Materials, Structures and Reliability
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Interface Bonding Quality for Delamination Resistance in Laminated Glass Systems: Comparative Testing

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Abstract

Laminated glass systems are widely utilized in modern architectural and structural engineering due to their enhanced safety, acoustic damping, and post-breakage load-bearing capacities. The structural integrity and durability of these composite systems are intrinsically linked to the interfacial bonding quality between the glass plies and the polymeric interlayer. This paper presents a comprehensive comparative analysis investigating the fundamental relationship between interface bonding characteristics and delamination resistance across different laminated glass configurations. By evaluating three primary interlayer materials, specifically Polyvinyl Butyral, SentryGlas ionomer, and Ethylene Vinyl Acetate, this study seeks to elucidate how variations in chemical adhesion and physical interlocking affect the macroscopic fracture energy required to propagate delamination. A rigorous experimental methodology is employed, encompassing standardized peel tests and compressive shear evaluations, followed by cyclic environmental conditioning to simulate long-term weathering. The findings demonstrate a pronounced correlation wherein higher initial interfacial shear strength translates directly into superior delamination resistance, although this relationship is non-linear and highly dependent on the viscoelastic properties of the specific polymer under varying temperatures and humidity levels. The insights generated from this research provide critical empirical evidence for optimizing lamination parameters and selecting appropriate interlayer materials in structural applications.

Keywords: Laminated Glass; Interfacial Bonding; Delamination Resistance; Polymeric Interlayers; Structural Engineering

1. Introduction

1.1 The Evolution of Architectural Glass Systems

The integration of glass as a primary structural material represents one of the most significant architectural advancements of the past century. Historically relegated to non-load-bearing window panes, glass is now routinely employed in facades, canopies, balustrades, and structural columns. This paradigm shift was largely facilitated by the development of laminated glass, a composite material consisting of two or more glass plies bonded together by a polymeric interlayer [1]. The primary function of the interlayer is to retain glass shards in the event of fracture, thereby minimizing the risk of laceration and providing a residual post-breakage capacity that prevents catastrophic structural collapse. As architectural designs continue to push the boundaries of transparency and lightness, the demands placed on laminated glass systems have increased exponentially [2]. Modern applications require these transparent composites to withstand severe environmental loads, including hurricane-force winds, seismic activity, and even blast loading. Consequently, the mechanical behavior of laminated glass, which is fundamentally governed by the shear transfer capabilities of the interlayer, has become a focal point of intense academic and industrial research [3]. The efficacy of this shear transfer, and by extension the structural performance of the entire system, relies heavily on the quality of the

bond formed at the glass-polymer interface during the manufacturing process [4]. Understanding the nuances of this interfacial bonding is therefore paramount for engineers seeking to design safe, durable, and highly transparent structures [5].

1.2 Failure Mechanisms and Delamination

Despite the exceptional performance of laminated glass under normal conditions, the system is susceptible to various degradation and failure mechanisms over its service life. Among the most critical of these is delamination, defined as the separation of the polymeric interlayer from the glass substrate. Delamination not only compromises the aesthetic quality of the glazing by introducing visible bubbles and cloudiness but also severely degrades the structural integrity of the composite [6]. When delamination occurs, the ability of the interlayer to transfer shear stresses between the glass plies is localized or entirely lost, effectively reducing the composite system to a series of independent, structurally inferior glass plates. The onset of delamination is typically instigated by a complex interplay of mechanical stresses and environmental factors. External loads, constrained thermal expansion, and moisture ingress can create localized stress concentrations at the glass-polymer interface [7]. If these interfacial stresses exceed the bonding strength, a delamination front initiates and propagates. The resistance to this propagation, termed delamination resistance, is a critical parameter that dictates the durability of the laminated glass panel [8]. While the bulk viscoelastic properties of the interlayer material contribute to energy dissipation during delamination, the foundational defense against the initiation and spread of interfacial separation is the intrinsic bonding quality achieved during lamination [9]. Therefore, establishing a quantifiable link between measurable bonding metrics and macroscopic delamination resistance is essential for predicting the long-term viability of structural glass installations.

1.3 Research Objectives and Scope

The primary objective of this paper is to rigorously investigate and quantify the relationship between initial interface bonding quality and subsequent delamination resistance in laminated glass systems. While previous studies have independently assessed adhesion strength or tracked delamination under weathering, there remains a critical gap in correlative testing that definitively links initial micro-mechanical bonding metrics with macroscopic resistance to delamination propagation under controlled shear loads [10]. To address this, the current study undertakes a comprehensive comparative analysis of laminated glass specimens prepared with the three most prevalent interlayer materials in the construction industry. By subjecting these specimens to a unified testing regimen that includes both baseline bonding evaluation and progressive delamination testing under varied environmental conditions, this research aims to isolate the variables that most significantly dictate structural longevity. The scope of this paper encompasses a detailed review of bonding mechanisms, a meticulous explanation of the experimental protocols, an extensive presentation of the comparative data, and an analytical discussion on how these findings can be leveraged to improve manufacturing standards and inform more robust design guidelines for structural glass applications.

2. Background and Literature Review

2.1 Polymeric Interlayers in Laminated Glass

The mechanical behavior of laminated glass is inextricably linked to the physical and chemical properties of the polymeric interlayer. Polyvinyl Butyral has been the industry standard for decades, prized for its excellent optical clarity, high elongation at break, and exceptional energy absorption capabilities under impact loads [11]. However, Polyvinyl Butyral is a highly viscoelastic material with a relatively low shear modulus at room temperature, making it prone to significant creep under sustained loading. Furthermore, it is highly hygroscopic, meaning it readily absorbs moisture from the environment, which can aggressively degrade the interfacial bond and promote edge delamination [12]. In response to the limitations of Polyvinyl Butyral in structural applications, ionoplast interlayers, commonly referred to by the trade name SentryGlas, were developed. Ionoplast polymers exhibit a stiffness that is orders of magnitude higher than standard Polyvinyl Butyral, alongside significantly enhanced tear strength and superior moisture resistance [13]. This makes them ideal for demanding structural applications such as glass fins, floor panels, and blast-resistant glazing. The third major category is Ethylene Vinyl Acetate, which offers a balance of moderate stiffness, good moisture resistance, and lower processing temperatures [14]. Ethylene Vinyl Acetate is heavily utilized in photovoltaic

encapsulation and interior decorative glass, though its use in heavy structural engineering is growing due to advancements in cross-linking formulations. The distinct molecular architectures of these three polymers dictate not only their bulk mechanical responses but also the specific mechanisms by which they adhere to the silicate network of the glass surface.

2.2 Interfacial Bonding Mechanisms

The adhesion between an inorganic glass substrate and an organic polymer interlayer is a multifaceted phenomenon relying on a combination of chemical bonding, physical interactions, and mechanical interlocking. The surface of float glass is populated by hydroxyl groups, which provide the primary active sites for chemical adhesion [15]. In the case of Polyvinyl Butyral, adhesion is predominantly mediated by hydrogen bonding between the hydroxyl groups on the polymer chain and the silanol groups on the glass surface. This hydrogen bonding is highly sensitive to the presence of water, which can competitively bind to the silanol sites, leading to reversible or irreversible bond degradation [16]. To modulate this adhesion, manufacturers often incorporate adhesion control additives, specifically alkaline metal salts, which compete for the bonding sites and ensure that the adhesion is optimized rather than maximized. Optimized adhesion is crucial; if the bond is too strong, the glass shards cannot slide and stretch the polymer during an impact, reducing the energy dissipation capacity and making the panel prone to brittle failure [17]. Conversely, ionoplast interlayers achieve adhesion through a different mechanism, relying heavily on ionic cross-linking and the inclusion of specific silane coupling agents that form robust, moisture-resistant covalent bonds with the glass surface. Ethylene Vinyl Acetate also relies heavily on silane chemistry, where the coupling agents form a chemical bridge, chemically reacting with both the polymer matrix and the inorganic glass during the thermal lamination process. Understanding these distinct bonding mechanisms is critical when evaluating how different systems will resist the stresses that lead to delamination [18].

2.3 Current Perspectives on Delamination Testing

Evaluating the bonding quality and delamination resistance of laminated glass has historically relied on a variety of standardized and bespoke testing methodologies. The pummel test is a ubiquitous quality control measure in the automotive and architectural glass industries. It involves striking a chilled laminated glass sample with a hammer and visually estimating the amount of bare glass exposed, yielding a subjective numerical value [19]. While useful for rapid factory floor assessments, the pummel test provides no quantifiable engineering data regarding shear strength or fracture energy. To obtain more rigorous mechanical metrics, researchers frequently employ compressive shear testing and peel tests. Compressive shear tests isolate the interfacial shear strength by pushing the two glass plies in opposite directions, generating a relatively pure state of shear stress at the interlayer. Peel testing, typically conducted at a ninety-degree or one-hundred-and-eighty-degree angle, measures the force required to pull the polymer film away from the glass, providing a direct measurement of the adhesive fracture energy [20]. Recent advancements in experimental mechanics have introduced sophisticated full-field measurement techniques, such as digital image correlation, to track the strain fields and localized stress concentrations ahead of the delamination front [21]. However, a significant portion of the literature focuses on testing unweathered specimens at room temperature. The critical gap addressed by this paper is the systematic correlation of these precise mechanical testing metrics with the macroscopic delamination phenomena observed after the composite system has been subjected to aggressive, cyclic environmental conditioning, thereby providing a more realistic assessment of in-service delamination resistance.

3. Methodology and Experimental Design

3.1 Material Selection and Specimen Preparation

To ensure a comprehensive comparative analysis, three distinct laminated glass configurations were designed, utilizing Polyvinyl Butyral, SentryGlas, and Ethylene Vinyl Acetate as the respective interlayers. All specimens were constructed using standard soda-lime silicate float glass, possessing a nominal thickness of four millimeters. Prior to assembly, the glass plates were subjected to a rigorous cleaning protocol to guarantee a consistent surface energy and eliminate any localized contaminants that could serve as artificial delamination initiation sites [22]. The cleaning sequence involved a deionized water rinse, scrubbing with an industrial non-

ionic detergent, a secondary deionized water rinse, and finally, drying in a controlled forced-air oven at sixty degrees Celsius. The polymeric interlayers, each with a nominal thickness of point seven six millimeters, were stored in a climate-controlled environment to prevent premature moisture absorption.

The lamination process was conducted in a cleanroom environment to prevent particulate inclusion. The sandwich structures, consisting of the interlayer positioned precisely between two glass plies, were placed into specialized vacuum bags. A primary vacuum de-airing process was conducted at room temperature to evacuate the interstitial air and create initial contact between the layers. The assemblies were then transferred to a laboratory-scale autoclave. The autoclaving parameters were meticulously calibrated according to the specific thermal requirements of each polymer type. For the Polyvinyl Butyral and SentryGlas specimens, the autoclave cycle involved a gradual temperature ramp to one hundred and forty degrees Celsius, accompanied by an increase in pressure to twelve bar. This peak state was maintained for a dwell time of ninety minutes to ensure complete polymer flow and the establishment of robust interfacial bonds, followed by a controlled cooling phase under pressure [23]. The Ethylene Vinyl Acetate specimens were processed at a slightly lower peak temperature of one hundred and twenty degrees Celsius to optimize the specific cross-linking kinetics of the formulation used. Following lamination, all specimens were allowed to condition in a standard laboratory environment for a period of fourteen days to ensure the relaxation of any residual thermal stresses introduced during the autoclaving cycle.

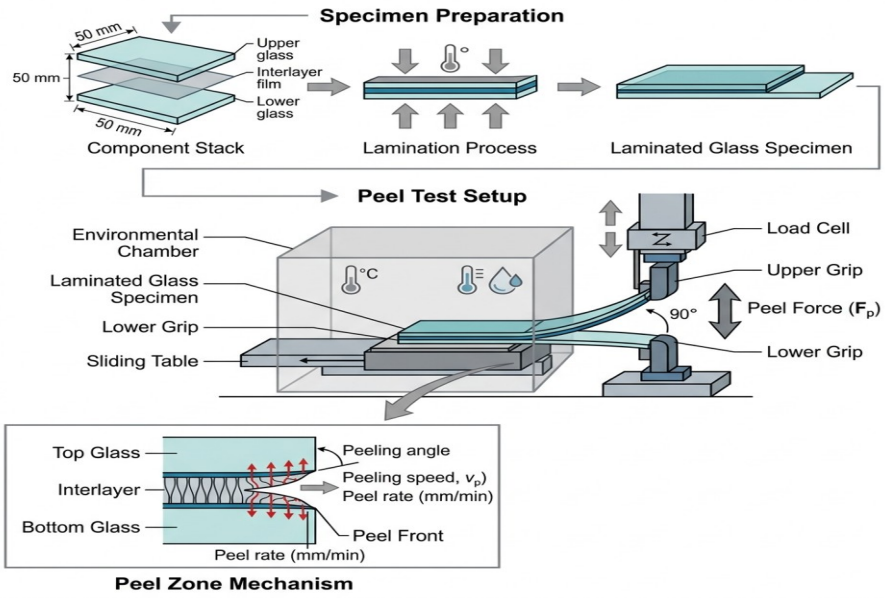

Figure 1: Comprehensive Schematic of Laminated Glass Specimen Preparation and Peel Test Setup

3.2 Testing Apparatus and Protocols

The experimental regimen was designed to evaluate both the baseline bonding quality and the dynamic delamination resistance under environmental stress. The testing framework was divided into two primary phases: initial mechanical characterization and post-weathering delamination assessment.

For the initial characterization, peel tests were executed using a high-precision universal testing machine equipped with a specialized ninety-degree peeling fixture. To perform this test, the top glass ply was intentionally omitted from a section of the specimen during lamination, leaving a free tab of the polymer interlayer. This tab was clamped in the pneumatic grips of the testing machine. The load cell, possessing a capacity of five kilonewtons, recorded the force required to peel the interlayer from the rigid glass substrate at a constant crosshead displacement rate of fifty millimeters per minute. The steady-state peeling force was divided by the width of the specimen to calculate the nominal peel strength, which serves as a direct indicator of the interfacial fracture energy under mode one loading conditions [24].

Following the peel tests, compressive shear tests were conducted to evaluate the mode two shear strength of the interface. Laminated glass squares measuring fifty by fifty millimeters were clamped in a custom-designed

shear fixture. The fixture held one glass ply stationary while a concentrated load was applied to the edge of the second glass ply, parallel to the bonding plane. The load was increased monotonically until catastrophic failure occurred, either through interfacial debonding or cohesive tearing of the polymer matrix.

To simulate long-term environmental degradation and its effect on delamination resistance, a separate cohort of specimens was subjected to accelerated weathering in a programmable environmental chamber. The weathering cycle was designed to induce maximum hygrothermal stress at the glass-polymer interface. Each twenty-four-hour cycle consisted of eight hours at sixty degrees Celsius and ninety-five percent relative humidity, followed by a rapid temperature drop to minus twenty degrees Celsius for eight hours, concluding with eight hours of ultraviolet radiation exposure at room temperature. This cyclic conditioning was maintained for a total duration of one thousand hours. Post-weathering, the specimens underwent a modified wedge-driven delamination test. A steel wedge with a predefined geometric angle was driven into the exposed edge of the polymeric interlayer at a constant velocity. The force exerted by the wedge and the corresponding length of the delamination crack propagating ahead of the wedge tip were simultaneously recorded using an integrated digital imaging and load cell system. This allowed for the continuous calculation of the critical strain energy release rate necessary to drive the delamination front, providing a definitive quantitative measure of delamination resistance under simulated service conditions.

4. Results and Discussion

4.1 Comparative Bonding Quality Analysis

The initial mechanical characterization revealed substantial disparities in the baseline bonding quality among the three interlayer materials, reflecting their distinct chemical compositions and adhesion mechanisms. The results of the compressive shear tests and the ninety-degree peel tests are summarized in the comparative table below.

Table 1: Baseline Mechanical Bonding Properties of Laminated Glass Interlayers

Interlayer Material	Average Peel Strength	Compressive Shear Strength	Predominant Failure Mode
Polyvinyl Butyral	6.8 Newtons per millimeter	14.5 Megapascals	Mixed Adhesive-Cohesive
SentryGlas Ionomer	12.4 Newtons per millimeter	28.2 Megapascals	Cohesive Tearing
Ethylene Vinyl Acetate	8.5 Newtons per millimeter	18.1 Megapascals	Adhesive Debonding

The data indicates that the SentryGlas ionomer exhibited the highest initial bonding quality across both testing modalities. The compressive shear strength of the SentryGlas specimens was nearly double that of the Polyvinyl Butyral specimens. Furthermore, during the peel testing of the ionomer, the force required to propagate the peel was so immense that failure predominantly occurred cohesively within the bulk polymer itself, rather than adhesively at the glass interface. This suggests that the covalent bonds formed by the silane coupling agents in the ionomer matrix exceed the internal yield strength of the polymer [25]. In contrast, the Polyvinyl Butyral specimens demonstrated a more moderate bonding profile. The peel test curves for Polyvinyl Butyral displayed characteristic saw-tooth fluctuations, indicative of a stick-slip delamination propagation where the hydrogen bonds yield and reform locally ahead of the advancing crack tip. The failure mode was consistently a mixed state, leaving thin residues of the polymer on the glass surface, which is characteristic of the optimized adhesion designed into architectural Polyvinyl Butyral formulations to maintain impact energy absorption. The Ethylene Vinyl Acetate specimens positioned themselves intermediately in terms of numerical strength values, but notably exhibited a clean, adhesive failure mode, cleanly separating from the glass substrate without significant internal tearing. This clean separation suggests a highly uniform, albeit slightly weaker, interfacial bonding layer compared to the deeply integrated chemical adhesion of the ionomer.

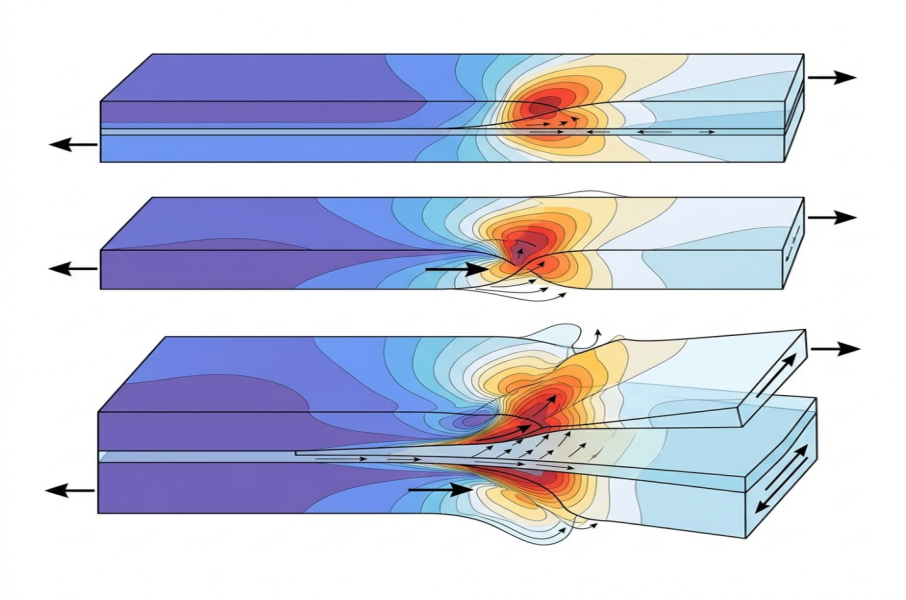

Figure 2: Analytical Visualization of Delamination Propagation and Interfacial Stress Distribution

4.2 Delamination Resistance and Environmental Effects

The transition from initial bonding metrics to dynamic delamination resistance, particularly following severe environmental conditioning, provided the most critical insights of this investigation. The one thousand hours of cyclic hygrothermal and ultraviolet weathering drastically altered the performance hierarchy established during the baseline testing.

The Polyvinyl Butyral specimens exhibited extreme sensitivity to the moisture ingress introduced during the high-humidity phases of the weathering cycle. Visual inspection prior to mechanical testing revealed localized edge delamination and subtle clouding extending several millimeters inward from the exposed perimeter. During the wedge-driven delamination tests, the force required to propagate the crack in the weathered Polyvinyl Butyral specimens dropped by nearly forty percent compared to the unweathered controls. This substantial reduction in delamination resistance is attributed to the ingress of water molecules, which aggressively penetrate the hydrophilic matrix of the polymer and disrupt the delicate balance of hydrogen bonds at the glass interface. As the water plastically softens the polymer near the edge, the localized shear transfer capacity diminishes, allowing the wedge to easily cleave the interface.

Conversely, the SentryGlas specimens demonstrated exceptional retention of their delamination resistance following the weathering protocol. The reduction in the critical strain energy release rate necessary to drive the wedge through the ionomer interface was less than five percent. This robust performance validates the hypothesis that the heavily cross-linked, ionic nature of the SentryGlas matrix, combined with its strong covalent interfacial bonds, effectively repels moisture ingress. The resistance to delamination remained high because the environmental stressors were unable to compromise the fundamental chemical anchorage at the interface.

The Ethylene Vinyl Acetate specimens displayed a moderate degradation in delamination resistance, losing approximately fifteen percent of their initial resistance capacity. While the cross-linked structure of Ethylene Vinyl Acetate provides better moisture resistance than standard Polyvinyl Butyral, it does not possess the extreme impermeability of the ionoplast material. The testing data clearly establishes a direct correlation between the inherent moisture resilience of the bonding mechanism and the sustained delamination resistance of the overall system. High initial peel strength, while an excellent indicator of baseline quality, is only predictive of long-term delamination resistance if the specific bonding chemistry is capable of withstanding prolonged hygrothermal cycling [26].

5. Conclusion

5.1 Summary of Findings

This comprehensive experimental study has systematically evaluated the fundamental relationship between initial interface bonding quality and long-term delamination resistance in structural laminated glass systems. By comparatively analyzing Polyvinyl Butyral, SentryGlas ionomer, and Ethylene Vinyl Acetate interlayers through a combination of initial mechanical characterization and post-weathering fracture mechanics, several critical insights have been established. The baseline testing confirmed that ionoplast interlayers achieve significantly higher initial shear and peel strengths compared to their traditional viscoelastic counterparts, primarily due to the formation of robust covalent bonds and extensive ionic cross-linking. The subsequent weathering phases demonstrated that high initial bonding strength is a necessary but insufficient condition for ensuring long-term delamination resistance. The structural longevity of the composite is ultimately dictated by the environmental stability of the interfacial bonds. Polyvinyl Butyral, despite its exceptional impact performance, exhibited profound vulnerability to hygrothermal degradation, resulting in a dramatic loss of delamination resistance due to moisture-induced bond disruption. In stark contrast, the SentryGlas configurations maintained near-complete structural integrity and resistance to wedge-driven delamination after severe cyclic weathering, proving the superiority of its moisture-resistant chemical adhesion profile.

5.2 Engineering Implications

The empirical evidence generated from this research holds substantial implications for the architectural and structural engineering communities. The clear correlation between interlayer chemistry, weathering degradation, and macroscopic delamination resistance underscores the critical need for context-specific material selection in structural glass design. For internal applications or environments where hygrothermal cycling is minimal, traditional interlayers may continue to provide adequate safety and structural coherence. However, for external facades, exposed canopies, and load-bearing structural elements operating in demanding climates, the utilization of advanced ionoplast polymers is highly recommended to mitigate the risks associated with edge delamination and subsequent loss of shear coupling. Furthermore, the findings highlight the inadequacy of relying solely on standard room-temperature peel or shear tests as definitive predictors of service life. Future quality control paradigms in laminated glass manufacturing must incorporate accelerated environmental conditioning followed by dynamic fracture testing to accurately assess the true delamination resistance of the product. By integrating these rigorous, correlative testing methodologies, engineers can more accurately model the long-term behavior of structural glass composites, ultimately leading to safer, more durable, and more reliable architectural innovations.

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