door, impact from the door closing forcefully can also create fractures that may look like stress cracks[125]. Impact fractures produce two types of surface fracture patterns: radial (originates at point of impact and moves away from that point) and concentric (broken series of concentric circles around the impact point)[126].

122 **Vent** – Small cracks at the edges of glass that can lead to breakage.
123 S. Hardingham, An Analysis of Stained Glass Fabric Specific to Conservation Assessment, p 8.
124 The 3 Types of Glass Cracks and How to Prevent Them from Spreading.
125 S. Hardingham, An Analysis of Stained Glass Fabric Specific to Conservation Assessment, p 8.
126 V. D. Crawford, Glass Analysis: Types Of Glass, How To Determine The Density Of Glass, And Analysis Of Glass Fracture Patterns, 2014, p 4.

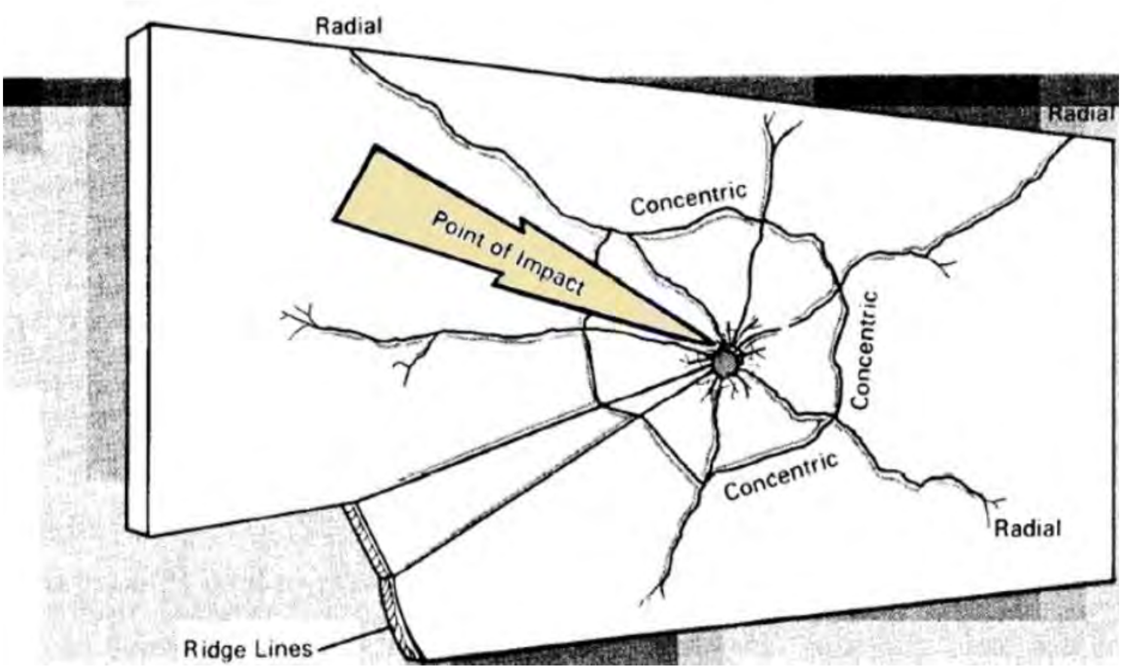

Figure 26: Figure Showing Radial And Concentric Cracks Upon Impact. Image from V. D. Crawford, Glass Analysis: Types Of Glass, How To Determine The Density Of Glass, And Analysis Of Glass Fracture Patterns, 2014, p 4.

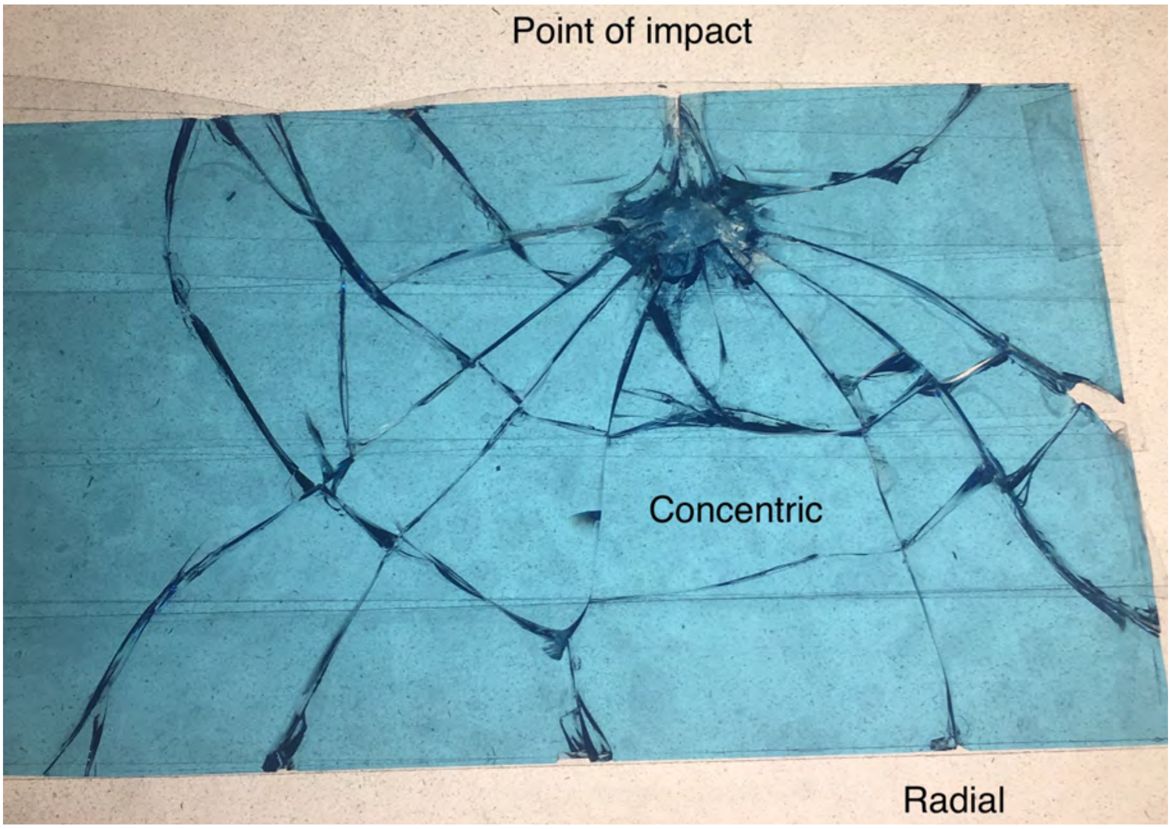

Figure 27: Impact crack caused by a stone throw to the piece of glass that was on the floor. Image by L.Ristal, 2021.

5.1.4. Heat crack

Heat cracks often look like vents, but have a characteristically wavy appearance to them. As the name suggests, the crack occurs after thermal shock. A quick drastic temperature change of the glass – where one area of the glass is heated very fast to an extreme temperature, but the area next to it is not[127].

For example, thermal shock can be caused by heat guns or during the soldering process, where the radiant heat can cause cracks[128]. But can also occur when a sheet of glass is taken from the kiln too quickly (while the glass is still warm) and placed on a surface with lower temperature than the glass itself.

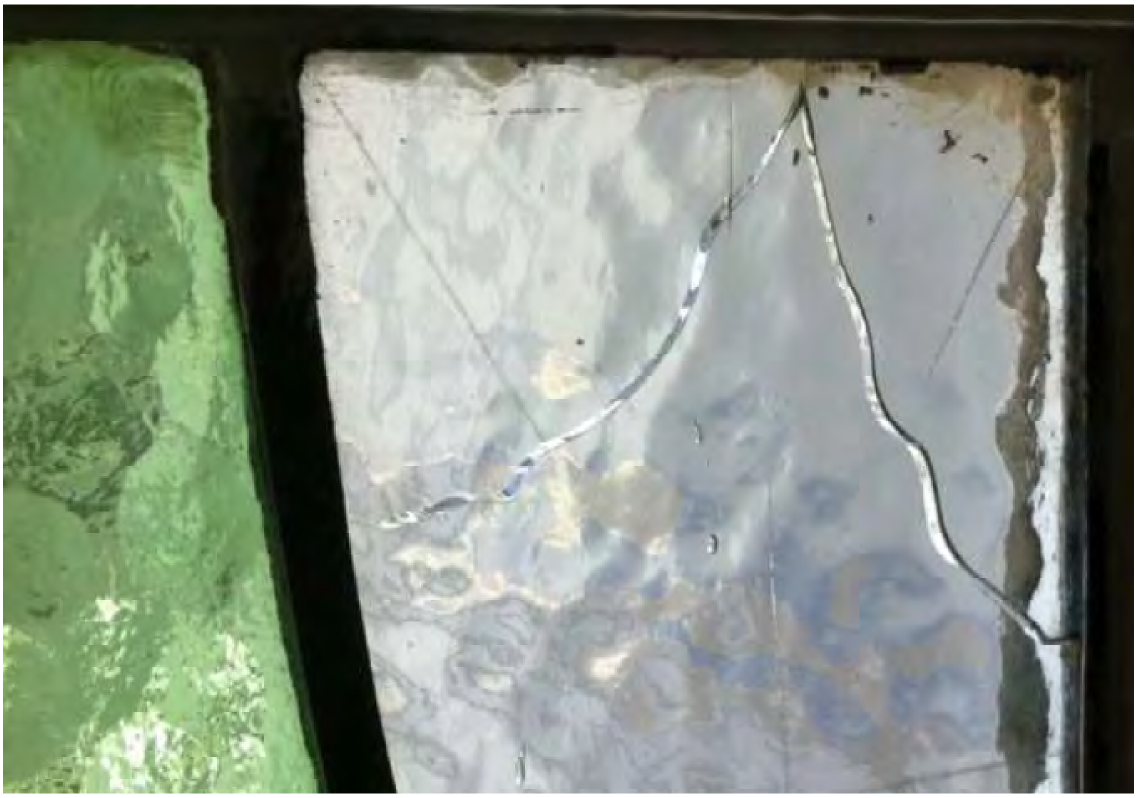

Figure 28: Heat crack. Image by S. Hardingham, An Analysis of Stained Glass Fabric Specific to Conservation Assessment, p 10.

127 P. Beveridge, I. Domenech, E.Pascual, Warm Glass, New York, Lark Books, 2005, p 62.
128 S. Hardingham, An Analysis of Stained Glass Fabric Specific to Conservation Assessment, p 10.

Figure 29: Incomplete heat crack caused by the tip of the soldering iron on glass. Image by L.Ristal, 2021.

6. The basics of conservation techniques

The first step of action of any of the conservation methods that will be mentioned in the following chapters is cleaning the glass and the edges of the fracture. Cleaning should be the first step after assessment in almost all cases, except when the original paint may be compromised.

Generally, it is recommended to use the least aggressive methods of cleaning possible. Usually a mixture of chemical and mechanical cleaning is used to best meet the needs of the glass in question. Chemical cleaning is usually done by ethanol, acetone or distilled water at different intervals and quantities, based on the state of the glass[129].

Mechanical cleaning can be done carefully with a sharp scalpel and a soft brush, that will not scratch the surface of the glass. Historical pieces are usually covered in grime consisting of a mixture of built-up dirt, soot, bird faeces, mould and algae, depending on the display conditions. Sometimes the edges of the glass are covered in leftover hardened putty, that was used for sealing the stained glass window previously[130].

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129 H. Römich, E. Jägers, M. Torge, W. Müller, K. Adam, Cleaning: a Balancing Act, 3.3. Chemical Cleaning Techniques, http://www.cvma.ac.uk/conserv/cleaning.html (Accessed 10.IV 2022).
130 S. Hardingham, An Analysis of Stained Glass Fabric Specific to Conservation Assessment, p 21.

7. Historical conservation techniques

The following sub-chapters consist of previously popular methods of dealing with a fracture in the glass. Although, since these methods are not always reversible and don't always support the integrity or the welfare of the pieces, they will be classified as historic conservation methods. Not all of the techniques mentioned will be used on the panel due to the availability of products, their relevance as actual methods or the low level of skill needed to execute them. Still, it is important to document them, as these methods were often used in the panels that are in need of conservation. The historical methods showcased on the panel are replacing, re-leading, false leading and the copper foil method.

7.1. Putty edge bond

The original purpose of a putty is to seal the leading to the glass, making it sit more secure and waterproof[131]. It is common to find cracks bonded by putty to mimic a lead line (fig. 31–33) or to cover a hole (fig. 30) in the glass[132]. The problem with putty repairs is that the putty itself is often weathered, very hard and thus difficult to remove from glass. As the putty dries and shrinks, it can also pull away the paintings on the glass thus damaging the paintwork. It is most often removed from the glass carefully with a sharp scalpel and the residue removed with either ethanol or acetone as not to damage the lead or the glass itself [133].

131 N. A. Vogel, R. Achilles, The Restoration and Repair of Historic Stained and Leaded Glass.
132 Winchester Cathedral, Conservation of Presbytery Clerestory Windows NII-NV, SII-SV, & EI, 1.6 General Condition and Window summary, Holy Well Glass, British Society of Master Glass Painters, X. 2015 – X. 2017, https://www.bsmgp.org.uk/wp-content/uploads/2018/12/winchester-presbytery-clerestory-conservation-report-no-printers-marks.pdf (Accessed 19.III 2022).
133 Cathedral Church of Our Lady & St. Philip Howard, ARUNDEL, Sussex, Stained Glass Conservation Report, 2018–2019 p 3, https://www.bsmgp.org.uk/wp-content/uploads/2019/06/Arundel-Stained-Glass-Conservation-Report.pdf (Accessed 19.III 2022).

Figure 30: Historic putty repairs of Great Rose Window on the West Front from the Cathedral Church of Our Lady & St. Philip Howard. Image from Cathedral Church of Our Lady & St. Philip Howard, ARUNDEL, Sussex, Stained Glass Conservation Report, 2018–2019.

Figure 31: Example of a putty edge bond. Image provided by M. de Caluwé, 2022.


Figure 32: Example of a putty edge bond. Image provided by M. de Caluwé, 2022.


Figure 33: Example of a putty edge bond. Image provided by M. de Caluwé, 2022.

7.2. Replacing

It is the unfortunate reality that when a piece of glass is too damaged (fig. 34) for repairs it is often replaced. Thankfully, when talking about replacing from the 20th century onward, in most cases, the replaced piece is minor compared to the rest of the panel and only a few isolated pieces are replaced. It is imperative that when a piece of glass is replaced, the original damaged piece is kept. The hardest and the most important part of replacing a piece is finding new glass that matches all the existing visual qualities of the damaged glass. This means colour, texture, pattern etc[134]. Replacing only a piece of glass in the panel without completely removing the whole leading of the panel is called a “drop-in,” “stop-in,” or “open-lead” repair[135]. The lead came around the piece is cut open near the soldering joint and folded back so the necessary piece can be removed. The damaged glass is then replaced with a new piece to match the shape, measurements and width of the original and placed back, with the last step being re-soldering the previously cut lead joints.

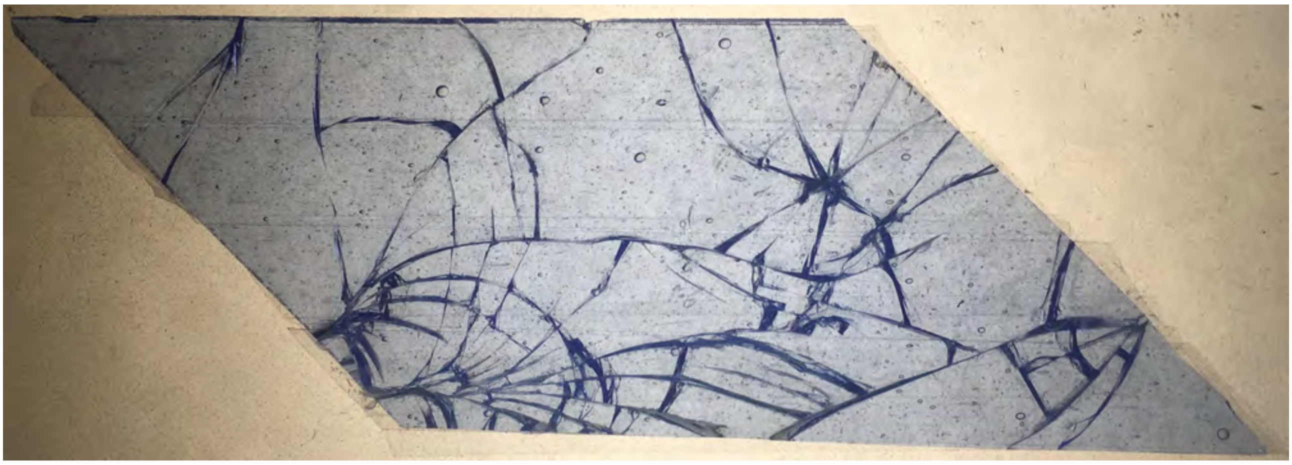

Figure 34: Picture of a severely impact damaged piece that had to be replaced. The piece was damaged by a chair falling onto it, as can be seen from the multiple impact points. Image by L.Ristal, 2022.

For replacing the piece on the panel, since I still had some of the original glass sheet left, I had the chance to use that for the replacement piece (fig.35). This is only possible because the panel is new and made by me. Under normal circumstances the replacement glass is almost never from the same sheet as the original.

134 M. F. Lynch, Stained Glass Restoration, APT Bulletin: The Journal of Preservation Technology, Association for Preservation Technology International (APT), Vol. 18, No. 4, 1986, p 8.
135 N. A. Vogel, R. Achilles, The Restoration and Repair of Historic Stained and Leaded Glass.


Figure 35: The new piece that was made to replace the damaged piece. Image by L.Ristal, 2022.

7.3. Leading

Lead is a soft flexible metal that doesn't chemically react with the glass, neither painted or stained. It is easy to solder, usually done with an alloy of lead and tin, when new and can combat weathering for centuries[136]. The biggest long term cause of degradation in lead is usually oxidation, which weakens the lead and can cause distortion in the panel itself[137].

Since lead was already a material used for stained glass craft, it was readily available to be used to restore cracks in glass. There were a few different most common ways that lead was used, which will be discussed in the following chapters.

7.3.1. Re-leading

In essence re-leading a piece of stained glass that is cracked consists of inserting a piece of lead in the crack of the glass (fig. 36) and soldering it to the nearest leading. This is quite an old method, already widely popular since the 20th century. Re-leading was often done to avoid replacing the

136 S. Hardingham, An Analysis of Stained Glass Fabric Specific to Conservation Assessment, p 33.
137 Ibid, p 34.

section of glass that was damaged, as it was often too expensive or time consuming. Instead the panel was dismantled and the broken sections were incorporated into the new lead network[138].

Re-leading is very durable and technically the original glass is retained instead of replaced, but on the negative side the new leadings often interfere with the original design (fig. 37; 38). Also, to make the lead insertion fit the broken glass in the panel, the edge of the break has to be grozed (trimmed) a few millimetres. Grozing is irreversible[139].To conserve the panel that has been re-leaded, the old leading should be removed to assess if the glass has been grozed and if so, to what extent. Afterwards, the broken pieces can be edge bonded or if there has been significant grozing the gaps can be filled with the appropriate adhesive.

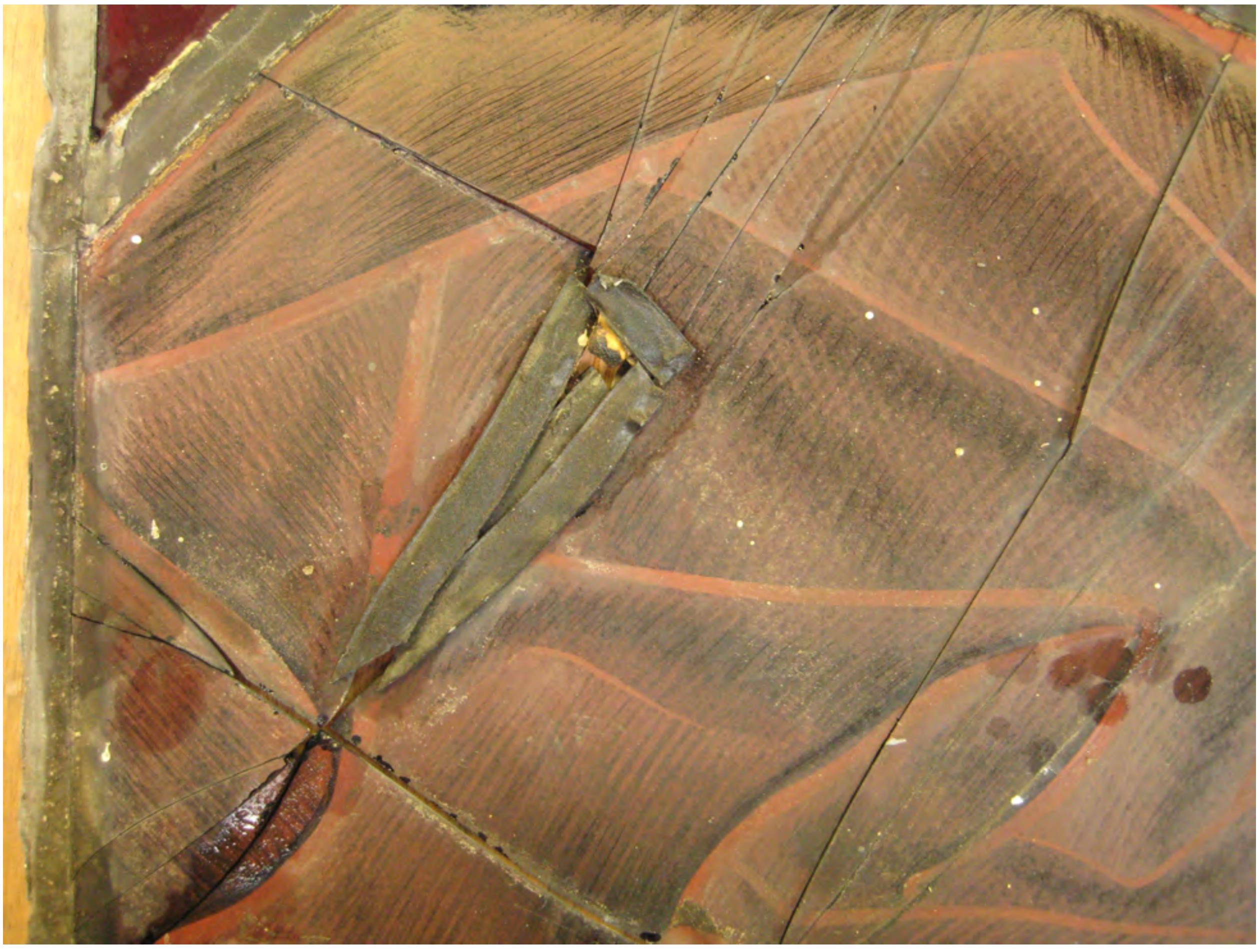

Figure 36: Example of re-leading, where the lead came is just inserted in the break and not even soldered. Image provided by M. de Caluwé, 2022.

138 M. Stumpff, Repairing Broken Glass, Boppard Conservation Project – Glasgow Museums, 13.V 2014, https://boppardconservationproject.wordpress.com/2014/05/13/repairing-broken-glass/ (Accessed 14.IV 2022).
139 J. H. Notman, N. H. Tennent, The Conservation and Restoration of a Seventeenth Century Stained Glass Roundel, Studies in Conservation, Taylor & Francis, Ltd. on behalf of the International Institute for Conservation of Historic and Artistic Works, Vol. 25, No. 4, XI.1980, p 167.

Figure 37: An example of a lead repair that is interfering with the integrity of the panel. Image by C. van den Wijngaert, 2005.

Figure 38: An example of a lead repair that is interfering with the integrity of the panel. Image by L.Ristal, 2021.

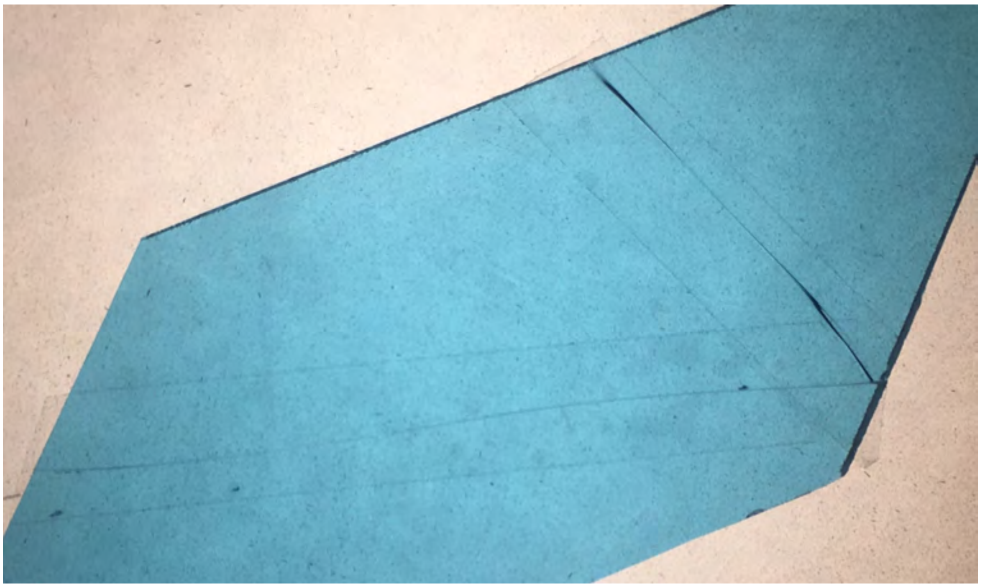

Figure 39: The piece from the panel that will be re-lead. The damage is a stress crack from dropping the piece and adding pressure with glass cutting pliers. Image by L.Ristal, 2022.

The steps of re-lead method are as followed:

1. The crack (fig. 39) is be measured and a piece of lead came should be cut longer than the crack itself (fig.40).

Figure 40: The glass with the lead came roughly cut. Image by L. Ristal, 2022.

2. The lead is inserted in the crack, moulding as needed so it would take the shape of a crack. Finally trimmed so it would fit between the adjoining leadings (fig. 41; 42).

Figure 41: The damaged piece with the lead cames measured and cut to size. Image by L.Ristal, 2022.

Figure 42: The piece with the lead came inserted into the panel, unsoldered. Image by L.Ristal, 2022.

3. Both joints are soldered on both sides of the panel (fig. 43).

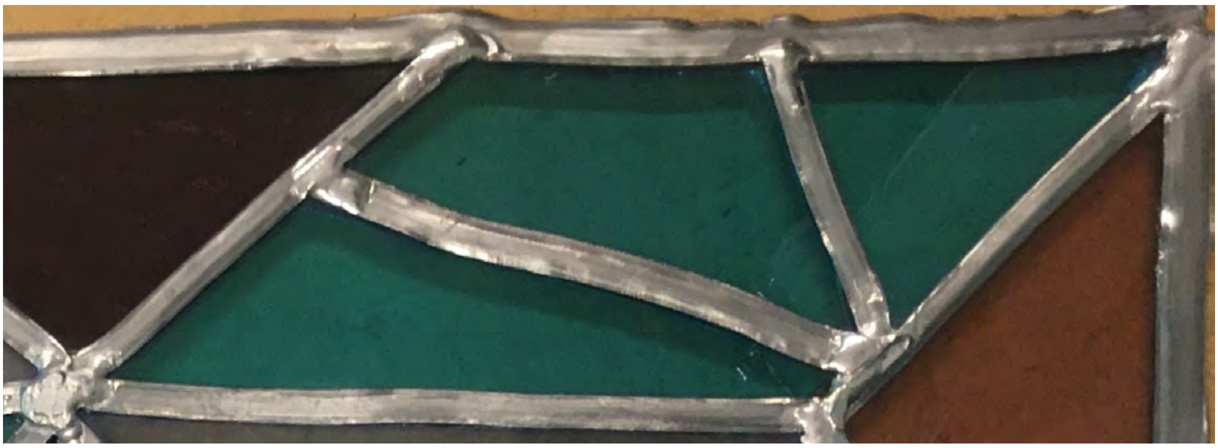

Figure 43: The finished lead repair in the panel. Image by L.Ristal, 2022.

7.3.2. False leading

The second common historical conservation technique using lead is called “false lead”,“the Dutchman” or “strap lead”[140]. This entails simply placing a strip of lead across the crack on the surface and the soldered to place. This method conceals the crack like re-leading, but is much simpler to execute and more reversible as the glass underneath is not grozed. This method can provide some support to the panel, but the glass underneath the false-leading is not bonded, so not completely stable and if putty is not added it is also not weather proof[141]. As with re-leading, this method also interferes with visual image of the panel and additionally, the false leading is often puttied, bringing a different set of problems as discussed earlier in sub-chapter 7.1.

The steps of false lead method are as followed:

1. The crack is be measured and a piece of lead came should be cut longer than the crack itself (fig. 44).

Figure 44: The glass with the lead came roughly cut to size of the crack. Image by L. Ristal, 2022.

140 M. Stumpff, Repairing Broken Glass.
141 M. Frances, Repairing a Broken Stained Glass Window, Everything Stained Glass, 30.V 2020, https://everythingstainedglass.com/broken-stained-glass (Accessed 14.IV 2022).

2. The top of the leading is separated from the lead came with a lead knife (fig. 45; 46).

Figure 45: The side profile of the lead came. Image by L.Ristal, 2022.

Figure 46: The lead came with one of the top parts separated. Image by L. Ristal, 2022.

3. The cut piece is shaped to fit over the crack and trimmed so it fits between the adjoining leadings (fig. 47).

Figure 47: Top of the lead came placed on the crack. Image by L.Ristal, 2022.

4. Both ends are be soldered (fig. 48).

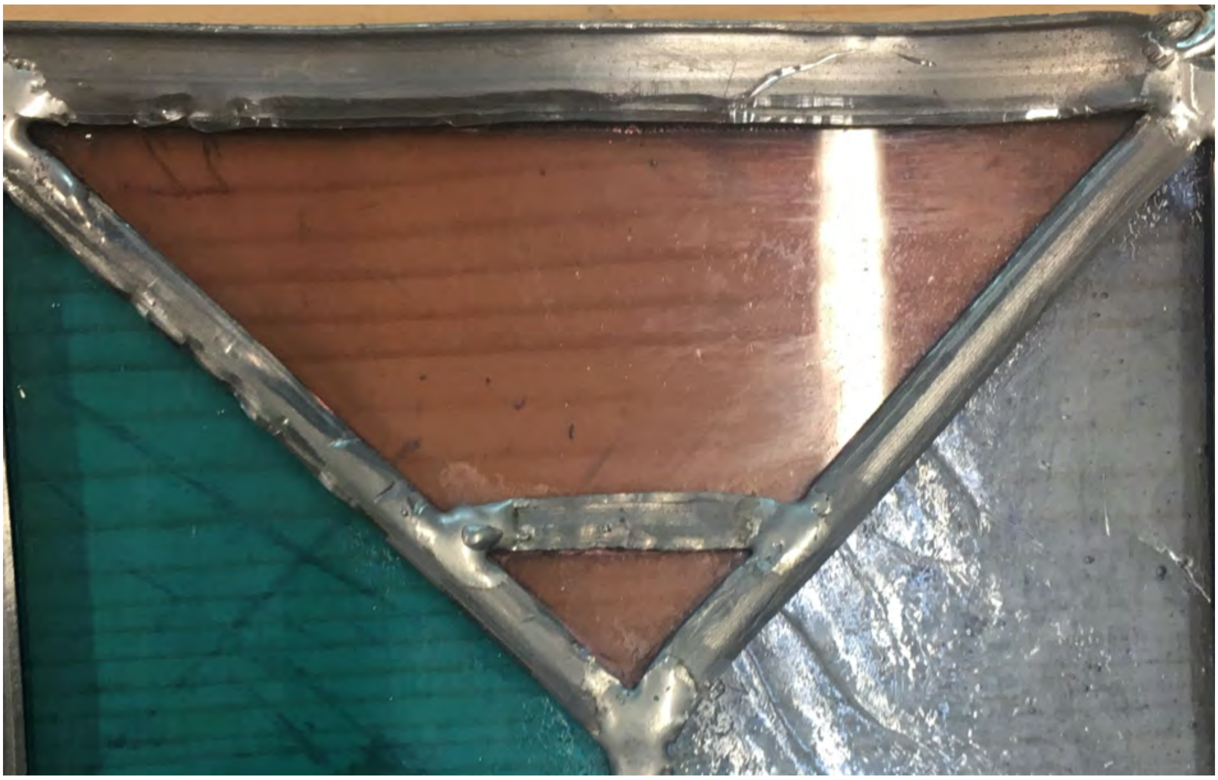

Figure 48: False lead soldered into place on the crack. Image by L.Ristal, 2022.

5. The steps are then repeated on the other side.

7.4. Copper-foil technique

Although the technique is with a long history, it can not be considered purely historic conservation, as it is still used today in some cases, mostly in Europe[142], like when the panel will be displayed outside or the crack is minimal visible. Nowadays copper tape with various widths and adhesive on one side, is used instead of a copper sheet that Tiffany used.

The copper-foil technique in conservation was adapted from the Tiffany Studios, as they showed the possibilities of producing thin lines when soldering[143]. This option is best used when the glass has a maximum of two cracks. Copper foiling does produce a strong repair on its own, copper wire can be soldered on top of the foiling for extra reinforcement if needed[144], and it is possible to get a watertight seal with good preparations and proper choice of glass (nothing too textured)[145]. Copper foiling is also reversible – the soldering can be re-melted and the pieces taken apart. On the other

142 N. A. Vogel, R. Achilles, The Preservation and Repair of Historic Stained and Leaded Glass, Preservation briefs, Vol. 33, 1993, p 12.
143 R. Rosa, Adhering To The Point, The use of adhesives in stained glass restoration, Serpentino Stained Glass Studio, http://www.serpentinostainedglass.com/adhesives.html (Accessed 02.V 2022).
144 N. A. Vogel, R. Achilles, The Restoration and Repair of Historic Stained and Leaded Glass.
145 S. Hardingham, An Analysis of Stained Glass Fabric Specific to Conservation Assessment, p 46.

hand, even though the aesthetic interference should be minimal as ideally the line should not be more than 1 mm in width, it is still noticeable, so it should not be used in major repairs. Most importantly, copper foiling should never be used on unstable glass due to the usage of heat needed to solder[146].

Black coated copper foil tape width the with of 0,5mm was used on the panel.

The steps of the copper foiling method are as followed:

1. The edges of the fracture are taped with copper foil tape (fig. 49).

Figure 49: The crack and copper foiled edges from the side and top point of view. Image by L.Ristal, 2022.

2. The pieces were placed together and secured in place with pieces of glass (fig. 50).

146 R. Rosa, Adhering To The Point.

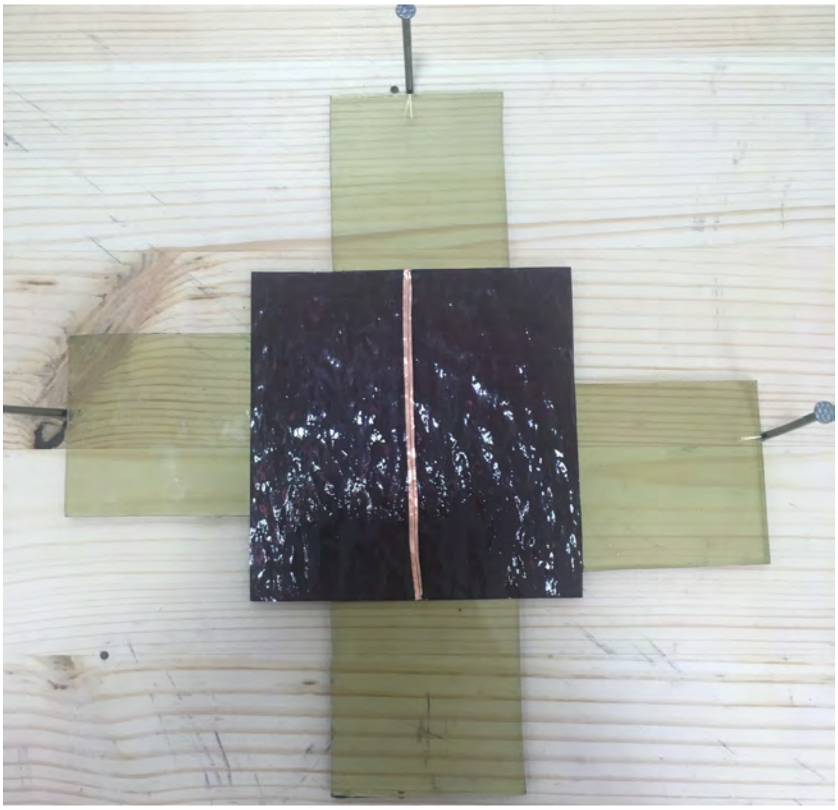

Figure 50: The two pieces secured in place with four pieces of glass. Image by L.Ristal, 2022.

3. Flux was applied to the copper foiled edges.
4. The copper foil was soldered following the line where the tape was applied on both sides (fig. 51)

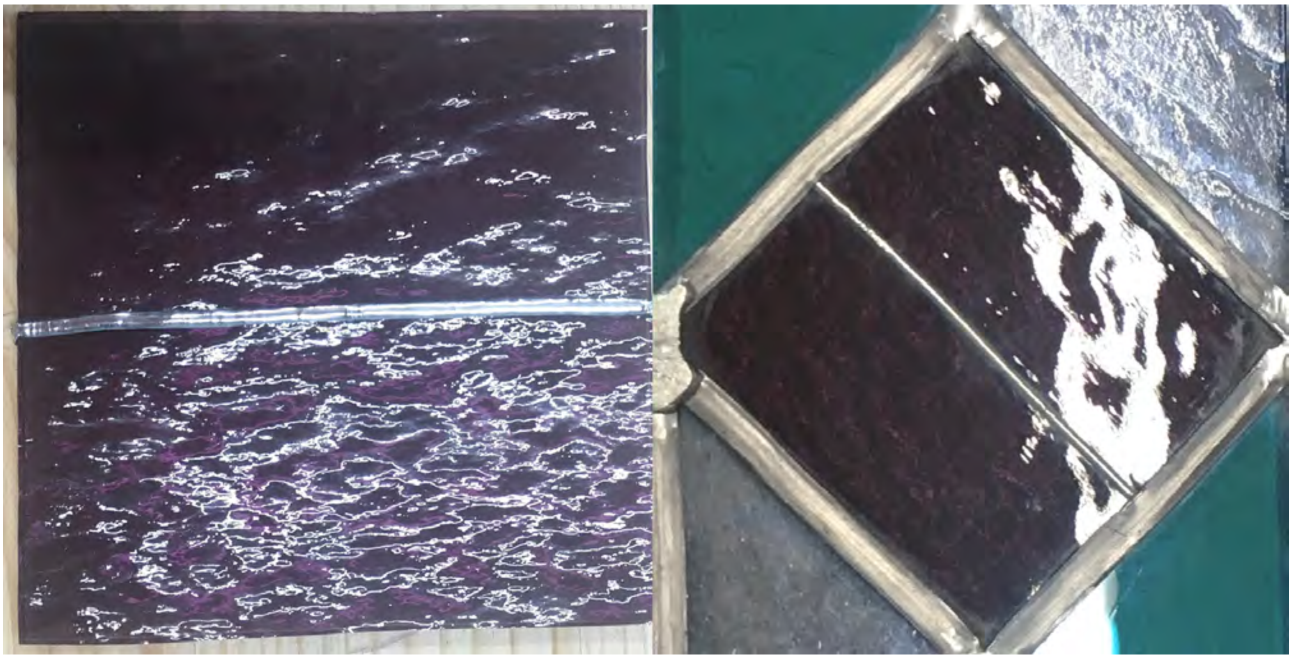

Figure 51: The pieces soldered together and showcased in the panel. Image by L.Ristal, 2022.

8. Modern conservation methods

The following methods are widely accepted as modern conservation methods most commonly used at the moment. For the purposes of showcasing the conservation methods on the panel, one of the following three methods (epoxy resin edge bonding) has been tried on the panel due to the reason of familiarity of the method. The majority of the sub chapter 8.1.1. has been compiled of my internship at the University of Antwerpen (L. Ristal, Internship report: Glass, University of Antwerp, Faculty of Design Sciences, 2021), where I was trained by the teaching assistant of the glass conservation department, Monique de Caluwé.

It is important to mention, that even though edge bonding is often the norm in glass conservation at the moment, the trends of conservation are also in constant change and should always be bettered.

1.

8.1. Edge bonding

As discussed before, glass is a fragile material and edge bonding is a popular method of repair used. The principle of edge bonding is the seep of an adhesive or consolidant into the crack by capillary forces[147]. Based on the needs of the piece, the viscosity might be increased or lowered from the norm. This is usually done by making changes in the factors that influence it, for example: concentration of polymers in the solution, the molecular weight of the polymers and the surrounding temperature, to name a few[148].

To avoid reflections from the break lines, for the best visual result, refractive indexes of the glass and the adhesive should be a very close match. Epoxy resins are frequently used, as they have varying curing times, viscosities and are usually commercially available. For more sensitive glasses adhesives like cellulose nitrates or acrylates are preferred, as they create weaker bonds which are not as hard to remove as with epoxy resin after ageing[149].

147 K. De Vis, J. Caen, K. Janssens, P. Jacobs, The Consolidation of Cracks and Fissures in Dalle de Verre: Assessment of Selected Adhesives, p 43.
148 Ibid, p 46.
149 H. Römich, Chapter 7: Glass and Ceramics, p 171.

8.1.1. Epoxy resins – Araldite2020, Fynebond, HXTAL NYL-1

The main reason of popularity for edge glueing with an epoxy is the almost invisible break line it leaves. This means it is excellent for the visual integrity, especially when a focal point has been damaged. In addition, the resins can be tinted with pigments as needed to get a better match on the glass thus reducing refraction and light transmission. Epoxy resins can also be used to saturate the microscopic cracks caused by the high temperatures from, for example, an open fire[150]. As epoxies cure they will produce a strong bond, this also means that, generally, it is the most difficult method of the above mentioned to reverse. Epoxies are also sensitive to the UV rays, which cause yellowing and deterioration, so if the panel is to be used as a window it will require a secondary glazing for protection. Out of all the techniques mentioned, it is usually the most expensive and takes the most practice[151].

Usually the adhesives used for edge bonding glass are epoxy based two component resins. The three most common brands used for glass conservation are Araldite 2020, Fynebond and Hxtal NYL-1, although there are other brands like Epotec and Ablebond etc. Each brand of epoxy resins has their own positives and negatives, depending on the needs of the object.

Name of the brand	Araldite 2020	HXTAL NYL-1	Fynebond
Cure time	24 hours	7 days	2–3 days
*Cost	Medium	Medium	High
Yellowing over time	Yellows	Yellows, but less than Araldite 2020	Yellows, but less than HXTAL NYL-1
Viscosity mPa.s at 20°C	150	180–250	–
**Reflective index	1.55	1.52	1.52

Table 2: Table comparing the properties of Araldite2020, HXTAL NYL-1 and Fynebond. Information from T. Winther, J. Bannerman, H. Skogstad, M. K. G. Johansson, K. Jacobson, J. Samuelsson, Adhesives for adhering polystyrene plastic and their long-term effect, Studies in Conservation, Vol. 60, No. 2, 2015, p 109.

*For cost, Araldite 2020 and HXTAL NYL-1 are in the 100€ price range depending on the seller and quantity, Fynebond is sold directly from the supplier Fyne Conservation Services, with the cost being a lot higher than the other two adhesives, but precisely unknown at the time.

**The refractive index of glass is about 1.52.

150 R. Rosa, Adhering To The Point, The use of adhesives in stained glass restoration.
151 N. A. Vogel, R. Achilles, The Restoration and Repair of Historic Stained and Leaded Glass.

As mentioned beforehand, the best way to ensure a bond is strong is to bond through “capillary action”. For that, before the adhesive is added to the break lines, the pieces need to be levelled and tightly secured. After that the liquid travels into the break and cures.

For edge bonding with Araldite 2020 (and other epoxy glues):

1. Taping.

The broken pieces of the glass have to be taped together, so they are held together as the glue hardens. If the glass has been painted, the tape should never be placed over the side with the paint, as the adhesive from the tape can leave a trace.

It is important to mention that the choice of the finish of the tape directly affects the finish of the glue when dried. For example tape with a matte finish means that the glue dries matte and tape with a shiny finish means that the glue dries shiny.

There are many ways to tape a piece of glass together. The main techniques are either: 1) many tiny pieces of tape horizontally over the fracture on both sides of the object (fig. 53), 2) one long strip of tape vertically covering the fracture on the bottom side and a few small pieces of tape horizontally on the top over the fracture (fig. 52). The third method is the one where the sides of the fracture are taped to about the quarter way leaving the tape longer than the object, and the centre on both sides is taped with small pieces.

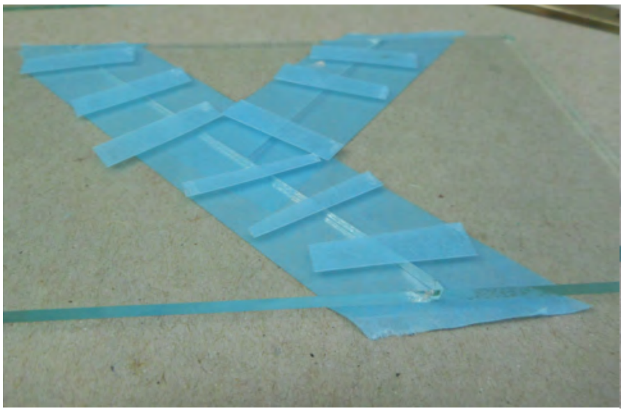

Figure 52: Example of a taping method 2. Image provided by M. de Caluwé, 2022.

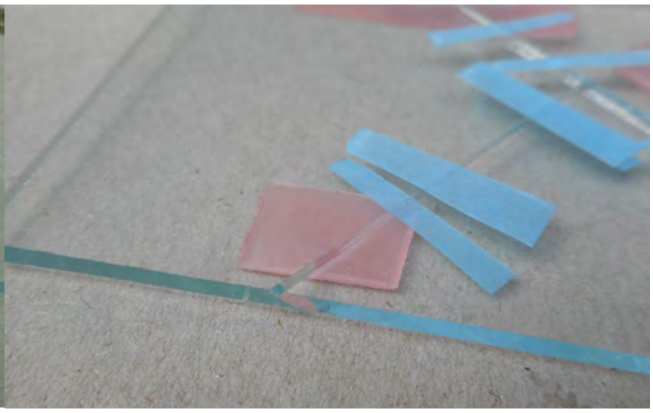

Figure 53: Example of a taping method 1. Image provided by M. de Caluwé, 2022.

The tapes are usually placed on a separate piece of clean glass and the desired sizes are cut out with a scalpel. The piece of the tape is then removed from the glass and placed on the fracture, attaching the broken pieces together.

When edge bonding with adhesive there is always a possibility that a mirror might occur (fig. 54). A mirror occurs when the glue is put on the glass and the air can't be pushed out due to the placement of the tape, therefore trapping the air in the glass. The mirror is visible only when the glass is looked at a certain angle. Mirroring is the reason why the adhesive should never be placed at both sides of the tape.

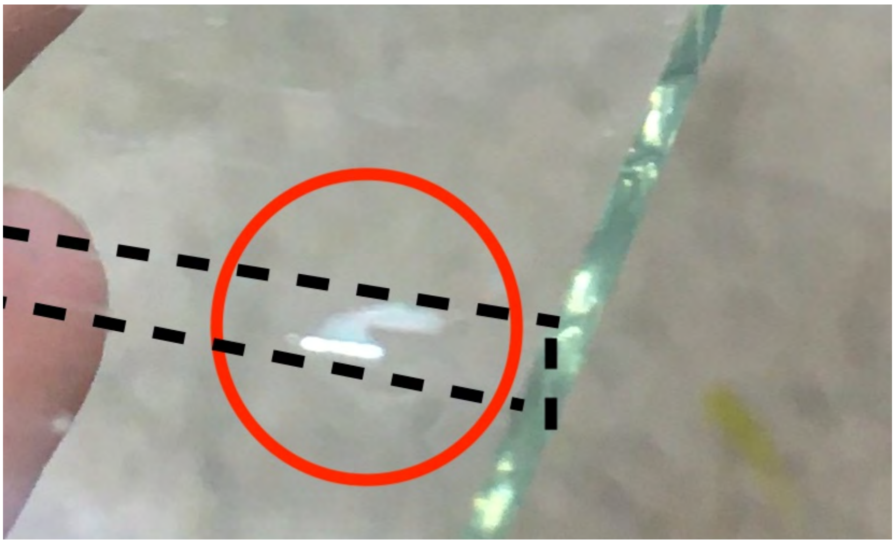

Figure 54: Example of a mirror. Image by L.Ristal, 2021.

2. Adjustments.

When the pieces are securely taped together, so that the glass is movable in one piece, it must be adjusted so that the patterns of the reflections match each other. When a non-textured piece of glass is broken, the pieces need to be perfectly on the same level so the glass does not lose the illusion of unity when bonded back together. It is possible to check if the pieces are on the same level from the reflection of a light source above or to touch the fractures to make sure there are no uneven spots. For adjusting, strips of wax are pushed under the glass as needed to level the pieces and ensure that in the case the adhesive comes through from the other side, the piece is not bonded to the surface beneath.

3. Mixing Araldite 2020.

Araldite 2020 consists of two components, A and B. The scale for measuring should be set on the 0,00g setting.

The longer the glue sits, the more it loses its viscosity. To make sure that the glue is in the best condition for use, it is best to use it in the first hour of making it. If a higher viscosity is desired it is preferable to keep the adhesive at a slightly warmer temperature.

4. Bonding the fracture.

The mixed adhesive is then placed in the form of drops on the fracture, making sure to leave room between one side of the tape for the air bubbles (fig. 55; 56). Araldite 2020 fully cures in 24 hours.

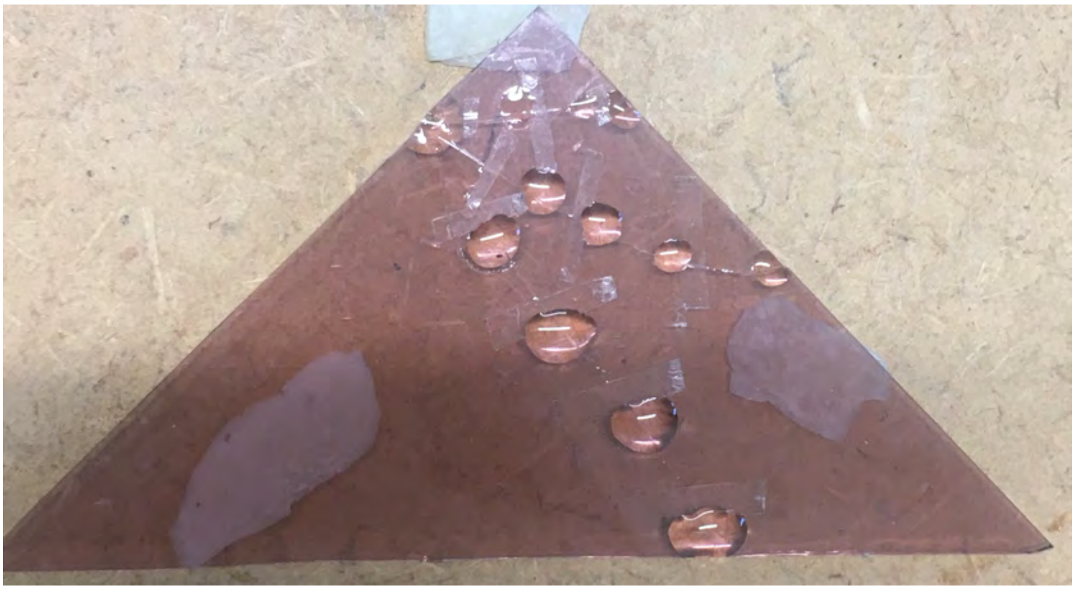

Figure 55: Piece for the panel after the drops of adhesive were placed on the fractures. The fractures were caused by a stress of glass pliers on the edge of the glass. Image by L.Ristal, 2022.

Figure 56: Example of the roundel that was previously lead repaired, while edge bonding. Image by L.Ristal, 2021.

5. Removal of the excess glue.

After the glue is cured and the piece is bonded, the leftover drops of the adhesive and the pieces of tape must be carefully removed from the edge of the crack (fig, 57; 58). It is best to remove the larger pieces slowly with a sharp scalpel and in case of any residue, either adhesive from the tape or Araldite2020, to use acetone (diluted with water if needed) to loosen the remnants of glue.

Figure 57: The piece after curing and the drops of adhesive were removed. Image by L.Ristal, 2022.

Figure 58: The roundel after the adhesive was removed and the breaks cold painted. Image by L.Ristal, 2021.

8.1.2. Acrylic resins – Paraloid B-72

PARALOID B-72 is a copolymer of ethyl methacrylate and methyl acrylate produced by Röhm and Haas[152]. To use Paraloid B72 as a consolidant, the pulverised particles must be mixed with a solvent like acetone or di-acetone-alcohol. Depending on the mixture, the viscosity is usually considered low, compared to other epoxy adhesives[153].

Unlike epoxies, Paraloid B-72 remains easily reversible and does not significantly yellow over time[154]. The strength of the Paraloid B-72 bond to glass is lower than epoxies, which can be safely used in glasses that are more damaged and would not benefit from such a strong bond, although it is limited optically when dealing with clear glass, such as historic glasses[155]. As Paraloid B-72 dries in the crack, it is constantly evaporating leaving behind tiny air bubbles. The miniature pockets of air refract light, thus being visually more noticeable, although they do not generally affect the strength of the bond. Paraloid B-72 also has the added benefit of being less costly than the epoxies mentioned above. Because the softening (glass transition temperature (Tg)) of Paraloid B-72 is quite low, being listed as 40°C, it should not be used on objects exposed to temperatures above that. For the same reason, it should also not be used on objects that are exposed to direct sunlight. Paraloid B-72 also has its limitations in more humid environments, often developing a white bloom as a result of the solvent absorbing the moisture[156].

The application method of Paraloid B-72 is usually either the same as with epoxy edge bonding with taping of the fragments and application of adhesive along the fracture line or by preparing the Paraloid B-72 as a thin solution and applying to one of the fragment edges. The fragments are then joined, squeezing out excess adhesive. The removal of the excess adhesive is done by wetting a soft brush with acetone[157].

152 R. Wielen, S. Groot, Thermocasting of PARALOID B-72: Solvent-Free Production of Acrylic Flat-Glass Restoration Casts, Recent Advances in Glass and Ceramics Conservation, 2019, p 111.
153 K. De Vis, J. Caen, K. Janssens, P. Jacobs, The Consolidation of Cracks and Fissures in Dalle de Verre: Assessment of Selected Adhesives, p 46.
154 R. Wielen, S. Groot, Thermocasting of PARALOID B-72: Solvent-Free Production of Acrylic Flat-Glass Restoration Casts, p 115.
155 S. P. Koob Paraloid B-72: 25 years of use as a consolidant and adhesive for ceramics and glass, Holding it All Together, edited by J. Ambers, C. Higgitt, L. Harrison, and D. Saunders, London: Archetype Publications Ltd, 2009, p 118.
156 Ibid, p 117.
157 Ibid, p 116.

8.1.3. Silicone edge

Usually, the bond between conservation silicone and glass is not as strong as the aforementioned edge bonding methods. Still, it provides an alternative to the epoxy and acrylate edge glueing. Because of the low strength of the bond, this method is useful when the window will be under continuous stress so a more flexible joint is needed to accommodate the inner expansions[158].

One of the biggest advantages of this method is the ease of reversibility, when done correctly the bulk of it should be easily removable with a scalpel. The residue can be removed with a solvent, for example acetone or ethanol. Silicone is almost as clear as epoxy, but there is a difference of refractions between glass and silicone, making the latter more noticeable[159]. Although pigments can be used in silicone to reduce the light transmission and refraction.

Unlike most epoxies, silicone is not as easily affected by temperature (although can become brittle when exposed to high temperatures), humidity or the UV light, meaning there is no need for secondary glazing[160]. Silicone is also, most commonly, the least expensive of the methods.

Since silicone is usually at a low viscosity, the capillary forces can not be used for application, as with resins. Thus silicone is applied like Paraloid B-72, with application of the solution to one fragment edge at a time, joining the fragments and removing the excess.

158 R. Rosa, Adhering To The Point, The use of adhesives in stained glass restoration.
159 N. A. Vogel, R. Achilles, The Restoration and Repair of Historic Stained and Leaded Glass.
160 R. Rosa, Adhering To The Point, The use of adhesives in stained glass restoration.

9. Terms and definitions

Definitions have been taken from the glass dictionary of Corning Museum of Glass, unless referenced otherwise. For the Estonian definitions, Eve Koha (MA, EAA, Faculty of Cultural Heritage and Conservation) has been consulted.

Ancient glass (Rooma aja klaas) – A term frequently used to mean all pre-Roman and ancient Roman glass.

Cast glass (klaasivalu)– Molten glass was poured into a mould in much the same way metals are cast[161].

Cloisonné – Cloisonné is an enamelling technique which consists of soldering to a metal surface metal strips bent to the outline of a design and filling the resulting cellular spaces, called *cloisons* (French: "compartments"), with vitreous enamel paste[162].

Copper-foil method (Tiffany/vaskteibi tehnika)– In the copper foil technique, edges of glass are wrapped in thin copper foil. The foil covers the entire edge of the glass and about one-sixteenth of the front and back sides. Unlike lead which is soldered only at points of intersection, the copper foil is soldered along the entire joint where it touches another piece of glass[163].

Core forming (tuumtehnika) – The technique of forming a vessel by winding or gathering molten glass around a core supported by a rod. After forming, the object is removed from the rod and annealed. After annealing, the core is removed by scraping.

Cristallo (Cristallo* klaas*) – Colourless glass. Italian, "crystal". A term first used in Venice in the 14th century to describe glass that resembles colourless rock crystal.

Crown glass (kroonklaas/taldrikmeetod) – Sheet glass made by blowing a parison, cutting it open, and rotating it rapidly, with repeated reheating, until the centrifugal force has caused it to become a flat disk. After annealing, the disk is cut into panes of the required shape and size. Bull's-eye panes come from the centres of the disks and preserve the thickened area where the parison was attached to the pontil.

Fusing (klaasisulatus) – Taking many separate pieces of glass, placing them side by side and heating them- as the pieces cool the edges of the glass pieces stick together and fuse to a single object.

Slumping (koolutus/koolutamine) – placing a piece of glass in/over mould. As the glass is heated it slumps over/into the mould taking the shape of the mould.

161 M. Taylor, No Pane, No Gain! - Roman window glass, Roman Glassmakers, 2000, Updated: 2003, http://www.theglassmakers.co.uk/archiveromanglassmakers/articles.htm#No

162 Cloisonné, Encyclopedia Britannica, Britannica, The Editors of Encyclopaedia, 31.V. 2018, https://www.britannica.com/art/cloisonne (Accessed 8.V. 2022).

163 M. Chervenka, The Copper Foil Technique, Real or Repro, https://www.realorrepro.com/article/The-Copper-Foil-Technique (Accessed 09.IV.2022).

Lancet window (lansettaken/teravkaaraken) – A narrow window with a sharp pointed arc[164].

Lead glass (pliiklaas) – Glass that contains a high percentage of lead oxide (at least 20 percent of the batch).

Opalescent glass (opaalne klaas) – A type of late 19th-century Art Glass, made by covering a gather of coloured glass with a layer of colourless glass containing bone ash and arsenic or minerals.

Plate glass (klaasikoogid/koogiklaas) – Flat glass of high quality, formed by rolling molten glass on a metal plate and later grinding and polishing it until the surfaces are parallel and completely smooth.

Pontil (naabel) – The pontil, or punty, is a solid metal rod that is usually tipped with a wad of hot glass, then applied to the base of a vessel to hold it during manufacture.

Potash (potas) – Potassium carbonate. It is an alternative to soda as a source of alkali in the manufacture of glass.

Rose Window (roosaken) – A round window divided into segments by stone mullions and tracery that imitate a multi-petalled rose[165].

Silver stain (hõbekollane/hõbeets) – A deep yellow stain made by painting the surface of the glass with silver nitrate or similar compounds and firing it at a relatively low temperature.

Soda ash (kaltsineeritud sooda) – Sodium carbonate. Soda is commonly used as the alkali ingredient of glass. It serves as a flux to reduce the fusion point of the silica when the batch is melted.

Tracery (ehisraamistik) – A pattern of interlacing lines, espescially one in a stained glass window, often made of wood, stone or cast iron[166].

Vent (mõra) – Small cracks at the edges of glass that can lead to breakage[167].

164 Lancet Window, Illustrated Architecture Dictionary, Buffalo as an Architectural Museum, https://buffaloah.com/a/DCTNRY/l/lancet.html (Accessed 23. X 2021).
165 Rose Window, Illustrated Architecture Dictionary, Buffalo as an Architectural Museum, https://buffaloah.com/a/DCTNRY/r/rose.html (Accessed 23. X 2021).
166 Tracery, Illustrated Architecture Dictionary, Buffalo as an Architectural Museum, https://buffaloah.com/a/DCTNRY/t/tracery.html (Accessed 23. X 2021).
167 Vents, Glossary, Viridian Glass, https://www.viridianglass.com/resources/glossary/ (Accessed 07.IV 2022).

Conclusion

This bachelor thesis is based partly on the practical documentation of methods via a stained glass panel and partly on research. The aim was to research the most common methods of conservation in case of a crack in stained glass, where five of the eight methods mentioned in the thesis were also tested on a stained glass panel. The reason that the crack conservation methods were chosen, is because often the crack is one of the most visually impairing damages. The chapters on history and materials gave context for stained glass as a medium of art and how it was used through different times. The historical part focused mostly on the development of different techniques in stained glass to understand the methods of conservation. Research showed that from the different crack patterns it is possible to figure the cause of the injury, which may hint at the possibilities of faults in the internal structure and the condition that glass has been kept in. For example, thermal cracks are occurring after sudden extreme temperature changes and mechanical crack patterns at an impact with an object hitting the glass.

The methods tested in the practical research were replacing, re-leading, false leading, copper foiling and epoxy edge bonding (Araldite2020). The traits of each conservation method discussed in the thesis are summarised in two tables below with the assessment of each category given on a scale from none existent to very high. The scale of the assessment is based on my personal experience in the field of art and glass conservation, research and practical testing.

Technique	Putty	Replacing*	Re-leading*	False lead*	Copper-foiling*
Visual interference	High	None existent	High	High	Medium
Bond strength	Low	–	Medium	Low–Medium	High
Deterioration	High	–	Medium–High	Medium–High	Low
Reversibility	Medium	High	Medium–Low	High	Medium–High
Complexity	Low	Medium	Medium	Low	High
Cost	Low	Medium–High	Low	Low	Low

Technique	Epoxy edge bond*	Acrylic edge bond	Silicone edge bond
Visual interference	Low	Low–Medium	Low–Medium
Bond strength	High	Medium	Medium–Low
Deterioration	Medium–High	Medium	Low
Reversibility	Low	Medium	High
Complexity	Very High	High	High
Cost	High	Medium	Medium

The methods used are marked with an asterisk.

In conclusion it can be said that all of the methods have their positive and negative indicators, with none of the methods being a perfect one-size-fits-all solution. Likewise with any other conservation methods the solution in conserving cracks in the stained glass should always be object based, taking into account the severity of the damage and the conditions that the object shall be displayed in. Right now, the consensus among glass conservators is that epoxy edge bonding with copper foiling in minor parts are the preferred methods of conservation in stained glass panels. Although protective windows must be used when using the epoxy edge bonding method on a panel that shall be displayed in the original setting as a window.

In the future, I would like to test all the remaining methods that were discussed in the thesis – putty repair, silicone and acrylate edge bond, to see the workings of the methods in real time.

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Interview

- Interview with Eve Koha, Glass Conservator and Artist, Teaching in Estonian Academy of Arts, Tallinn, Estonia on 13. V 2022.

10. Resümee

Vitraaži murru ajaloolised ja kaasaegsed konserveerimismeetodid. Viie valitud meetodi praktiline uurimus.

Liis Ristal

Käesolev bakalaureusetöö keskendub vitraažide kahjustusena esinevate pragude erinevatele konserveerimismeetoditele, uurides nii ajaloolisi kui kaasaegseid meetodeid ja nende teostusviise.

Töö esimeses osasantakse lühiülevaade klaasi kui vitraaži põhimaterjali ajaloost. Vitraaži ajaloo ülevaates keskendutakse selle kunstiliigi ajaloolilsele ja kultuurilisele kontekstile ning vaadeldakse tõuse ja mõõnu vitraaži kasutusajaloos. Ülevaade keskendub enamasti vitraažikunstile Euroopas.

Klaasikahjustuste puhul on konsrveerimisotsuste tegemiseks on vajalik teada klaasi omadusi ning vitraaži valmistamise tehnikaid. Järgnevates peatükkides seletatakse lahti klaasi füüsikalised omadused ja selle keemiline koostis, tuuakse välja erinevate ajastute variatsioonid klaasi koostises ning sellega kaasnevad muutused klaasi vastupidavuses.

Mainitakse viis peamist klaasitüüpi (opaalne, värviline, kahelisklaas, katedraal ja antiikne), mille järgi on erinevaid klaase võimalik visuaalselt kategoriseerida, määrata nende ajalugu ning võimalikku vanust. Arvesse tuleb võtta ka seda, et üks klaas võib olla kombinatsioon mitmest kategooriast.

Murdude tüüpe ja põhjuseid käsitlevas peatükis on välja toodud pragude sagedasemad tekkepõhjused ning nende poolt põhjustatud mustrid. Murdude tekkepõhjuste abil saab aimu klaasi eelnevatest hoiustamistingimustest ja üldisest seisundist.

Töös on antud lühikokkuvõte klaasi konserveerimise põhitõdedest, detailselt on kirjeldatud erinevaid konserveerimismeetodeid läbi aegade. Keskendutakse meetodite sobivusele vitraažide konserveerimisel ning vaadeldakse nende mõju erinevaid aspekte. Ükski meetod pole täiuslik, kuid mõni võib olla klaasi lausa kahjustav.

Töö praktilises osas katsetati viit erinevat konserveerimismeetodit spetsiaalselt bakalaureusetöö jaoks valmistatud vitraažil. Läbiproovitud meetodid olid: kahjustunud klaasitüki asendamine, pliilindiga prao stabiliseerimine, võltspliilindi meetod, Tiffany ehk vaskteibi meetod ja epoksiidliimiga (Araldite 2020) murdude liitmine.

Loodetavasti on töö autoril võimalus edaspidi katsetada ning uurida ka teisi meetodeid ning saada seeläbi kogemus, mida saab praktiliselt kasutada vitraažide konserveerimisel.

Extra 1

Mixing formula for Araldite2020

Component A	Component B
10.0 g	3.00 g
8.00 g	2.40 g
7.00 g	2.10 g
6.00 g	1.80 g
5.00 g	1.50 g
4.00 g	1.20 g
3.00 g	0.90 g
2.50 g	0.75 g
2.00 g	0.60 g
1.66 g	0.50 g