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RESEARCH PAPER

Optical distortions in architectural glass: review of categorization, evaluation and measurement methods

Thomas Henriksen · **Edwin Stokes** · **Christian Louter** · **Mauro Overend**

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Abstract This paper is a review of methods to determine optical distortion in architectural glass, with a focus on the methods described in the current available standards and guidelines. Examples from building projects are used as reference points in the review of the methods. In addition to the review initials measurement studies are performed in a laboratory to determine the physical phenomena behind the optical distortion. The paper concludes on the different types of optical distortion seen, the methods which were used for the survey and how it corresponds to the current standards and guidelines, with a proposal for future research directions. Based on the findings in this paper it is suggested that the best method to determine optical distortion is to measure the changes in milli diopters, based on the current methods utilized for monolithic glass when measured in transmission. However, this method would need to be expanded to laminated glass, IGUs and potentially to curved glass, as well as a method to measure optical distortion in reflection. These methods will have to be developed through further research to better understand the causes behind the different optical phenomena.

Keywords Glass · Architectural glass · Optical distortion · Insulated glass units

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1 Introduction

The manufacturing technologies for producing architectural glass have advanced significantly since the advent of float glass in the 1960's (Belis et al. 2019). This has given rise to the development of production processes, materials, checking procedures and product standards that together achieve high levels of quality in the marketplace, yet optical distortions may still occur. The causes of optical distortions are well understood in monolithic glass and adequate (in-production) evaluation methods are available for tempered glass (Dellieu et al. 2023).

Optical distortion in glass occurs as described in (Youngquist et al. 2015) and as shown in Fig. 1 when light changes direction when passing through glass. Refraction of light in glass occurs when light waves change direction as they pass from air into the denser medium of glass, resulting in the changing angle of the light path please see Fig. 2, according to Snell's Law (Hecht, 2014). Ideally architectural glass would have

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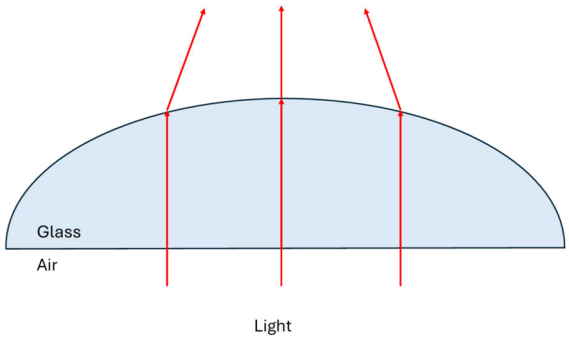


Fig. 1 Diagram showing the path of light glass with one flat surface and one curved surface. The light rays change direction at the interface between the glass and air, at angles dependent on the curvature and refractive index of the glass

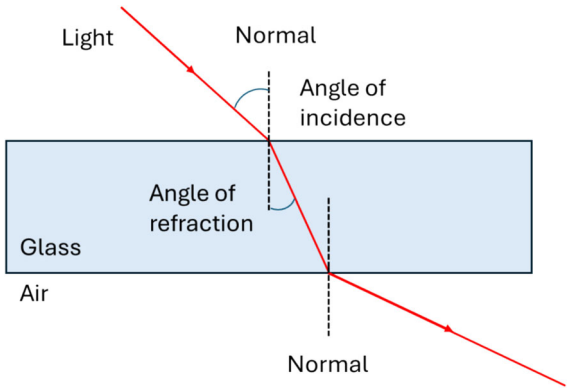


Fig. 2 Diagram showing the refraction of light incident in glass

two flat, parallel surfaces such that the direction of incident light does not change, despite light refraction at the surfaces. However, if the glass has changing curvature then light will be refracted differently dependent on the curvature.

The causes of optical distortions in multi-layered glass are, however, more complex and currently less well controlled in production (Neugebauer and Stavrić 2014; Hundevad 2013).

The typical form of architectural glazing is the insulated glass unit (IGU), which commonly comprises heat treated and/or laminated glass panes separated by a hermetically sealed cavity. This paper maps the optical distortions that may occur in such multi-layered glass, the causes of which can be complex, as they may be amplified/magnified by optical superposition effects. There is currently a lack of adequate (in-production or on-site) evaluation methods to assess and control these distortions.

Eight main types of optical distortion in multi-layered IGU's have been identified and categorised in this paper through case study examples, six of which are presently not addressed by standards. The paper, in turn, outlines existing literature, current standards and methods to determine optical distortion in the individual components of architectural glass.

In addition, preliminary laboratory tests have been carried out at Institute XX (blinded) to further explore the characterisation of optical distortion in samples of multi-layered IGU's. The findings of which are discussed, and further work is suggested to develop the understanding of the phenomena.

2 Categorization of optical distortions

This section discusses and categories different phenomena of optical distortions commonly seen in architectural glass (Wiederhorn and Clarke 2022; Schlösser 2019; Neugebauer and Stavrić, 2014). The mapping is based on samples of IGU's gathered from different buildings in recent years.

The categories of optical distortion addressed in this paper are as follows:

a) Roller wave and edge dip.
b) Distortion from polishing.
c) Lensing effect.
d) Linear edge distortion.
e) Localised edge distortion.
f) Dishing.
g) Anisotropy.
h) Longitudinal fine wave.

These categories of optical distortion are discussed in the following sub sections with reference to standards associated with their definition, where applicable.

2.1 Roller wave and edge dip

During the heating phase of the toughening or heat-strengthening process, glass softens and is prone to deformations due to slumping of the glass over the rollers of the heat treatment furnace (Aronen and Karvinen 2012). The thinner the glass, the more prone it is

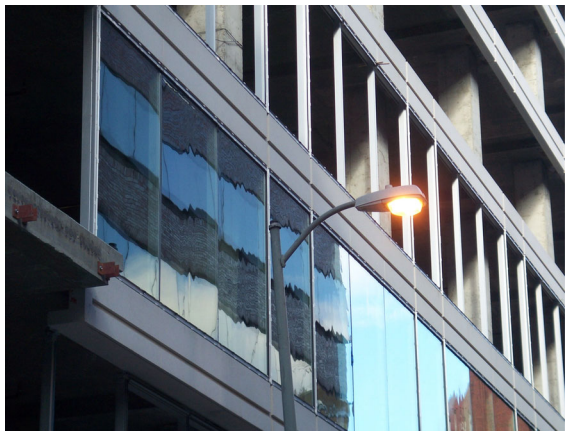


Fig. 3 Photograph showing an example of roller wave, apparent in the reflected image of a nearby building



Fig. 4 Photograph taken on site with optical distortion originating from polishing shown highlighted by a red dotted ring

to such slumping (notably 3–5 mm thick glass). This slumping between the rollers gives rise to a wave in the surface of the glass and a dip at the edge of the sheet (Aronen and Karvinen 2009). The slumping is caused by excessively high temperatures for the specific thickness of glass. The direction of the wave is aligned with the direction of travel of the glass through the heat treatment furnace. These effects are known as roller wave and edge dip or called "edge lift", as defined in EN 1863-1 (European Committee for Standardization 2011) and EN 12150 (European Committee for Standardization 2015), as illustrated in Fig. 3. If the process is not adequately controlled, this can lead to an optical distortion.

The effects of roller wave and edge dip are inherent in the manufacturing process, therefore they are present to some degree in all thermally pre-stressed (heat strengthened and fully toughened) glass, but the magnitude of the effects can be controlled to measurable specified limits. The surface quality of glass can, therefore, be measured to assess these effects. Measurements are typically done as the glass leaves the quench (Abbott and Madocks 2001; Dix et al. 2022). Equipment is also available to measure roller wave on site. The edge dip arises as the ends of the glass cantilevers between the rollers, when moving inside the furnace. ASTM C1651-08 (ASTM C1651-08 Standard Test Method for Measurement of Roll Wave Optical Distortion in Heat-Treated Flat Glass 2008) also offers a method of characterising roller wave through computational analysis of digital photographs using grid screens (refer to Sect. 3.1 for more details).

2.2 Distortion from polishing

Optical distortion caused from polishing glass may appear both in reflection and transmission, as a result of abrading the surface using handheld equipment (mechanical polishing disc) e.g. to remove scratches. Such polishing distortions may arise from localised or irregular abrasion that effectively create curvatures in the surface, therefore, affecting reflections and causing lensing effects.

Figure 4 shows an example of optical distortion from polishing. Polishing is typically identifiable from a viewing distance $\geq$ 2 m, as a function of the focal length of the optical distortion.

Note that EN 1863-1 and EN 12150-1 explicitly warn against working the surface of the glass post heat treatment (e.g. polishing), as this would erode the compressive zone in the thermally pre-stressed glass, ultimately affecting the fracture strength of the glass. Therefore polishing may affect the structural performance of glazing as well as its aesthetic quality.

2.3 Lensing effect

Lensing is a form of optical distortion affecting the whole or majority of an IGU, causing a magnification of the image seen through it. An example photograph is shown in Fig. 5.

Lensing effects can occur due to polishing of the glass with abrasive tools to remove scratches. In addition, rollerwaves or edge dip in heat treated glass that



Fig. 5 Two examples of an overall lensing effect. The red arrows on the images indicate local points of distortion affecting the IGU's

form part of insulated glass units can also contribute to lensing effects. The same applies to laminated glass, especially if they form part of a insulated glass unit. Lensing effect in laminated glass can occur if excessive clamping of the laminated glass happens as part of the lamination process when the glass is autoclaved.

2.4 Linear edge distortion

Linear edge distortion is a form of optical distortion that has been found to affect one or more edges of IGUs. An example photograph is shown in Fig. 6. Such distortion is similar to but distinctly different from edge dip, as it is a less regular and more pronounced effect. Examples of it have been found where it was visible perpendicular to the roller wave i.e. indicating that it was not an effect caused directly by the rollers in the heat-treatment furnace. Such distortion could potentially be caused by uneven handheld polishing along affected edges (refer to Sect. 2.2 regarding polishing).

2.5 Localised edge distortion

Localised edge distortion is a form of optical distortion focussed on discrete points along edges of IGUs as opposed to across the length of the edge as is the case in linear edge distortion. An example photograph is shown in Fig. 7. Like linear edge distortion, this effect could also potentially be caused by uneven handheld polishing along affected edges (refer to Sect. 2.2 regarding polishing).

2.6 Dishing

Dishing—also known as quench dishing—is an effect caused by overheating the glass and, when quenched,

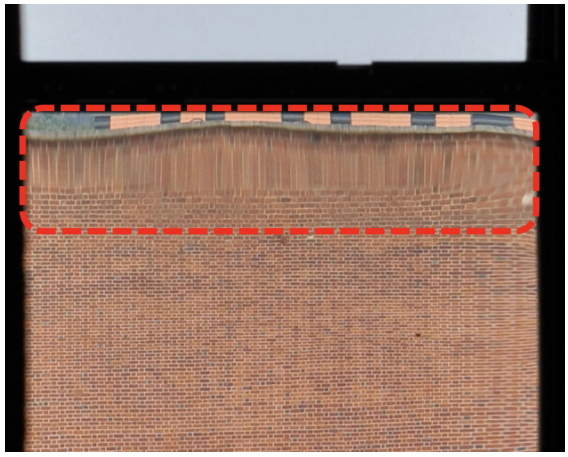


Fig. 6 Linear edge distortion is shown highlighted by a red dotted rectangle

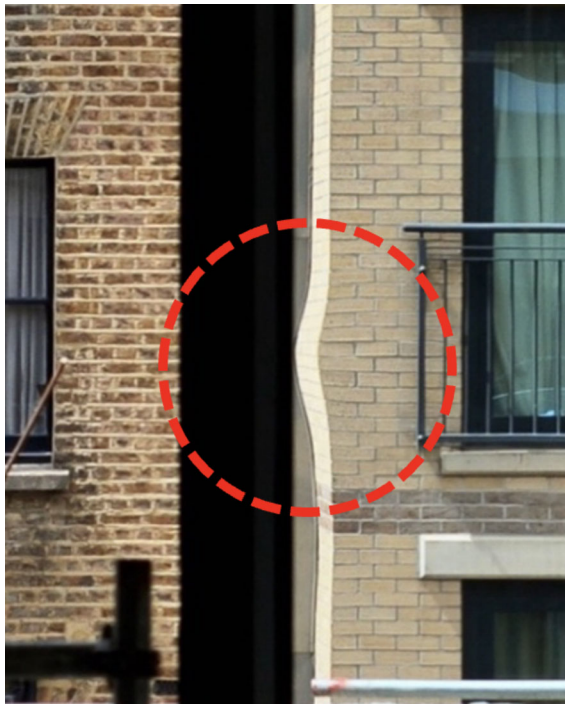


Fig. 7 Local edge distortion is shown highlighted by a red dotted ring

the contraction of the edges (which cool quicker) buckles the glass in the centre while it is still soft. The characteristic visual effect of dishing is an elliptical crease (depending to an extent on the shape of the pane). Quench dishing appear in the geometric centre of rectangular panes of thermally pre-stressed glass.



Fig. 8 Photograph showing an example of dishing (Henriksen and Leosson 2009)



Fig. 9 Example of anisotropy (cross pattern type)

An example photograph is shown in Fig. 8. Note that dishing can be difficult to photograph (Henriksen and Leosson 2009).

2.7 Anisotropy

In the architectural glass industry, "anisotropy" or "leopard spots" refer to rainbow-colored patterns or alternating dark and light patterns in heat-treated glass, examples of which are shown in shown in Figs. 9 and 10. Anisotropy was first described by Henriksen and Leosson (2009). The effect is caused by residual stress-induced birefringence, from the uneven cooling process due to the positioning of the air nozzles. The effect is visible when viewed through a polarizer but does not affect the glass's appearance under normal unpolarized light.



Fig. 10 Example of anisotropy (coloured pattern type)

Anisotropy is another type of a visual effect that could also be categorised as a visual fault rather than an optical fault (as defined in EN 572-1), since it does not cause distortion of the shape of an image, however, it is not caused by a physical topographical fault on or in the glass. Instead, it is an effect caused by small degrees of anisotropy of the refractive index of the glass. It differs in nature from the other visual faults. This anisotropy of refractive index is also referred to as bifringence (Henriksen and Leosson 2009; Dix et al. 2023).

2.8 Longitudinal fine wave

Longitudinal patterns are seen in different forms. Firstly; narrow lines (width in the order of 10–20 mm) caused by circular bands on the quench rollers. Secondly; semi-narrow lines (width of about ten millimetres) caused by air nozzles in the quench. The distance and width of these lines depend on how the quench nozzles are placed and how narrow the air jet is, this can occur if the air nozzles are placed in one straight line. This can be controlled if the air nozzles have a zigzag distribution, or if the air nozzles in the quench oscillate sideways. The lines shown in Fig. 11 most likely originate from a quench with air nozzles placed in a straight line. Thirdly; wider lines (in the order of several centimetres) with more unclear shape are presumably a result of slight temperature differentials originating from the furnace. The glass may not have been flat all the time in the furnace and those parts which have touched rollers for an increased amount of time are a few degrees hotter. The unevenness in radiative or convective heating (which are never absolutely even) also causes temperature differences.



Fig. 11 Faceted distortion, flat glass (Longitudinal fine waves)

3 Existing methods for determination of optical distortions

3.1 Measuring optical distortion in flat glass in accordance with ASTM 1652/C1652M

ASTM 1652/C1652M (ASTM International 2019) specifies methods for measuring optical distortion in flat glass products using the digital photography of grids. The procedure involves photographing a grid either in reflection or transmission, as shown by the diagrams in Figs. 12, 13 and 14. The amount and nature of the optical distortion caused by the glass is determined through computer image comparison between the photographed grid lines and the grid lines as printed.

3.2 Assessment of monolithic float glass in accordance with EN 572-2

EN 572-2 (European Committee for Standardization 2012) specifies a method for assessing the optical quality of monolithic glass in the production stage, before processing. The standard defines optical faults as “fault

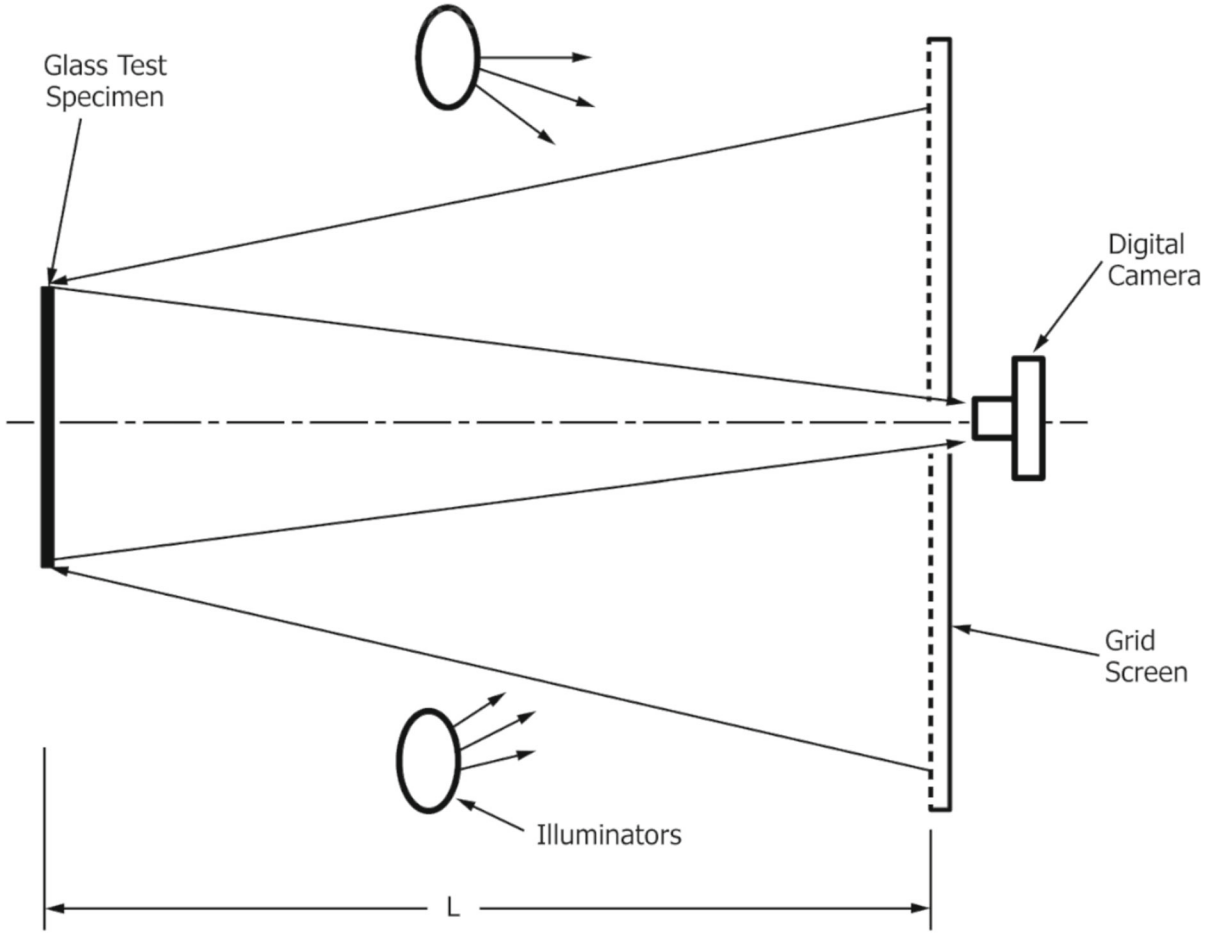


Fig. 12 Diagram extracted from ASTM 1652/C1652M

which leads to distortions in the appearance of objects observed through the glass" and states that "one quality level is considered in this European Standard. This is determined by the evaluation of optical and visual faults".

Monolithic float glass is examined by observing a screen bearing an assembly of black and white stripes (zebra) through the glass. The glass to be examined is held vertically in a support frame. The centre of the glass shall be at a distance of 4.5 m from the screen and on a line normal to the centre of the screen. The glass is rotated around a vertical axis and is held with the direction of draw of the glass vertical. Appropriate critical viewing angles, α, formed by the glass and the screen are indicated in EN 572-2 (see Fig. 15). The observer stands still at a distance of 9 m from the centre of the screen on a line passing through the axis of rotation.

The glass being examined is rotated from an angle $\alpha = 90°$ until there is no longer any distortions of the lines on the screen. The angle, α, at which this occurred is noted.

The glass sample taken, with a length, H, between 300 and 500 mm and a width, B, of 3 210 mm, is split into four. This gives samples of a width of approximately 800 mm. The distortion is measured in zone D and zone d (refer to EN 572-2).

When viewed under the conditions of observation as described in the standard, the angle, α, at which there is no disturbing distortion shall be not less than the appropriate critical viewing angle given in Table 1.

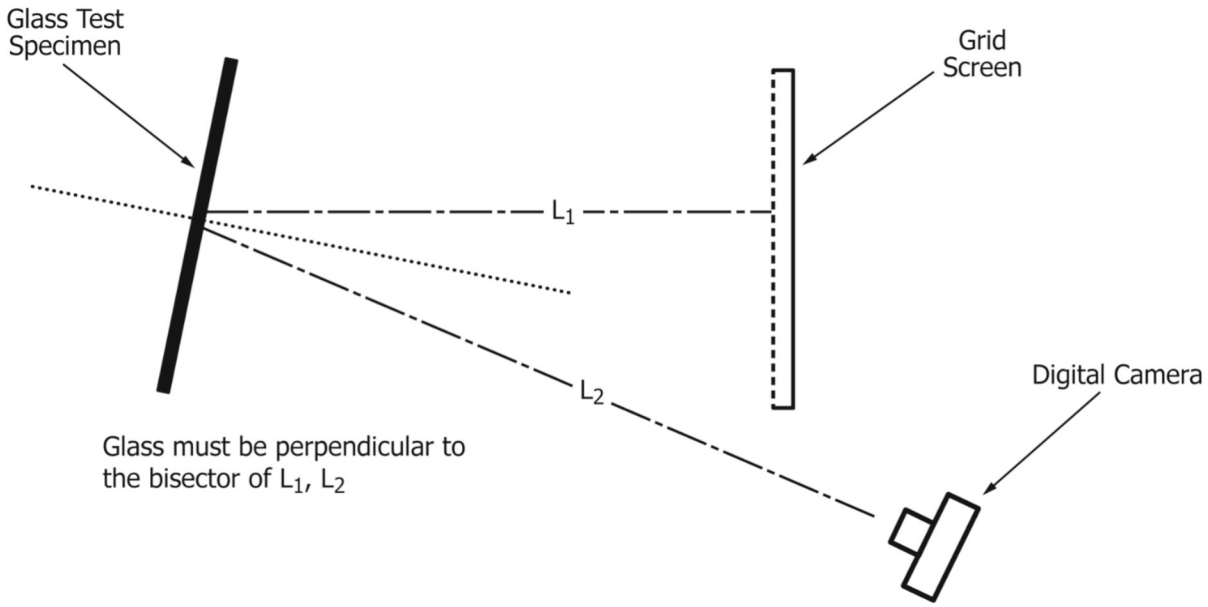


Fig. 13 Diagram extracted from ASTM 1652/C1652M

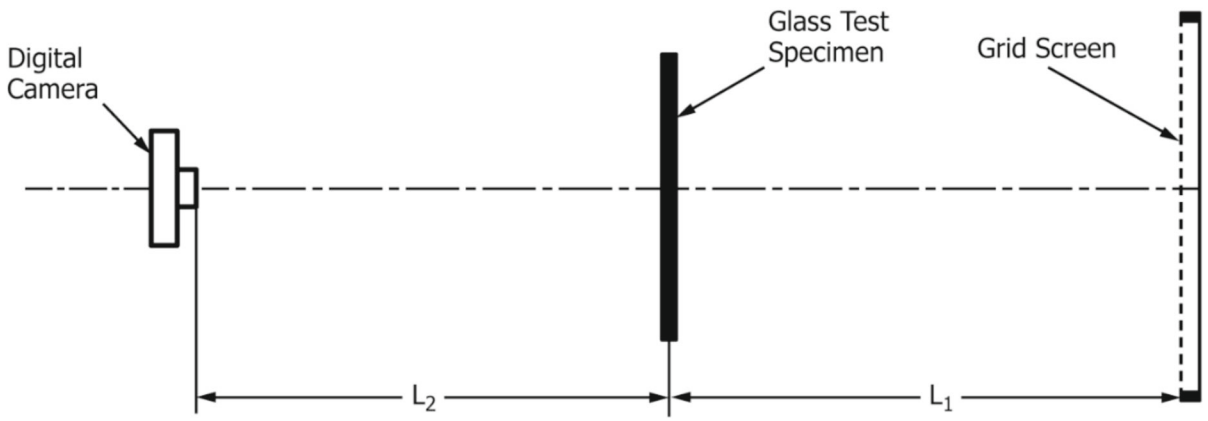


Fig. 14 Diagram extracted from ASTM 1652/C1652M

The methodology described in EN 572-2 is intended for in-factory optical assessment of monolithic float glass, but might be interesting to adopt for on-site optical assessment of (multi-layer) glass panels as well. However, the method can be impractical to carry out on site, due to space limitations on-site, challenges in rotating the investigated glass panel and the potential inability to place the screen and observer on opposite sides of the glass panel at the required distances.

3.3 Assessment of monolithic thermally pre-stressed glass in accordance with EN 1863-1 and EN 12150-1

EN 1863-1 and EN 12150-1 define methods for assessing roller wave in heat strengthened and toughened glass, respectively. The assessment methodologies defined therein involve using a roller wave gauge, or straight edge and feeler gauges, to measure the amplitude of the waves and the edge lift (also known

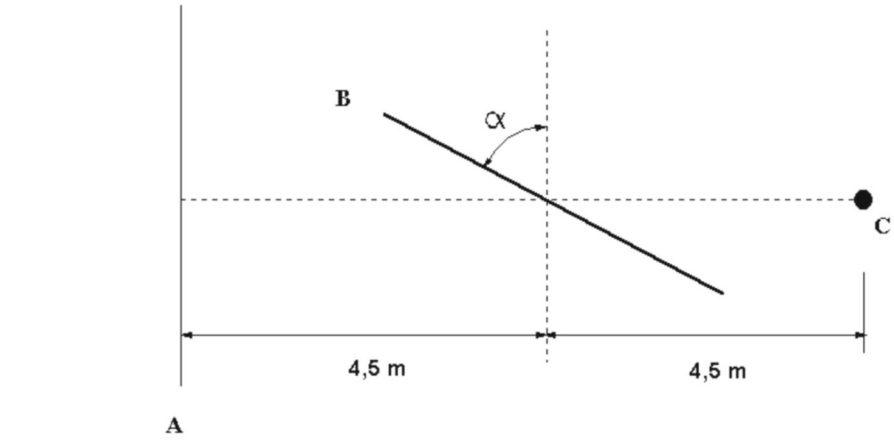
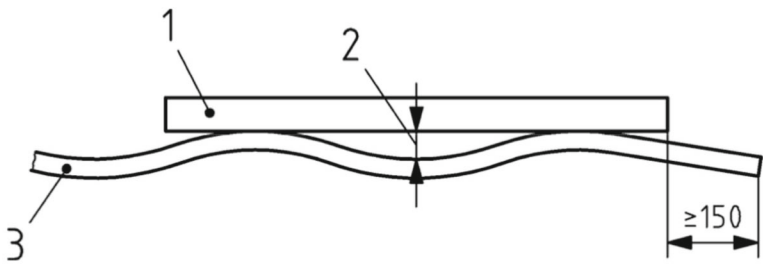


Fig. 15 Diagram showing the arrangement of apparatus for assessing optical faults in float glass (extracted from BS EN 572-2)

Key
A screen
B glass sample
C observer



Key
1 straight edge
2 roller wave distortion
3 heat strengthened glass

Fig. 16 Diagram showing measurement of roller wave, extracted from BS EN 1863-1

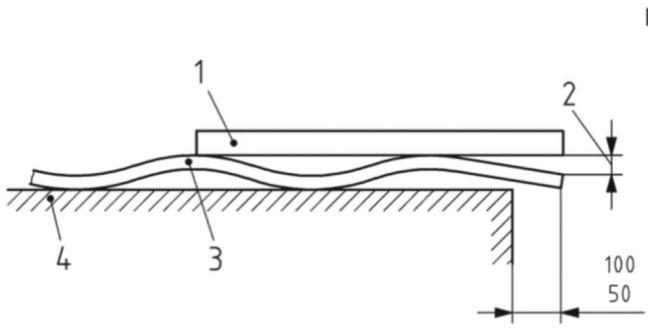
Table 1 Diagram showing the critical viewing angles for assessing optical faults in float glass (extracted from BS EN 572-2)

Nominal glass thickness mm	Angle α in zone D degrees	Angle α in zone d degrees
2	45	40
3 and greater	50	45

as edge dip). The measurements are to be taken at right angles to the roller waves. The standards define limits for both roller wave and edge dip with respect to the edge zone, as shown in Figs. 16 and 17.

3.4 Assessment of laminated glass in accordance with EN ISO 12543-6

Optical distortions due to roller wave and edge dip (and anisotropy) can be visible in laminated glass that incorporates one or more thermally treated glass products,



Key

1 straight edge
2 edge lift
3 heat strengthened glass
4 flat support

Fig. 17 Diagram showing measurement of edge lift (also called edge dip) extracted from BS EN 1863-1

originating from the thermal treatment processes. Such distortion can be amplified in laminated glass if the waves in the plies of glass are aligned out of phase, causing a lensing effect.

Another lensing effect can occur if the interlayer thickness is inconsistent, leading to distortion of the glass plies. Such variation in interlayer thickness can result from inappropriate clamping of edges or inappropriate stacking of glass during the laminating process i.e. causing squeezing of the interlayer. Ideally, they should be positioned vertically on stillages without the use of clamps or stacking of the glass with spacers between other laminated glass build-ups. The use of vacuum bags will generally improve the quality of laminated glass.

EN ISO 12543-6 (European Committee for Standardization 2021) states that the applicable standards for thermally treated products regarding optical distortions and anisotropy are equally valid for laminated glass incorporating thermally treated glasses. This suggest that the assessment criteria for heat strengthened glass in BS EN 1863 also apply to laminated heat strengthened glass. EN 1863-1 also references the assessment criteria for float glass in EN 572-2 (European Committee for Standardization 2012), so they may also apply.

3.5 Assessment of insulated glass units in accordance with EN ISO 1279-1

Optical distortion is not addressed directly in EN ISO 1279-1 (European Committee for Standardization 2018), however, section F.1 of the standard states that "the optical and visual quality requirements for glass components shall be taken from the appropriate European Standards".

The requirements in EN 12543-6, EN 1863-1 and EN ISO 572-2 limiting optical distortion in the respective components apply. Notably, EN 572-2 defines limits for optical distortion.

4 Laboratory tests on multi-layer glass panels

To investigate the possibilities for detecting optical distortions in multi-layer glass products, a series of exploratory laboratory tests are executed at Institute XX (blinded). These tests include reflective distortion tests, see Sect. 4.1, and transmissive distortion tests, see Sect. 4.2. These tests are executed on optically defective insulating glass units (IGUs) consisting of laminated glass panels both for the interior and exterior ply of the double glazed unit (DGU). Four different specimens were investigated in these tests, of which the dimensions and glass build-up are provided in Table 2.

Table 2 Overview of specimens used for the reflective and/or transmissive distortion tests

Panel name	Length [m]	Width [m]	Internal pane	External pane
IGU-1	1.787	0.476	44.2 HS	44.2 HS
IGU-2	0.476	0.352	44.2 HS	44.2 HS
IGU-3	2.170	0.352	44.2 HS	44.2 HS
IGU-4	2.170	0.870	44.2 HS	44.2 HS

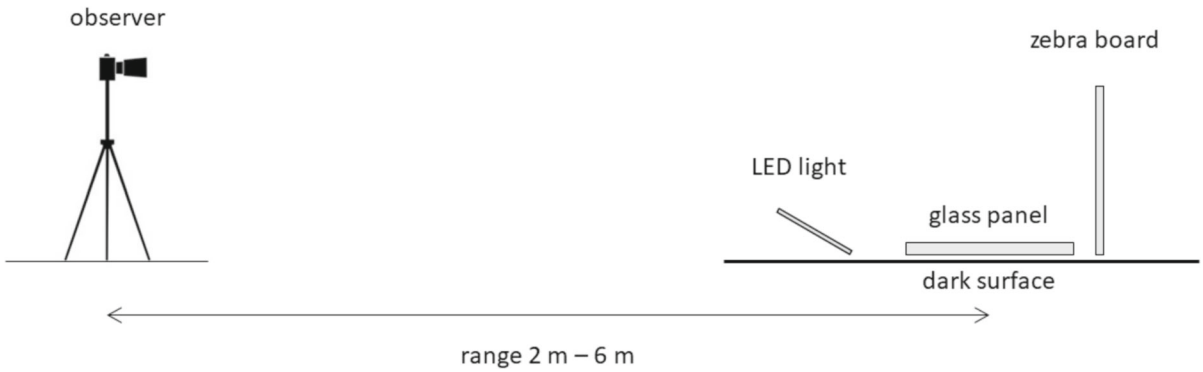


Fig. 18 Schematic representation of the setup for the reflective distortion tests (side view)



Fig. 19 Photographs of the setup for the reflective distortion tests

4.1 Reflective distortion tests

4.1.1 Method

For the reflective distortion tests, the glass panels are placed flat on a dark surface, see Figs. 18 and 19. Perpendicularly to the glass panel a zebra board is placed containing parallel black stripes in an 45° angle, 6mm wide and 6mm apart, compliant with ASTM 1652/C1652M (ASTM International 2019). The zebra board is illuminated by two LED panels (each with length 1.2 m, width 0.3 m) that are positioned across the zebra board in an inclination. Photographs of the reflective glass surface are taken either in close-up or at a distance ranging from 2 to 6 m from the centre of the glass panel, see Figs. 18 and 19.

4.1.2 Results

The tests revealed two types of optical patterns, namely (i) swirling patterns and (ii) wavy patterns.

Examples of the detected swirling patterns in IGU-1 are shown in Figs. 20 and 21. These swirling patterns are likely to arise from local polishing of the glass surface, causing a local dent in the glass. Similar on-site observations of such distortions from polishing are also discussed and shown in Sect. 2.2.

Examples of the detected wavy patterns in panels 2 and 3 are shown in Figs. 22, 23 and 24. The wavy

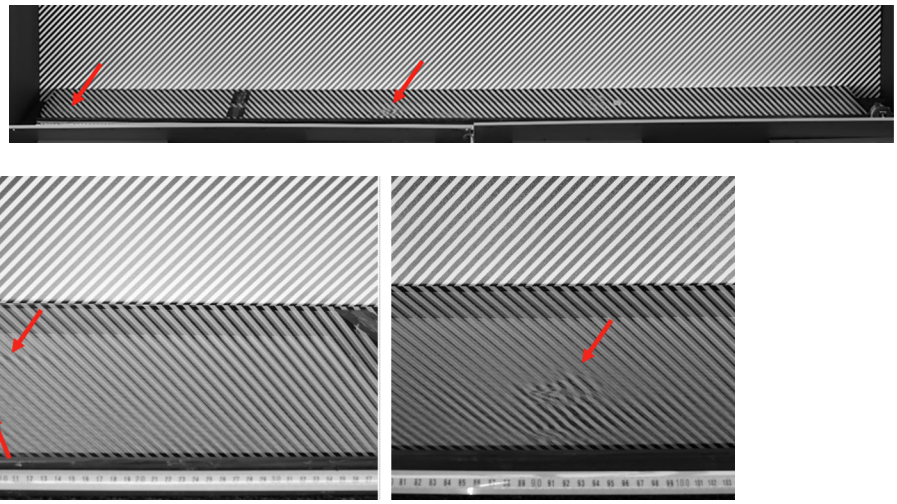


Fig. 20 Swirling patterns observed for IGU-1, by means of the reflective distortion tests

Fig. 21 Swirling patterns observed for IGU-1, surface #4, by means of the reflective distortion tests, indicating assumed local polishing of the glass surface

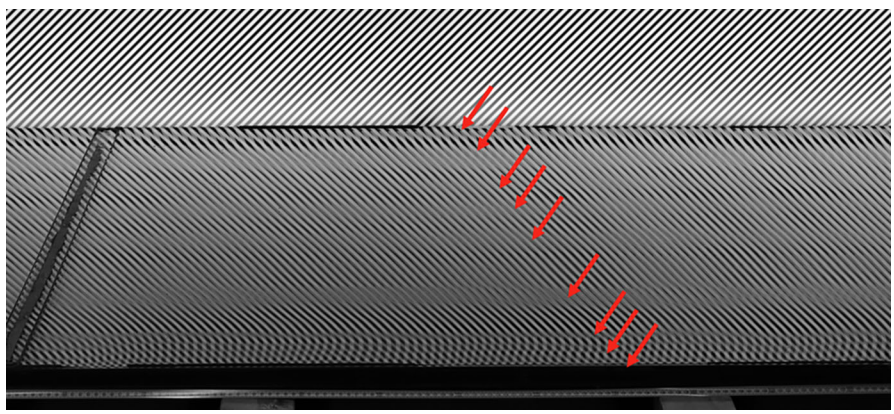


Fig. 22 Parallel wavy patterns observed in IGU-2, surface #1

patterns appear mostly parallel to each other along the long edge of the panels, see Figs. 22 and 24, and curved when reaching the short edge of the panel, see Fig. 23.

In addition, wavy patterns in a concentric semi-circular array were observed along the IGU edges, see Fig. 25. These localised patterns resemble the localised edge distortions discussed in Sect. 2.5, and may relate to local clamping of the glass during the lamination process of the laminated glass pane.

4.2 Transmissive distortion tests

4.2.1 Method

For the transmissive distortion tests, the glass panels are placed in vertical/upright position in front of a zebra board, see Fig. 26. The zebra board contains parallel black stripes in an 45° angle, 25mm wide and 25mm apart, compliant with EN 572 (European Committee for Standardization 2012). The centre of the glass panel is positioned 4.5 m in front of the zebra board. A photo camera (observer) is positioned at a distance of 9 m from the centre of the zebra board on a line passing through the centre of the glass panel, compliant to the distances specified in EN 572 (European Committee for Standardization 2012), see Fig. 26. The IGU is firstly placed perpendicular to the viewing direction ($\alpha = 0°$) and afterwards rotated by 15°, 30°, 45°, 50°, 60° and 75°, taking a photo at each of these angles. According to EN 572 (European Committee for Standardization 2012), no distortion should be present at angles lower than 50° for the middle measurement zone and

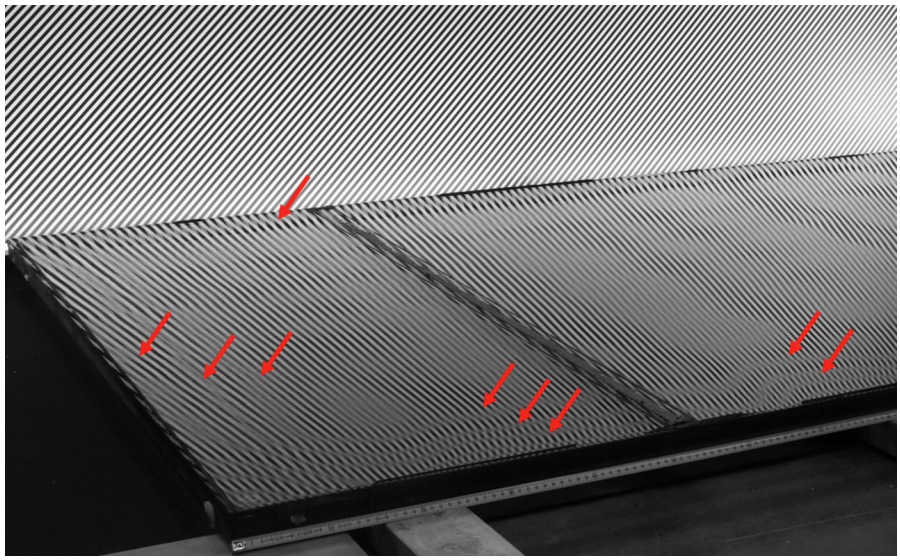


Fig. 23 Parallel wavy patterns observed in IGU-2, surface #1

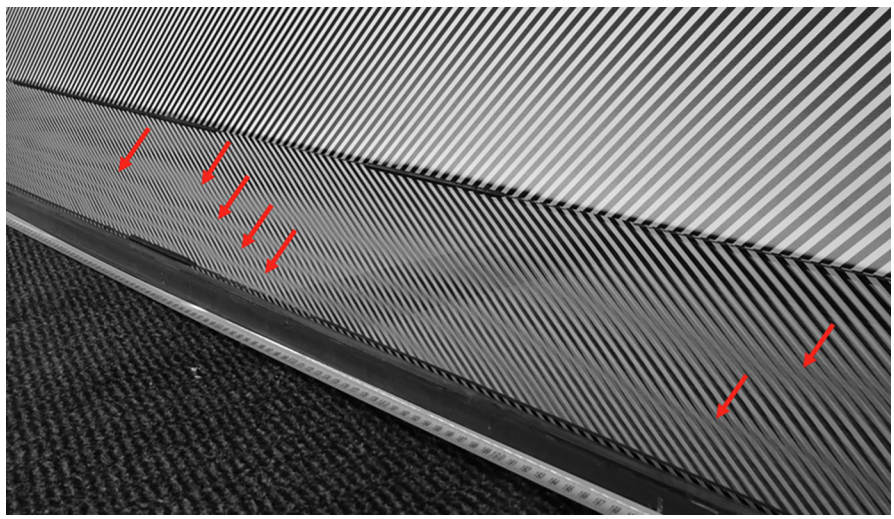


Fig. 24 Parallel wavy patterns observed in IGU-3, surface #1

lower than 45° for the side viewing zone (100 mm edge width), see Sect. 3.2.

The zebra board is illuminated from the front instead of back illuminated, as adopted from ASTM C1652/C1652M-21, by three rectangular (0.3m × 1.2m) and two square (0.3m × 0.3m) LED panels. The light intensity within one meter from the zebra board was measured with a digital lux meter and amounted to 430 lx, in compliance with the 400–1200 lx range specified in EN 572-2 (European Committee for Standardization 2012).

The transmissive distortion tests are performed both on the complete IGU build-up and on the individual laminated panels. For the latter, the IGU is separated by cutting through the primary and secondary seal of the IGU with a Stanley knife.

In addition to the IGU panels, a small monolithic annealed glass ply was tested as a reference.

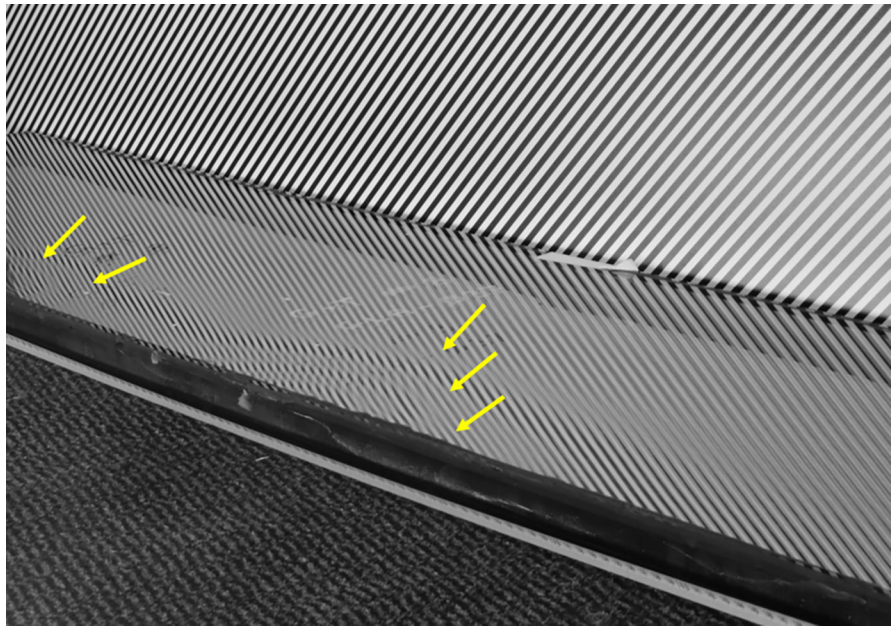


Fig. 25 Semi-circular array of wavy patterns observed for IGU-4, surface #4

4.2.2 Results

Figure. 27 shows the photographs taken of the monolithic annealed glass reference pane. No optical distortions were observed at any of the investigated rotation angles.

Figure 28 shows the photographs taken of IGU-3. From the photographs it is seen that optical distortions are subtle at a 0° rotation angle and intensify for larger rotation angles. Since the optical distortions are already clearly visible below an angle of 45°, the panel would not pass the requirements specified in EN 572 (for monolithic glass), see Sect. 3.2. At larger angles of 60° and 75° the observed distortion is excessive.

Figures 29 and 30 show the photographs taken of the inner and outer laminated glass pane, respectively, after separation of IGU-3. From the photographs it is seen that optical distortions are present in both laminated glass panes. The combination of these two laminated glass panes in one IGU may have led to an amplification of the observed optical distortions.

4.3 Discussion of test results

It should be noted that the tests described in the preceding sections are of an exploratory nature. They are intended to reveal possible optical distortions in the investigated IGUs, rather than determining the precise cause of the observed optical distortions. The cause can be determined from additional investigations, such as roller wave measurements, thickness measurements or glass surface stress measurements, etc. A complicating factor here is that such measurements might be best done on the individual monolithic glass sheets, but separation of those glass sheets from a laminate is impractical to achieve.

5 Discussion

The authors have noted a discernible trend of the increasing prevalence of optical distortion within the industry. Optical faults are addressed in different ways in the standards referenced, however, the standards fail to fully address all of the effects described, especially when they occur in IGU's with complex build ups comprising heat-treated and laminated glass. Additionally, the authors have encountered several uncertainties from façade contractors and glazing manufacturers regarding these effects in IGU's, which also relates to the standards (as referenced in project specifications) not fully addressing them. Collectively, these factors underscore a requirement in the industry to better address the characterisation, measurement, and control of optical distortion in IGU's.

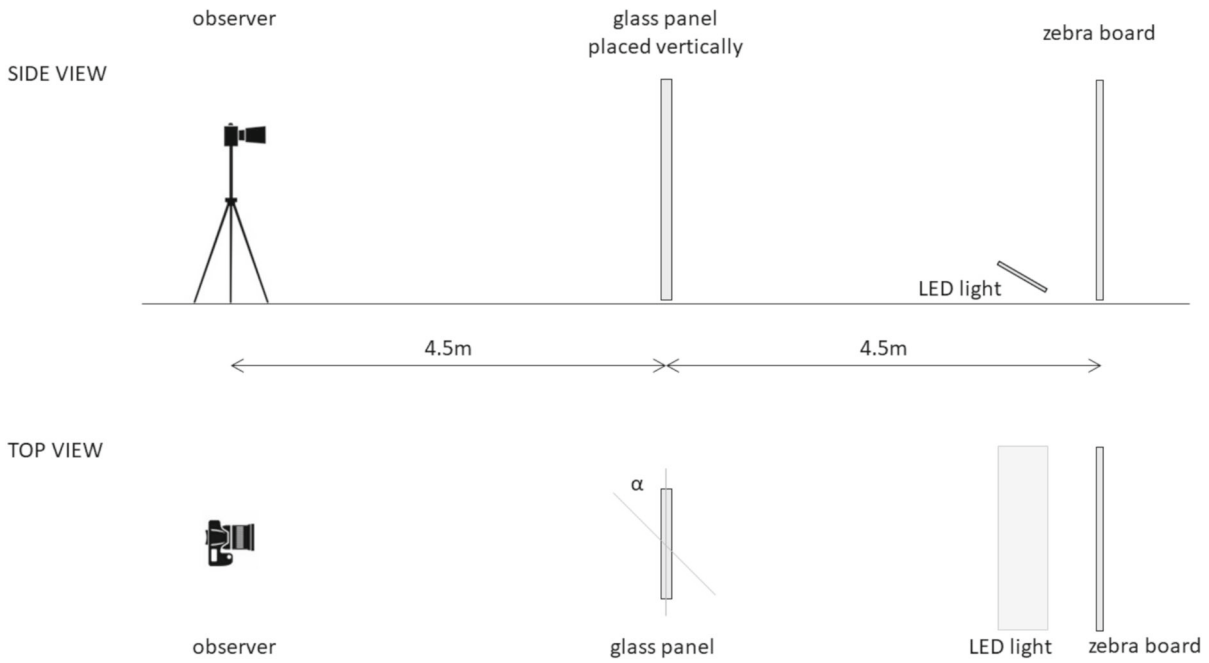


Fig. 26 Schematic representation of the setup for the transmissive distortion tests

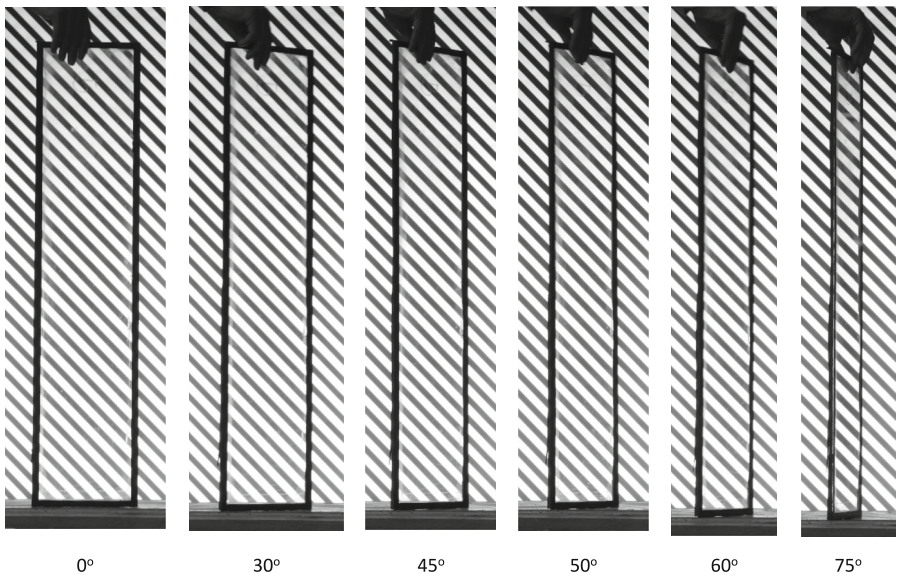


Fig. 27 The monolithic annealed glass reference pane shows no optical distortions

When referring to "optical distortion" within the context of architectural glazing, we fundamentally mean visual distortions of images in transmission or reflection. Geometrical distortions can, in principle, be measured in a number of ways, such as aberrometry, interferometry and image comparison (Neugebauer and Stavrić 2014; Youngquist et al. 2015). Optical distortion in architectural glazing could also, therefore, be measured directly and controlled accordingly, rather than only by controlling the physical effects in the glazing that give rise to optical distortion. Using such an approach would, in principle, enable specifiers to

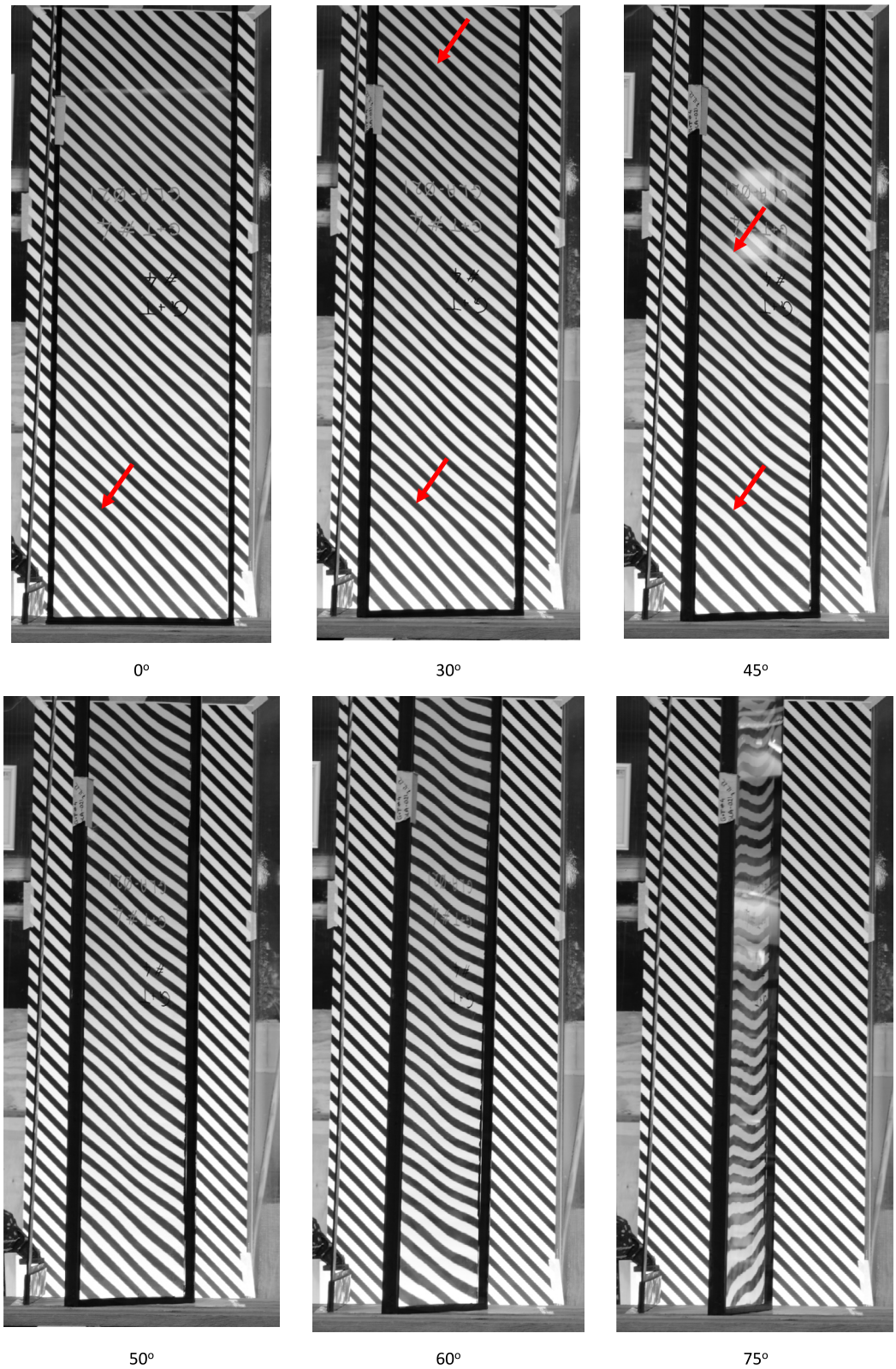


Fig. 28 Transmissive distortion test results of IGU-1, indicating optical distortions already at 0° rotation angle and intensification of optical distortions at larger angles

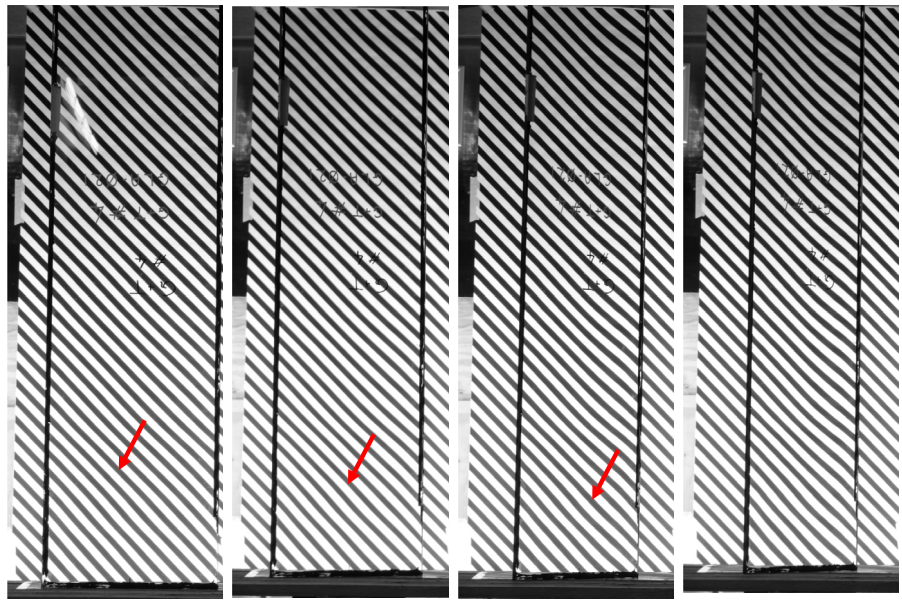


Fig. 29 Transmissive distortion test results of the inner laminated glass pane of IGU-1, after separation of the IGU

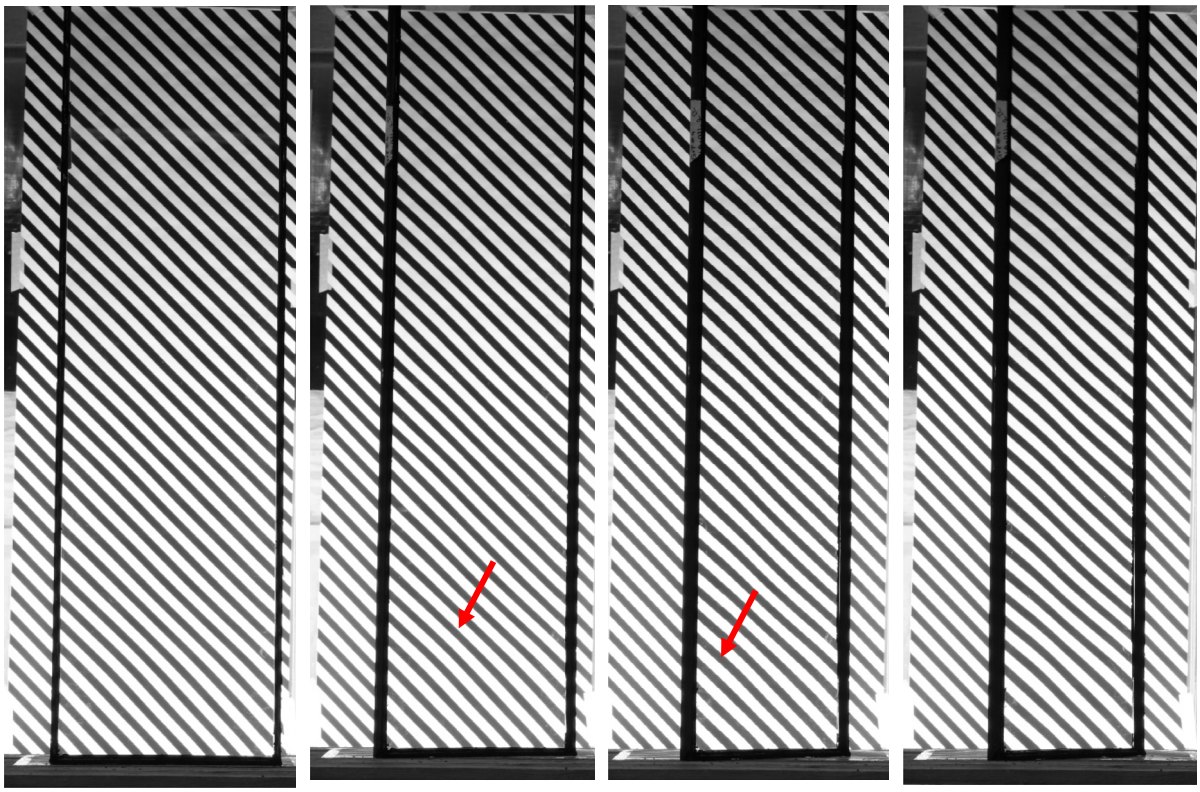


Fig. 30 Transmissive distortion test results of the outer laminated glass pane of IGU-1, after separation of the IGU

establish criteria for the optical quality of glazing that would be independent from the build of the glazing, the nature of the individual plies and the various techniques involved in the manufacture of IGU's.

A methodology like this could form a basis for specifying objective limits for acceptable optical distortion, based on empirical measurement (e.g. in terms of millidiopters). This would be analogous to how methods were developed for characterising and controlled anisotropy in architectural glazing when previously the subjective limits based on visual inspection were relied upon.

Building upon the principles of optical distortion measurement methods discussed above, a promising area for future scientific work lies in the development of techniques and apparatus that can measure optical distortion during the production of architectural glazing and for use on site where the glazing is installed. In conjunction, other work could be done to determine effects that are visually disturbing to the naked eye and establish acceptable criteria for the building user which involves aspects of behavioral science, physiology and human-facade interaction (Luna Navarro 2020). Such work could consider parameters like viewing distance and angle.

It is also clear that there are numerous different effects that can give rise to optical distortion, as outlined in Sects. 2 and 3 e.g. polishing, roller wave, edge clamping and combinations thereof. There is, therefore, also further work to be done to characterize optical distortion associated with different physical effects that can arise in architectural glazing through laboratory assessment of different glass build ups. The findings of which could then, in turn, be studied to find potential correlations with optical distortion measurements and perhaps methods that could identify the causes as well as measure magnitudes of optical distortion in architectural glass.

6 Conclusions and outlook

Optical distortion in architectural glass is becoming an important topic, and in recent years there has been an increased focus on the main causes behind the phenomena and how to measure it and potentially standardise the effects. This paper has identified and categorised 8no. main types of distortion and provided a review of existing literature and current standards and methods to determine optical distortion in architectural glass.

From the review it has become apparent that systematically determining optical distortion in architectural glass beyond monolithic glass does not exist. Therefore, one of the main conclusions of this paper is that it is necessary to further investigate the phenomena and better understand the causes behind them. This would need to start with annealed monolithic glass, then IGUs made of monolithic annealed glass, then progressing into annealed laminated glass, IGUs with annealed laminated glass, progressing to IGUs with tempered glass. The same methodology could also be applied to curved glass.

Based on the findings in this paper it can be concluded that the best method is to determine optical distortion is to measure the changes in millidiopters, based on the current methods utilized for monolithic glass when measured in transmission. However, this method would need to be expanded to laminated glass, IGUs and potentially to curved glass. Initially in transmission however it would be necessary to develop a method where this can also be utilised in reflection, potentially similar to the method described in the ASTM C1652M shown in Fig. 13: Diagram extracted from ASTM 1652/C1652M. Figures 12 and 13.

These methods will have to be developed through further research to better understand the causes behind the different optical phenomena and to objectively assess their effects on the aesthetic quality of architectural glass. Such work would include both the development of an optical assessment system and the characterisation of physical effects in an appropriate range of different glass build ups.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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