IJCIET

INTERNATIONAL JOURNAL OF CIVIL ENGINEERING AND TECHNOLOGY

Journal ID: 6971-8185

IAEME Publication
Chennai, India
editor@iaeme.com/ iaemedu@gmail.com
https://iaeme.com/Home/journal/IJCIET

International Journal of Civil Engineering and Technology (IJCIET)
Volume 16, Issue 5, September-October 2025, pp. 123-136, Article ID: IJCIET_16_05_007
Available online at https://iaeme.com/Home/issue/IJCIET?Volume=16&Issue=5
ISSN Print: 0976-6308 and ISSN Online: 0976-6316
Impact Factor (2025): 24.58 (Based on Google Scholar citation)
Journal ID: 6971-8185; DOI: https://doi.org/10.34218/IJCIET_16_05_007

CLEANROOM CONSTRUCTION ERRORS TO AVOID: A CIVIL ENGINEER'S PERSPECTIVE ON ACHIEVING ZERO-DEFECT DELIVERY IN SPACE SECTOR

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ABSTRACT

Clean rooms are artificially engineered space designed to minimize particulate and microbial contamination, critical to industries such as pharmaceuticals, biotechnology, semiconductors, and space. While mechanical and electrical systems dominate discussions on cleanroom design, civil engineering plays a pivotal role in ensuring desirable quality, airtightness, durability, and precision of the physical enclosure. This paper examines common civil engineering errors in cleanroom construction, their impact on validation and certification, and methods to prevent them. The paper highlights issues such as execution errors in RCC foundation with vibration isolation, roof slab, erection of structural steel members, joinery, wall panelling, surface irregularities in ESD flooring, joint leakages, dampness issues, improper finishing and inadequate sealing etc. The study concludes with a framework for civil engineers to achieve zero-defect delivery in clean room projects for the space sector. This paper is more specifically applicable for large clean rooms with areas in the range of 500sqm and above with highbays ceiling height greater than 21m.

Keywords: Civil Engineering, Clean room, Construction Quality, Errors, Zero-Defect Delivery

Cite this Article: Sravan Kumar P, Mohit Chaturvedi. (2025). Cleanroom Construction Errors to Avoid: A Civil Engineer's Perspective on Achieving Zero-Defect Delivery in Space Sector. *International Journal of Civil Engineering and Technology (IJCIET)*, 16(5), 123-136. DOI: https://doi.org/10.34218/IJCIET_16_05_007

1. General Introduction

Cleanrooms are specialized environments where air quality, temperature, humidity, and vibration must be controlled to stringent limits. Despite their importance, civil engineering contributions to cleanroom performance are often underestimated. Execution errors in structural works, flooring, partitions, wall openings and finishes etc., or coordination with HVAC can jeopardize compliance, delay certification, and escalate project costs. In cleanroom construction, the structure itself becomes part of the contamination control system. RCC structures offer mass and stiffness but risk cracking and moisture ingress, while structural steel offers precision and modularity but is prone to vibration and air leakage. Achieving ISO 14644 compliance requires strict control on geometry, sealing, surface cleanliness, and vibration performance. This paper emphasizes the civil engineering perspective of cleanroom construction and outlines strategies to avoid errors.

2. Role of Civil Engineering in Clean room Construction

a) Foundations and Floors: high flatness tolerances, epoxy/vinyl flooring, vibration isolation.
b) Structure – RCC framed/ Structural Steel works strictly as per Drawings/Specifications/Codes
c) Walls and Partitions: Masonry in fill walls, modular aluminum or GI partitions
d) Openings: hermetically sealed doors/windows, integration with airlocks.
e) Ceilings: walkable ceilings, airtight sealing around diffusers, light fittings. Civil execution quality directly influences contamination control and operational safety.

3. Common Errors in Civil Execution and Preventive measures

3.1 Execution Issues in RCC Roof Slab Affecting Cleanroom Performance

In cleanroom construction, the RCC roof slab is the first barrier of the controlled environment. Any defect like honeycombing, cracking, congestion-induced voids, or unsealed openings compromises air pressure cascade, dust containment, humidity and temperature control, paint adhesion and cleanability.

3.1.1 Honeycombing in RCC Roof Slab

Honeycombing refers to voids, coarse aggregate exposure, or porous concrete zones due to incomplete compaction or poor mix flow. Poor compaction due to congested reinforcement, inaccessible vibrator insertion points near beam-column junctions, segregation due to long pump discharge drop, leaky formwork allowing mortar loss, Improper concrete mix design (low workability, high aggregate size) etc., can cause Honeycombing in the RCC members. This may lead to,

- Air Leakage Paths: Honeycombed areas are highly porous, creating uncontrolled air paths through the roof or ceiling surface — compromising room pressurization balance.
- Dust Generation: Loose particles from weak concrete continuously shed dust — a major contamination source in Class 10000–100000 cleanrooms.
- Water Ingress: Porosity allows moisture migration, which affects humidity and causes microbial growth risk inside the cleanroom.
- Coating Failure: Epoxy or PU paint on slab soffit delaminates due to poor substrate integrity.
- Thermal Leakage: In satellite testing, honeycombed areas degrade thermal insulation performance of roof envelopes.

These issues can be prevented by

- Use SCC (Self-Compacting Concrete) in congested or inaccessible zones.
- Seal formwork joints tightly to prevent grout leakage (use mastic tape).
- Epoxy grouting or micro-concrete repair for any honeycombing found before false ceiling installation.

Fig 1. Typical illustration of Honeycombing in RCC members

3.1.2 Congestion of Reinforcement in Roof Slab

Reinforcement congestion occurs when bars are closely spaced, leaving inadequate space for concrete flow and compaction — especially in long-span slabs (like 6 m × 25 m).This is caused by using large diameter bars (e.g. 25–32 mm) at close spacing in long spans, overlapping of top and bottom reinforcement with conduit and duct inserts, improper detailing near supports and openings (duct cut-outs, AHU risers).

These issues can be prevented by

- Adopting SCC or pumpable concrete mix with smaller aggregates.
- BIM coordination before slab pour to resolve rebar–duct–sleeve clashes.
- Ensure adequate clear spacing between bars as per IS 456:2000.
- Provide mechanical couplers to reduce lap congestion.

Fig 2. Congestion of Reinforcement in Roof Beam / Slab

3.1.3 Improper Waterproofing on RCC Roof

Improper waterproofing causes moisture ingress from terrace increasing relative humidity, which affects satellite assembly, integration and testing. Dampness leads to mold growth behind ceiling panels, whereas Hydrostatic pressure causes paint delamination on soffit.

These issues can be prevented by

- Providing Multi-layer PU or Synthetic membrane waterproofing with slope ≥ 1:100
- Ponding test (24–48 hrs) to check leaks before insulation and false ceiling installation,
- Mixing of Integral water proofing compounds in the RMC.

3.2 Column Alignment, Plumb, and Size Deviation

Even small deviations in column alignment or size can cause major installation problems for cleanroom wall and ceiling systems. This may result in wall Panel misalignment which causes uneven wall joints or visible gaps, air leakage and aesthetic defects.

These issues can be prevented by

- Checking plumb using laser or total station before and during each pour.
- Provide proper bracing and tie systems in formwork to resist lateral pressure.
- Maintain dimensional tolerance as per relevant IS codes

3.3 RCC Foundations (with Vibration Isolation Considerations)

A vibration-isolated foundation in a cleanroom is not just a structural element – it is a part of the environmental control system. Any construction defect (cracks, voids, uneven surface, or filled isolation joint) can defeat the isolation purpose, leading to transmission of floor-borne vibration, contamination risk, reduced precision of equipment and failure to meet cleanroom performance class.

3.3.1 Improper Foundation Bearing and Compaction

Inadequate subgrade compaction causes uneven settlement, even a few millimetres of which can disturb vibration isolation system alignment. This may lead to transfer of unwanted vibration to precision equipment (e.g., test tables, satellite integration fixtures), causes loss of vibration damping efficiency in spring or neoprene pad isolators, and also leads to cracks in epoxy floor or mismatch in floor joint levels.

This can be prevented by ensuring 95–98% MDD (Modified Proctor) compaction under foundations.

3.3.2 Poor Reinforcement Detailing or Congestion in Foundation Block

Vibration-isolated foundations often require thick RCC blocks with dense reinforcement, sometimes with embedded anchors for isolator plates leading to congestion.

This causes honeycombing due to poor concrete flow and voids below embedded plates or bolts. Cleanroom is impacted further due to reduced stiffness of the foundation block which generates altered vibration frequency response. This can be prevented by use of self-compacting concrete (SCC) for congested blocks.

Fig 3. Reinforcement Congestion in Foundation Block

3.3.3 Improper Installation of Vibration Isolators or Pads

During execution uneven concrete surface under isolator and premature loading of isolator before concrete reaches full strength can cause reduced isolation efficiency, equipment alignment errors etc.

This can be prevented by

- Use precision levelling plates or non-shrink grout pads under isolators.
- Install isolators after 28-day strength achievement.

3.4 Structural Steel Frame Structures

3.4.1 Surface Preparation and Painting / Coating Quality of structural steel members

Improper surface preparation of structural steel members may lead to flaking paint or rust particles fall into cleanroom, reduced corrosion resistance causes humidity-related rust in AHU plenum area, poor adhesion of final epoxy/PU top coat.

This can be prevented by

- Surface preparation by blast cleaning.
- Painting the steel surfaces with Epoxy/PU primers and paints.

3.4.2 Roof and Wall Envelope Sealing

Gaps between roofing panels and structure leads to loss of positive pressure in cleanroom, water or dust infiltration during monsoon and temperature instability in critical clean zones.

This can be prevented by

- Use of double-skin insulated sandwich panels (PUF, 0.5 mm GI skin).
- Apply butyl sealant tape at all panel joints.
- All penetrations are sealed with silicone or EPDM gaskets.
- Avoid roof sheet overlaps above cleanroom critical areas (use standing seam if possible).

3.5 Flooring

Flooring is a critical component in cleanroom construction, as it directly affects cleanliness, durability, and electrostatic discharge (ESD) control. Two common options are vinyl flooring and epoxy flooring. Both can be installed as non-ESD or ESD-compliant systems depending on the application.

A common error arises when non-ESD flooring is used in industries where ESD protection is mandatory. For instance, in semiconductor, aerospace, and certain electronics manufacturing cleanrooms, ESD-safe flooring is essential to prevent static discharge that can damage highly sensitive components and devices. Failure to specify or install ESD flooring in such facilities can lead to product failures, yield losses, and operational risks.

Additionally, poor installation practices—such as improper seam welding in vinyl, uneven epoxy application, inadequate grounding, or neglecting to test resistivity values—can compromise the cleanroom's compliance and safety.

3.5.1 Outgassing of Concrete Substrate

A frequent source of flooring defects in cleanroom construction is outgassing from the existing concrete base. If concrete is not properly evaluated and sealed before epoxy application, trapped air and moisture vapour can migrate upward during curing. This results in pinhole formation, blistering, or bubbling in the epoxy surface, which weakens the finish and compromises cleanroom performance.

These issues can be prevented by:

- Accurate moisture measurement: Moisture content must be checked using a concrete moisture meter. Use of a wood moisture meter is inappropriate and leads to false readings.

Fig 4. Moisture meter

- Surface preparation: Techniques such as diamond grinding or shot blasting help open pores and release trapped air before coating.
- Presence of water table at shallow depths: To prevent the capillary rise of water through the pores of concrete substrate, HDPE sheet may be laid below the RCC flooring.
- Primer application: A low-viscosity epoxy primer or moisture vapour barrier should be applied to seal the surface and prevent vapour migration.
- Pinholes after priming: If pinholes still appear, they should be filled with a silica fume–epoxy primer mix, followed by an additional moisture barrier coat.
- Environmental control: Temperature fluctuations accelerate outgassing and can disturb epoxy curing. Hence, it is recommended to carry out flooring works only when ambient temperature variations are minimal—typically in the early mornings or evenings.

Fig 5. Error in laying ESD flooring at the steel and concrete interface

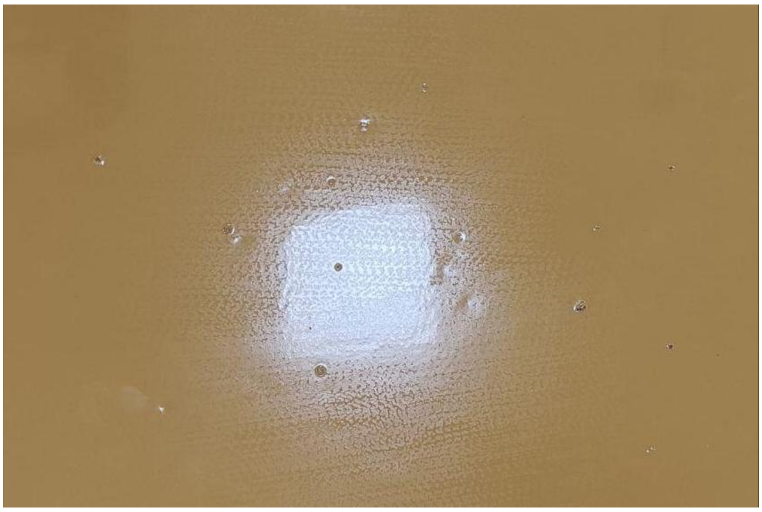

Fig 6. Formation of pinholes due to outgassing of concrete

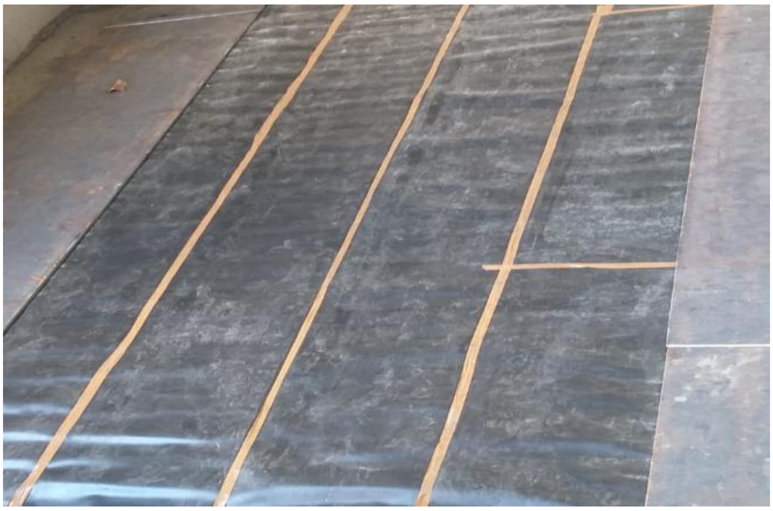

Fig 7. HDPE Sheet below RCC flooring

3.6. Treatment of Expansion Joints in Cleanrooms

Expansion joints are necessary in concrete structures to accommodate thermal and structural movements. In cleanroom flooring systems and walls, however, they can become weak points leading to particle generation, microbial growth, or ESD discontinuity, air leakage, surface cracking or delamination if not treated correctly.

Common Errors in Expansion Joint Treatment:

- Leaving joints unsealed, which allows dust accumulation and microbial ingress.
- Using incompatible sealants that outgas or degrade under cleanroom cleaning chemicals.
- Using continuous copper bridging strips across joints, which may crack or fail when the joint expands or contracts.

These issues can be prevented by:

- During joint preparation, laitance, dust, and loose material shall be removed. It shall be ensured that joint edges are sound and dry before treatment. For controlling sealant depth and three-sided adhesion a closed-cell polyethylene backer rod shall be placed.
- It is recommended to use a cleanroom-compatible, non-outgassing, chemical-resistant elastomeric sealant (e.g., epoxy, polyurethane, or specialty cleanroom sealants), which shall be Finished flush with the surrounding flooring to ensure a smooth, dust-free surface.
- While Maintaining ESD Continuity, instead of a single copper bridging strip across the joint (which can break due to movement), provide separate copper strips installed on either side of the joint. This ensures conductivity of the ESD flooring while still allowing the expansion joint to function without stressing the copper conductor.
- After sealing, a suitable expansion joint plate over the joint shall be installed. These plates provide mechanical protection, smooth cleanable surface, and aesthetic finish, while still allowing for structural movement. Plates shall be compatible with cleanroom cleaning protocols and, if ESD is required, conductive or grounded.
- Expansion joints are high-risk points and should be periodically inspected and resealed if deterioration, cracking, or conductivity loss is observed.

3.7. Joinery

During execution, doors, windows, or cabinetry not installed flush with wall surfaces/panels, results in uneven joints and dust-collecting ledges. Poor joinery workmanship can create gaps, ledges, or misalignments, which act as dust traps, microbial growth sites, and air leakage points, ultimately reducing the cleanroom’s performance. Use of unsuitable sealants that outgas or deteriorate under disinfectants and cleaning chemicals leads to undesirable issues in maintaining cleanroom parameters.

For preventing these issues all the joinery shall be flushed with walls/panels in a clean room. Windows used as view glazing shall be provided with sub-frame to ensure proper finishing & alignment. Wood, MDF, or other absorbent materials shall not be used for framing or cabinetry, which are not cleanroom-compatible.

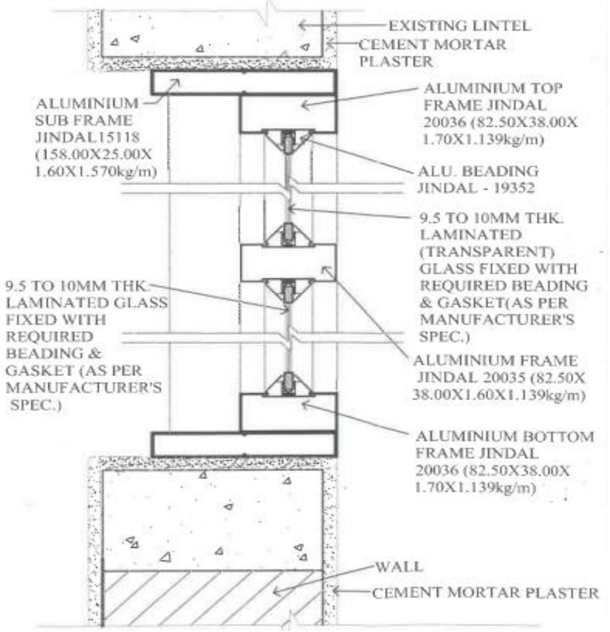

Fig 8. Typical joinery details for view glazing in cleanroom

Fig 9. Sealing strip at the bottom of the door

3.8 Ceiling systems in cleanroom

The false ceiling system in a cleanroom serves multiple critical functions, it conceals HVAC ducting and utilities, supports HEPA filters, integrates lighting, and forms part of the air circulation envelope. Therefore, any errors during erection directly affect cleanroom performance, air balance, and cleanliness class.

The following types false ceilings are predominantly used in cleanrooms

- Clip-in Metal Ceiling Panels
- Calcium Silicate / Gypsum Ceiling (Painted with Epoxy Polyurethane Paint)
- Sandwich PUF / Aluminium Honeycomb Panels

Common issue during execution

- Improper levelling causes uneven ceiling panels, visible joints, and air leakage at HEPA filter frames.
- Gaps between tiles or around penetrations (lights, diffusers) cause air leakage and dust ingress
- Use of undersized or excessive spacing between hangers, leading to sagging or vibration of panels.
- Use of dust shredding or porous materials increases particle count in the cleanroom.
- Ceiling not coordinated with HEPA filter, light fittings, and diffusers, causing misalignment or obstruction of airflow.
- Failure to provide removable panels or access hatches for maintenance of ducts, lights, or filters.

These issues can be prevented by:

- Use laser levels during framing and final alignment.
- Use approved cleanroom-grade silicone sealant, gaskets, or neoprene tape.
- Ensure joints are airtight and continuous.
- Use SS304 rods or epoxy-coated GI for the suspension system.
- Isolate hangers near equipment with vibration dampers.
- Only use non-shedding, anti-static, washable materials.
- Paint surfaces with PU or epoxy for sealed finish.

4. Summary

The key engineering insights drawn from the discussion are listed below:

- No uncovered openings shall be left; ventilation shall be by artificial means to prevent dust contamination.

- Protrusions, niches, offsets etc. shall not be recommended to avoid dust collection
- Walls shall be true and plastering rendered smooth epoxy resin based paint or equivalent. All corners, edges etc. shall be turned and smoothly curved.
- No gaps at the bottom of door shutters shall be left. If inevitable, the gaps shall be covered with PVC or treated rubber flaps (flexible type).
- All steel elements, structural and components provided in cable trench steel doors (if any) and OH cranes shall be painted with epoxy resin based paint.
- Cable trenches and/or floor openings shall be covered with Anodized aluminium chequered sheets or fabricated aluminium gratings. The seating elements shall be epoxy painted. The inside of earth trenches shall be epoxy painted.
- False ceiling grids, any artificial supporting system and panelling inside cleanroom shall be fabricated from out of non-shedding material
- All corners and edges of floor trenches shall be smoothly curved and epoxy painted.
- If considered desirable, the inside of cable trenches and bottom side of cable trench covers shall be treated with fire resistant coatings as per approved specifications.
- All load-bearing structural steel members forming part of the cleanroom envelope or exposed within the cleanroom shall be provided with intumescent fire-resistant coating which shall be suitable for cleanroom application (smooth, non-shedding, and low VOC)

5. Conclusion

Civil engineering forms the backbone of cleanroom performance, influencing airtightness, cleanliness, vibration control, and durability. Errors such as honeycombing, poor waterproofing, reinforcement congestion, or improper sealing can compromise pressurization, cause contamination, and delay validation. Achieving zero-defect delivery requires precision in execution, strict adherence to IS codes, and close coordination with HVAC and other disciplines. Use of SCC concrete, epoxy/PU coatings, non-shedding ceiling materials, and cleanroom-compatible sealants ensures durability and compliance.

In large cleanrooms civil precision is crucial for maintaining controlled environments for satellite testing and integration. The analysis highlights that with meticulous planning, execution control and high-quality materials, civil engineers can transform conventional construction into precision-driven practice, ensuring structurally sound, contamination-free, and high-performance cleanrooms that meet the stringent demands of the space sector.

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Citation: Sravan Kumar P, Mohit Chaturvedi. (2025). Cleanroom Construction Errors to Avoid: A Civil Engineer's Perspective on Achieving Zero-Defect Delivery in Space Sector. International Journal of Civil Engineering and Technology (IJCIET), 16(5), 123-136.

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