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Fracture Analysis of a Laminated Window Structure

by Jeffrey J Swab and Parimal J Patel

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14. ABSTRACT

The glass layer on a number of laminated glass/polymer window structures experienced in-service fractures for no obvious reason. A fracture analysis was performed on one of these windows in an attempt to determine the fracture initiation site, fracture origin, estimated stress at fracture, and the fracture process. The analysis revealed that glass layers were scratched, most likely by the action of the wiper blades pulling/pushing debris across the glass. Cracking started due to damage from one of the scratches, and the crack pattern indicates that crack propagation was thermally driven due to the diurnal weathering environment. Fracture mechanics was used to estimate the stress at fracture, which was in excellent agreement with values reported for the glass that was scratched and then loaded in tension under controlled laboratory conditions.

15. SUBJECT TERMS

fracture analysis; glass/polymer window; thermally driven fracture; fracture mechanics; estimated fracture stress

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1. Introduction and Background

Glass/polymer laminated structures are being used to increase the impact resistance of windows used in a variety of applications that require transparency in the visible spectrum. These structures are used as vehicle windows whereby any loss of visibility greatly reduces the functionality of the window. Loss of visibility can be caused by scratches, fractures, clouding, delamination, impact, or a combination of any or all of these events. Borosilicate and soda-lime silicate float glasses are the common glasses employed as the outer layer of the structure, the layer that is exposed to the environment. These glasses are manufactured using a float process whereby the molten glass is floated on a molten tin bath that enables the economic fabrication of large glass sheets of uniform thickness. This float process results in a glass with two sides that have slightly different hardness and strength values. The side in contact with the molten tin is labeled the "tin" side and is typically stronger with the opposite side exposed to the air, labeled the "air" side. The air side can be slightly harder, but the hardness value depends on the indentation load used to create the hardness indentation. It is beneficial to have a hard, damaged-resistant material on the surface exposed to the environment. Utilizing different materials or a harder surface, such the air side of float glass, is common practice.

1.1 Problem

The top glass layer on a significant number of these laminated windows fractured in service for no obvious reason. Eye witnesses did not report any low-velocity impacts from rocks, debris, or other such items. Fracture occurred during normal diurnal weathering with repeated exposures to subfreezing temperatures followed by subsequent exposure to elevated temperatures (approaching 38 °C). The observed fracture only occurred in the top layer (glass) of the window while the rest of the window remained intact. There were concerns about the degradation of visibility caused by this fracture and that the impact resistance of the window had been compromised.

1.2 Objectives

A study was needed to determine the cause of the fracture so a methodology can be developed to mitigate this problem. The objectives of this analysis were to perform a fractographic examination of a fractured window to determine, if possible, 1) the fracture initiation site; 2) the fracture origin; 3) an estimation of the stress at fracture and 4) the fracture process. This reports details the fractographic analysis performed.

2. Results and Discussion

The examination included a visual examination of the crack branching pattern in the glass on an intact laminated window as well as a more detailed examination using a handheld magnifying glass. This window was large and heavy so normal fractographic tools, such optical and scanning electron microscopes, could not be used. The crack branching pattern observed in the visual examination showed that fracture initiated in the glass layer at the location highlighted by the large white arrow in Fig. 1. The crack propagated from this location approximately 50–60 mm in both directions (small white arrows in Fig. 1), and then crack branching began at points A and B. Once the branching began, the subsequent cracks tended to meander and curve, which is an indication of a thermally driven fracture process (thermal stresses from the diurnal weathering were driving the crack growth). What stresses are present or develop in the laminated structure and their potential role in the crack growth behavior is unknown. There appears to be some level of tensile stress near the edge of the laminated window as the cracks labeled 1–4 in Fig. 1 all stop curving at approximately the same distance from the window edge and then propagate straight to the edge.

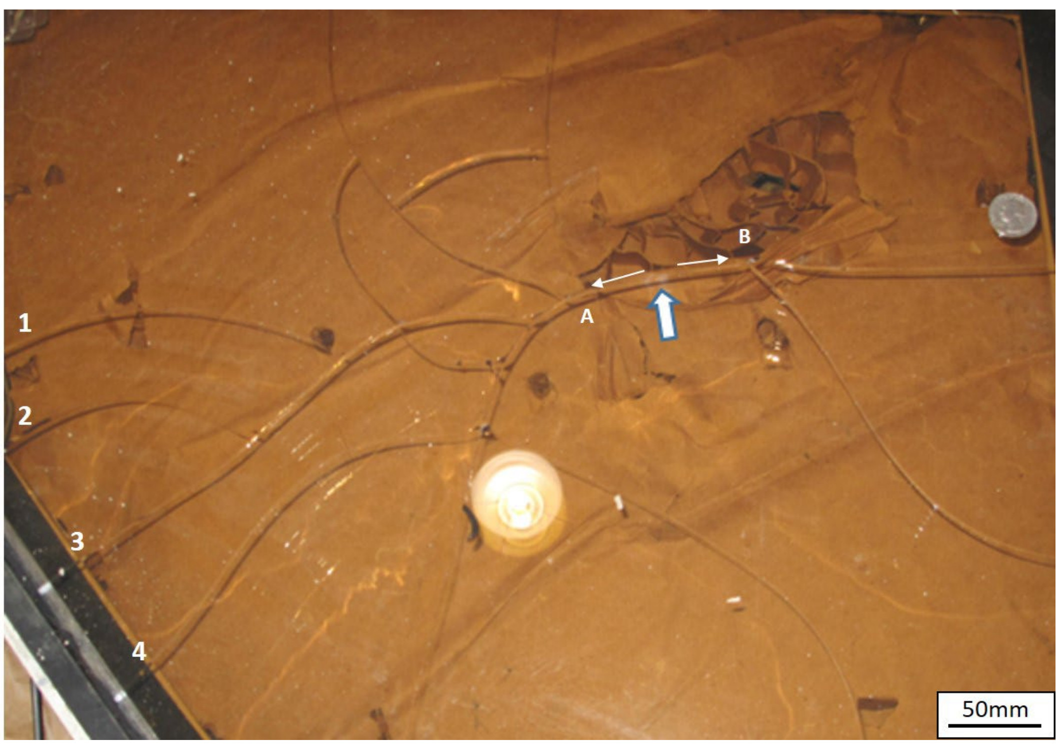

Fig. 1 Overall crack pattern in the glass surface of the window. Fracture initiates at the location highlighted by the large white arrow and propagates in both directions from this point (small white arrows). Crack branching occurs at points A and B.

Further examination of the primary crack, shown in Fig. 1, with a handheld magnifying glass and lighting at different angles to the crack front revealed an anomalous feature (white arrow in Fig. 2) that appears to be where the fracture origin is located. There was no evidence on the glass surface anywhere in the vicinity of the primary crack indicating that an impact event occurred, corroborating the eyewitness reports. The flaw size inside this white feature is difficult to measure accurately since the glass layer and the window are both still intact, but it is estimated to be approximately 0.5 mm deep and 1 mm wide.

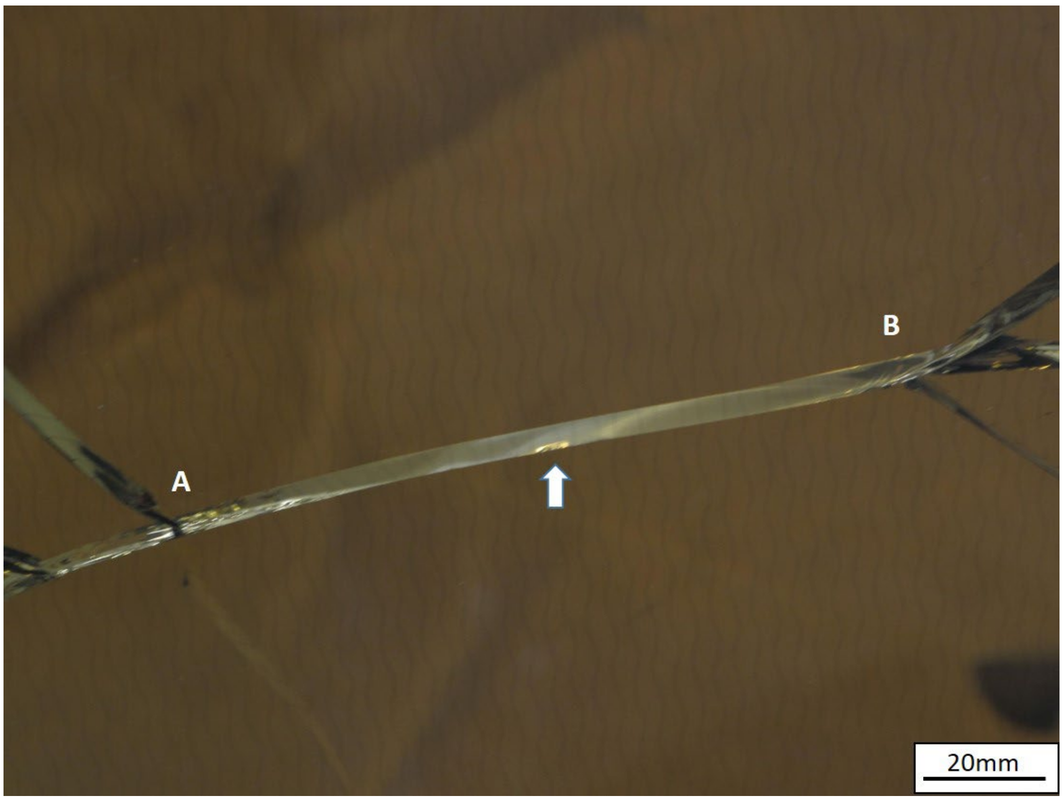

Fig. 2 Close-up of the likely fracture origin (white arrow) in the glass layer and the crack branching locations A and B

Further optical examination of the window shows that there are numerous scratches on the glass surface, red arrows in Fig. 3. Many of these scratches run parallel to each other in an arc across the window as well as being parallel to the path of the primary crack. It is possible that these scratches were created by the action of the wiper blades pulling/pushing grit, sand, or small rocks that got trapped under the blade, across the glass surface when they were in use. The hardness of float glass is very low (HK1 = 4.3 GPa)[1], thus it can be scratched or damaged easily by these items. The creation of scratches in glass can generate a significant amount of damage on the glass surface; this damage penetrates to varying depths beneath the surface.

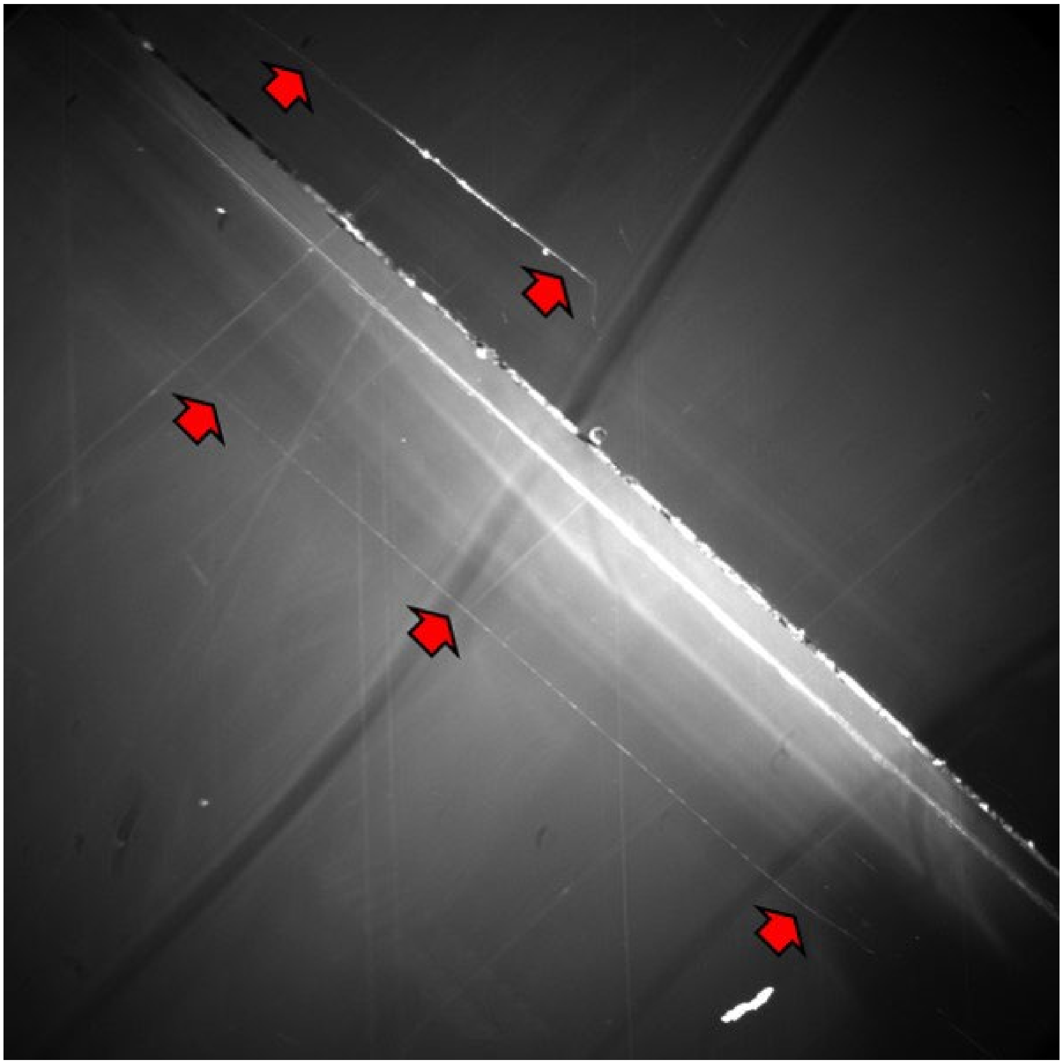

Fig. 3 Red arrows highlight additional scratches observed on the glass surface

Knowing the approximate depth (a) of the flaw and that the fracture toughness (K_{Ic}) of borosilicate float glass when tested in air is 0.61MPa√m,[2] fracture mechanics [$\sigma = K_{IC}/(Y\sqrt{a})$] was used to estimate the level of stress (σ) that initiated fracture. Since the geometry of the flaw in Fig. 2 approximates a semicircle, a value of 1.17[3] was used as the shape factor (Y) in the fracture mechanics equation. The flaw depth could not be accurately measured since the glass layer was still intact; Table 1 shows the estimated fracture stress based on different flaw depths between 0.02 and 1 mm (20 and 1000 μm).

Table 1 Estimated stress at fracture as a function of flaw depth

a (mm)	Estimated σ (MPa)
0.02	117
0.05	74
0.10	52
0.20	37
0.30	30
0.40	26
0.50	23
0.60	21
0.70	20
0.80	18
0.90	17
1.00	16

The equibiaxial flexure strength of a borosilicate float glass has been shown to be approximately 125 MPa for the air side and approximately 160 MPa for the tin side.[4] These strength values are higher than any of the estimated values listed in Table 1 and are appreciably higher than the 23 MPa estimated for a 0.5-mm-deep flaw. However, the reported strength of both the air and tin side of borosilicate float glass drops significantly, to approximately 40 MPa, once a scratch has been introduced on the glass surface.[5] This value is much more in line with many of the estimated strength values in Table 1.

3. Summary

The glass outer layer of numerous laminated window structures experienced an unexplained fracture. A fractographic examination of one of these intact windows was able to identify where fracture originated in the glass layer and revealed that damage from a scratch, probably created by the action of the wiper blades pulling/pushing an unknown hard item across the glass surface, resulted in the formation of a strength-limiting feature approximately 0.5 mm deep. Based on the crack growth behavior, it appears that the crack propagation was driven, at least in part, by thermal stresses that were generated during normal diurnal weathering conditions. The estimated stress at fracture was computed over a range of flaw depths using the fracture toughness of borosilicate float glass in the fracture mechanics equation. The resulting stress estimates were in line with values reported after a borosilicate float glass plate is scratched and then loaded in tension under controlled laboratory conditions. This confirms that the scratch created by the wiper blades pulling a hard item across the glass surface coupled with the diurnal weather environment lead to the fracture of the glass layer of this window. This analysis is critical to understanding the problem in order to effectively mitigate potential future fractures.

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