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ENGINEERING **RESEARCH REPORT · Engineering research report**

Clamping Force, Deformation, and Surface Protection in Handling Large Automotive Sheet-Metal Panels

Public-source research, engineering derivation, and verification methods for assisted handling and custom tooling in the automotive industry

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Research and Verification Methods · Not Product Certification or Evidence of Customer Acceptance

Report structure

> Research Boundary Standards, papers, and vendor data in the main text are used to support the methodological framework; example calculations contain assumptions. Project applications must be supplemented with real workpiece, tooling, action curves, risk assessments and original test evidence.

> Research boundary — Document type: public-source research and engineering design methods. This report contains no qualification-test results for any specific customer project. Example parameters illustrate the calculation procedure only and cannot replace testing on actual parts, risk assessment, or project acceptance.

00 Executive Summary

Large automotive exterior body panels combine large dimensions, thin walls, low local stiffness, and stringent surface-quality requirements. Even when a handling system provides sufficient total lifting force, it can still fail because of local suction-induced draw-in, excessive support span, reduced tangential friction due to oil film, edge vibration caused by acceleration and deceleration, or contamination of the pre-paint surface by contact materials. Published research shows that flexible sheet metal in handling must be treated as a flexible body driven by motion boundary conditions rather than as a rigid body; the nonlinear stiffness of the suction cups, sealing-lip preload, and vacuum load also affect local deformation [1][2].

This study proposes a three-objective design framework: load-bearing safety, shape stability, and acceptable surface quality. Load-bearing safety is checked using the normal suction margin and tangential slip-resistance margin. Shape stability is evaluated jointly from plate-and-shell stiffness, suction-point span, local vacuum pressure, and dynamic acceleration. Surface protection is closed out through permitted contact zones, suction-cup material, cleanliness, contact duration, and reinspection conditions. The engineering process should not select the number of suction cups first and then search for locations. It should first establish the part-family parameter matrix and prohibited/restricted zones, and then converge through suction-point layout optimization, dynamic trajectory load reduction, and testing on actual parts.

Core conclusion

- Adequate total suction force does not by itself make handling reliable; in vertical or inclined orientations, tangential friction and peel resistance are often the governing factors.
- The local stiffness of sheet metal increases with the cube of its thickness. Thickness, stiffeners, and suction-point span therefore have much greater effects than merely increasing the vacuum level.
- Suction cups with internal supports or anti-draw-in features can reduce local dimpling. Oiled sheet also requires a purpose-designed high-friction texture and dedicated slip verification [3][4].
- Surface protection must be determined by sample inspection with "specified lighting, specified cleaning status, and specified waiting time" and cannot be inferred solely from the suction cup material name.
- The final released configuration shall be the complete combination of part version, suction-cup version, vacuum threshold, motion recipe, and inspection rules—not an isolated tool.

01 Research scope, objects and evidence boundaries

The study covers large stampings such as outer door panels, hood outer panels, roof panels, body sides, fenders, and tailgate outer panels, as well as thin-walled parts with local reinforcement before and after body-in-white assembly. Handling is based primarily on vacuum suction, with additional consideration of soft mechanical stops, edge supports, and hybrid gripping. The scope covers pickup, separation from a die or rack, translation, rotation, short-duration holding, and placement. It excludes the strength of the stamping die itself, in-service vehicle crash performance, and certification of coating-process formulations.

The evidence has four layers. The first comprises machinery and pneumatic-system safety principles such as ISO 12100 and ISO 4414 [5][6]. The second comprises dynamics, finite-element, and control research on flexible sheet metal and vacuum gripping [1][2]. The third comprises public technical information from automotive sheet-metal suction-cup suppliers, used to identify common industrial designs and limits of use [3][4]. The fourth comprises this report's engineering derivations and example calculations. The fourth layer establishes project methods only and cannot, in reverse, demonstrate that a specific product or tool has passed verification.

study variables	Recommended minimum data set	Typical distortion effects
Part geometry	CAD version, thickness, curvature, flanging, ribs, holes	Suction cup spanning a stiffener, local unsupported area, peel-off
Material and condition	Material grade, yield strength, surface oil content, temperature, protective film	Permanent deformation, slippage, contamination
Quality attributes	Mass, center of gravity, inertia, incoming material deviation	Eccentric load, swinging, braking overload
Permitted contact zone	Suctionable area, no suction area, appearance A side, sealant/solder joint area	Imprints, crushing, and post-process defects
Motion envelope and constraints	Orientation, speed, acceleration, emergency stop, path envelope	Edge vibration, interference, part drop

02 Failure mechanism and control variables

02.1 Normal Failure: Seal Failure and Peeling

Ideal suction force is the product of pressure differential and effective area, but actual suction cups are affected by sealing-lip deformation, surface curvature, oil film, dust, grooves, and eccentric loading. In particular, when the tool orientation changes, the resultant force line shifts away from the geometric center of the suction cup and creates a peel tendency at one side of the sealing lip. Peeling is not simply a shortage of total force; the local contact edge loses stability first. The local surface normal, installation angle, and structural compliance of each suction cup must therefore be controlled.

$$F_{N,usable} = (\Delta p \cdot \Sigma A_{eff} \cdot \eta_{seal}) / S_N$$

In the equation, Δp is the verified minimum operating pressure differential, A_{eff} is the effective area of each suction cup, η_{seal} is the combined reduction factor for curvature, contamination, manufacturing variation, and line losses, and S_N is the project safety factor. Use worst-case rather than nominal values for every quantity.

02.2 Tangential failure: oil film, acceleration and slip

When the sheet metal is nearly vertical, the load is transmitted mainly through tangential friction between the suction cups and the sheet. Oil film can substantially change the friction conditions, so a bench-test friction coefficient for ordinary suction cups cannot be applied directly. Public supplier information commonly uses textured or friction-enhancing features to improve tangential capacity on oiled sheet and emphasizes that dynamic handling requires purpose-designed structures [3][4]. Engineering verification shall record vacuum, tangential displacement, and motion acceleration simultaneously so that a failure in which vacuum appears normal while the workpiece is already slipping can be detected.

$$F_{T,demand} = m \cdot |g_t + a_t| + F_{disturbance}$$
$$F_{T,capacity} = \Sigma(\mu_{i,min} \cdot N_i) / S_T$$

If $F_{T,capacity}$ is less than $F_{T,demand}$, first reduce trajectory acceleration, change the orientation, add slip-resistant supports, or change the suction-cup design rather than merely increasing the vacuum level. A higher vacuum level also increases local contact pressure and may worsen sheet marking and local draw-in.

02.3 Shape failure: local deep drawing, global deflection and edge vibration

The bending rigidity of a thin sheet can be approximated by its plate-and-shell flexural rigidity:

$$D = E \cdot t^3 / [12 \cdot (1 - \nu^2)]$$

For similar materials and boundary conditions, halving the thickness reduces the bending rigidity to approximately one-eighth. Local vacuum beneath a suction cup, suction-point spacing, and free-edge length may therefore govern deformation. For similar panels, $w \propto qL^4/D$ can be used as a trend relationship: the fourth-power effect of span L shows that suction-point layout and support span are usually more effective levers than further increasing suction force. This relationship does not replace finite-element analysis for complex curved surfaces, flanges, and stiffeners.

03 Integrated Design of Gripping Force and Layout

Design shall begin with the set of worst-case operating conditions. Maximum mass is not necessarily the most severe case; the combination with the greatest center-of-gravity offset, thickest oil film, tightest local curvature, smallest permitted suction area, or most unfavorable emergency-stop direction may be more critical. Encode all operating conditions as a scenario set G={part version, orientation, temperature, surface condition, motion segment, abnormal state}, and verify each scenario separately.

03.1 Example calculation (only used to illustrate the method)

Assume an exterior panel with a mass of 24 kg, handled by 6 suction cups of 80 mm diameter. The minimum verified pressure differential is 60 kPa, the sealing and variation reduction factor is $\eta_{seal}=0.75$, and the normal safety factor is $S_N=2.5$. The theoretical total pressure-differential force is approximately 1.81 kN. After applying the reduction factor and dividing by the safety factor, the available normal load capacity is approximately 0.54 kN, which exceeds the static gravitational load of 0.235 kN.

However, if verification on a vertical, oil-coated workpiece gives a minimum friction coefficient of only 0.20 and a tangential safety factor of 2.0 is used, the conservative tangential capacity is approximately 0.136 kN, below the static gravitational load; the design is therefore unacceptable. This example shows that the same suction-cup set can pass horizontal lifting yet fail by tangential slip during vertical rotation. Improvements include increasing the verified friction capacity, adding geometric support, reducing acceleration in vertical motion segments, or changing the suction-point locations.

> Research boundary — The example parameters are neither AUREK product ratings nor project recommendations. Suction-cup effective area, minimum vacuum, coefficient of friction, and safety factor must be established from the specific product data, risk assessment, and tests on actual parts.

03.2 Layout rules

- The suction points should form a polygon around the center of gravity as much as possible to avoid all being concentrated in a narrow band.
- Prefer locally stiff regions, but do not span sharp stiffeners, holes, weld spots, or no-contact zones.
- Align the center axis of each suction cup with the local surface normal as closely as practicable. Height-compliance elements compensate only for manufacturing and incoming-part variation; they shall not be used to force the workpiece flat.
- Add supports or shorten the span at long free edges and large overhangs; do not use higher vacuum to pull down a vibrating edge.
- Divide the vacuum system into zones so that a sealing fault at one point does not immediately collapse the entire circuit, while ensuring that each individual zone still has adequate capacity.

04 Surface Protection and Contamination Control

Surface protection is not simply a matter of selecting a so-called mark-free suction cup. Suction-cup material, hardness, surface texture, contact slip, suction duration, temperature, oil, cleaning agent, dust, and number of reuse cycles can all affect marking and contamination. For exterior panels before painting, also consider silicone and other substances that may affect coating. Any material-compatibility claim shall be supported jointly by supplier documentation and customer process approval.

risk	Formation mechanism	design control	Verification evidence
circular imprint	Local surface pressure, sealing lip slippage, long-term maintenance	Limit vacuum and contact time, optimize support, choose suitable materials	Visual inspection, profiling or imaging recording under prescribed lighting
scratch	suction cup or gloves containing hard particles	Cleaning classification, closed storage, shift change inspection	Cleaning records and magnified inspection
Oil film migration	Contact parts carry oil and transfer across regions	Tool zoning, directional cleaning, no mixed use	Surface cleanliness or post-process confirmation
local depression	Local draw-in at the suction-cup cavity or concentrated support points	Internal support, increase support area, reduce span	Three-dimensional scan / checking-fixture comparison
Paint contamination	Material separation or cleaning agent residue	Material approval, chemical compatibility verification	Customer process approval or special testing

Define the viewing surface, illuminance, viewing angle and distance, waiting time, and cleaning method for surface inspection. Recoverable marks visible immediately after cup removal must be assessed separately from permanent deformation. A claim of “no visible marks” is not repeatable unless these conditions are standardized.

05 Simulation, bench and real sample verification

It is recommended to use three levels of verification. The first level is analytical verification and tolerance analysis, used to eliminate obviously unsatisfactory solutions; the second level is finite element or digital prototypes to identify sheet deflection, local indentation, suction point load distribution and trajectory envelope; the third level is real sample testing to confirm sealing, slippage, deformation and appearance. Simulation cannot reliably cover surface oil volume, dust, suction cup wear and cleaning status, and therefore cannot replace physical testing.

Verification Item	Input Conditions	Recommended measurements	Acceptance Criteria
Vacuum Establishment	Curvature and incoming material deviation combination	Vacuum establishment time and lamination status of each area	Lifting is permitted only after every zone reaches its project threshold
static hold	Minimum vacuum, maximum dwell	Pressure decay, displacement, appearance	Do not cross the warning threshold within the specified time

Verification Item	Input Conditions	Recommended measurements	Acceptance Criteria
Dynamic handling	Maximum speed, acceleration, emergency stop	Acceleration, vacuum, slip, edge amplitude	No drop, no excessive displacement, and no exceedance of the deformation limit
single point of failure	Single suction cup leakage or interruption	Zone pressure, control response	Entering a conservative state with a safe margin
Appearance re-inspection	Temperature, oil volume, number of repetitions	Optical inspection, three-dimensional comparison	Meets the customer's surface-quality and dimensional criteria
Durable	Representative cycles and cleaning cycles	suction cup wear, vacuum trend, replacement points	The trend can be monitored and the maintenance interval can be implemented

Dynamic tests must cover starting, braking, steering, overturning intermediate postures and abnormal stops. Just "lifting and letting it rest" cannot represent the production trajectory. If workpiece will change from horizontal to vertical, the normal load bearing, tangential slip-resistant and the most unfavorable posture for peeling should be verified respectively.

06 FMEA and fault control

failure mode	main consequences	Existing / Recommended Controls	Verification method
Single suction cup seal failure	Load redistribution and propagation of peeling	Vacuum zoning, check valve, and per-zone monitoring	Fault injection and hold time testing
Oil film causes slip	Positioning error or part drop	High-friction features, supporting restraint, and trajectory acceleration limits	The most unfavorable oil quantity dynamic test
suction cup cross rib/hole	Slow vacuum establishment or false suction	CAD restricted areas, visual/in-place confirmation	Inspection of samples from multiple versions
Thin plate deep drawing	The appearance is dented and the size is out of tolerance.	Internal support, reduced local pressure differential, and shorter span	Three-dimensional scanning and checking-fixture inspection
suction cup wear	Increased leakage and changes in marks	Life counting, trend monitoring, inspection standard	Retest after durability

failure mode	main consequences	Existing / Recommended Controls	Verification method
Model recipe error	The suction point falls into the restricted area	Part identification and tooling/recipe consistency interlock	Mismatch fault injection
Accidental release	workpiece dropped or bumped	Support confirmation, dual-condition release, and control verification	Issue release command in non-positioned state

FMEA prioritization shall not rely solely on a subjective RPN. For failures that can cause a dropped load, personal injury, or major product loss, inherent-safety measures, geometric support, stored-energy retention, and prevention of inadvertent release shall take priority even when the estimated occurrence probability is low. The required performance level for control-system safety functions shall be determined by the project risk assessment; this report does not prescribe it directly [5][7].

07 Project implementation and acceptance information package

Divide the project into seven gates: data freeze, concept review, prototype testing, design freeze, FAT, on-site SAT, and mass-production monitoring. At each gate, maintain traceability of the part version, tooling version, and motion recipe. Any change in sheet thickness, material, stamping process, oil, stiffener, or surface-quality standard shall trigger an impact assessment.

Minimum Delivery Evidence

- Part family parameter matrix, allowed contact area and forbidden limit area diagram.
- Load-case table, suction and slip-resistance calculations, assumptions, and sources of reduction factors.
- Suction point layout diagram, vacuum zone diagram, pipeline and sensor list.
- Definitions of trajectory speed/acceleration limits, emergency-stop conditions, and loss-of-pressure states.
- Raw test data and photographs from actual parts, plus three-dimensional scan or checking-fixture reports.
- FMEA, risk assessment, control logic, maintenance and reset instructions.
- Templates for first-piece, changeover, cleaning, suction-cup replacement, and abnormal-release records.

08 Conclusion and applicable limitations

The essence of handling large automotive sheet-metal parts is finding a verifiable balance among flexible workpieces, dynamic loads, and stringent surface-quality requirements. A reliable solution shall simultaneously address normal suction, tangential slip resistance, local peeling, overall deflection, surface quality, and contamination control, and shall be verified using worst-case parts and actual trajectories. Merely showing that total suction force exceeds weight is not sufficient for engineering release.

The methods in this report are suitable for concept design, technical agreements, verification plans, and design reviews. They do not constitute product certification, third-party type testing, or evidence of customer acceptance. Competent mechanical, electrical, safety, and quality personnel shall complete final confirmation for each project using current regulations, standards, supplier data, and customer specifications.

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