Needle in a Haystack: Identifying Failure Origin Pieces in Heat-Treated Glass

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Abstract

Failure analysis of heat-treated glass (tempered or heat-strengthened) is often complicated due to the location of the glass in service, manner in which the glass fails, and number of potential causes of failure. Indirect methods of analysis involving intact panels or systems may provide insight into the cause of failure; however, direct analysis is possible if the failure origin can be located.

Due to internal stresses in heat-treated glass, failure results in fracturing of the entire panel creating hundreds or thousands of individual pieces. While the identification of the failure origin pieces from the glass debris can be a challenge; it is feasible to identify the failure origin pieces from failed glass if the evidence is properly collected and maintained. Methodology and case studies discussed herein outline possible methods for preserving, collecting, and/or testing glass debris and other evidence after a failure has occurred, recovering fracture origin pieces from debris, and identifying potential causes of failure from the fracture origin if recovered. The purpose of this paper is to educate the engineering and scientific community regarding the preservation of glass evidence and the methodology for locating fracture origin pieces when evaluating heat-treated glass failures.

Introduction

A basic understanding of the fractography of heat-treated glass allows an informed investigator to form a systematic approach to recovery of the failure origin pieces and determination of cause. Due to the heat-treating process, the outer surfaces of the cross-section of heat-treated glass are in compression while the interior portion is in tension (i.e., tension and compression zones). An initial fracture (i.e., failure origin) creating an imbalance of the internal stresses in the glass can propagate throughout the panel in an instant. The series of fractures and failure of the entire panel occur in rapid sequence outward from the origin, producing a branching, radial fracture pattern. This fracture pattern can help identify the approximate location of the failure origin if the pattern is not lost during failure or prior to the investigators involvement in the failure analysis.

Failure of heat-treated glass in service most-often occurs from surface contact or impact; however, internal imperfections (such as nickel sulfide inclusions) may also cause failure. The properties of the glass and nature of the cause of failure affect the fracture pattern; however, the fracture pattern is always radial from the origin and it is common for two distinctly-shaped pieces of glass to form at either side of the fracture plane at the origin of the failure (Quinn 2007).

The geometry and size of the origin pieces are often distinct in comparison with the remaining fracture pieces from a failed panel. The origin pieces are often larger than other pieces, resembling a hexagon or polygon shape, and containing more sides than the other pieces. Figure 1 depicts the contrast between failure origin pieces and typical pieces of glass from a fractured heat-treated glass panel.

Figure 1: Recovered failure origin pieces in comparison with other pieces from a panel failure.

Methodology

The methodology contained herein is intended to educate the scientific and engineering community regarding preservation and collection of heat-treated glass after failure and an effective method for locating the origin of the failure. It is important to note that some failures will not result in formation of distinct origin pieces; thus this methodology may not always result in recovery of failure origin pieces or identification of the cause of failure.

The methodology and case studies discussed herein will include three scenarios for evaluation of a heat-treated glass failure:

1) Fully intact panel - the glass panel remains whole even though it is fractured throughout. The fracture pattern and origin are visible by initial inspection. This is commonly the case for heat-treated glass that is laminated or coated with a film.
2) Partially intact panel – a significant portion of the panel remains together though the panel is fractured throughout. Groupings of pieces and individual pieces fall out of plane and a portion of the fracture pattern is lost or displaces from its original position. The origin pieces may remain with the intact portion or may have fallen from original position.
3) Panel not intact – a majority (or all) of the panel falls from its original position. The fracture pattern is lost and the origin pieces fall with all other pieces.

Preservation of the fracture pattern, any intact portion of the panel, and collection of all pieces immediately after a heat-treated glass panel failure can be of extreme importance to a forensic investigation (although it may not always be feasible or the primary consideration). Proper safety measures should be taken to avoid injury to pedestrians or those working to collect debris. Ideally, the investigator would be present soon after the failure to document the fracture pattern and conditions at the failure prior to removal and collection of the evidence; however, this may not always be feasible. If the evidence must be disturbed or removed prior to evaluation, documentation and preservation of the failed panel(s) by those handling the glass debris will increase the likelihood of recovering the failure origin and determining the cause of failure.

Preservation and maintenance of the orientation of any intact portion(s) of the breakage is integral to this process. Clear tape, plastic film, or plastic wrap can be used to hold intact panel portions together and keep them from falling apart during removal from the failure site. These intact panel portions or groupings can be removed and laid on a flat surface adjacent to one another to preserve a portion of the fracture pattern. It is vital to maintain all pieces that have fallen or displaced, since the location of the origin piece would be unknown (essentially random) if it were among the debris. Collecting dispersed pieces in containers according to location relative to the panel may also be useful (e.g., center of panel, near the left/right side, or near the top/bottom), especially if the fracture pattern is partially visible and indicates the general location of the fracture origin, which may correlate to a particular area of debris below.

It is important to keep in mind that the fracture pattern and characteristics of the failure origin are key concepts in this methodology. The fracture pattern evident in any intact portion of the panel may be used to deduce the specific or approximate location of the origin pieces. If the panel is no longer intact, and there is no increased likelihood of finding the origin pieces in any one area of the debris, then locating the origin is accomplished by carefully examining the debris; however, a trained eye may more easily find the distinct size and shape of the origin pieces among hundreds or thousands of pieces.

The recommended technique for locating an origin piece among an array of ordinary glass pieces and debris involves a well-lit area and a systematic approach. It is recommended to have a large, flat surface on which to spread the debris material, with bright lighting above (e.g., 8' folding table covered with a section from a paper roll under florescent lighting). The authors have found that light-colored surfaces are easier to work on in comparison with dark-colored surfaces.

The investigator should work with manageable quantities of material, which will vary depending on the size of the viewing surface and volume of material from the failure. If the material is from a panel that was partially intact, the investigator should first work with material that was nearest the location of the origin or most likely to include origin pieces. Then continue to other material until all material has been viewed or the origin piece(s) is/are recovered. If the material is from a panel that was not intact, then material from any area is equally likely to contain an origin piece.

When searching through material, the investigator should keep an area of the viewing table clear and transfer material to this area as it is inspected. After a quantity of material has been inspected, it can be placed into a container and the next quantity of material can be inspected, and so on. The authors have found it efficient to first inspect groupings of individual pieces, then the remaining individual pieces can be spread over the viewing surface. Finally, working with small areas of the dispersed material, the investigator can more readily look for the distinct shape of an origin piece among the other pieces.

Case Study #1 – Fully Intact Panel

After a series of failures of non-laminated heat-treated glass, the remaining glass panels were coated with a plastic film and the attachment of the panels was modified to alleviate safety concerns and to maintain the fracture pattern if another failure occurred. An additional failure occurred and the modifications performed as intended, leaving the panel intact after failure. The failure origin was easily located upon inspection due to fracture pattern and distinct shape/size of the origin pieces. The panel was documented prior to removal, carefully removed, and the origin pieces recovered. Figure 2 depicts the intact panel failure and fracture pattern with a close-up of the origin (see inset photo for close-up).

Figure 2: Fracture pattern of tempered glass panel that remained intact and detail of failure origin.

Case Study #2 – Partially Intact Panel

After a series of failures of heat-treated glass in service, all glass panels were removed from the structure and placed in storage, stacked upright in groups against the wall of the storage area (refer to Figure 3). A panel failed while in storage. The failed panel was within the interior of the stack (i.e., there were panels in front of and behind the failed panel) such that when the panel failed, the fracture pattern remained partially intact and large groupings of pieces were still visible. Upon initial inspection, the fracture pattern indicated that the failure originated near the upper right quadrant of the panel. Therefore, the origin pieces were most likely either attached to the intact portion near the approximate location of the origin, or were within the glass material that had fallen to the floor below this area. Figure 3 depicts the partially intact panel and the most likely area where the failure origin pieces would be located, as deduced from the fracture pattern.

The first origin piece recovered was in fact still attached to the intact portion of the panel and carefully removed without disturbing the remainder of the panel (Figure 4). The second origin piece was located within the material that had fallen to the right of the origin location (Figure 5). Due to the glass panels in front and behind the failed panel, which held portions of the failed panel in place while allowing visibility of the failed panel, locating the origin pieces was relatively easy.

Figure 3: Partially intact tempered glass panel. Failure origin pieces are indicated.

Figure 4: Detail of fracture origin piece remaining on the intact portion of the panel.

Figure 5: Detail of fracture origin piece among the fallen debris.

Case Study #3 – Panel Not Intact

After a panel failure several stories above ground level, the debris was collected by building maintenance personnel. No documentation of any intact portion of the panel was maintained immediately after failure. The authors utilized the methodology contained herein. The debris was removed from the site and taken to a well-lit area and spread over a viewing surface (Figure 6). Groupings of pieces were sorted and inspected first and moved to the edges of the viewing surface (Figure 7). Then the remaining pieces were spread over the viewing surface and small, manageable quantities of the pieces were inspected and set aside before inspecting another quantity. In this particular case, a fracture origin piece was located by the authors while spreading the smaller pieces, due to its distinct size and shape in comparison with the other pieces (Figures 8 and 9).

Figure 6: Material from container poured onto viewing surface.

Figure 7: Material spread, larger groupings separated.

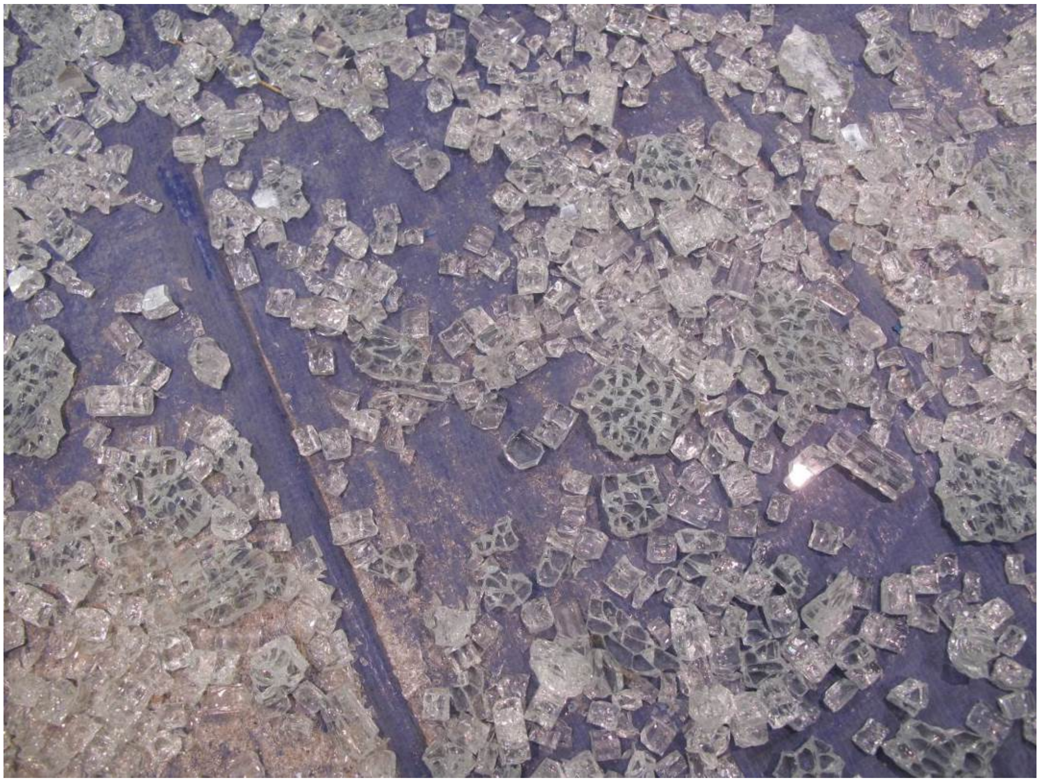

Figure 8: Small groupings and pieces dispersed.

Figure 9: Closer view of previous figure. Failure origin distinct among other pieces.

Testing

While the testing of glass is not the focus of this paper, a brief discussion of testing performed on glass panels and/or origin pieces for determination of the cause of failure is helpful to inform the reader why it is important to find the failure origin piece(s). Testing is generally performed to determine the presence or absence of breakage-inducing inclusions (such as nickel sulfide) within the glass matrix of the subject panels.

For investigation of glass failure due to nickel sulfide inclusions in the glass, unbroken panels may be heat-soak tested. Heat-soaking is a technique wherein glass is placed in an oven at a high temperature for a predetermined time to allow for expansion of any nickel sulfide inclusion within the glass. If such an inclusion is present and expands sufficiently, the tested panel will fracture. One of the above-noted methods can then be used to find the origin pieces, which can be subjected to further examination.

Heat-soak testing is designed to expedite glass failure due to a nickel sulfide inclusion; however, a similar failure can be observed for panels which experience temperature fluctuations either while remaining in use or while contained in storage. Case Study #2 herein discussed the breakage of such a panel which fractured while in storage.

When origin pieces are recovered, the fracture surfaces should be examined for evidence of an anomaly, such as an inclusion. For the Case Studies detailed herein, the origin pieces had anomalies at the fracture surfaces, which were evaluated with a microscope and were determined to be from inclusions within the glass. These inclusions were subjected to chemical testing through energy dispersive spectroscopy (EDS) and were determined to contain high concentrations of both nickel (Ni) and sulfur (S), indicating that the inclusions were indeed nickel sulfide.

Conclusion

Assessing cause of failure of heat-treated glass may involve locating the failure origin. Unfortunately, this is made difficult by the propagation of fractures throughout the panel after a failure initiates at the origin. Utilizing the characteristics of the fractography of heat-treated glass, it is possible in many cases to recover the origin pieces. It is vital to preserve information and evidence after a failure has occurred, because it may increase the likelihood of recovering the origin pieces and reduce the amount of time to reach a determination regarding the cause of failure. Once origin pieces are collected, further testing can be performed to conclusively determine the presence or absence of a breakage-inducing inclusion to aid in determination of the cause of failure.

References

Quinn, Geoge D. *Fractography of Ceramics and Glasses.* Washington, DC: National Institute of Standards and Technology (NIST), 2007.