Hettiarachchi, H.A.Y.G. and Pathiraja, M.G., 2024. Design tolerance as a pedagogical tactic: The possible role of architectural design in facilitating on-site labour training. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 423-434. DOI: https://doi.org/10.31705/WCS.2024.33. Available from: https://ciobwcs.com/papers/

DESIGN TOLERANCE AS A PEDAGOGICAL TACTIC: THE POSSIBLE ROLE OF ARCHITECTURAL DESIGN IN FACILITATING ON-SITE LABOUR TRAINING

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ABSTRACT

This paper is the initial publication from a research project examining the role of architectural design in enhancing the skills of the construction workforce in Sri Lanka. For years, the country has faced challenges in implementing effective capacity-building initiatives, resulting in a proliferation of substandard buildings and hindering the socio-economic advancement of construction workers. Regretfully, the practice of architecture rarely develops pragmatic strategies to confront labour training as a design prerogative. Birthed off in such a context, this paper investigates the potential contribution of architectural design to labour upskilling by adopting the function of 'Design Tolerance' as a pedagogical tactic. Given the theory-driven nature of this inquiry, the paper first evaluates 'Design Tolerance' as a theoretical construct before elucidating its contextual significance within the scope of the broader investigation on labour upskilling, particularly on the use of real building projects as on-site training grounds. Placing 'Design Tolerance' at the crux of the dual objective of 'compromising precision' and 'accommodating error', the theoretical arguments then lead to a case-study analysis organised under three categories: (i) tolerance by the system, (ii) tolerance by detail, and (iii) tolerance by procurement. Subsequently, 13 design tactics attributing to the idea of 'Design Tolerance' are identified, offering a technical foundation to re-interpret and define the role of architectural design in on-site labour training.

Keywords: *Architectural Design; Design Tolerance; Labour Training; On-site Upskilling.*

1. INTRODUCTION

A critical observation of the Sri Lankan construction industry; both empirical and embodied, reveals that the increasing skill shortage of its construction workforce is drastically hampering the demand and supply behaviour of the local building stock. Such labour market behaviour has inevitably contributed to distressing technical, social,

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political, and institutional outcomes. Technically, substandard constructions have propagated the country's urban and rural landscapes, inducing significant environmental and social costs due to the reduced lifetime performances of the building units (Pathiraja & Tombesi, 2023). Socially, the construction workforce is among the most under-organised and regressive of the local labour profiles, being employed under conditions of low remuneration, inferior health and safety standards, and lack of job continuity (Fernando et al., 2016; Manoharan et al., 2022). Politically, the approaches taken to overcome skill and training limitations have been traditional, fragmented, and limited in their industrial potential; there has been little or no attempt to relate training needs to the workforce's cultural conditions, career development aspirations, and socio-economic growth (Silva et al., 2018). Institutionally, the formal upskilling programs initiated by the state-affiliated actors have not risen to the challenge, both quantity and quality-wise (Dundar et al., 2014; UNESCO-UNEVOC, 2018).

The failure to advance construction labour skills on the technical, social, political, and institutional fronts calls for drastic action by all industrial stakeholders to find alternative strategies to propel industry-wide upskilling and knowledge dissemination. However, such strategies must align with the limitations and potential of existing labour market behaviour, as otherwise, they will fail to enforce a meaningful impact on the situation on the ground. Generally, across developing economies and particularly in Sri Lanka, the construction workforce is organised informally concerning work access, training procedures, working conditions, and wage structures (Jayawardane & Gunawardena, 1998; Pathiraja & Tombesi, 2009; Pathiraja, 2010). Training follows an informal apprenticeship setup where an unskilled worker learns skills gradually on-site by seeing and doing tasks under the supervision of a master builder (Basunnehe in Sinhalese) or a construction manager (Pathiraja & Tombesi, 2009).

While this site-based informal apprenticeship supports industrial skill dissemination to a certain degree, it is nonetheless hindered by the unplanned, ad-hoc, and project-based nature of learning centred on an immediate technical outcome rather than structured and focused training. Furthermore, in this makeshift form of learning, the knowledge transferred to the trainee is confined to the exposure and capacity of the person who transfers that knowledge in the first place. But, given that a high majority of workers are daily wage earners who do not have either time or money to spend on institutionalised learning, ‘on-site apprenticeship’ offers the only viable option to advance their skills to remain employed in the building industry.

Such a problematic context of skill building raises a compelling question: can a particular type of architectural design strengthen the on-site apprenticeship by transforming real building sites into planned training grounds? In other words, can informal apprenticeship be formalised enabling on-site skill transferring is endorsed by design professionals and facilitated through focused design interventions? Discursively, the above inquiry also questions whether architectural design; as an intellectual activity, can play a role in overcoming labour-training limitations, fostering the industry's labour capacity, and supporting the socio-economic growth of its workforce.

Yet, suppose real building projects are to be used for upskilling the labour force. In that case, the subsequent architectural designs must tolerate permissible mistakes and affordable errors, as mistakes and errors will predictably happen during the learning process (Pathiraja, 2010). This is where the notion of 'design tolerance' becomes critical to the proposed on-site training strategy and the theoretical underpinning of this paper. To that end, 'design tolerance' presents the foundational theoretical body that forms the intellectual base of this theory-led research and, subsequently, the focus of this paper. The task of building up the theoretical base here is accomplished through a literature review supported by a pilot study that investigates 'tolerance' as a design tactic to accommodate - and train - less-skilled labour gangs.

2. THE NOTION OF 'DESIGN TOLERANCE'

The function of 'design' is generally understood as a process of creative and critical thinking. However, its etymology denotes actions of pragmatic aims – i.e., '*to point out*' (Hoad, 1996, p. 121), '*to plan, purpose and intend*' (Hoad, 1996, p. 121), and '*to delineate, draw'* (Hoad, 1996, p. 121). Used as both a noun and a verb, the term 'design' connotes, on the one hand, *'the general arrangement of the different parts of something… such as a building*' and, on the other hand, '*deciding how something will look and act… and planning something for a particular purpose or use*' (Hornby, 2005, p. 413). Collectively, 'design' exemplifies a problem-solving process that provides a cognitive framework for analysis, synthesis, evaluation, and action (Zande, 2006).

Such a 'problem-solving' notion of 'design' considers human needs or problems as the point of departure to a specific intellectual and technical process that formulates schemes or solutions through a problem-solver, either a human or a machine. The solutions thus derived inevitably depend on the nature of the problem and the capacity and, in the case of humans, the worldview of the problem solver (Lawson, 1972). However, as Jeremy Till claims, the history of architectural practice places its importance mainly on the performances of its end-products and the solutions thus generated rather than the contexts that birth the results in the first place (Till, 2009). In other words, architectural design is regarded for its ability to produce precise end-products with little or no regard for the contextual demands of widespread practice. However, shifting the focus from the product to the process i.e., from the solution to the path that led to it, can highlight the design's ability to address broader contextual challenges. This shift may also reveal the potential for design to facilitate on-site labor training and enhance skill development.

'Tolerance' is a term adopted from the old French word 'tolerance' (14c.), which, in turn, is an adoption of the Latin 'tolerantia' (Hoad, 1996, p. 497), depicting the ideas such as '*disposition to be indulgent'* (18c.) and '*endurance'* (Hoad, 1996, p. 497). The Oxford Dictionary defines 'tolerance' as *'the amount by which the measurement of a value can varies without causing problems*' (Hornby, 2005, p. 1615). However, within architecture, the idea of 'tolerance' has been historically presented as a confluence of two seemingly opposing meanings. On the one hand, it refers to the degree of dimensional variation that affects construction accuracy, thereby placing it as a function that strengthens construction precision (Taron, 2024). On the other hand, it denotes the allowable deviation for human or machine error in assembling building components, elements, and systems, thus aligning its purpose with overcoming construction errors (Baudoin, 2016). As Boudoin (2016) highlights, the idea of 'tolerance' in building production lies where the two opposites 'construction precision' and 'construction error' meet.

McVicar (2016), Bates and Sergison (1999), and Pathiraja (2010) provide further insights into the concept of 'design tolerance,' which primarily pertains to the task of on-site assembly. Accordingly, 'design tolerance': (i) provides an opportunistic response to overcome various challenges of the on-site building activity (McVicar, 2016), (ii) presents a design tactic with latitude for errors to inhabit varying socio-cultural performances (Pathiraja, 2010), (iii) offers a technological framework to use building systems and components for purposes other than for their prescribed use (Bates & Sergison, 1999), and (iv) postulates an architectural idea that helps compromising precision to accommodate on-site labour training (Pathiraja, 2010). This dual objective of 'compromising precision' and 'accommodating error' provides a key point of departure for understanding design tolerance's role in on-site labour upskilling.

3. PRECISION VS ERROR

Tracing back to its etymology, the 16th century French word précision referred to the act of "cutting off abstraction and the freedom from inessential elements," while the Latin word praecisionem conveyed a similar meaning of "a cutting off". However, from the 17th century onwards, the term 'precision' appeared to be associated with the "*quality or state of being precise*" (Harper, 2024). The Oxford Dictionary, for example, defines precision as "*the quality of being exact, accurate, certain and careful*" (Hornby, 2005, p. 1184).

This idea of 'precision' as 'reassuring certainty' has significantly influenced the agreements on the role of the architect-in-practice over the last few centuries (McVicar, 2016, as cited in Bartholomew, 1840). In reviewing the historical influence of 'precision' in architectural practice, McVicar (2016) even recalls Vitruvius's stipulation that 'architectural drawings' must present ' precise' communication of architectural intent. In a more critical review of the architectural work, Hughes (2014) claims that the obsession with 'precision' and the fear of 'error' has made architects hesitant to accept the gap between their conceptual thinking and the actual realisation of it. The author further suggests that the idea of 'precision' generally excludes inevitable realities of practice-on-site.

It must be mentioned firmly, however, that the specific notion of 'error' emphasised here does not align its meaning with the performance 'failures' of buildings. Instead, it is concerned with 'allowable' errors that accommodate labour and material realities by not relying on overly precise construction systems and applications. As Hughes (2014) repeatedly emphasises, the 'precision' encountered today in architectural design and practice is often excessive; this version of 'precision' has outgrown the intention of mitigating performative failures and maintaining accuracy in building construction to become one with an authoritative domineer.

The problem with the notion of excessive 'precision' is that it excludes human error in practice, thereby framing architecture within the exclusive realm of high culture, unaffordable by those who need to possess the means to achieve an elevated level of technical accuracy. Especially in construction industries subjected to low labour skills and limited spending capacities, the thrive for precision has created a restrictive framework for architecture to address the social building needs of the masses while forming challenges for on-site capacity building (Pathiraja, 2010). Inevitably, a low-skilled labour gang learning while building on-site would make construction mistakes and formal oversights. If the technological environment of individual projects refuses to accommodate such technical volatility of the building process, their ability to provide a sound pedagogical platform for on-site labour apprenticeship will be lost.

4. ON-SITE LABOUR TRAINING AND ITS DEMAND

The task of on–site labour training has always been one of the most natural modes of skill building for construction workers. As Coomaraswamy (1956) states, apprenticeship has been the cornerstone of craftsmanship training in historic Sri Lanka. In the 15th century Kandyan kingdom, for example, the buildings for royal patronage were built by a set of artisans i.e., carpenters (Vaduvo), masons, blacksmiths, etc. who worked under the guidance and supervision of a foreman-cum-master-builder called Mul-acharya (meaning 'first-guru' or the 'learned mentor' in English). These master builders were responsible for transferring craftsmanship skills to their disciples through structured training programs implemented in workshops and actual building sites.

Even now, learning on the job remains significantly evident and appears particularly impactful in industrialised economies such as Germany and the Netherlands. For example, the prominent labour theorists Linda Clarke and Christine Wall discuss how Germany and the Netherlands; as countries with comparatively comprehensive skill development and systematic training programs, have given significance to on-site training (Clarke & Wall, 1998). The authors further argue that the gradual move away from on-site training has resulted in the United Kingdom's abstract nature of construction skills and the subsequent deskilling of its workforce (ibid).

In contrast to the planned on-site training programs in Germany and the Netherlands, an unplanned, ad-hoc, and informal learning process occurs on construction sites in countries such as Sri Lanka, where formal training is often unavailable and unaffordable for most of the daily-waged workforce. Studies on the Sri Lankan construction industry reveal that almost all skill-building needs in masonry, carpentry, plumbing, and steel welding trades are fulfilled experientially on real building sites (Fernando et al., 2016; Jayawardena et al., 2007). For example, a labour market survey by Jayawardhana and Gunawardhana (1998) suggests that 86% of the local construction workers have entered the industry through informal channels and only gained informal training in a process characterised by ad-hoc on-site learning, poor discharge of skills, and the absence of regulations in practice.

Be that as it may, the urge to pursue on-site construction training in developing economies such as Sri Lanka seems obvious, given the prospective workers' socio-economic challenges, cultural difficulties in undergoing formal learning, the inflexibility of the formal training programs themselves, and the general lack of alternative employment choices. This creates a never-ending demand for on-site training in the construction industry, regardless of whether it has been implemented by choice or by default. It is, therefore, evident that any form of restructuring of construction worker training must consider the possibilities for on-site training, acknowledging its known benefits as a successful training model while overcoming its apparent failures in knowledge construction. The starting point for such an approach naturally lies in how much building professionals can support on-site training, not only ideologically and administratively yet design-wise, by designing real building projects to accommodate the technical volatility of on-the-job labor upskilling.

5. METHODOLOGY AND BUILDING UP THE THEORY

In endeavouring to define 'design tolerance' as applicable to architectural design that values and supports on-site labour training, this study took up a two-tier approach: a literature review and a case-study review. To that end, the ideas and information gathered from the literature review were critiqued, analysed, amended, advanced, and verified through the review of a case-study project, which has been developed to transfer skills during the on-site building process. Subsequently, 13 design tactics attributing to the idea of 'design tolerance' have been derived through a lengthy cross-examination between the literature and case-study findings and semi-structured questionnaires posed to the workers (construction labour) and architects (design labour) of the case-study project. Due to the space limitations of this paper, the outcome of this entwined two-tier approach: i.e., the 13 design tactics-is presented as a singular framework with brief examples extracted from the case study project.

The project subjected to the study concerned building two sanitary blocks for a public school in Kandy, one of Sri Lanka's major urban centres located in the central highlands. Designed by the local architectural firm Robust Architecture Workshop (RAW), co-directed by one of the authors of this paper, the sanitary blocks were part of a larger project aimed at providing social infrastructure to a physically derelict, socially neglected, economically challenged, and institutionally maltreated public school system. Due to the project's financial constraints, a team of volunteer Air Force soldiers was appointed to provide construction labour in masonry, carpentry, and steel work, thus requiring upskilling on the site to meet the targeted formal and environmental expectations of the building outcome.

In organising the theoretical framework for 'design tolerance', the study emphasised 'building' as both a noun and a verb – i.e., a product and a process. As a noun, 'building' is a product that consumes capital and labour to transfer wealth from one form to another (Groak, 1992); a physical representation of several interdependent systems and sub-systems that, using joints and details, must be connected, coordinated, and integrated with the building's overall three-dimensional form and spatial structure (Ching, 2008). On the other hand, Turin (2003), for example, emphasises the dynamic process that shapes building as an activity, which focuses on assembling inputs or resource flows; such as materials, knowledge, and labour. In such a definition of 'building' as a verb, the roles of the participants and their changing relationships are also included as critical to the success of the final product (ibid). Following this dual comprehension of 'building' as a product and a process, the framework on 'design tolerance' was deemed necessary to organise under three categories: (i) tolerance by the system, (ii) tolerance by detail, and (iii) tolerance by procurement.

6. STRATEGIES OF DESIGN TOLERANCE

6.1 TOLERANCE BY SYSTEM

Under 'tolerance by system', the design of building systems and components to withstand unexpected technical deviations to their formal, dimensional, and organisational conditions have been considered. To that end, it becomes important to design building systems and components with a greater level of clarity and intelligibility in their technical formation while imparting an adequate level of technical complexity to trigger the training needs. This objective forms the first principle identified under 'tolerance by system': *complexity by completing - clarity in the making (DTS-01)* (Refer to Figure 1).

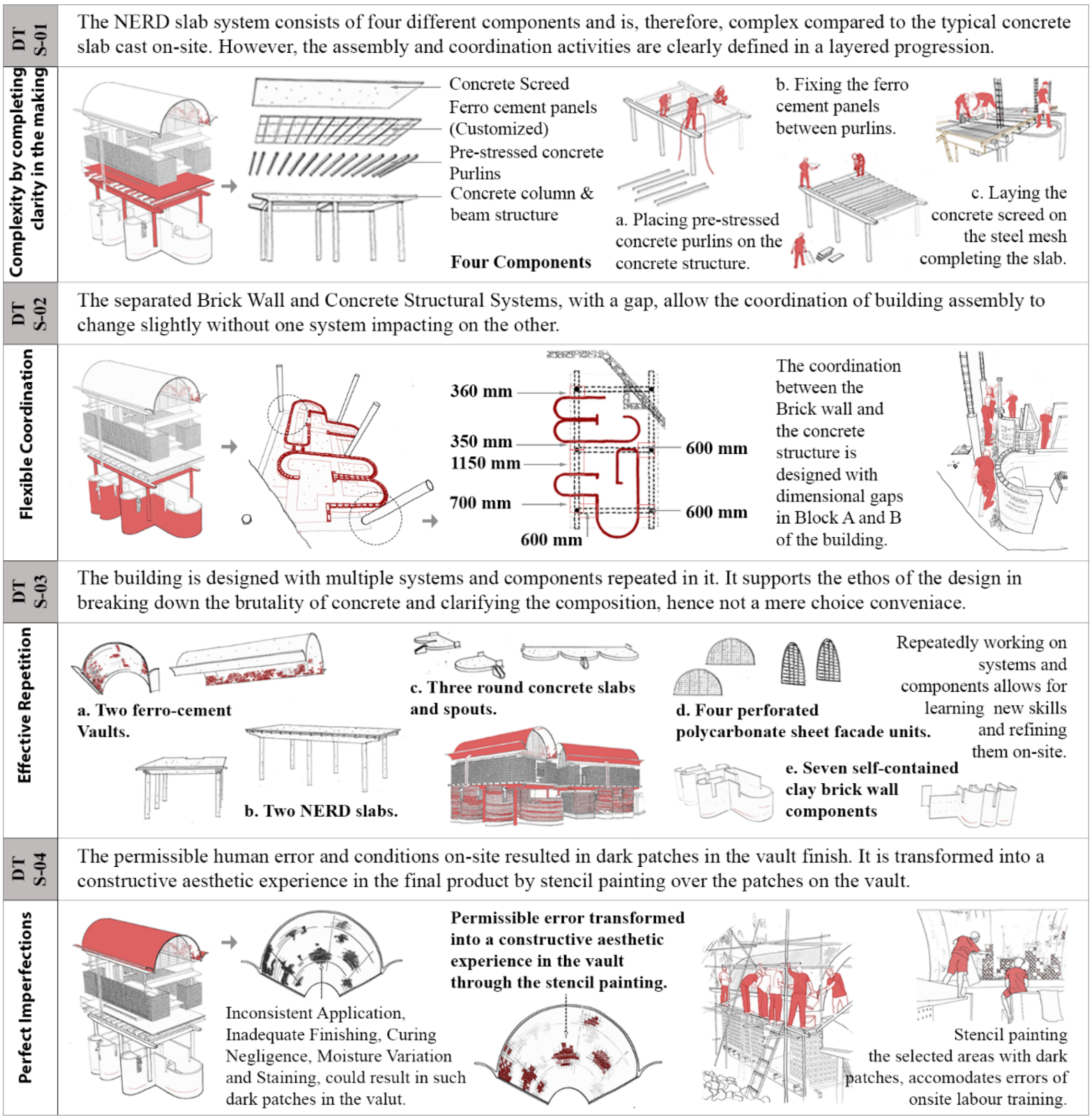

Figure 1: Building example - tolerance by system

Secondly, a degree of *flexible coordination (DTS-02)* between building systems, sub-systems, and components must be established so that their assembly on site can accommodate unexpected and varying site conditions without resulting in performative failures (refer to Figure 1).

Thirdly, the architectural design must strategically involve replication of the systems and sub-systems without subjecting negatively to economic or experiential effectiveness, as repetition and intensification of activities support gradual skill improvement on-site *(effective repetition-DTS-03)* (Refer to Figure 1).

Fourthly, to accommodate unavoidable human error, formal imperfections of the final product must be acknowledged and, where possible, celebrated by making them opportunistically part of the intended design ethos *(perfect imperfections-DTS-04)* (refer to Figure 1).

6.2 TOLERANCE BY DETAIL

‘Tolerance by detail’ focuses on achieving technical tolerance when two components are joined. The first principle acknowledged under this theme; 'loose fit', calls for joints to be 'fit' to achieve a given performative attribute while being 'loose' enough to accommodate slight changes in sizes, dimensions, and technical imperfections. Thus, it caters to the need for components and systems to be installed with a capacity to endure dimensional fluctuations in their positioning and laying (Refer to Figure 2).

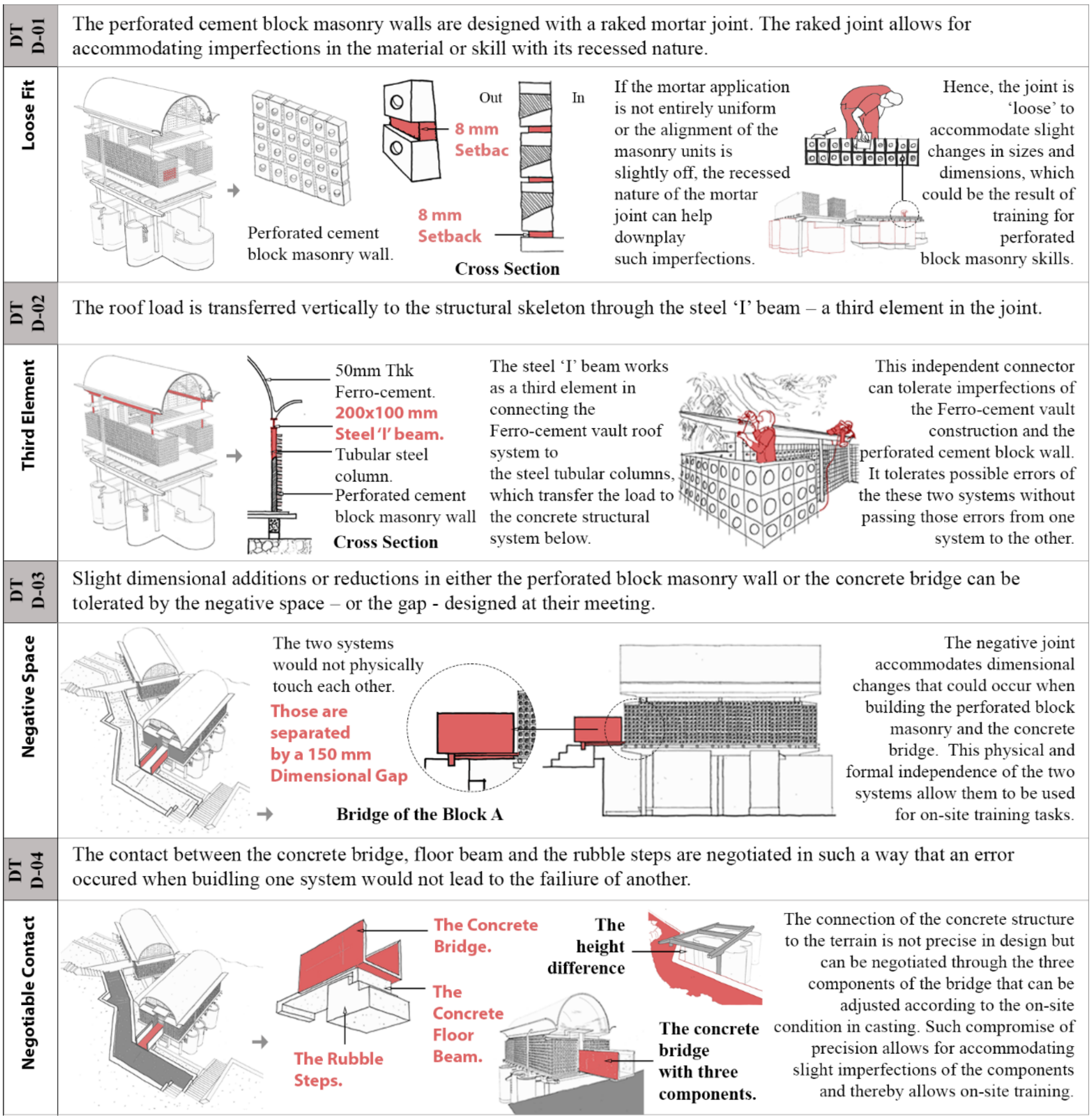

Figure 2: Building example - tolerance by detail

Secondly, when joining two components or systems, a *Third element (DTD-02)* can be used as a tolerance mediator to house various imperfections of the first two systems/components (refer to Figure 2).

Thirdly, instead of detailing two components or systems as a direct physical touch between them, their meeting can be planned as a separation by a gap so that the space in-between could take up any unforeseen addition or reduction of dimensions between the two *(Negative space-DTD-03)* (refer to Figure 2).

Fourthly, and partly related to the first principle (loose fit), adequate provision must be kept for unforeseen on-site changes through possible technical negotiations at the point of joining different systems or components together. This principle is identified as *Negotiable contact (DTD-04)*. While ‘loose fit’ refers to achieving a level of technical flexibility when ‘fitting’ one component within the space of another, thereby requiring the first component to accommodate a specific design configuration to facilitate such technical suppleness, the ‘negotiable contact’ calls for both components to traverse the unforeseen technical variations at the point of their contact (refer to Figure 2).

6.3 TOLERANCE BY PROCUREMENT

The third subset of the theoretical framework posited here; ‘tolerance by procurement’, looks at how a level of technical and cultural tolerance to accommodate pressures of on-site training can be imparted at the level of organising and strategising the building process. To that end, it becomes essential to seek the contribution of all actors throughout the on-site construction work, not only in their predefined roles or limited stages, thus demanding everyone to work collaboratively as a team on-site. Accordingly, *Collaborative work (DTP-01)* furnishes the first principle acknowledged under 'tolerance by procurement' and such a collection of means by human resources could support finding unique design solutions against various on-site challenges (refer to Figure 3).

Secondly, architects' *On-site engagement (DTP-02)* must be direct and effective in acknowledging, accepting, and interpreting unforeseen on-site changes without penalising the anticipated design ethos (refer to Figure 3).

Thirdly, architectural projects must be procured with flexible resource flows supported by well-established technical and cultural links between all actors involved (including suppliers and manufacturers) to enrich the project's resource base and help it grow organically while accommodating unforeseeable changes and requirements during the construction phase *(Organic links-DTD-03)* (refer to Figure 3). In addition, architectural practice must cultivate working relationships with actors already involved in the formal training of construction workers, such as industry development authorities and technical colleges, to seek their input when implementing upskilling programs on site.

Fourthly, industrial practices must be adjusted according to the specific project context; economic, technical, environmental, and cultural, to bring out alternative design and building solutions instead of always conforming to popular and pre-defined material and resource practices *(Industrial adaptability-DTP-04)* (Refer to Figure 3).

Fifthly, it is imperative to follow a *Robust design language (DTP-05)* that does not overly depend on the perfection of singular elements but on the appropriateness of the overall composition and construction, where the assembly, formation, and coordination between systems, sub-systems, and components are organised with latitude for errors and non-optimal application (refer to Figure 3).

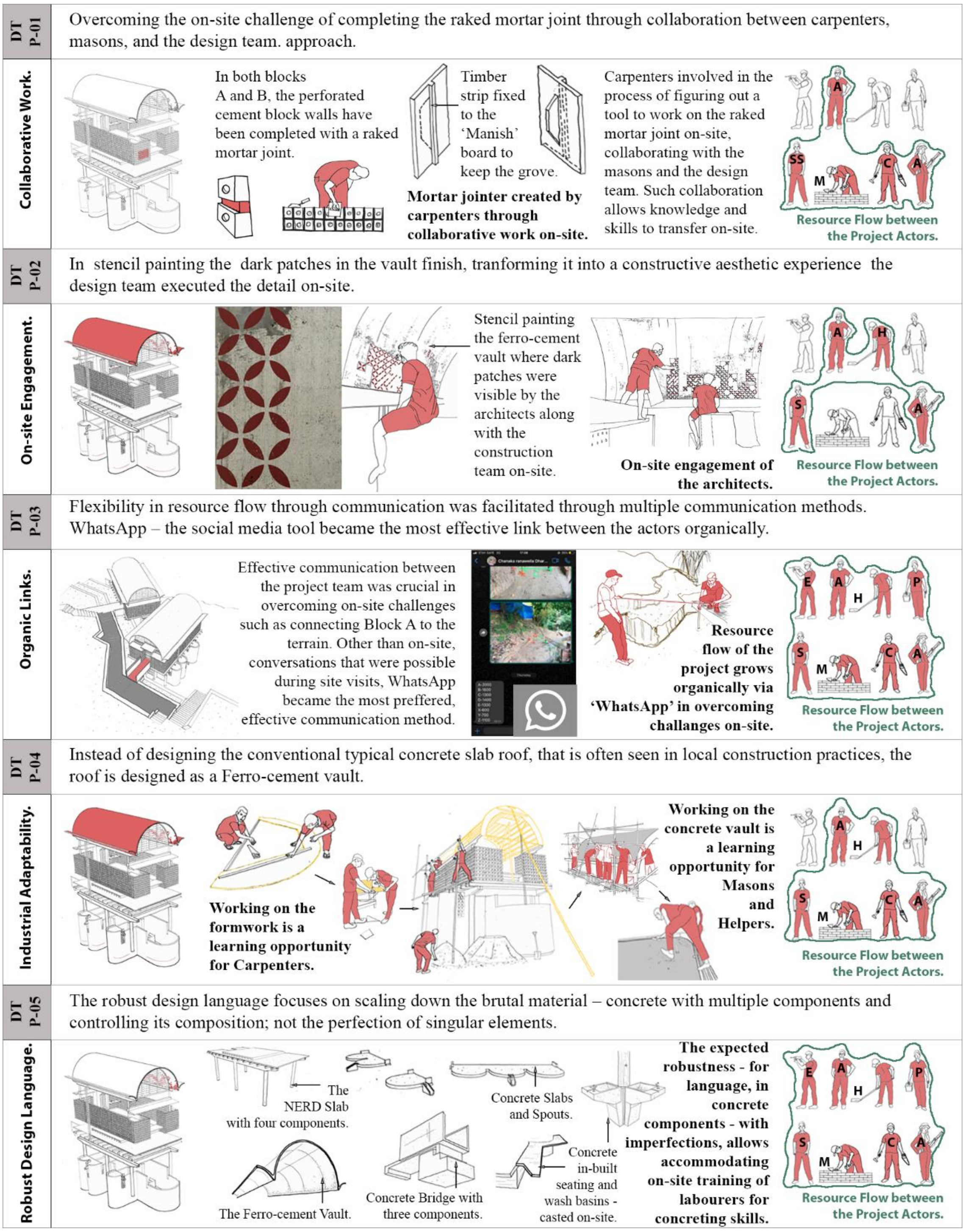

Figure 3: Building example - tolerance by procurement

7. CONCLUSIONS

The framework on 'design tolerance' presented in this paper is built on redefining architectural design's role in supporting the on-site labour training needs of the construction industry, especially in developing economies (refer to Table 1). As a theoretical construction, the first two categories of this framework; i.e., 'tolerance by system' and 'tolerance by detail', identify eight design principles in enabling building systems, sub-systems, components, and details to compromise their precision to accommodate permissible errors without penalising the performative attributes of the building artefact. The third subset i.e.; 'tolerance by procurement', focuses on building as a process emphasising flexible sourcing and managing resources.

Table 1: Theoretical framework- design tolerance for on-site labour training

			Design principles	
Designing for tolerance	**Tolerance by System**	1.	Complexity by completing; clarity in the making.	**Building as a product**
		2.	Flexible Coordination.	
		3.	Effective Repetition.	
		4.	Perfect Imperfections.	
	Tolerance by Detail	5.	Loose Fit.	
		6.	Third Element.	
		7.	Negative Space.	
		8.	Negotiable Contact.	
	Tolerance by Procurement	9.	Collaborative Work.	**Building as a process**
		10.	On-site Engagement.	
		11.	Organic Links.	
		12.	Industrial Adaptability.	
		13.	Robust Design Language.	

However, for such a framework to successfully disseminate on-site labour training as a formal strategy, it must draw professional interest, discursive acceptance, and institutional support.

8. ACKNOWLEDGEMENTS

The data collection for the case study was supported by the Robust Architecture Workshop (RAW), specifically by design team members Sajeewa Mendis and Sajith Sivayogaraj.

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