

Thermo-Mechano-Electromagnetic Multi-Physics Coupling Analysis, Unified-Datum Tolerance Coordination and Full-Lifecycle Experimental Verification of Triple-Functional Integrated Automotive Laminated Windshield Glass

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Abstract

Intelligent new-energy vehicles increasingly require front windshield laminated glass to integrate electrochromic dimming, low-temperature rapid defrosting and an embedded digital-television (DTV) antenna. The superposition of multilayer polymer films, screen-printed silver conductive traces and embedded flat wiring harnesses, however, introduces thermo-mechano-electromagnetic coupling failure modes. Here, we propose three hierarchically optimized substructures—a stepped-gradient ceramic anti-corrosion shielding layer, a 0.2 mm-protrusion full-wrap harness bonding configuration and full-wrap silicone sealing for marginal un-melted polyvinyl butyral (PVB) zones—and couple them with an ISO 5459-conformant unified symmetric datum (PD-A) tolerance chain model. A fully coupled thermo-mechano-electromagnetic finite-element numerical model, validated through a four-level mesh-convergence study and a five-factor parametric sensitivity matrix, is developed to quantify interfacial stress evolution and electromagnetic interference attenuation. A coupon-grade multi-station test fixture (denoted 8S10Z-39J-900) is fabricated and used for systematic cleavage peeling, alternating thermal cycling, hygrothermal/UV accelerated aging, optical modulation, electrothermal defrost and antenna electromagnetic tests. All quantitative results are reported as mean $\pm$ standard deviation of $n = 6$ parallel specimens and analyzed by one-way ANOVA followed by Tukey HSD post-hoc test at $\alpha = 0.05$. The optimized harness scheme reduces the maximum interfacial shear stress from 18.46 ± 0.42 MPa to 10.58 ± 0.31 MPa (42.7 % reduction, $p < 0.001$), while the experimental average peeling force reaches 246.3 ± 4.8 N at 23 °C—23.1 % above the 200 N industrial threshold. After 1200 cycles of -30 °C $\leftrightarrow$ +80 °C thermal cycling, 1000 h of 85 °C / 85 % RH hygrothermal exposure and 500 h of UV irradiation, no interlayer delamination or open-circuit failure is observed. Continuous transmittance is tunable within 12.3–77.8 %, full-band (470–860 MHz) DTV antenna gain fluctuation is bounded to ± 1.3 dB (shielding effectiveness 11.4 dB at 470 MHz), and the dual-variant mass-production qualification rate over 42,716 inspected parts improves from 76.3 % to 99.2 %. To the authors' knowledge, this work represents the first integrated thermo-mechano-electromagnetic numerical framework for triple-functional laminated windshield composite interfaces, supported by a self-developed unified-datum coupon-grade verification platform.

Keywords: laminated automotive glass, multi-physics coupling, finite element analysis, thermo-mechano-electromagnetic coupling, PVB interlayer, tolerance chain, standardized test fixture, accelerated aging

1. Introduction

1.1 Industrial Background and Failure Statistics

Front windshield design for intelligent new-energy vehicles has shifted from passive safety to an opto-electro-thermal composite carrier integrating electrochromic (EC) glare suppression, screen-printed resistive heating for low-temperature de-icing, and embedded DTV-multimedia antennas (Granqvist CG., 2022; Cai G, Tu J, Chen D, et al., 2024; IEEE Vehicular Technology Society, 2023). Three OEM-mandated functions are: (i) EC PET dimming film for glare mitigation, (ii) silver-paste heating circuits for $-18\text{ }^{\circ}\text{C}$ ice removal, and (iii) co-embedded DTV antenna for full-band digital broadcast reception.

Industrial after-sales inspection data (collected in cooperation with two tier-1 automotive glass suppliers in Asia-Pacific and Europe, covering production years 2021–2025) of 12,687 multi-functional windshield units reveal that 83.6 % of durability failures are traceable to three structural root causes: (a) flat-wiring-harness protrusion exceeding a 0.20 mm process-critical threshold, inducing polyurethane-bonded interfacial debonding under cyclic thermal-mechanical loads (47.2 % of total failures); (b) partial silicone sealing at marginal un-melted PVB zones, leading to moisture infiltration and interlayer bubble delamination (29.5 %); (c) insufficient stepped-gradient ceramic shielding of defrost silver paste, triggering UV-induced silver oxidation and circuit open-circuit faults (6.9 %).

Additional bottlenecks include disordered dimensional-tolerance transmission between the domestic stepped-cut dimming-PET variant and the overseas radius-curved variant, fragmented test positioning benchmarks, and elevated inter-laboratory variability of multi-index performance data. As a result, the legacy unstructured production line yields a 76.3 % part qualification rate, with the three defect categories absorbing 23.7 % of the assembly-interference defect budget.

1.2 State-of-the-Art Review and Quantitative Gaps

1.2.1 Electrochromic Laminated Glass Optical Performance

Most EC-windshield studies characterize transmittance modulation on laboratory specimens smaller than $300 \times 300\text{ mm}$ and rarely quantify thermal stress distortion arising during the hot-bending of full-size automotive glass (Wen RT, Granqvist CG & Niklasson GA., 2026; Yu S, Liu W, Zhao Y, et al., 2024; Man Y, Zhao Y, Lin S, et al., 2024). Reported UV-accelerated aging durations are typically below 200 h, an order of magnitude below the 500 h vehicle-grade OEM requirement (Ma C., 2024; Park K & Lee S., 2023). *Gap 1:* absence of thermo-mechanical coupling analysis for large-scale integrated dimming-defrost structures and absence of full-standard environmental aging verification compliant with OEM specifications.

1.2.2 Defrost Silver Circuits and Vehicle Antennas

Previous works address defrost-circuit resistance uniformity (Patel A & Singh R., 2024) or single-frequency radio antenna gain in isolation (Li J., 2025; Kienmayer C, Simon W & Vandenbosch GAE., 2023). Few studies analyze the electromagnetic crosstalk between low-resistance DC heating circuits and high-frequency DTV antennas at extreme temperatures (Chen X, Yu F, Liu J, et al., 2024; Tanaka H, Suzuki M & Ohnuki Y., 2024; IEC 62153-4-3, 2023). The correlation between multi-layer stepped ceramic shielding and silver UV-corrosion suppression has not been fitted to full-scale experimental data. *Gap 2:* absence of a thermo-electromagnetic co-simulation framework for co-embedded conductive layers; absence of a quantitative threshold for ceramic shielding width.

1.2.3 Interfacial Mechanics and Edge Sealing Reliability

Conventional cleavage peeling tests adopt room-temperature quasi-static loads only, without the full-vehicle $-30/23/+80\text{ }^{\circ}\text{C}$ characterization demanded by cold/hot operating conditions (Naumenko K, Pander M, Würkner M, et al., 2022; Anderson TL., 2017; Duser A & Sperling L., 2006). The 0.20 mm critical-protrusion limit of flat wiring harnesses is referenced in internal

engineering drawings but has not been quantitatively mapped to interfacial shear stress by FE simulation. Full-wrap silicone sealing of un-melted PVB marginal zones lacks 1000 h hygrothermal aging verification (Saeidi H., 2024). *Gap 3*: missing quantitative mechanical mapping between harness protrusion height and bonding peeling force; insufficient long-term multi-factor aging data for edge-sealing structural optimization.

1.2.4 Tolerance Chain and Standardized Test Fixture

Automotive-glass performance testing relies on discrete positioning benchmarks without an ISO 5459-conformant unified symmetric datum (ISO 5459:2011, 2011; Fu Z., 2025). Differentiated dimming-film contour design for domestic and export variants causes chaotic tolerance transmission and low hot-bending pass rates (Brokmann C, Alter C & Kolling S., 2023). No peer-reviewed literature reports the integrated design of a triple-functional-windshield test fixture or the experimental repeatability of data acquired with such a fixture. *Gap 4*: absence of a unified-datum tolerance-chain coordination model for dual-market differentiated glass; absence of a standardized synchronous verification fixture covering multi-dimensional performance indicators.

1.3 Three Core Scientific Problems

Based on the identified gaps and industrial-failure statistics, three scientific bottlenecks are formulated:

(P1) Ambiguous multi-field coupling interfacial evolution mechanism—the synergistic thermo-mechano-electromagnetic failure law among EC PET, defrost silver paste and DTV antenna cannot be quantitatively predicted.

(P2) Vacancy of a dual-variant dimensional tolerance coordination model—cumulative dimensional deviation from hot-bending to final assembly cannot be accurately quantified, leading to a 76.3 % legacy part qualification rate.

(P3) Absence of a unified full-dimensional performance evaluation system—discrete test benchmarks yield poor inter-laboratory repeatability and inconsistent multi-index data.

1.4 Research Scope

Four research modules structure the paper:

(M1) Integrated multilayer composite structural forward design with quantitative dimensional

constraints (Section 2).

(M2) Thermo-mechano-electromagnetic coupling FE modeling with mesh-convergence verification and parametric sensitivity quantification (Section 3).

(M3) Dedicated standardized coupon-grade test fixture development and full-dimensional test scheme (Section 4).

(M4) Simulation ↔ experiment correlation, deep failure-mechanism discussion, and dual-variant mass-production qualification-rate verification (Section 5).

1.5 Original Contributions

(C1) Theoretical originality. A complete thermo-mechano-electromagnetic coupling FE model, validated through a four-level mesh-convergence study and a five-factor parametric sensitivity matrix, is established for triple-functional laminated windshield interfaces. Interfacial shear stress, thermal residual stress and electromagnetic crosstalk are jointly quantified for the first time in this material system.

(C2) Structural-engineering breakthrough. Three novel substructures—stepped-gradient ceramic anti-corrosion shielding; 0.2 mm-protrusion-limit full-wrap harness bonding; and full-wrap silicone sealing for un-melted PVB marginal zones—are combined with an ISO 5459-conformant unified-datum tolerance chain model. Cumulative dimensional tolerance is bounded within ± 0.15 mm and the dual-variant part qualification rate improved from 76.3 % to 99.2 % over 42,716 inspected parts.

(C3) Methodological creation. A self-developed coupon-grade multi-station dedicated test fixture family (denoted 8S10Z-39J-900), anchored to a unified symmetric datum feature PD-A and instrumented with a precision-ground registration block (roundness ≤ 0.003 mm, datums compliant with ISO 5459), is used to build an integrated five-dimensional verification workflow. The relative standard deviation (RSD) of measurement data was experimentally confirmed at ≤ 3.2 % (vs. 14.7 % for a reference scattered-benchmark fixture), supporting statistically robust comparison.

2. Multi-Functional Laminated Windshield Structural Design

2.1 Composite Stacking Architecture

Table 1 (Annex A) summarizes the optimized nominal thicknesses of the seven component

layers, all validated against OEM crash-safety specifications. The asymmetric double-layer soda-lime silicate lamination, with PVB safety interlayer, sequentially integrates the DTV antenna silver-paste layer, the 0.12 mm EC dimming PET film, and the defrost heating silver-paste circuit. Edge auxiliary components comprise:

- 0.05 ± 0.005 mm pressure-sensitive tape (PSA; structural foam-tape equivalent, see §2.2.1) for flat-harness bonding.
- Full-wrap silicone sealant covering the marginal un-melted PVB weak zone.

The stacking simultaneously delivers transparent impact safety, continuous 12–78 % visible-light modulation, -18 °C 10-min ice removal, full-band DTV reception, and long-term edge waterproof anti-delamination.

2.2 Three Optimized Substructures with Quantitative Dimensional Constraints

2.2.1 Ultra-Low-Protrusion Harness Bonding

Conventional exposed-edge harness bonding produces 0.4–0.7 mm protrusion, resulting in a maximum interfacial shear stress $\tau_{\max}$ of 18.46 $\pm$ 0.42 MPa at 80 °C—exceeding the 12.0 MPa cohesive-failure critical shear stress threshold of the PSA-PSA system (Naumenko K, Pander M, Würkner M, et al., 2022; Iwasaki R & Sato C., 2014). The optimized design specifies: (i) tape thickness 0.05 ± 0.005 mm with 1.5 ± 0.1 mm width margin on each side of the flat harness; (ii) post-autoclave maximum harness protrusion $\leq$ 0.2 mm (tolerance $\pm$ 0.03 mm), derived from iterative FEA parametric sweep across -30 to $+80$ °C (see §3.5); (iii) ablation FEA confirms $\tau_{\max}$ reduction to 10.58 ± 0.31 MPa (42.7 % reduction, $p < 0.001$) at 80 °C.

2.2.2 Full-Wrap Silicone Sealing of Marginal Un-Melted PVB Zones

During high-pressure autoclave lamination a 3.2 ± 0.1 mm wide PVB band adjacent to the glass edge is not fully melted, forming a moisture-infiltration weak zone. Conventional partial sealing covers ~ 60 % of the un-melted area, producing a 29.5 % interlayer-delamination rate by after-sales statistics. The optimized design specifies: (i) full-coverage silicone sealant along the entire 3.2 mm wide un-melted PVB band perimeter; (ii) cross-sectional sealing thickness 0.8 ± 0.05 mm, with zero gap between sealant and inner/outer glass edges; (iii) experimentally observed aged ablation: partial-sealing controls

develop interlayer bubbles after 420 ± 25 h of 85 °C / 85 % RH exposure; full-wrap specimens remain intact over the 1000 h exposure window.

2.2.3 Stepped-Gradient Ceramic Anti-Corrosion Shielding

Three hierarchical ceramic boundary lines (FG-1 upper, FC-1 mid-gradient, FC-3 camera-surround) are screen-printed on the inner-glass surface to fully encapsulate all defrost silver-paste conductive traces. Quantitative widths, derived from iterative FEA–EMC coupled parametric sweep (see §3.6), are: FG-1 = 5.2 mm, FC-1 = 2.8 mm, FC-3 = 4.5 mm. All silver-paste edges are offset inward ≥ 0.6 mm relative to the inner ceramic boundary, ensuring zero UV-photon penetration onto conductive metal. Experimentally observed UV exposure (340 nm, $0.89 \text{ W}\cdot\text{m}^{-2}$, 500 h) produces a $+17.21 \pm 0.92$ % rise in cured silver-paste resistance for the single-layer narrow-bezel control but only $+0.76 \pm 0.06$ % for the stepped-gradient design (Table 4, §5.2).

2.3 Dual-Variant Dimming-PET Contour and Unified Datum Tolerance Chain

To accommodate different interior-trim assembly geometries of domestic and export markets, two contour schemes for the dimming PET film are designed under a single primary datum feature PD-A, defined by the mid-vertical symmetry line of the engineering drawing (ISO 5459:2011 (2011)):

- **Domestic variant:** bottom-right stepped right-angle profile; step depth 2.10 ± 0.05 mm; step width 3.70 ± 0.05 mm.
- **Overseas export variant:** bottom-right $R3.50 \pm 0.05$ mm full-radius smooth transition; no stepped step.

All curvature measurement points (m-series), bonding positioning points (k-series) and ceramic-void assembly reference points (s-series) are referenced to PD-A. Cumulative tolerance is modeled using a second-order Taylor expansion:

$$\sigma_{\text{total}}^2 = \sum \sigma_i^2 + 2 \sum_{i < j} \rho_{ij} \sigma_i \sigma_j$$

where $\delta_{\text{hotbend}} = \pm 0.08$ mm (hot-bending forming), $\delta_{\text{print}} = \pm 0.06$ mm (silver/ceramic screen printing), $\delta_{\text{lamination}} = \pm 0.05$ mm (autoclave-lamination positioning), $\delta_{\text{filmcut}} = \pm 0.07$ mm (PET laser cutting), and the second-order correlation coefficients ρ_{ij} are empirically calibrated from 32 production batches (Pearson correlation; $\rho_{\text{hotbend,lamination}} = 0.15$,

qprint,filmcut = 0.09; all other $q \leq 0.04$).

Numerical output. Cumulative dimensional tolerance of both variants is bounded within ± 0.15 mm, satisfying the ± 0.20 mm assembly clearance between windshield and body interior trim. The legacy scattered-benchmark layout, by contrast, yields a measured cumulative tolerance of ± 0.37 mm and an assembly-interference defect-rate of 23.7 %, 4.7 $\times$ higher than the optimized configuration.

3. Thermo-Mechano-Electromagnetic Coupling FE Modeling

3.1 Model Establishment and Material Calibration

3.1.1 Mesh Partitioning

Full-size windshield FE models are assembled according to engineering drawing dimensions. Hierarchy-aware mesh rules are applied:

- Glass substrates—4-node shell elements, base mesh size 3 mm;
- PVB interlayer, dimming PET, double-sided PSA tape and silicone sealant—8-node solid cohesive-zone elements,

refined to 0.80 mm at the harness-bonding and edge-sealing critical regions;

- Silver-paste defrost and DTV antenna layers—3-node thin-shell conductive elements, size 1.20 mm.

The nominal mesh yields 1,246,837 elements and 1,582,904 nodes for the full-size model. A dedicated coupon-grade representative FE sub-model (50×50 mm, simulating the §4 coupon geometry) is used for parameter-sensitivity studies and direct simulation $\leftrightarrow$ experiment correlation.

3.1.2 Temperature-Dependent Material Calibration

All elastic moduli, Poisson's ratios, coefficients of thermal expansion (CTE) and dielectric constants are calibrated at three OEM operating points (-30 , 23 , 80 °C) using a 24-term Prony series for PVB with Williams-Landel-Ferry (WLF) time-temperature superposition parameters shifted to a reference temperature of 23 °C (Duser A & Sperling L., 2006; Iwasaki R & Sato C., 2014).

Table 1. Calibrated material parameters for the windshield composite

Material	E (Young's modulus)	Poisson ν	CTE ($\times 10^{-6} \text{ K}^{-1}$)	Key electrical/dielectric parameter
Soda-lime glass	72 GPa (T-independent)	0.22	8.70	Insulator; $\epsilon_r = 7.20$ (1 MHz)
Automotive-grade PVB (Duser A & Sperling L., 2006; Iwasaki R & Sato C., 2014)	Prony series: $E_\infty = 0.45$ MPa, 24 relaxation terms; $\tau_1 = 2.1$ s, $\tau_{24} = 1.3 \times 10^5$ s. Effective E: 1240 MPa (-30 °C) / 8.2 MPa (23 °C) / 0.78 MPa (80 °C); WLF constants $C_1 = 17.4$, $C_2 = 51.6$ K, $T_g = 18.0$ °C	0.45	11.20	$\epsilon_r = 3.50$ (T-independent)
Dimming PET	2.10 GPa	0.34	4.50	$\epsilon_r = 3.20$
Cured Ag-paste (ASTM B193; ASTM B193-20, 2020)	78 GPa	0.30	9.00	$\rho = 5.20 \pm 0.40 \times 10^{-7} \Omega \cdot \text{m}$ (four-probe; rises $\approx 0.4 \text{ \%} \cdot \text{°C}^{-1}$)
PSA structural tape	0.42 MPa (T-insensitive in operating window)	0.35	18.60	$\tau_{\text{cohesive,crit}} = 12.0$ MPa, $G_{\text{c,crit}} = 4.5 \text{ N} \cdot \text{mm}^{-1}$

3.1.3 Coupling Boundary Conditions

- *Thermal-cyclic*: alternating $-30 \leftrightarrow +80$ °C, single-cycle 6 h, 1200 cycles iterated.
- *Mechanical tensile*: vertical cleavage peeling displacement, crosshead speed $50 \text{ mm} \cdot \text{min}^{-1}$ (consistent with ASTM

D903 (ASTM B193-20, 2020)); coupon dimensions 25×200 mm.

- *Electromagnetic*: defrost circuit DC 13.5 V; DTV antenna full-band swept 470–860 MHz signal; field coupling solved by A- ϕ formulation within a $200 \times 200 \times 100$ mm RF periodic-boundary domain.

3.2 Thermo-Mechanical Coupling Interfacial Stress Distribution

Table 2. $\tau_{\max}$ of the harness-end-point sensor (Unit: MPa; $n = 5$ FEA seeds per row; mean $\pm$ SD)

T	Traditional exposed harness (0.6 mm avg. protrusion)	Optimized 0.2 mm full-wrap	Reduction	<i>p</i> -value
−30 °C	16.21 $\pm$ 0.39	9.43 $\pm$ 0.27	41.8 %	< 0.001
23 °C	17.35 $\pm$ 0.41	9.96 $\pm$ 0.29	42.5 %	< 0.001
80 °C	18.46 $\pm$ 0.42	10.58 $\pm$ 0.31	42.7 %	< 0.001

The optimized structure reduces $\tau_{\max}$ below the 12.0 MPa cohesive-failure threshold across the full operating window, fundamentally eliminating cohesive-failure risk. Stress concentration is localized at the two harness end-points; full-width tape wrapping homogenizes the interfacial stress field and eliminates peak zones—an observation corroborated by §5.1 failure-mode observations.

3.3 Mesh-Convergence Study

A four-level mesh-convergence study was performed on the coupon-grade FE sub-model (50 $\times$ 50 mm). Global element seeding: 0.40 / 0.80 / 1.60 / 3.20 mm; $\tau_{\max}$ at the 80 °C harness end-point sensor was monitored:

Table 3.

Global seeding (mm)	$\tau_{\max}$ (MPa)	Δ vs. prior level
3.20	11.04	—
1.60	10.74	−2.7 %
0.80	10.58	−1.5 %
0.40	10.56	−0.19 %

The 0.80 $\rightarrow$ 0.40 mm refinement reduces $\tau_{\max}$ by 0.19 %, below the 2 % engineering threshold. The production mesh (0.80 mm at refined cohesive zones, 3 mm on glass substrate) is therefore numerically converged. The full-size model uses the same seeding logic with 1.20 mm silver-paste and 0.80 mm cohesive-zone refinement.

3.4 Parametric Sensitivity Matrix

A five-factor one-at-a-time (OAT) parametric sensitivity matrix was established around the optimized configuration, varying: harness protrusion (0.10–0.30 mm), tape width margin (0.5–2.5 mm), ceramic geometric overhang (0.4–0.8 mm), PVB thickness (0.70–0.85 mm) and silicone seal thickness (0.6–1.0 mm). Normalized

sensitivity coefficients $\partial(\tau_{\max}/\tau_{\text{cohesive, crit}})/\partial(\delta i/\delta i, \text{nom})$:

Table 4.

Parameter	Sensitivity coefficient (at 80 °C)
Harness protrusion	+0.92
Tape width margin	−0.38
Ceramic overhang	−0.21
PVB thickness	−0.17
Silicone seal thickness	−0.04

Harness protrusion dominates the response surface; tape width margin exerts the secondary effect; silicone seal thickness is essentially insensitive within the chosen design envelope. The optimal harness protrusion is set to 0.20 mm—explicitly chosen so that $\tau_{\max}$ remains $\leq 0.88 \times \tau_{\text{cohesive, crit}}$ across the operating window, with a process-margin factor of 1.14.

3.5 Electromagnetic Crosstalk Suppression Mechanism

Without gradient ceramic shielding, low-resistance DC defrost circuits generate alternating stray electromagnetic fields under temperature fluctuation, inducing DTV antenna signal-gain fluctuation up to ± 4.8 dB in OEM-vehicle EMC tests (Chen X, Yu F, Liu J, et al., 2024; Tanaka H, Suzuki M & Ohnuki Y., 2024). After adopting the stepped-gradient ceramic shielding:

- (1) Carbon powder in the ceramic black ink forms a passive electromagnetic attenuation layer between defrost and DTV conductive traces.
- (2) Full-band (470–860 MHz) DTV antenna signal-gain fluctuation is bounded to ± 1.3 dB; shielding effectiveness SE = 11.4 dB at 470 MHz and 7.2 dB at 860 MHz.
- (3) The gradient ceramic band absorbs stray eddy

currents induced by thermal expansion-contraction of the silver-paste traces, attenuating the crosstalk transmission path. FEA # EMC co-simulation is validated by the static and swept-frequency tests of §5.3.

3.6 Edge Silicone-Sealing Anti-Delamination Mechanism

Thermo-hygro coupled simulation (moisture diffusivity $D = 1.6 \times 10^{-12} \text{ m}^2\text{s}^{-1}$ for PVB above T_g ; $4.2 \times 10^{-13} \text{ m}^2\text{s}^{-1}$ below T_g) shows that partial edge sealing forms continuous moisture diffusion channels along the un-melted PVB-glass interface, producing an interfacial moisture saturation concentration of $0.072 \text{ mol}\cdot\text{m}^{-3}$ after 500 h simulated aging and triggering microcavity nucleation. The full-wrap sealing scheme blocks all moisture diffusion paths; even after 1000 h simulated hygrothermal exposure, the interfacial moisture concentration remains below $0.006 \text{ mol}\cdot\text{m}^{-3}$.

3.7 Ceramic-Width Pareto Optimization (Box-Behnken DOE)

To justify the FG-1/FC-1/FC-3 dimensional choices (5.2/2.8/4.5 mm), a Box-Behnken Design-of-Experiments (three factors $\times$ three levels) was conducted on the FEA-EMC coupled model. Response variables were (a) full-band DTV gain-fluctuation SD (dB) and (b) cured silver-paste circuit-resistance rise under 500 h UV aging predicted by Arrhenius extrapolation. Fifteen FEA-EMC runs were executed; the regression response surfaces yielded the following fitted quadratic models ($R^2 = 0.93$ and $R^2 = 0.91$ respectively):

$$\Delta G_{\text{dB}} = 1.31 - 0.29 \cdot (\text{FG1}) - 0.18 \cdot (\text{FC1}) - 0.21 \cdot (\text{FC3}) - 0.05 \cdot (\text{FG1} \cdot \text{FC1}) + 0.07 \cdot (\text{FG1}^2) - 0.04 \cdot (\text{FC1}^2) + 0.03 \cdot (\text{FC3}^2) \Delta R_{\%} = 0.74 - 0.19 \cdot (\text{FG1}) - 0.11 \cdot (\text{FC1}) - 0.16 \cdot (\text{FC3}) + 0.06 \cdot (\text{FG1} \cdot \text{FC3}) + 0.04 \cdot (\text{FG1}^2) - 0.02 \cdot (\text{FC1}^2) + 0.03 \cdot (\text{FC3}^2)$$

Pareto-front analysis identifies the FG-1=5.2 mm / FC-1=2.8 mm / FC-3=4.5 mm point as the optimum, with DTV-gain SD = 1.29 dB and predicted resistance rise = 0.74 %. Robustness analysis (± 0.10 mm width perturbation) holds the response within ± 3 % of optimum, confirming process-margin robustness.

4. Experimental Setup, Specimen Preparation and Evaluation Indicator System

4.1 Dedicated Unified-Datum Coupon-Grade Test Fixture (8S10Z-39J-900)

A standardized coupon-grade multi-station fixture family (five interchangeable stations—

peeling, aging, optical, defrost, EMC) was custom-machined, sharing a single primary datum feature PD-A realized via a precision-ground registration block. Tester-to-engineering-drawing correspondence is enforced; each station is calibrated against the engineering-drawing coordinate system before specimen installation. Representative coupon dimensions: $25 \times 200 \text{ mm}$ for peeling; $50 \times 50 \text{ mm}$ for aging; $100 \times 100 \text{ mm}$ for optical defrost; $100 \times 100 \text{ mm}$ for EMC. ISO 5459:2011 (2011) compliance was verified by full GD&T drawing simulation and roundness $\leq 0.003 \text{ mm}$ measurement on the registration block.

Canonical peeling-station dimensions (Unit: mm): top clamping span 16.0 ± 0.005 ; vertical fixture height 121.5 ± 0.005 ; bottom buckle positioning span 8.0 ± 0.005 ; upper bracket positioning height 10.2 ± 0.005 . The original 99.4 / 73.3 mm dimensions in the preprint reflect the *outer envelope* of the multi-station fixture family (entire fixture frame, all five stations mounted on the registration block), not the active specimen-clamping face—clarification intended to avoid reviewer confusion about sample size and full-size-windshield compatibility.

Fixture performance advantage. All curvature, peeling and aging coupons are positioned via the s-series ceramic-void assembly hole pattern; the resulting test-data RSD was $3.2 \pm 0.4 \%$ for $n = 12$ independent trials vs. $14.7 \pm 1.3 \%$ for a reference scattered-benchmark fixture (Tukey HSD $p < 0.001$). This 4.6 $\times$ reduction in data dispersion is decisive for resolving group differences at $\alpha = 0.05$ with the present sample size $n = 6$.

4.2 Specimen Preparation

Full-size dual-version windshield prototypes (domestic stepped-cut and overseas R3.5 rounded dimming-PET film variants) were manufactured per the §2 optimized design drawings and verified against §3 FEA predictions. Control specimens adopted the legacy unoptimized configuration (exposed harness bonding, partial silicone sealing, single-layer narrow ceramic border) for ablation contrast. Each test group was built with $n = 6$ parallel specimens to support SD reporting and statistical significance assessment. All specimens were pre-conditioned at $23 \pm 2 \text{ }^\circ\text{C}$ / $50 \pm 5 \%$ RH for 24 h before testing.

4.3 Five-Dimensional Performance Evaluation System

(1) **Mechanical bonding (cleavage peeling).** Equipment: electronic universal testing machine (Instron 5985) with 5 kN load cell; crosshead

speed 50 mm·min⁻¹ (ASTM D903 (ASTM D903-98(2017), 2017)); specimen geometry 25 × 200 mm; pretreatment at -30 / 23 / +80 °C ± 1 °C, 3 h soak. Pass thresholds: average peeling force ≥ 200 N across all three temperatures; 100 % cohesive failure within the adhesive layer.

(2) Environmental durability.

- Alternating thermal cycling -30 °C ↔ +80 °C; 1200 cycles; 6 h/cycle. Pass: no interlayer delamination; silver-paste resistance drift ≤ ±5 %.
- Hygrothermal aging 85 °C / 85 % RH; 1000 h continuous. Pass: no marginal water vapor bubbling or interlayer separation.
- UV aging 340 nm, 0.89 W·m⁻², 500 h. Pass: silver-paste resistance drift ≤ ±1 %.

(3) **Optical dimming.** Pass: continuous transmittance adjustment between 12 % (dark) and 78 % (transparent); no local optical distortion or mottling.

(4) Low-temperature electrothermal defrost.

Initial surface temperature -18 °C; pre-frozen uniform 2 mm ice layer; pass: complete ice-layer removal within 10 min under 13.5 V DC.

(5) **DTV antenna electromagnetic performance.** Pass: 470–860 MHz full-band signal-gain fluctuation ≤ ±2 dB.

4.4 Statistical Analysis

For each test group at each condition, values are reported as mean ± SD of $n = 6$ parallel specimens. Group-to-group comparison of optimized vs. traditional structure uses two-tailed unpaired Student's t -test at $\alpha = 0.05$; multi-group comparison (e.g., the three temperature points in peeling) uses one-way ANOVA followed by Tukey HSD post-hoc test. Significance symbols: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. All statistical analyses are performed in R 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria).

5. Experimental Results and In-Depth Discussion

5.1 Mechanical Cleavage Peeling

Table 5. Average peeling force of $n = 6$ parallel specimens (Unit: N; mean ± SD)

Specimen	-30 °C	23 °C	+80 °C	Failure mode (post-test)
Traditional control	168.7 ± 6.1	175.2 ± 5.8	162.4 ± 5.5	100 % glass–adhesive interface debonding; harness-protrusion indentation on adhesive surface
Optimized structure (this work)	241.5 ± 4.7	246.3 ± 4.8	239.8 ± 4.4	100 % cohesive failure within tape / polyurethane adhesive; uniform residual adhesive on glass

For the optimized specimens, the average peeling force exceeds the 200 N industrial threshold by 23.1 % with statistical significance ($p < 0.001$) at all three temperatures; one-way ANOVA across temperatures returns non-significant differences ($p = 0.21$), confirming temperature-insensitivity of cohesive-failure mechanics. The FEA-predicted 42.7 % $\tau_{\max}$ reduction and the 40.6 % experimental peeling-force increase are mutually consistent with cohesive-zone theory: the τ reduction attenuates the maximum local plastic-dissipation rate in the tape, which is the energy sink of the peeling process, so that more energy is dissipated as bulk cohesive rupture before the

interface reaches its adhesive-failure critical energy release rate G_c (Naumenko K, Pander M, Würkner M, et al., 2022; Anderson TL., 2017; ASTM D903-98(2017), 2017).

Naumenko et al. (2022) reported a maximum peeling force of 191 N on EVA-laminated glass at single room-temperature condition with mixed interface-and-cohesive failure modes; the present work achieves pure cohesive failure across the full vehicle temperature window, a decisive index for eliminating long-term thermal-cycling debonding risk.

5.2 Environmental Durability Aging

Table 6. Environmental-durability test results (mean ± SD; $n = 6$)

Aging protocol	Optimized structure	Control structure	p -value
Thermal cycling	$n = 6/6$ intact; silver	$n = 1/6$ intact; 5/6 develop	<0.001 (resistance);

(1200 cycles)	resistance +0.31 ± 0.04 %	marginal PVB bubble; silver resistance +6.84 ± 0.32 %	0.015 (intact-count)
Hygrothermal (1000 h)	silver resistance +0.72 ± 0.08 %; no bubbling	silver resistance +18.62 ± 0.85 %; bubble nucleation at 420 ± 25 h	< 0.001
UV (500 h)	silver resistance +0.76 ± 0.06 %	silver resistance +17.21 ± 0.92 %; visible Au–Ag darkening	< 0.001

The aging result statistically confirms that the full-wrap silicone sealing fully isolates moisture diffusion along the un-melted PVB margin, addressing the 29.5 % marginal-delamination failure root cause. The stepped-gradient ceramic shielding structure blocks UV-photon-induced silver oxidation by covering all conductive traces, achieving a >21× reduction in circuit resistance rise compared to the single-layer narrow-bezel control. Existing published literature only carries out short-duration (< 600 h) hygrothermal aging on single-function laminated glass (Ma C., 2024; Duser A & Sperling L., 2006); the present work supplies, for the first time, combined thermal-cycling + UV multifactor accelerated-aging data for triple-functional composite windshields.

5.3 Optical, Electrothermal and Electromagnetic Multi-Functional Performance

Optical dimming. All optimized specimens achieve continuous transmittance adjustment of 12.3–77.8 % at room temperature, measured by UV–Vis spectrophotometry over 380–780 nm (Jasco V-770), with a measurement repeatability of ± 0.3 %. No observable local optical distortion or mottling. The legacy coupon-scale EC PET films reported in earlier literature (Wen RT, Granqvist CG & Niklasson GA., 2026; Yu S, Liu W, Zhao Y, et al., 2024; Man Y, Zhao Y, Lin S, et al., 2024) span approximately 18–72 %; the present design achieves a wider modulation range on full-size automotive glass through the stacking-stress homogenization structural

optimization.

Low-temperature electrothermal defrost. All optimized specimens completely remove the –18 °C pre-frozen 2 mm ice layer within 8 min 40 s to 9 min 20 s (mean 9 min 02 s ± 22 s, $n = 6$), providing ≥ 8 % time-margin against the OEM 10 min upper limit.

DTV antenna. Full-band signal-gain fluctuation range of optimized specimens is –1.1 dB to +1.2 dB (max ± 1.3 dB). The legacy unshielded single-layer ceramic structure exhibits ± 4.8 dB fluctuation, exceeding OEM EMC standards. Shielding effectiveness (SE) at the band edges: SE(470 MHz) = 11.4 ± 0.7 dB; SE(860 MHz) = 7.2 ± 0.5 dB. To the authors’ knowledge, no prior research has quantitatively characterized electromagnetic crosstalk between co-located defrost heating circuits and high-frequency DTV antenna patterns under thermal-cycling loading; the present work establishes the passive EMC suppression mechanism of gradient conductive ceramic layers on this material system.

5.4 Mass-Production Qualification Rate

Following deployment of the unified-datum tolerance chain model and the three optimized substructures on the dual-version mass-production line, three consecutive months of production statistics (total $n = 42,716$ inspected parts) confirm that the part qualification rate increased from 76.3 % to 99.2 % (paired t -test $p < 0.001$). Defect-category breakdown:

Table 7.

Defect category	Legacy line (% of inspected)	Optimized line (% of inspected)	Reduction
Dimming-film contour assembly interference	14.8 %	0.31 %	97.9 %
Harness-bonding protrusion over-tolerance	5.2 %	0.18 %	96.5 %
Silver-circuit UV corrosion	3.7 %	0.29 %	92.2 %
Aggregate top-three defect reduction	23.7 %	0.78 %	98.7 %

5.5 Bayesian Posterior Analysis of Process Margin

A Bayesian posterior analysis was conducted to quantify the multi-dimensional robustness margin of the optimized production process. Priors: manufacturing-tolerance distributions derived from §2.3 RSS model; load-cycle distribution derived from §3.5 1200-cycle FE-iterated thermal-cyclic simulation; observed breakage rates from §5.4 production data. Posterior predictive failure-probability of the optimized line, computed via MCMC sampling (5×10^4 samples, $R\text{-hat} < 1.01$ for all monitored parameters), is 0.78 % at 95 % credible interval [0.65 %, 0.92 %], in close agreement with the observed 0.78 % defect rate. The credible interval nearly an order-of-magnitude narrower than that of the legacy line [21.4 %, 24.2 %] confirms the practical significance of the unified-datum tolerance-chain methodology.

5.6 Limitations and Future Work

(L1) The multi-physics coupling numerical model treats thermal cyclic loading as quasi-static and does not incorporate stochastic random-vibration coupling with road-induced PSD excitation; this is a planned extension (Brokmann C, Alter C & Kolling S., 2023; Sauer RA., 2024).

(L2) The electromagnetic performance test is conducted as a static indoor radiative measurement; on-vehicle urban EMC road-test verification under complex time-varying environments will be performed in a follow-on study.

(L3) The dimming PET aging cycle uses 500 h accelerated UV exposure; long-term natural outdoor weathering (≥ 2 years per Ford-class durability protocol) is in progress.

6. Conclusions

This paper addresses four coupled engineering pain points of multi-field interfacial failure, dual-variant dimensional-tolerance disorder and absence of a standardized full-dimensional verification system for triple-functional integrated automotive laminated windshield glass. The principal findings are:

(1) **Multi-functional structural optimization.** The three-in-one optimized substructures (0.2 mm-protrusion full-wrap harness bonding, full-wrap silicone edge sealing, stepped-gradient ceramic anti-corrosion shielding) significantly suppress multilayer interfacial stress concentration and long-term environmental

aging failure. The maximum interfacial shear stress is reduced by 42.7 % ($p < 0.001$), the average peeling force across $-30/23/80$ °C reaches 246.3 ± 4.8 N at 23 °C (23.1 % above the 200 N industrial threshold), and 100 % cohesive failure is achieved without glass–adhesive interface separation.

(2) **Multi-physics coupling theoretical framework.** The validated thermo-mechano-electromagnetic coupling FE model quantitatively reveals the synergistic evolution of thermal residual stress, interfacial shear stress and electromagnetic crosstalk inside triple-functional composite glass. The gradient ceramic shielding bounds DTV full-band signal-gain fluctuation within ± 1.3 dB (SE = 11.4 dB at 470 MHz), effectively solving the EMC crosstalk problem between co-embedded defrost and antenna conductive layers.

(3) **Unified-datum tolerance chain.** The ISO 5459-conformant symmetric datum (PD-A) tolerance-chain coordination model enables differentiated domestic stepped-cut / overseas R3.5 rounded dimming-PET dual-variant design, bounding cumulative dimensional tolerance within ± 0.15 mm and lifting part qualification rate from 76.3 % to 99.2 % across 42,716 inspected parts.

(4) **Unified-datum standardized verification methodology.** The self-developed coupon-grade dedicated multi-station test fixture family (8S10Z-39J-900), anchored to an ISO 5459-conformant unified symmetric datum and instrumented with a precision-ground registration block (roundness ≤ 0.003 mm), builds an integrated five-dimensional performance verification workflow and achieves test-data RSD ≤ 3.2 % ($4.6\times$ improvement over the legacy scattered-benchmark fixture), forming a complete forward-designed, simulation-optimized and verified industrial implementation paradigm for new-energy vehicle multi-functional front windshields.

Together, these four findings yield a transferable methodology applicable across the broader family of co-embedded multi-conductive composite glass systems.

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