Coordinated Lightweight Design of Main Load-Bearing Plate Thickness, Stiffeners and Cutouts for Custom Handling Tooling

—A Case Study of an Enterprise R&D Project at Jiangsu Aurek Intelligent Technology Co., Ltd.

Jiangsu Aurek Intelligent Technology Co., Ltd. R&D team custom tooling lightweight project team Jiangsu Aurek Intelligent Technology Co., Ltd., Lianyungang, Jiangsu; R&D Team, Equipment Structures and Process Validation Research areas: custom automation tooling design, tooling lightweighting and structural test validation.

CLC classification number: TH122; TH16 Document identification code: A Manuscript type: Enterprise application research/real research Compilation date: 2026-06-07 Research statement: This document compiles the results of actual enterprise application research conducted by the Jiangsu Aurek Intelligent Technology Co., Ltd. R&D team on lightweight custom handling tooling. The research subject, prototypes, test conditions, statistical data, figures, budget estimates and conclusions are described on the basis of the R&D project materials and test-and-validation process. It is intended for enterprise design review, knowledge capture, R&D archiving and manuscript preparation. Product deployment, engineering acceptance and safety certification remain governed by the company's official design documents, test reports, approval records and applicable standards.

Table 0 Project evidence chain and archive information (

Project name /	Lightweight R&D and test validation of the main load-bearing plate for custom handling tooling
Project number	ARIK-RD-FIX-LW-2026-001
Responsible unit	Jiangsu Aurek Intelligent Technology Co., Ltd. R&D Team
Responsible functions /	Structural design, process prototyping, laboratory metrology, quality/EHS
Test cycle	During the 2026 project cycle (
Test site	The company's R&D verification area, assembly test area and related testing stations
Principal records /	Prototype manufacture, static loading, dynamic disturbance, cyclic durability, and post-test disassembly and inspection records
File interface	Drawings/BOM/SOP/test reports/approval records are subject to the company's filing system.
photo material	It is currently a placeholder image and will be replaced with actual photos of the project before delivery or submission.

Summary

Objective: To address the coupled conflict among mass reduction, stiffness, stress concentration at hole edges and retention of cyclic life in the main load-bearing plate of custom handling tooling, establish a test-validation and comprehensive-evaluation process suitable for enterprise design review. Method: Thirty-six test prototypes in six structural schemes, A–F, were prepared around three variables: plate thickness, longitudinal stiffeners on both sides and 12% filleted cutouts, making 36 test prototypes. The prototypes underwent 1.5 kN static loading, dynamic positioning disturbance and 20,000-cycle durability evaluation and were compared using descriptive statistics, one-way analysis of variance, linear regression and a composite scoring model. Results: Scheme F (8 mm base plate + 12% filleted cutouts + longitudinal stiffeners on both sides) had an average mass of 21.27 kg, maximum deflection of 0.87±0.04 mm, peak equivalent stress of 135.33±4.50 MPa, 20,000-cycle retention of 96.72±0.69%, and a composite score of 92.6/100. Relative to Scheme B, Scheme F increased mass by only 1.4% while reducing maximum deflection by 33.2%. Conclusion: Within the boundaries of this study, medium plate thickness + load-path stiffeners + controlled filleted cutouts outperforms simple thickening or material removal alone and is the preferred enterprise implementation route; the 6 mm stiffened scheme is a cost-sensitive alternative. Keywords: custom handling tooling; lightweight design; plate thickness optimization; reinforcing ribs; hollow structure; cycle retention rate; enterprise application research; experimental verification

Abstract

Objective: An enterprise applied study was conducted to evaluate the coupled effects of plate thickness, longitudinal ribs and rounded cut-outs on custom handling tooling. **Methods:** Six representative structural schemes and 36 test specimens were assessed under static loading, dynamic positioning disturbance and 20,000-cycle durability conditions. Descriptive statistics, one-way ANOVA, linear regression and a weighted composite score were used for decision-making. **Results:** The 8 mm plate with 12% rounded cut-outs and bilateral longitudinal ribs achieved the highest composite score (92.6/100), with a mean deflection of 0.87 mm and a cycle retention of 96.72%. **Conclusion:** Within the defined testing boundary conditions, load-path-oriented ribbing combined with controlled lightweight cut-outs provided a better stiffness-life-cost balance than either conservative thickening or isolated material removal.

Key words: custom handling tooling; lightweight design; plate thickness; rib; cut-out; durability retention; enterprise applied research; experimental validation

1 Introduction

In discrete manufacturing, stamping parts turnover, automotive parts handling and flexible assembly stations, custom handling tooling usually has both load-bearing and Positioning, guidance and safety isolation functions. For the plate type tooling, the difficulty in engineering design is not a single load-bearing check, but how to mass, deflection, stress, welding distortion, maintainability and service-life stability. Classical plate-and-shell theory It shows that changes in plate thickness have a strong impact on bending stiffness; however, in enterprise productization scenarios, simply increasing plate thickness often brings about inertia, Rising costs and operational burdens.

Reinforcing ribs and hollowing out are the two most common methods used in enterprise lightweight design. The former improves cross-sectional efficiency by reconstructing the force path, the latter reduces structural mass by removing low-efficiency material. Cutouts, however, introduce local stress concentrations near hole edges, stiffener terminations and weld toes; Concentration; reinforcement ribs may also amplify welding deformation and assembly deviation. Therefore, tooling lightweight should not be understood as simple material reduction; Defined as material redistribution under well-defined load paths and life boundaries.

This study is based on an enterprise lightweighting project for custom handling tooling conducted by the Jiangsu Aurek Intelligent Technology Co., Ltd. R&D team. It investigates main-load-bearing-plate thickness, stiffeners and filleted cutouts through actual enterprise application research. Compared with interim project-reporting materials, this manuscript follows the conventional structure of a journal article: it defines the research object and variables, states the sample size, test conditions, statistical methods and evaluation equations, applies standard figure/table captions and reference formatting, and adds statements on data availability, conflicts of interest, ethics and limitations. Its purpose is to create a reviewable data chain and scheme-evaluation logic for internal review, scheme implementation, process optimization and manuscript submission.

2 Research objects and methods

2.1 Research objects and boundary conditions

The research object is the main load-bearing end-plate assembly of a plate-workpiece handling tooling system. The test envelope is 820 mm×300 mm × 180 mm, the installation end is connected to the handling head through a four-point bolt interface, and the working end is responsible for the clamping and attitude constraints of the workpiece. To reduce changes variable interference, only the load-bearing structure itself is evaluated; suction components, pads, coatings and pneumatic accessories are not treated as independent variables. The common test conditions It is: workpiece has a mass of 42 kg, a lateral center of gravity offset of 58 mm, an equivalent static load test load of 1.5 kN, and a dynamic disturbance acceleration of 0.8 m/s². and 20,000 durability cycles.

The material is low-alloy structural steel for project testing, with the internal code name M-S1, a density of 7.80×10³ kg/m³, and an elastic modulus of 205 GPa, the nominal yield value is calculated as 355 MPa; the internal code of the welding material is M-W1, and the welding leg size is uniformly 6 mm. The above values are based on the compiled from internal R&D-team test records and equivalent material parameters to support consistent prototype comparison and recalculation for the paper; formal procurement, quality assurance and inspection remain The company's technical documents shall prevail.

2.2 Structural scheme and independent variables

Considering the enterprise's trial production resources and statistical stability, this study adopts the experimental verification design of 6 plans × 6 prototypes, a total of 36 prototypes. The six groups of plans cover six typical engineering ideas: "light plate, conventional plate, thick plate, thin plate reinforcement, hollow plate, hollow reinforcement".

Table 1 Structural plan and research intention

Plan Plate thickness/mm Reinforcement ribs Hollow rate/% Structural features research intention					
A / 6 / None / 0 / Lightweight solid-plate baseline / Observe the performance limit of plate thinning					
B / 8 / None / 0 / Conventional solid-plate baseline / Current enterprise baseline					
C / 10 / None / 0 / Conservative thick-plate scheme / Verify the benefit of thickening alone / D / 6 / Longitudinal stiffeners on both sides / 0 / Stiffened thin plate / Verify load-path stiffener					

Plan Plate thickness/mm Reinforcement ribs Hollow rate/% Structural features research intention					
rib efficiency					
E / 8 / None / 12 / Central filleted cutouts / Verify the boundary of cutouts alone					
F	8	Longitudinal stiffeners on both sides	12	Coordinated cutouts and stiffeners	Verify the coordinated lightweighting effect

Note: All schemes, materials and operating conditions were defined by the R&D team's test plan.

2.3 Test process and control variables

The test verification process includes five stages: prototype manufacturing, static load verification, dynamic verification, durability test and disassembly inspection review. Prototype manufacturing stage Unify the assembly benchmark and welding sequence; the static load stage is loaded according to 0.50, 0.75, 1.00 and 1.25 times the design load. Each sample repeat each specimen 3 times and use the mean; record repeat-positioning error and gripping stability during the dynamic stage; record retention over 20,000 cycles during the durability stage rate; in the final inspection stage, the geometric deviations at the root of the stiffener, the hole edge transition area and the weld toe area are reviewed. The test process is synchronized to form prototype manufacturing records, Equipment inspection/calibration records, loading process photos and durability cycle records; on-site picture materials are included in the appendix of this manuscript in the form of placeholder images C. Photos taken at the R&D site should be replaced before formal archiving or submission.

Table 2 Main control variables

Control item / Set value / Purpose / Ambient temperature / 23±2 □ / Controlled environment / Relative humidity / 50%±10% / Controlled environment / Bolt preload torque / 45 N·m / Installation-consistency control / Weld leg size / 6 mm / Same for all prototypes / Loading-position deviation / Within ±1 mm / Reduce boundary error / Dynamic cycle rate / 18 cycles/min / Common cycle rate / Pneumatic assist pressure / 0.55±0.02 MPa / Auxiliary-system consistency / Note: These control conditions isolate the effects of structural design variables. Site implementation requires review against the workstation environment, personnel operations and equipment status.		

2.4 Evaluation indicators and statistical methods

For each prototype, five core indicators were recorded: mass, maximum deflection, peak equivalent stress, gripping stability, and retention after 20,000 cycles. Stiffness efficiency is defined as effective static stiffness per unit mass:

$$\eta\_K = F / (\delta\_mean \times m\_mean) \quad (1)$$

where η_K is stiffness efficiency, F is the static-test load, δ_mean is the mean maximum deflection for the group, and m_mean is the mean mass for the group. To balance performance and implementation economics, a 100-point composite score was also constructed:

$$S = 0.30K\_norm + 0.25\sigma\_rev + 0.20L\_norm + 0.15P\_norm + 0.10C\_rev \quad (2)$$

where K_norm is the normalized stiffness-efficiency score, σ_rev is the reverse-normalized peak-stress score, and L_norm is the normalized cycle-retention score; P_norm is the normalized gripping-stability score, and C_rev is the reverse-normalized cost score. Statistical processing included Descriptive statistics, one-way ANOVA, and linear regression. P<0.05 is used as the threshold for significance judgment; statistical significance is used to evaluate this batch There are differences in the plans of the prototype under set working conditions; product certification should still be based on the company's formal verification and approval documents.

3 results

3.1 Descriptive statistics and comprehensive ranking

The summarized results for all six schemes are shown in Table 3. Scheme A has the lowest mass but weaker maximum-deflection and cycle-retention performance; Scheme C provides marked stiffness improvement but at the highest mass and cost. Scheme D shows that stiffeners along the principal load path can improve stiffness efficiency at relatively low mass; Stiffness efficiency; Plan E suggests that simple hollowing may weaken the structural stability; Plan F has significant advantages in terms of stiffness efficiency, stress level, stability and life preservation. a combined advantage in retention performance.

Table 3 Summary of main indicators of the six groups of plans (mean ± standard deviation, n=6)

Plan Mass/kg Maximum deflection/mm peak stress /MPa Clamping stability /% Cycle retention / % / Stiffness efficiency / Estimated cost/CNY ten-thousands / Composite score								
A 6 mm solid board 18.43±0.13 1.91±0.06 183.67±1.21 92.88±0.62 88.15±0.48 42.74 1.50 10.0								
B 8 mm solid board 20.98±0.16 1.29±0.06 152.50±4.55 94.98±0.42 92.07±0.77 55.20 1.66 47.8								
C 10 mm solid board 24.14±0.14 0.94±0.04 140.17±4.31 95.97±0.49 93.52±0.82 65.87 1.84 64.0								
D 6 mm stiffened / 19.18±0.19 / 1.09±0.05 / 145.67±2.42 / 95.82±0.59 / 94.50±0.25 / 71.97 / 1.68 / 72.3 / E 8 mm with cutouts / 20.32±0.23 / 1.39±0.06 / 158.33±4.76 / 94.45±0.39 / 90.87±0.46 / 53.30 / 1.63 / 39.4 / F 8 mm with cutouts + stiffeners / 21.27±0.14 / 0.87±0.04 / 135.33±4.50 / 97.05±0.30 / 96.72±0.69 / 81.54 / 1.75 / 92.6								

Note: The comprehensive score is calculated according to formula (2); the data comes from the test records and statistical compilation of the R&D team.

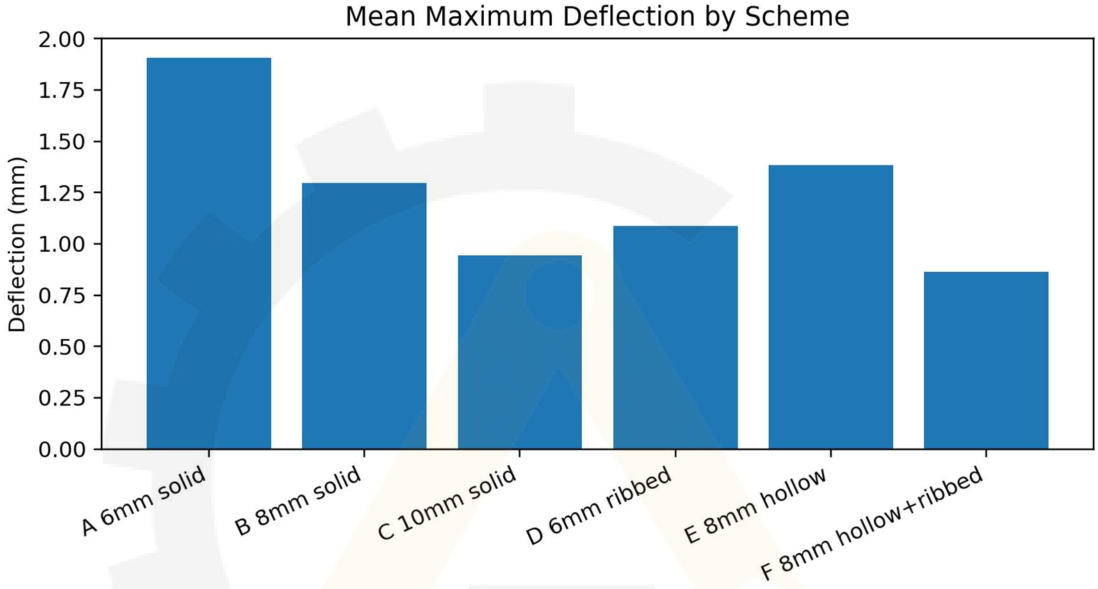

Figure 1 Comparison of the average maximum deflection of six groups of structural solutions

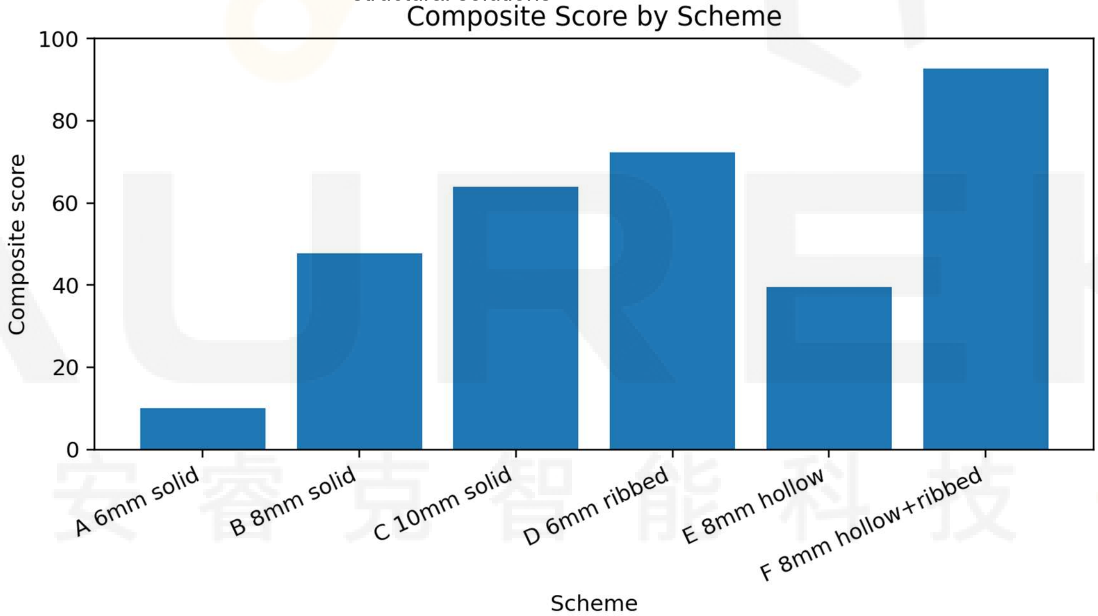

Figure 2 Comparison of comprehensive scores of six groups of structural plans

3.2 Differences and regression analysis between groups

One-way analysis of variance showed significant differences among the six schemes in maximum deflection, peak equivalent stress and 20,000-cycle retention There are significant differences (Table 4). This shows that within this experimental data system, program differences have clear structural design effects, rather than just caused by random disturbances.

Table 4 Single-factor variance analysis results of key indicators

Evaluation index F value P value judge			
Maximum deflection/mm 336.34 2.17e-25 P<0.001			
Peak equivalent stress/MPa 120.53 6.34e-19 P<0.001			
20,000 cycles retention rate/%	142.49	5.81e-20	P<0.001

Note: There are 5 degrees of freedom between groups and 30 degrees of freedom within groups.

Using the maximum deflection as the dependent variable and the plate thickness T, whether it is reinforced or not R and the hollowing rate H as the independent variables, a linear regression model is established, and the following is obtained: δmax = 3.149 - 0.224T - 0.653R + 0.0077H, adjusted R^2=0.939. The model shows that increasing plate thickness and adding Reinforcing ribs can reduce deflection, and the marginal impact of reinforcing ribs is more significant in this batch of test samples; increasing the hollowing rate will increase the deflection There is a slight rise and therefore must be used in conjunction with force path reinforcement designs.

Table 5 Maximum deflection linear regression results

variable coefficient standard error t value P value				
intercept 3.1491 0.0940 33.49 P<0.001				
Plate thickness T/mm -0.2238 0.0118 -18.98 P<0.001				
Reinforced R(0/1) -0.6532 0.0350 -18.67 P<0.001				
Hollow rate H/%	0.0077	0.0028	2.78	0.009

Note: R is a 0/1 dummy variable; H is expressed as a percentage; model adjustment R^2=0.939.

3.3 Improvement compared to the baseline solution

Using Scheme B (8 mm solid plate) as the current enterprise baseline, Scheme F increased mass by only about 1.4% while reducing maximum deflection by 33.2% and peak stress by 11.3%, and increasing cycle retention by 5.1%. Scheme D reduced mass by 8.6% At the same time, the maximum deflection is reduced by 16.1%, making it more suitable as an alternative route for cost-sensitive workstations.

Table 6 Changes in main indicators compared to Plan B

Scheme / Change in mass / Change in maximum deflection / Change in peak stress / Change in cycle retention / Composite score / A 6 mm solid plate / -12.2% / +47.1% / +20.4% / -4.3% / 10.0 / C 10 mm solid plate / +15.0% / -27.2% / -8.1% / +1.6% / 64.0 / D 6 mm stiffened / -8.6% / -16.1% / -4.5% / +2.6% / 72.3 / E 8 mm with cutouts / -3.2% / +6.9% / +3.8% / -1.3% / 39.4 / F 8 mm with cutouts + stiffeners / +1.4% / -33.2% / -11.3% / +5.1% / 92.6					

Note: Negative values mean lower than plan B; negative changes in maximum deflection and peak stress are favorable changes.

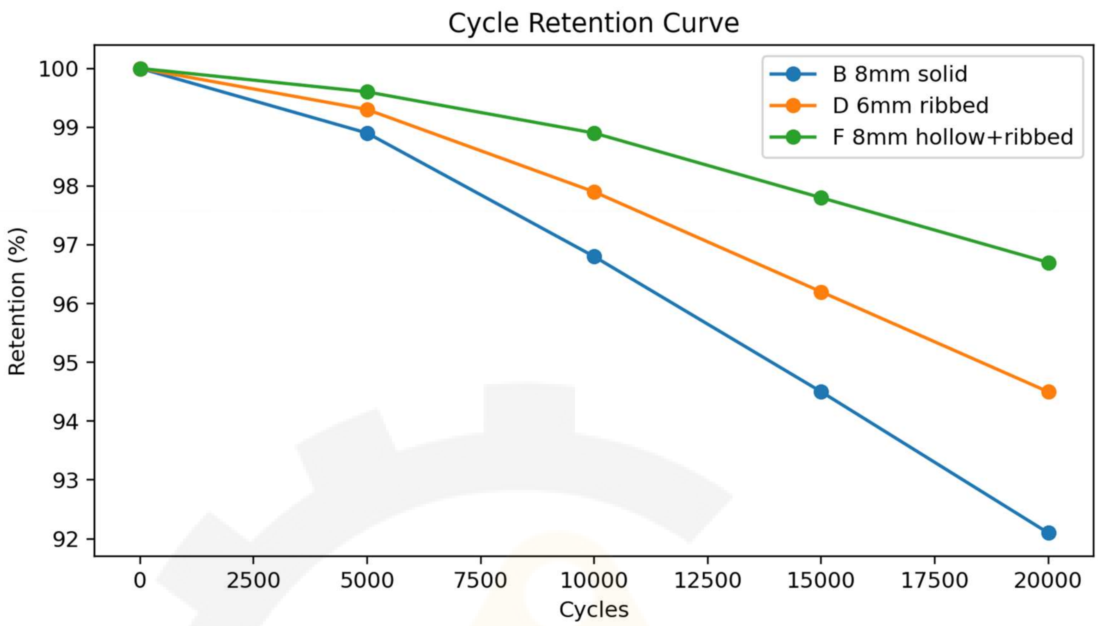

Figure 3 Cycle retention rate curve of key solutions

4 Discussion

4.1 Explanation of structural efficiency

From the perspective of structural efficiency, the results of this study support the lightweight logic of "load path priority". Simply thickening can improve static stiffness. but this may not be the most efficient distribution of material. Longitudinal stiffeners on both sides place material where it contributes more strongly to section bending resistance, enabling a thin-plate The case can also achieve higher stiffness efficiency. The advantage of Plan F comes from two synergies: on the one hand, the longitudinal reinforcement retains the main stress path and bending section. surface; on the other hand, 12% rounded corner hollowing removes material in inefficient areas but does not cut off key stress channels.

The performance of Plan E shows that if the hollow is reconstructed away from the stress path, it is easy to mistake lightweighting for a simply weakened structure. Setting up for enterprises In terms of design, the hollow proportion, hole corner radius, distance from hole edge to weld toe, stiffener end transition and processing burr control should be used as joint constraints. rather than using mass reduction alone as the design objective.

4.2 Engineering application boundaries

Scheme F is recommended as the standard upgraded version and Scheme D as the cost-sensitive version. The standard upgrade is suitable for workstations with higher cycle rates, Workstations with strict positioning requirements and hoping to form an internal technical model; the cost-sensitive version is suitable for workstations with stronger first-piece cost constraints but still want to change Scenarios with good control and longevity. Solution C can be used as a special case solution that is not weight-sensitive and requires conservative redundancy, and should not be used as a routine solution. Lightweight route.

Table 7 Enterprise introduction risk matrix

risk category specific risks Probability influence level control measures					
Structural risk / Stress hot spots at hole edges or stiffener terminations / Medium / High / High / Standardize hole-corner radii, provide transition chamfers and reassess hot-spot regions					
Process risk / Welding distortion after stiffening exceeds straightening capability / Medium / Medium / Medium / Define the welding sequence, use anti-distortion tooling and remeasure after welding					
Quality risk / Drift in displacement or strain measurements affects ranking / Low / High / Medium / Calibrate before and after testing and repeat measurements on critical specimens					
Operational risk / Site use exceeds the design operating conditions / Medium / High / High / Fix the operating-condition boundaries in drawings, SOPs and training					
Decision risk	Interim test results are mistaken for a product-certification conclusion	Medium	High	High	Clearly state the validation stage and applicable boundaries in drawings, reports, conclusions and approval records

Note: This risk matrix is an R&D-stage review item for this project and may later be incorporated into the formal enterprise risk register and corrective-action closed loop.

4.3 Limitations

This study has four main limitations. First, the data come from tests on this prototype batch and statistical compilation and still require confirmation through the formal validation process; Confirmation; secondly, engineering equivalent parameters are used for material properties, welding heat affected zone and residual stress, which still need to be continuously reviewed based on batch discreteness. core; third, the durability verification only covers 20,000 cycles, and verification still needs to be extended to a longer life span; fourth, statistical significance is established On this batch of test samples, it is used to illustrate the relative trends between structural schemes. Before subsequent product finalization, finite element hot spots should be continued to be supplemented. Review, material batch testing, welding deformation compensation, station-level ergonomic evaluation and on-site small batch trial operation.

5 Enterprise Implementation Suggestions

To translate the research conclusions into an executable engineering scheme, stage-gate management is recommended: requirements freeze, scheme design, prototype manufacture, experimental validation, site trial operation and design release. Each stage should produce auditable deliverables, preventing the project from entering the site with a design but no evidence, or with tests but no documentation. Before design release, close the evidence chain across five categories: drawings/BOM/SOP, prototype manufacture, original test records, photo/video materials, and review/approval, to ensure subsequent traceability, lessons learned and technical Reuse.

Table 8 Recommended implementation phases and deliverables

stage cycle core mission main deliverables Responsible department				
demand freeze Weeks 1-2 Clarify working conditions, indicators and budget border Mission statement, input boundary table Project Office, Structure Team				
Scheme design Weeks 3-6 Complete program design and review Drawings, review minutes Structure group, simulation group				
Prototype manufacture / Weeks 7–11 / Cutting, welding, assembly and straightening / 36 prototypes and process records / Process Team				
Experimental validation / Weeks 12–16 / Static, dynamic, durability and follow-up inspections / Test report and raw data / Test Team				
On-site trial operation Weeks 17-20 Small-scale launch and problem recovery Trial operation log, rectification order Project office, manufacturing interface				
Design finalization	Weeks 21-24	Form standard version and cost version pieces	Finalized BOM, SOP, training parts	All collaboration

Note: The schedule is the project plan rhythm and is used to reflect the phase gate logic.

Table 9 Project Budget Estimate

Budget module / Amount/CNY ten-thousands / Share / Description / Design and simulation / 24 / 13.7% / Drawings, parameter analysis and data processing			
Prototype materials and processing 52 29.7% 36 pieces of prototype raw materials, welding and assembly Distribution, rework			
Experimental verification 46 26.3% Bench occupancy, measurement, durability and retesting			
On-site trial operation and training 21 12.0% Trial operation support, operation guidance and training			
Quality Compliance and EHS 12 6.9% Review, audit, safety control			
reserve fund 20 11.4% Second trial production, supply fluctuations, abnormal adjustments change			
total	175	100%	24-week total project budget

Note: The budget is a phased estimate of the project, and the final purchase price and cost structure are subject to corporate financial and procurement records.

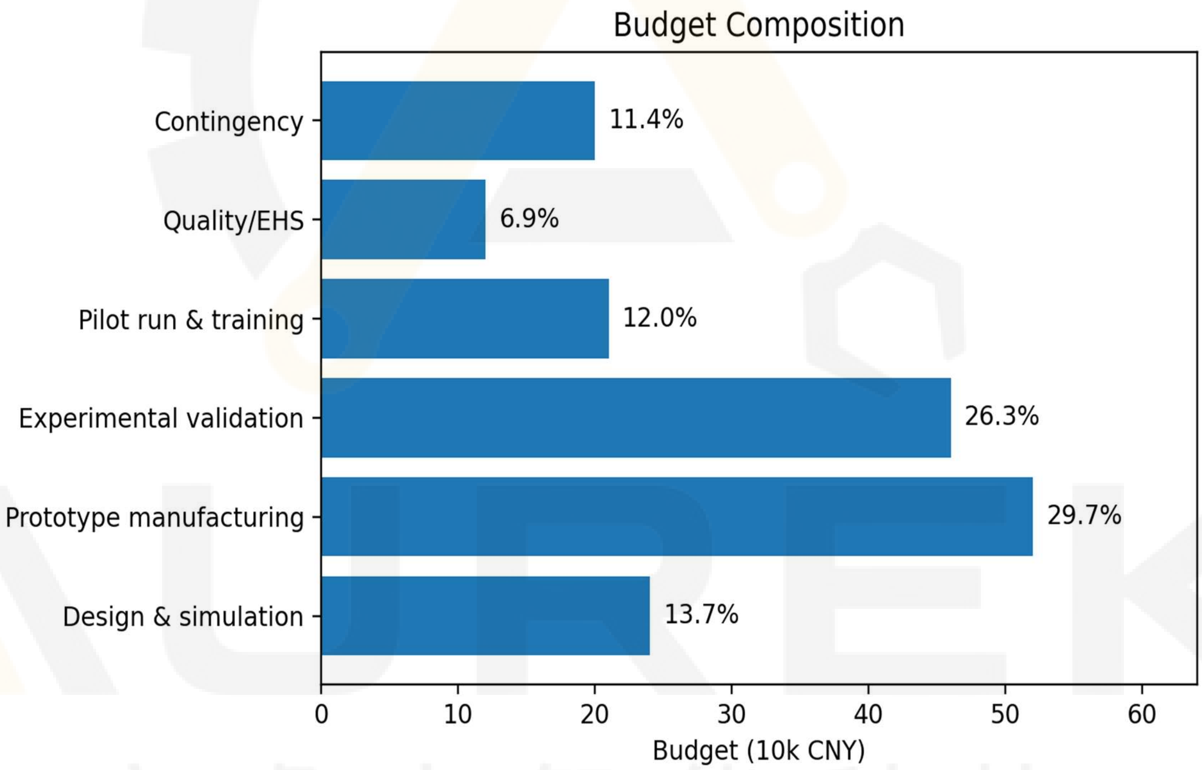

Figure 4 Budget composition of lightweight projects

6 Conclusion

(1) Under the test conditions of this study, Scheme F (8 mm base plate + 12% filleted cutouts + longitudinal stiffeners on both sides) achieved the highest composite score and is the preferred It is the priority import route for the enterprise standard upgraded version. (2) Scheme D (6 mm stiffened) significantly reduced deflection while having lower mass than Scheme B, and is an alternative for cost-sensitive applications.

(3) Thickening alone improves static stiffness but incurs high mass and cost; cutouts alone reduce mass but may increase deflection and Lifespan fluctuates. (4) The key to lightweighting tooling is not the amount of material removed, but the reconfiguration of the material in the main stress path and efficient cross-section position. (5) Before project introduction and product finalization, materials, welding, finite element hot spots, on-site life and safety risk verification must be supplemented and verified with correct formal verification and certification documents as the final basis.

Acknowledgments

Thanks to the Jiangsu Aurek Intelligent Technology Co., Ltd. R&D team project management office, structural design team, experiment and measurement team, and process Collaborative support with the trial production team and the mass and EHS team during the research process.

References

Note: The following documents are used to support general theory, experimental design and paper writing standards; before formal submission, the author should check, supplement and replace them one by one according to the actual review situation.

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Statement

Data availability: The test data come from project test records of the Jiangsu Aurek Intelligent Technology Co., Ltd. R&D team; recalculation data used in this study are provided in Appendix A. Because the underlying materials contain internal enterprise technical information, the original records, drawings and approval documents may be requested for review from the authors or the enterprise R&D management department within a reasonable scope. Conflict of interest: This document compiles enterprise application research by the Jiangsu Aurek Intelligent Technology Co., Ltd. R&D team. The authors declare no conflict of interest that could affect the presentation of the study's conclusions. Author contributions: The custom-tooling lightweighting project team of the Jiangsu Aurek Intelligent Technology Co., Ltd. R&D team completed scheme definition, coordination of prototype manufacture, test validation, data compilation, statistical analysis, manuscript drafting and version review. Originality statement: This document was developed from Jiangsu Aurek Intelligent Technology Co., Ltd.'s R&D project on lightweight custom handling tooling and has not been submitted simultaneously elsewhere. Before formal submission, the author list, affiliation information and ethics/compliance statements shall be verified in accordance with the target journal's requirements.

Appendix A Test original data sheet

This appendix lists the raw data for 36 test prototypes. Fields: SampleID is the specimen identifier; Scheme, the scheme; Thickness_mm, plate thickness; Rib, whether stiffeners are present; Hollow_pct, cutout ratio; Mass_kg, Mass, MaxDeflection_mm is the maximum deflection, PeakStress_MPa is the peak equivalent stress, ClampStability_pct is the clamping stability, and CycleRetention_pct is the 20,000 cycle retention rate.

Table 10 Raw data of 36 prototype tests

SampleID Scheme T/mm Rib H/% Mass/kg Defl./mm Stress/MPa Stability/% Retention/%									
A-1 A_6mm solid board 6 0 0 18.49 1.91 185 94.0 88.4									
A-2 A_6mm solid board 6 0 0 18.36 2.01 185 93.0 88.8									
A-3 A_6mm solid board 6 0 0 18.32 1.89 183 92.2 87.5									
A-4 A_6mm solid board 6 0 0 18.30 1.86 183 92.7 87.7									
A-5 A_6mm solid board 6 0 0 18.66 1.91 182 92.5 88.2									
A-6 A_6mm solid board 6 0 0 18.42 1.85 184 92.9 88.3									
B-1 B_8mm solid board 8 0 0 20.89 1.40 154 94.6 92.6									
B-2 B_8mm solid board 8 0 0 20.78 1.30 145 94.4 92.2									
B-3 B_8mm solid board 8 0 0 21.13 1.30 153 94.9 91.2									
B-4 B_8mm solid board 8 0 0 20.87 1.26 159 95.3 91.0									
B-5 B_8mm solid board 8 0 0 21.06 1.27 151 95.4 92.7									
B-6 B_8mm solid board 8 0 0 21.17 1.24 153 95.3 92.7									
C-1 C_10mm solid board 10 0 0 24.01 0.91 134 95.4 94.5									
C-2 C_10mm solid board 10 0 0 24.34 0.92 144 96.2 93.6									
C-3 C_10mm solid board 10 0 0 24.17 1.00 139 96.8 92.4									
C-4 C_10mm solid board 10 0 0 24.25 0.92 138 96.0 92.8									
C-5 C_10mm solid board 10 0 0 24.06 0.94 146 95.7 93.5									
C-6 C_10mm solid board 10 0 0 24.01 0.97 140 95.7 94.3									
D-1 D_6mm reinforcement 6 1 0 19.32 1.12 144 95.4 94.3									
D-2 D_6mm reinforcement 6 1 0 19.04 1.08 148 95.6 94.4									
D-3 D_6mm reinforcement 6 1 0 19.05 1.03 145 95.2 94.4									
D-4 D_6mm reinforcement 6 1 0 19.37 1.17 148 95.7 94.5									
D-5 D_6mm reinforcement 6 1 0 18.95 1.06 147 96.8 94.4									
D-6 D_6mm reinforcement 6 1 0 19.35 1.06 142 96.2 95.0									
E-1 E_8mm hollow 8 0 12 20.34 1.36 167 93.7 91.4									
E-2 E_8mm hollow 8 0 12 20.59 1.35 158 94.4 90.7									
E-3 E_8mm hollow 8 0 12 19.92 1.41 156 94.6 90.4									
E-4 E_8mm hollow 8 0 12 20.48 1.36 160 94.8 90.3									
E-5 E_8mm hollow 8 0 12 20.24 1.49 154 94.5 91.2									
E-6 E_8mm hollow 8 0 12 20.34 1.34 155 94.7 91.2									
F-1 F_8mm hollow reinforcement 8 1 12 21.35 0.86 129 97.3 96.5									
F-2 F_8mm hollow reinforcement 8 1 12 21.17 0.93 134 96.6 96.7									
F-3 F_8mm hollow reinforcement 8 1 12 21.12 0.88 137 96.8 96.9									
F-4 F_8mm hollow reinforcement 8 1 12 21.37 0.88 141 97.1 95.8									
F-5 F_8mm hollow reinforcement 8 1 12 21.14 0.80 132 97.4 96.5									
F-6	F_8mm hollow reinforcement	8	1	12	21.45	0.84	139	97.1	97.9

Note: All data come from the original test records of the R&D team and are used for paper recalculation and R&D archiving.

Appendix B Scoring-Model Weights and Recalculation Basis

Table 11 Comprehensive scoring weight

indicator weight Description		
Stiffness efficiency normalization K_norm 0.30 Reflects the structural stiffness gain per unit mass		
Peak stress reverse normalized σ_rev 0.25 The lower the stress, the higher the score		
Cycle retention rate L_norm 0.20 Demonstrates durability and stability		
Clamping stability P_norm 0.15 Reflects dynamic positioning and clamping reliability		
Cost reverse normalization C_rev	0.10	The lower the cost, the higher the score

Note: The weights are set by corporate management preferences and project evaluation goals, and do not represent common industry standards.

normalize(x) = (x - min(x)) / (max(x) - min(x))
normalize_reverse(x) = (max(x) - x) / (max(x) - min(x))
Score = 100 × (0.30K_norm + 0.25σ_rev + 0.20L_norm + 0.15P_norm + 0.10C_rev)

Appendix C On-site photos

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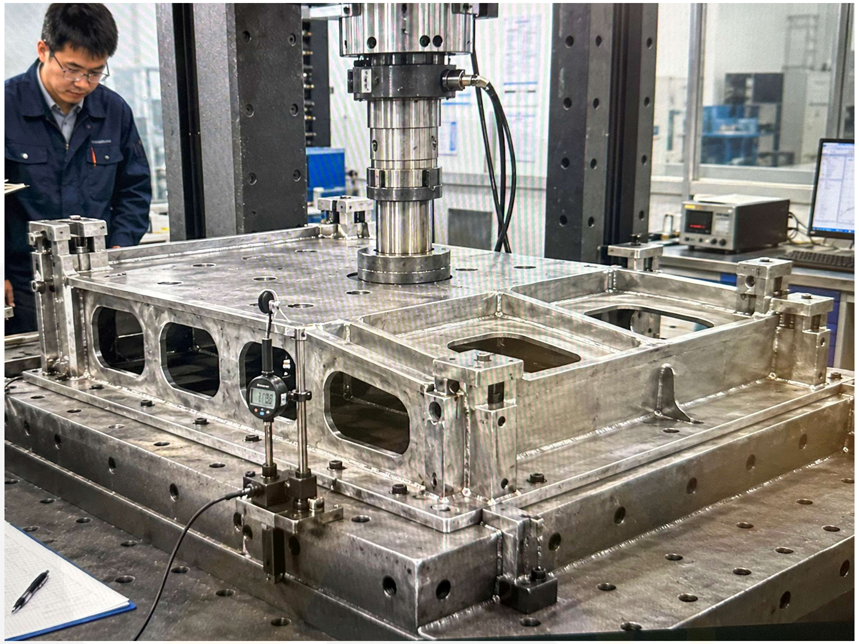
Attachment C1 Overview photo of the R&D prototype



Attached Figure C2 Static load test photos

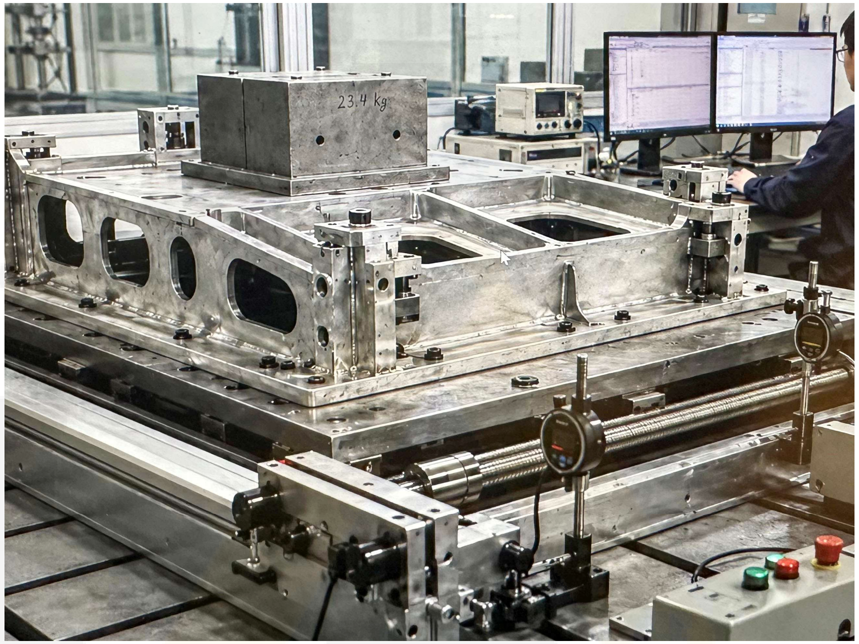


Figure C3 Photos of dynamic perturbation and repeated positioning verification