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Fracture mechanics of impacted laminated glass subjected to various fatigue stressing conditions

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ABSTRACT

This paper investigates the fracture mechanics of micro-cracks in the laminated glass plates of car windshields. Foreign objects such small pieces of gravel impacting a car windshield can induce micro-cracks, which may propagate and lead to dangerous glass fracture events. A major issue is to identify the parameters controlling fracture propagation from the initial micro-crack to catastrophic macroscopic failure. The main conclusion of this study is that cyclic fatigue is not a controlling factor in crack propagation in impacted glass. A subcritical propagation effect, related to chemical reaction between SiO_2 glass and humidity, appears to be the main mechanism of crack propagation. An equivalent "stress intensity factor – time" power formalism is introduced to rationalize crack propagation endurance, for constant and variable cyclic stress conditions.

1. Introduction

Laminated glass is a safety glass used, for example, for car windshields. In the event of sudden braking, it is held in place by an interlayer preventing the glass from breaking up into sharp fragments. A crucial issue concerns predicting crack propagation from an existing crack chip.

A literature review reveals that numerous studies have investigated the crack propagation process of SiO_2 glass under static and stressed conditions [1–6]. These investigations highlighted a so-called "subcritical" crack propagation process [7–12]. This subcritical cracking effect was observed under constant tensile conditions and is in fact controlled by a "corrosion" process operating at the crack tip. When subjected to tensile stress, the crack propagates due to water dissolution of the SiO_2 liaison. Hence, "Arrhenius" time-dependent formalisms were derived to formalize such a water corrosion damage process for a given loading state. However, very few investigations have sought to formalize the relative influence of static stress on the crack propagation rate and even fewer the effect of varying cyclic fatigue stress as in the real-life situation of a car windshield.

The purpose of this paper is to address such aspects and to establish laws for varying cyclic stress, by inducing potential fatigue processes and also by activating cyclic closing/opening at the crack tip, which can enhance the subcritical cracking process by facilitating the access of water molecules. To achieve these objectives, a dedicated experimental strategy was performed. Firstly, an original impacting set-up was developed, combining an optimally-shaped impactor to access a repetitive crack chip well-oriented in length and shape. The impacted glass specimens were then tested under controlled relative

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Nomenclature

σ	stress (MPa)
SIF	stress intensity factor (MPa m$^{1/2}$)
K_{Ic}	glass toughness (MPa m$^{1/2}$)
$K^{i}_{I,max}$	SIF at initial time under σ_{max} stress loading (MPa m$^{1/2}$)
$K^{f}_{I,max}$	SIF at final failure time under σ_{max} stress loading (MPa m$^{1/2}$)
$K^{th}_{I,max}$	infinite lifetime threshold under σ_{max} stress loading (MPa m$^{1/2}$)
K^{i}_{Ieff}	effective SIF defined as $K^{i}_{Ieff} = (K^{i}_{I,max} - K^{th}_{I,max})$ (MPa m$^{1/2}$)
a	half horizontal projected crack width (mm)
W	half width of sample (mm)
β	crack form parameter (dimensionless)
R	fatigue loading ratio (dimensionless)
f	frequency of fatigue loading (Hz)
E_g	glass Young modulus (Pa)
E_{PVB}	polyvinyl butyral polymer Young modulus (Pa)
r^2	linear regression quality parameter (dimensionless)
p-Value	parameter of variance analysis (dimensionless)
N_R	number of cycles (cycles)
A	invert of the SIF rate for the exponential approximation (MPa^{-1} m$^{-1/2}$ s)
B	value at $t \to 0$ of exponential approximation (s)
H	variable of the time endurance power formalism defined as $H = \exp(B)$ (s)

humidity, applying constant stress to address subcritical propagation phenomena, and varying tensile stress conditions to investigate the effect cyclic fatigue stress. An original optical system, triggered at maximum stress, was developed to follow crack extension with optimal accuracy over time. Crack propagation rates were formalized as a function of the computed stress intensity factor (SIF) K_I applied at the crack tip over the loading cycle and/or loading time.

2. Material and experimental set-up

2.1. Sample material and design

The laminated glass specimen was similar to a conventional car windshield laminated glass compound (see Fig. 1). It consisted of two 2.1 mm thick silicate glass plates glued together by an intermediate 0.7 mm polyvinyl butyral (PVB) plate [13].

PVB polymer displays strong mechanical properties and good adhesion with glass, retaining glass fragments in a crash, thus improving safety. The Young modulus of the glass is about E_g = 70 GPa, whereas that of PVB is E_{PVB} = 0.05–0.1 GPa [14]. Hence the PVB layer can be neglected in the following stress analysis, assuming that all the stress loading is transferred to the two lateral glass plates of the laminated composite.

2.2. Experimental test procedure

The global strategy of experimental analysis is described in Fig. 2. Rectangular specimens, 40 mm in width and 160 mm in length, were extracted from a specific large flat laminated PVB glass plate, provided by Carglass®, the structure of which was equivalent to a real car windshield (Fig. 1).

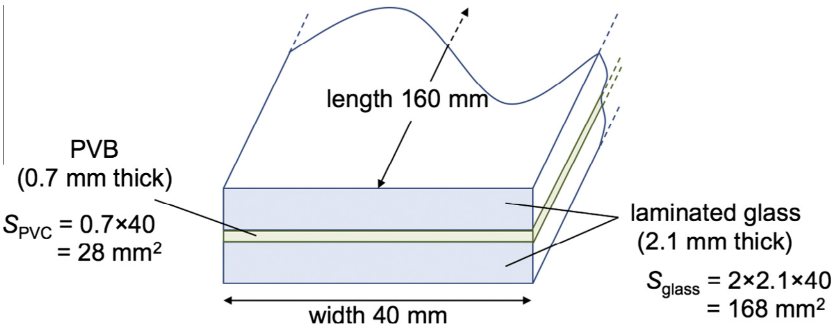

Fig. 1. Description of laminated PVB glass specimens, with calculation of transversal sections for PVB layer and glass plates.