Feature

Glass Distortion: Not Such a Clear View

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GLASS DISTORTION

When utilizing heat-treated architectural glass, reflected images on the glass surface will have some degree of distortion. High-quality glass fabricators strive to produce "flat" glass, but achieving perfection is not possible. Glass distortion is inherent to the fabrication process and is discussed in ASTM C1048, *Standard Specification for Heat-Strengthened and Fully Tempered Flat Glass*.[1]

There are circumstances in which glass distortion is not a high priority, allowing the contractor to competitively price shop between different glass fabricators. On the other end of the spectrum, there are projects that necessitate minimal glass distortion; this limits the selection pool of qualified glass fabricators who are capable of consistently producing a high-quality product. A certain level of glass distortion is generally tolerable on a project. However, unless the project specifications require specific and quantifiable criteria, the acceptability of the glass distortion remains in the eye of the beholder.

Figure 1. *Zebra board visual evaluation of glass distortion on heat-treated glass.*

A rudimentary check could include gauging the reaction of a casual observer. If the glass distortion is noticeable, but only after bringing it to their attention and soliciting specific feedback, then presumably there is not a quality concern. Conversely, if their first impression of the building is overwhelmed by an egregious distortion of reflected images, there is likely a glass quality issue. Obviously, this would be considered an informal, subjective, and reactionary approach to quality assurance, which could be a very costly proposition for the project team.

TRADITIONAL GLASS DISTORTION EVALUATION METHODS

The glazing specification section of a project manual will usually include glass quality requirements. In addition to ASTM C1048,[1] other glass quality standards generally include ASTM C1036, *Standard Specification for Flat Glass*,[2] and ASTM C1376, *Standard Specification for Pyrolytic and Vacuum Deposition Coatings on Flat Glass*.[3]

It is common for architects to specify the roll wave pattern of heat-treated glass to be parallel to the ground. Beyond that, the specifications will usually vary from project to project for glass distortion requirements.

Prior to the advent of modern electronic glass scanning technology, glass fabricators relied on a "zebra board" for a subjective visual evaluation of the glass distortion (**Fig. 1**). Zebra boards are composed of straight lines (alternating black and white) and are positioned at the back end of the oven's cooling section. This quality-control tool allows the operators to evaluate the glass right after it has been heat treated, and before it is unloaded for the next step

Figure 2. *Example of roll wave pattern in heat-treated architectural glass.*

of the fabrication process. It should be noted there are limitations associated with this visual inspection technique, as it is not a reliable means for identifying all potential distortion anomalies associated with the heat-treating process.

A common type of distortion inherent to glass that is heat-treated in the horizontal position is a roll wave pattern (**Fig. 2**). This is the result of the glass being transported through the oven on rollers, becoming "soft" as it heats up, and then sagging between support points. When the glass is cooled, the deformation becomes permanent. Roll wave distortion can be quantified by measuring the depth of the valleys relative to the peaks (**Fig. 3**), using a flat-bottom gauge (**Fig. 4**). There are no industry quality standards for roll wave pattern, though a common criterion for architectural glazing applications is a maximum of 0.003 in. (0.08 mm) in the center of glass and a maximum of 0.008 in. (0.20 mm) at the leading or trailing edge of glass. While this can be a useful guideline to identify an excessive roll wave pattern, there are other types of distortion this evaluation method cannot detect. In addition, there are physical limitations associated with this tool as it cannot measure lift or kink at the leading and trailing edge of the glass. Further, the use of

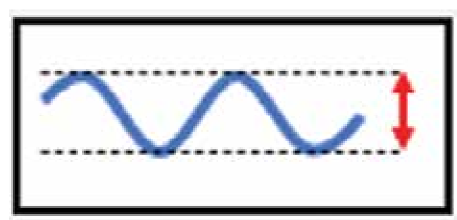

Figure 3. *Representation of peak-to-valley roll wave distortion.*

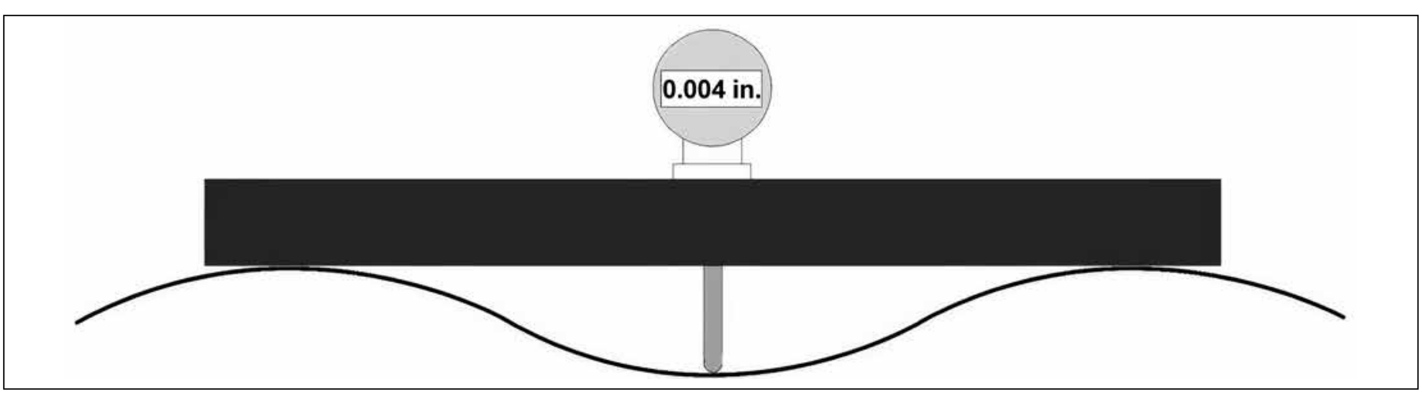

Figure 4. *Example of flat-bottom gauge measurement. Note: 1 in. = 25.4 mm.*

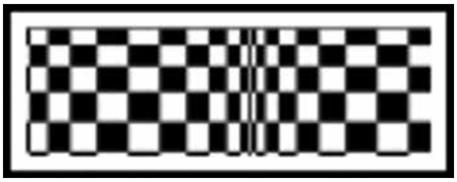

Figure 5. *Representative reflected image of a checkerboard on distorted heat-treated glass.*

a flat-bottom gauge is an operator-performed quality check, usually at a predetermined frequency of time or production throughput, and thus it would be impractical to expect a measurement on every lite of glass.

OPTICAL DISTORTION

Project stakeholders will undoubtedly expect a higher level of quality in high-visibility commercial building applications compared with glass used in shower doors, handrails, and storefront applications. For those instances in which glass "flatness" is a critical design consideration, another way to communicate glass curvature is in terms of optical power (aka optical distortion). This provides an objective and quantitative means for evaluation, which also is a direct correlation to how the human eye perceives glass distortion (**Fig. 5**).

Glass curvature can be shaped either convex or concave, both of which will distort how an image is perceived. For the purposes of this article, only the effect of visible light being reflected on a glass surface (i.e., mirror-like) will be discussed (**Fig. 6**). Optical distortion describes the severity (or magnitude) of the glass curvature; the following summarizes how it is described and quantified.

- Optical distortion is measured in units of diopters.
- A higher diopter measurement indicates more severe glass curvature, which ultimately results in more optical distortion.
- Optical distortion is inversely proportional to the focal length[6] (equation 1), which is where all the light rays are focused.
- A positive diopter measurement indicates a concave glass shape, which magnifies an image (when the viewer is inside the focal length). Conversely, a negative diopter measurement indicates a convex glass shape, which demagnifies an image.

Equation 1: $Ø = 1/f$
where
$Ø$ = optical distortion in diopters
f = focal length in meters

An alternative means for correlating optical distortion to focal length is to quantify the glass curvature (**Fig. 7**). The following summarizes how glass curvature correlates to optical distortion.

- A complete circle can be extrapolated out when reviewing the curved portion of a glass sample.
- The radius of glass curvature is two times the focal length (equation 2), and thus the relationship between optical distortion and the radius of glass curvature can be simplified by equation 3.
- As the radius of glass curvature decreases, the optical distortion increases (see **Table 1** for a select few data points).

Equation 2: $R = 2 \times f$
where
R = radius of glass curvature in meters
f = focal length in meters

Equation 3: $Ø = 2/R$
where
$Ø$ = optical distortion in diopters
R = radius of glass curvature in meters

Table 1. Comparison between radius of glass curvature and optical distortion

Radius of curvature (meters)	Optical distortion, (mD)
∞ (flat glass)	0
100	20
40	50
20	100
10	200
6.67	300
5	400
4	500

Note: 1 ft = 0.3048 m.

Note, optical distortion is typically expressed in units of millidiopters (1,000 millidiopters = 1 diopter), which is abbreviated as mD.

ASTM C1651-11, *Standard Test Method for Measurement of Roll Wave Optical Distortion in Heat-Treated Flat Glass*,[4] and ASTM C1652, *Standard Test Method for Measuring Optical Distortion in Flat Glass Products Using Digital Photography of Grids*,[5] are industry standards that include equations for calculating optical distortion based on measuring peak-to-valley roll wave distortion. It should be noted this standard assumes a theoretical perfect sine wave for the equations (**Fig. 8**). However, **Fig. 9** shows the same wavelength and peak-to-valley roll wave distortion measurement even though there is a drastically different amount of glass curvature. Thus, it is possible this standard may not provide an accurate value to convey how the human eye perceives the severity of the optical distortion.

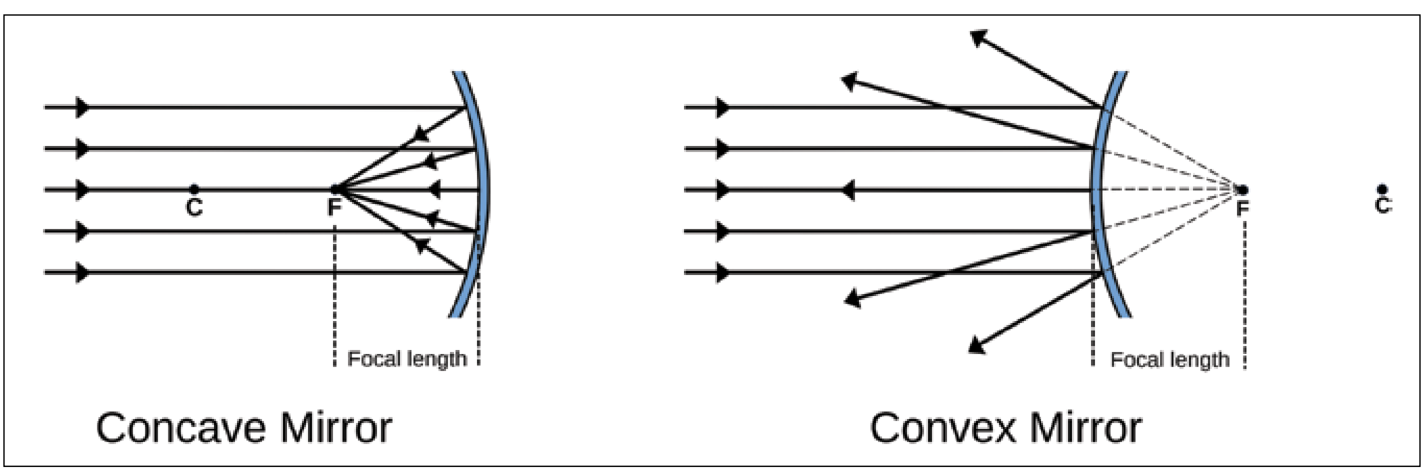

Figure 6. *Illustrative examples of focal length with respect to concave and convex glass curvature, when viewed in reflection.*

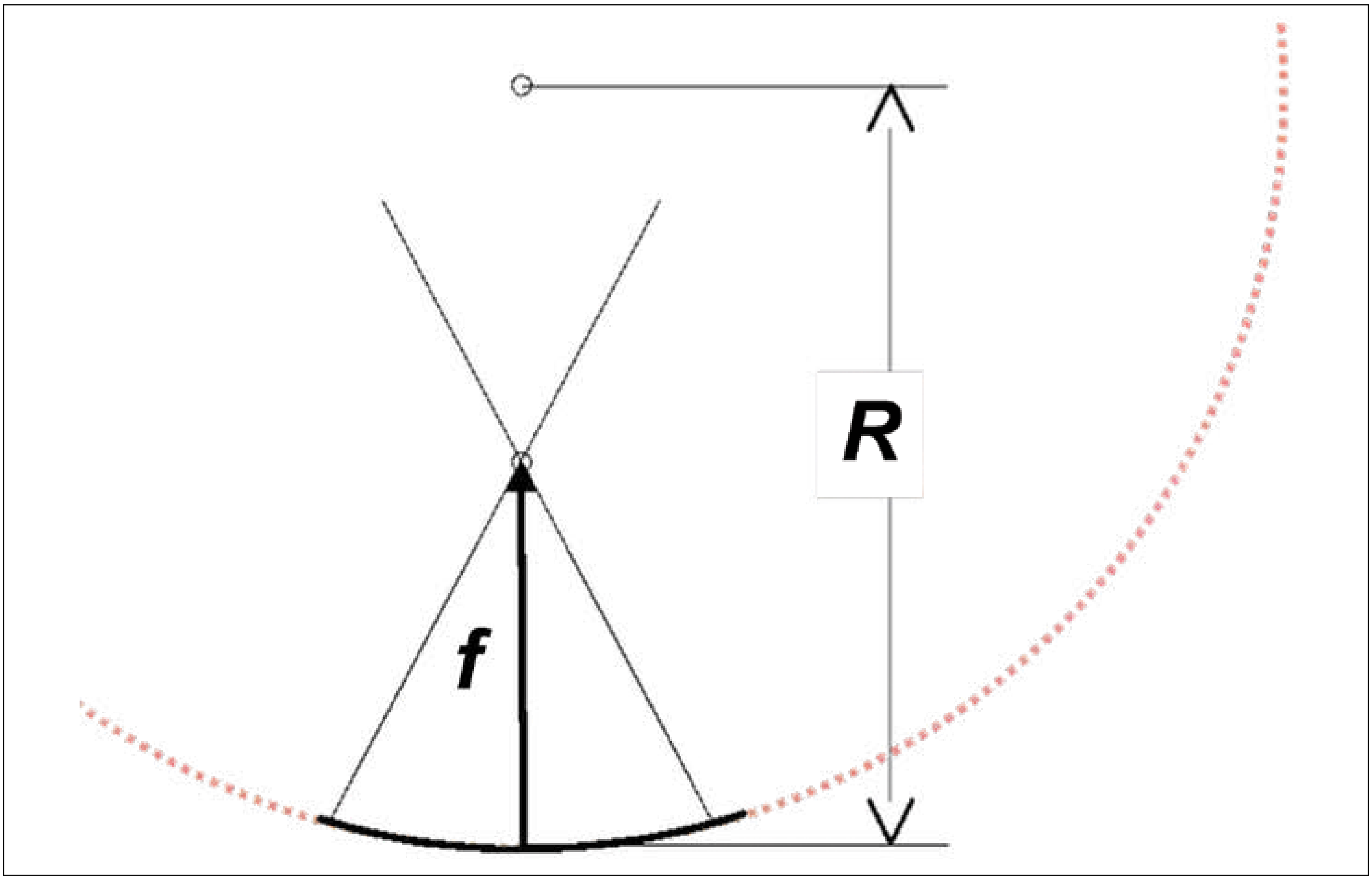

Figure 7. *Representative relationship between radius of concave glass curvature,* R, *and focal length,* f.

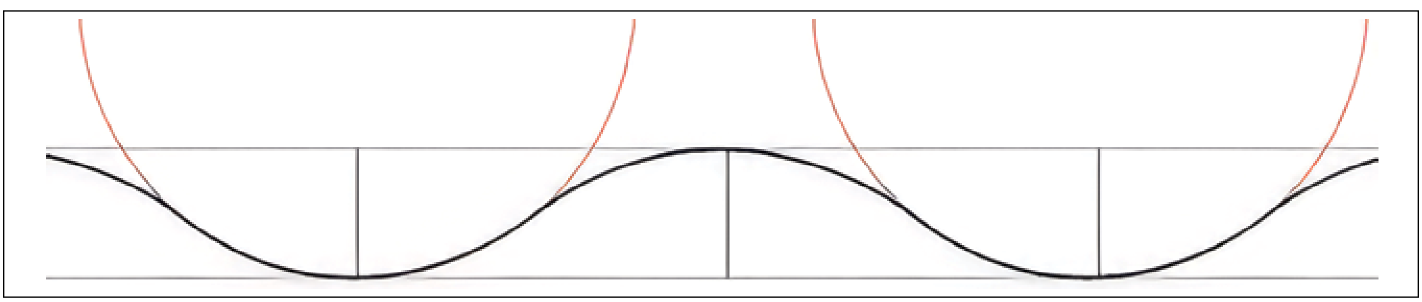

Figure 8. *Roll wave pattern where both valleys have the same radius of glass curvature.*

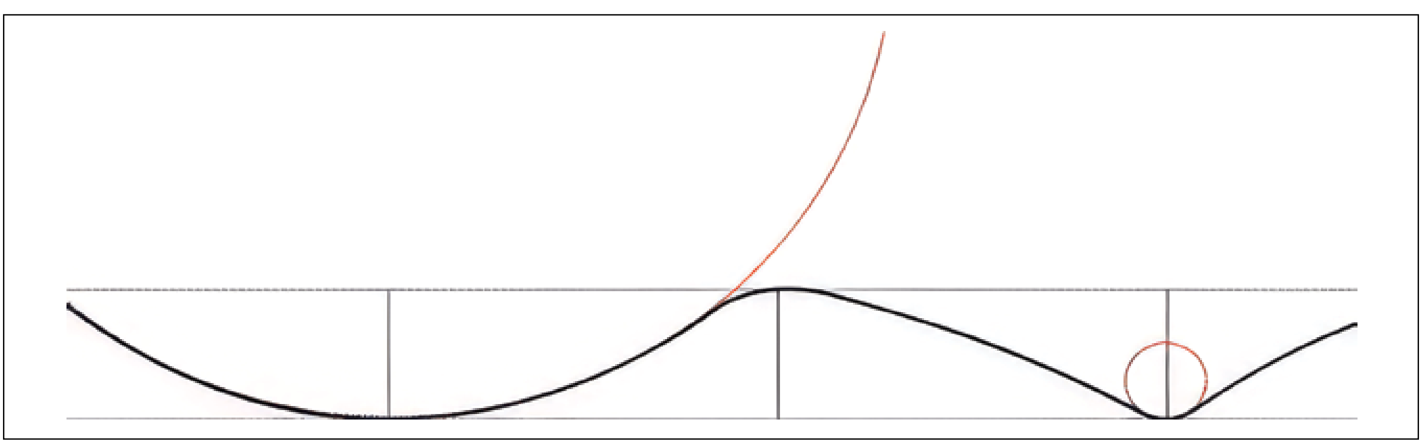

Figure 9. *Roll wave pattern with one valley (left) having a large radius of glass curvature (low optical distortion) and the other valley (right) having a small radius of glass curvature (high optical distortion).*

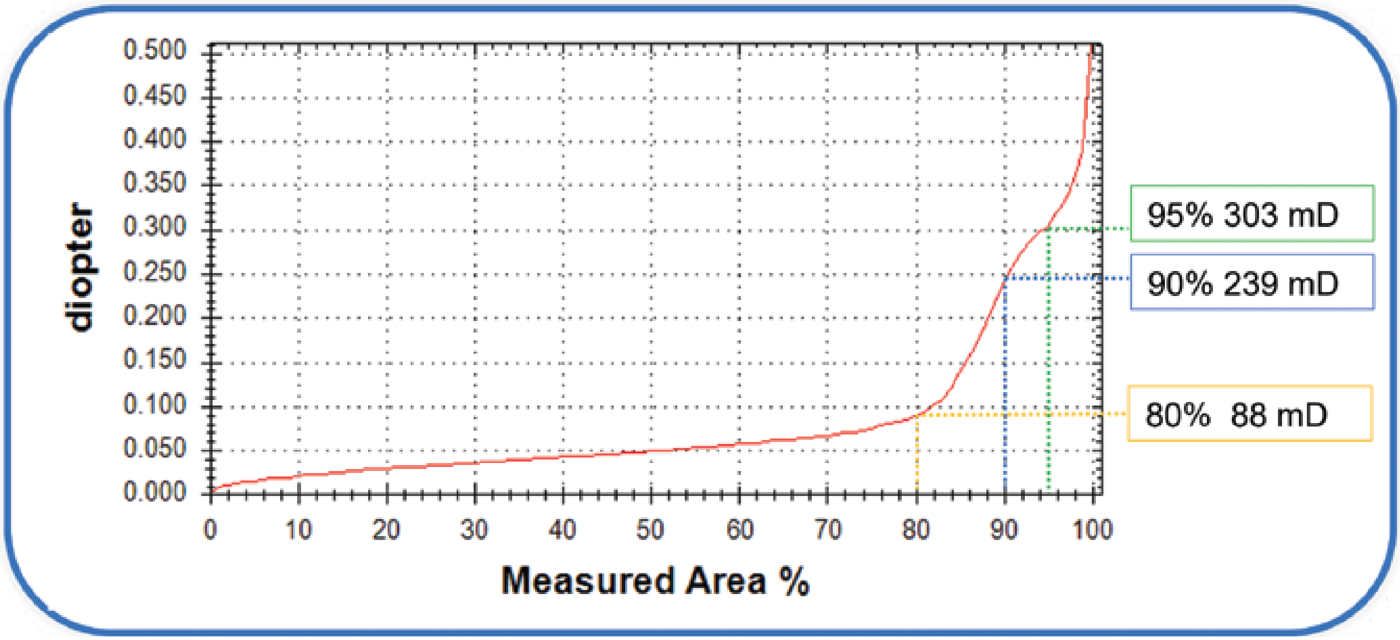

Figure 10. *Optical distortion measurements over an entire piece of glass. Based on experience, the authors feel the above data is indicative of glass distortion that would likely be perceived as objectionable in a high-profile application.*

ENHANCED EVALUATION FOR HIGH-QUALITY ARCHITECTURAL GLASS

Today's technology allows for the distortion of every lite of glass to be electronically scanned and measured during the fabrication process (some limitations apply based on substrate/coating type). This provides a quantifiable and objective means for evaluation, which includes the entire glass surface. The distortion measurements can then be tallied and sequentially ordered from least to greatest, expressed in terms of percentile. Architects specifying high-quality architectural glass typically request that the output be summarized and communicated in either one (or both) of the following:

- In terms of optical distortion in units of millidiopters at a specific percentile measurement of the glass area. For example, 303 mD is the 95th percentile measurement of the entire glass surface **(Fig 10)**.
- In terms of glass surface area (%) in which the optical distortion is less than a specific measurement. For example, the optical distortion for 90% of the entire glass surface is less than 239 mD **(Fig 10)**.

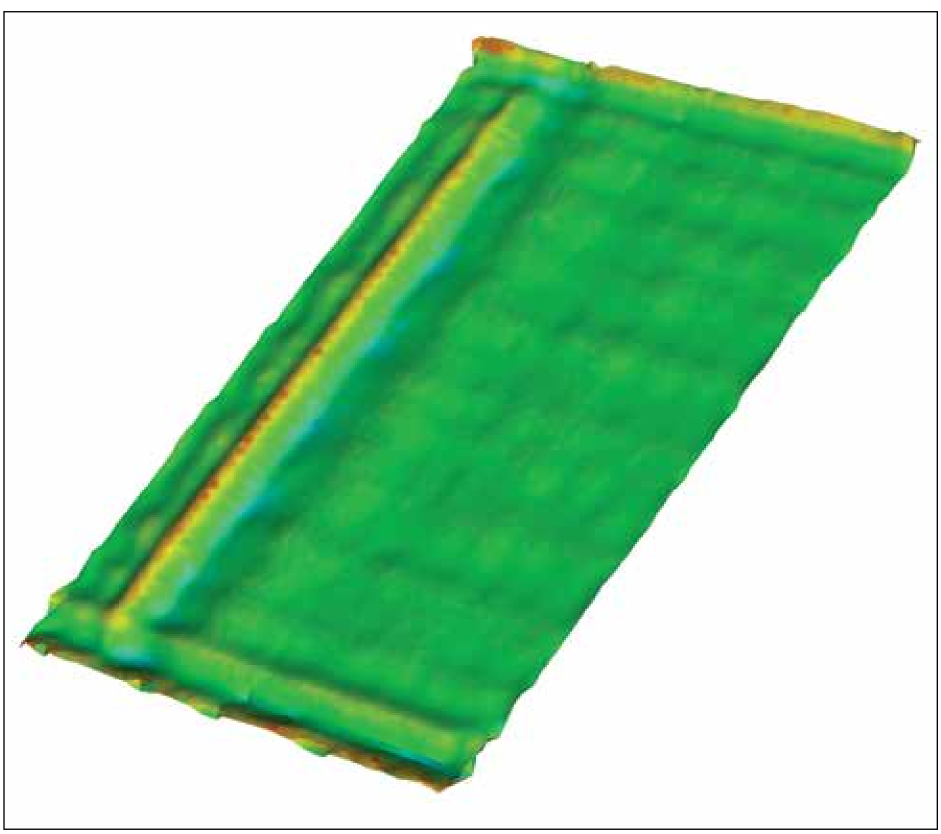

Figure 11. *Three-dimensional electronic glass scan showing a vertical distortion streak.*

Although no national standards exist regarding allowable optical distortion, float glass suppliers have attempted to differentiate the fabricators that can produce high-quality heat-treated glass for commercial glazing applications. As a point of reference, the authors of this article are aware of a float glass supplier that requires their certified fabricators to produce glass with a maximum optical distortion of +/–100 mD for over 95% of the glass surface.[7]

However, looking solely at this output can be misleading because it may not reveal all glass-distortion-related issues. For example, **Fig. 11** shows a heat-treated glass sample with a vertical distortion streak. Because this piece of glass has a relatively large area compared with the localized distortion issue, the vertical streak is not overly apparent when looking at the overall glass distortion data. There are multiple manufacturers of electronic glass-scanning equipment, some of which have developed their own proprietary algorithms to identify and quantity different types of localized distortion.

CONCLUSION

There are various levels of quality for architectural glass, and at this point in time there is no comprehensive industry standard that addresses all the different types of glass distortion. For monumental projects having stringent expectations related to glass flatness, the authors recommend performing the following due diligence.

- Review the project's glass quality requirements. If there are no specific distortion guidelines, mutually agreed-upon criteria should be established prior to awarding a contract.
- Solicit a high-level summary of the glass fabricator's quality management system.
- Request a full-size mock-up for visual evaluation and approval by the project stakeholders.
- Require quality assurance/quality control submittal logs showing electronic distortion measurements during production of the project glass.

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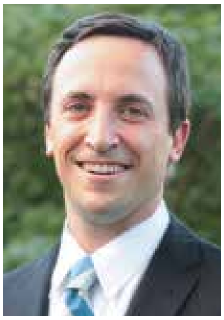

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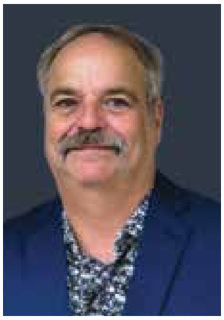

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Special interest

Feeling Disconnected?

Let *Fika* Drive Your *Trivsel*

EMPLOYERS STRUGGLING TO help their workers feel connected since the pandemic might want to look to the Swedes for inspiration.

The Swedish ritual of *fika*—a daily, office-wide coffee break—can foster socialization and collaboration among colleagues, wrote Anne Marie Chaker in a *Wall Street Journal* article.

Chaker cited Gallup data that shows employees feel less engaged in their jobs than in pre-pandemic times. "In addition, bonding with colleagues has become harder and less of a priority for many people in the hybrid world of work," Chaker noted. "Some employers worry the lack of social cohesion is harming company culture and operations."

Enter *fika*, which may include pastries and snacks, and which is "meant to be a deliberate pause to provide space and time for people to connect." And there's a bonus: Stockholm School of Economics professor Micael Dahlen told Chaker that *fika* drives *trivsel*—a term combining workplace enjoyment and thriving.