



# Relation between edge stress, bending strength, surface stress and fracture pattern of thermally toughened glass

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Received: 15 March 2024 / Accepted: 1 July 2024 / Published online: 24 July 2024  
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**Abstract** Thermally toughened safety glass must meet safety requirements in the building industry. Here, destructive tests are defined in the product standards, which must be carried out on small, standardized format (360 mm × 1100 mm) glass elements to determine the fracture pattern and bending strength. This is costly and not in the interests of sustainability. As part of the quality control of optical anisotropy effects in thermally toughened glass, isochromatic scans that can provide information on the edge stress are acquired. The evaluation of the isochromatics and retardations at the edge with deduction of the edge stress and transfer to bending strength and fracture pattern could provide essential findings for assuring the safety requirements of thermally toughened glass. In this experimental investigation, the surface and edge stress were measured on standardized format thermally toughened safety glass, with

different edge processing and glass thicknesses from three different suppliers. Afterwards, the fracture pattern is controlled, or the bending strength is analyzed in a destructive four-point bending test. Conclusively, the results from the photoelastic and destructive tests are compared to determine whether the photoelastic measurement methods used to measure surface and edge stress can be employed as quality control.

**Keywords** Edge Stress · Surface Stress · Bending Stress · Fracture Pattern · Quality Control

## 1 Introduction

### 1.1 Motivation

The use and production of thermally toughened glass have continuously increased in recent years due to the architectural demand for larger glass structures. In the construction industry, requirements are placed on the construction product thermally toughened safety glass to meet the safety level described. The most important properties of this are the mechanical bending strength and the fracture pattern. The tests to ensure these properties have not changed since the first publication of the relevant European product standard (EN 12150–1 2020) in 1996. As part of the factory production control, destructive tests must be conducted on small glass elements (360 mm × 1100 mm) produced in parallel to determine the fracture pattern and bending strength.

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Fracture pattern analyses and bending tests on full-size project panes are often not calculated as part of such projects and lead to economic losses due to the destructive tests on the panes. In addition, destructive tests are costly and not in the interest of sustainability.

## 1.2 State of the art

The bending strength of glass is a statistical value linked to the fracture probability and the load type. One method described for determining the bending strength is the four-point bending test according to EN 1288–3 (2000), in which the glass pane is supported on two rotating rollers at a distance of 1000 mm and loaded by two rollers at a distance of 200 mm until it breaks. The bending stress is calculated from the breaking force, depending on the test specimen's actual geometry and the glass pane's dead weight. For statistical assurance, at least ten samples per batch of thermally toughened glass must be tested and analyzed as required by EN 12150–1 (2020) using the test setup of EN 1288–3 (2000). The 5% quantile with a 95% confidence level must achieve the characteristic bending strength depending on the prestress level. The characteristic strength should be at least 120 MPa for thermally toughened safety glass made of float glass.

The quality control of thermally toughened glass is conducted through fracture tests, wherein the glass is examined to ascertain compliance with the prescribed fracture pattern EN 12150–1 (2020). Five glass panes measuring 360 mm × 1100 mm without holes, perforations, or cutouts are utilized for a fracture test. Using a sharp steel tool, these panes are fractured by striking the midpoint of the long edge, 13 mm away from the edge. The panes are held without clamping at the edges by a frame to avoid scattering of glass fragments without impeding the expansion of the pane. Subsequently, the fracture pattern is evaluated, with a region around the impact point having a radius of 100 mm and strips of 25 mm width at the edges excluded from the evaluation (Fig. 6).

The evaluation of the fracture pattern must be completed within 5 min. It is carried out by counting the crack-free fragments within a 50 mm × 50 mm mask at the point with the coarsest fracture structure. All fragments only partially in the mask are counted as half a fragment. The glass is classified as thermally toughened if the number of fragments within the evaluation

field is at least 40 (for glass thicknesses between 4 and 12 mm). In addition, the length of the longest fragment within the entire test sample (excluding the edge areas and the impact area) must not exceed 100 mm.

## 1.3 Photoelastic measurements

Photoelastic measurement methods can examine tempered glass non-destructively due to the resulting residual stresses. The rapid cooling process during prestressing of glass creates compressive stresses on the surface and tensile stresses inside the glass, which are distributed in a parabolic form across the thickness of the glass. Due to the three-dimensional cooling behavior with the additional edge surface, a membrane compressive stress forms around the pane's edges with high retardations.

The induced stresses in the thermally toughened glass cause retardations, which can be visualized or quantified with the appropriately selected photoelastic instruments. The basics of photoelasticity in the glass field can be found in Aben and Guillemet 1993, Ajovalasit et al. 2015, Ramesh and Sasikumar 2020, Dix 2024. The measured retardations correlate with the stresses in the glass according to the stress-optical law (Wertheim's law, see Eq. (1)). It describes the relative retardation  $\delta$  that occurs when polarized light with wavelength  $\lambda$  is directed at right angles to a plate with thickness  $t$  and photoelastic constant of material  $C$ , thereby splitting it into two components that can be expressed directly with the principal stresses ( $\sigma_1$ – $\sigma_2$ ):

$$\delta = \frac{C}{\lambda}(\sigma_1 - \sigma_2)t \quad (1)$$

During the cooling process of thermal toughening, the cooling behavior differs at the glass edges. For reasons of equilibrium, the stress perpendicular to the edge becomes zero so that the stress parallel to the edge (referred to as edge stress) can be determined using the relationship of Wertheim's law.

As part of factory production control, EN 12150–1 (2020) permits surface stress measurement using the scattered light method to verify bending strength. Aben et al. (2010), Mognato et al. (2018), Pourmoghaddam and Schneider (2018), Mognato et al. (2020) investigated relations between surface stress, strength, and

fracture pattern. However, this method is very time-consuming because it measures at discrete points. An alternative that can be integrated into the production process would be to measure the edge stress.

In the American standard ASTM C 1048 (2018), edge stress measurement is authorized to verify bending strength within factory production control. In contrast, it has yet to be used in the European standard (EN 12150–1 2020). In ASTM C 1048, in addition to the surface stress with a minimum value of 69 MPa, a minimum value of 67 MPa for edge stress is specified for fully tempered glass, corresponding to the European standardized thermally toughened glass.

#### 1.4 Scope and outline

This paper investigated thermally toughened safety glass test specimens with different thicknesses and edge processing nondestructively by photoelastic methods and destructively with four-point bending tests and fracture tests. While measuring surface stress using scattered light is widely practiced, determining edge stress is more complex. This study describes an approach and evaluation method via the multiple wavelength photoelasticity method for quantifying the edge stress. After the photoelastic investigations, the samples were examined destructively to determine the fracture pattern and the bending strength.

The data from the individual tests are analyzed primarily to determine the influence of the glass manufacturer, glass thickness, and edge processing. For each test method, it is checked whether the criteria of the glass types fulfill the requirements of EN 12150–1 (2020) and ASTM C 1048 (2018). An initial assessment of whether the photoelastic measurement methods used to measure surface and edge stress can be employed as quality control will be checked.

## 2 Methodology of experimental investigations

### 2.1 Specimens

This study investigated a series of clear float glass specimens of thermally toughened safety glass produced by three distinct manufacturers to ensure the representativeness of the data concerning industry variations. The chosen specimen size of 360 mm × 1100 mm is

| Measured Variable | Manu-<br>facturer                               | Thickness                                                                              |  |  | Number<br>samples |
|-------------------|-------------------------------------------------|----------------------------------------------------------------------------------------|--|--|-------------------|
| Edge Stress       | <div><div>A</div><div>B</div><div>C</div></div> | <div><div>4</div><div>6</div><div>8</div><div>10</div><div>12</div><div>15</div></div> |  |  | 85x               |
| Surface Stress    |                                                 |                                                                                        |  |  | 85x               |
| Bending Stress    |                                                 |                                                                                        |  |  | 123x              |
| Fracture Pattern  |                                                 |                                                                                        |  |  | 30x               |
| KGN + KGS         |                                                 |                                                                                        |  |  |                   |

**Fig. 1** Number of specimens for each test

required for the four-point bending and fracture pattern tests in factory production control. The glass specimens were fabricated in thicknesses, specifically 4 mm, 6 mm, 8 mm, 10 mm, 12 mm, and 15 mm (only manufacturer C). In terms of edge processing, two types of edge finishing were considered for the thickness of 4 mm, 6 mm, and 8 mm: seamed edge (labeling as KGS according to DIN 1249–11, which forms a transition between edge and glass surface) and ground edge (labeling as KGN according to DIN 1249–11 (2023), matt ground edge surface with seamed edge).

Figure 1 shows the number of test specimens analyzed for each test and parameter.

### 2.2 Bending stress

For the bending stress, five test specimens per series were tested in a four-point bending test. The panes were subjected with a stress rate of 2 MPa/s until breakage to obtain the breaking force. The bending stresses were determined following the equation specified in the EN 1288–3 (2000) standard, considering the breaking forces and the measured geometries for the width and thickness of the glass. According to the statistical method, which requires the 5% quantile at a confidence level of 95%, the number of test specimens is crucial. As a result, the limited number of five test specimens can significantly affect the validity of the calculated 5% quantile.

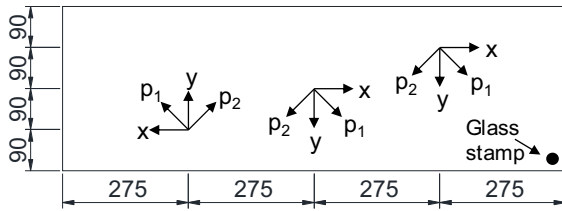


**Fig. 2** Positions for surface stress measurements, dimensions in mm

### 2.3 Surface stress

The SCALP-05 (GlasStress Ltd. 2013) was used to measure the surface compressive stresses of at least two test specimens per series. A local regression method with fit closeness of 0.5 was used for the determination of the surface stress, which means that the SCALP approximates the measured retardation by splines of third-degree polynomials.

Surface stresses can vary significantly within a toughened glass. High differences in the surface stresses can indicate strong optical anisotropy effects, visible in anisotropy scans. Three measuring points were selected on a diagonal of the upper side of the test specimen to be able to detect any strongly scattered surface stresses on a test specimen. Furthermore, the anisotropy scan was employed to control whether the sample is homogeneously prestressed. Care was taken to ensure that a sufficiently large distance to the edge was maintained to prevent the edge stress from influencing the measurement results. Furthermore, a sufficiently large distance to the edge simplifies the measurement because the reflection of the laser at the edge of the specimen does not reach the measurement field.

Each measuring point was investigated in x-direction, y-direction, and  $p_1$ -direction, or x-direction, y-direction,  $p_1$ -direction, and  $p_2$ -direction (see Fig. 2). The x and y directions run parallel to the edges of the pane, direction  $p_1$  lies at a  $45^\circ$  angle in between and direction  $p_2$  in  $135^\circ$  angle. The different measurement directions are required to be able to calculate the principal stresses in the plate plane. Whether three or four directions were measured per measuring point depended on the research institute. Since Thiele et al. (2022) showed only slight deviations between the two methods, no distinction is made below between the measurement methods.

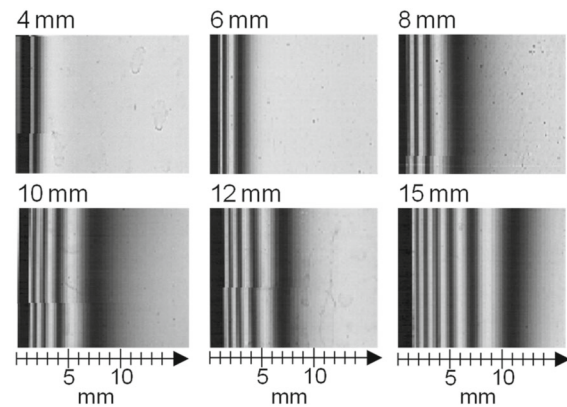


**Fig. 3** Isochromatics parallel to the glass edge shown on increasing thickness from 4 to 15 mm at 100–110 MPa surface stress

### 2.4 Edge stress

Differences between the two principal stresses  $\sigma_1$  and  $\sigma_2$  cause optical retardations. In the region of the undisturbed area of the glass far enough away from the edge, corner, or cut-outs, the measured retardations are typically low, minor as 300 nm, which corresponds to about 0.5th fringe (Dix et al. 2022). Towards the edge, the retardation increases steadily in an area of approximately the glass thickness (Laufs 2000). The maximum retardation is reached at the outermost edge. In photoelastic images acquired by polariscope setup, isochromatics parallel to the edge can be recognized, the number of which depends on the glass thickness with the same prestress level (see Fig. 3).

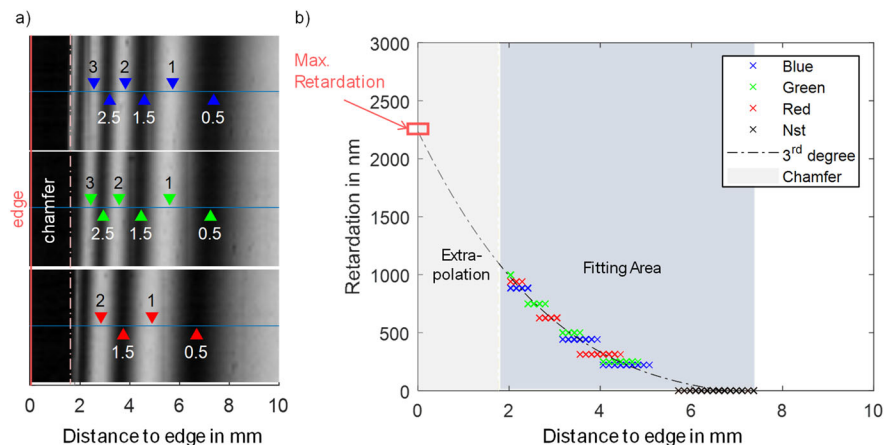
#### 2.4.1 Calculation of edge stress

While the individual components of the principal stresses cannot be measured separately using the full-field method due to the parabolic curve, only the principal stress difference across the glass thickness, the edge stress can be calculated due to the stress state ( $\sigma_1 = 0$ ) at the edge by rearranging the Wertheim's law (Aben and Guillemet 1993):

$$\sigma_{edge} = \frac{\delta * \lambda}{t * C} \quad (2)$$

The glass thickness  $t$  is the measured thickness of the specimen. The photoelastic constant  $C$  depends on the material of the specimen. For glass, the material constant  $C$  is ranging from 2.61 to 3.03 Brewster units

**Fig. 4** **a** Counting fringe orders shown as intensity minima and maxima starting with 0.5th isochromatic for the three wavelengths blue, green, red until the chamfer shown as opaque, dark area; **b** assigning the fringe order to the wavelength and plotting of the retardation data points in the diagram, then fitting of the curve and extrapolating over the chamfer to the edge to obtain maximum retardation



(Dix 2024). This paper used the same value for measuring surface stress, 2.7 Brewster units, according to GlasStress Ltd. (2013). The wavelength  $\lambda$  corresponds to the light of the photoelastic measuring device used to detect the retardation  $\delta$  at the edge.

#### 2.4.2 Necessity for extrapolation

The edges of thermally toughened architectural glass, which are sharp and irregular after cutting, must be chamfered for safety and strength, particularly before tempering, as specified in (EN 12150–1 2020). Edge finishing standards are detailed in DIN 1249–11 (2023) and vary based on the glass application. Edge processing for thermally toughened glass ranges from a basic 45° chamfer with a coarse finish to a highly polished, transparent edge for aesthetic applications. The width of the bevel is usually between 0.5 and 1.5 mm, depending on the glass thickness, to ensure safety during and after the tempering process.

However, due to the chamfer of the glass, the retardation cannot be read directly at the edge. The sloping surface of the chamfer deflects the light so that no reliable retardations can be measured in this area. Figures 3 and 4a) were taken via the multiple wavelength photoelasticity method (MWP), showing that the chamfer is not transparent and is displayed as a dark area. This means that the retardation can only be accurately measured up until the beginning of the chamfer. For the retardation value required in Eq. (2), the curve must therefore be extrapolated across the width of the chamfer towards the edge. ASTM C 1279 (2009) offers a method with reference points for measuring the retardation, which is extrapolated linearly. However, the chamfer in the architectural glass is too wide for the position

of the reference points to use this method. Efferz et al. (2024) compared different extrapolations and evaluation methods and chose the polynomial extrapolation of 3rd degree. In this paper, the retardation at the edge is also determined with a polynomial of 3rd degree.

#### 2.4.3 Multiple wavelength photoelasticity method

The glass samples were investigated using the multiple wavelength photoelasticity method. Its main application is in the assessment of optical anisotropies in thermally toughened architectural glass that exhibit low relative retardation (Hidalgo and Elstner 2018; Dix et al. 2022; Dix 2024). The measuring instrument Linescanner by Softsolution GmbH (2023) is a bright-field circular polariscope with telecentric LEDs and a resolution of 200 dpi. The measuring device located at the University of Applied Sciences Munich acquired three isochromatic images simultaneously in wavelengths of blue (442.35 nm), green (499.3 nm), and red (626.8 nm). After a software change in the measuring device of the CulletScanner at TU Darmstadt, the isochromatic images can be recorded with the same measuring system as that of the Munich University of Applied Sciences, with the difference that this measuring device is equipped with two wavelengths of blue and green.

Figure 4a shows the basic principle of analyzing the three isochromatic images by automatically counting the edge isochromatic orders shown as intensity minima and maxima starting with the 0.5th isochromatic due to the bright-field configuration, then ascertained with the associated wavelengths to obtain the retardation (Schaaf et al. 2017).

**Fig. 5** Scanner table with sample

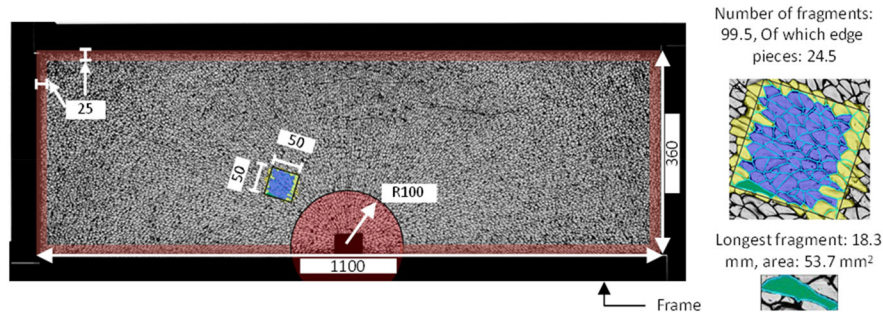
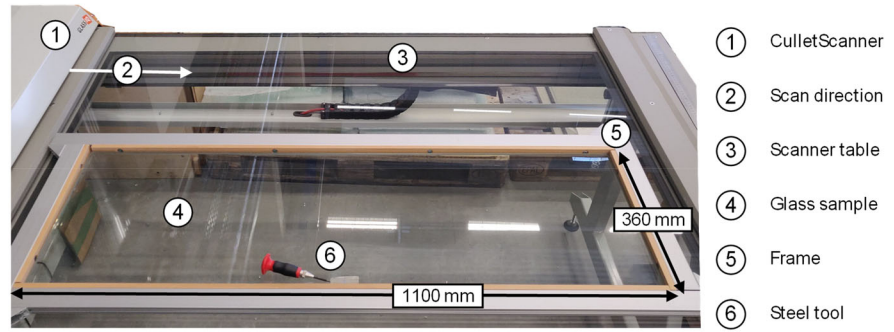


**Fig. 6** Exemplary sample of 8 mm in fracture test according to EN 12150-1. **a** Scan of fractured sample; dimensions in mm. Black: frame, red: from evaluation excluded area, center of circle: impact position (13 mm from glass edge). **b** The number of fragments (yellow: fragments that are partly in the evaluation mask) and the longest fragment (green)

In this work, the peaks were analyzed on 50 sections on both longitudinal edges of the specimen with sufficient distance from the corner. The obtained data was not evaluated per section because of significant deviations. However, instead, the retardation values (in nm applied on the y-axis) with the position of the peaks (in mm applied on the x-axis) were aggregated into one comprehensive diagram per sample, shown exemplarily in Fig. 4b, serving as the basis for the fit of the curve towards the edge (Efferz et al. 2024). After extrapolating the fitting curve over the chamfer towards the edge of the glass with a polynomial of 3rd degree, the maximum retardation value was read and used in Eq. (2) for the calculation of the edge stress.

## 2.5 Fracture pattern

The tests were performed as described in Sect. 1.2 according to EN 12150-1 (2020) on five specimens per series. A spring-loaded center punch was used to induce fracture. The CulletScanner (Fig. 5) from Soft-solution was used to evaluate the fracture pattern. The scanner uses light with a wavelength of 940 nm and

automatically searches for the point with the coarsest fracture pattern and counts the fragments at this point. In addition, the length and position of the longest fragment are output (Fig. 6).

It is already known from the literature (Pourmoghadam et al. 2019) that the fracture pattern of thermally toughened glass depends on the surface compressive stress and the thickness of the glass pane. The tempering process imprints elastic energy  $U$  into the glass pane, which is released during breakage.

This is calculated as:

$$U = \frac{1}{5} \frac{(1 - \nu)}{E} t \sigma_s^2 \quad (3)$$

wherein  $\nu$ : Poisson's ratio (0.23),  $E$ : Young's modulus (70000 MPa),  $t$ : glass thickness,  $\sigma_s$ : surface stress.

## 3 Results of the experimental investigations

### 3.1 Bending stress

Figure 7a illustrates the bending stress divided according to the glass thickness, whereby an increase in bending stress can be observed with an increase in thickness

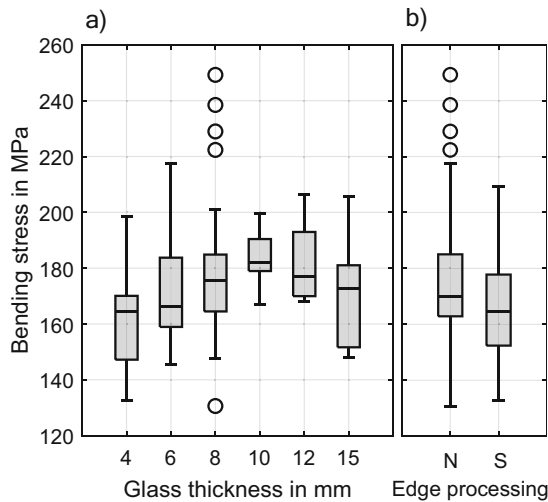


**Fig. 7** Bending stress depending on **a** glass thickness, **b** edge processing (4–8 mm)

and then a maximum with medium glass thicknesses. In particular, samples with a glass thickness of 8 mm are characterized by many outliers. An analysis of the data shown in Fig. 8 reveals a distinct scattering of the results, which can be attributed to the glass manufacturer B. The origin of the fracture was both at the edge and in the surface. Figure 7b reveals that samples with edge processing KGS tend to exhibit lower bending stresses.

Figure 8 presents the results separately for each manufacturer. In the case of manufacturer B, remarkably high stress values were recorded for a thickness of 8 mm

and KGN. Furthermore, test specimens with KGS from manufacturers B and C show lower bending stress values than those with KGN. In the case of specimens from manufacturer A, higher bending stresses were found in some KGS samples than in those with KGN.

### 3.2 Fracture pattern and number of fragments

Figure 9 exemplary shows two fracture patterns of a 6 mm and an 8 mm sample with labelling of the 5 cm × 5 cm selection area with the coarsest fracture pattern.

All panes meet the standard's requirements. Figure 10 shows the number of fragments in the analyzed 5 cm × 5 cm masks. A difference can be recognized between the edge finishes on the 6 mm test specimens. This can be explained by the fact that these test specimens were prestressed in two batches separated according to edge processing. The authors assume that there is therefore no difference in the edge processing.

### 3.3 Surface stress

Figure 11 shows the results of the surface stresses. One point represents the mean value of the surface stress  $\sigma_1$  measured at three measuring points for one test specimen. All samples fulfill the requirement of the ASTM C 1048 (2018) with a minimum value of 69 MPa. The edge processing seems to have no significant influence on the surface stress. Manufacturer B has slightly

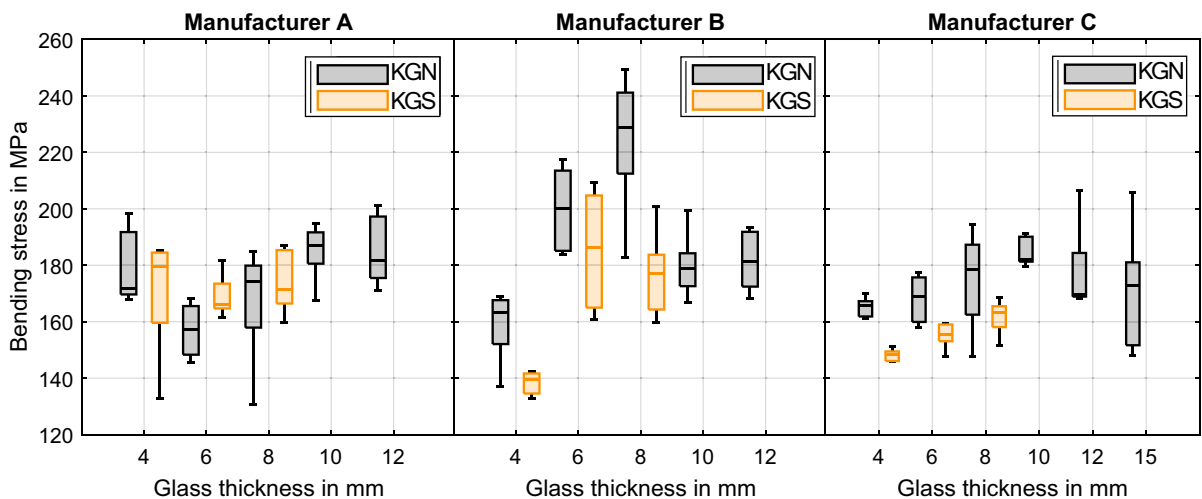


**Fig. 8** Bending stress divided by the manufacturer

**Fig. 9** Fracture patterns of **a** 6 mm sample with 97.5 fragments and a surface stress of 116 MPa; **b** 12 mm sample with 76.5 fragments and a surface stress of 110 MPa

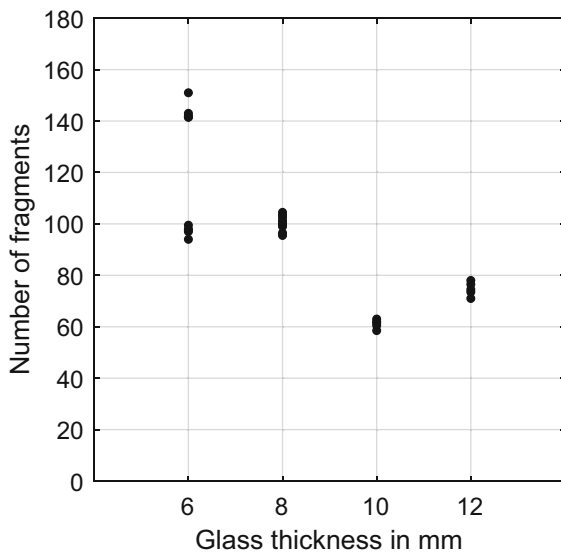
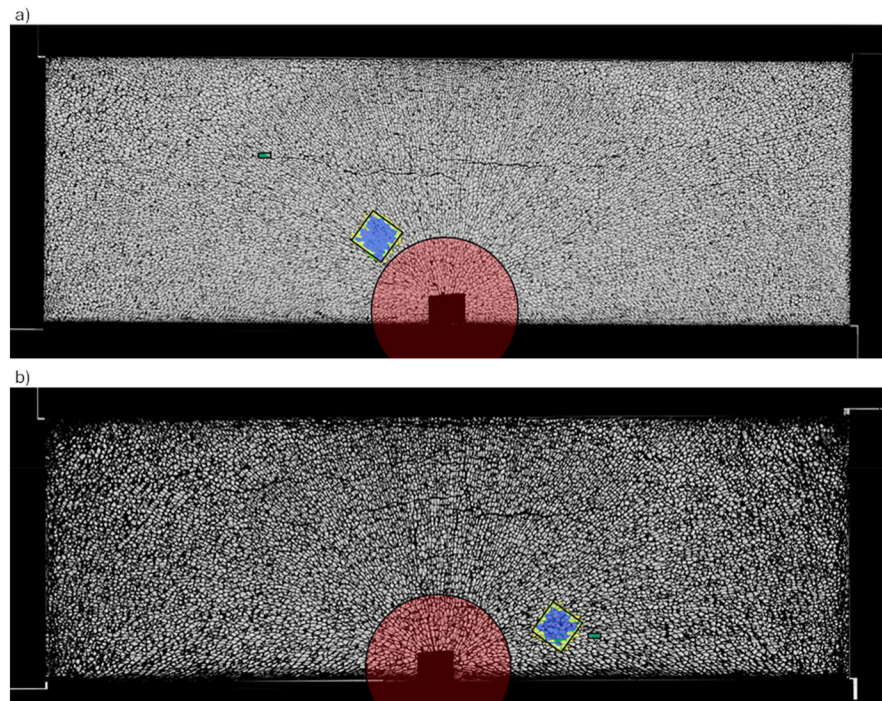


**Fig. 10** Number of fragments depending on glass thickness and edge processing

greater scattering at smaller thicknesses than the other two manufacturers because of two batches for the edge processing during the tempering on these test specimens.

### 3.4 Edge stress

The edge stress is determined by means of 50 measuring points per long side of the glass on five specimen per series. As already explained, in the present study, the test specimens from manufacturer B were measured using two different measuring devices to determine the edge stress. One part of the test series consisting of 5 samples each was analyzed by a measuring system that exclusively generates two isochromatic images, while the other measuring device acquires three such images. To visualize the resulting differences in the determination of the edge stresses, the data from the test specimens of manufacturer B, which were acquired with two or three wavelengths, are plotted in Fig. 12, depending on the glass thickness.

The results of the two- and three-wavelength analyses demonstrate no significant discrepancies. The additional wavelength provides more interpolation points, but the effects appear to be minimal.

For this reason, the specimens whose edge stresses were determined with two wavelengths are not labeled separately in the ongoing evaluation process. The test specimens from manufacturers A and C were only examined using the three wavelengths measurement approach.

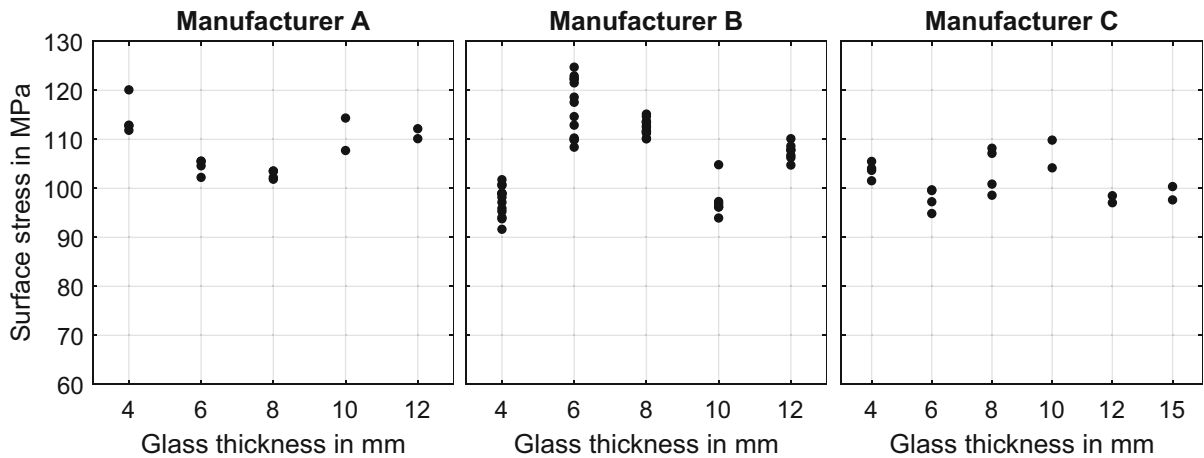


**Fig. 11** Surface stress divided by the manufacturer

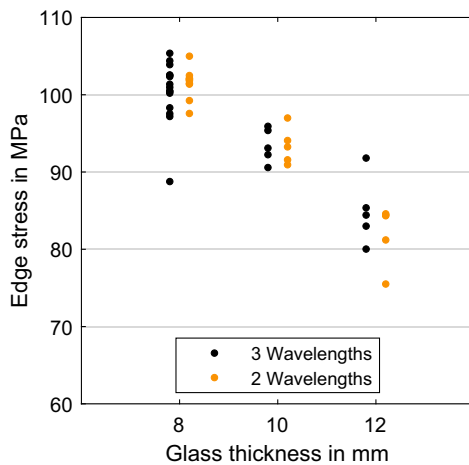


**Fig. 12** Comparison between measuring devices with two and three wavelengths generating isochromatic images using test specimens from manufacturer B

Figure 13 shows the calculated values of the edge stresses of all test specimens as a dependency of various parameters. Figure 13a illustrates the relationship between the edge stress and the glass thickness. It can be observed that the edge stress tends to decrease with increasing glass thickness. The larger scattering width at a glass thickness of 8 mm can be explained by the differences depending on the manufacturer.

Figure 13b shows the measured edge stresses for the two edge treatments analyzed. As described above, extrapolation to the edge is necessary when calculating the edge stress. The width of the chamfer and therefore the width of the non-measurable area in the multiple

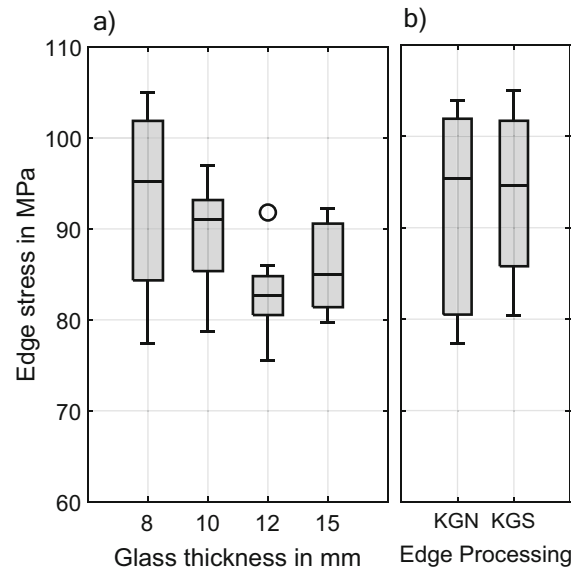


**Fig. 13** Edge stress depending on **a** glass thickness, **b** edge processing (only 8 mm)

wavelength photoelasticity method can vary from processing type to processing type and from manufacturer to manufacturer. The results in Fig. 13b show that the edge processing has no significant influence on the calculated edge stresses.

Accordingly, Fig. 14 shows the results separated by the three manufacturers regarding the glass thickness. The edge stresses of the test specimens from manufacturer A are very similar for all glass thicknesses, while

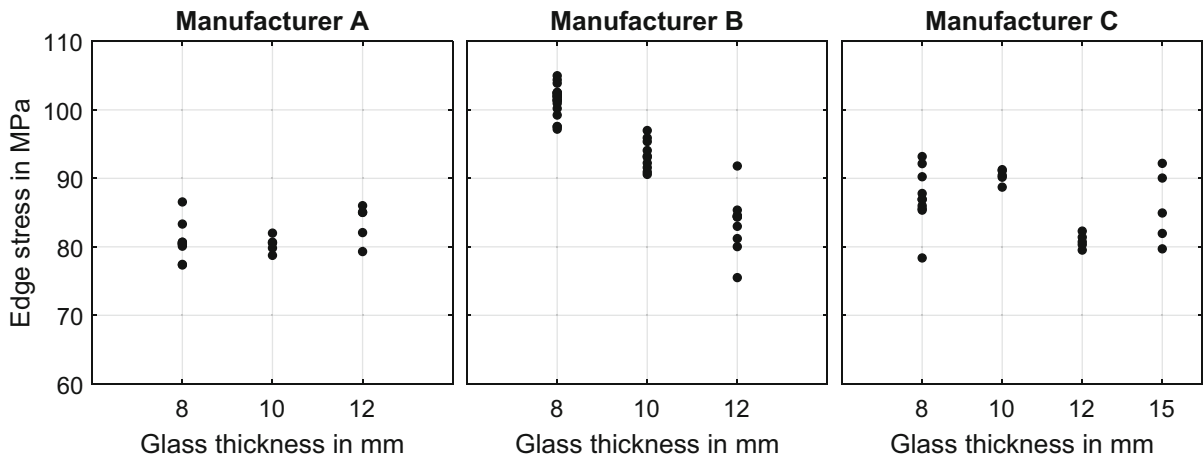


**Fig. 14** Edge stress divided by the manufacturer

the values for manufacturer B decrease with increasing thickness. In the case of manufacturer B, high edge stresses (over 100 MPa) at a glass thickness of 8 mm are noticeable. Most of the edge stress values of all manufacturers are above 80 MPa.

#### 4 Discussion

This chapter establishes the dependency of the various measured variables analyzed and compares the results with literature. A dot represents the (averaged) value of a measured variable for one test specimen. The dashed line in the figures symbolizes a straight line of origin with a gradient of one to illustrate a direct one-to-one relationship. The diagrams in Figs. 15 and 16 also show the respective minimum limits for edge stress (67 MPa) and surface stress (69 MPa), as specified by the ASTM C 1048 standard. The relation between surface and bending stress shown in Fig. 15a can apparently be identified as a rather medium strong but linear correlation with influence of the glass thickness.

The relationship between surface compressive stress and the number of fragments has already been analyzed by Mognato et al. 2011, Lee et al. 2012, Pourmoghaddam and Schneider 2018, Pour-Moghaddam 2020. Lee et al. (2012) investigated smaller (500 mm × 500 mm and 600 mm × 1100 mm) and thinner glass panes (2.1, 2.5, 2.8 and 3.2 mm). The surface stresses were approximately between 90 and 140 MPa. Pourmoghaddam and Schneider (2018) examined panes in standard format (360 mm × 1100 mm) with different

thicknesses (4 mm, 8 mm, 12 mm) and different surface compressive stresses (approx. 50–120 MPa). Both authors found that higher surface compressive stresses are required for thinner glass to achieve the same degree of fragmentation. Mognato et al. (2011) investigated standard format thermally toughened safety glass panes (360 mm × 1100 mm) with thicknesses of 4–15 mm and surface stresses of approx. 75–120 MPa. However, they observed that the surface stress and fragmentation number correlation is generally independent from glass thickness, except for pane thicker than 10 mm. They determined a minimum surface stress of 90 MPa (glass thickness ≤ 10 mm) resp. 85 MPa (glass thickness ≥ 12 mm) to obtain “safe” fracture patterns according to EN 12150 (2020). They additionally derived linear relations between the number of fragments and the surface stress. This relation can also be confirmed in Fig. 15b.

In contrast to Mognato et al. (2011), a clear distinction between the glass thicknesses can also be recognized for thinner thicknesses in Fig. 15b. This can be explained by the physical relationship between glass thickness and elastic energy, as demonstrated Eq. 3 and in Pourmoghaddam (2020).

This strong influence of the glass thickness can also be seen in Fig. 15b. Nevertheless, the elastic energy does not appear to be suitable for linear characterization of the number of fragments, probably precisely because of the dependence of the glass thickness in Eq. 3.

Furthermore, Mognato et al. (2017) examined the relation between surface stress and bending stress and stated a lower boundary of 85 MPa for ensuring the bending strength of uncoated FTG. In a more recent

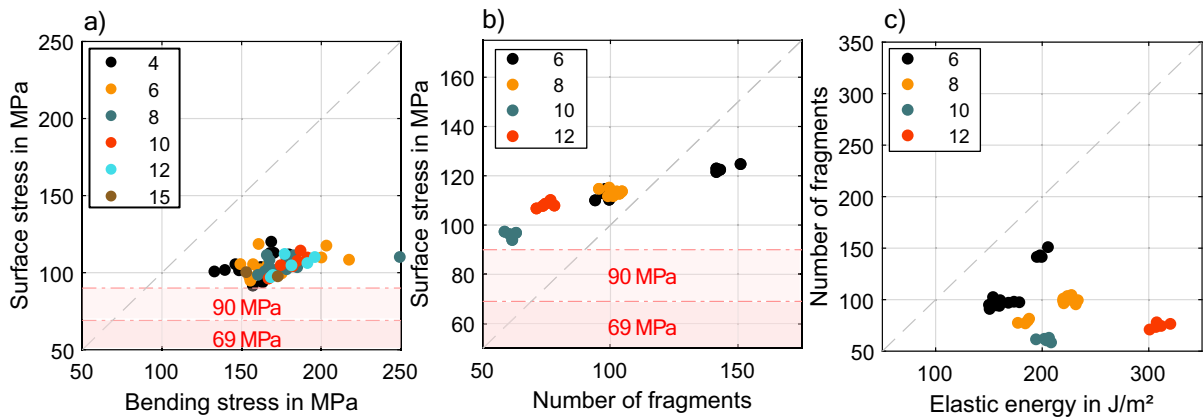


**Fig. 15** Correlation between **a** surface stress and bending stress; **b** surface stress and fragmentation number; **c** elastic energy and fragmentation number, depending on glass thickness

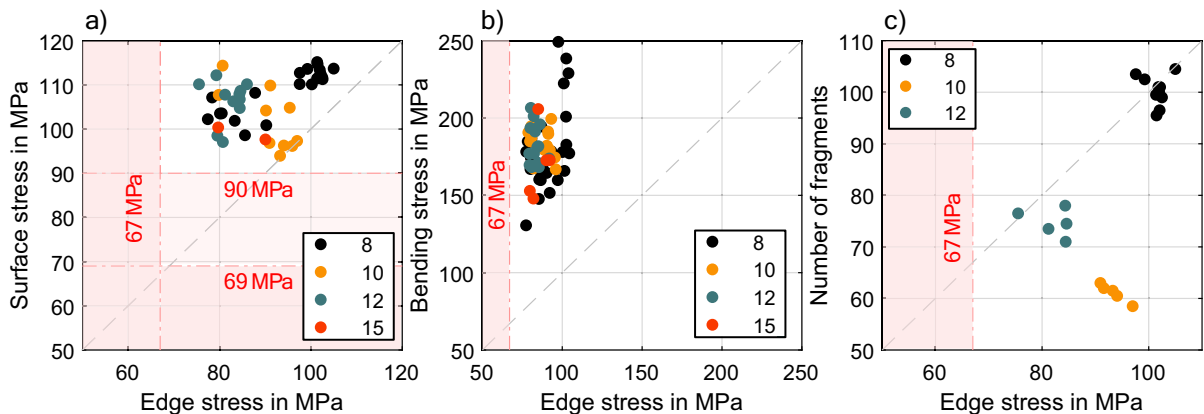


**Fig. 16** Correlation between **a** edge stress and surface stress; **b** edge stress and bending stress; **c** edge stress and fragmentation number, depending on glass thickness

study, Mognato et al. (2018) suggest a higher minimum limit of 90 MPa for the surface stress of toughened safety glass made of clear float to ensure the characteristic fracture pattern and bending strength. This value is shown in the relevant figures as an area marked in lighter red and is achieved by all test specimens.

Figure 16a analyses the relation between edge stress and surface stress. This relation was also studied in Aben et al. (2015). However, the available data cannot support the one-to-one correlation between edge stress and surface stress, as stated by Aben et al. (2015). In this study, the values for the surface stress are generally higher than those for the edge stress. A clear linear correlation cannot be recognized, but there is an increasing trend. The apparent point cloud can be explained by the fact that the values of edge stress and surface stress are

in a narrow range and the differences within the pre-stressing level are apparently too small.

Figure 16b compares edge stress and bending stress. The high variance found in the bending stress values is not reflected in the measured values for edge stress. The authors suspect an influence of surface defects that led to fracture rather than overcoming residual stresses.

Tests in Lohr (2019) resulted in edge stress values (at the fracture origin of the four-point bending test) of 61 to 80 MPa (8 mm) and 52 to 69 MPa (10 mm) for FTG, which were extrapolated with 3rd degree polynomial. In comparison to the findings of this study, these values indicate a relatively low edge prestress. The low residual stresses were also demonstrated by the surface stresses for the 10 mm samples with values of 85 to 91 MPa, which rarely reach the limit of 90 MPa by

Mognato et al. (Mognato et al. 2020). In addition, since the four-point bending tests were carried out around the strong axis in Lohr (2019), the results of the relation between edge stress and bending stress cannot be compared with this study.

Finally, Fig. 16c illustrates the correlation between the number of fragments and the edge stress. An influence of the glass thickness is clearly recognizable, but a linear correlation cannot be identified. The measured sizes are approximately the same for the 8 mm and 12 mm, in contrast to the 10 mm, which do not reflect the high edge stresses in the number of fragments.

Relative factors were created to analyze the relation between two measured variables in the context of photoelastic investigations. They are defined as the ratio of a target variable to the respective photoelastic measured variable, representing the surface or edge stress. Using these relation factors makes it possible to determine the respective target variable (number of fragments or bending stress) approximately after performing photoelastic measurements. So, Fig. 17 provides an initial reference point for drawing conclusions about the destructive quality assurance tests, using non-destructive variables. Figure 17 presents an overview of these ratios based on the experimental data, with the values organized according to the thickness of the glass samples. The factors of bending stress to surface stress (BS/SfS) start at around 1.3 for thin samples. For glass samples with increasing thickness, the factors rise to values between 1.55 and 1.8, with individual values for samples with a thickness of 6 mm and 8 mm being considered outliers. The ratios describing the number of fragments as a function of the surface stress (Fr/SfS) lie between 0.8 and 1.2 for thin glass, while they range around 0.66 for thicker glass. The factor of surface stress to edge stress (SfS/ES) varies between 1 and 1.5 across all evaluated glass thicknesses. For the relationship between bending stress and edge stress (BS/ES), factors with an extensive scatter range of 1.5–2.5 were determined for glass samples with a thickness of 8 mm. As the glass thickness increases, the lower limit of these ratios also rises so that for samples with a thickness of 12 mm and 15 mm, the factors start at a minimum of 1.9. The upper limit of these factors remains almost constant at a value of around 2.5 for all glass thicknesses. At a glass thickness of 8 and 12 mm, the number of fragments shows an almost one-to-one relation with the edge stress (Fr/ES). For the 10 mm specimens, the ratio decreases to 0.6.

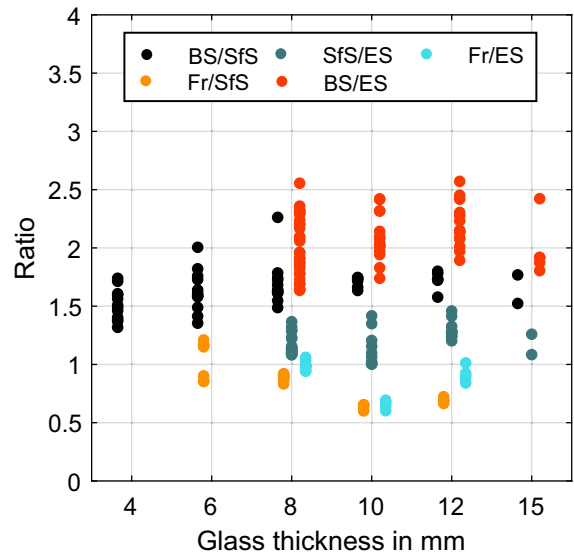


**Fig. 17** Ratio between bending stress (BS), number of fragments (Fr), surface stress (SfS), and edge stress (ES) as a ratio of the target variable to a photoelastic measured variable depending on glass thickness

## 5 Conclusion

Flat glass products, such as thermally toughened safety glass, must fulfill specific requirements. Mechanical bending strength and fracture pattern are decisive properties for guaranteeing safety. Factory production control prescribes destructive tests on small glass elements to monitor these properties.

This study analyzed thermally toughened safety glass of six different thicknesses, two edge processing, and three manufacturers using non-destructive photoelastic methods to measure surface and edge stress.

The scattered light method measured surface stresses on three points on the samples. All specimens achieved the minimum surface stress value of 69 MPa specified by the ASTM C 1048.

The isochromatic images generated by the multiple wavelength photoelasticity methods were analyzed to determine the edge stress. The retardation can be calculated based on the intensity and order of the edge isochromatics. As the beveled edge influences the light transmission, no retardation values can be measured on the chamfer. Therefore, a curve with a 3rd degree polynomial is fitted through the measurement points using the retardations and then extrapolated to the edge. The maximum retardation value read at the edge was used to calculate the edge stress for specimens greater than or

equal to 8 mm. An analysis of all test specimens showed that the edge stress tends to decrease with increasing glass thickness. A comparison between the edge processing methods showed a negligible influence on edge processing. The influence of the manufacturer is recognizable. Overall, most edge stress values are above 80 MPa and thus reach the limit value of 67 MPa specified in ASTM C 1048.

After the non-destructive tests, the samples were destructively tested to determine the fracture pattern and bending strength. In the fracture tests, all samples fulfill the 40 fragments required by EN 12150 in the examined 5 cm × 5 cm mask. All single specimens exhibited a fracture stress of over 120 MPa in the four-point bending tests.

The study showed the relation between the measured variables. An increasing trend can be seen in the ratio of bending and surface stress as well as bending and edge stress, even if it is difficult to derive a clear correlation between bending stress and surface stress. This can be explained by the fact that other influences in the bending strength tests, such as surface defects or inhomogeneities of the prestressing process, were not investigated or detected. It may not be possible to explain an exact physical correlation, but the paper is intended more as a basis to facilitate quality control.

In contrast, a clear correlation is recognizable between the number of fragments and surface stress, as well as between the number of fragments and edge stress. The values for surface stress are generally higher than those for edge stress, with surface stress showing a lower range.

In addition, dimensionless factors were calculated to determine the relation between the target value and the photoelastic measured surface or edge stresses. In particular, the ratios of bending to surface stress and bending to edge stress show an increasing behavior depending on the glass thickness. In contrast, the relationships of the fragments to surface stress and edge stress show a decreasing trend. However, the bending-to-edge stress ratio shows an extensive scattering range, especially for the thinner panes.

Even if the strength also depends on surface defects and their crack depth, the paper shows, that photoelasticity has potential to be used in quality control to reduce destructive tests. To summarize, the factors determined for the various stress ratios provide insight into the relationship between photoelastically measured variables and the required measured variables

to ensure the quality of the glass. Conclusions on the destructive quality control tests using non-destructive variables can be drawn from these factors.

To integrate the photoelastic methods of local measurement of the surface stress and the automated measurement of the edge stress integrated in the tempering process into the quality process of production control and thus reduce the destructive tests, further investigations must be carried out, especially for heat-strengthened glass. In addition, a detailed statistical evaluation of the correlations between the parameters is planned after the end of the project with the complete data sets. It must also be checked whether the findings from the small-size formats can also be transferred to glass in component size so that the quality control can be performed non-destructively on the actual size, thus saving resources.

**Acknowledgements** The investigations are conducted as part of a research project “NEMA” funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) as part of the funding program “WIPANO”.

**Funding** Open Access funding enabled and organized by Projekt DEAL.

## Declarations

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

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