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Anisotropy as a defect in U.K. architectural float heat-treated glass

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Declaration

I hereby declare that my dissertation **"Anisotropy as a defect in the U.K. architectural float heat-treated glass"** is comprised of my own personal work and research, except where mentioned and referenced within the body of the text.

A complete list of the references is included.

Saverio Pasetto

September 2014

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Abstract

Anisotropy, or leopard spots, is the term used in the façade industry to describe the manifestation, under certain light and viewing conditions, of patterns and colourful areas in heat-treated glass. The phenomenon is often the subject of disagreements, that may eventually lead to disputes, between the cladding supply chain, who do not consider it a defect, and designers/specifiers and their clients, who consider it a flaw and want to avoid it.

The causes of anisotropy and the conditions that may affect it are reviewed in detail with an appraisal of the current State of The Art as it relates to production and measurement processes that aim to minimise its visibility. The review reveals that the phenomenon is dependent on polarised light, viewing angle and stresses in the glass plate: the latter are a function of the temperatures distribution during the heat treatment process.
State of The Art scanners allow measurements and analysis of the anisotropy patterns and in turn enable a dedicated design and operation of the tempering ovens to reduce anisotropy visibility: this is an important step for the glass industry which has historically sustained that the issue, which remains unavoidable, could not be mitigated.

The development of measuring equipment is also crucial to objectively define acceptance and rejection parameters: these may be incorporated in future revisions of the regulating standards and guidelines for which anisotropy is currently **not** a defect but a visible effect. This is in contrast with a number of specifications that demand glass with reduced anisotropy or with no anisotropy.

The results of a 15-question survey administered to 35 key stakeholders (architects, glass suppliers, specialist façade contractors and façade consultants) shows the division between the supply chain, that accepts the phenomenon, and designers and their clients, who aspires to have glass with reduced anisotropy. It also highlights the need for a detailed explanation of anisotropy and the inadequacy of current standards, which lack objective acceptance parameters as much as specifications, thus attracting protracted qualifications and potential for disputes.

Anisotropy is an important matter for the stakeholders who would like to receive updated information on what causes the phenomenon and what the industry can do about it. This study may be used to support such action and initiate further research.

Acknowledgments

To Nicola and the Boys for the Patience and Support

To Zio Nino for the Inspiration

To Skanska for the Opportunity

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Abbreviations and Nomenclature

Al_2O_3	Aluminium Oxide
BS EN	Eurocode - British Annex
CaO	Calcium Oxide
CWCT	Centre for Window and Cladding Technology
GGF	Glass and Glazing Federation
Low-E	Low emissivity coating
m/s	Metre per second (Speed)
MgO	Magnesium Oxide
MPa	Mega Pascal
Na_2O	Sodium Oxide
PDF	Portable Document Format (Adobe)
SiO_2	Silicon Dioxide
TN	Technical Note

1. Introduction

Glass façades play an important role in contemporary architecture. Despite the upcoming trend of reducing the window-to-wall ratio, i.e. the proportion of transparent surfaces versus the opaque ones in order to improve the wall thermal performance and meet more demanding energy codes (Thomsen, 2013), there still is a considerable demand for extensive glass façades.

The 13-storey "groundscraper" currently being built at 5 Broadgate in the City of London is, with its extensive use of metal panels, an example of the former trend and it is in contrast with the highly transparent façade design of five other iconic commercial buildings either being built or recently completed in central London: 20 Fenchurch Street, The Heron Tower, 52 Lime Street, 122 Leadenhall Street and The Shard.

Figure 1.1: No. 5 Broadgate (Kollewe 2011)

Figure 1.2: No. 20 Fenchurch (Alden 2013)

Figure 1.3: The Heron Tower

Figure 1.4: No. 52 Lime Street (Waite 2012)

The requirements for building envelope transparency and the designers' obsession for high glazing ratios are nowadays satisfied by extensively using large and high performance floor-to-floor glazing.

The structural requirements of such large glass units are met by exploiting the structural performance of increasingly thick glass panes, laminated and heat-treated glass, often used in combination with one another and resulting in rather complex glass products.

Figure 1.5: No. 122 Leadenhall Street

Figure 1.6: The Shard

While heat-treating anneal glass considerably improves its structural performance, the process potentially, and unfortunately, produces a number of undesirable phenomena and visual distortions (Henriksen and Leosson 2009, pp. 834-839).

One of these issues is known as anisotropy or leopard spots and is the subject of this dissertation.

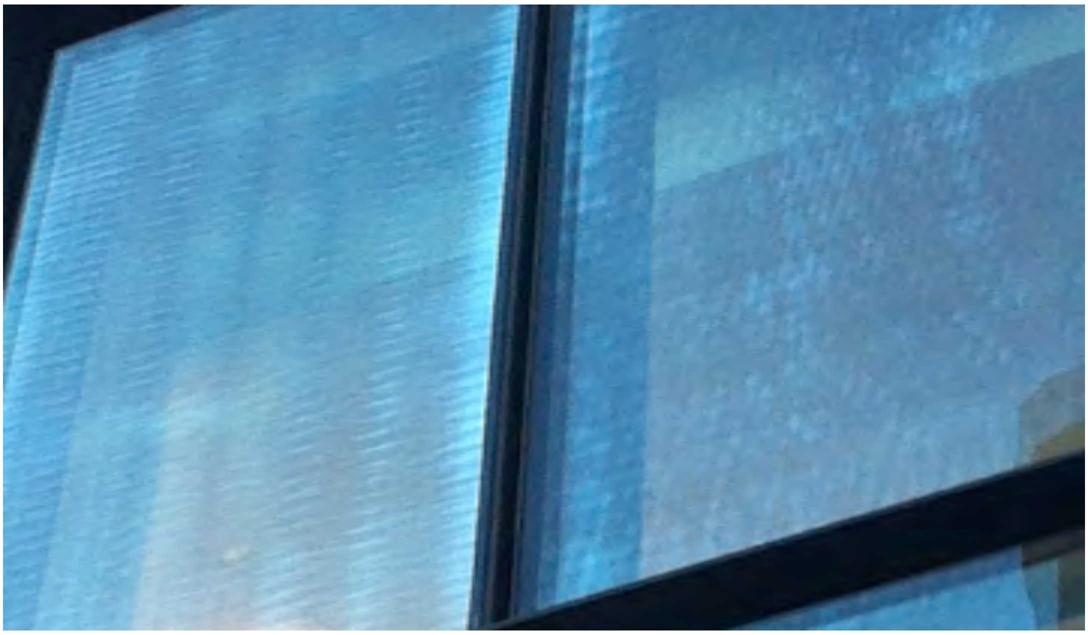


Figure 1.7: Anisotropy in glass

1.1 Support for Subject Selection: The Need for Clarification

The current glass industry standards and guidelines recognise anisotropy in glass, more generally referred to as “leopard spots”, as an unavoidable characteristic of heat-treated glass when exposed to certain light conditions (CWCT TN 35 2003, p. 7).

Equally, the glass industry does not acknowledge the phenomenon as a defect.

Cladding specifications have always been consistent with such standards, however specifications have become, in recent years, increasingly stringent by frequently demanding glass with reduced anisotropy or anisotropy-free glass and by effectively redefining the phenomenon a defect for which glass may be rejected. One of the main objectives of this dissertation will be to assess the scale of the problem.

On the other hand, the cladding industry is struggling to meet these latest demands due to the limitations of the glass processing which determines what the industry can actually offer.

In addition, factory and on-site glass acceptance and rejection in relation to anisotropy are essentially based on subjective inspection criteria and supported by extensive sampling, as it is not clear if, and how, the anisotropy can be measured and controlled.

Notably, CWCT Technical Note No. 35 goes as far as stating that, as it is not a defect, “no inspection criteria apply” (2003, p. 7).

This lack of objectivity in the inspection process is naturally very difficult to manage, especially considering that visible and disturbing anisotropy is apparently highly dependant on light conditions and amount of polarised light. As the production and inspection light conditions are likely to be different from the installed conditions, the issue represents a considerable risk to carry on a project, especially when this is large and prestigious.

An initial pilot survey of 15 stakeholders confirms that the above problems are not isolated occurrences but are widespread in the façade industry. It also appears to suggest that the industry is divided between designer and specifiers reserving the right to reject glass products due to anisotropy and the façade specialists struggling, or unable, to meet these new demands.

These concerns are also confirmed in an earlier study by I'Anson, where most participants confirmed to have issues with anisotropy (2011, p. 39).

The pilot survey also suggests that there is confusion regarding what anisotropy actually is and what causes it. The guidelines, e.g. CWCT Technical Note No. 35 and Hadamar 10/96 "Guideline to Assess the Visible Quality of Insulating Glass Units", and standards, e.g. BS-EN 12150-1:200 and BS-EN 1863-1:2011, provide only limited explanations for anisotropy.

Conversely, detailed knowledge of the phenomenon resides with expert glass consultants and in specialist books, such as the "Glass Construction Manual" by Schittich et al. (2007).

Moreover, the pilot survey highlights the existence of one glass supplier that is apparently capable of supplying glass with non-disturbing anisotropy as well as providing a degree of scanning and reading of the phenomenon, however the availability and limitations of this new product and process are not totally clear.

As a result of this confused situation, an increasing number of specifications cannot be met, thus resulting in protracted qualifications and, potentially, costly legal disputes when the issue is not adequately resolved at tender stage. If this issue is not resolved to the satisfaction of all parties then this situation will only get worse and more confused, as demands for virtually fault-free glass become ever more prevalent.

There is an urgent need to collate updated information on the subject, objectively appraise the current industry status and inform the industry main stakeholders: architect, façade consultants, glass suppliers and façade specialist contractors. This will potentially facilitate the redaction of more realistic and achievable specifications. It will also support the cladding procurement and construction processes by providing a common knowledge that may limit disputes, qualifications and litigations.

Figure 1.1.1 maps the above main topics to the dissertation chapters: these evolve into key sections of a 15-question survey issued to 37 stakeholders that play a leading role in the U.K. commercial building market.

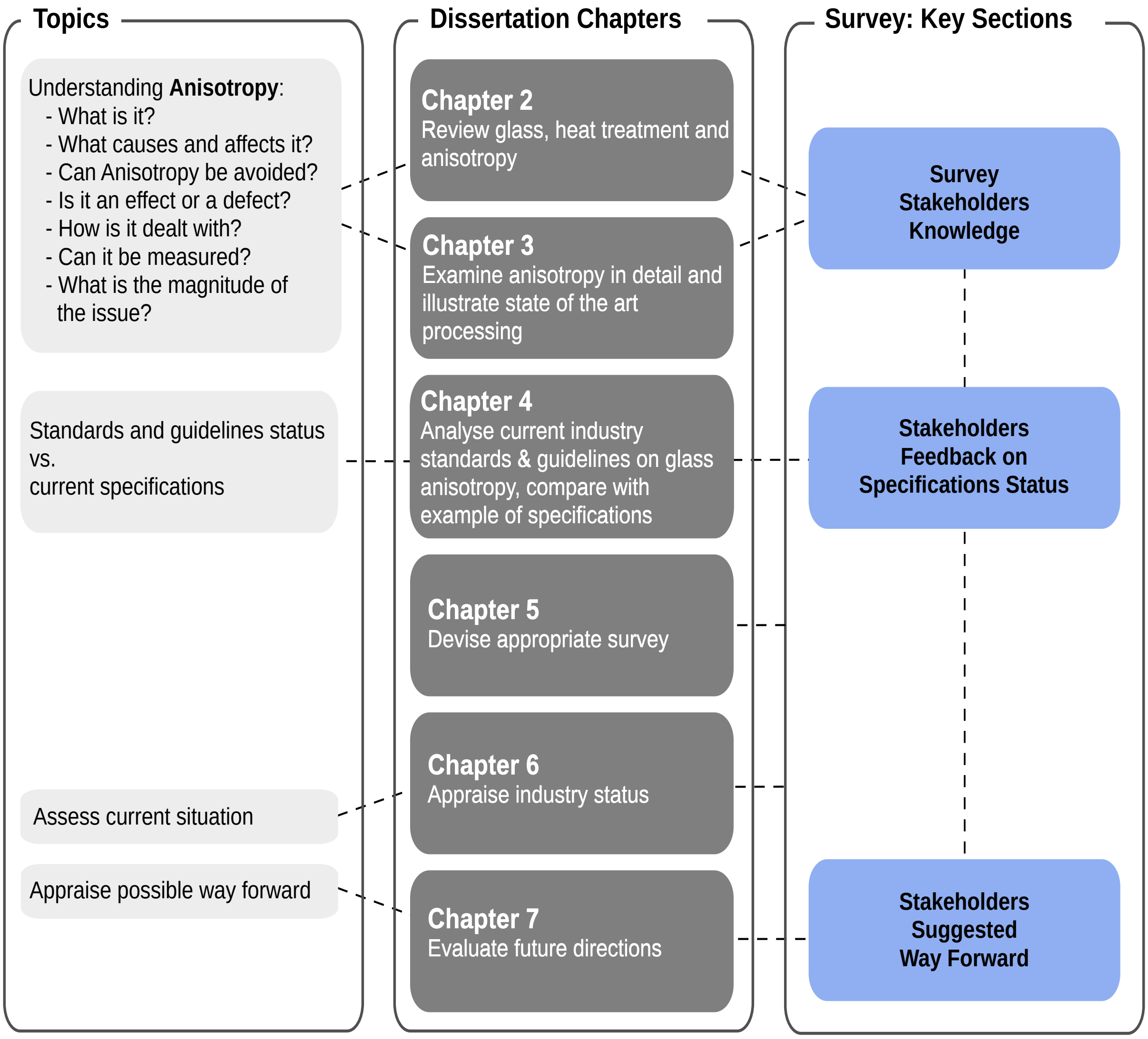


Figure 1.1.1: Topics mapped to dissertation structure and survey

1.2 Dissertation Objectives and Outline

One of the aims of the dissertation is to identify the extent to which anisotropy in heat-treated glass is perceived as a defect by the main stakeholders in the façade industry (clients, designers and specifiers, glass suppliers and cladding contractors), and how this affects the cladding and glass industry, which currently do not consider it as a flaw.

The study also aims to identify what clarification is required, what the industry state of the art is and examine future challenges and possible ways forward.

The second chapter of the dissertation introduces glass as a product and the need for those additional processes associated with anisotropy. This supports a basic explanation of what the phenomenon actually is and what causes it. It also forms the background of the research while answering one of the items highlighted by the pilot survey: the confusion around what anisotropy is.
There is a lack of detailed descriptions of the term “Anisotropy” when it comes to architectural glass, (Henriksen and Leosson 2009, p. 834).

Chapter three describes the phenomenon in more detail and examines the current industry state of the art as it relates to measuring and controlling disturbing anisotropy in architectural glass.

Anisotropy is generally not recognised as a defect by the glass industry: the fourth chapter of the dissertation will investigate the industry standards, most recent guidelines and specialist publications as well as present examples of specifications. This will help to highlight the tension between the demand for anisotropy-free glass in current specifications and the challenges faced by the façade industry, which relies on the glass industry, in meeting such demands. This chapter will also serve as a useful reference tool recapping applicable standards and guidelines.

A questionnaire will be developed from the initial pilot survey to assess the façade industry stakeholders’ knowledge and perception as it relates to anisotropy in glass, collect feedback on specification status and gather suggested ways forward. This will help in establishing the magnitude of the problem, highlight any associated shortcomings and present how the different stakeholders currently deal with anisotropy.

The questionnaire reasoning, structure and questions, response rate and participant distribution list are presented in chapter 5, which is followed by the response analysis and survey assessment in chapter six.

The dissertation is concluded with chapter 7, where the aim is to identify and predict a sustainable way forward while illustrating the industry status.

Table 1.2.1 in the next page maps the dissertation objectives with the research methods.

Objectives	***Research method***	***Chapter***
1. Review glass, heat treatment and anisotropy	Desk study: • Literature review	**2**
2. Examine anisotropy in detail and illustrate State Of The Art processing	Desk Study: • Literature review • Review glass industry publications • Interviews with supply chain • Review current technology and limitations	**3**
3. Analyse current industry standards and guidelines on glass anisotropy, compare with example of specifications	Desk Study: • Collate and review industry standards, specialist publications and guidelines • Present example of specifications • Identify standards and specifications shortcomings	**4**
4. Devise appropriate survey	Desk study: • Establish survey structure to key stakeholders	**5**
5. Appraise industry status	Desk Study: • Appraise and present the result of a questionnaire to key stakeholders • Summarise façade industry knowledge and perception of anisotropy • Identify order of magnitude of the issue	**6**
6. Evaluate future directions	Desk Study: • Interpret the dissertation findings to assess the overall industry status and predict potential way forward	**7**

Table 1.2.1: Dissertation objectives mapped to research methods

1.3 Research Boundaries

The study is limited to understanding the effect of anisotropy on architectural, floated and heat treated soda-lime silicate glass in the U.K. cladding industry, and in particular its affect on non-residential commercial buildings. The boundaries of this dissertation are those highlighted in bold in Figure 1.3.1 below.

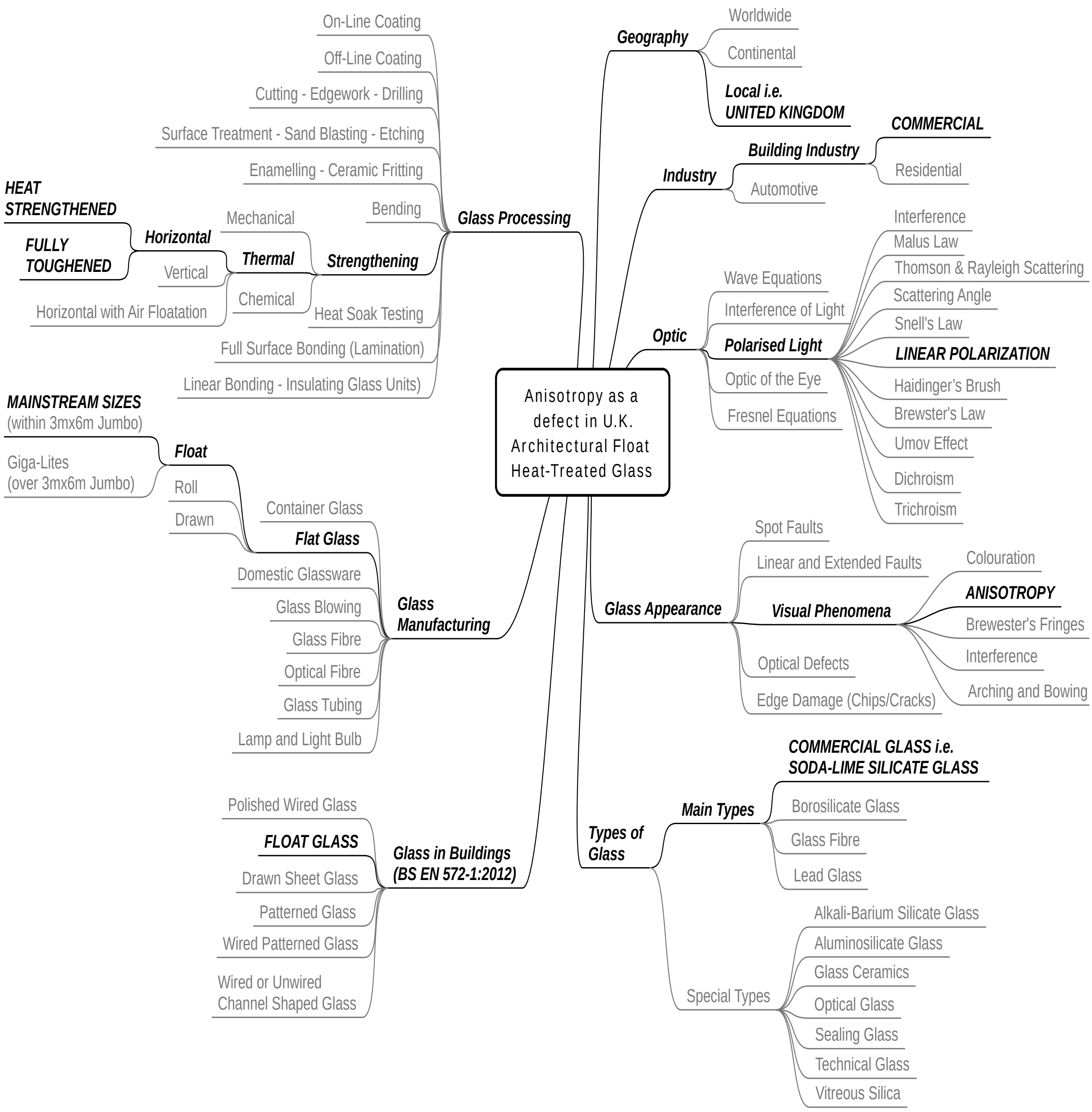


Figure 1.3.1: Dissertation boundaries

2. Glass, heat treatment and anisotropy

In general physics, a material that shows uniform physical properties in all directions is defined as “Isotropic”. Conversely, the term “Anisotropic” is used to identify a material whose physical properties depend on the direction of measurement.

In the glass, façade and building industry, certain colour variations, typically characterised by alternating light/dark and/or colourful patches within the same glass plate, are generally referred to as “leopard spots”, or more technically “anisotropy” or “iridescence”.
This phenomenon, which appears in different patterns, is visible on heat-treated glass under polarised light conditions and when viewed at particular angles, as in the picture below.

Figure 2.1: Anisotropy or leopard spots in heat-treated glass

This chapter of the dissertation introduces the glass product and focuses on the main production processes, and the need for these, that may be associated with anisotropy in glass. This provides the background for a basic explanation of why the phenomenon is correlated with heat-treated glass, as well as supporting further discussion in the following chapters.

2.1 Introduction to Glass: Early Production Methods

Glass is a material that has been known to mankind for thousands of years. It was initially used by ancient civilisations to form vessels and jewellery, and later incorporated in windows.

The product of fusion, glass can be found in nature as solidified lava, as a result of volcanic eruptions (Wurm 2007, p. 34). In this form it is known as natural glass or "obsidian" (Schittich et al. 2007, p. 60).

While the origins of glass are uncertain, archaeological findings appear to confirm that some form of rudimentary glass material was used in Egypt as far back as the pharaohs around 3500 BC, as well as in Mesopotamia around the 5th century BC.
Syrian craftsmen are considered responsible for the invention of the blowing iron, a couple of centuries later, to form thin glass walled vessels, while the Romans certainly used a form of bluish green glass, which was cast and drawn, in windows at Pompeii and Herculaneum. This method of production, which involved pouring and stretching the viscous paste, spread in the Middle Ages, when the blown cylinder sheet glass and crown glass processes were also widely developed. These two methods involved the creation of a glass bubble by means of drawing and blowing molten glass with a blowing iron.
In the blown cylinder method, the bubble was shaped into a long and thin cylinder, which ends were cut before the cylinder was split open and flattened. In the crown glass technique, the bubble was spun to form a disc and flattened. The flattened product was cut to the required shape and dimension in both processes, which remained the main glass production techniques until the 20th century (Schittich et al. 2007, pp. 10-11).

The blown cylinder method allowed the production of larger panes compared with the crown glass process. However the latter fire-polished surface finish offered better optical quality than the blown cylinder sheet glass, which glass surface was affected by the contact with the roughness of the flattening furnace.

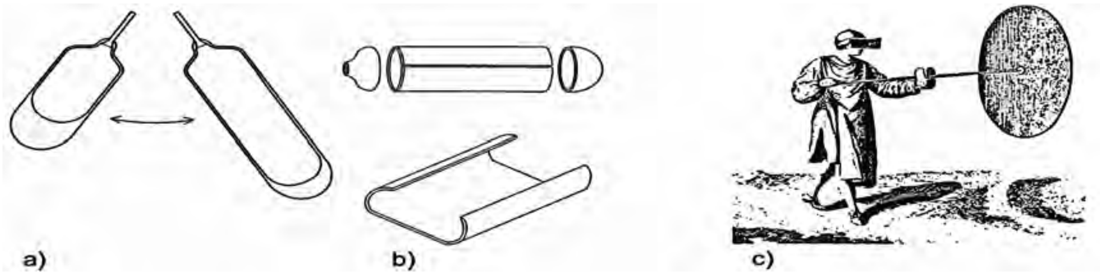


Figure 2.1.1: Blown cylinder (a, b) and Crown c) glass production methods (Schittich 2007)

The Belgian Emile Fourcault achieved an important step in the evolution of glass processing at the beginning of 1900 with the invention of the drawing method, where the molten glass is drawn vertically and continuously out of the bath. The process allows the production of industrial quantities of glass with decent optical quality, however linear distortions may be present (Weller et al. 2009, p. 8).

In 1919 Max Bicheroux combined several steps of glass production to roll a continuous glass melt into a ribbon from which large glass panes, up to 3 by 6 metres, were cut and cooled on tables: a crucial step in the production of cast glass was achieved (Schittich et al. 2007, p. 12).

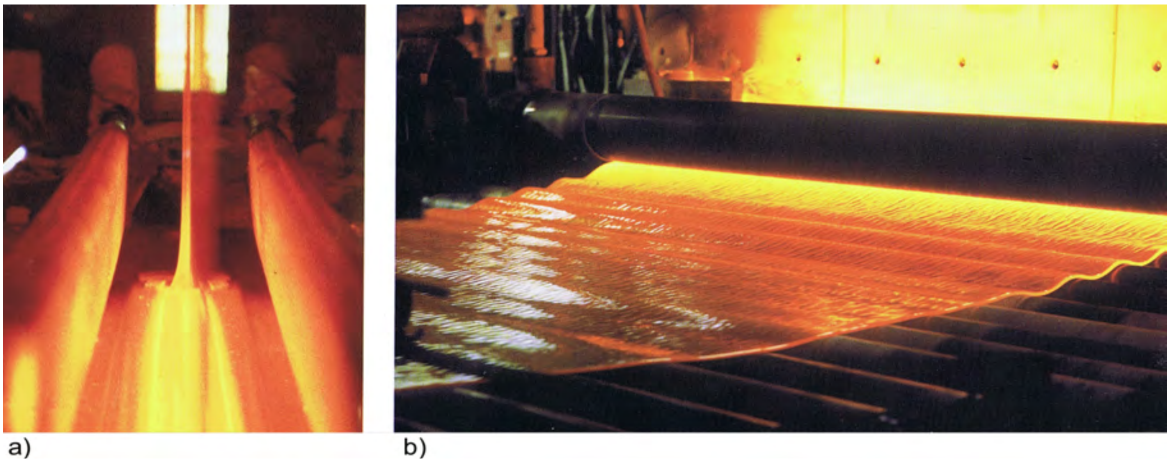


Figure 2.1.2: Modernised drawn (a) and rolled (b) glass production processes (Wurm 2007)

It was however in the 1950s that the glass production industry was revolutionised by Alastair Pilkington's float glass process invention, which continuously float the glass out of the furnace onto a flat bath of molten tin, where it stays until it cools and solidifies. The process addressed, at that time, the irregularities caused by the drawn process while avoiding the expensive grinding and polishing associated with the early rolled or cast glass processes (Pilkington 2013).

Glass manufacture has been characterised through the centuries by the search for a production methodology capable of dealing with the increasing market demand for a cheaper product to be sold in larger quantities and dimensions. While anisotropy may not have been in the early days part of this scenario, the demand for a higher quality of the end product has been, and still is, a fundamental aspect of such process. Limiting, if not avoiding, the amount of operations, e.g. grinding and polishing, to be carried out to remove increasingly unacceptable imperfections naturally reduces glass cost.

2.2 Flat Glass Production

The increasing demand for high quality flat glass, for both building envelope and mirror applications, to be industrially produced in larger dimensions and at cheaper cost has driven glass production innovation in the last couple of centuries.

Flat glass for building applications is nowadays industrially produced by the rolled or cast process, by the drawn process and by the float process. Button and Pye state that more than 90% of flat glass is produced by the latter method (1993, p. 21).

Figure 2.2.1 below is sourced from Wurm and illustrates, in principle, the various stages of flat glass manufacturing and processing (2007, p. 34). The processes that have been highlighted in bold and shaded are of particular interest to discuss anisotropy and will be reviewed within this chapter.

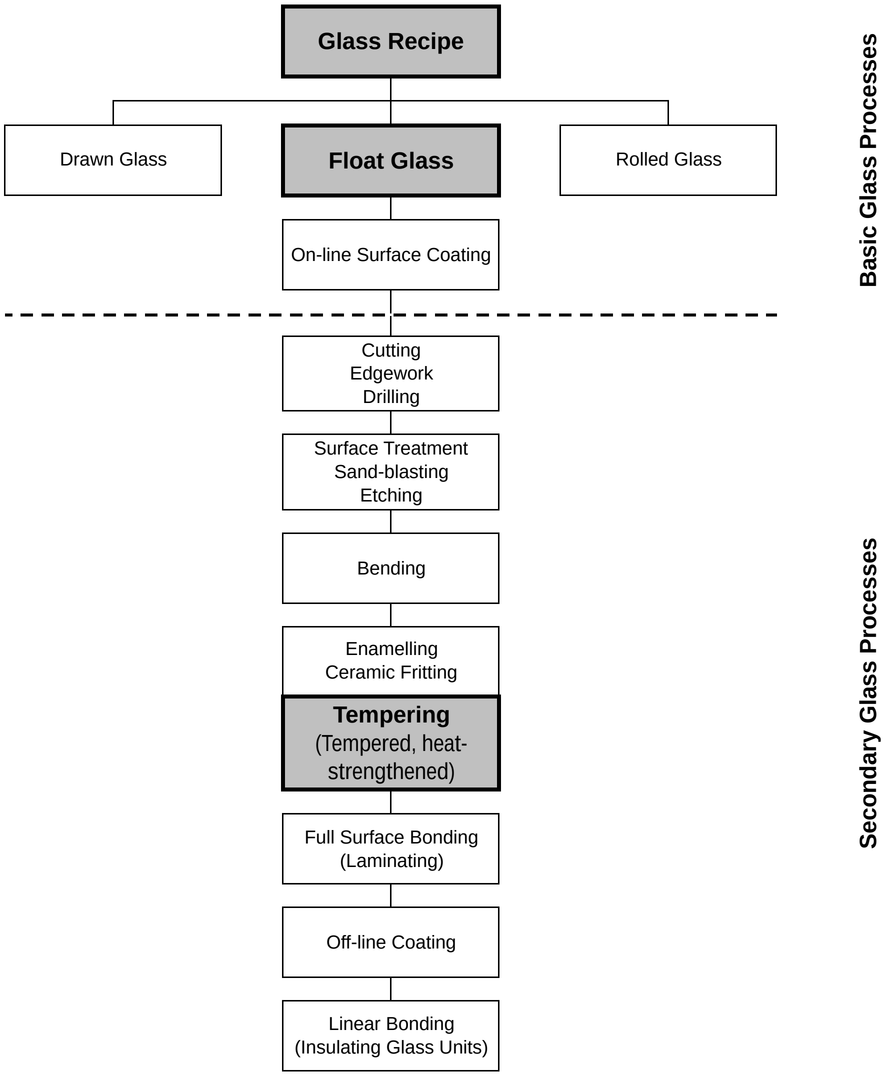


Figure 2.2.1: Flat glass processes (Wurm 2007)

2.3 Glass: The Recipe For Transparency

Glass used in the building industry, and in particular as part of its glazed envelope and interiors, is generally soda-lime-silicate glass. Borosilicate glass is also used, however this is in limited quantities and mainly used for fire-resistant glazing: this type of glass will not be discussed any further in this dissertation.
In addition, from this point onward in this dissertation the word “glass” will be used to refer to annealed soda-lime-silicate glass produced by the float process.

The typical chemical composition of soda-lime-silicate glass in United Kingdom is regulated by the standard BS EN 572-1:2012 and is captured for reference in Table 2.3.1. The standard also defines the “*float*” as a “*flat, transparent, clear or tinted soda-lime silicate glass having parallel and polished faces obtained by continuous casting and floatation on a metal bath*” (p. 5).

Constituent	***Magnitude of proportion by mass***
Silicon Dioxide (SiO_2)	69% to 74%
Calcium Oxide (CaO)	5% to 14%
Sodium Oxide (Na_2O)	10% to 16%
Magnesium Oxide (MgO)	0% to 6%
Aluminium Oxide (Al_2O_3)	0% to 3%
Others	0% to 5%

Table 2.3.1: Principle constituents of soda-lime-silicate glass (BS EN 572-1:2012)

Other additives and substances may be added to the above ingredients to alter colour and other properties, for example to produce body tinted glass, however these do not affect the glass mechanical strength (Schittich et al. 2007, p. 60). Conversely, the presence of small amount of impurities in the raw material mixture gives this basic glass a greenish colour (Guardian 2012a).

Special production processes are in place with most floaters to reduce the amount of impurities and in particular iron oxide, and in turn greatly reduce the compound natural green colour. The result is a product generally known as low-iron glass, which is sold under different trade names by each glass supplier, that aims to meet clients and designers current demand for a particularly clear, not-green, glass product.

The product is also know as clear soda-lime-silicate glass and offers a high natural light transmission that is virtually unaffected by the pane thickness (Wurm 2007, p. 45).

Figure 2.3.1: Low-Iron glass (top) compared to normal float glass (bottom) (Guardian 2013)

Figure 2.3.1 above clearly shows the considerable difference between Guardian normal float glass and their low-iron product, the Guardian Ultra-White.

While the ingredients per se may not directly affect the level of anisotropy, they do affect the softening temperature of the glass, as noted by Boaz (2009, p. 589). The differences in glass composition also affect the material property at high temperature as well as its thermal properties (Aronen 2012, p. 7, 8).

In addition, according to Jukka Vehmas, R&D director of leading tempering oven producer Glaston, low iron glass is more difficult to heat as it absorbs less heat and as a result requires a longer period in the tempering furnace, approximately 10% longer than normal float glass (Vehmas 2014).

Low-iron glass therefore not only looks different from normal float glass but also requires to be tempered with due consideration and this may affect the resulting anisotropy.

In addition, one may expect a more transparent and clear product like low-iron glass to be more susceptible to show the phenomenon, as the typically darker areas are more evident on a clearer surface. This appears to be confirmed by the NSG Group (Pilkington) Technical Bulletin ATS-157, which states that the anisotropy typical spots and lines are more visible when the glass is **clear** and treated with a lightly reflective coating (2013, p.1). While the latter is confirmed by the feedback provided by the industry stakeholders in this dissertation questionnaire responses (see chapter 6.7), the former is not.

Low iron glass has become increasingly popular in the façade industry in recent years. Notably, the responses to question no. 4 of this dissertation questionnaire shows that the number of disputes that relate to anisotropy have also increased.

Conversely, highly reflective or tinted, darker glass was more common a decade or so ago when, according to the same response, disputes regarding glass anisotropy were also less of an issue.

This trend, and the considerations in previous paragraphs, would therefore imply that anisotropy in glass is more visible when low-iron glass is used.
Unexpectedly, the questionnaire responses marginally suggest otherwise, with four participants stating that anisotropy is worse when glass is not low-iron as opposed to only three participants stating that it is worse when glass is low-iron (see Question no. 7, in particular responses 3 and 4).

2.4 The Floating Process

The manufacturing of flat glass by the float process makes the product “the most important basic glass” (Wurm 2007, p. 45).

Figure 2.4.1 is sourced from Schittich et al. and shows the main phases of the glass floating process (2007, p. 61).

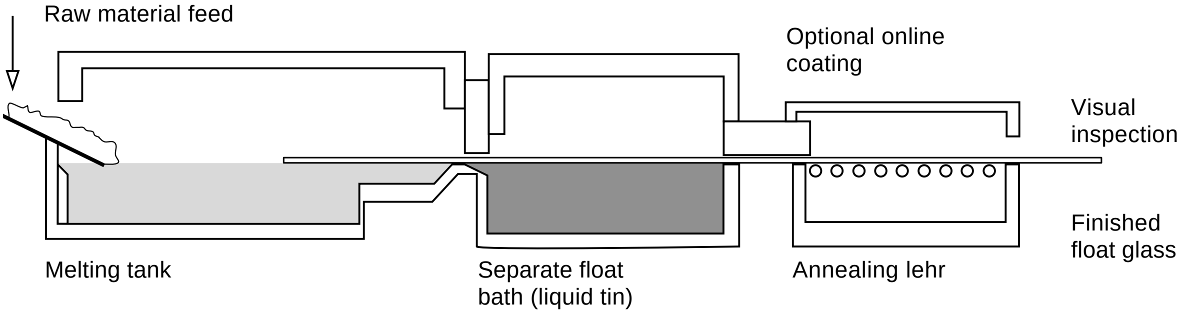


Figure 2.4.1: Main phases of glass floating process (Schittich 2007)

According to Guardian, the mixed, fine-grained ingredients enter a furnace heated at 1500°C where they melt to form glass: from here the molten mass continuously flows onto a bath of molten tin. This is initially at 1100°C but it is gradually cooled to 600°C, thus allowing the glass to leave the float bath as a solid ribbon and enter the annealing lehr. In this heat-treatment furnace the ribbon is further, slowly, cooled, under highly controlled conditions, and **its internal stresses**, inherited during the initial cooling phase of the float, **are released** (2012b).

The resulting product is a high quality glass plate, **virtually stress free**, and with parallel surfaces known as annealed glass or annealed float glass.

Annealed glass shows amorphous **isotropy**, as its physical properties, including and in particular visible light refraction, do not depend on the direction they are measured (Schittich et al. 2007, pp. 60, 67).

Metal oxides may be spread on the glass while this is still hot so as to bond them to its surface, and in turn provide the final product with enhanced solar or thermal control performance (Schittich et al. 2007, p. 64).
These products are known as pyrolytic coated glass and were widely used in façades a decade or two ago; nowadays high performance coatings are applied off-line by the magnetron process. A detailed discussion of the glass coatings, and in particular their effect on anisotropy, is outside the boundaries of this dissertation.

Following the annealing process, the glass is cut to size in accordance to customer's order or to the standard large "jumbo" size of 3210mm (wide) by 6000mm (long), for further processing or direct use.
Typical glass thicknesses are from 2mm to 25mm, however sub-millimetre glass is also available (Guardian, 2012b).

Oversized glass panes with length over the standard 6000mm and up to 18000mm, which are increasingly becoming known as "Giga-Lites", may be available upon request, however this is only for special orders or "campaigns" that require considerable planning and investments. Further glass processing of oversized panes maybe limited by the constraints of existing equipment, as generally illustrated on Figure 2.4.2 which is sourced from Interpane (Wassink, H., *pers. comm.*, 8 November 2013).

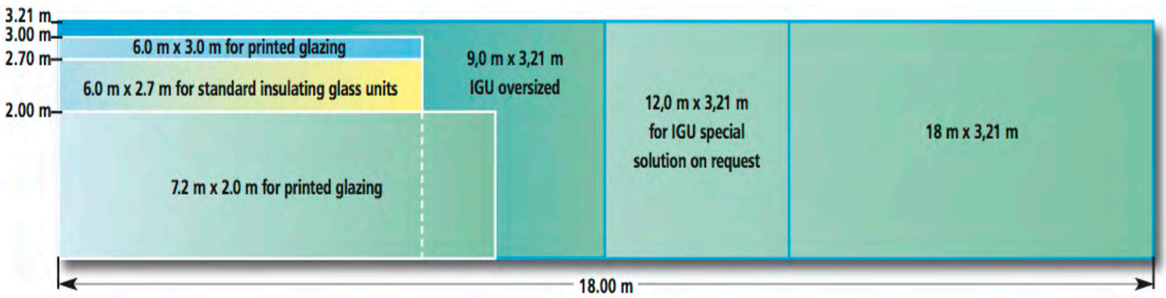


Figure 2.4.2: Technical overview of Interpane "Giga Lites" (Interpane 2014)

Heat treatment of these extra large products may require dedicated machinery, procedures and controls that may directly or indirectly affect the level of anisotropy, in particular as it relates to spatial limitation on the oscillation of the glass within the tempering oven. The tempering of oversized glass panes will not be discussed further as it is outside the boundaries of this dissertation.

Colour variations in annealed float glass are generally due to changes in the proportions of the various ingredients, in particular iron, between different producers or batches, or in the thickness of the end product. **These colour variations are not anisotropy which is not visible in annealed glass.**

2.5 The Strengthening of Glass

Annealed float glass does not exhibit anisotropy or leopard spot and is therefore, in principle, the product of choice for designers and clients aiming to avoid any issue or risk associated with the phenomenon. However, the product cannot be used in all situations as it may not meet, for example, the mechanical performance requirement related to increasingly large glass panes and loads or it may not be able to sustain thermally induced stresses. In addition, contrary to toughened glass that breaks in small relatively harmless dices, annealed float glass breaks in large, dangerous shards: a breakage pattern which is not considered safe.

Glass is a very strong, brittle material characterised by a perfectly elastic behaviour until failure. Despite the high quality of modern glass production, microscopic flaws mark the material surface. These flaws are generally known as Griffith's flaws and are shown in Figure 2.5.1 below, which is sourced from Schittich et el. (2007, p. 90).

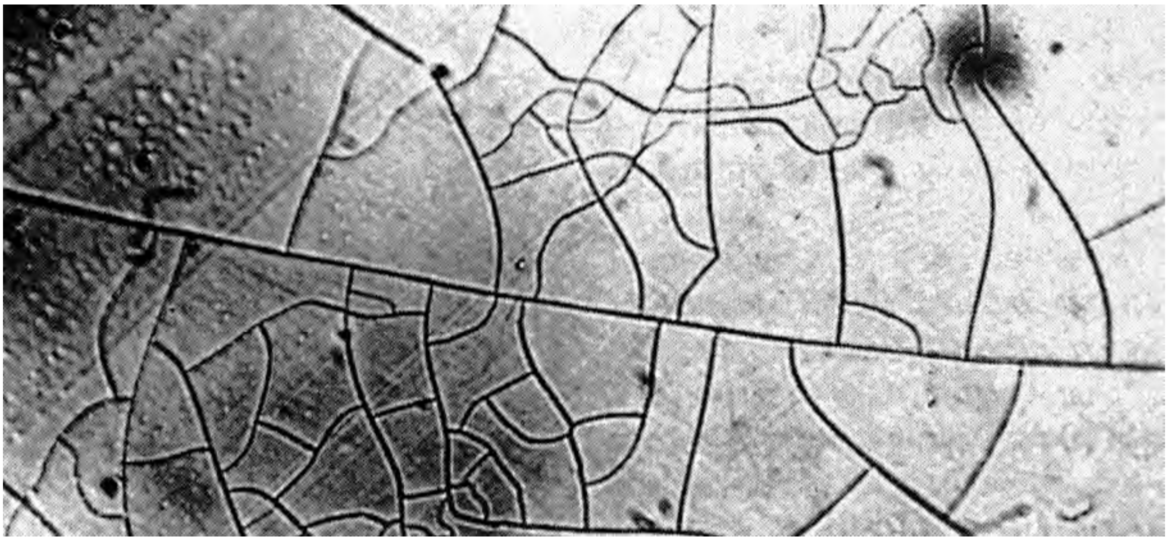


Figure 2.5.1: Griffith flaws (Schittich 2007)

These vents and cracks, which could be the result of surface abrasion, are also particularly present, unavoidable and critical, at holes and edges: the degree of damage inevitably affects the usable strength of the glass product (Schittich et al. 2007, p. 91).

When the glass surface is subject to compression, for example when an external load is applied as shown in Figure 2.5.2, the vents will naturally tend to close: conversely they will open if the surface is in tension and this may eventually instigate fracture.

This explains why *“annealed soda-lime-silica glass is weak under tension but strong under compression”* (Aronen 2012, p. 1).

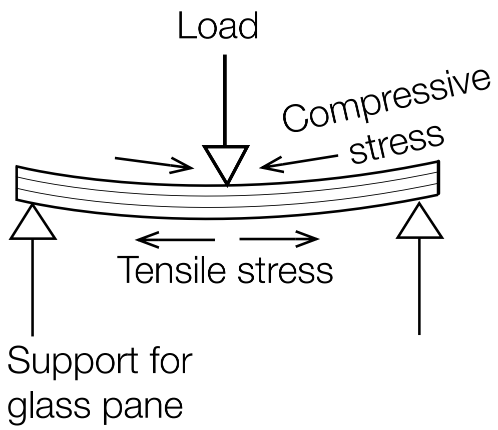


Figure 2.5.2: Compressive and tensile stresses - Effect on vents (Schittich 2007)

An early study by Bartholomew and Garfinkel (cited by Aronen 2012, p. 1) suggests that the most effective way to improve the strength of glass is to make the flaws “inoperative”, as opposed to removing or avoiding them. This can be achieved by introducing a compressive stress stratum on the glass surface, either by applying external forces (for example a dead load or a spring) or by processing the glass further by means of chemical or **thermal treatment**. The latter is of particular interest as it relates to glass anisotropy and shall be therefore discussed further in this dissertation.

Glass strength increases as a result of the introduced surface compression, which counteracts the effect of induced tensile stresses while the top of the flaws will tend to remain closed. Schittich et al. also states *”only after the precompressive force has been fully neutralised on the tension face does a tensile stress occur in the glass”* (2007, p. 92).

While annealed glass may be the ideal product in terms of optical quality, it comes with some limitations in terms of strength: this is further reduced by additional processing like drilling and notching.

These limitations can be addressed by thermally treating the glass, however this inevitably introduces **anisotropy**.

2.6 Thermal Treatments for Strengthening: Toughening and Heat Strengthening

The strengthening of glass by thermal treatment involves the use of a tempering oven, which is diagrammatically shown in Figure 2.6.1 below; the glass is generally washed at some point before entering the furnace.

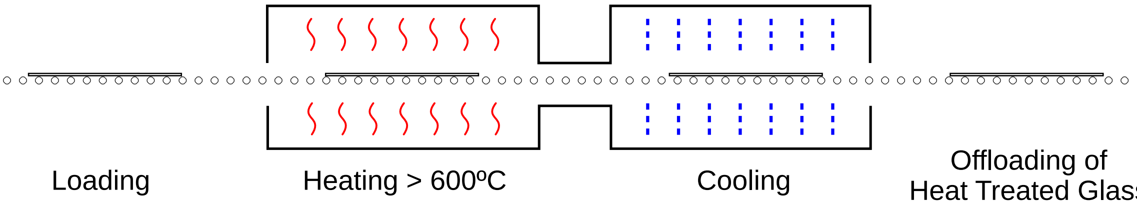


Figure 2.6.1: Tempering oven diagram

The glass plate to be treated enters the process cut to its final size, and inclusive of any edge working, notching and drilling, as these mechanical operations cannot be carried out after the heat treatment without causing breakage of the glass plate. Conversely, the process is used to address the weakening caused to the product by these operations, and it is also employed to bake ceramic pigments on the glass surface to create enamelled glass.

After its loading onto a roller conveyor, where it will stay for the duration of the process, the glass enters the oven section where it is heated above 600°C. The plate is then moved to the cooling section where it is "quenched" by jets of cold air. During the quenching process, the outer surfaces of the glass plate contract and solidify quicker than its inner core as they cool more rapidly, "*instantaneously*" according to Schittich et al. (2007, p. 92).

As the glass core then cools and solidifies, the outer surface opposes to its contraction and is therefore compressed. It is this surface compression, in balance with the tension in the core, which enhances the glass strength (for the reasons previously explained).

Different levels of compressive stress can be achieved by varying the speed of the cooling: the faster the cooling the higher the stresses.

Thermally treated glass with surface compressive stresses in excess of 80-100 MPa is referred to as tempered (or fully tempered or toughened) glass, whereas stresses in the region of 45-65 MPa will produce heat-strengthened glass (Aronen 2012, p. 1).

It should be noticed that the latter is indicatively twice as strong as annealed glass and have a similar breakage pattern, i.e. in large shards, and, if used as a single pane, cannot be classified as a safety glass. On the contrary, toughened glass, which may be four or five times stronger than annealed glass, breaks in small dices, which are likely to cause fewer injuries, and can be therefore classified as safety glass.

The standard BS EN 12150 regulates the physical and mechanical characteristic, including but not limited to the fragmentation requirements, of thermally toughened (soda lime silicate) safety glass for its use in the building industry. Conversely, the standard BS EN 1863 regulates the characteristics of heat-strengthened glass.

The heat treatment process unfortunately affects the visual quality of the glass.

The complex thermodynamics of the heating, transfer and cooling processes along with the need to support and move the glass during the entire operation affect:

- The plate shape, surface quality and planarity, which results in defects like roller marks, “roller pluck” and waves, as well as bowing and dishing: these are not anisotropy.
- **The glass isotropic behaviour: the introduction of stresses and the inhomogeneous cooling by air jets forms areas of denser glass that alter the way light is refracted** (Schittich et al. 2007, p. 67)**.**
  Under certain light and viewing conditions, patterns of lighter and darker areas or multicolour areas may be visible: this phenomenon is referred to as anisotropy or leopard spots.

White haze is another possible and undesirable flaw of the process: this is **not** anisotropy and is the result of dust particles scratching and contamination. It is mainly due to uneven surface contact between the glass surface and the rollers, as a result of the deformation of the glass plate under temperature.
Anisotropy, however, **is likely to occur at white haze location**, as the contact with the rollers will inevitably change heat transfer and consequently glass density (Henriksen and Leosson 2009, p. 836).

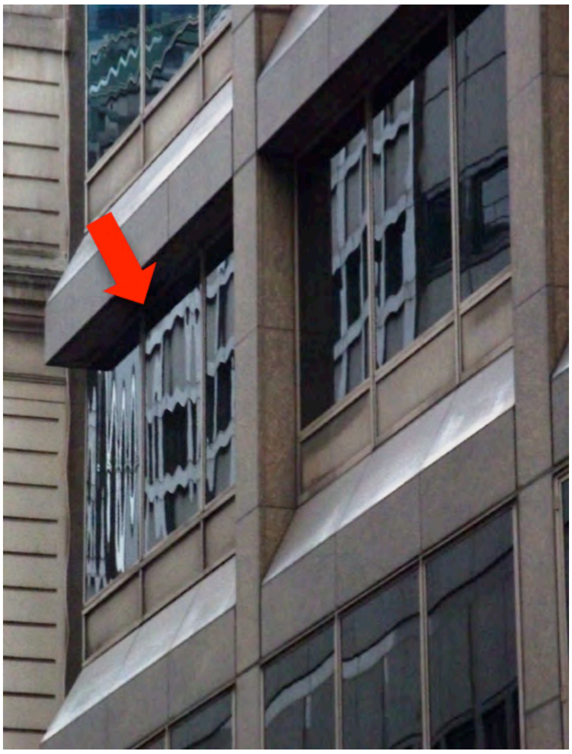


Figure 2.6.2: Roller waves

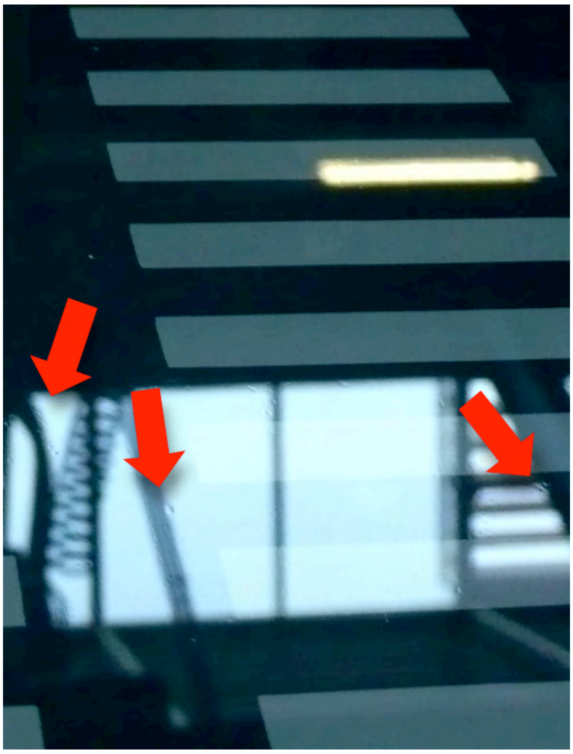


Figure 2.6.3: Roller pluck

Figure 2.6.4: White haze (Henriksen and Leosson 2009)

Figure 2.6.5: Anisotropy (stripes)

2.7 Conclusions

Mankind has exploited glass for millennia: the product is now a fundamental aspect of modern architecture and building envelope.
This latter application has been one of the main drivers for improving glass production techniques to lower cost while delivering increasingly larger, high quality flat glass panels.

The floating process has been the protagonist of this quest in the last fifty years: the original basic ingredients have remained virtually unchanged through the centuries, but the ultimate product is now a near perfect, annealed and **isotropic** flat glass, continuously and cheaply produced in industrial quantities and very large dimensions.

The product is heat treated to improve the annealed float glass ultimate bending strength and its thermal fatigue resistance, to address the weakening produced by drilling and notching operations or simply to produce toughened safety glass (where its high level of fragmentation is exploited) and to manufacture enamelled glass.

One of the repercussions of the heat treatment is that the material behaviour as it relates to light is no longer isotropic, but **anisotropic**: the resulting lighter and darker spots or colourful patterns visible on the glass in certain light conditions may be undesirable but are unavoidable.

Figure 2.7.1 illustrates in principle how the introduction of the heat treatment affects the likelihood of anisotropy, which will be discussed in further details in the next chapter.

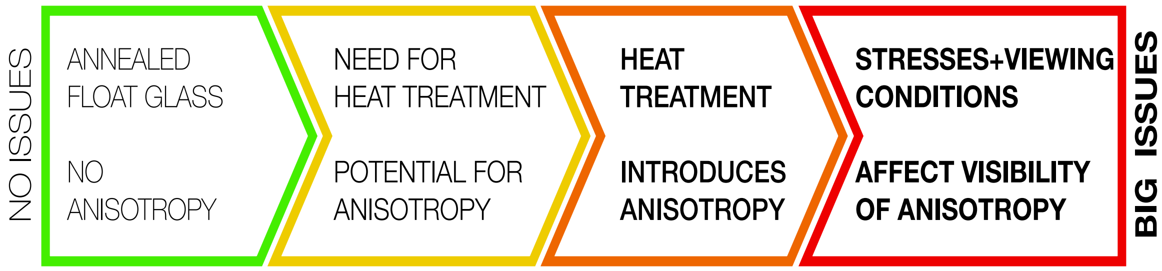


Figure 2.7.1: From anisotropy-free glass to anisotropic glass

3. Understanding and Addressing Anisotropy in Glass

The undesirable effects that the heat treatment processes have on annealed glass are so badly perceived that there is currently a trend to avoid using toughened and heat-strengthened glass to avoid issues. This trend is confirmed by the responses to question no. 9 of this dissertation questionnaire.

However, the use of heat-treated glass is essential in a number of applications where annealed glass simply cannot be used.

The initial review of the literature as it relates to anisotropy highlights that the phenomenon is visible when stresses are present in the glass plate and when this is viewed under particular light conditions.
These two factors and their relationship as it relates to anisotropy need to be reviewed in further details in order to better understand the phenomenon.

The complex thermodynamics of the heat treatment process and its effect on anisotropy is also further reviewed. The industry State Of The Art processes and equipment to measure and reduce anisotropy are investigated.

3.1 Polarisation of Light: Reflection and Scattering

Natural light, such as sunlight, is an electromagnetic wave that oscillates perpendicularly to its direction of propagation (transverse wave). The angle of the plane of vibration is random and may alternate several times per second. Light with these characteristics is defined as unpolarised, i.e. its polarization plane is continuously changing (Können 1985, pp. 3-8).

When unpolarised light is reflected or scattered/dispersed by for example gas particles and minute dust molecules in the atmosphere, metallic and non-metallic surfaces or water, the electromagnetic wave oscillation may be altered and forced to occur only in one plane. This type of light is defined as (linearly) polarised (Können 1985, pp. 131-143).

Pye notes that polarisation of light is unavoidable: as the sun is generally not looked at directly, the light reaching our eyes does so because it is either reflected or scattered (2001, p. 102).

Figure 3.1.1 below illustrates the principle of light polarisation by reflection on water and scattering in the atmosphere (Wehner 2001).

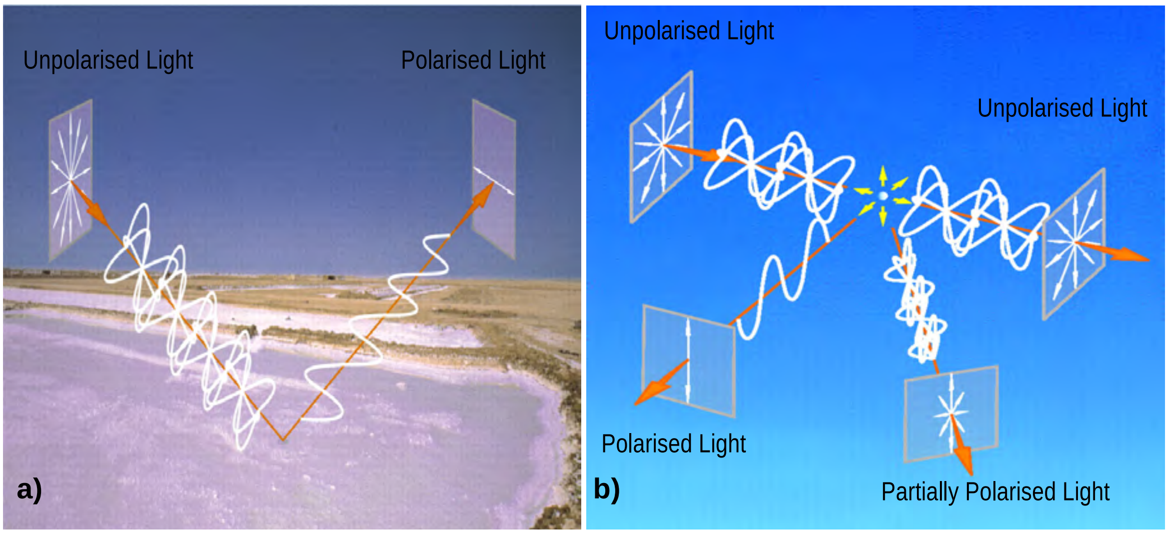


Figure 3.1.1: Polarisation of light: a) Reflection on water, b) Scattering in atmosphere (Wehner 2001)

The stresses introduced on a glass pane by the heat treatment process may become visible under polarised light: in the façade industry the phenomena is referred to as anisotropy or “leopard spot” (CWCT TN 35 2003, p. 7).

3.2 Stress patterns and polarisation by double refraction

Polarisation of light also occurs when the electromagnetic wave enters a *birefringent or doubly refractive* material, such as heat-treated glass.

By means of heating and rapidly cooling the glass plate, the heat-treatment process induces a compression stress in the surface of the glass that is balanced by a tensile stress in its core. Figure 3.2.1 (Wurm 2007, p. 54) diagrammatically illustrates the different stress profiles of toughened glass and heat-strengthened glass.

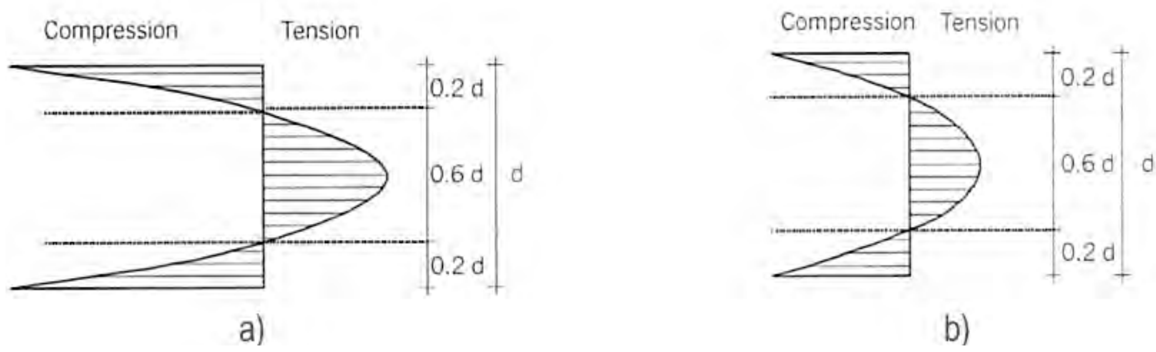


Figure 3.2.1: Stress cross sectional diagrams: a) toughened, b) heat strengthened
(Wurm 2007)

The parabolic distribution of the stresses shown above develops during the **cooling** phase of the heat treatment (quenching phase) and relates to the glass plate surface temperature gradient. During the **quenching**, oscillation of the glass plate, differential cooling rate of edges, nozzle layout and air flow uniformity affect the distribution of the surface compression and as a result the stresses are not uniformly distributed (Redner and Bhat 1999a, p. 671).

Small variations in the stress distribution are also present as a result of the inhomogeneous **heating** of the plate in the furnace and as a consequence of the different heat transfer occurring where the glass is in contact with the supporting rollers throughout the process.
Conversely, small changes in the glass density take place in association with the stresses (ATS-157 2013, p. 3,4).

As a result of the above, the glass plate is characterised by localised density fluctuations distributed through its thickness and across the plate. These variations make the material **anisotropic**: this affects the behaviour of light and causes a double refraction effect (as well as a modified reflection). Where the density changes (boundary surface) the incident light beam is split and changes its speed and direction, thus resulting in the familiar anisotropy or “strain” patterns (Schittich 2007, p. 67).

Dehner, a technical manager with glass supplier Arcon, affirms that the visibility of anisotropy patterns is in particular the result of the permanent membrane stresses caused by the inhomogeneous temperature distribution during the whole heat treatment process (Dehner 2014).

Different areas of the heat-treated glass therefore transmit and reflect relatively different amounts of light, hence resulting in different lighter and darker areas. (ATS-157 2013, p. 4).

On the contrary, the density fluctuations are not present in isotropic, virtually stress-free annealed float glass, thus the beam of light splitting and anisotropy do not occur (Schittich 2007, p. 67).

Pedrotti et el. affirms that the double refraction phenomenon, which is also known as birefringence, is due to the coexistence of two indexes of refraction within the same material (2007, p. 373).

In addition, according to Können, when an *unpolarised* light beam enters a doubly refracting material, like anisotropic glass with internal stresses, it is not only split into two separate beams but also these beams are *completely polarised beams (polarization by double refraction)* that have vibration directions perpendicular to each other and that follow different paths at different speeds through the material.
Anisotropic glass therefore converts unpolarised light into polarised light and in the process potentially highlights the locked-in stresses; however, as “refraction is a less effective polariser than reflection” the visibility of the strain pattern may not be obvious and may be difficult to detect (1985, pp. 9, 89-92, 140-141).

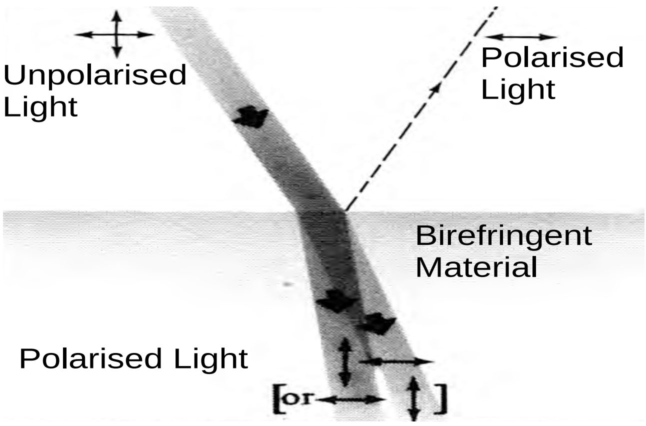


Figure 3.2.2: Splitting of incident beam by birefringent material (Können 1985)

Redner points out that the retardation, or relative distance between the waves, is a function of the principal stresses and the material thickness (1995).

According to the Brewster's law, birefringence is "proportional to the difference of principal stresses in the plane perpendicular to the ray of light" (Redner and Bhat 1999b, p. 169).

Conversely, the strain patterns are more visible when the incident light is already polarised: the higher the polarization of the incident light, the more visible the patterns.

The level of stress in the material therefore influences the amount of double refraction: the higher the stresses, the higher the double refraction. Equally, the level of stress and corresponding amount of double refraction also directly dictate the degree of deviation of the two beam paths and in particular their different speeds: this result in a *"gradual phase-shift between the two beams"*. The outcome is that polarised light leaving the glass will have its vibration direction altered, or it will be converted into *circularly polarised light*, which is polarised light characterised by a sense or rotation as opposed to a vibration direction (Können 1985, p. 5, 151-153).

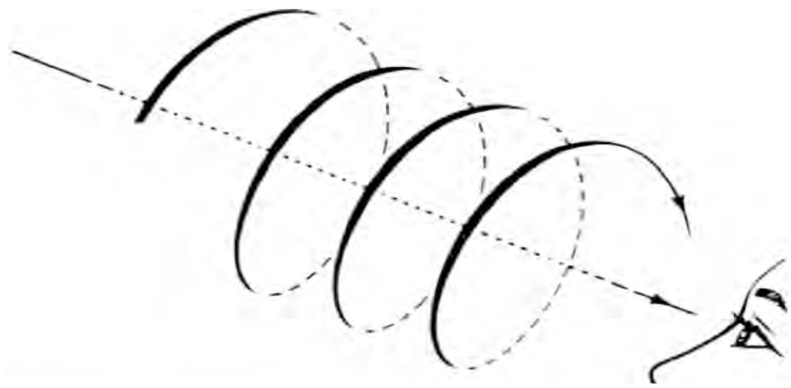


Figure 3.2.3: Schematic representation of circularly polarised light wave (Können 1985)

This optical phenomenon, which is also known as *chromatic polarization*, manifest as colour change and is affected by the degree of "retardation" of the waves and by the colour and wavelength of the incident polarised light (Können 1985, p. 5, 151-153). According to Redner, the phenomenon is the result of the interference between the two emerging light waves (1995).

The NSG Technical Bulletin ATS-157, states that the "rotation" of the plane of polarised light is proportional to the stress (2013, p. 4); according to Schittich the light beams are split into their constituent colour (i.e. the red to violet spectrum) by the double refraction caused by the glass density fluctuations resulting from the heat treatment (2007, p. 67).

Conversely, Können also observes that the colour effects are less noticeable when the incident light is only partially polarised (1985, p. 151-153).

The degree of visibility of the anisotropy multicolour patterns and lighter and darker spots therefore and inevitably varies in relation to the amount and degree of polarised light present at the time of the viewing: the less polarised light, the less visible anisotropy.

The anisotropy patterns are potentially more visible when the glass is viewed in the presence of a blue sky, as clouds or a hazy sky are less polarised, or in the presence of reflective surfaces, such as adjacent glazed buildings, water or dark/wet asphalt that will convert unpolarised light into polarised light by reflection. The glass-air interface at the back of the glass may also provide reflection and in turn polarised light and the effect become more visible with the aid of polarised filter and/or polarised sunglasses.

Figure 3.2.4 is sourced from Können and schematically represent a number of possible situations under which the anisotropy pattern may become visible: “1” indicates the point at which light becomes linearly polarised whereas “2” indicates the point at which light passes a second polariser (Können 1985, p. 29, 34, 89-92).

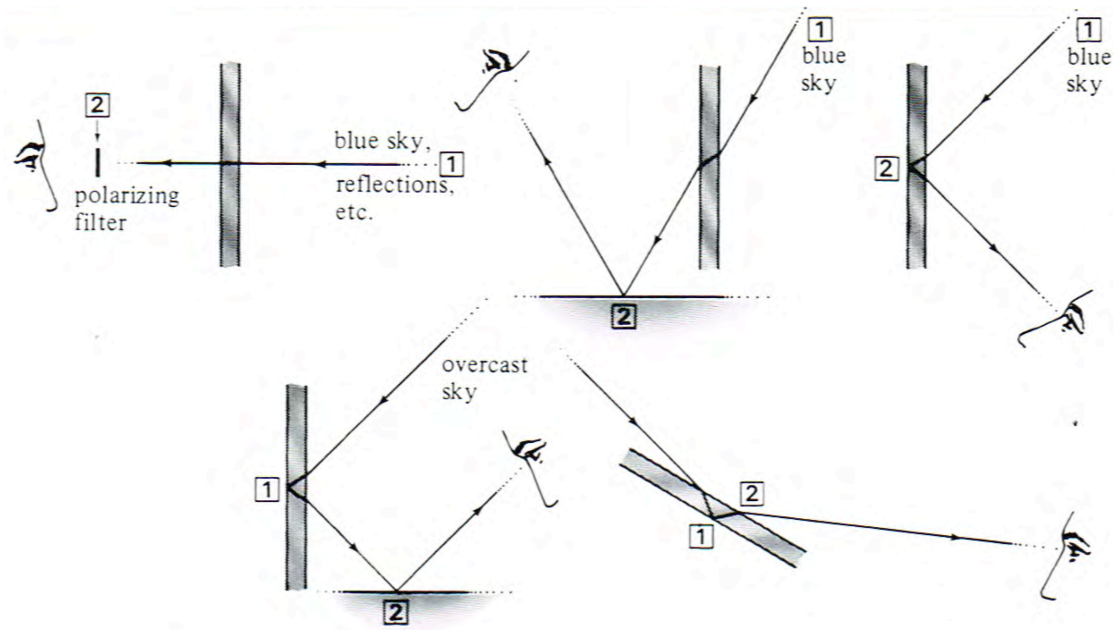


Figure 3.2.4: Visibility of colour patters (Können 1985)

The degree of polarization of the light reflected by the glass is regulated by the Brewster’s law and is a function of the light incident angle and the index of refraction of the material. While a detailed discussion of the Brewster’s law, and other optic laws, falls outside the boundaries of this dissertation, it should be noticed that, according to this law, when the angle of the incident light is at approximately 57º to the glass (Brewster's angle), the reflected ray of light is **completely polarised** and is perpendicular to the refracted ray (Pye 2001, p. 74).

Henriksen and Leosson affirm that at this angle the light polarised parallel to the plane of incidence (p-polarised) is transmitted through the air-glass interface without reflection, thus only the component perpendicular to the plan of incidence (s-polarised) is reflected. In addition, the reflected light is at least 80% polarised (i.e. it is highly polarised) for incident light angles between 45º and 70º (2009, p. 834-835).

There is therefore a fairly large range of incident light angles that may result in high levels of polarised light which status can be altered by the glass birefringence and potentially become visible.

One additional optical feature resulting from the fact that, as per all optically anisotropic material, the index of refraction of the heat-treated glass is not the same in all directions (Können 1985, p. 9), is that the multicolour patterns in a glass plate will look different from different angles, as shown in the picture below.

The phenomenon visibility is in this case amplified by illumination of the glass via polarised lamp and enhanced contrast due to black background.

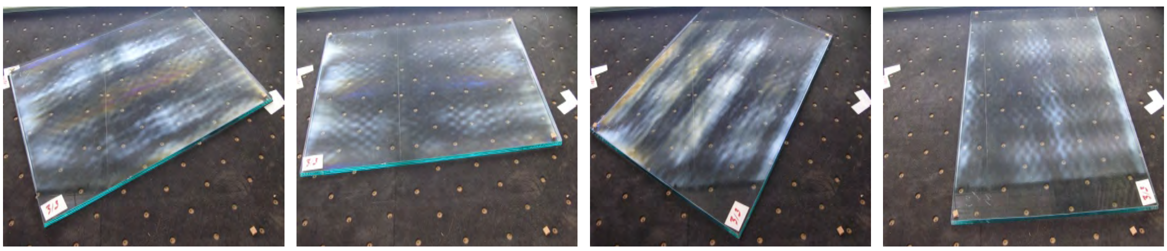


Figure 3.2.5: Effect of viewing angle on anisotropy pattern (Schweitzer 2014)

The visual review of anisotropy is rather complicated as its visibility is not only subjective – note that according to Können the human eye is barely sensitive to polarised light (1985, p. 3) – but also highly influenced by invariably changing light conditions and viewing angles.

3.3 The effects of tempering oven design on anisotropy

The complex alterations of light path and speed associated with the birefringent nature of toughened and heat strengthened glass are related to the nature of the stresses introduced by the heat treatment processes. As a result of the complicated thermodynamics of the tempering process, such stresses, and associated material density, are not uniformly distributed across the glass plate. Their distribution is strongly dependent on the design of the tempering equipment and, without limitations, its furnace and chiller design, the glass load (number of panels and dimensions) and equipment settings and operation, the configuration and design of rollers and quenching nozzles, the speed and temperature of the glass plate during the whole process. In turn, these directly or indirectly influence the anisotropy of the end product and its degree of visibility and relevant patterns.

The picture below is sourced from Vitkala and highlights the complexity of the heat transfer in the heating phase of the tempering process, in particular as it relates to modern coated glass and their asymmetrical emissivity. Radiation heating only was traditionally used in horizontal tempering lines; the implementation of forced convection, initiated by the need to deal with the tempering of low-E coatings, increases the furnace efficiency and improves heat transfer (1997, p. 103-107). The thermodynamics of the process is complicated, in particular on coated glass. While the analysis of the effect of coatings on anisotropy falls outside the boundaries of this dissertation, it is noted the comment from Dehner that it is easier to control anisotropy on non-coated glass due to its less complex heat transfer (Dehner 2014).

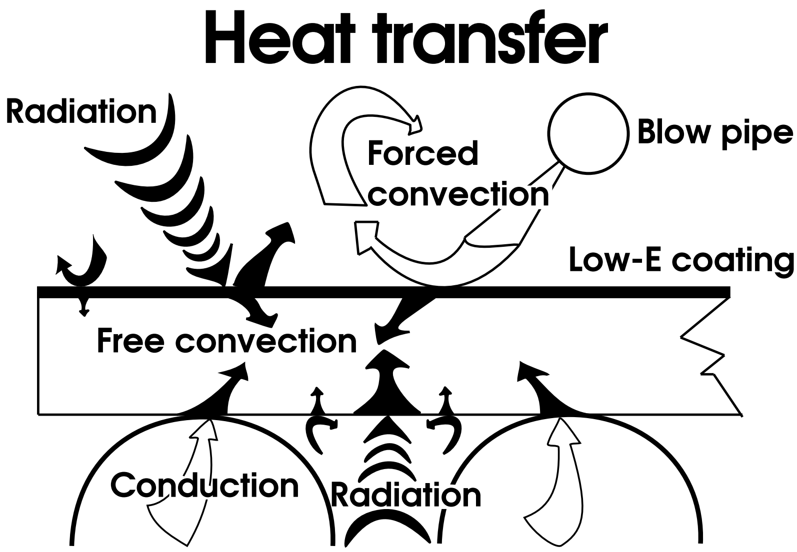


Figure 3.3.1: Complexity of heat transfer (Vitkala 1997)

The direct contact of the glass with the supporting rollers throughout the process leads to localised temperature and stress differences at the point of contact.

The areas of glass located directly below the quenching nozzles will cool slightly differently from the area between the nozzles, as schematically shown in Figure 3.3.2.

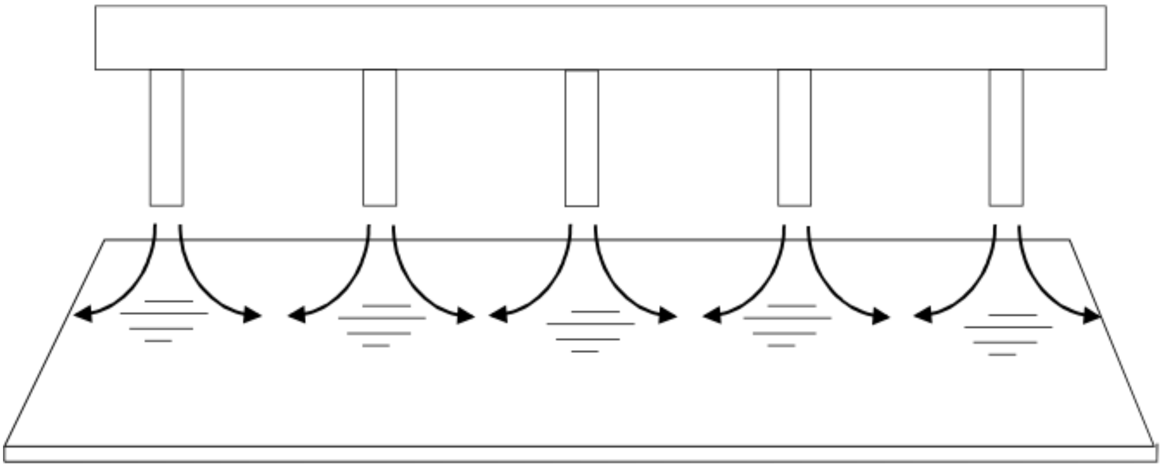
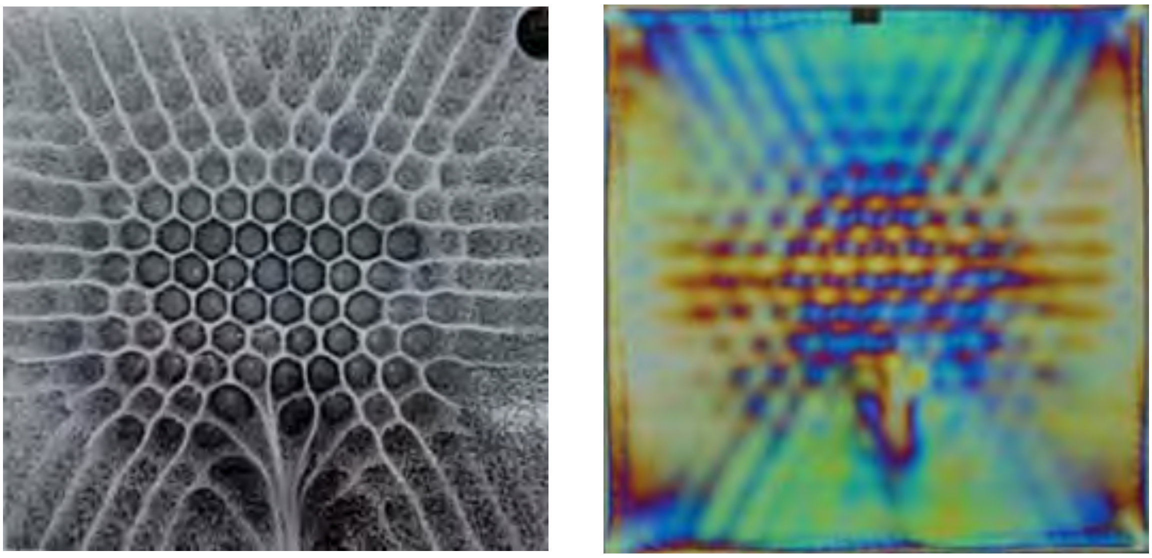


Figure 3.3.2: Quenching jets non-uniform flow (ATS-157 2013)

The distribution of the stresses under the jets is not isotropic, as demonstrated by a study by Chen that emphasis how the design of the cooling jets highly influences the inhomogeneous distribution of the stresses. According to Chen, the area directly below the quench jets has the highest compressive stress. An example of the jet air streamlines and resulting interference pattern is shown below (Chen 2013, p. 45-46).



a) b)

Figure 3.3.3: Quenching jet streamline (a) and interference pattern (b) (Chen 2013)

The combination of the contact of the glass with the rollers and design and behaviour of the quench nozzles results in an intricate layout of areas with different temperatures that, by cooling slightly differently from each other, will translate into areas of different glass density and stresses, thus resulting in a particular anisotropy pattern. The matter becomes even more complex when the other parameters previously cited are considered.

Only limited explanations of what causes specific anisotropy patterns have been readily found in the literature during the course of this dissertation.

Henriksen and Leosson explain that the cross pattern shown in Figure 3.3.4 results from the glass contact with the spirally wounded support rollers, shown inset, during the quenching, while moving in a tempering line.

The alternation of clockwise and anticlockwise spirals on consecutive rollers produces crossing strips: the strips may become shorter and the pattern mixed-up if oscillation of the glass (i.e. a forward and backward movement) in the quenching is introduced (2009, p. 835-836).

Figure 3.3.4: Anisotropy cross pattern (Henriksen and Leosson 2009)
Inset: Spirally wounded support rollers (Glaston 2013)

Conversely, if the glass is stopped altogether during the quenching, the localised effect of the cooling blowers is rather clear, as shown in Figure 3.3.5.

The importance of the oscillation of the glass plate during the quenching is highlighted by Vehmas, who also stresses that – to minimise anisotropy – it is crucial that the glass is below a certain temperature when the first oscillation commences (i.e. the first backward movement in the chiller).

According to Vehmas, controlling the phenomenon visibility is more difficult on heat-strengthened glass than on toughened glass, at least for thicknesses above 8mm (thicknesses below 8mm presents the same level of difficulties). This is partially because the slower cooling process required by the heat-strengthening makes the control of the temperatures more difficult (Vehmas 2014).

Figure 3.3.5: Anisotropy pattern on glass stationary during quenching (Vehmas 2014)

The impact of the support rollers configuration and design on the anisotropy pattern can be appreciated by observing and comparing Figure 3.3.6 and Figure 3.3.7 below.

It should be noted that both pictures were taken with the aid of a polarised screen and filter, which amplify the pattern visibility.

The effect of the roller spiral wounding, interrupted to allow its connection with a support, clearly affects the heat distribution in the oven and the resulting anisotropy layout and creates a central longitudinal band which is visually prominent and disturbing.

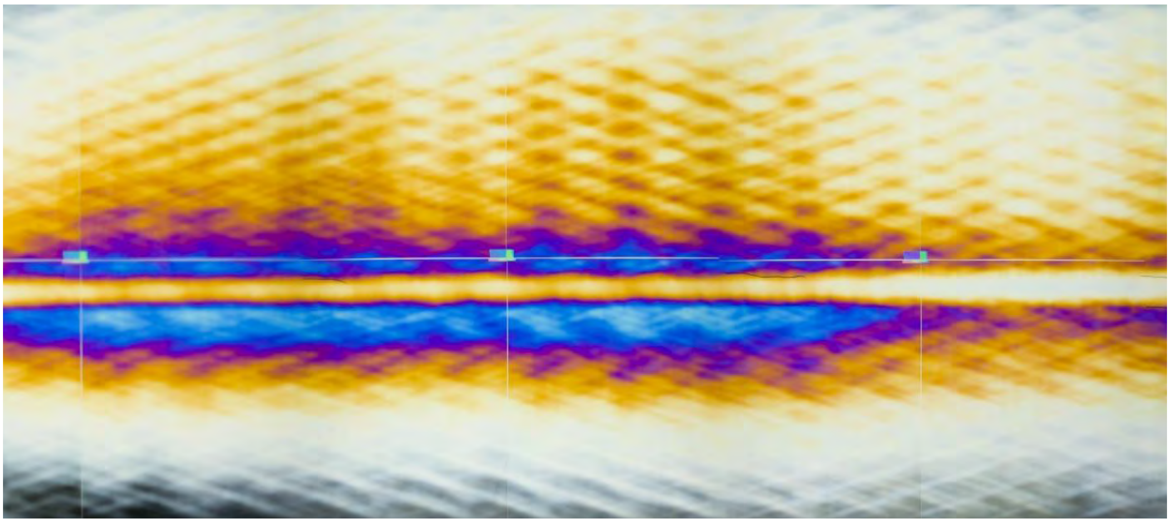


Figure 3.3.6: Anisotropy pattern: interrupted spiral wounding (Anon. 2014a)

The replacement of the rollers with ones without support and continuous spiral wounding creates a more uniform heat distribution that eliminates the central longitudinal band and in turn results in a more homogeneous and less disturbing anisotropy pattern.

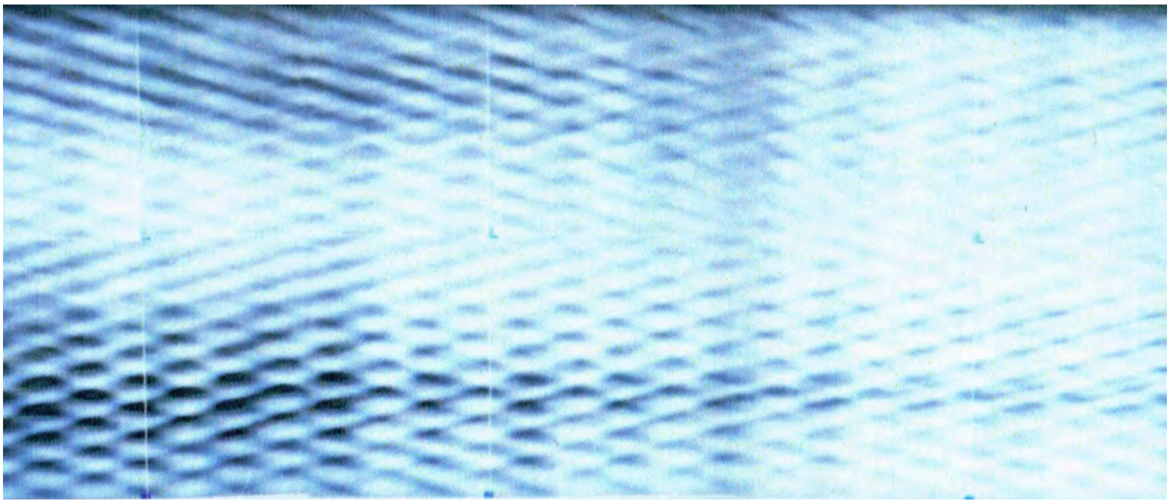


Figure 3.3.7: Anisotropy pattern: continuous spiral wounding (Anon. 2014a)

Quench rollers equipped with circular bands, may give raise to an anisotropy pattern characterised by narrow, few millimetres wide lines. The longitudinal pattern is similar to that shown in Figure 3.3.8, which is however likely to be the result of quenching nozzles positioned in a straight line: the width of the bands and their distance is a function of the nozzle arrangement and air jet size. A “zigzag” arrangement and oscillation of the nozzles may be implemented to reduce anisotropy (Henriksen and Leosson, 2009, p. 835-836).

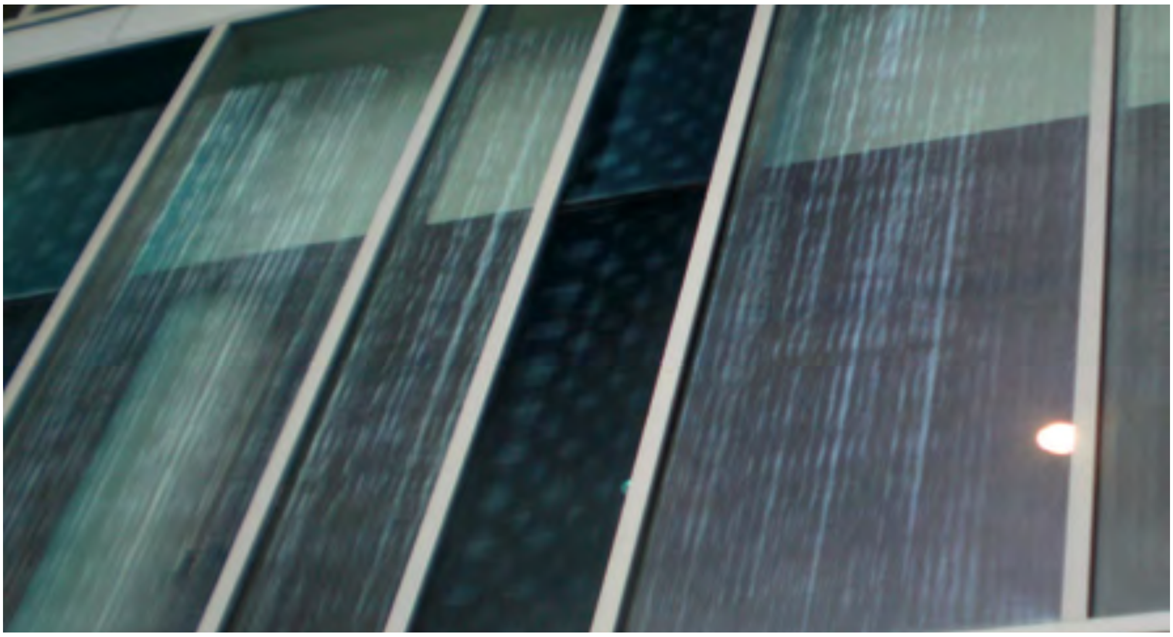


Figure 3.3.8: Anisotropy longitudinal pattern (Henriksen and Leosson 2009)

The NSG (Pilkington) Technical Bulletin ATS-157 refers to anisotropy and iridescence as “quench marks”. While the design, layout and behaviour of the quenching nozzle is certainly crucial to ensure even cooling of the glass plate and reduce disturbing anisotropy, it is also important to ensure that the glass plate is homogenously heated ahead of the quenching, as differential temperature in the heated plate may result in differential cooling and localised stress differences.

Anisotropy patterns characterised by several centimetres wide, less defined bands may be, according to Henriksen and Leosson, the result of temperature differences in the furnace. If the glass is not completely flat in the furnace (the glass plate may be deformed by inhomogeneous heating), certain areas of the plate may be in contact with the rollers more than others, thus resulting in localised temperature differences (2009, p. 836).

This issue is also confirmed by Vehmas that states that the iridescence bands and patterns highlighted in Figure 3.3.9 are the result of convection furnace issues, such as a broken heater or a badly located heating pipe or blower.

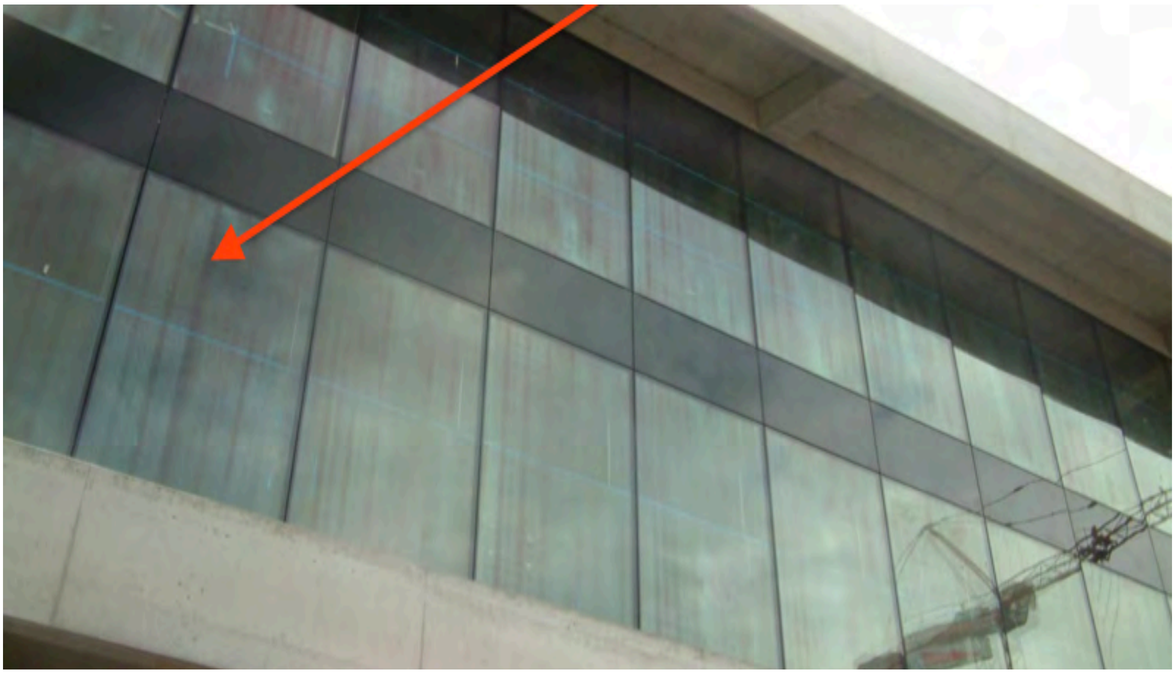


Figure 3.3.9: Anisotropy caused by convection issue in furnace (Vehmas 2014)

Uneven furnace heating and non-uniform quenching issues may also be present at the same time on the same plate (or on different glass panes combined to form an insulated glass unit or a laminated pane) to result in fairly disturbing patterns as shown in Figure 3.3.10 sourced from Vehmas (2014).

Figure 3.3.10: Anisotropy caused by quench (Narrow) and furnace (Wide) (Vehmas 2014)

Notably the anisotropy visibility on the picture above (left) may be amplified by a higher amount of polarised light resulting from the light reflecting on the adjacent water.

The design and operation of the tempering oven clearly affects the visibility of anisotropy and its patterns. Older equipment may not have been specifically designed with iridescence and anisotropy in mind, thus it is possible for glass heat-treated in such ovens to exhibit a higher degree of anisotropy.

Conversely newer technologies, dedicated equipment and know-how appear to be currently available on the market to deal with the anisotropy issue.

This is potentially an important change for the glass industry, which, consistent with the relevant standards, has historically maintained that anisotropy is not only unavoidable but also cannot be mitigated.

It is also a potentially important change for clients, designers and specifiers alike who may be able to satisfy their aspiration for glass with reduced anisotropy.

3.4 State of the art production

The glass market and that of the glass heat-treatment equipments appears to have acknowledged the growing demand for reducing, if not avoiding, anisotropy.

Specialist glass supplier sedak has carried out specific investigations on how the configuration of the rollers in their tempering ovens affects temperature distribution, the resulting stresses and in turn the anisotropy pattern. The implementation of a polarised screen and a photographic camera equipped with polarised filter was used as a simple yet effective method to amplify and record the anisotropy pattern thus facilitating its examination. While the pattern could not be measured, its interpretation resulted in a modification of the tempering equipment via a change of the rollers design, which ultimately resulted in a different, more uniform and less disturbing anisotropy pattern (N. Diller, pers. comm. 21 July 2014).

Another leading glass supplier, which prefers to remain anonymous, confirmed in an interview for this dissertation that their quest for glass quality involves specific investments to reduce disturbing anisotropy in heat-treated glass. While recognising that the matter is an intrinsic characteristic of toughened and heat strengthened glass, they aim to improve the quality of their products, as it relates to anisotropy, by working closely to their tempering oven manufacture to procure custom made equipment. Once received and set-up, the tempering ovens are further tailored to optimise the heat treatment process, which is supported by specific procedures and measurements to reduce disturbing anisotropy. This is achieved by exploiting the tempering oven manufacturing experience of some of their in-house senior personnel. While the details of such adaptations, procedures and measurements have not been disclosed, the supplier confirmed during the interview that the same do not specifically impact on the cost of the end product (Anon. 2014b).

The effect that the residual stresses in the glass plate have on light and the principles of photoelasticity are exploited by the glass industry to establish detailed, numerical information on stress levels and in turn check glass quality and validate stress compliance with regulating standards.

Various types of polariscopes (or polarimeters) are implemented for this purpose to provide non-destructive stress measurements, however the devices currently on the market do not appear to provide information on the relationship between the measured stresses and the visibility of anisotropy.

In response to this, specialist glass supplier Arcon teamed-up with tempering oven manufacturer Glaston to patent and produce a non–destructive, off-line measurement device that reads and analyses the stress levels in the glass and determines the critical stress levels that may result in disturbing anisotropy.

Specifically developed software is paired with an off-line stress scanner to provide detailed information on the critical stresses, their distribution on the glass plate and simulate the anisotropy pattern.

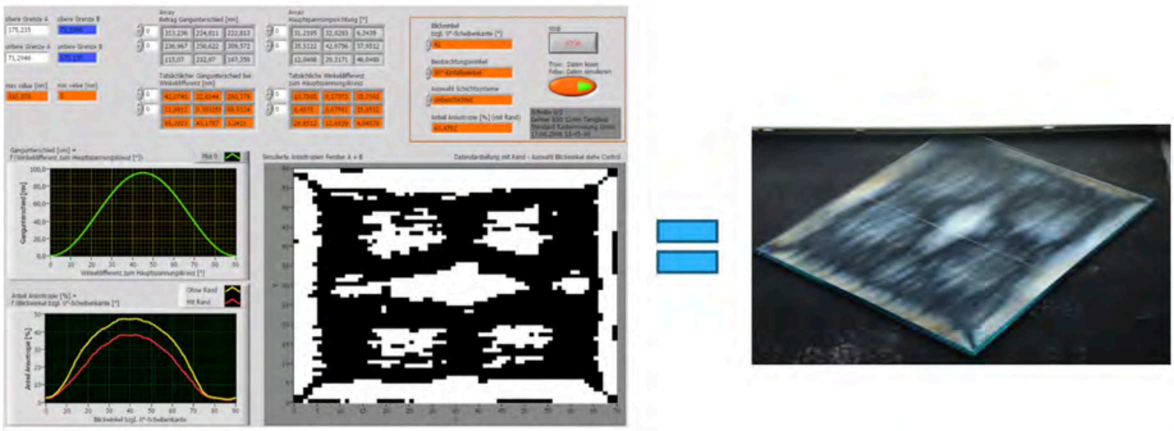


Figure 3.4.1: Arcon software simulation vs. actual anisotropy pattern (Dehner 2014)

The equipment, which is produced and sold by Glaston under the name of IriControL™, also determines the heat-treated glass **Isotropy Value**, which is defined by Arcon as the "***Percentage of the surface of the glass which does not show critical levels of anisotropy***" (Schweitzer 2014).

This is an important aspect of the process as it allows a quantitative and objective measurement of the issue: this is an aspect that the glass industry and regulating standards have been lacking.

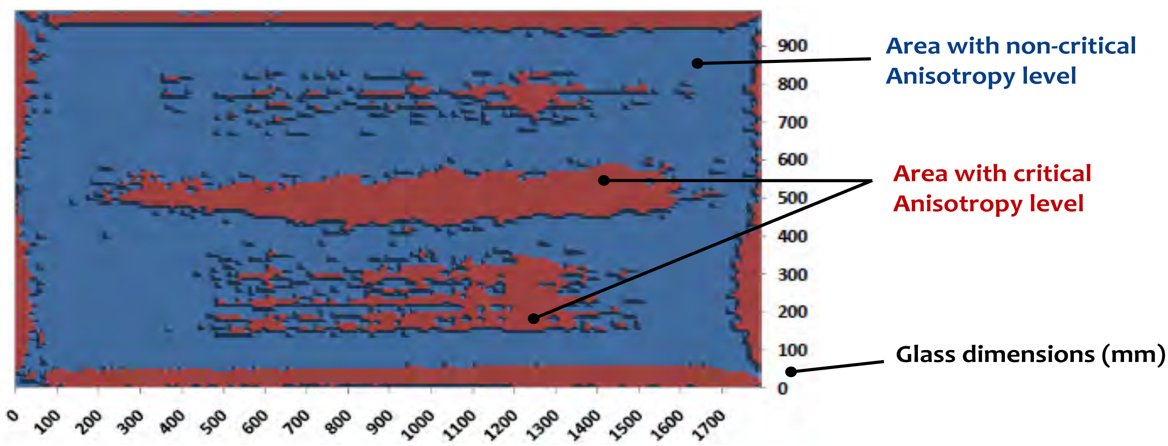


Figure 3.4.2: Arcon simulation of critical vs. non-critical anisotropy (Schweitzer 2014)

Conversely, Marcus Illguth, of German specialist glass consulting firm *Labor für Stahl - und Leichtmetallbau*, confirmed in an interview for this dissertation that they have developed a full field anisotropy scanner for laboratory use. The equipment, which is currently a prototype, is capable of simulating the anisotropy and its pattern by measuring the “retardation”, as shown in picture Figure 3.4.3 (Illguth and Schuler 2014).

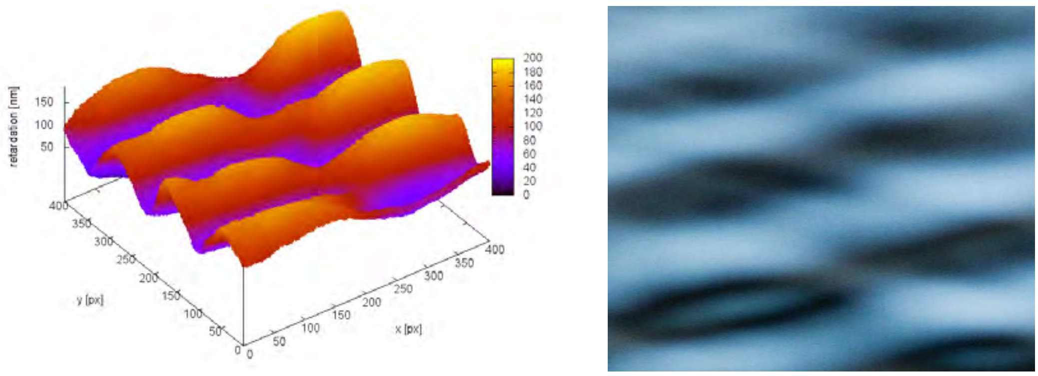


Figure 3.4.3: Retardation measurement and anisotropy pattern simulation (Illguth and Schuler 2014)

Arcon and Glaston affirm that according to their studies, which include extensive on-site statistical tests under different light conditions, glass plates with measured isotropy values above 95% will not show anisotropy (or iridescence) to the unaided/naked eye.

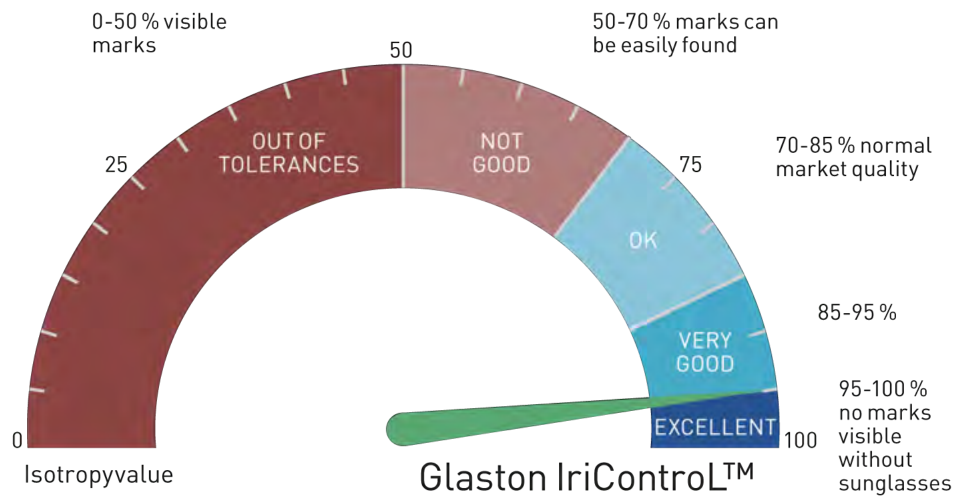


Figure 3.4.4: Glaston IriControL ™ isotropy scale (Vehmas 2014)

The availability of anisotropy measuring systems allows the objective analysis and simulation of the anisotropy pattern and enables the definition of objective parameters of acceptability. It also permits a detailed examination of heat distribution, stresses and anisotropy pattern. Such analysis may therefore be taken into account in the **tempering oven design and operation** to produce heat-treated glass with less disturbing anisotropy.

While stating that they **cannot avoid** anisotropy, Arcon claims that with their technology they can produce heat-treated glass (the product Arcon "Topview") with a level of anisotropy *"reduced to such an extent that it is not visible to the naked eye as a disturbing element"* (Arcon 2014). This, however, comes at a premium.

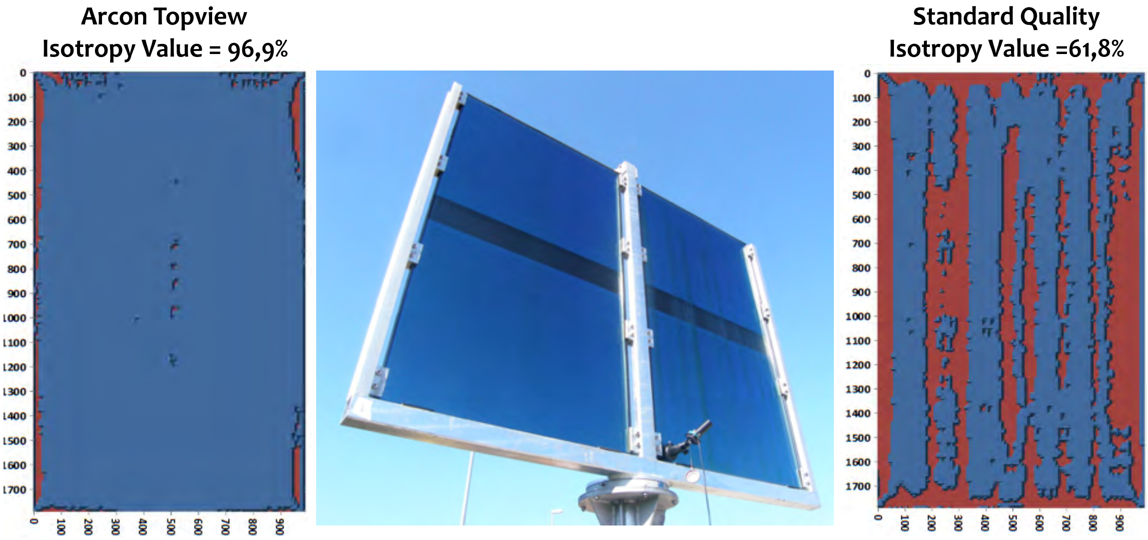


Figure 3.4.5: Arcon "Topview" vs. standard quality (Arcon 2014)

Glaston has patented and adopted, in its new flat tempering lines, a "cross-wise-moving" quench bar solution, see Figure 3.4.6. This is used in combination with shifted heating modules, heating profiling (that optimises the tempering process in relation to glass size and position in the oven), rollers temperature control and nozzles distribution to **minimise temperature difference** and in turn reduce iridescence (Glaston 2013).

The homogeneous distribution of the temperatures and in turn of the stresses is therefore crucial to reduce the visibility of anisotropy.

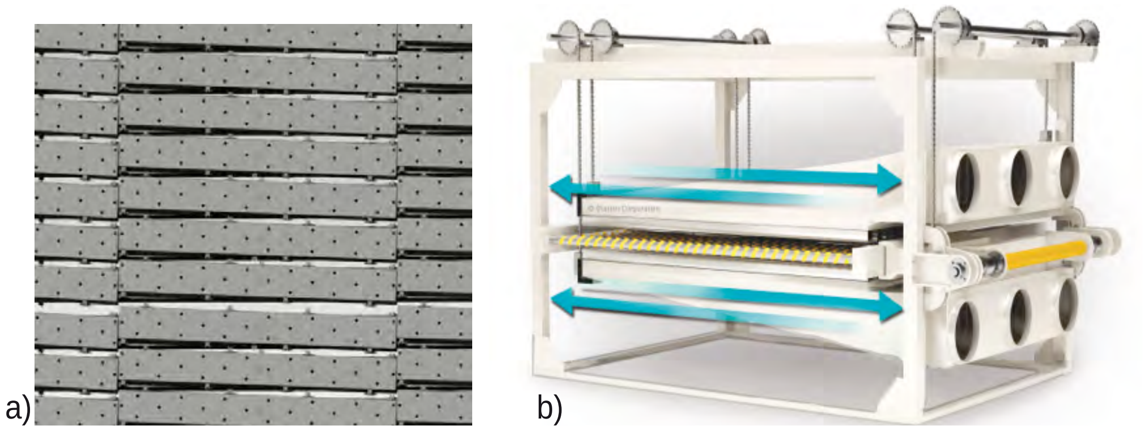


Figure 3.4.6: Glaston shifted heating modules (a) and crosswise-moving quench bar (b) (Glaston 2013)

The tempering oven producer also claims to be able to provide glass with reduced anisotropy by exploiting its new air floatation technology, which involves supporting the glass via an air cushion, however a detailed discussion of this novel technology falls outside the boundaries of this dissertation.

Notably, both Arcon and Glaston do **not** state that with their technologies disturbing anisotropy or iridescence is completely eliminated: **despite all current efforts the phenomenon appears to remain unavoidable**; this is an observation also highlighted by an earlier study by I'Anson (2011, p. 58).

There however appears to be methods and processes that can be used to affect the phenomenon and "reduce" its visibility. The "**reduction**" can only be intended to be in comparison with what the industry has been generally capable of: in absence of an agreed objective baseline or standardised benchmarks the term remains subjective and un-defined.

All the interviewed suppliers stress the importance of operating the tempering oven correctly to obtain the best results: this involves specific attention to the whole process, detailed training of operators and rigorous maintenance regimes.

3.5 Conclusions

The control and distribution of the temperatures on the glass plate throughout the heat-treatment process is an intricate matter that affects the embedded stresses and density of the glass as well as their distribution on the plate. This unavoidably affects the behaviour of light and in turn the visual appearance of the glass plate: under certain viewing conditions anisotropy (also referred to as birefringence, iridescence, leopard spots, quench marks or strain pattern) may be visible.

The degree of visibility of the phenomenon as it relates to light and viewing conditions is highly dependent on the viewing angle and the amount of (inevitable) polarised light passing through the glass at the time of the observation. The mechanism of this optical process is complex and the perception of the anisotropy pattern highly subjective and inevitably affected by the viewing environment.

The complicated thermodynamics of the glass heat-treatment process, as a whole and not just the quenching phase, affects the nature and distribution of the stresses and defines anisotropy patterns and visibility. While there appears to be limited information in the published, and readily available, literature to describe the specific causes for said patterns, there is a considerable amount of knowledge on the matter within the glass and tempering oven industry.

Some industry stakeholders are reacting to the market demand for glass with less disturbing anisotropy by researching and developing design and processes that aim to address the issue. The homogeneous distribution of the stresses on the glass plate appears to be key to delivering heat-treated glass with less disturbing anisotropy. This may be achieved by specifically managing the temperatures during all the phases of the tempering process, which in turn may require not only particular operator know-how but specifically designed (or modified) and well maintained ovens.

The detailed analysis and measurement of the anisotropy pattern is of crucial importance not only to obtain a better visual appearance of the end product but also to define anisotropy objective acceptance and rejection parameters. Measuring and simulating equipment is becoming available however the processes and acceptance/rejection criteria are not yet standardised or industry recognised.

Anisotropy remains an unavoidable phenomenon however it would appear that its visibility can be influenced and “reduced” to obtain glass of better visual quality. This may come at a premium, which clients appear not to be necessarily happy to pay, at least according to the questionnaire response (see question No. 10).

4. Current industry standards and guidelines review

A number of British Standards are available to regulate the production of glass for the building industry.

Specific façade industry guidelines also exist: these are produced by glass and façade industry associations and information providers, such as the Centre for Windows and Cladding Technology (CWCT) and the Glass and Glazing Federation (GGF).
The main glass suppliers also produce guidelines and technical notes.

The most relevant standards and guidelines recognising anisotropy are reviewed in this chapter: the main clauses and definitions are abstracted and presented where possible so as to facilitate review, comparison and future referencing. A list of standards related to glass in buildings that do not refer to anisotropy, but perhaps should, is also provided.

Table 4.1 recaps the reviewed documents and highlights which document refers to anisotropy and whether the phenomenon is clearly recognised within as a defect, if it can be avoided or mitigated.
It also captures the reference to alternative terminology to describe the phenomenon, as it is important to ensure consistency of language. For over 60% of the participants to this dissertation questionnaire there is confusion on what anisotropy is (Question no. 5, response no. 1). Question no. 2 of the same questionnaire shows that the term “leopard spots”, which is widely used and recognised, identifies anisotropy for 31 out of 35 participants. However one of the respondents definitely disagrees and three are unsure.

In the table, the British Standards that refer to anisotropy have been grouped together for ease of presentation and for the same reason the document names have been simplified.

The chapter is concluded with an appraisal of typical cladding specifications in relation to the above documents and to their degree of deliverability and risk.

British Standard or Industry Guideline	Recognise anisotropy?	Is anisotropy a defect?	Can anisotropy be avoided?	Can anisotropy be mitigated?	Alternative terms for anisotropy?
BS EN 1863	**YES**	**NO**	not stated	not stated	leopard spots iredescence
BS EN 12150	**YES**	not stated	not stated	not stated	leopard spots iredescence
BS EN 14179	**YES**	not stated	not stated	not stated	leopard spots iredescence
BS EN 410	**NO**	not applicable	not applicable	not applicable	not applicable
BS EN 572	**NO**	not applicable	not applicable	not applicable	not applicable
BS 952	**NO**	not applicable	not applicable	not applicable	not applicable
BS EN 1096	**NO**	not applicable	not applicable	not applicable	not applicable
BS EN 1279	**NO**	not applicable	not applicable	not applicable	not applicable
BS 5713	**NO**	not applicable	not applicable	not applicable	not applicable
BS 6262	**NO**	not applicable	not applicable	not applicable	not applicable
BS EN ISO 12543	**NO**	not applicable	not applicable	not applicable	not applicable
BS EN 12898	**NO**	not applicable	not applicable	not applicable	not applicable
BS EN 14449	**NO**	not applicable	not applicable	not applicable	not applicable
CWCT TN 35	**YES**	**NO**	**NO**	**NO**	leopard spots
GGF Data Sheet 4.4	**YES**	not stated	not stated	not stated	leopard spots iredescence
GGF Data Sheet 4.1	**YES**	**NO**	not stated	not stated	leopard spots iredescence
HADAMAR	**YES**	not stated	not stated	not stated	
AGC Interpane	**YES**	not stated	not stated	not stated	*Note: refers to Hadamar*
ECKELT (Saint Gobain)	**YES**	not stated	not stated	not stated	
NSG (Pilkington)	**YES**	**NO**	not stated	not stated	quench marks quench pattern
GUARDIAN	**YES**	not stated	**NO**	not stated	strain pattern leopard spots

Table 4.1: Reviewed standards and guidelines: list and comparison

4.1 Anisotropy according to the current British Standards

Document	**BS EN 1863-1: 2011** Glass in building – Heat strengthened soda lime silicate glass Part 1: Definition and description
Page, Chapter and Text	**Page 27, chapter 9.2 Anisotropy (iridescence)** The heat strengthening process produces areas of different stress in the cross section of the glass. These areas of stress produce a bi-refringent effect in the glass, which is visible in polarised light. When heat strengthened soda lime silicate glass is viewed in polarised light, the areas of stress show up as coloured zones, sometimes known as "leopard spots". Polarised light occurs in normal daylight. The amount of polarised light depends on the weather and the angle of the sun. The bi-refringent effect is more noticeable either at a glancing angle or through polarised spectacles. **Anisotropy is not a defect but a visible effect.**
Document	**BS EN 12150-1: 2000** Glass in building – Thermally toughened soda lime silicate safety glass Part 1: Definition and description.
Page, Chapter and Text	**Page 18, Chapter 9.2 Anisotropy (iridescence)** The toughening process produces areas of different stress in the cross section of the glass. These areas of stress produce a bi-refringent effect in the glass, which is visible in polarized light. When thermally toughened soda lime silicate safety glass is viewed in polarized light, the areas of stress show up as coloured zones, sometimes known as ‘leopard spots’. Polarized light occurs in normal daylight. The amount of polarized light depends on the weather and the angle of the sun. The bi-refringent effect is more noticeable either at a glancing angle or through polarized spectacles.
Document	**BS EN 14179-1: 2005** Glass in building — Heat soaked thermally toughened soda lime silicate safety glass.Part 1: Definition and description.
Page, Chapter and Text	**Page 24-25, Chapter 11.2 Anisotropy (iridescence)** The toughening process produces areas of different stress in the cross section of the glass. These areas of stress produce a bi-refringent effect in the glass, which is visible in polarised light. When heat soaked thermally toughened soda lime silicate safety glass is viewed in polarised light, the areas of stress show up as coloured zones, sometimes known as 'leopard spots'. Polarised light occurs in normal daylight. The amount of polarised light depends on the weather and the angle of the sun. The bi-refringent effect is more noticeable either at a glancing angle or through polarised spectacles.

Table 4.1.1: Comparison of anisotropy definition in current British Standards

The definitions of anisotropy in the current British Standards regulating the heat treatment of soda lime silicate glass are collected and compared in the above table. The phenomenon is described under the “*physical characteristics*” section of all the above standards. The text used to described anisotropy is virtually the same across all the documents, the only, important, difference being that, as highlighted in green in Table 4.1.1, ***BS EN 1863-1: 2011 Glass in building – Heat strengthened soda lime silicate glass*****,** additionally concludes the description of this physical characteristic by stating that ***“Anisotropy is not a defect but a visible effect”.***

It should be noticed that this latter document is the most recent of all the standards of Table 4.1.1: conversely *BS EN 12150-1:2000* is due to be superseded soon and the provisional ***pr****EN 12150-1:2012 Glass in building – Thermally toughened soda lime silicate safety glass,* was issued as DRAFT and was available for comments until 14 May 2012. While the document is provisional, the proposed text as it relates to anisotropy is similar to the current standard but, crucially, also concludes by stating ***“Anisotropy is not a defect but a visible effect”*** (p. 25, chapter 9.2). It is reasonable to expect that this clause will remain in the final issue of the document, as ***BS EN 1863-1*** underwent a similar change: the 2000 edition did not have the above conclusive statement which was introduced with the 2011 edition. No provisional or proposed revised text for BS EN 14179-1: 2005 was available for review during the course of this study.

The additional conclusive statement is very important, as it leaves no room for disputes or interpretations: one may otherwise argue that being a physical and recognised characteristic does not necessarily mean “not being a defect”. However, and crucially, anisotropy is not listed under the “Dimensions and tolerances” section of the standards, where measurement and limitations for compliance are specifically described: it therefore should not be considered a defect. As there are currently no official methodology for measuring anisotropy, the phenomenon cannot be objectively assessed, hence the definition of formal and standardised acceptance and rejection criteria cannot be made.

On the other hand, stating that anisotropy is not a defect in these standards may not encourage the industry to cooperate and move forward by researching methods for measuring and addressing the phenomenon, this maybe perhaps done by exploiting recent experience, know-how and State of The Art technology previously described.

The following is a list of standards associated with glass for use in buildings and typically referred to in the glass and façade industry, including in specifications, over and above those listed in Table 4.1.1:

- **BS EN 410:2011**
  Glass in buildings - Determination of luminous and solar characteristics of glazing
- **BS EN 572 (Parts 1 to 8):2012** and **BS EN 572 Part 9:2004**
  Glass in buildings – Basic soda lime silicate glass products
- **BS 952-1:1995** and **BS 952-2:1980**
  Glass for Glazing
- **BS EN 1096 (Parts 1 to 3):2012** and **BS EN 1096 Part 4:2004**
  Glass in building - Coated glass
- **BS EN 1279 Part 1:2004, Parts 2, 3, 4, 6 :2002, Part 5 2005 + A2 2010** Glass in buildings – Insulating glass units
- **BS 5713:1979** (Obsolete but still in use)
  Specification for hermetically sealed flat double glazing units
- **BS 6262:2005**
  Glazing for buildings
- **BS EN ISO 12543:2011**
  Glass in building - Laminated glass and laminated safety glass
- **BS EN 12898:2001**
  Glass in building — Determination of the emissivity
- **BS EN 14449:2005**
  Glass in building — Laminated glass and laminated safety glass - Evaluation of conformity/Product

It is important to note that none of the above standards refers to anisotropy or leopard spots or iridescence: this despite the fact that some of the documents, like for example BS 952, contain detailed description of heat-treated glass.

Glass is hardly used as a monolithic product these days. Heat-treated glass may be coated, fritted, laminated and be used in combination to form complex products which in turn can be used to form complicated double and triple insulated glass units. These numerous and varied configurations may influence the visibility of anisotropy, which therefore should be referred to in the relevant standards alongside comprehensive guidelines. The detailed assessment of such influence may require dedicated studies, however these fall outside the boundaries of this dissertation.

4.2 Review of Industry Guidelines

A number of glass and façade industry guidelines clearly identify and discuss anisotropy.

The CWCT Technical Note No. 35 "*Assessing the appearance of glass*" is rather thorough and not only describes the issue, but also provides guidance in a tabulated format on how to deal with anisotropy in specifications and on site. In the guideline, Anisotropy is listed under *Table 1 – Factor affecting glass colour*.
A snapshot of the guideline is provided below for ease of reference: statements of particular interest have been highlighted in green and are reviewed further.

Factor	Technical guidance	Specification	Site inspection
Anisotropy	Heat strengthening or toughening glass produces areas of different stress in the cross section of the glass. These areas of stress produce a bi-refringent effect in the glass, which is visible in polarized light. When such glass is viewed in polarized light, the areas of stress show up as coloured zones. This is referred to as "anisotropy" and is also known as 'leopard spots'. Polarized light occurs sometimes in normal daylight conditions, often for a few hours at a time. The amount of polarized light depends on the weather and the angle of the sun. When this occurs, the stress marks in such glass become very visible. There is no known means of mitigating this effect in heat strengthened or toughened glass.	The specification should recognise that: (a) anisotropy can occur in heat strengthened or toughened glass; (b) there is no known means of mitigating the effect in such glass types; (c) anisotropy is an unavoidable feature in heat strengthened and toughened glasses.	Anisotropy is a feature permitted in BS EN 1863 for heat strengthened glass and in BS EN 12150 for toughened glass. It is not a defect. Thus no inspection criteria apply.

Table 4.2.1: Anisotropy according to CWCT Technical Note 35 (CWCT 2003)

The document clearly asserts that anisotropy or "leopard spots", is unavoidable and it is a **permitted** feature of heat-treated glass: it supports these statements by referring to the British Standard for toughening and heat strengthening glass previously discussed in chapter 4.1. The guideline also clearly states that anisotropy is not a defect and therefore no site inspection criteria apply. It also affirms ***"there is no known means of mitigating the effect"*.**

However, based on the findings of this dissertation, this statement may no longer be applicable, as it would appear that there are now tempering oven and glass suppliers capable of at least mitigating the phenomenon. The reference to the glass supplier Arcon, that claims to be able to produce tempered glass with reduced anisotropy, is also widely present in the responses of this dissertation questionnaire.

Document	**GGF: Data Sheet 4.10 January 2010** Products, Glazing Techniques and Maintenance Appearance/Visual Quality Specification for Insulating Glass Units and Maintenance
Page, Chapter and Text	**Chapter 5.3.1 Specific effects of thermal treatment process** The process may give rise to a degree of haze, i.e. a cloudy look to the surface, especially at oblique angles of incidence. The process may, under some viewing conditions, result in an effect that is known as anisotropy (iridescence). This is the result of stress patterns in the cross section of the glass becoming visible. These areas of stress produce a bi-refringent effect in the glass, which is visible in polarised light. When viewed in polarised light these areas show up as coloured zones, sometimes referred to as 'leopard spots'. The bi-refrigent effect is more noticeable at glancing angles. This is not considered as a fault in the glass and is a naturally occurring phenomenon.
Document	**GGF: Data Sheet 4.4 February 2011** GGF Data Sheet for the Quality of Thermally Toughened Soda Lime Silicate Safety Glass for Building
Page, Chapter and Text	**Chapter 8.3 Anisotropy (iridescence)** The thermal toughening process produces areas of different stress in the cross section of the glass. These areas of stress produce a bi-refringent effect in the glass, which is visible in polarised light. The viewing of thermally toughened soda lime silicate safety glass under polarized light results in areas of stress showing up as coloured zones. These zones are, known as "leopard spots". Polarised light occurs in normal daylight. The amount of polarized light depends on the weather and the angle of the sun. The bi-refringent effect is more noticeable either at a glancing angle or through polarized spectacles.
Document	**Hadamar June 2009** Guideline to Assess the Visible Quality of Glass in Buildings
Page, Chapter and Text	**Chapter 4.2.3 (Explanation of Terms)** Anisotropy is a physical property of heat-treated glass resulting from the internal distribution of stresses. It is possible that dark rings or stripes can be perceived, which vary with the viewing angle, if the glass is viewed in polarised light and/or through polarising glasses. Polarised light is present in normal daylight. The extent of polarisation depends on the weather conditions and the position of the sun. The effect of birefringence is more evident at an oblique viewing angle or for glass panes mounted at right angles to each other across a façade corner.

Table 4.2.2: Anisotropy according to GGF and Hadamar

Table 4.2.2 presents how anisotropy is dealt with in two Glass and Glazing Federation (GGF) guidelines and in the notorious Hadamar guideline. The documents provide an explanation of the phenomenon that is consistent with that of the British Standards and CWCT Technical Note 35 previously reviewed.

Notably, one of the GGF guidelines presented states that the natural phenomenon is **not** a fault (GGF Data Sheet 4.10) and both lack recommendations for specifications and inspections. Conversely, recommendations are provided in the Hadamar guideline, which lists anisotropy among other "*physical properties*" (Chapter 4.2.3) and, as such, is introduced as an "*inevitable physical phenomena that occur in the visible glass surface may not be taken into account when assessing the visual quality*" (2009), before explaining the term as shown in Table 4.2.2.

The main glass supplier's guidelines also appear to agree on what causes anisotropy and how polarised light and viewing angle may affect its visibility.

Eckelt, a specialist glass company part of the Saint Gobain group, describes anisotropy as a physical effect in its Tolerance Handbook and highlights that "*the double refraction becomes more noticeable using a flat viewing angle or also with glass facades facing at right angles*" (2011, p. 65).
However the handbook does not specifically say that anisotropy is not a defect or that it is unavoidable.

AGC Interpane's Tolerance Handbook as it relates to anisotropy is consistent with the Hadamar guideline, which is entirely reproduced in the handbook to form most of the "Visual Assessment" section (i.e. section 11) of the document (2013).

The Technical Bulletin ATS-157 issued by the NSG Group, which owns Pilkington, is a six-page specific technical note on the *"The Appearance of Quench Marks in Heat Strengthened and Tempered Glass"* (2013). The document provides a comprehensive explanation of the phenomenon and concludes that anisotropy is not a defect. It also states that the phenomenon is worst when the glass is viewed at an angle, when the sky is clear blue and not overcast, when the multiple heat-treated panes are combined into one product and when the glass is clear.
It also states that anisotropy is worse when the glass is thick, a statement that is true for over 35% of the participants to the questionnaire as shown in chapter 6.7.

Guardian's *"Anisotropy in Heat Treated Glass"* guideline support its explanation of the phenomenon by citing the BS EN 12150-1, and affirms that while the strain pattern may vary between suppliers, it is an effect that cannot be eliminated. It also emphasises that only identical glass panes (e.g. same glass type and thickness, composition, tempering oven, coating, etc.) viewed under identical light conditions should be compared (2012c). However, while it is difficult to recreate specific light conditions, especially if this needs to be done on site, in absence of recognised measurement processes and objective assessment criteria, the result of any comparison will inevitably be affected by an element of subjectivity.

4.3 Façade specification review

A review of recent façade specifications produced by leading façade consultants for commercial U.K. projects was carried out during the course of this dissertation. The review shows that the specifications may be grouped into four different types: these are recapped in Table 4.3.1 below, alongside an assessment of their consistency with current industry standards and guidelines. The table also aims to evaluate whether each type is deliverable and what the risk of disputes might be. The appraisal is supported by a specific critique in the "Commentary" column.

It should be noted that the texts used in the second column of the table are summarised and paraphrased from the reviewed specifications, also to ensure confidentiality.

Type of specification in relation to anisotropy	This type of specification requires heat treated glass to …	Consistent with Standards and Guidelines	Deliverable	Risk of disputes	Commentary
No reference to anisotropy	… only comply with relevant British Standards. **No further requirement**.	YES	YES	LOW	The lack of reference to anisotropy may lead to uninformed clients and design teams that may potentially lead to disputes.
Anisotropy is not a defect	… only comply with relevant British Standards and additionally states that **anisotropy is not a defect.**	YES	YES	VERY LOW	The reference to anisotropy draws attention to the matter and informs client and design teams, thus facilitating the management of expectations and in turn potentially reducing risk of disputes.
Reduce anisotropy	... comply with relevant British Standards but additionally introduces a requirement to **"minimise"** anisotropy by, for example, controlling the heat treatment process or coating selection (or similar statements), often referring to the use of bechmarks and samples.	NO	MAYBE	MEDIUM	The reference to anisotropy draws attention to the matter and informs client and design teams, however the requirement to **"minimise"** anisotropy may attract qualifications and protracted discussions at tender stage. Compliance with this requirement may limit the number of glass suppliers that can be used, thus potentially affecting cost and reducing the number of aesthetic and performance options. Benchmarking may not be a satisfactory process due to current lack of objective measuring criteria: "minimised" compared to what?
Avoid anisotropy	… comply with relevant British Standards but additionally introduces a requirement to **"avoid"** anisotropy by taking all reasonable measures (or similar statement), often referring to the use of bechmarks and samples.	NO	NO	VERY HIGH	The requirement to **avoid** anisotropy enhances client expectations that cannot be met. This may either lead to protracted discussions and qualification or risk of disputes when not qualified. Benchmarking of glass without anisotropy is not an available option.

Table 4.3.1: Facade specification review

The table highlights that the four types of specifications are equally divided between those that are consistent with industry standards and guidelines and those that are not. The latter type inevitably presents more challenges than the former and, while typically requiring protracted discussions and qualifications, carry a higher risk of disputes as noted.

The challenges may be particularly difficult for the façade contractor that is caught between the aspirations of clients, specifiers and design teams alike and the limitations of the majority of its glass supply chain that complies with the industry standards and is unable to meet such aspirations.

While it may be possible to reduce the visibility of anisotropy, there are currently no standards to regulate the phenomenon processes and measurement methodologies as well as its acceptance and rejection criteria. Specifications appear to compensate for these shortfalls by referring to benchmarking and samples however their evaluation is inevitably subjective.

It is also unclear in the specifications how, where and by whom samples are to be reviewed. The heat-treated glass panes ultimately need to be acceptable on the finished building where light conditions may be different from the light conditions of the production environment; notably this can be in a different country or continent. As a result of this situation, panels that are acceptable in production may be unacceptable on site and panels rejected in production may be acceptable on site.

For over 80% of the questionnaire respondents agreed specifications fail to address anisotropy acceptance and rejection criteria (see question no. 12 response).

4.4 Conclusions

Anisotropy is clearly recognised as an inevitable effect of the heat treatment processes by current British Standards regulating such processes and glass industry guidelines: the reviewed documents appear to be consistent in terms of explanations for the phenomenon.

Four of the reviewed documents, only one of which is a British Standard, clearly state that anisotropy is **not** a defect. **This important statement is expected to appear in the next review of the British Standard for toughened glass and may contribute to improve the clarity of the standards,** as for 69% of the questionnaire participants the current documents are inadequate (see responses to question no. 13).

However the reason for such response may be that some of the current standards and guidelines do not reflect the current industry state of the art and either fail to mention if anisotropy can be mitigated or state that it cannot be mitigated. Either way the questionnaire response highlights the need for action.

It is key that a measuring methodology is agreed and incorporated in the standards if anisotropy is to be considered a defect: if anisotropy cannot be measured than there is no baseline for improvement and objective acceptance and rejection criteria cannot be defined.

Once the above is resolved, the directives may need to be incorporated in a number of glass related British Standards that currently do not refer to anisotropy.

Façade specifications appear to refer to anisotropy in different ways, with some approaches potentially attracting more risks than others.

There is a clear aspiration to procure glass with reduced anisotropy or with no anisotropy at all: the responses to question no. 11 of the questionnaire show that this is the case for 60% of the participants. These aspirations are not compatible with the content of current industry standards and guidelines. While specifications demanding no anisotropy cannot be delivered, it remains difficult to deliver those demanding reduced anisotropy due to the lack of baselines and standardised measurement and acceptance criteria.

5. Devise appropriate survey

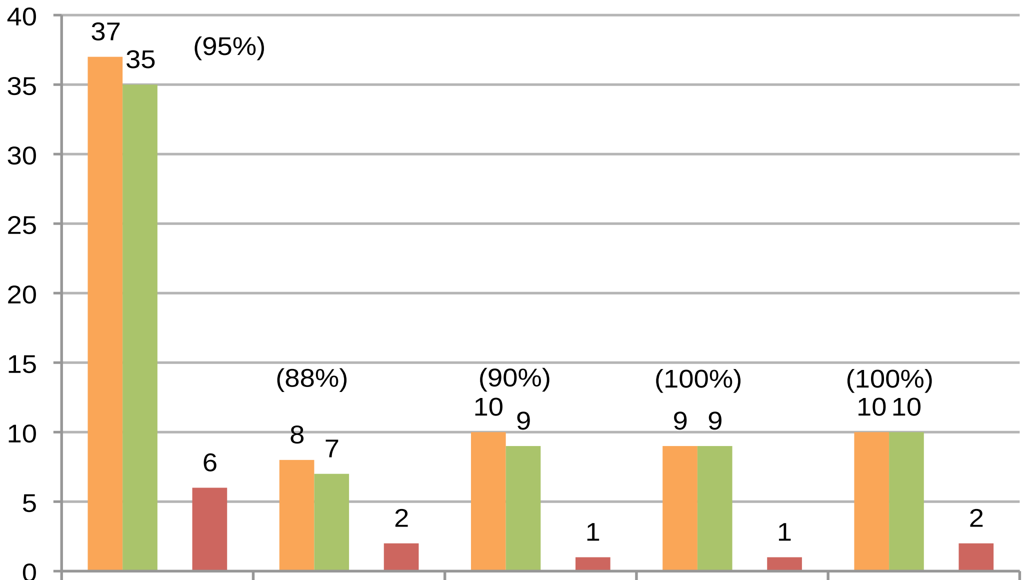
One of the main aims of this dissertation is to assess the cladding industry knowledge and perception as it relates to anisotropy in heat-treated glass in commercial buildings.

It was decided that this would be done by surveying key industry stakeholders: architects, façade consultants, façade contractors and glass suppliers.

The firms within each group were selected because of their involvement on large and prestigious building projects in the U.K. (façade and glass production not necessarily in U.K.) where attention to glass quality and façade specialist knowledge is paramount.

The personnel within each firm were contacted because of their understanding and interest as it relates to anisotropy in glass. In some instances the person initially contacted delegated the participation to others considered more knowledgeable and appropriate for the task, thus potentially ensuring a higher quality of the firm response.

Figure 5.1 below shows the numbers of participants for each group along with their rate of response and the number of participants that requested to remain anonymous.



	Total	Glass Supplier	Architects	Façade Consultants	Façade Contractors
Issued	37	8	10	9	10
Answered	35	7	9	9	10
Answered %	95%	88%	90%	100%	100%
Anonymous	6	2	1	1	2

Figure 5.1: Number of participant by group and relevant response rate

The overall response rate of 95% is high and demonstrates a considerable industry interest on anisotropy. It is interesting to note that six participants decided to remain anonymous: this shows that 17% of those interviewed do not feel comfortable with sharing their views on anisotropy. Furthermore, 2/3 of these are from the supply chain, which is perhaps less inclined to openly share their opinion for marketing reasons.

The following table lists all the survey participants, their roles and firms.

Group	No.	Name	Surname	Position	Company
Façade Contractors	1	Corne	Zijlmans	Deputy CEO / Director	Scheldebouw
	2	Terje	Vallestad	Operations Director	Gartner
	3	Ray	Phillips	Managing Director	Focchi
	4	Massimo	Mazzer	Sales Director	Lindner
	5	Name1	Surname1	Sales Director	Company1
	6	Thomas	Geissler	CEO (*Managing Director)	Frener-Reifer (*ex-seele)
	7	John	Conboye	Director	Waagner-Biro
	8	Alistair	Lazenby	CEO / Managing Director	Yuanda
	9	Ivano	Zottini	Sales Manager	Permasteelisa
	10	Name2	Surname2	Technical Sale Director	Company2
Façade Consultants	1	Neesha	Gopal	Associate Director	Meinhardt
	2	Zara	Edwards	Façade Engineer	Interface
	3	Damian	Rogan	Façade Group Leader	Eckersley O'Callaghan
	4	Sergio	De Gaetano	Vice President / Director	ThorntonTomasetti
	5	Simon	Webster	Director	FMDC
	6	Name3	Surname3	Associate Director	Company3
	7	Graham	Dodd	Arup Fellow	Arup
	8	Greg	Sinclair	Director	Wintech
	9	Roberto	Fabbri	Associate Façade Engineer	Buro Happold
Architects	1	Charles	Olsen	Senior Associate Principal	KPF
	2	Lorenzo	Poli	Associate	Foster and Partners
	3	Mark	Bagley	Director	EPR
	4	David	Evans	Director	Lynch Architects
	5	David	Kelly	Architectural Consultant	Sheppard Robson
	6	Wolfgang	Frese	Senior Project Architect	AHMM Architects
	7	Name4	Surname4	Architect	Company4
	8	Mike	Kininmonth	Associate Director	Bennetts Associates Architects
	9	Bart	Akkerhuis	Associate	Renzo Piano Building Workshop
Glass Suppliers	1	Albert	Schweitzer	Technical Consultant	Arcon
	2	Darren	Kearns	Director	Saint Gobain
	3	Name5	Surname5	International Business Manager	Company5
	4	Aldo	Brun	Technical Manager	Tivitec
	5	Volker	Herrmann	International Technical Director	Glaströsch
	6	Name6	Surname6	Architectural Specification Manager	Company6
	7	Yves	Lecoq	Quality Manager	AGC

** Was at seele when invited and at Frener-Reifer when the questionnaire was completed*

Table 5.1: List of questionnaire participants

The names of the participants who wished to remain anonymous have been replaced by placeholders e.g. Name1, Surname1, Firm1, Name2, etc. This also applies to their relevant questionnaire responses. It should be noted that the option to remain anonymous was specifically offered in the questionnaire invitation email.

The questionnaire was administered using a web based survey service (*SurveyMonkey*). This convenient method not only facilitated the redaction and distribution of the questionnaire but also aided the collection of data resulting from it. It also provided the questionnaire with a simple and user-friendly interface.

The collected data was downloaded for a detailed analysis, presentation and preparation of the graphs (as and where applicable) using different softwares (e.g. Microsoft Excel, Indeeo iDraw, IdeasOnCanvas MindNode).

In order to increase the response rate, the questionnaire scope and structure was explained to each participant via phone and email. It should be also noted that a number of participants had been previously contacted via phone during the pilot survey to assess the need for the study. An electronic copy (PDF) of the survey was sent to those participants that required further review to confirm participation.

In addition, email remainders were sent, which were supported by phone calls, in the last week of the survey period, which was initially three weeks. This period was eventually extended by a couple of weeks to ensure further participation and increase response rate.

Notably, the off-line review of the questions was also used by some participants to evaluate the questions and collect answers with other personnel within their organization prior to filling in their final response on-line, thus potentially improving response quality.

The survey is arranged over three key sections that are consistent with the dissertation structure: Figure 5.2 in the next page maps the questionnaire layout and conceptual topics to the dissertation chapters.

The figure is followed by a blank copy of the questionnaire as distributed to the participants. The results will be presented in the next chapter.

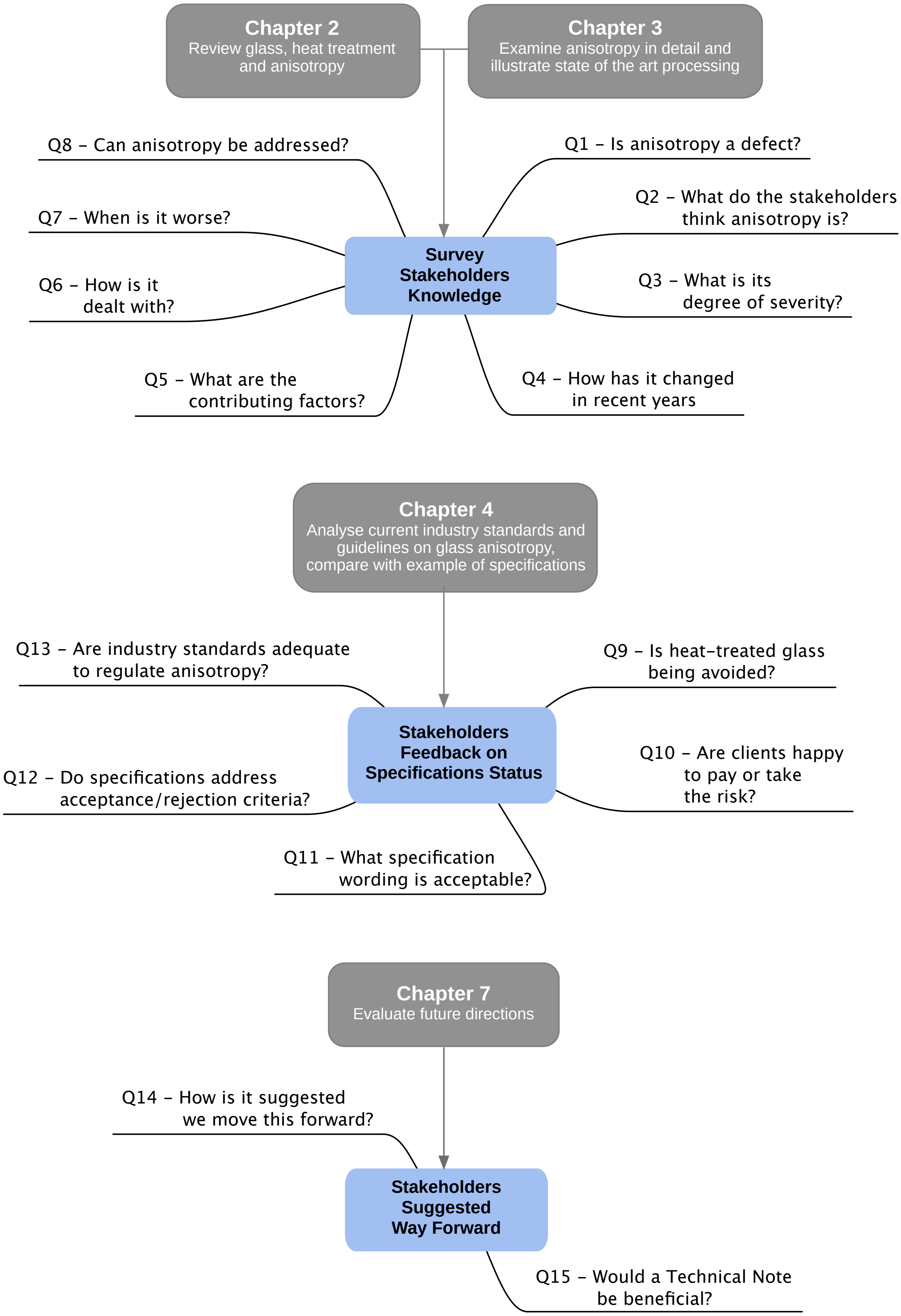


Figure 5.2: Questionnaire layout and questions mapped to dissertation structure

Questionnaire on anisotropy as a defect in U.K. architectural float glass

1. Stakeholders Knowledge

1. Do you consider anisotropy in architectural float glass to be a defect?

- Yes
- No
- Don't know

2. In brief, do you believe anisotropy in architectural float glass is:

	No	Maybe	Yes	Don't know
the result of the toughening process	○	○	○	○
the result of the heat strengthening process	○	○	○	○
the result of uneven heat distribution during the heat treatment process	○	○	○	○
a bi-refringent effect resulting from internal stresses in heat treated glass	○	○	○	○
the appearance of alternating patterns of light and dark areas	○	○	○	○
the appearance of multicolour patterns known as "leopard spots"	○	○	○	○
the appearance of dishes and/or roller waves	○	○	○	○
the appearance of a multicolour band known as "white haze"	○	○	○	○
only visible in polarised light	○	○	○	○
only visible with polarised spectacles or filters	○	○	○	○
affected by the viewing angle	○	○	○	○

Other (please specify)

Questionnaire on anisotropy as a defect in U.K. architectural float glass

3. Please rate how much of a problem you think anisotropy is for the facade industry:

	It is not an issue	It is a minor issue (easily resolvable)	It is an important issue (considerable effort required to resolve)	It is a critical/deal breaker issue (very difficult to deal with)	Don't know
at tender	○	○	○	○	○
in production	○	○	○	○	○
at handover	○	○	○	○	○
post completion	○	○	○	○	○

Any other comment?

4. Please identify how frequently you have had an issue (of any kind e.g. specification qualification, dispute, non-conformance, etc.) associated with anisotropy in the last:

	not applicable / cannot remember	never	up to 20% of the projects/bids	up to 50% of the projects/bids	up to 80% of the projects/bids	always (on all projects/tenders)
9 to 12 years	○	○	○	○	○	○
4 to 8 years	○	○	○	○	○	○
in the last 3 years	○	○	○	○	○	○

Questionnaire on anisotropy as a defect in U.K. architectural float glass

5. In your opinion the relevant issues associated with anisotropy are:

	No	Maybe	Yes	Don't know
Confusion on what anisotropy is	○	○	○	○
Confusion on what the glass industry can and can't do about it	○	○	○	○
Anisotropy is not a defect, this needs to be accepted	○	○	○	○
Specifications conflict with industry standards and guidelines	○	○	○	○
Quality of heat treatment has worsened hence anisotropy is more visible	○	○	○	○
Client/designers have higher glass quality expectations	○	○	○	○
The glass industry is not doing enough to address anisotropy in glass	○	○	○	○
The risk cannot be quantified	○	○	○	○
Acceptance is subjective, no objective inspection parameters available	○	○	○	○
Project light conditions affecting anisotropy cannot be predicted	○	○	○	○

Other (please specify)

Questionnaire on anisotropy as a defect in U.K. architectural float glass

6. In your experience, how are disputes on anisotropy dealt with:

At tender:

In production:

On site:

Is any scanning/photography/measurement used, what type?

7. In this question please choose all that apply and note options may be mutually exclusive; leave blank if irrelevant in your opinion.
In your experience, is anisotropy generally worse when the glass is:

- ☐ Thin (up to 5mm)
- ☐ Thick (more than 5mm)
- ☐ Not Low-Iron
- ☐ Low-Iron
- ☐ Toughened
- ☐ Heat Strengthened
- ☐ Viewed form Inside
- ☐ Viewed from Outside
- ☐ Reflective
- ☐ Non-reflective
- ☐ Tinted
- ☐ Not Tinted

What is the worst combination? Any other comments?

8. Do you believe anisotropy in architectural float glass can be addressed?

- ○ Yes
- ○ No
- ○ Maybe
- ○ Don't know

Any comment to support the above answer?

Questionnaire on anisotropy as a defect in U.K. architectural float glass

2. Stakeholders Feedback on Specification Status

9. Are designers and specifiers NOT using or specifying the use of heat treated glass so as to avoid issues with anisotropy?

- Yes
- No
- Don't know

10. Are clients prepared to pay more to avoid issues associated with anisotropy or to take the risk?

- Yes
- No
- Don't know

Any other comment?

11. In principle, what wording would you consider acceptable in a specification (or suggest alternatives):

- ... the phenomena is more visible in polarised light: anisotropy or "Leopard Spots" are unavoidable and are not defects.
- ... the phenomena is more visible in polarised light: all heat treated glass shall be free from anisotropy or "Leopard Spots".
- ... the phenomena is more visible in polarised light: heat treatment processing shall be rigorously controlled to minimise the appearance of anisotropy or "Leopard Spots".

Other (please specify)

12. Do agreed specifications clearly address acceptance and rejection criteria?

- Yes
- No
- Don't know

Other (please specify)

Questionnaire on anisotropy as a defect in U.K. architectural float glass

13. Do you consider current glass industry standards and guidelines adequate to regulate anisotropy?

- ○ Yes
- ○ No
- ○ Don't know

Questionnaire on anisotropy as a defect in U.K. architectural float glass

3. Stakeholders Suggested Way Forward

14. Suggested way forward:

15. Do you think the industry would benefit from a technical note or a white paper, discussing the subject and the current industry status? Please provide feedback.

Yes, I would like in particular to read about...

No, because...

6. Appraise Industry Status

This chapter presents and reviews the outcome of the responses to a 15-question survey administered to 35 key stakeholders: architects, glass suppliers, specialist façade contractors and façade consultants.

Charts have been used extensively to present the collected data and are supported by a brief critique that takes into account the content of open-text boxes where applicable.

The open-ended text nature of questions No. 6 and 14 did not allow the illustration of the collected data in a graphic form, hence a full test commentary has been provided.

The collected responses (raw data) are enclosed in Appendix B.

6.1 Question no. 1

Do you consider anisotropy in architectural float glass to be a defect?

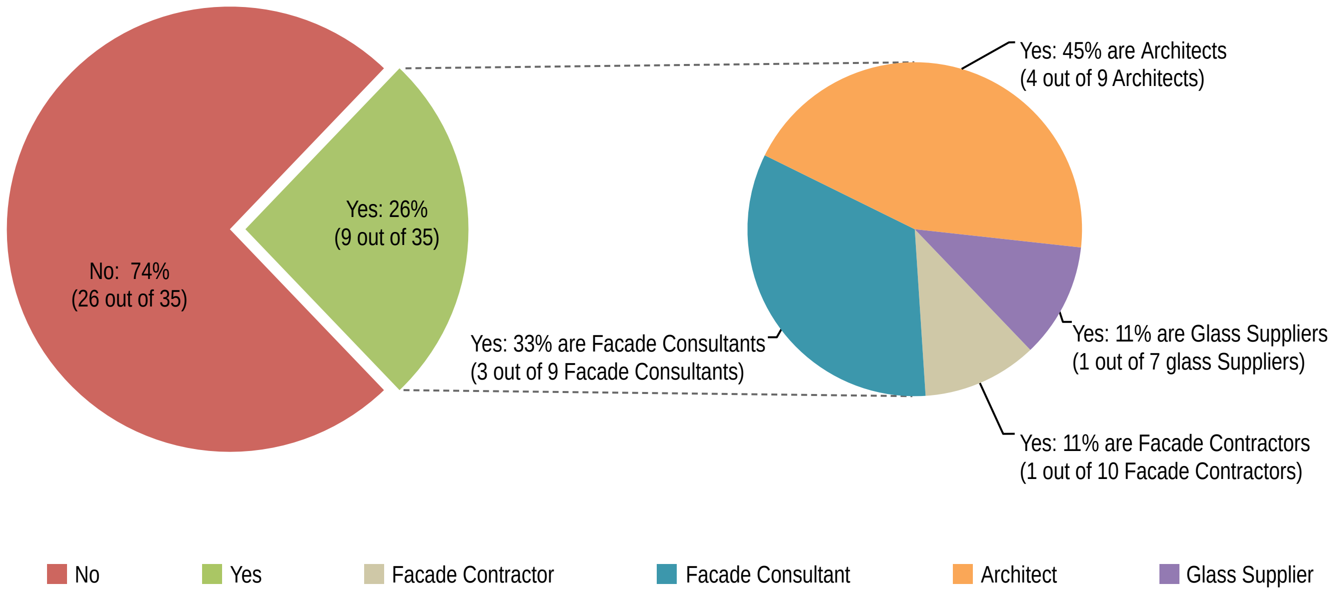


Figure 6.1.1: Question no. 1 responses pie-in-pie chart

Despite not being defined a defect by glass industry standards and guidelines as previously discussed, anisotropy is perceived as a fault by 26% of those interviewed.

Perhaps not surprisingly, a further analysis of the data reveals that Architects and Façade Consultants account for 78% of those who answered “Yes”: for these two groups building aesthetic is paramount hence a higher demand for quality is expected.

Conversely, the position of the remainder is consistent with that of the current glass regulating standards.

6.2 Question no. 2

In brief, do you believe anisotropy in architectural float glass is:

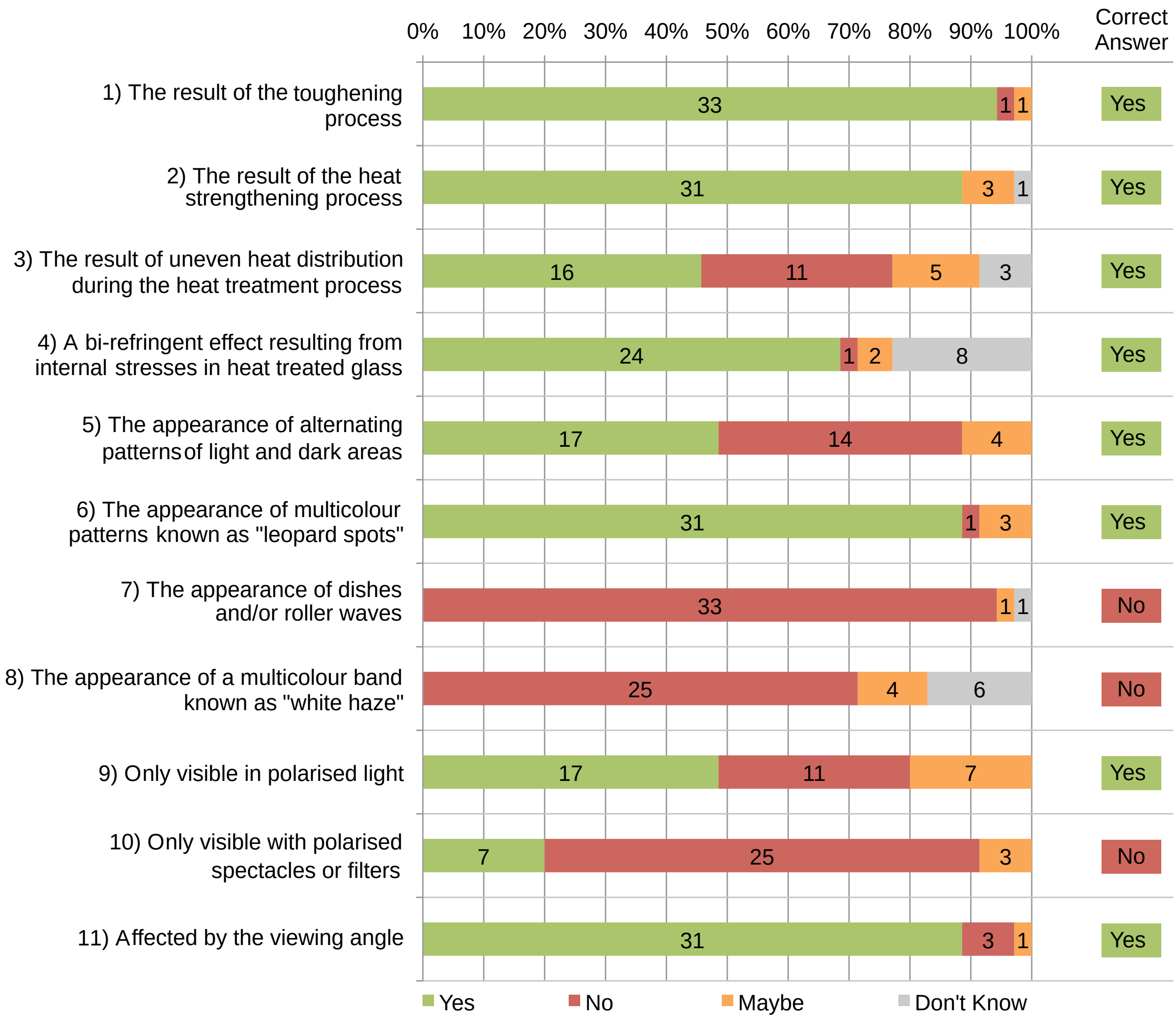


Figure 6.2.1: Question No. 2 responses stacked bar chart

The responses to this answer appear to indicate that overall the stakeholders have a good level of general knowledge on what is and causes anisotropy in glass, as indicated by the number of answers which are consistent with the findings of this dissertation (the number on each coloured bar indicate the number of responses per colour/answer).

Only a small number of participants are incorrect, unsure or do not know that anisotropy results from heat treatment of the glass, as can be seen in responses 1) and 2) above.

Conversely, responses 3) and 4) show that a deeper level of knowledge, as it relates to the thermodynamics of the heat treatment process and the effect on light caused by the glass internal stresses, is more limited.

31 out of 35 respondents agree that anisotropy appears as a multicolour pattern referred to a “leopard spot”, however only 17 recognise that it may also look like alternating lighter and darker areas. This suggests that a more formal and wider definition of anisotropy in glass may be necessary. This despite the descriptions of the phenomenon that are present in a number of industry standards and guidelines, as highlighted in Chapter 4.

Most participants recognise the difference between anisotropy and other defects resulting from glass heat treatments, like dishes, roller waves and “white haze”. The latter however appear to be in need of further clarification, as ten participants (29%) either do not know or are unsure: while “white haze” is not anisotropy, the two may occur in the same location as explained in chapter 2.6.

The last three responses focussed on the effect of viewing conditions: most participants correctly agree that the viewing angle greatly affect how visible anisotropy is. However there seems to be a need to explain further the effect of polarised light and spectacles or filters: notably the effect of light and viewing conditions is the subject of seven out of ten open-text comments provided to this question.

6.3 Question no. 3

Please rate how much of a problem you think anisotropy is for the facade industry:

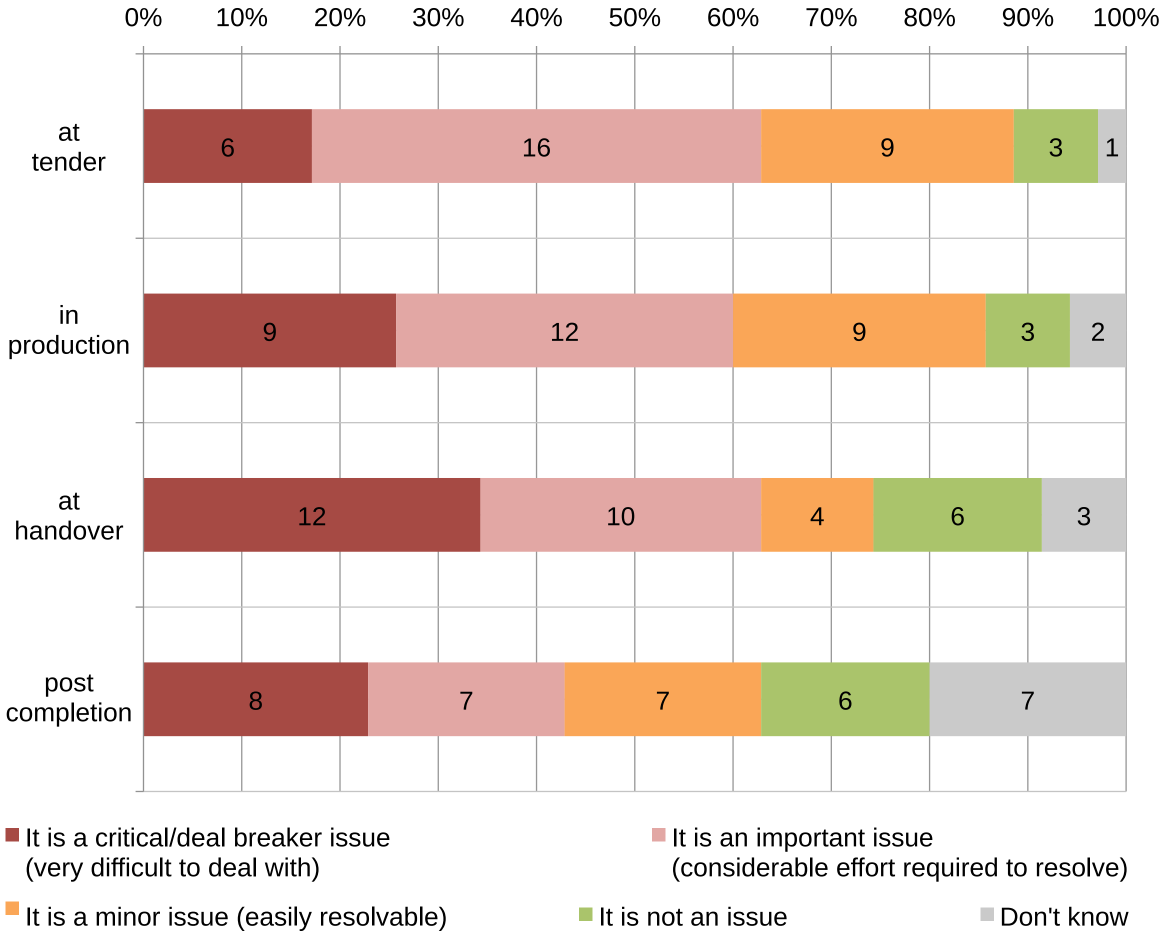


Figure 6.3.1: Question No. 3 responses stacked bar chart

Anisotropy appears to be an important if not critical issue for at least 60% of the participants not only at tender stage but also in production and at handover. It appears to be slightly less of an issue after the project completion.

The overall response is consistent with the feedback provided by the open-text option: this highlights, in particular, the need to resolve the issue at early stages by managing subjective expectations and agreeing, and specifying, adequate deliverables. The comments also suggest that this is carried out in relation to what the industry has to offer. This, along with the nature of anisotropy, does not seem to be particularly clear, with one respondent suggesting avoiding heat treated glass altogether. The latter topic will be specifically examined in question no. 9 of this survey.

6.4 Question no. 4

Please identify how frequently you have had an issue (of any kind e.g. specification qualification, dispute, non-conformance, etc.) associated with anisotropy in the last:

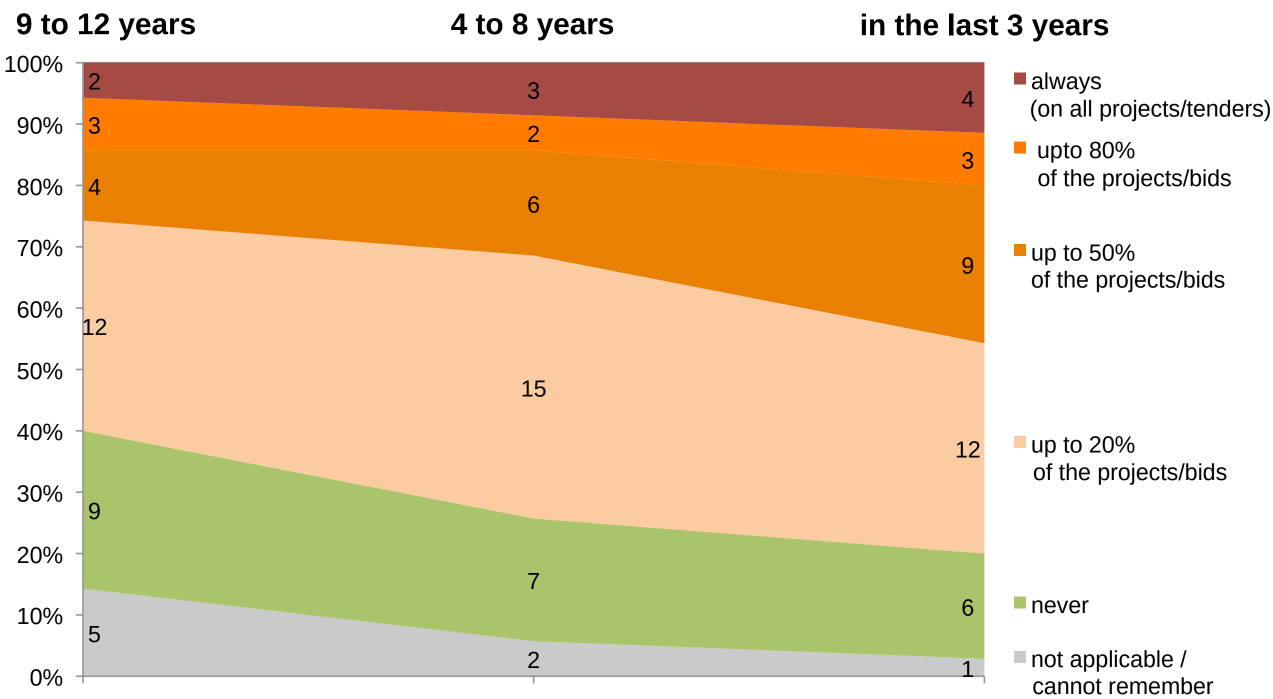


Figure 6.4.1: Question No. 4 responses stacked area chart

The answers to the fourth question confirm that, as expected and consistently with the findings of the initial pilot survey, the issues associated with anisotropy have increased in recent years.

Notably, the total number of participants having issues on all their projects, up to 50% or up to 80% of their projects a decade or so ago was nine (26%): when comparing the data for the last three years this number has increased to 16, which represent a significant 46% of all the participants.

A further, detailed analysis of the responses shows the group that appears to affect such increase is that of the Specialist Façade Contractor.

The number of participants that never have issues with anisotropy on their projects has dropped by a third in the same period.

6.5 Question no. 5

In your opinion the relevant issues associated with anisotropy are:

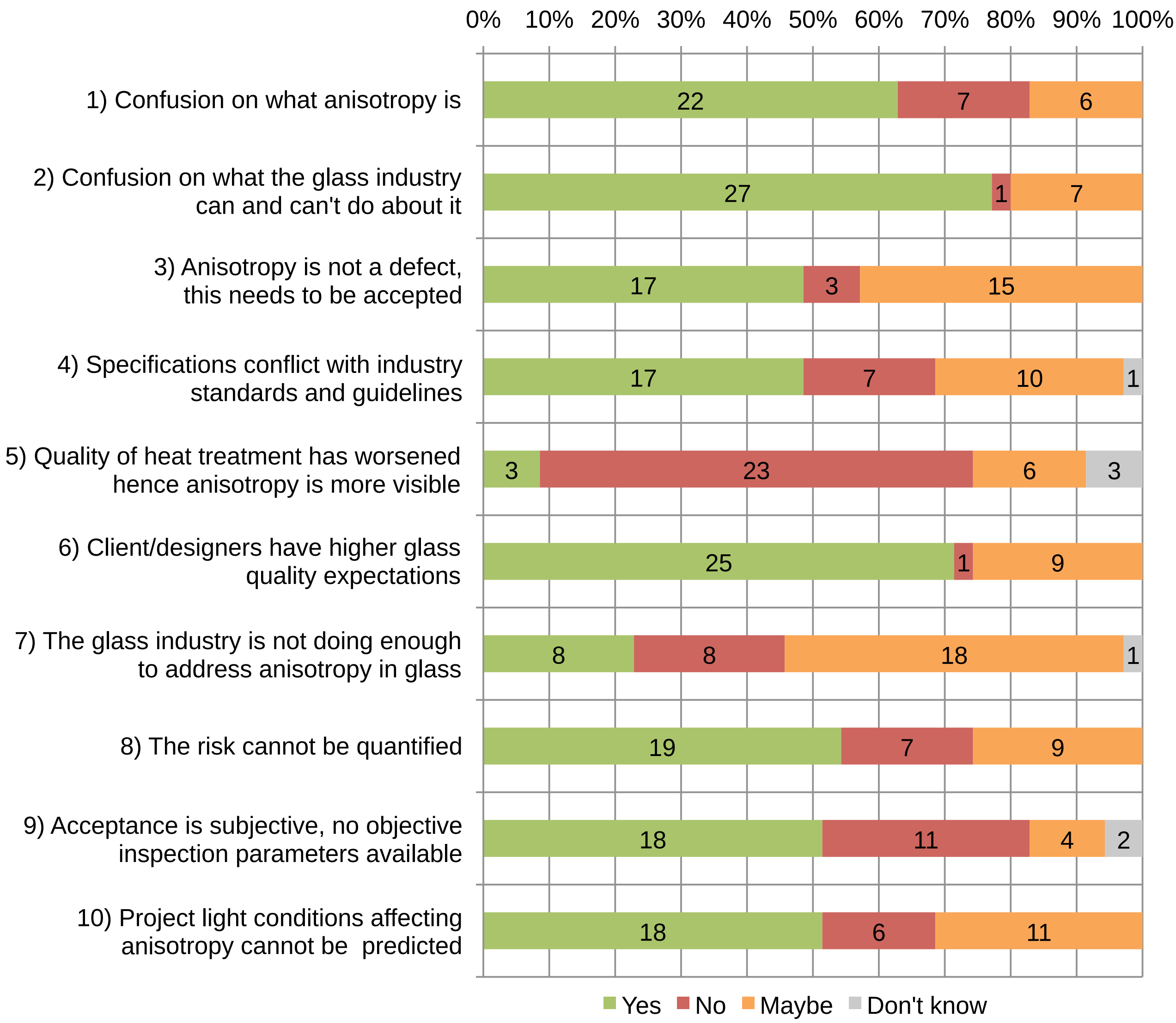


Figure 6.5.1: Question No. 5 responses stacked bar chart

The first and second responses highlights that most of the stakeholders believe that two of the main problems associated with anisotropy are the confusion around what anisotropy is and what the glass industry can do about it.

The open-ended section of the question also shows that some of these responses may be affected by the fact that one supplier is claiming to be able to supply heat-treated glass with a substantially reduced level of visible anisotropy, thus proving that the phenomena can be somehow influenced.

About 50% of the respondents concur that anisotropy is not a defect and that specifications conflict with standards and guidelines. Moreover, it should be noted that 15 out of 35 participants are not sure whether to consider anisotropy a defect (15 participants answered “maybe” in response 3) of this question). While it is not clear why these latter responses are not consistent with those from question no. 1, they confirm that a considerable number of participants potentially disagree with the standards and guidelines, which do not consider it a flaw as highlighted in chapter 4 of this dissertation.

This may inevitably result in the specification contradictions highlighted by response no. 4, which is also supported by the feedback provided in the open-ended part of the question.

Response no. 5 shows that two third of the respondents agree that the quality of the heat treatment has not worsened. This appear to be consistent with the results of the following response, which shows that just about the same number of participants concur that clients and designers have higher glass quality expectations.

In the last three responses, over half of the participants agree that the most relevant issues associated with anisotropy are that:

- Its risk cannot be quantified;
- Its acceptance is subjective due to the current lack of objective inspection parameters;
- It is affected by unpredictable project light conditions.

The need to define of objective inspection parameters has also been stressed in the open-ended section of the question.

6.6 Question no. 6

In your experience, how are disputes on anisotropy dealt with:

- At tender: …

- In production: …

- On site: …

- Is any scanning/photography/measurement used, what type? …

This question is presented in the form of four open-ended responses: the feedback analysis is presented in text format only, with a sub-paragraph allocated to each response.

At tender

About half of the respondents state that anisotropy is dealt with by negotiating and qualifying specifications to ensure that they are ultimately deliverable. However, a fifth of the participants say that the matter is not discussed at tender stage.

These responses confirm the initial dissertation predictions: uninformed anisotropy expectations are increasingly stipulated in specifications, thus inevitably attracting unnecessary qualifications and negotiations. On the other hand, they generate unmanaged risks when not discussed.

Four respondents suggest that samples and mock-ups are used at tender stage however it is not clear what inspection methodologies and acceptance parameters are employed.

A similar number of stakeholders state that avoiding heat-treated glass is also a solution to the problem: this will be specifically discussed in question no. 9 and has been reiterated by one respondent in question no. 3.

In production

About of quarter of the responses show that nothing is done in production, with some going as far as stating that it is too late to address the issue at this stage.

About a third of the participants state that inspection and review of benchmarks and samples are used in production. However, as per the previous stage, it is not clear what inspection methodologies and acceptance parameters are employed, except in the case of one respondent referring to “measurement of surface compression” (though no explanation of how this is used to assess and control anisotropy is given).

Nevertheless, sample inspection and benchmarking appear to be key not only to manage client and design team expectations but also to control the production process.

For seven respondents out of 35, anisotropy is dealt with at this stage by carefully controlling the heat treatment process and in particular the quenching phase, with some suppliers apparently being more capable than others. The details of such processes have not been provided in the responses.

On site

While six participants state that inspection and benchmarking continue to be carried out on site, the underlining message is that it is now too late to address anisotropy.

The overall feedback suggests that anisotropy disputes on site are dealt by reviewing the affected glass panels, occasionally with the involvement of third party and industry experts.

Seven respondents suggest that the issue is resolved by explaining the phenomena, however for four participants it would appear that glass replacement is the only solution in case of dispute. It is not clear from the responses who bears the cost and responsibility associated with the glass replacement, or indeed what actions are taken to ensure that the new glass does not have the same issue.

One respondent suggest to install problematic panels in locations where they will not adversely impact the aesthetic of the façade.

Is any scanning/photography/measurement used, what type?

Approximately half of the participants appear not to have an answer to this question or have no knowledge or experience with measuring anisotropy. Otherwise, photography and polarising filters, in most cases used in combination, appears to be the tools in use, however it is not clear how these are implemented.

Four respondents refer to the use of scanning equipment: in three of these cases the reference is to the equipment of a specific glass supplier, Arcon, which claims to be capable of producing heat-treated glass with reduced anisotropy. It is not clear from the responses how the equipment works and how it is implemented to reduce anisotropy.

6.7 Question no. 7

In this question please choose all that apply and note options may be mutually exclusive; leave blank if irrelevant in your opinion. In your experience, is anisotropy generally worse when the glass is:

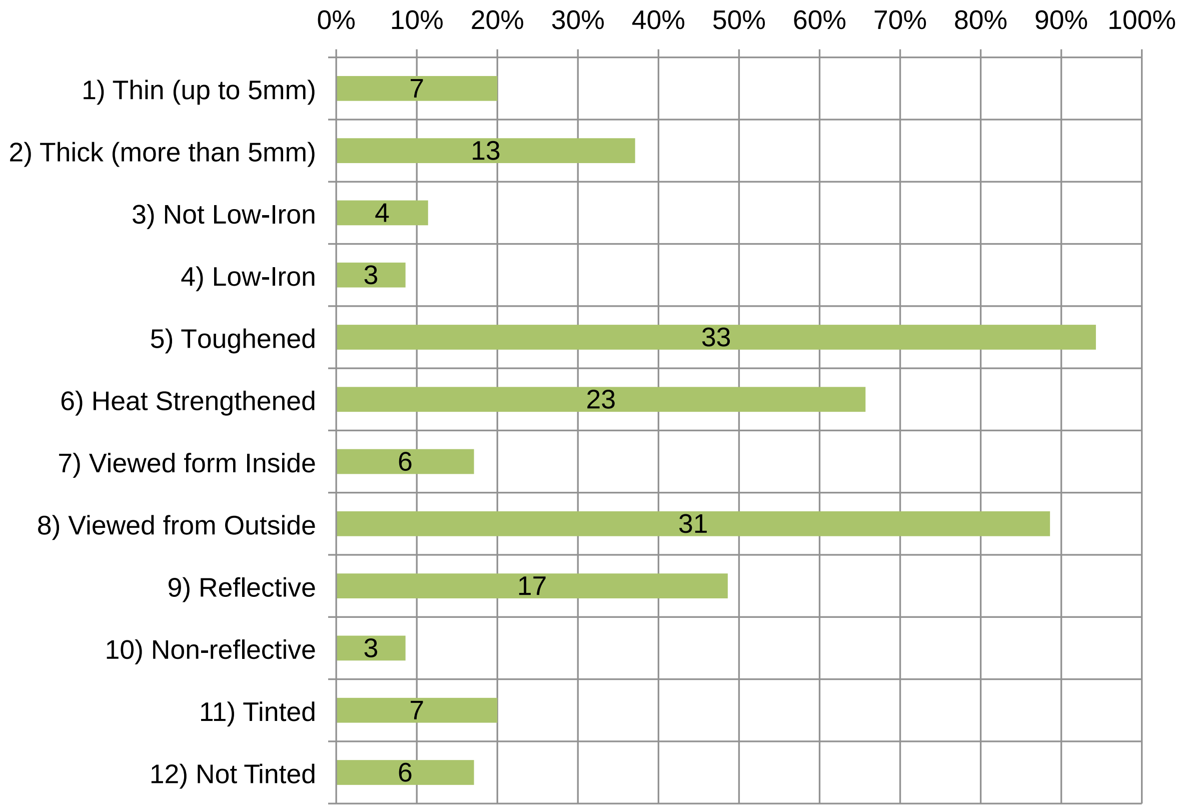


Figure 6.7.1: Question No. 7 responses bar chart

The feedback provided by the first two responses of this question suggests that anisotropy is worse when the glass is thicker, an assertion also stated in ATS-157 (2013, p.1). The same document also affirms that the phenomenon is more visible in clear glass (see also considerations in chapter on 2.3 of this dissertation), a statement that does not appear to be supported by the feedback provided by responses 3, 4 and 11, 12 of this question.

The phenomenon appears to be more prominent in toughened glass than in heat strengthened glass: while this is consistent with what stated by Wurm (2007, p. 56) it however appears to contradict the opinion of Vehmas as discussed in chapter 3.

Anisotropy seems to be more of a problem for glass viewed from outside as opposed to inside, as confirmed by responses 7 and 8. It also appears to be more of an issue when the glass is reflective (response no. 9 vs. 10).

According to the comments provided in the open-ended section of the question, the phenomenon is particularly visible when multiple panes of heat-treated glass are used in combination, like for example as part of a laminated pane and/or within an insulated glass unit. For six respondents, anisotropy is also amplified by the use of coated glass. Further studies may be needed to examine how coated glass and other glass products influence the visibility of anisotropy and in turn support the revision of the relevant regulating standards.

The feedback also draw attention on the importance of the light conditions and viewing angle, while three participants commented that anisotropy is particularly visible when the glass is curved (the impact of anisotropy on curved glass falls outside the boundaries of this dissertation).

6.8 Question no. 8

Do you believe anisotropy in architectural float glass can be addressed?

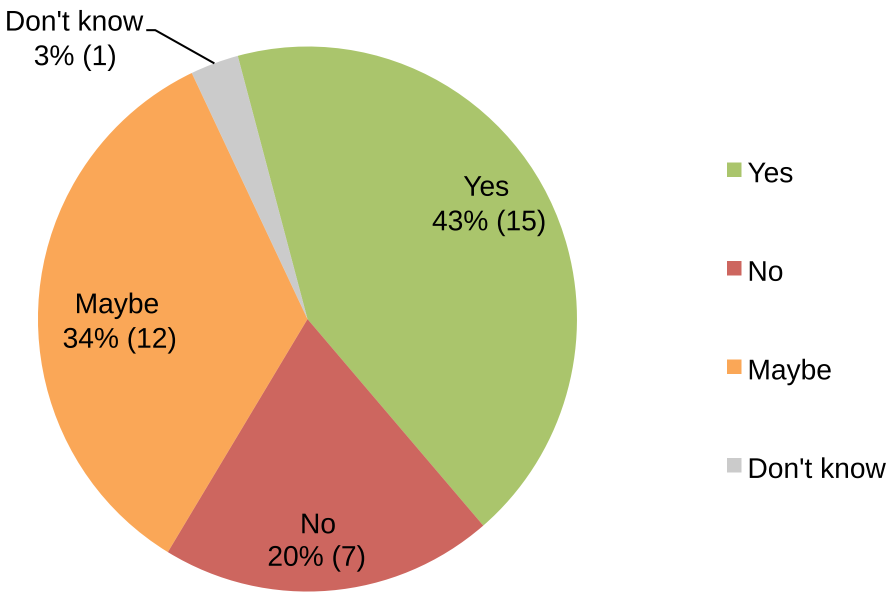


Figure 6.8.1: Question No. 8 responses pie chart

While the majority of the questionnaire participants believe that anisotropy in glass can be addressed, there is also a noticeable amount of uncertainty as over a third are not sure that this is the case.

The feedback provided in the open-ended section of the question is generally consistent with the above. Six respondents support their statements that the phenomenon can be addressed by making clear references to the glass supplier Arcon. The supplier claims to be able to produce glass with reduced anisotropy, therefore, and contrary to the historical position of the glass industry, it is physically possible to influence it. Some participants stress the importance of controlling the heat treatment process to reduce the visibility of anisotropy, in particular during the quenching phase. It is also however appreciated, in the responses, that this may require the use of modern machinery that some suppliers may need to procure. For seven respondents the objective measurements of anisotropy is a fundamental aspect of this quest.

Conversely, a limited number of open-ended responses are used to reiterate that anisotropy is not a defect and should be accepted as such.

6.9 Question no. 9

Are designers and specifiers NOT using or specifying the use of heat-treated glass so as to avoid issues with anisotropy?

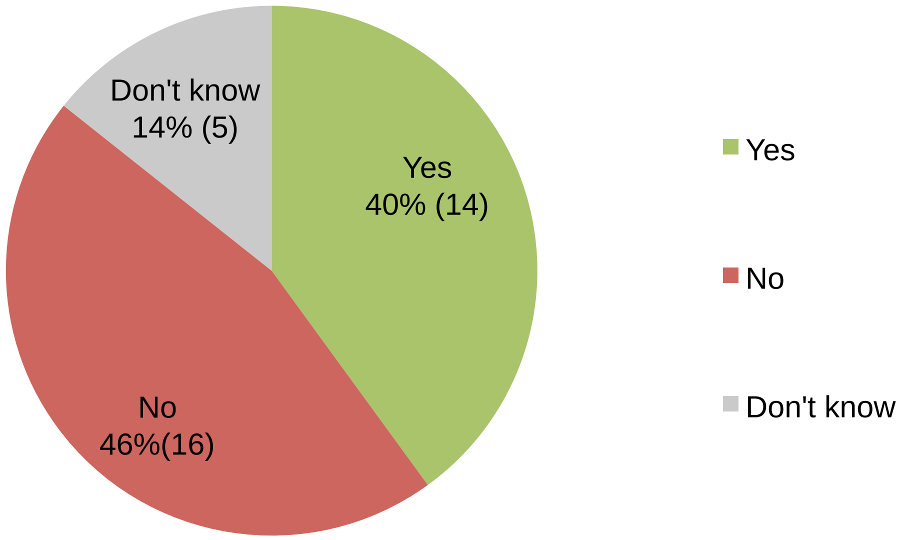


Figure 6.9.1: Question No. 9 responses pie chart

There currently appears to be a trend to avoid the use of heat-treated glass so as to avoid issues with anisotropy. This is confirmed by 40% of the questionnaire respondents: while this proportion is not the majority of the participants, it certainly is a considerable part.

It should also be noticed that not specifying heat-treated glass has been put forward as a solution to anisotropy in previous questions no. 3 and no. 6.

One tempering oven manufacturer contacted during the course of the dissertation was surprised, and concerned, to see the above response, as the tendency of not using heat treated glass could potentially result in less demand for tempering ovens.

However, as previously observed, avoiding heat-treated glass altogether is not always possible due to the variety of applications that the product is suitable for, hence its avoidance is not a sustainable solution to the anisotropy issue.

6.10 Question no. 10

Are clients prepared to pay more to avoid issues associated with anisotropy or to take the risk?

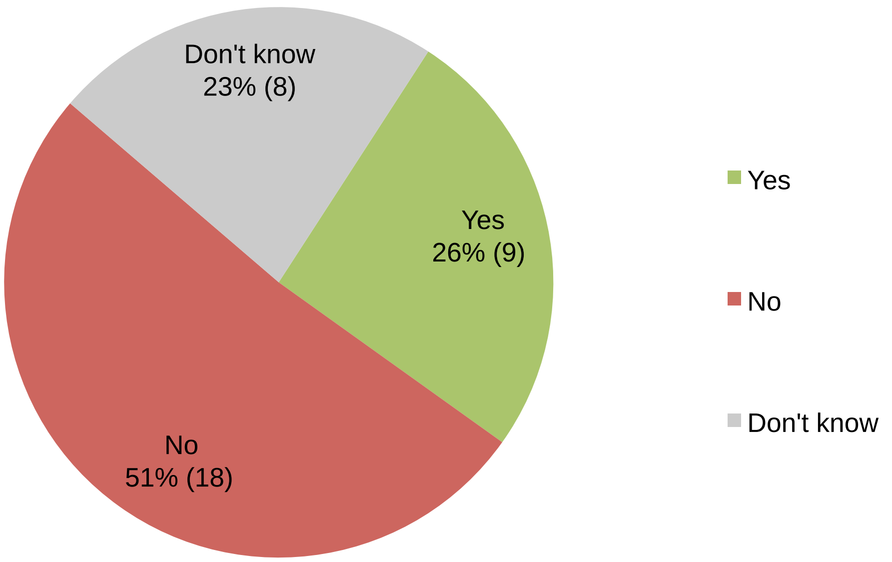


Figure 6.10.1: Question No. 10 responses pie chart

The majority of the respondents confirmed that their clients are not prepared to pay more to avoid issues, or take the risk, associated with anisotropy. Depending on the type of contract and specifications, the risk is, in this case, conveniently transferred “free-of-charge” to the supply chain.

One respondent further commented that the premium to be paid is currently too high in relation to the potential occurrences, However, despite the investigations carried out during the course of this study, the details of such premium are not clear.

On the other hand, just over a quarter of the participants state that clients may be prepared to pay more to reduce risks associated with anisotropy.

The feedback provided in the open-ended section of the question highlights the need for clients to be adequately informed in order to make such decision, which according to some respondents may also be dependant on the ultimate degree of residual risk.

6.11 Question no. 11

In principle, what wording would you consider acceptable in a specification (or suggest alternatives):

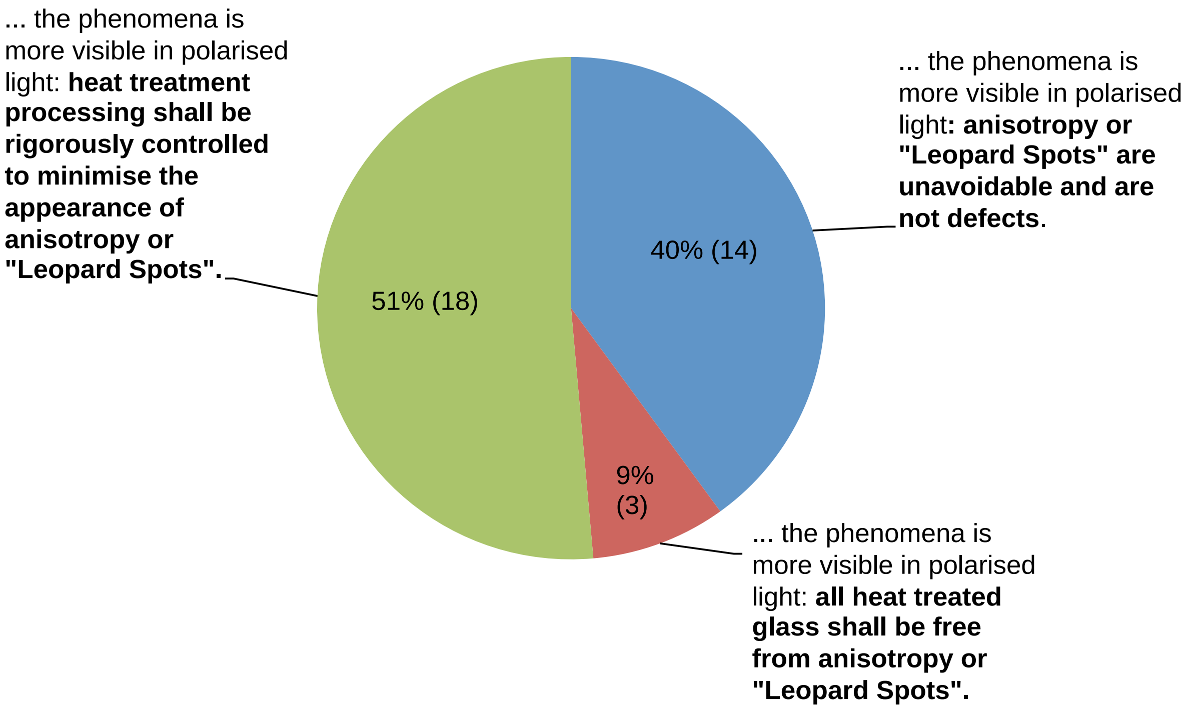


Figure 6.11.1: Question No. 11 responses pie chart

Over half of the respondents agree that the heat treatment process should be controlled in such a manner to minimise anisotropy. However, one respondent questioned how this is carried out in practice, while another states he would sign-up to this wording only if the client was happy to pay for the additional cost of going single source.

Notably, 40% of the participants affirm that the acceptable specifications wording are those that acknowledge that anisotropy is **not** a defect and is unavoidable.

Some participants point out the need to agree wording for benchmarking and control/measuring procedures so as to manage all parties' expectations. One respondent points out that benchmarking should take into account the project light conditions.

One other participant suggested that a clear statement that anisotropy is not a defect should always be included regardless of the wording, while another points out that the standards that regulate heat-treatment processes already have the required wording.

Only three respondents state that an acceptable wording should state that all heat-treated glass should be free from anisotropy or "Leopard Spots": none of these respondents is a façade specialist contractor, and only one is a glass supplier. As anisotropy remains unavoidable, wording to this effect makes the specifications non-deliverable.

6.12 Question no. 12

Do agreed specifications clearly address acceptance and rejection criteria?

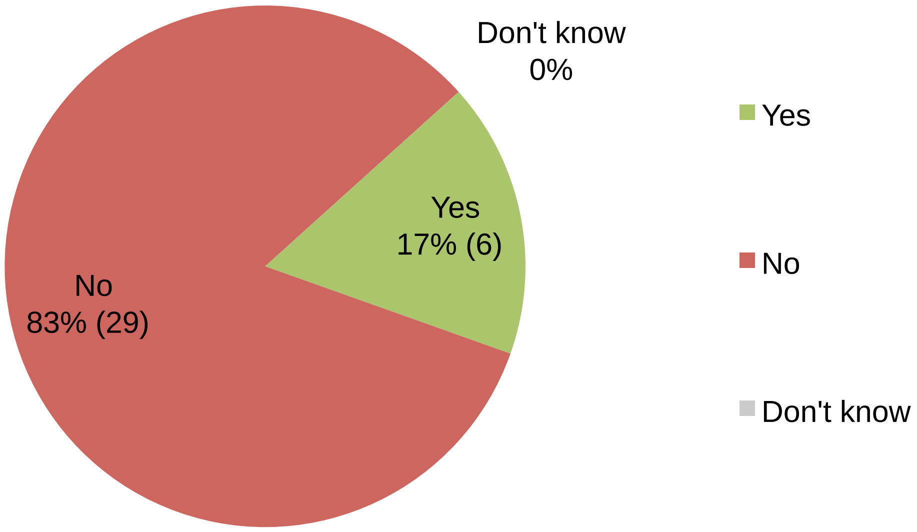


Figure 6.12.1: Question No. 12 responses pie chart

Only six participants are of the opinion that agreed specifications clearly address acceptance and rejection criteria. Surprisingly, five out of six of these participants are specialist façade contractors. One of them comments that agreed specifications state that anisotropy is not a defect: it is possible that this statement silently applies to the other four specialist façade contractors to support their position.

The vast majority of the participants are however clearly of a different opinion, with none of the participants answering that they “Don’t know”.
In the open-ended section, one respondent goes as far as stating that they never get to a satisfactory agreement, while a façade consultant draws attention to the contradiction in some specifications that do not accept anisotropy and yet refer to standards which describes it a natural phenomenon.

The feedback in this section also highlights that while control samples are usually specified, they may not be of a suitable size to allow for an adequate inspection, which in any case remain subjective due to lack of measurement procedures. Two respondents also state that, so far, their attempts to obtain samples to control anisotropy have been unsuccessful.

6.13 Question no. 13

Do you consider current glass industry standards and guidelines adequate to regulate anisotropy?

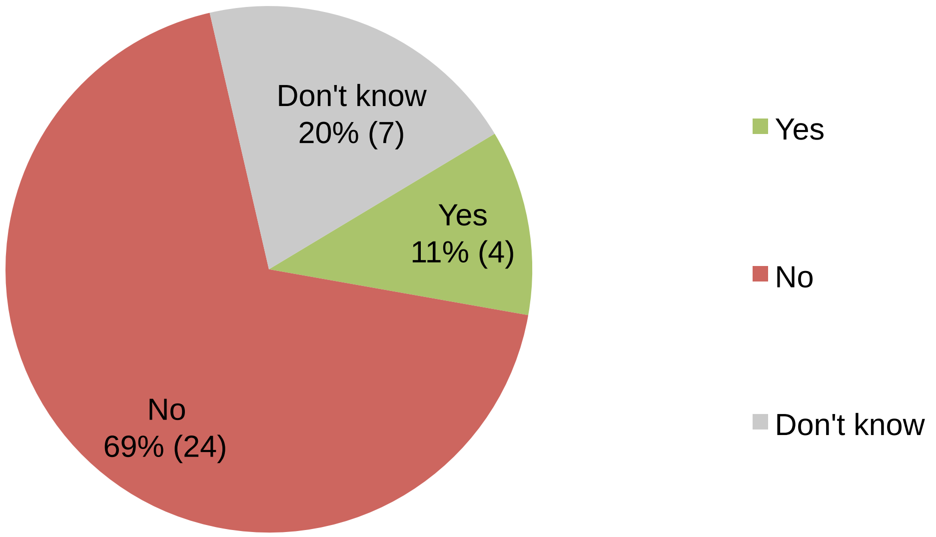


Figure 6.13.1: Question No. 13 responses pie chart

Chapter 4 highlights that anisotropy is not considered a defect by the current glass industry regulating standards and guidelines.

For only four participants, none of whom is an architect (2 glass suppliers, 1 façade contractor and 1 façade consultant), the current status of these documents is sufficient to deal with the phenomenon.

This position is in contrast with over two thirds of the questionnaire participants that **do not** consider the current glass industry standards adequate to regulate anisotropy. Further analysis of these responses is unfortunately not possible, as the question was structured as a multiple-choice answer only, with no open-text box. In spite of this, this response highlights the need for the standards to be clearer on the phenomenon. Future revisions of the documents may need to take into account the progress made by some industry stakeholders in recent years in terms of measuring and controlling anisotropy. In contrast to this, the review of the most recent standards confirms that the documents are being revised to further clarify that the phenomenon is not a defect.

A fifth of the respondents do not know if the standards and guidelines are adequate or not. Further clarification on the documents status in relation to the industry status may be therefore required to address this lack of knowledge.

6.14 Question no. 14
Suggested way forward: …

This open-ended question provokes and encourages the questionnaire participants to suggest a way forward. While a handful of respondents appear to suggest either to do nothing or not specifying heat-treated glass as a way forward, the majority of the participants are indeed keen to resolve the matter.

For at least seven participants it is important to move the industry forward by providing more information on the heat treatment process and adequately educate the stakeholders on what is and causes anisotropy in glass. It is suggested that this would promote awareness and facilitate the management of realistic expectations.

The respondents, in at least ten cases, stress the need for researching anisotropy in heat-treated glass not just to eliminate or reduce it, but also to objectively measure it.

The responses also suggests that this important deliverable is key to agree acceptance criteria not just at project level but, more importantly, at industry level, with some participants going as far as suggesting amending the current industry standard accordingly.

It is evident from the answers that the stakeholders are particularly expecting the glass supply chain to initiate and lead the resolution of this matter and improve glass quality.

6.15 Question no. 15

Do you think the industry would benefit from a technical note or a white paper, discussing the subject and the current industry status? Please provide feedback.

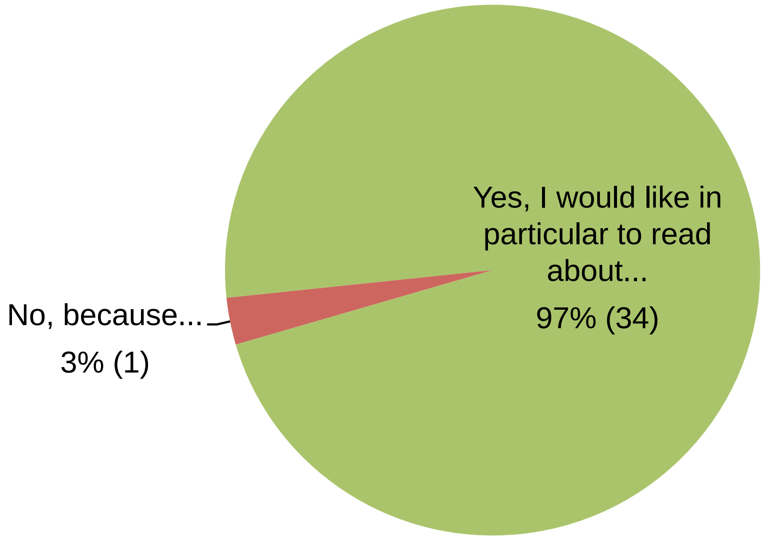


Figure 6.15.1: Question No. 15 responses pie chart

The responses to this question show that it is important for the stakeholders to learn more about what causes anisotropy and the processes associated with it, with all but one questionnaire participants expressing their interest in reading more about the subject.

Some participants suggest that the vehicle to inform the stakeholders could be a comprehensive technical note or white paper covering not only anisotropy causes and associated processes but also measurement and assessment methodologies.

The feedback shows an underlying yet clear interest in understanding the façade industry status as it relates to anisotropy, with some participants going as far as complaining that the glass supply chain is not taking the issue seriously.

Some stakeholders are aware of one glass supplier that claims to be capable of supplying heat treated glass with “reduced” disturbing anisotropy: this highlights the need to understand, and perhaps share know-how, on how anisotropy can be “minimised” and widen the market to create competition thus reducing processing cost while increasing glass quality.

6.16 Summary of Questionnaire Results

The questionnaire responses confirm that anisotropy is an important matter for the majority of the stakeholders.

Issues associated with the phenomenon have increased in recent years and require a solution at the early stages of the project to efficiently agree deliverables and to manage expectations. This can be achieved by adequately informing all parties on the presence of anisotropy and its magnitude. To support the latter, the industry would benefit from supporting information to explain what anisotropy is in more detail while updating the stakeholders on the current State of The Art technologies in relation to glass processing and measurement of anisotropy. This should also clarify what can and what cannot be done to address the issue and ideally at what cost.

The façade industry is divided between the supply chain accepting the phenomenon, a position that they support by referring to the glass regulating standards, and designers and specifiers seeking to have glass with “reduced” or “minimised” anisotropy. However the absence of objective and quantified parameters makes this highly subjective. The latter group upholds their position by referring to the progress and products of a single glass supplier that claims to be able to satisfy their glazing aspirations.

On the other hand clients appear **not** to be necessarily willing to pay, despite the cost being unclear, to resolve the issue, thus suggesting that the problem is for the glass industry to resolve.

The conditions under which the phenomenon is worse could not be precisely established due to contradictions among the responses (question no. 7) and because some of the answers contradicted statements found in guidelines and recorded in interviews. However, this highlights once again how subjective the assessment of anisotropy is in the absence of objective and quantifiable parameters.

The questionnaire responses also suggest that regulating standards are currently inadequate. These may need to be updated to reflect the current industry progress and list objective acceptance and rejection criteria to be used in specifications, as these are also considered inadequate. This will facilitate the redaction of deliverable specifications and in turn reduce the risk of protracted qualifications and disputes.

Question No. 13 (adequacy of standards and guidelines) could have benefitted from an open-text box to collect recommendations and supplementary feedback on the responses.

Nearly all the participants would like to read more about anisotropy and recognise the need for a Technical Note or a similar document to better inform the industry on the phenomenon.

While designers and specifiers are prepared to **not** specify heat-treated glass so as to avoid risks with anisotropy, it would appear that their clients would not be willing to invest money to avoid the phenomenon.

7. Final conclusions and recommendations

7.1 Review glass, heat treatment and anisotropy

The initial review of the literature highlights the evolution of the glass production processes through the centuries: such evolution is characterised by the quest to produce increasingly larger glass while improving its quality and lower its cost.

Soda-lime-silicate glass produced by the floating process is currently the leading glass product for the building industry. The annealed glass produced by this process offers the best visual quality however surface flaws limit its strength: this can be improved by means of thermal treatment to produce fully toughened and heat strengthened glass. Such treatments are exploited to widen the range of application of the glass and as part of further product processing.

The thermal toughening and heat strengthening processes induce stresses in the glass that, while improving the product strength, makes it anisotropic: this is unavoidable and may result in undesirable colourful patterns that may be visible in certain light conditions.

The responses to question 9 of the dissertation survey confirm the current industry trend to not specify heat-treated glass so as to avoid anisotropy, however the variety of applications of the product may means that this is an unsustainable solution.

7.2 Examine anisotropy in detail and illustrate State Of the Art processing

The detailed analysis of what causes the manifestation of anisotropy patterns in heat treated glass reveals that its visibility is dependent on three conditions: polarised light, viewing angle and stresses in the glass plate. The latter are a function of the temperatures distribution during the heat treatment process.

The optical mechanisms and thermodynamics processes associated with the visibility of the phenomenon are complex and have proven difficult to explain in simple terms. The literature research extended beyond glass industry publications to include books and journals in the fields of optics and physics, however the information therein did not necessarily refer back to the glass and its heat-treatment processes.

A considerable amount of knowledge resides with specialist glass suppliers, glass consultants and tempering oven manufacturers, however, this is not readily available and requires one-to-one interviews, discussion and permissions to reveal.

This research process is inevitably, and understandably, restricted by an element of confidentiality, with some companies willing to share more information than others. Sharing know-how may however be the key for the glass industry to resolve such complex matters.

Specific investments and research by some industry players appear to confirm that the degree of visibility of the phenomenon, which remains unavoidable, can be altered and minimised to produce glass with less disturbing anisotropy. However the magnitude of the associated cost remains unclear and may require a dedicated market study. The design of the tempering oven, and in turn temperature and stress distribution, is critical to address the visibility of the pattern; conversely its operation and maintenance are also crucial.

There appears to be good progress with the development of anisotropy measurement devices. Such equipment is critical to analyse the stresses and their distribution, and in turn optimise tempering oven design and heat treatment temperatures to reduce anisotropy visibility. The measuring equipment is also crucial to **objectively** define acceptance and rejection parameters. These can be used for benchmarking, sampling and quality control but also, if and when agreed by the industry as a whole, to redefine the regulating standards.

7.3 Analyse current industry standards and guidelines on glass anisotropy, compare with example of specifications

Current glass industry standards and guidelines recognise anisotropy, as an unavoidable effect of the toughening and heat strengthening processes. The phenomenon is not defined or listed as a defect: conversely, the current British Standard that regulates the heat strengthening process clearly states that the phenomenon **is not a defect but a visible effect**. The statement is expected to be incorporated in the next revision of the British Standard that regulates the toughening process: such statements in a Standard are important, as they leave no room for interpretation.

A number of standards related to glass products that can incorporate heat-treated glass may need to take into account anisotropy in future revisions, however this may require further studies on the matter.

Further revisions of glass standards may also need to consider the progress currently being made by the glass industry to assess and reduce the phenomenon, and ideally list measurement processes along with anisotropy acceptance and rejection criteria.

The current standards are being revised to clarify that anisotropy is not a defect but, on the other hand, the glass industry, or rather some of its key players, are making good progress to quantify and minimise the phenomenon and its effects. This may create an impasse that could be resolved ad-interim by guidelines and Technical Notes, but ultimately require future revisions of the standards. Unfortunately this may take some time due to the latency in revised documents' consultation periods prior to ratification and final publication.

Façade specifications demanding glass without anisotropy contradict the current industry standards and guidelines and cannot be delivered: they also potentially initiate protracted qualifications and attract a high risk of disputes.

Conversely it may be possible to meet – at a premium – specifications demanding glass with reduced anisotropy, which also contradict current industry standards and guidelines. However the objective acceptance and rejection parameters currently missing in these specifications should also be defined and agreed: ideally these should be supported by the revised and updated standards mentioned above. Some of these specifications refer to anisotropy benchmarking and sampling procedures, however the details of such processes are not described in the reviewed documents and therefore could not be appraised.

7.4 Devise appropriate survey

The survey and its structure, including the number of questions within, have proven a satisfactory tool to collect the information for this study.

Key to administering the questionnaire and collating the relevant responses was the use of an on-line system. However the data analysis, chart preparation and editing for incorporation in the body of the dissertation took longer than expected, especially in relation to the analysis of the open-ended questions which inevitably required a higher degree of interpretation than multiple choice questions.

Crucial to achieving a high response rate were direct requests to participate and the explanation of the questionnaire aims via personal communication with the participants, via telephone and email.

7.5 Appraise industry status

The results of the questionnaire highlights that the façade industry is divided between the supply chain accepting anisotropy, and designers/specifiers seeking to have glass with reduced anisotropy. The matter is important for the stakeholders and issues associated with the phenomenon have increased in recent years.

However, while progress and products of a single glass supplier claim to be able to satisfy their glazing aspirations, clients are not willing to pay the additional costs.

The questionnaire responses confirm that there is currently a trend of not specifying heat-treated glass to avoid issues with anisotropy.

Regulating standards are currently inadequate and may need to be updated to reflect current industry progress with objective acceptance and rejection criteria for use in specifications.

The questionnaire participants would like to read more about what causes anisotropy and the processes associated with it.

7.6 Evaluate future directions

The stakeholders' interest to be more informed on anisotropy has been clearly expressed not only via the responses to question No. 15 of the questionnaire, but also during the course of interviews and via the correspondence that supported this dissertation. This confirms the validity of the study. The results of the questionnaire are of particular interest to the industry: numerous requests for its publication or sharing have been received.

The findings of this study may be used to write a specific Technical Note on anisotropy, or provide support for discussions at workshops, prepare conference talks, presentations and proceedings as well as papers. These may be focused or be structured around:

- A detailed explanation of anisotropy and what causes it
- An update on the current State Of The Art technology as it relates to:
  - Anisotropy measurement processes and equipment
  - Anisotropy acceptance and rejection parameters
  - Anisotropy mitigation processes and equipment
- The highlighting of the current status of the relevant glass standards and guidelines: these require to be updated to reflect industry progress
- The presentation of the results of this dissertation questionnaire

The findings of the dissertation may also support and initiate further actions to:

- Define anisotropy measuring and acceptance/rejection parameters and procedures to be used in regulating standards and guidelines
- Identify what parameters may need to be taken into account in the design, modification and operation of the tempering equipment
- Investigate how coatings and multiple glass build-up in insulated glass units and laminated glass units (and their combination) influence the visibility of anisotropy
- Resolve current impasse and update glass production regulating standards, to reflect the industry progress as it relates to measure and reduce anisotropy
- Identify the cost associated with procuring glass with reduced anisotropy
- Carry out on-site assessment of polarised light levels
- Create an on-line knowledge base hub where information may be transparently collected and shared. This may facilitate debate and provide updated links to supply chain websites, conferences and workshop presentations and proceedings, papers and studies.

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