

Advanced Weld Failure Prediction in Crashworthiness CAE

A Physics-Based, Test-Calibrated, and Uncertainty-Aware Framework for Automotive Structures

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Abstract- Weld separation can redirect load paths, accelerate structural collapse, and create large discrepancies between physical crash tests and finite-element predictions. The difficulty is not limited to assigning a single rupture force. Automotive joints experience mixed-mode normal, shear, bending, and torsional loading; sheet tearing may compete with nugget pull-out or interfacial fracture; local heat-affected-zone softening and geometric eccentricity alter the effective resistance; and mesh size, connector formulation, strain rate, manufacturing scatter, and model assembly quality all influence the numerical response. This paper presents a comprehensive methodology for advanced weld failure prediction in crashworthiness computer-aided engineering (CAE), with emphasis on resistance spot welds, gas metal arc and metal inert gas seam welds, laser welds, projection welds, and mixed-material joints represented in explicit finite-element solvers such as LS-DYNA. The framework separates joint behavior into elastic stiffness, plastic deformation, damage initiation, mixed-mode interaction, progressive degradation, final separation, and post-failure contact. It defines a hierarchical test pyramid, parameter-identification workflow, verification matrix, full-vehicle validation strategy, uncertainty treatment, and governance process. Particular attention is given to solid nugget, beam/connector, tied-contact, cohesive, and detailed heat-affected-zone approaches; force-based versus stress/strain-based criteria; mesh-objective regularization; and model transfer across gauges, grades, stack-ups, and loading rates. A staged implementation is proposed in which screening-level connectors are retained for non-critical joints while high-fidelity representations are deployed along dominant crash load paths. The resulting process improves physical realism without imposing uncontrolled model size or calibration complexity. The paper concludes that predictive weld modeling is best treated as a system-identification problem supported by coupon, component, subsystem, and vehicle evidence, rather than as isolated tuning of failure thresholds.

I. INTRODUCTION

Welded joints are structural switches within a vehicle body. Before separation, they couple adjacent panels and allow closed sections, reinforcements, brackets, rails, rockers, pillars, cross-members, and suspension attachments to act as integrated load-carrying systems. After separation, the same components may deform independently, rotate about remaining attachments, or lose the section stability needed for progressive energy absorption. Consequently, a small number of failed joints can change global pulse shape, intrusion, wheel kinematics, occupant-compartment integrity, battery protection, and the sequence of structural engagement.

Classical crash models often idealize thousands of welds using simple rigid links or beam connectors with a constant force or displacement cutoff. Such models may be adequate when no joining failure occurs and the objective is stiffness prediction. They become unreliable when a joint is near its resistance envelope, when a load path depends on sequential separation, when high-strength steels transfer greater force into the nugget, or when aluminum and mixed-material structures introduce heat-affected-zone and parent-sheet failure. Published work has identified spot-weld rupture as an important source of mismatch between vehicle crash tests and simulation, and has shown that detailed material rupture and calibrated weld models can improve prediction of structural deformation and intrusion [1]–[4].

The central engineering challenge is therefore to represent the correct failure mode at the correct location and time without converting the entire body-in-white into an impractically detailed metallurgical model. A robust strategy must answer five questions: What physical mechanism controls the joint? Which test set identifies that mechanism? Which finite-element formulation preserves it at vehicle mesh scale? How should uncertainty and manufacturing scatter be incorporated? What evidence is required before the model is declared predictive?

This paper addresses these questions through a multi-level framework. The proposed methodology is intended for industrial crashworthiness development, where model turnaround, repeatability, traceability, and design sensitivity are as important as local

correlation. It does not prescribe one universal keyword or solver card. Instead, it establishes a disciplined method for selecting, calibrating, validating, and governing weld representations according to joint type and crash relevance.

II. FAILURE PHYSICS OF AUTOMOTIVE WELDS

A. Joint Families and Structural Functions

Automotive structures contain several joining families. Resistance spot welds discretely connect overlapping sheets and dominate body-in-white assembly. Projection welds attach studs, nuts, straps, and brackets through localized current concentration. Laser welds and laser-brazed seams provide continuous or intermittent joining with a narrow thermal zone. Gas metal arc welding, including MIG/MAG processes, joins thicker steel or aluminum members such as frame rails, castings, extrusions, and brackets. Adhesive-weld hybrids carry distributed shear before local weld loading increases, while self-piercing rivets and flow-drill screws may coexist with welds in mixed-material architectures. The weld model must represent the structural function, not merely the manufacturing label.

TABLE I. WELD FAMILIES, DOMINANT FAILURE MODES, AND MODELING IMPLICATIONS

Joint family	Typical crash role	Dominant candidate modes	Recommended representation
Resistance spot weld	Discrete transfer between sheet stack-ups	Interfacial fracture; button pull-out; sheet tearing; HAZ failure	Beam/connector for screening; solid nugget plus HAZ for critical paths
Projection weld	Stud, nut, strap, or bracket attachment	Nugget shear; prying; sheet pull-through; local HAZ tearing	Multi-point connector or solid projections with eccentricity
MIG/MAG seam weld	Thick-section rail, casting, extrusion, bracket joint	Weld-metal fracture; toe/root cracking; HAZ rupture; base-metal tearing	Discrete calibrated beams for efficient vehicle models; solids/cohesive zone for local studies
Laser weld	Continuous narrow seam	Interfacial separation; HAZ fracture; terminal peel failure	Segmented beam/cohesive seam with local orientation
Hybrid weld plus adhesive	Distributed joint with local discrete retention	Adhesive debonding followed by weld overload	Cohesive adhesive plus weld connectors; capture load redistribution

B. Competing Failure Modes

A joint can fail within the fused nugget, along the sheet interface, through the surrounding heat-affected zone (HAZ), or through the parent sheet. In resistance spot welding, interfacial failure produces a crack through or around the nugget interface, whereas pull-out creates a button and tears the adjacent sheet. Coach-peel loading adds strong bending and prying, while lap-shear loading is dominated by in-plane transfer but still contains local secondary bending. Cross-tension emphasizes opening. Real crash loading combines these modes and may reverse direction as panels fold. A model calibrated only to peak lap-shear force can therefore reproduce one coupon while predicting the wrong vehicle-level failure sequence.

C. Mixed-Mode Loading

Let the resultant local weld actions be axial force N , two shear forces V_1 and V_2 , two bending moments M_1 and M_2 , and torsional moment T . A general normalized interaction index may be expressed as:

$$I = (|N|/N_c)^a + (V/V_c)^b + (M/M_c)^c + (|T|/T_c)^d, \quad \text{where } V = \sqrt{V_1^2 + V_2^2} \text{ and } M = \sqrt{M_1^2 + M_2^2}.$$

Damage initiation occurs when I reaches unity, but this expression is only a convenient macroscopic envelope. The exponents and capacities must be identified from a test matrix, and coupling terms may be required because normal force and bending often act on the same fracture plane. Lim et al. proposed a macroscopic spot-weld formulation that treats normal and bending actions together while maintaining a separate shear contribution, improving simplicity and accuracy for dissimilar stack-ups [2].

D. Heat-Affected Zone and Metallurgical Gradients

The thermal cycle changes hardness, yield stress, ductility, residual stress, and microstructure around the weld. For advanced high-strength steels, local softening or embrittlement may control pull-out. In aluminum, loss of heat-treatment strength near MIG or laser welds may shift failure away from the weld metal. A vehicle-scale connector that ignores the HAZ may appear strong in coupon calibration if its threshold is tuned, yet it can transfer excessive load to the surrounding shell and produce an incorrect tear path. Detailed models should therefore distinguish weld metal, HAZ, and parent material when the observed fracture crosses these regions.

III. LIMITATIONS OF CONVENTIONAL CAE PRACTICE

Single-threshold calibration. A constant rupture force collapses a multidimensional resistance surface into one number. It cannot distinguish peel from shear, nor preserve performance when sheet thickness or stack-up changes.

Connector over-constraint. Rigid spiders can artificially stiffen the joint footprint, suppress local sheet bending, and raise the apparent joint capacity. The attachment radius and distribution of constrained nodes must reflect the physical nugget and surrounding load transfer.

Mesh dependence. When sheet tearing is represented by element erosion without regularization, predicted energy dissipation and crack path vary with element size and orientation. A finer mesh can localize strain differently and change separation timing.

Instantaneous deletion. Abrupt removal of a connector releases stored energy and can generate nonphysical kinetic spikes. Progressive stiffness degradation or a controlled failure displacement generally provides a more stable and physical transition.

Ignoring post-failure contact. Separated sheets may continue to interact through bearing, friction, folding, or remaining welds. Deleting the weld does not mean deleting contact between the joined parts.

Tuning to one vehicle test. Adjusting capacities until one full-vehicle response matches can compensate for unrelated errors in material curves, thickness, contact, or build condition. Such a model is correlative rather than predictive.

IV. HIERARCHICAL MODELING STRATEGY

A. Fidelity Levels

TABLE II. RECOMMENDED MODEL-FIDELITY HIERARCHY

Level	Purpose	Representation	Evidence required
0: Retained joint	Stiffness/load-path studies where failure is not credible	Rigid/elastic connector, no failure	Proof that demand remains below screened capacity
1: Screening failure	Large full-vehicle models and early design	Beam or connector with mixed-mode force/moment criterion	Basic lap-shear, cross-tension, and peel data
2: Calibrated progressive joint	Production crash prediction in critical regions	Connector with plasticity, cumulative damage, progressive degradation	Multi-mode coupon tests and component validation
3: Detailed nugget and HAZ	Root cause and high-risk load paths	Solid nugget, shell/solid HAZ, damage material	Metallography, hardness map, local material tests, detailed coupons
4: Process-sensitive model	Research, joining-process optimization	Thermo-mechanical history, residual stress, microstructure-dependent properties	Process simulation and extensive physical characterization

A mixed-fidelity full-vehicle model is usually optimal. Most joints remain at Level 0 or 1. Joints along rails, hinge pillars, rockers, roof rails, battery side structures, suspension load paths, wheel-deflector attachments, tie straps, and restraint anchorages are elevated after demand-capacity screening or test evidence indicates sensitivity. The fidelity assignment should be stored as model metadata so that critical-joint coverage is auditable.

B. Resistance Spot Weld Representations

Beam-based spot welds are computationally efficient and can carry axial, shear, bending, and torsion. Their principal weakness is that local sheet deformation and load spreading are controlled by the connector topology and attached-node pattern. A calibrated beam should therefore include the correct effective length, local coordinate system, connection footprint, elastic stiffness, plastic response, damage interaction, rupture displacement or energy, and post-failure contact. Solid nugget models provide a physical volume and more realistic stress transfer, but require compatible mesh density, robust attachment to shell sheets, and a weld/HAZ material description. They are most valuable where the local failure mode itself is an output of interest.

C. Seam and Arc Weld Representations

Continuous seams can be represented by a row of discrete beams, cohesive segments, or explicit solid weld geometry. Discrete beams are effective when coupon-based envelopes of force and rupture displacement are available. In a published small-overlap study, aluminum MIG welds joining thick components were represented by discrete beams using an LS-DYNA damage material, with stiffness, loads, and rupture displacement adjusted to component tests; the calibrated approach contributed to improved full-vehicle correlation [3]. The segmentation length must be chosen consistently with the calibration, because changing segment pitch changes the force assigned to each connector and can alter crack propagation.

D. Cohesive-Zone Modeling

Cohesive formulations resolve traction-separation behavior across an interface. They are attractive for laser seams, adhesive layers, and detailed weld interfaces because they separate initiation from fracture energy. A typical law defines normal and shear stiffnesses, a mixed-mode initiation surface, and an energy-based evolution rule. The area represented by each cohesive element must be accounted for so that strength and fracture energy are mesh objective. Cohesive models require careful contact treatment after decohesion and can be sensitive to penalty stiffness and explicit stable time step.

E. Parent-Sheet and HAZ Damage

Damage models such as GISSMO describe failure strain as a function of stress state, and can accumulate damage along nonlinear loading paths. GISSMO was developed to support crash failure prediction and transfer of manufacturing history, and its calibration requires multiple specimen types spanning relevant triaxialities and loading modes [1], [4]. For weld applications, separate cards may be needed for parent metal, softened HAZ, hardened HAZ, and weld metal. The HAZ width should be based on measurement or a validated process model rather than chosen solely to fit a crash test.

V. TEST PYRAMID AND PARAMETER IDENTIFICATION

A. Material and Process Characterization

The test program begins with the actual production-representative material, coating, gauge, stack-up, weld schedule, electrode condition, seam geometry, and heat treatment. Record nugget diameter, indentation, weld length, penetration, porosity, hardness traverse, HAZ width, sheet thickness, and failure morphology. Material coupons should characterize elastic-plastic response, rate sensitivity, anisotropy, and fracture under multiple stress states. Digital image correlation is preferred where local strain and necking are important. For HAZ characterization, miniature coupons or inverse identification from detailed joint tests may be necessary.

B. Joint Coupon Matrix

TABLE III. MINIMUM JOINT TEST MATRIX FOR CRASHWORTHINESS CALIBRATION

Test	Primary action	Key outputs	Model parameters
Lap shear	In-plane shear plus secondary bending	Force-displacement, peak, energy, mode	Shear stiffness/capacity, plasticity, damage
Cross tension	Opening normal force	Peak force, opening displacement, pull-out mode	Normal capacity and degradation
Coach peel	Peel and strong local bending	Moment-sensitive response, tear path	Bending coupling, HAZ/sheet failure
Torsion or asymmetric coupon	Torsion/mixed mode	Torque-rotation and initiation site	Torsional capacity and coupling
Dynamic joint coupon	Crash-rate loading	Rate scaling, mode stability	Rate dependence of strength and displacement
Dissimilar stack-up series	Gauge/grade asymmetry	Mode transition and weaker-sheet response	Transferability and scaling law

C. Parameter-Identification Objective

Calibration should minimize discrepancies across all tests simultaneously. A representative objective is:

$$J(\theta) = \sum_j w_j [w_F e_{F,j}^2 + w_U e_{U,j}^2 + w_E e_{E,j}^2 + w_M e_{M,j}^2] + \lambda R(\theta),$$

where θ is the parameter vector; e_F , e_U , and e_E are normalized errors in peak force, displacement at failure, and absorbed energy; e_M penalizes an incorrect failure mode or crack location; w terms define test and metric importance; and R regularizes nonphysical parameter combinations. Curve-shape error should also be measured over force-displacement history. Optimization may use response surfaces, Bayesian calibration, gradient-free search, or a staged manual-to-automated sequence, but parameters must remain physically bounded.

D. Separation of Calibration and Validation

At least one geometry, stack-up, loading angle, or rate should be withheld from calibration. The withheld cases test prediction rather than curve fitting. A model that reproduces only the specimens used for identification is not validated. Replicates are necessary to quantify scatter and to avoid calibrating to an outlier.

VI. ADVANCED FAILURE CRITERIA

A. Force/Moment Interaction Envelopes

Macroscopic envelopes are efficient and directly compatible with connector resultants. Their accuracy depends on coordinate consistency and representative coupon coverage. Because a weld can experience non-proportional loading, a maximum instantaneous index may miss cumulative degradation. A practical extension introduces damage D with an increment based on effective deformation or dissipated work:

$$\Delta D = (\Delta \kappa / \kappa_f(\eta_m))^p, \quad D_{n+1} = \min(1, D_n + \Delta D),$$

where κ is an effective connector deformation, κ_f is the failure deformation as a function of a mode parameter η_m , and p controls damage accumulation. Separation occurs at $D = 1$. The formulation should distinguish reversible elastic cycles from irreversible damage-producing deformation.

B. Stress-State-Dependent Ductile Damage

For solid weld and HAZ elements, failure depends on stress triaxiality, Lode parameter, plastic strain, strain rate, temperature, and possibly anisotropy. GISSMO-type approaches define a failure strain curve over stress state, accumulate damage, and may include instability and regularization. Published guidance emphasizes that true plastic strain, correct loading mode, nonlinear strain path, discretization, pre-strain, HAZ effects, rate, and material scatter all influence ductile-failure prediction [1], [4]. The calibration test set must span tension, shear, plane strain, and compression-dominated conditions that occur around the joint.

C. Energy-Based Evolution

Strength controls initiation, while fracture energy controls the work required for propagation. Energy-based evolution is useful for cohesive seams and for regularizing element erosion. If G_c is fracture energy per unit area, element deletion should dissipate approximately G_c times the represented crack area, independent of mesh size. In connectors, an analogous rupture work can be defined from the area under the post-peak force-displacement curve. This reduces sensitivity to abrupt deletion and allows the model to reproduce gradual load loss observed in tests.

D. Probabilistic Resistance

Production weld properties vary with nugget size, electrode wear, fit-up, contamination, current shunting, porosity, seam penetration, and local gauge. Treating every weld at nominal capacity can overstate structural robustness. A stochastic model may assign correlated resistance multipliers by assembly zone or weld gun rather than independent random values. Reliability studies should propagate measured distributions of strength, failure displacement, and missing-weld occurrence. The output is not only mean response, but also the probability of critical separation, intrusion exceedance, or load-path loss.

VII. MESH OBJECTIVITY, NUMERICAL STABILITY, AND QUALITY CONTROL

A. Mesh and Connector Scaling

The connector footprint, beam length, shell mesh, and failure parameters form one calibrated system. If the vehicle mesh differs from the coupon mesh, local stiffness and strain concentration change. Scaling laws may be needed for segment pitch, represented weld length, or element characteristic length. The preferred solution is to maintain a controlled modeling standard and verify sensitivity at at least two practical mesh sizes. Failure time, peak force, absorbed energy, and crack path should remain within predefined tolerances.

B. Time Step and Mass Scaling

Detailed solid nuggets and cohesive elements can reduce the stable explicit time step. Added mass must be monitored locally and globally because artificial inertia can delay joint deformation. Selective mass scaling, coarsened non-critical HAZ detail, or submodeling may be used, but the effect on joint kinetics must be demonstrated. Hourglass energy, contact energy, sliding energy, internal energy, and total-energy balance should be reviewed around each critical separation event.

C. Failure Deletion and Contact

After connector or element failure, automatic contact should prevent nonphysical penetration while permitting realistic sheet sliding and bearing. Contact thickness, friction, soft options, and eroding-contact definitions must be compatible with deleted elements. A common defect is a tied constraint that remains active after the intended weld failure, silently preserving the load path. Automated model checks should search for duplicate connectors, disconnected nodes, conflicting ties, incorrect normals, zero-length beams, unassigned HAZ parts, and welds outside the intended overlap.

D. Model Diagnostics

TABLE IV. REQUIRED DIAGNOSTICS FOR CRITICAL WELD ASSESSMENT

Diagnostic	Purpose	Acceptance concept
Mode-resolved force/moment history	Identify the action driving initiation	Dominant mode consistent with test and structural mechanics
Damage index and failure time	Verify sequence and rate of degradation	No unexplained early numerical deletion
Local sheet strain and HAZ damage	Distinguish nugget failure from sheet tearing	Failure path consistent with physical evidence
Connector energy and deleted energy	Identify artificial energy release	Smooth transition; no destabilizing energy spike
Post-failure contact status	Ensure realistic separated-part interaction	No retained hidden tie or gross penetration
Demand/capacity map	Prioritize critical joints across vehicle	Stable ranking across reasonable numerical settings

VIII. COMPONENT, SUBSYSTEM, AND VEHICLE VALIDATION

A. Component-Level Validation

Component tests should reproduce the local geometry and boundary stiffness that generate mixed-mode loading. Examples include hat-section crush, T-joints, rail-to-bracket bends, strap attachments, pillar reinforcements, and welded extrusion-to-casting nodes. Validation metrics include joint load, displacement, absorbed energy, crack initiation location, failure sequence, final deformation, and high-speed-video kinematics. Correlation should not be judged from one scalar peak alone.

B. Subsystem Validation

Subsystem tests bridge coupons and vehicles by introducing realistic load redistribution among multiple joints. A rail or rocker section with production stack-ups can reveal progressive weld-row unzip, competing sheet tearing, and interaction with adhesives.

Instrumentation may combine load cells, accelerometers, displacement transducers, strain gauges, DIC, and synchronized high-speed video. The model must predict which weld fails first and how the remaining joints pick up load.

C. Full-Vehicle Correlation

Vehicle validation should use weld failure as one part of a complete correlation hierarchy. First confirm build content, mass, material/thickness, barrier, initial velocity, contacts, and boundary conditions. Then compare global energy balance and pulse, followed by structural engagement, local deformation, joint separation, intrusion, and occupant response. A published small-overlap application reported improved prediction of velocities, intrusion, wheel kinematics, and physical deformation after adding detailed material rupture, solid spot-weld nuggets with a damage material, solid fasteners, and calibrated discrete-beam MIG welds [3]. This illustrates that weld fidelity is most effective when combined with consistent material and fastener modeling rather than adjusted in isolation.

D. Validation Metrics

Recommended quantitative metrics include peak and timing error, integrated absolute curve error, CORA-type shape rating where appropriate, absorbed-energy error, intrusion error at defined gauges, and a categorical failure-mode score. A joint-level confusion matrix can classify predicted and observed states as intact, damaged, partially separated, or fully separated. False negatives are generally more serious for safety-critical load paths, but false positives can also lead to unnecessary mass and reinforcement.

IX. APPLICATION TO KEY CRASH LOAD CASES

A. Small-Overlap and Oblique Frontal Impact

Small-overlap loading bypasses the main rail and places severe demand on wheel-deflector systems, suspension attachments, hinge pillars, rockers, rail tips, tie straps, and local brackets. Joint failure may determine whether the wheel is redirected or driven into the occupant compartment. High-fidelity weld modeling should be concentrated where the tire, suspension, or barrier creates localized high-rate prying and where the load path transitions between thick and thin members.

B. Full-Overlap and Offset Frontal Impact

In distributed frontal loading, welds influence progressive rail folding and prevent section opening. Premature seam separation can lower mean crush force, while an unrealistically strong seam can suppress a physical split and overpredict pulse. The important validation quantities are fold wavelength, seam opening sequence, rail crush force, toe-board intrusion, and energy allocation among rails, subframe, and upper load paths.

C. Side Pole and Moving Deformable Barrier

Side impacts generate strong local bending and peel in rocker, B-pillar, roof-rail, seat cross-member, and battery-sill joints. Spot weld rows can unzip under combined opening and shear. For battery electric vehicles, seam and joint integrity also affects battery enclosure intrusion and the retention of side structures. The attached reference format paper emphasizes that side-pole loading is localized and that intrusion control is critical near high-voltage components [5]; weld modeling is the mechanism that ensures the intended multi-cell sill and reinforcements remain structurally integrated long enough to absorb energy.

D. Rear and Roof Loading

Rear crashes can load rear rails, floor cross-members, tow structures, and battery mounts through mixed axial and bending actions. Roof crush and rollover introduce quasi-static to dynamic peel and shear around pillars, roof rails, and header joints. Although failure rates differ from frontal crash, the same calibration principles apply; rate dependence should match the specific event rather than being assumed from a high-speed coupon alone.

X. DESIGN OPTIMIZATION USING PREDICTIVE WELD MODELS

Once validated, the weld model becomes a design variable rather than merely a failure switch. Optimization can vary weld pitch, nugget diameter, seam length, flange width, access, local emboss geometry, adhesive coverage, reinforcement gauge, and joining-process selection. Objectives may include intrusion, mass, peak acceleration, absorbed energy, number of critical welds, cost, and robustness. Constraints should prevent the optimizer from exploiting numerical artifacts such as concentrating load into an unrealistically strong connector or deleting a sacrificial joint to reduce pulse while violating compartment integrity.

Surrogate models and machine learning can reduce the computational cost of full-vehicle design space exploration, but training data must preserve failure discontinuities. Classification of failure mode may be combined with regression of continuous responses. Active learning should add simulations near the boundary between intact and separated states. The final design must be revalidated with the full solver model and checked against manufacturing limits.

XI. UNCERTAINTY QUANTIFICATION AND ROBUSTNESS

A deterministic nominal model answers whether a design works for one assumed joint population. Robust crashworthiness asks whether it works across production variation and uncertain loading. Candidate variables include sheet gauge, yield curve, fracture curve, nugget diameter, weld length, HAZ width, connector location, missing welds, adhesive property, impact angle, vehicle mass,

and temperature. Screening methods first identify influential variables; Latin hypercube, polynomial chaos, Gaussian-process surrogates, or importance sampling can then estimate response distributions.

Correlations among variables should be retained. For example, neighboring welds produced by the same gun may share electrode-wear effects, and HAZ width may correlate with nugget size. Spatially correlated weak joints can be more damaging than independent scatter because they create a continuous weak path. Robust design targets should therefore include a margin between predicted demand and lower-tail resistance, not merely a nominal interaction index below one.

XII. IMPLEMENTATION WORKFLOW FOR INDUSTRIAL CAE

TABLE V. END-TO-END IMPLEMENTATION WORKFLOW

Step	Activity	Deliverable / gate
1	Classify joint family, stack-up, material, process, and structural function	Joint taxonomy and criticality ranking
2	Collect production-representative geometry, weld quality, and material data	Traceable input-data package
3	Execute multi-mode, multi-rate coupon test matrix with replicates	Curves, images, modes, scatter distributions
4	Select connector, solid nugget, cohesive, or HAZ model by fidelity need	Model-form decision with assumptions
5	Identify elastic, plastic, initiation, damage, and separation parameters	Version-controlled parameter card
6	Verify single-element behavior, coordinate systems, units, and energy	Solver-level verification report
7	Validate withheld coupons and at least one component/subsystem	Independent predictive evidence
8	Deploy mixed fidelity in vehicle model and run automated QA	Audited weld database and error-free assembly
9	Correlate globally first, then evaluate local failure sequence	Vehicle validation report
10	Quantify uncertainty and establish applicability limits	Robustness margin and model-use envelope
11	Freeze release, document changes, and monitor new test evidence	Governed production CAE method

A. Automated Preprocessing and QA

Industrial deployment requires automation. Preprocessors should generate connectors from manufacturing data, orient local axes, assign stack-up-specific parameters, include seam segmentation rules, and tag critical joints. QA scripts should compare expected and modeled weld counts, identify missing attachments, check distance to flanges, verify material sets, and generate a demand/capacity dashboard after each run. Visualization should use common legends for intact, damaged, suspect, and failed joints so that design teams can review load-path evolution efficiently.

B. Governance and Traceability

Each parameter set should have an identifier linked to material grade, gauge range, stack-up, process window, test report, solver version, mesh standard, and validation status. Changes to weld cards should be reviewed like changes to structural materials. The release record should state whether a card is calibrated, validated, provisional, or extrapolated. Extrapolation beyond validated thickness, grade, loading mode, rate, or temperature must be explicitly flagged.

XIII. COMMON FAILURE MODES IN THE MODELING PROCESS

TABLE VI. MODELING PITFALLS AND CORRECTIVE ACTIONS

Observed issue	Likely modeling cause	Corrective action
Welds fail too early in all load cases	Threshold fit to one weak coupon; wrong units or area scaling	Recheck units, represented area, specimen statistics, and coordinate system
Lap shear correlates but coach peel fails	No bending coupling; attachment footprint too rigid	Add mixed normal-bending interaction and refine local sheet representation
Correct peak force but excessive energy	Failure displacement or damage evolution too high	Calibrate complete curve and fracture work, not peak only
Vehicle shows abrupt kinetic-energy spike	Instantaneous deletion or conflicting contact	Use progressive degradation; audit contact and remaining constraints
Failure location shifts with mesh	Unregularized sheet/HAZ erosion	Use characteristic-length regularization and mesh sensitivity study
All joints remain intact despite physical unzip	Hidden tied contacts, excessive connector strength, or missing HAZ weakness	Audit constraints and include relevant local damage mechanism
Good one-test correlation, poor design sensitivity	Compensating calibration error	Validate withheld cases and separate material, joint, and boundary-condition effects

XIV. RESEARCH GAPS AND FUTURE DIRECTIONS

First, transferable models are needed for dissimilar materials and thicknesses without testing every combination. Physics-informed scaling based on nugget diameter, sheet strength, thickness, and failure morphology is promising, but must preserve transitions between interfacial fracture, pull-out, and sheet tearing.

Second, virtual manufacturing should be coupled more tightly with crash. Weld schedule, forming pre-strain, thinning, residual stress, local hardness, adhesive cure, and assembly distortion can alter resistance. Mapping these histories into crash models is technically feasible but requires controlled data interfaces and uncertainty management.

Third, machine-learning models should augment, not replace, mechanics. Useful applications include inverse parameter identification, failure-mode classification from test images, active selection of the next coupon, and rapid screening of weld criticality. Generalization must be assessed on unseen stack-ups and crash modes.

Fourth, validation databases should report complete force-displacement histories, strain fields, high-speed images, nugget/HAZ measurements, and replicate scatter. Peak values alone are insufficient for calibrating progressive damage.

Finally, mixed-material EV structures require unified treatment of spot welds, arc welds, rivets, screws, adhesives, castings, and extrusions. Load-path reliability depends on interactions among these joints, and the failure of one joining family can overload another.

XV. RECOMMENDED ENGINEERING PRACTICE

1) Model the observed mechanism. Do not force every failure into connector rupture if physical evidence shows sheet or HAZ tearing.

2) Calibrate across modes. Use shear, opening, peel, and mixed-mode tests, with dynamic data where crash-rate sensitivity matters.

3) Separate initiation from propagation. Represent peak resistance and post-peak work independently when the formulation permits.

4) Preserve mesh objectivity. Control connector footprint, segment pitch, characteristic length, and fracture energy.

5) Validate progressively. Use withheld coupons, then components, subsystems, and vehicles. Maintain a clear distinction between calibration and validation.

6) Deploy mixed fidelity. Reserve solid nugget and detailed HAZ models for joints that govern load-path integrity or design decisions.

7) Quantify scatter. Use measured distributions and correlated weak-zone scenarios for critical load paths.

8) Govern the method. Version-control cards, document applicability limits, automate QA, and revalidate after solver or modeling-standard changes.

XVI. CONCLUSION

Advanced weld failure prediction is essential when crash performance depends on the continuity, release, or progressive unzip of structural joints. Predictive modeling cannot be achieved by assigning a universal weld strength. It requires a consistent representation of joint stiffness, mixed-mode plasticity, damage initiation, degradation, final separation, HAZ and parent-sheet fracture, post-failure contact, mesh sensitivity, strain-rate effects, and manufacturing variation.

The most effective industrial strategy is hierarchical. Efficient connectors provide broad full-vehicle coverage, calibrated progressive models are applied to joints approaching their interaction envelope, and detailed nugget/HAZ or cohesive models are reserved for critical load paths and root-cause investigations. A test pyramid from material coupons through full-vehicle events supplies independent evidence and prevents tuning to one crash test. Automated QA, version control, demand/capacity mapping, and uncertainty quantification convert the method from specialist practice into a repeatable enterprise capability.

When these elements are integrated, weld failure models can reproduce not only whether a joint separates, but also when it separates, by which mode, how the load redistributes, and how global vehicle response changes. That level of prediction supports safer structures, more efficient physical testing, targeted reinforcement, reduced mass, and faster design convergence across steel, aluminum, and mixed-material vehicle architectures.

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APPENDIX A. EXAMPLE WELD CARD DATA SHEET

TABLE A1. MINIMUM PARAMETER-CARD METADATA

Field	Required content
Identification	Card ID, revision, owner, release date, solver version
Applicability	Joint family, material grades, coating, thickness range, stack-up, nugget/seam range
Elastic/plastic behavior	Stiffness, yield surface, hardening, rate law
Failure behavior	Interaction equation, capacities, exponents, damage law, degradation, rupture work/displacement
Local material zones	Weld metal, HAZ zones, parent properties, mapped pre-strain
Numerical standard	Element type, mesh range, segment pitch, connector footprint, contact
Evidence	Calibration tests, withheld validation tests, component/subsystem/vehicle status
Limitations	Unsupported modes, extrapolation rules, temperature/rate limitations