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Fragmentation of Heat-Strengthened Glass: Implications for Glass Not Conforming to ASTM C1048

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Heat-strengthened glass with residual surface compressive stresses above those allowed by ASTM C1048 was installed in a curtain wall in the mid-Atlantic region of the United States. To address building ownership's concerns regarding post-breakage glass fallout, fragmentation tests were performed using a protocol adapted from EN 1863. Consistent with previous research, no significant difference in fragmentation was noted between samples with residual surface compressive stresses conforming to ASTM C1048 and those with residual surface compressive stresses well beyond the established ASTM limits. Simplistic analyses revealed that, under certain modes of failure, risk of glass fallout is comparable for conforming and nonconforming heat-strengthened glass. The completed testing also has implications for glass quality control processes.

Keywords: Fragmentation, Residual Surface Compressive Stress

1. Project Background

Shortly after construction of a 12-story commercial office building in the mid-Atlantic region of the United States, concerns were raised regarding the insulating glass units in the building's curtain wall. The units consisted of a 6 mm heat-strengthened outboard lite, a 12 mm sealed air space, and a 6 mm fully tempered (thermally toughened) inboard lite. Most of the units were fabricated by the original supplier; additional units were provided by a second supplier. Specific concerns, which only pertained to the units provided by the original supplier, included residual surface compressive stress (RSCS) above the allowable ASTM C1048 range [1] and visible distortion of the outboard heat-strengthened lites.

With regard to the high RSCS measured on in-situ heat-strengthened lites, two related concerns were raised: the increased risk of spontaneous breakage (if the glass contained deleterious nickel sulfide inclusions) and the increased risk of post-breakage glass fallout. This latter concern is the focus of this paper. The relative risk of glass fallout was evaluated by examining the fragmentation behavior of the original nonconforming heat-strengthened glass and the conforming glass provided by the second supplier. The visible distortion and spontaneous breakage concerns were addressed separately and are outside the scope of this paper.

2. ASTM C1048 History

To evaluate the risks associated with heat-strengthened glass that does not conform to the current ASTM C1048 [1], an understanding of the history of this standard is beneficial.

2.1. Pre-1997

Prior to its revision in 1997, ASTM C1048 [2] defined heat-strengthened glass as having a RSCS between 24 and 69 MPa. Fully tempered glass was defined as having a minimum RSCS of 69 MPa or a minimum edge RSCS of 67 MPa. As such, there was not a clear distinction between heat-strengthened and fully tempered glass for an RSCS near the 69 MPa limit. Though fragmentation requirements for safety glazing are specified in other standards, no explicit fragmentation requirements for heat-strengthened or fully tempered glass were included in ASTM C1048 [2].

2.2. Revision of ASTM C1048 in 1997

In the 1997 revision of ASTM C1048 [3], a clear distinction was made between heat-strengthened and fully tempered glass. While the definition for fully tempered glass did not materially change, a revised allowable RSCS range between 24 and 52 MPa was specified for heat-strengthened glass. Thus, heat treated glass with an RSCS from 52 MPa up to, but not including, 69 MPa would not conform to requirements of either heat-strengthened or fully tempered glass. This ASTM definition for heat-strengthened glass has not changed since 1997.

Since the impetus for the change in definition of heat-strengthened glass is not well-documented in the literature, selected U.S. glass experts were queried. From these discussions, the rationale for the change likely included:

- Reduced likelihood of nickel sulfide breakage of contaminated heat-strengthened glass batches.
- Heat-strengthened breakage characteristics resulting in glass that, when broken, is more likely to remain in a glazed opening (i.e., generally similar fragmentation to that of annealed glass).
- The need to make a clear distinction between heat-strengthened and fully tempered glass.

Expert opinions differed regarding the primary impetus for the change. In addition to RSCS, fragmentation may also be a function of breakage method, other applied stresses, glass size, and geometry.

Limited fragmentation testing appears to have been performed prior to the revision of the standard. Similar to previous versions of the standard, the 1997 revision did not include any requirements for fragmentation. It merely states that "When broken, the fragments are generally similar to that of annealed glass." There is no known U.S. standard that specifies fragmentation criteria for heat-strengthened glass.

2.3. Literature from Heat-Strengthened Glass Fabricators

Given the context of changes to ASTM C1048 [3], selected recent published literature from U.S. glass fabricators was reviewed to determine what characteristics of heat-strengthened glass are being publicized. Following are some paraphrased excerpts from this review:

- It generally fractures in a manner similar to annealed glass and tends to remain in the opening when broken.
- The fragments of the broken glass are larger and more likely to remain in the frame.
- Heat-strengthened glass is produced with an RSCS of 28 to 48 MPa in order to minimize the potential for nickel sulfide breakage.
- Heat strengthening does not result in a safety glass product; heat-strengthened glass breaks in a pattern similar to annealed glass.

It is apparent that some fabricators advertise fragmentation characteristics, while others refer to reduced risk of nickel sulfide breakage. However, no mention of specific fragmentation criteria was found in the fabricator's literature.

3. Glass Fragmentation Literature Related to ASTM C1048

3.1. Testing Performed Prior to 1997 ASTM C1048 Revision

There is limited information in the public domain regarding testing to determine a relationship between RSCS and fragmentation of glass. Among some U.S. glass experts, there is speculation that fragmentation testing may have been performed by certain glass fabricators prior to the 1997 ASTM C1048 revision [3]; however, the results of such testing were never publicly released.

In 1990, Joehlin [4] published results of testing on 6 mm heat-strengthened and fully tempered glass. The samples were all approximately 600 mm by 900 mm and were broken at the center with a punch. The number and size of glass fragments were compared for samples with an RSCS ranging from 22 to 90 MPa. In this publication, Joehlin stated, "While the surface compressive stress is not an exact correlation to fragment size, it is possible to separate the general ranges of tempered, high-, medium-, and low-heat-strengthened glass by examining the break pattern." Statements such as these may have led fabricators of heat-strengthened and fully tempered glass to first utilize some type of break pattern criteria (e.g., cubes versus long runs) as a quality control procedure for determining conformance with ASTM C1048 [3]. In fact, the fabricator providing glass on the subject curtain wall used fragmentation criteria as a means to assess conformance.

3.2. Testing Reported Subsequent to 1997 ASTM C1048 Revision

In 1999, Joehlin [5] published a paper examining the relationship of break pattern and RSCS levels in heat-strengthened and fully tempered glass. This publication was more targeted than his 1990 paper in that it discussed fragmentation in light of the newly imposed ASTM C1048 [3] RSCS limits for heat-strengthened glass. Glass samples were approximately 600 mm by 900 mm and were broken at the center with a punch. The number and size of glass fragments were compared for samples with an RSCS ranging from 27 to 97 MPa. This testing program included a broader sampling of glass than that reported in the 1990 Joehlin paper, especially for glass in the new RSCS range for heat-strengthened glass.

For glass with an RSCS of 62 MPa (significantly above the allowable range for heat-strengthened glass), Joehlin indicated, "This pattern has the general appearance of heat-strengthened, but is well above the 7,500 psi [52 MPa] limit." When comparing test specimens, he also reported, "Both have an almost identical seven fragment pattern, yet the 5,700 psi [39 MPa] is right in the middle of the acceptable heat-strengthened range, and the 9,000 psi [62 MPa] is in the high half of the unacceptable mid range."

Based on this additional testing, Joehlin concluded, "The fragment counts recorded in the range from 3,900 to 9,000 psi [27 to 62 MPa] were so variable it appears that fragment count is not an acceptable method for predicting conformance with the ASTM requirements for heat-strengthened glass." He also indicated that measuring the RSCS directly using a grazing angle surface polarimeter as described in ASTM C1279 [6] is a more reliable method to monitor surface stress in heat-strengthened glass. These conclusions were a significant departure from those made in his 1990 publication. The discovery that heat-strengthened glass with an RSCS in excess of the ASTM C1048 [1] limit of 52 MPa could have substantially similar fragmentation characteristics was of particular significance for the subject curtain wall.

4. EN 1863 Part 1

In order to evaluate potential differences in post-breakage fallout of the nonconforming (high RSCS) and conforming heat-strengthened glass, a fragmentation protocol was required. Since there are no explicit fragmentation requirements for heat-strengthened glass in any U.S. standard, the European Norm for heat-strengthened glass, EN 1863 [7], was reviewed.

4.1. Fragmentation Criteria

EN 1863 [7] contains fragmentation criteria for relatively small standardized specimens measuring 360 mm by 1100 mm. Unrestrained specimens are to be laid flat on a table and impacted with a pointed steel tool 20 mm from the edge at the midpoint of the longest side. "Excluded areas" include a 25 mm border along the perimeter of the specimen and a semicircular area with a 100 mm radius centered on the impact point. "Particles" are defined as fragments less than 100 mm^2 with no edges reaching excluded areas; "islands" are larger fragments with no edges reaching excluded areas. Acceptance criteria include a limit on the number and size of island fragments, as well as a limit on the total area of all particles and islands.

4.2. Literature Related to EN 1863 Fragmentation Criteria

In 2005, Schiavonato et al. [8] published a review of test results including fragmentation related to EN 12150 [9], the European Norm for thermally toughened glass, and EN 1863 [7] criteria. Most of the review pertaining to fragmentation was related to the minimum RSCS necessary to meet the toughened glass fragmentation criteria of EN 12150 [9]. The only discussion related to heat-strengthened glass read, "As concerns conformity to EN 1863-1 fragmentation requirements, we estimated an optimal range from 35 MPa to 60 MPa, strictly depending on the glass thickness; in some cases fragmentation conformity can be reached also with higher values." Similar to the Joehlin [5] study, these findings appeared to indicate that fragmentation behavior of glass above the ASTM C1048 [1] RSCS limit of 52 MPa could be similar to glass with an RSCS below this limit.

5. Comparative Fragmentation Test Protocol Adapted from EN 1863

Since the subject glass was significantly larger (1460 mm by 2010 mm) than the standard EN 1863 [7] test specimen, a modified test protocol for evaluating relative fragmentation behavior was required. The following protocol, patterned after EN 1863 [7], was developed.

The RSCS of actual project glass samples are measured in the laboratory in general conformance with ASTM C1279 [6]. Each sample is impacted by a spring-loaded center punch, the point of which has a radius of curvature of approximately 0.2 mm. The point of impact and the excluded areas are identical to those of EN 1863 [7]. An "isolated fragment" is defined as a fragment greater than 100 mm^2 with no edges reaching excluded areas. For each sample, the number and size of isolated fragments is recorded. The goal of this protocol was to determine the relationship between RSCS and the number/size of isolated fragments.

6. Results of Project-Specific Fragmentation Testing

A total of twenty-one insulating glass units, measuring approximately 1460 mm by 2010 mm, were removed from selected areas of the facade. The units were disassembled and the 6 mm heat-strengthened outer lites were tested according to the fragmentation test protocol developed specifically for this project. The RSCS of the samples ranged from 41 to 67 MPa, with all 16 original glass samples having an RSCS greater than the ASTM C1048 [1] limit of 52 MPa. Examples of tested lites with numbered isolated fragments are shown in Figures 1 and 2.

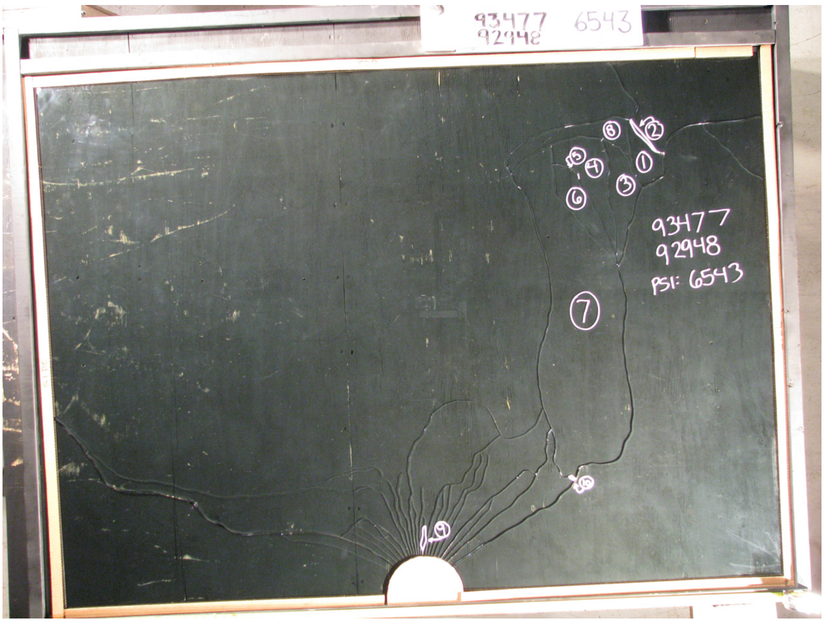

Figure 1: Example of tested lite with residual surface compressive stress of 45 MPa.

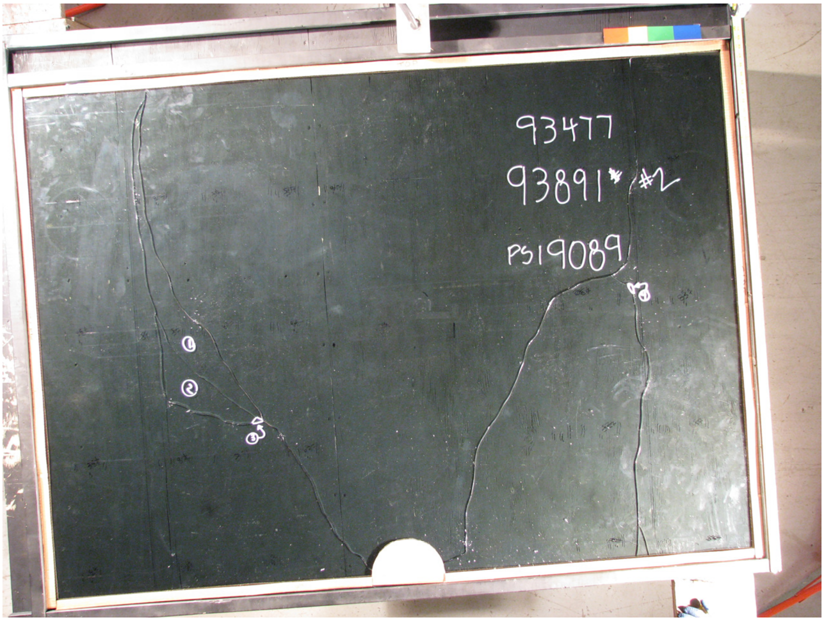

Figure 2: Example of tested lite with residual surface compressive stress of 63 MPa.

The test results were analyzed in terms of RSCS versus number of isolated fragments, overall size of all isolated fragments, and fragment size distribution. A graph of RSCS versus number of isolated fragments is shown in Figure 3. Note that there were two samples with an RSCS of approximately 62.5 MPa and 1 isolated fragment; therefore, only one related data point is visible on the graph. For the five samples within the ASTM C1048 [1] RSCS range of 24 to 52 MPa (all provided by the second glass supplier), one with an RSCS of approximately 45 MPa had 9 isolated fragments while the remainder had none. In fact, this was the only sample with an RSCS below approximately 62 MPa to have any isolated fragments. Below approximately 62 MPa, the probability of developing isolated fragments based on this sample set was 1/12 (0.083).

At an RSCS of approximately 62 MPa, the fragmentation behavior appeared to change significantly. Of the nine tested samples with an RSCS above this value, seven developed isolated fragments resulting in a probability of 7/9 (0.778). Of these seven, only four have a greater number of isolated fragments than the sample with an RSCS of 45 MPa. Using the latter sample as a benchmark, the probability of developing nine or more isolated fragments is 1/12 (0.083) for samples with an RSCS below approximately 62 MPa and 4/9 (0.444) for samples with an RSCS above approximately 62 MPa.

The relatively similar fragmentation behavior of samples with an RSCS ranging from 41 to 62 MPa correlates well with the findings presented in the later Joehlin publication [5]. Interestingly, the upper end of this range nearly coincides with the upper end of the optimal RSCS range proposed by Schiavonato et al. [8] for meeting the requirements of EN 1863 [7].

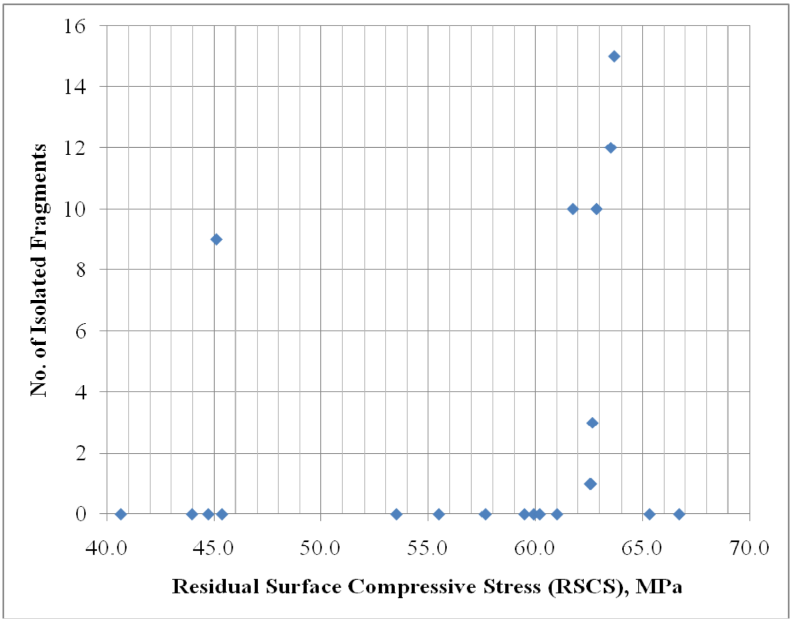

Figure 3: RSCS vs. Number of Isolated Fragments.

Figure 4 illustrates the relationship between RSCS and total area of isolated fragments. This relationship appears similar to that shown in Figure 3. Note that there are two values with an RSCS of approximately 62.5 MPa and a total area of isolated fragments less than 27 cm^2; therefore, only one data point is visible on the graph. Of the seven samples with isolated fragments and an RSCS above approximately 62 MPa, only two have a greater total area than the sample with an RSCS of 45 MPa; only one has significantly greater area.

For each of the eight samples with isolated fragments, the number of fragments in four size ranges (0 to 10 cm^2, 10 to 100 cm^2, 100 to 500 cm^2, and over 500 cm^2) was determined. As shown in Figure 5, there does not appear to be a clear distinction of fragment size distribution among samples with varying RSCS. For the two largest size ranges and for samples with more than 1 isolated fragment, the distributions are relatively similar.

In general, these test results corroborate previous findings [5], which indicate substantially similar fragmentation behavior in the RSCS range of 27 to 62 MPa. The upper end of this range is significantly higher than the ASTM C1048 [1] maximum allowable RSCS of 52 MPa for heat-strengthened glass. Therefore, the use of qualitative or quantitative fragmentation criteria to assess conformance with specified ASTM RSCS limits is inadvisable. Furthermore, while there generally appears to be a greater likelihood of developing more isolated fragments and fragments with larger total size for glass with an RSCS greater than 62 MPa, the higher RSCS also results in a lower probability of initial failure under certain loading conditions.

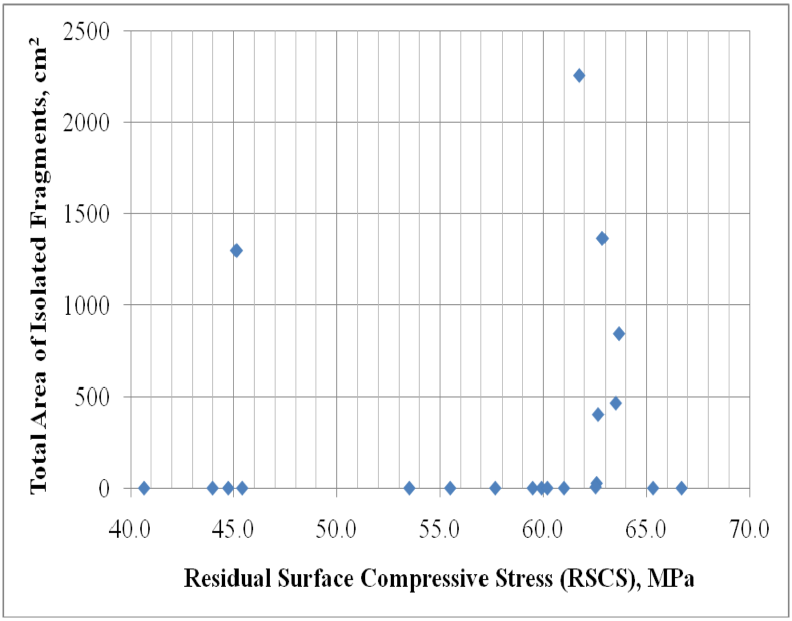

Figure 4: RSCS vs. Total Area of Isolated Fragments.

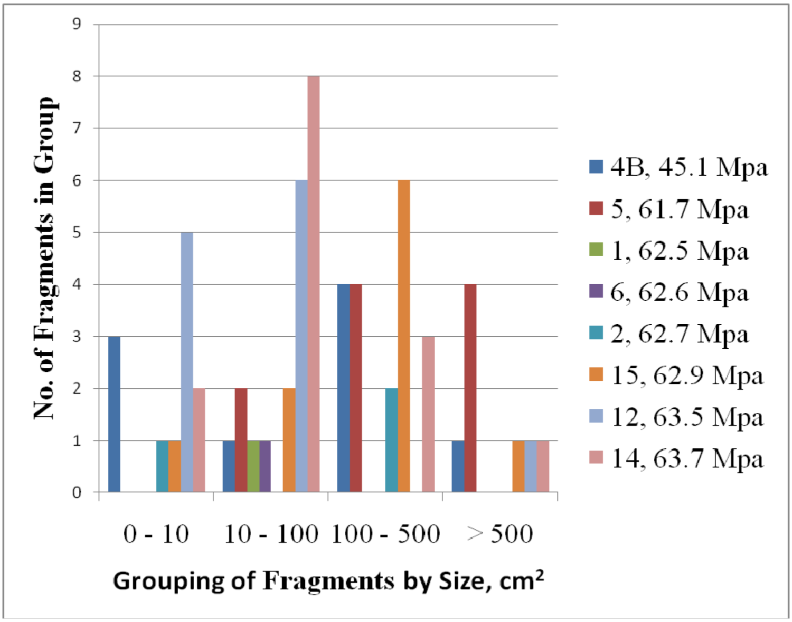

Figure 5: RSCS vs. Total Area of Isolated Fragments.

7. Application of Test Results

Although the documented fragmentation patterns may not be similar under other loading conditions, glass sizes, and glass geometries, it appears reasonable to use the reported findings for determining relative probabilities of failure with associated development of isolated glass fragments.

For example, the subject insulating glass units measure approximately 1460 mm by 2010 mm with an outboard 6 mm thick heat-strengthened lite and an inboard 6 mm thick fully tempered lite. The units are supported along all four sides. According to ASTM E1300 [10], the allowable service load resistance of this unit is approximately 6.6 kPa. Due to equal load share factors, the outer lite would then resist 3.3 kPa. Using recent research by Norville [11], the load resistance (for a probability of failure of 0.008) for heat treated glass with varying RSCS can be calculated. Using the given size, the load resistance for glass with an RSCS of 45 MPa and 62 MPa is 6.52 kPa and 7.98 kPa, respectively. (Note that some extrapolation of the graphs in [11] is necessary, since 62 MPa is outside the limits of both heat-strengthened and tempered glass.)

For simplicity, the load resistance of the heat treated glass can assumed to be normally distributed with a coefficient of variation of 0.15. Based on this assumption and the load resistance values calculated from Norville [11], the probability of failure for glass with an RSCS of 45 MPa and 62 MPa under application of the maximum permissible service load of 3.3 KPa can be determined. These probabilities can, in turn, be multiplied by the probabilities of attaining one or more isolated fragments for a given range of RSCS values. The resulting values represent the combined probability of glass fracturing (under application of the maximum permissible service load) and also developing isolated fragments. Though approximate, this analysis reveals that the combined probabilities are comparable for glass with an RSCS of 45 MPa and glass with an RSCS of 62 MPa. Therefore, the risk of developing isolated fragments as a result of breakage from application of the maximum permissible service load is comparable for glass within the allowable ASTM C1048 [1] RSCS range and glass with an RSCS of approximately 62 MPa. To calculate similar combined probabilities for failures initiated by impact, the relationship between RSCS and impact resistance would be required.

8. Conclusions

A fragmentation test protocol, patterned after EN 1863 [7], was applied to 21 glass samples with RSCS ranging from 41 to 67 MPa. In terms of developing isolated fragments (as defined herein), the fragmentation behavior of the samples did not vary significantly within the RSCS range of 41 to 62 MPa, which compares favorably with previously published findings [5]. These findings indicate that fragmentation of heat treated glass with RSCS well beyond the ATSM C1048 [1] heat-strengthened range of 24 to 52 MPa may be similar to glass within the range. Furthermore, simplistic probabilistic analyses revealed that the risk of glass fallout (i.e., development of one or more isolated fragments) as a result of breakage from application service load pressures is comparable for glass conforming to ASTM C1048 [1] and glass with an RSCS of approximately 62 MPa.

Considering the relatively similar fragmentation behavior of glass with an RSCS of up to approximately 62 MPa, heat-strengthened glass fabricators should not rely on qualitative or quantitative fragmentation tests as a quality control measure to assure compliance with ASTM C1048 [1] RSCS limits. While many fabricators agree that heat-strengthened glass will tend to stay in the opening after fracture, consideration should be given to referencing the EN 1863 [7] protocol if more specific fragmentation behavior is desired.

9. References

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