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Failure probability of laminated architectural glazing due to combined loading of wind and debris impact

Mahesh S. Shetty, Lokeswarappa R. Dharani *, Jun Wei, Daniel S. Stutts

Mechanical and Aerospace Engineering Department, Missouri University of Science and Technology, Rolla, MO 65409-0050, USA

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ABSTRACT

Building façades are vulnerable to wind and wind-borne debris during extreme weather conditions like hurricanes. Laminated glazing is widely used as window glazing material to ensure the integrity of the building interiors. Wind-borne debris has been classified as small-hard and large soft missiles representing small gravel to large wooden bars that constitute the debris impacting the glazing during severe storms. Failure of laminated window glazing due to combined effect of wind and debris is studied. Stress analysis is done using finite element code ABAQUS. This is used in conjunction with a mechanics based statistical model to predict the cumulative probability of inner glass ply breakage in laminated glazing. A parametric study involving failure probability of inner glass ply for different geometry of laminated glazing is also performed.

1. Introduction

Laminated glazing, in recent years, has become one of the popular forms of window glazing for protection against hurricanes. It consists of two soda lime glass plies sandwiching a layer of polymer like Polyvinyl Butyral (PVB). Windborne debris combined with strong winds is the main reason for failure of glazing in the buildings. Unlike monolithic glazing, which breaks into dangerous shards and thus resulting in breaching of building envelope, laminated glazing holds the broken pieces of glass in its interlayer and also maintains the building integrity with the interlayer holding onto the frame.

Many researchers have studied the response of architectural glazing impacted by wind and debris. The small missile impact response of laminated glazing has been studied in detail. Flocker and Dharani [1–4] conducted a stress analysis of laminated glazing subjected to small missile impact studying the response for different PVB properties and geometry of laminated architectural glazing (LAG). They also developed a fracture model based on Hertzian cone crack to simulate the fracture in outer glass ply. This model was used by Dharani et al. [5] to predict the failure of inner glass ply of laminated glazing with outer glass ply used as "sacrificial ply". The outer ply is allowed to crack and the failure probability of inner ply is determined using a mechanics based analytical model. The stresses are computed using finite element code DYNA-2D. Behr et al. [6] validated Flocker and Dharani's model [1] for LAG subjected to low velocity small missile impacts. In their work, impact velocity, interlayer thickness, glass thickness, and glass type were varied. Dynamic strains predicted by the finite element analysis agreed with those measured using a high-speed strain gauge data acquisition system. Ji et al. [7] studied the probability of damage at the impact site in the outer glass ply of LAG subjected to low velocity small missile impacts. A dynamic nonlinear finite-element analysis was performed to compute the stress response due to impact. They characterized the cumulative probability of damage to the outer glass ply using the cumulative damage theory presented by Tuler and Butcher [8] and Brown [9]. The PVB interlayer thickness had only a negligible effect on damage to the outer glass ply when

* Corresponding author. Tel.: +1 573 341 6504; fax: +1 573 341 4607.
E-mail address: dharani@mst.edu (L.R. Dharani).

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the impacts were made on the outer glass ply. Experimental investigation of small steel ball impacts on laminated glazing by Kaiser et al. [10] and Saxe et al. [11] revealed that inner glass ply thickness and PVB interlayer thickness are more significant on the failure of inner glass ply. This experimental work also included the effects of impact velocity of missile, missile size and glass type.

Duser et al. [12] studied the response of laminated glass panels subjected to uniform lateral pressure using finite element code ABAQUS. The stress analysis results were combined with statistical model to find the probability of failure of inner surface of laminated glazing. Tsai and Stewart [13] studied the stress and deflection characteristics of large plates undergoing large defections due to wind load through a series of experimental tests and finite element simulations on glass plates of different geometric configuration.

Wei and his co-workers carried out some initial analytical work on LAG subjected to blast loading. Their work included dynamic and stress response [14], fracture [15] and failure analysis [16,17]. More recently, several researchers have studied extensively the dynamics response and the effect of hazard mitigation mechanisms such as cable net façade and dissipative devices [18–25] for LAG subjected blast loading. These studies include both analytical modeling and experimental investigation.

In studying the damage to LAG during windstorms and hurricanes, earlier works cited above dealt with wind loading or debris impact separately. This study deals with the response and failure probability of laminated glazing subjected to combination of wind loading and debris impact. Debris impact studies have been largely restricted to studying the response of small missile impacts. Large debris impact studies have been done typically for circular glazing [26]. Rectangular glazing configuration is the most common form for window glazing. The combination of wind loading and debris impact on rectangular glazing configuration has not been studied extensively. Recently, the pre-failure stress response and damage response of the LAG due to the combined loading of wind and windborne debris impact has been studied by Shetty et al. [27,28]. The failure probability of rectangular LAG subjected combined loading has not been studied and hence the motivation for this study. As in Shettyet al. [27,28], a finite element analysis is performed to find the stresses due to wind and debris impact. This is used in conjunction with a statistical model, a two-parameter Weibull distribution, to describe the cumulative probability of failure of inner ply of laminated glazing. The influence of LAG geometry on failure probability of inner glass (exposed to the building interior) is studied parametrically.

2. Failure prediction model

According to Griffith's crack growth criterion, fracture of brittle solids occurs due to the existence of surface flaws or cracks in the presence of a tensile stress field. In the case of glass panels, these flaws are introduced during manufacturing processes and/or during its service life. A failure prediction model developed by Beason and Morgan [29] is adopted in this study. The model relates the lateral loading and surface strength parameters 'm' and 'k' discussed below. Norville and Minor [30] also adopted this model [29] in their study of failure of aged and new glass panels under lateral pressure loading. These parameters represent strength characteristics of the plate surface and can be used to measure deterioration in the strength of glass surfaces. They are independent of load duration, panel surface area and geometry. This model predicts the failure at the surface of the glass panel and has been used successfully for LAG [5–7]. The cumulative probability of damage (p_f) of monolithic glass panel subjected to wind and debris impact is given by [29,30,5–7],

$$P_f = 1 - \exp[-kB_0] \tag{1}$$

where k is the surface flaw parameter, and B_0 is the risk factor that is given by,

$$B_0 = \int_0^a \int_0^b [c(x,y)\tilde{\sigma}_{\max}(x,y)]^m \mathrm{d}x\mathrm{d}y \tag{2}$$

where m is the surface flaw parameter and c is the biaxial stress correction factor given by,

$$c = \left[\frac{2}{\pi}\int_0^{\varphi} (\cos^2\theta + \lambda\sin^2\theta)^m d\theta\right]^{\frac{1}{m}} \tag{3}$$

where λ is the ratio of the minimum to maximum principal stresses, φ is the angle of the surface flaw orientation to the maximum principal stress, and

$$\varphi = \begin{cases} \frac{\pi}{2}, & \text{if both principal stresses are positive} \\ \tan^{-1}\left|\frac{\tilde{\sigma}_{\min}}{\tilde{\sigma}_{\max}}\right|^{\frac{1}{2}}, & \text{if minimum principal stresses is negative.} \end{cases} \tag{4}$$

The equivalent sixty-second constant stress is [29,30,5–7],

$$\tilde{\sigma}_{\max}(x,y) = \left[\frac{1}{60}\int_0^{t_f} \sigma_p(x,y,t)^n \mathrm{d}t\right]^{\frac{1}{n}} \tag{5}$$