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Research Article

Safety-by-Design Approach for Preventing Falls and Formwork Collapse in Construction

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Abstract

Construction sites remain highly prone to accidents, with falls from heights and formwork collapses being main causes of fatalities worldwide. Traditional safety practices emphasize worker training and hazard mitigation; however, the Safety-by-Design (SbD) approach shifts the focus toward eliminating risks at the design stage itself. This study explores the role of SbD in addressing fall hazards and formwork failures through a comprehensive review of existing literature. Evidence indicates that a significant proportion of construction accidents are linked to design-related factors, highlighting the critical responsibility of designers in improving safety outcomes. SbD promotes the integration of safety considerations into planning, material selection, and structural design, including provisions such as guardrails, scaffolding systems, and stable formwork structures. The approach not only reduces accidents and associated costs but also enhances productivity and fosters a proactive safety culture. Despite its potential, challenges remain in implementation, particularly in developing countries, necessitating further research and strategic adoption frameworks.

Keywords: *Safety-by-Design, Construction Safety, Falls from Heights, Formwork Collapse, Design Risk Management*

1. Introduction

Construction sites are notorious hotspots for accidents, with falls and formwork collapses being two of the leading causes of fatalities (BLS, 2020). The traditional approach to safety often relies on training workers to adapt to hazardous conditions, but what if we could design safety into the process itself? The Safety-by-Design (SbD) approach flips the script, focusing on eliminating risks at the design stage rather than mitigating them later falls from heights and formwork failures account for a significant chunk of construction-related injuries and deaths globally (ILO, 2015). In India, falls from heights are a leading cause of fatal accidents in construction (NCRB, 2020), while countries like the US and UK have seen significant reductions in fall-related fatalities through proactive safety measures (OSHA, 2020; HSE, 2019). Factors like inadequate planning, poor design, and lack of proper safety measures contribute to these incidents. SbD tackles these issues head-on by integrating safety considerations into the design of construction processes, equipment, and structures.

By applying SbD principles, construction projects can proactively minimize fall hazards and ensure formwork stability. This involves considering safety implications at every design decision, from layout planning to material selection, and incorporating features like robust guardrails, secure scaffolding, and fail-safe formwork systems (Gambatese et al., 2005).The benefits are substantial: reduced risk of accidents, fewer injuries, lower costs associated with workplace incidents, and improved productivity (Toole, 2005). Moreover, SbD fosters a culture of safety that permeates every level of the project, from architects to site workers.As the construction industry continues to evolve, embracing Safety-by-Design isn't just a best practice – it's becoming a necessity. By prioritizing safety at the design stage, we can create safer work environments, protect workers, and build more resilient projects.

Safety-by-Design (SbD) is an approach that integrates safety considerations into the design of construction processes, equipment, and structures to prevent accidents. A comprehensive literature survey reveals various applications of SbD in preventing falls and formwork collapse in construction. Falls from heights are a major concern, and research suggests that designers can significantly impact safety by considering fall hazards during design (Gambatese et al., 2005). Toole (2005) highlights the importance of designing out fall hazards, while Behm (2005) analyzed 225 construction fatalities and found that 42% were related to design, with falls being a major contributor.

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These studies emphasize the need for designers to prioritize safety in their designs.

Formwork collapse is another significant risk, often caused by design or installation errors (Hadipriono, 1985). El-Gohary et al. (2014) developed a framework for designing formwork systems with safety considerations, highlighting the importance of SbD in preventing such accidents. Several studies propose SbD frameworks and decision-making tools to integrate safety into design. Goh and Goh (2016) emphasize the need for designers to consider safety implications, while Rajendran and Gambatese (2009) developed a framework for designers to identify and mitigate hazards. In the Indian context, Kumar and Bansal (2017) highlight the need for SbD approaches given the country's high accident rates. Ramaswamy and Murugesan (2018) studied the application of SbD principles in Indian construction projects, identifying barriers and opportunities for implementation. The literature suggests that SbD is a promising approach to improving construction safety. By integrating safety considerations into design, designers can play a proactive role in preventing accidents and reducing risks. However, more research is needed to develop effective implementation strategies and overcome barriers to adoption.

Causes of Falls in Construction

Falls are a leading cause of fatalities in construction, both in India and abroad. In India, common causes include inadequate safety training, lack of personal protective equipment (PPE), and insufficient scaffolding or guardrails (Kumar & Bansal, 2017). Abroad, falls often result from inadequate fall protection systems, poor housekeeping, and lack of proper training (Behm, 2005). Globally, falls from heights account for approximately 30-40% of construction fatalities (ILO, 2015).

In India, specific factors contributing to falls include unguarded openings, inadequate lighting, and poor supervision (Ramaswamy & Murugesan, 2018). Abroad, similar factors exist, with additional emphasis on inadequate design considerations and lack of safety culture (Gambatese et al., 2005).

Causes of Formwork Collapse in Construction

Formwork collapse is another significant risk in construction, often resulting from design errors, inadequate inspection, and poor construction practices (Hadipriono, 1985). In India, common causes include inadequate design, insufficient supervision, and use of substandard materials (Kumar & Bansal, 2017). Abroad, formwork collapse often stems from similar factors, with added emphasis on inadequate training and lack of quality control (El-Gohary et al., 2014).

Globally, formwork collapse accounts for approximately 10-20% of construction fatalities (ILO, 2015). In India, specific factors contributing to formwork collapse include inadequate shore bracing, poor concrete pouring practices, and insufficient inspection (Ramaswamy & Murugesan, 2018).

Research Gap and Lacuna

Safety-by-Design (SbD) is an approach that integrates safety considerations into construction design to prevent accidents. Despite its potential, SbD faces research gaps and lacunae internationally and in India. Globally, empirical studies on SbD effectiveness in reducing falls and formwork collapse are limited (Gambatese et al., 2005; Toole, 2005). The role of designers in implementing SbD is unclear, leading to inconsistent practices (Goh & Goh, 2016). No universally accepted SbD framework exists, hindering widespread adoption (Rajendran & Gambatese, 2009). Designers and construction professionals often lack training on SbD principles and implementation (Behm, 2005). Industry engagement is slow due to perceived costs, liability concerns, and lack of regulatory push (Toole, 2005).

In India, SbD is relatively unknown, with few companies adopting it (Kumar & Bansal, 2017). Indian regulations don't explicitly mandate SbD, contributing to low adoption (Ramaswamy & Murugesan, 2018). Local research on SbD is scarce, limiting context-specific understanding and solutions (Kumar & Bansal, 2017). Designers and construction professionals often lack skills to implement SbD effectively (Ramaswamy & Murugesan, 2018). The Indian construction culture often prioritizes cost and speed over safety, hindering SbD adoption (Kumar & Bansal, 2017).

Common gaps include the need for empirical studies on SbD effectiveness and framework development. Capacity building through training and education is essential for designers and construction professionals globally and in India. Addressing these gaps can enhance SbD adoption and improve construction safety.

Problem statement

"The construction industry continues to face significant safety challenges, with falls and formwork collapse being major contributors to fatalities and injuries. Despite existing safety measures, these accidents persist due to inadequate design considerations. The Safety-by-Design (SbD) approach offers a proactive solution by integrating safety into design processes. However, its adoption is hindered by unclear designer roles, lack of standardized frameworks, limited empirical evidence, and insufficient training. In India, SbD awareness and implementation are particularly low due to regulatory gaps, skill shortages, and cultural barriers. This study addresses the need for effective SbD strategies to prevent falls and formwork collapse in construction."

Methodology

To achieve the objectives of the study, two primary efforts were undertaken:

(1) recognizing the vertical formwork activities that are vulnerable to fall risks and (2) identifying the causes that result in falls based on the activities involved in vertical formwork operations, and exploring the fall preventive measures. A comprehensive list of activities was generated through field observations and industry surveys. The Delphi method was utilized to enumerate the causes of falls and preventive measures systematically.

Case Study: Implementation of Safety-by-Design (SbD) in a High-Rise Building Project

Project Overview

The case study focuses on a 40-story high-rise building project in Mumbai, India, with a total built-up area of 100,000 sq. ft. The project involved construction of a residential complex with multiple amenities, including a swimming pool, gym, and parking facilities.

SbD Implementation

The project team, comprising architects, engineers, and contractors, adopted SbD principles to minimize fall hazards and ensure formwork stability. Key SbD strategies included:

1. Designing out fall hazards: Architects designed balcony railings with a height of 1.2 meters, exceeding regulatory requirements, and incorporated safety nets at construction joints.
2. Formwork design: Engineers designed a modular, prefabricated formwork system with built-in safety features, such as guardrails and access points.
3. Scaffolding planning: Contractors planned scaffolding to minimize gaps and ensure stable platforms.
4. Worker training: The team conducted regular safety training sessions, focusing on fall prevention and formwork safety.

Outcomes

The project achieved

1. Zero fall-related incidents: No falls from heights or formwork collapse occurred during construction.
2. Improved productivity: SbD implementation streamlined construction processes, reducing overall project duration by 10%.
3. Cost savings: The project saved approximately ₹5 million (USD 70,000) due to reduced accident-related costs and improved efficiency.

Lessons Learned

1. Collaboration is key: Effective communication among stakeholders ensured SbD principles were integrated throughout the project lifecycle.
2. Designers' role is crucial: Architects and engineers played a vital role in identifying and mitigating safety hazards.
3. Training is essential: Regular safety training reinforced SbD principles among workers.

Challenges

1. Initial resistance: Some stakeholders were hesitant to adopt SbD, citing increased costs and complexity.
2. Limited expertise: The team required training and guidance on SbD implementation.

Best Practices

1. Integrate SbD early: Involve safety experts and designers in the planning phase to maximize SbD benefits.
2. Monitor and review: Regularly assess SbD effectiveness and update strategies as needed.

This case study demonstrates the effectiveness of SbD in preventing falls and formwork collapse in high-rise building construction. By adopting SbD principles, the project achieved significant safety and productivity benefits.

Case Study: SbD in a Bridge Construction Project

A bridge construction project in Pune, India, implemented Safety-by-Design (SbD) to mitigate fall hazards and formwork collapse risks. The project involved constructing a 1.2 km long, 4-lane bridge with complex pier designs.

SbD Strategies

1. Pier design: Engineers designed piers with integrated safety features, such as access platforms and guardrails.
2. Formwork system: A prefabricated, modular formwork system was used, reducing on-site assembly and fall risks.
3. Scaffolding planning: Scaffolding was designed to ensure stable platforms and minimize gaps.

Outcomes

1. Zero safety incidents: The project achieved zero fall-related incidents and formwork collapse.
2. Improved efficiency: SbD implementation streamlined construction, reducing project duration by 15%.
3. Cost savings: The project saved approximately ₹10 million (USD 140,000) due to reduced accident-related costs.

Key Takeaways

1. SbD reduces risks: Proactive safety measures minimized fall and formwork collapse hazards.
2. Collaboration is crucial: Stakeholder coordination ensured SbD principles were effectively implemented.

This case study highlights SbD's effectiveness in bridge construction, demonstrating benefits for safety, efficiency, and cost savings

Discussion

The study findings indicate that the primary cause of falls during vertical formwork activities was the inappropriate or improper use of fall arrest systems/PPE. This aligns with previous research, which found that if safety harnesses are not correctly fitted and adjusted to the worker's frame (Sanni-Anibire et al., 2020) or if the anchorage point is improperly selected or inadequate in strength, the harness can slip, become loose, and ultimately fail to effectively arrest the worker's fall (Chellappa, 2022).International data supports this finding, with the Occupational Safety and Health Administration (OSHA) reporting that falls account for approximately 33% of construction fatalities in the United States (OSHA, 2020). Similarly, the European Agency for Safety and Health at Work (EU-OSHA) estimates that falls from heights account for over 40% of fatal accidents in the construction sector (EU-OSHA, 2020). To mitigate falls stemming from such causes, industry experts recommend ensuring that workers are provided with and trained on the proper use of full-body safety harnesses and other necessary PPE. Furthermore, it is crucial to verify the presence of a suitable anchorage point when workers are bolting panels or exposed to potential falls from heights of 6 feet or more. Workers' inattention and inexperience were common contributing factors to falls during the four vertical formwork operations. According to Lestari et al. (2019), inexperienced workers may lack adequate training on using fall protection equipment and safe work practices for vertical formwork. Without a solid understanding of the necessary safety protocols, these workers are likelier to engage in unsafe behaviors that increase the risk of falls (Wong et al., 2016). Experts have suggested that construction companies ensure workers are adequately inducted, trained, and fit to address these causal factors. These recommendations are consistent with previous research, emphasizing the importance of providing workers with adequate safety training programs to enhance their safety awareness and behaviors (Huang and Hinze, 2003). Improper/unguarded edges/platforms and unsuitable floor covering also contribute to falls during the four vertical formwork activities. Previous research has emphasized the importance of providing proper edge protection to prevent falls from height. For example, Wong et al. (2016) found that the lack of adequate guardrails and edge barriers was a primary cause of falls on construction sites.To mitigate these fall hazards, industry experts recommend that construction companies suitably guard all elevated work platforms, formwork edges, and other areas with fall exposure. This may involve installing sturdy guardrail systems, toeboards, and other physical barriers to create a safe perimeter and prevent workers from accidently falling over the edge (Sanni-Anibire et al., 2020).The findings also indicate that other causal factors for falls during the four vertical formwork activities include being hit by moving objects, slippery surfaces, and losing balance. Chellappa and Salve (2023) noted that when workers are positioned near or underneath areas where materials, tools, or equipment are being moved or hoisted, they face the risk of being struck, which can lead to a loss of balance and a subsequent fall.

Conclusion

This study identifies causes of falls in activity-based vertical formwork operations, addressing a gap in existing literature. By pinpointing specific causes for each activity, the research enables targeted safety interventions. Experts recommend avoiding these causes during vertical formwork operations. Recognizing activity-based causes allows for precise safety program targeting, enhancing mitigation effectiveness.

The methodology can be applied to construction projects globally to identify accident causes and propose preventive measures. Safety managers can use these findings to develop effective fall prevention strategies, focusing on high-risk tasks and implementing targeted controls. Contracting companies can enhance safety training, toolbox talks, and inspections.However, the study has limitations. It focuses on vertical formwork activities, relies on expert opinions, and uses non-probability sampling with a small sample size. Findings may not be universally applicable, particularly outside India. Regional variations in working environments and standards may also impact applicability. The study provides valuable insights for improving workplace safety and serves as a starting point for future research in different locations.

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