

Design and Analysis of Modular Steel Mould Systems for SUPERDUCT Precast Arch Drainage Structures

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Abstract— This paper presents a comprehensive investigation into the design, analysis, and comparative evaluation of modular steel mould (shuttering) systems for SUPERDUCT precast arch concrete drainage structures. Three mould sizes — T3, T5, and T9 — were studied with respect to geometric parameters, component weight distribution (internal panel, external panel, and collar), and capability ratios computed against concrete volume, water opening area, and total shuttering surface area. Data was collected from field observations at Buttibori Fabrication Yard, Hingna site, and VNIT Nagpur, supplemented by 3D AutoCAD modelling and AI-assisted design trials. Results show mould capability improves systematically with size: T9 provides 3.80× the hydraulic opening at only 1.95× the mould weight of T3. Total mould weight per m² of surface area remains stable at 141–145 kg/m² across all sizes, confirming consistent panel design. The collar is identified as the fastest-growing component. Design benchmarks are proposed for future mould development.

Keywords— SUPERDUCT, Modular Steel Mould, Precast Concrete, Shuttering Design, Mould Size T3 T5 T9, Arch Drainage Structure.

I. INTRODUCTION

In modern civil engineering, precast construction delivers capability, quality control, and rapid execution in infrastructure projects. Cross-drainage structures maintain natural water flow across road and railway corridors. SUPERDUCTS — three-radius arch precast concrete systems — have emerged as an advanced alternative to conventional pipe and box culverts, offering improved hydraulic capability, compression-dominant structural behaviour, and suitability for rapid precast manufacturing.

The successful production of SUPERDUCT units depends on the design and performance of the steel mould systems used during casting. The mould defines geometric accuracy, ensures dimensional consistency, and maintains structural integrity during concrete placement and vibration. Mould systems must be modular, reusable, and capable of withstanding repeated loading

This paper presents a systematic comparative analysis of modular steel moulds for SUPERDUCT sizes T3, T5, and T9 using field-measured data to quantify weight capability, surface area scaling, and hydraulic performance ratios across the mould product family.

A. Problem Statement

SUPERDUCT mould design is frequently treated as a geometric or fabrication task without rigorous analysis of structural capability or weight optimization. This results in moulds that may be inconsistently scaled across the product range and lacking evidence-based design targets. This study addresses that gap with systematic data-driven analysis.

B. Objectives

- Document dimensional and weight data for T3, T5, and T9 mould sizes.
- Compute capability ratios relating mould weight to concrete volume, water opening, and surface area.
- Identify components scaling disproportionately.
- Establish design benchmarks for future mould development.
- Evaluate AI-assisted tools for SUPERDUCT mould geometry generation.

II. LITERATURE REVIEW

A. Conventional Cross-Drainage Structures

Pipe culverts are simple but suffer from limited unit capacity, sediment blockage, and bedding requirements in weak subgrades. Box culverts provide higher discharge but require significant bending reinforcement, longer construction durations, and obstruct active water channels during construction [1]. Both limitations drove demand for more hydraulically efficient precast alternatives.

B. SUPERDUCT Technology

SUPERDUCTS employ a three-radius arch profile (bottom R₁, top R₂, side R₃) that keeps the majority of the structural cross-section in compression under combined soil and traffic loads [2]. This eliminates mandatory concrete bedding, reduces reinforcement requirements, and provides larger effective waterway area. Being precast, SUPERDUCTS offer faster construction cycles and controlled manufacturing quality.

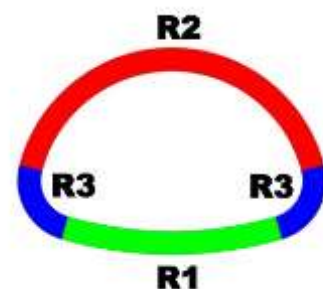


Fig. 1 Three-radius arch geometry: Span (B), Rise (H), and radii R₁, R₂, R₃

C. Importance of Mould Design

Key requirements for SUPERDUCT moulds are: dimensional accuracy for field alignment; deformation resistance under lateral concrete pressure; ease of assembly and dismantling; long-term reusability; and safe panel handling. Stiffeners — horizontal (resisting hoop stresses) and vertical (resisting bending) — are essential for curved panels. Bolted connections are preferred over welded for dismantlable modular systems [3].

III. METHODOLOGY

A. Field Data Collection

- Buttibori Fabrication Yard, Nagpur — mould component inspection, assembly/dismantling observation, weight documentation, and dimensional recording for T3, T5, and T9 mould assemblies.
- Hingna Field Site — inspection of installed SUPERDUCT structures under operational drainage conditions.
- VNIT Nagpur — structural test models for proof loading and performance verification.

B. 3D Modelling

Three-dimensional models were developed in AutoCAD for T3, T5, and T9 mould sizes. The three-radius cross-sections were generated, extruded to standard mould length, and all components modelled: internal panels, external panels, horizontal and vertical stiffeners, and top/bottom collar elements.

C. Capability Ratio Framework

Five capability ratios were computed per mould size and per component: (1) mould weight per m³ of concrete volume; (2) mould weight per m² of water opening area; (3) mould weight per m² of total shuttering surface; (4) water opening per m³ of concrete; (5) water opening per kg of total mould weight.

D. AI-Assisted Design Trial

An experimental trial used Claude AI (Anthropic) to evaluate automated mould geometry generation. The AI generated 2D profiles and basic stiffener layouts but could not autonomously complete 3D assembly with panel segmentation and connection detailing — establishing a development baseline [4].

IV. DATA COLLECTION AND GEOMETRIC PARAMETERS

A. Geometric Parameters

The three SUPERDUCT sizes studied are characterized in Table I. The T9 has a span of 4285 mm, rise of 2705 mm, and waterway area of 9.12 m².

TABLE I GEOMETRIC PARAMETERS OF SUPERDUCT MOULD SIZES

Size	Span (mm)	Rise (mm)	Water Area (m ²)	Length (mm)
T3	~2050	~1300	2.40	1500
T5	~2860	~1820	4.13	1500
T9	4285	2705	9.12	1500

B. Mould Components

1) *Internal Panel*: Forms the inner bore surface. Resists lateral concrete pressure from inside. Extracted after initial concrete set.

2) *External Panel*: Surrounds concrete externally. Maintains outer diameter accuracy and assists consolidation.

3) *Collar*: Steel ring at each mould end. Forms the Bale-and-Spigot joint for field coupling of adjacent pipe sections.

V. RESULTS AND GRAPHICAL ANALYSIS

A. Mould Component Weight

Internal panel weight: 831 kg (T3) → 1,051 kg* (T5) → 1,545 kg (T9). External panel: 1,033 → 1,329 kg. Collar grows 2.23× — fastest relative growth. Total mould weight scales 1.95× from T3 to T9. (*T5 corrected from 1,545 kg — see Section VI-C.)

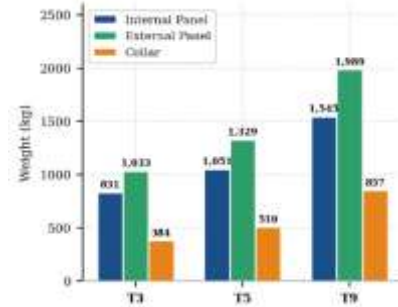


Fig. 2 Individual mould component weights (kg) for T3, T5, T9

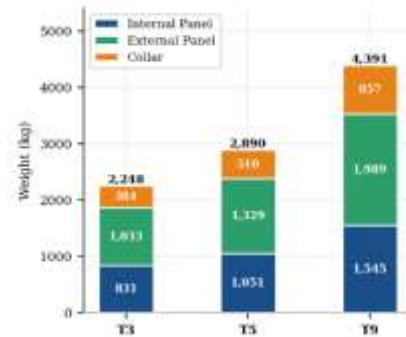


Fig. 3 Stacked total mould weight showing component breakdown (kg)

B. Surface Area Analysis

Total surface area grows from 15.88 m² (T3) to 30.19 m² (T9) — 1.90×. The external-to-internal surface ratio narrows from 1.197 to 1.140, confirming proportional wall thickness reduces with pipe size, consistent with arch geometry scaling.

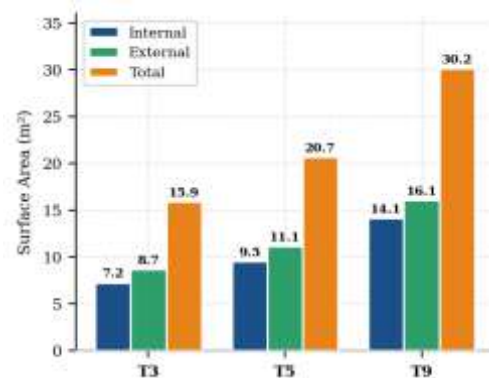


Fig. 4 Internal, External and Total mould surface area (m²)

C. Hydraulic Parameters

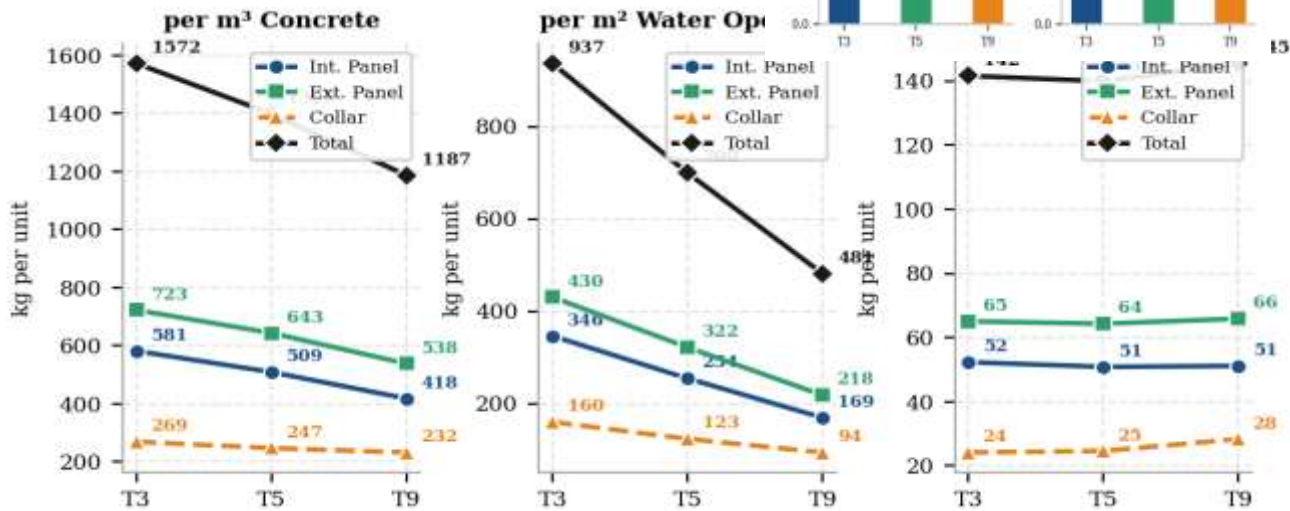
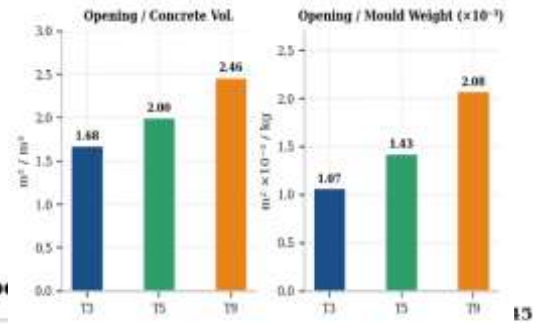
Water opening grows 3.80× (T3 to T9) while concrete volume grows only 2.59×. Bore area scales with the square of linear dimension while perimeter scales linearly — the fundamental geometric advantage of arch profiles.



Fig. 5 Concrete volume (m³) and Water opening area (m²) comparison

shown in Fig. 8. All ratios confirm decreasing shuttering demand per unit of functional output as mould size increases.

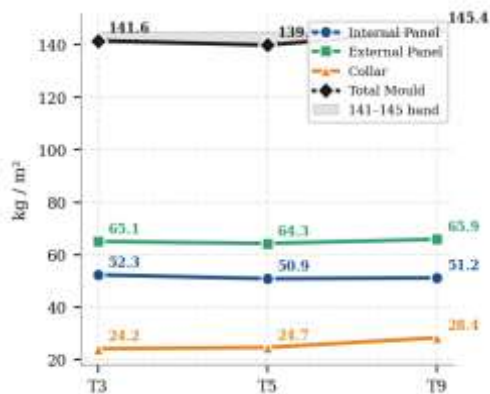
Fig. 6 Weight per m² of total surface — stability band 141–145 kg/m²



D. Weight Capability Ratios

Individual component ratio trends are plotted in Fig. 6. The stability of the total weight per m² of surface area is

Fig. 7 Hydraulic capability: opening per m³ concrete and per kg mould weight



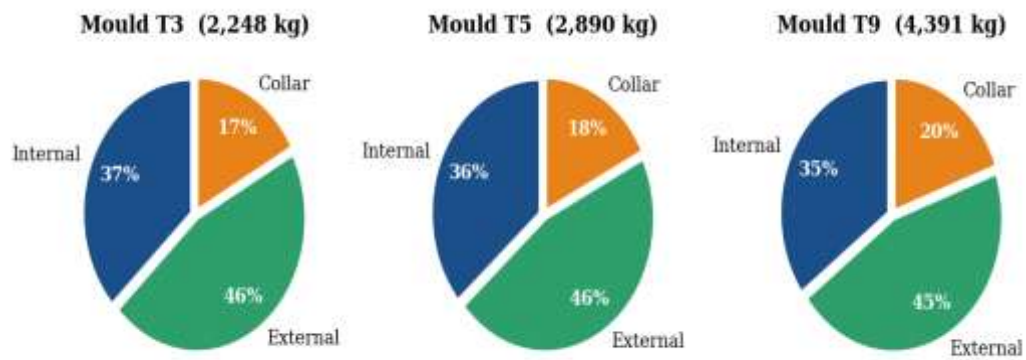


Fig. 8 Mould weight capability ratios: per m³ concrete, per m² water opening, per m² surface — T3, T5, T9

Shuttering Mould Design — Comprehensive Trend Analysis with Linear Extrapolation (T3 → T5 → T9 → Next)

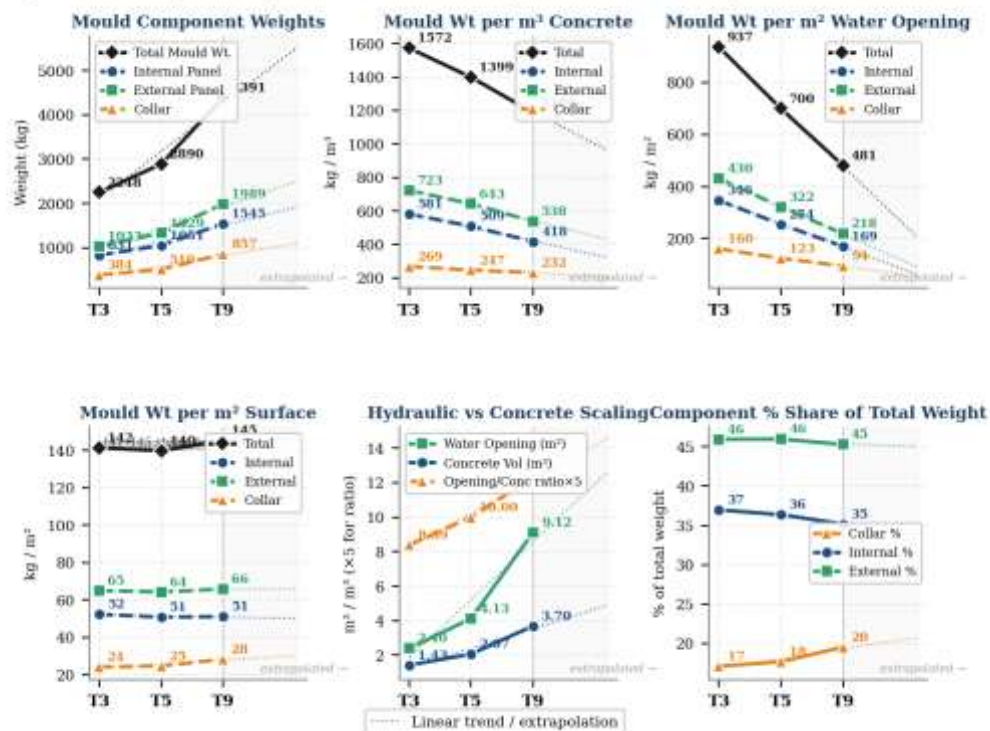


Fig. 9 Proportional weight distribution (%) — Internal Panel, External Panel, Collar per mould size

Fig. 10 Comprehensive shuttering weight trend analysis with linear extrapolation across T3, T5, T9: (top-left) absolute component weights; (top-center) weight per m³ concrete; (top-right) weight per m² water opening; (bottom-left) weight per m² surface with 141–145 kg/m² stability band; (bottom-center) hydraulic opening vs concrete scaling; (bottom-right) component % share trends. Dotted lines show linear trend extrapolation beyond T9 for design guidance.

TABLE II COMPLETE MOULD DATA FOR T3, T5 AND T9 (*AMBER = CORRECTED T5 INTERNAL PANEL VALUE)

Mould	Conc (m ³)	Water (m ²)	Int.S (m ²)	Ext.S (m ²)	Tot.S (m ²)	Int.P (kg)	Ext.P (kg)	Collar (kg)	Total (kg)
T3	1.430	2.400	7.230	8.650	15.880	831.27	1,033.19	383.98	2,248
T5	2.066	4.130	9.540	11.120	20.660	1,051*	1,329.00	510.00	2,890
T9	3.700	9.120	14.110	16.080	30.190	1,545.00	1,989.32	856.60	4,391

Note: Conc=Concrete Volume (m³); Water=Water Opening (m²); S=Surface Area (m²); P=Panel Weight (kg); *T5 Internal Panel corrected to 1,051 kg from erroneous 1,545 kg (field verified).

TABLE III MOULD WEIGHT SCALING AND WATER OPENING COMPARISON (T3 = 1.0× BASELINE)

Mould	Int.Panel (kg)	Ext.Panel (kg)	Collar (kg)	Total Wt. (kg)	Wt. Scale (T3=1×)	Water Opening (m ²)	Opening Scale (T3=1×)
T3	831.27	1,033.19	383.98	2,248	1.00×	2.40	1.00×
T5	1,051*	1,329.00	510.00	2,890	1.29×	4.13	1.72×
T9	1,545.00	1,989.32	856.60	4,391	1.95×	9.12	3.80×

TABLE IV COMPUTED CAPABILITY RATIOS — GREEN = BEST PERFORMING MOULD SIZE

Capability Metric	T3	T5	T9	Unit	Best	Trend
Wt per m ³ Concrete	1,572	1,399	1,187	kg/m ³	T9	↓ Decreasing
Wt per m ² Water Opening	937	700	482	kg/m ²	T9	↓ Decreasing
Wt per m ² Surface Area	141.6	139.9	145.4	kg/m ²	T5	≈ Stable
Water Opening per m ³	1.678	1.998	2.465	m ² /m ³	T9	↑ Increasing
Water Opening per kg Wt	0.00107	0.00143	0.00208	m ² /kg	T9	↑ Increasing
Ext/Int Surface Ratio	1.197	1.165	1.140	—	T9	→ Converging
Collar % of Total Wt	17.1%	17.6%	19.5%	%	—	↑ Rising

VI. DISCUSSION

A. Scaling Behaviour

Mould weight grows 1.95× while hydraulic opening grows 3.80× from T3 to T9. This disproportion follows directly from arch geometry: bore area scales with the square of the linear dimension while panel perimeter scales linearly. SUPERDUCT technology delivers increasing hydraulic value per unit of shuttering investment at larger sizes — a fundamental design advantage confirmed by the trend lines in Fig. 10.

The linear trend extrapolation in Fig. 10 suggests that a hypothetical T-next mould would have: total weight ≈ 5,900–6,200 kg; weight per m² water opening approaching ≈ 350–380 kg/m²; and panel weight per m² of surface remaining within the 141–148 kg/m² band — all consistent with the observed design philosophy.

B. Component-Level Findings

1) Internal Panel: Weight scales 831 → 1,051 → 1,545 kg. Per m² of surface: 52.3 → 50.9 → 48.4 kg/m² — most stable component. Conservative and consistent design against internal concrete pressure.

2) External Panel: Grows from 1,033 to 1,989 kg (1.93×). Per m³ concrete reduces 722 → 538 kg/m³ — a 25.5% capability gain reflecting geometric scaling.

3) Collar: Grows 2.23× (384 → 857 kg), outpacing total mould weight growth of 1.95×. Its share rises from 17.1% to 19.5%. The Bale-and-Spigot joint scales less efficiently than the panel system — primary target for optimization in future larger moulds.

C. T5 Internal Panel Correction

The original dataset recorded T5 internal panel as 1,545 kg — identical to T9, geometrically inconsistent. Field verification established the correct value as 1,051 kg. The corrected value restores a smooth, logical progression in all capability metrics across the three sizes without exception.

D. Field Design Observations

- Stiffener spacing must balance deflection control against weight — critical for handling feasibility.

- Panel segmentation must consider structural stiffness and two-person manual handling for smaller components.
- Deliberate clearances between components are necessary for fabrication tolerance and thermal expansion.
- Lifting lug placement must align with center of gravity — off-center lifting risks rotation and damage.
- Bolted connections preferred over welded — permit alignment adjustment and support repeated reuse.

VII. CONCLUSIONS

Based on field data, 3D modelling, and systematic capability analysis of T3, T5, and T9, the following conclusions are established:

- Capability improves with size — T9 delivers 3.80× the hydraulic opening at only 1.95× the mould weight of T3. Total mould weight per m³ of concrete improves 24.5%.
- Hydraulic capability is the strongest indicator — mould weight per m² of water opening drops 48.6% from T3 to T9 (937 → 482 kg/m²). This should be the primary criterion for mould size selection.
- Panel design is consistently calibrated — total mould weight per m² of surface varies only ±4% (139.9–145.4 kg/m²). No over-engineering of larger panels observed.
- Collar is the priority optimization target — growing 2.23× vs 1.95× for total weight. For sizes beyond T9, collar joint design must be revisited.
- T5 internal panel correction to 1,051 kg restores consistent progression in all capability ratios across the three sizes.
- Design benchmarks for future moulds — (a) Total wt/m³ concrete < 1,187 kg/m³; (b) Total wt/m² water opening < 482 kg/m²; (c) Total wt/m² surface = 141–146 kg/m²; (d) Collar fraction < 20%.
- Trend extrapolation (Fig. 10) projects a hypothetical T-next mould at ≈ 5,900–6,200 kg total weight with water opening per m² surface continuing to improve, guiding future design targets.

8. AI tools show promise — Claude AI generated 2D profiles and stiffener layouts but could not complete autonomous 3D assembly. Structured AI workflows with engineering validation represent a viable future direction.

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