INTEGRATED SIMULATION IN ARCHITECTURE, ENGINEERING, AND CONSTRUCTION FOR INNOVATIVE AND SUSTAINABLE STRUCTURAL DESIGN

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Abstract: The construction industry faces significant challenges related to cost efficiency, delays, and design complexity. This study aims to highlight the importance of utilizing integrated simulation in architecture, civil engineering, and construction to enhance structural safety, sustainability, and performance. The methodology involves digital modeling using the 3DEXPERIENCE platform and Abaqus software to analyze loads, deformations, and the impact of structural failures in bridges and high-rise buildings. Simulation results demonstrate that this approach can predict critical stress, detect early design weaknesses, and optimize material usage by up to 10%. Case studies such as the *Sun Valley Structure* and the *CCTV Building* in Beijing confirm the effectiveness of simulation in supporting complex designs. Consequently, this approach offers a holistic solution that promotes project efficiency and structural innovation in the modern construction era..

Keywords: Structural Simulation, Architectural Design, Construction Efficiency, 3DEXPERIENCE Technology

1. Introduction

Over the past decade, the fields of architecture, engineering, and construction (AEC) have undergone significant transformation, driven by the growing demand for structures that are more innovative, safe, sustainable, and efficient. Projects such as organically shaped skyscrapers, futuristically designed bridges, and 3D-printed buildings have become icons of technological advancement within the industry [1]. To address such complexity, conventional design and construction methods are no longer sufficient. There is a pressing need for approaches that seamlessly integrate design processes, structural engineering, and construction planning—and this is where digital simulation plays a critical role.

In the AEC context, simulation refers to the use of virtual models to represent and analyze various structural aspects, including load distribution, deformation, seismic response, as well as cost and duration estimates [2]. This technology not only accelerates decision-making but also minimizes planning errors, which are often the main contributors to project delays and cost overruns [3].

According to Dassault Systèmes, integrated simulation solutions such as the *3DEXPERIENCE* platform and *Abaqus* software enable the entire project team—architects, engineers, and construction managers—to collaborate within a unified digital ecosystem. This allows real-time data synchronization and visualization of the impact of any design change [4]. Digital simulation not only improves workflow efficiency but also enhances the ability to predict structural behavior—an essential capability for constructing complex structures such as bridges and high-rise buildings.

For instance, Figure 1 below illustrates the simulated distribution of longitudinal tensile stress on a bridge under live load from a train. The red areas indicate zones of highest stress, serving as critical references in evaluating structural strength.

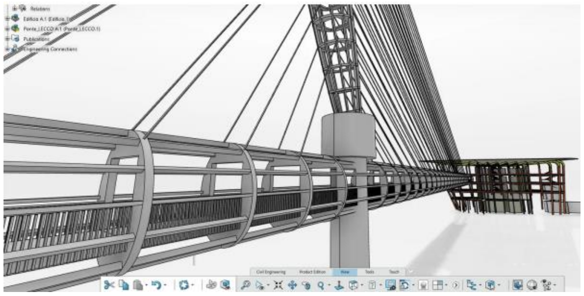

Figure 1. Contour of longitudinal tensile stress along the bridge axis due to train live load [4].

Such simulations provide valuable visual insights for determining whether a design can proceed to production or requires modification. This approach also facilitates analysis of potential structural failure scenarios, such as the collapse of the truss arch bridge over the Mississippi River in 2007 [5]. Finite element simulation using *Abaqus* revealed that the gusset plates lacked sufficient thickness to withstand additional loading, particularly during on-deck construction activities.

Simulation also plays a vital role in building design. In a case study involving a 25-story steel structure, shown in Figure 2, a simulation was conducted to model the loss of central support. The results indicated a significant increase in vertical displacement and bending moments in the affected area, signaling a high risk of failure without local structural reinforcement [6].

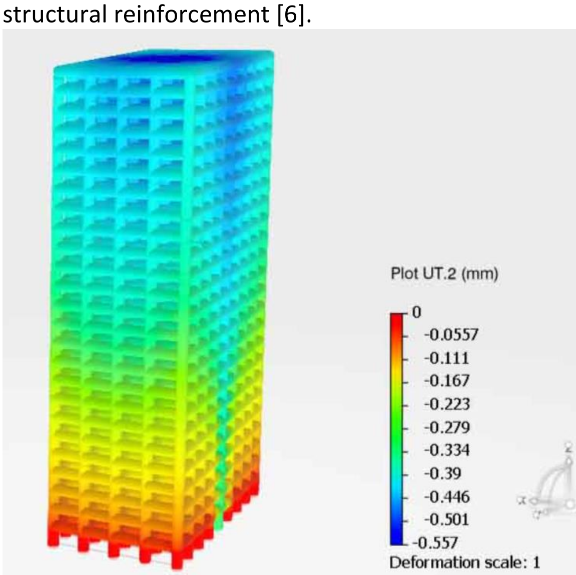

Figure 2. Contour of vertical displacement in a 25-story building structure due to central support loss [6].

Simulation technology also contributes to material optimization and cost efficiency. For example, the Shanghai Xian Dai Architectural Design Group (SXDA) achieved a 10% reduction in steel usage for the *Zendai Himalayan Art Center* by using *Abaqus* to identify areas requiring more or less reinforcement [7].

Additionally, simulation supports multiphysics approaches, such as dynamic seismic analysis, temperature effects, and fluid flow in foundations and tunnels. This broadens the scope of structural performance prediction under extreme conditions [8].

The key benefits of integrating simulation in AEC include:

- Reducing manual design iterations and accelerating decision-making [9],
- Improving cost and time estimation accuracy,
- Detecting potential structural failures at an early stage,
- Optimizing material usage and internal structure design,
- Supporting sustainability through more efficient resource planning.

The adoption of simulation in AEC is part of the broader transition toward full digitalization of the construction industry. With advanced simulations integrated across all project phases, stakeholders can develop design solutions that are not only innovative but also cost-effective and safe. In an era of rapid urbanization and extreme climate change, simulation-based approaches have become a fundamental pillar for building future-ready structures that are resilient and sustainable [10].

2. Research Method

This study adopts a case-based approach utilizing digital simulation to evaluate design and construction processes within the architecture, engineering, and construction (AEC) industry. The process begins with the development of conceptual models using Computer-Aided Design (CAD) software for structures such as bridges and high-rise buildings. These models are then converted into numerical simulations using an integrated platform that enables structural analysis, including load simulations, deformation analysis, and scenarios involving support loss and localized failures.

Subsequently, simulations are performed using the Finite Element Method (FEM) to extract data on stress distribution, displacement, and bending moments across various structural components. The simulation results are analyzed to assess the structural response under various loading conditions, both static and dynamic, including seismic loads. This process also involves evaluating construction sequences and estimating material requirements.

The entire workflow is designed to replicate real-world conditions during the design and implementation phases of construction projects. This approach facilitates an integrated assessment of design efficiency, structural safety, and potential cost and time optimization—ultimately producing more accurate and adaptable solutions that respond effectively to design changes and technical challenges in the field.

3. Discussion

The role of simulation in the architecture, engineering, and construction (AEC) sector has evolved rapidly alongside advancements in information technology and the growing demand for more efficient, high-precision, and adaptive design approaches for complex projects. Today, simulation is no longer seen merely as a visualization tool; it has become an integral part of the design process, decision-making, and performance testing—well before actual construction begins.

Early architectural simulation software was primarily intended to save time and reduce design costs. However, challenges such as low accuracy and long processing times limited its effectiveness [11]. To address these issues, system-based simulation architecture frameworks—such as *The Six Pillars of Simulation Architecture*—were introduced. These six pillars—composition, functionality, structure, behavior, mechanization, and doctrine—serve as a comprehensive framework for developing complex and real-time simulation systems, as demonstrated in applications like Lockheed Martin's flight systems [12].

In the context of building architecture, Building Energy Performance Simulation (BEPS) has become central to achieving high-performance buildings. BEPS enables architects to assess thermal behavior, energy efficiency, and thermal comfort from the early stages of design [13]. The integration of simulation with data management (DM) systems—such as those found in integrated simulation architectures—has significantly improved design and analysis efficiency by reducing manual interventions [14].

To ensure architectural functionality, Software Architecture Simulation (SASIM) is utilized to comprehensively model and analyze system architecture. This type of simulation supports precise architectural verification and facilitates a wide range of functional analyses using platforms like SPIN [15]. This aligns well with educational demands, where simulation has been adopted as an interdisciplinary teaching tool across architecture and engineering—enhancing collaboration in designing sustainable buildings [16].

Simulation not only serves technical validation purposes but also acts as a conceptual design methodology. The architectonic design approach integrates market demands, core values, and design elements within a simulation framework, as seen in the development of business simulation models tailored to industrial needs [17]. This is further supported by virtual simulation technologies in architectural design, which not only enhance cost control but also mitigate design risks [18].

Architectural simulation also extends to agent-based modeling for analyzing dynamic system interactions. The application of discrete event simulation in multi-agent systems provides deep insights into system interoperability in complex construction environments [19]. In terms of design practice, digital simulation approaches such as exoskeletal and endoskeletal modeling enable the generation of structural and aesthetic forms that would be difficult to achieve using conventional methods [20].

Furthermore, game-based educational simulations have been implemented to train future architecture professionals. These tools have proven effective in helping students understand legal processes and contract management through interactive learning [21]. This underscores the importance of developing scientifically grounded and integrated simulation curricula and textbooks for architectural education [22].

In the realm of operational system architecture, simulation approaches must align with standards such as the *Data Distribution Service (DDS)* and *High-Level Architecture (HLA)* to ensure system security and interoperability—especially in large-scale and autonomous simulation environments [23]. A notable development in this field is the *Complex Modelling* approach, which integrates structural design simulations with advanced fabrication techniques—such as *Lace Wall* and *A Bridge Too Far*—enabling dynamic feedback between micro and macro design scales [24].

To support the development of hybrid simulation environments, software engineering principles are applied in the creation of object-oriented simulation systems—such as *Smile*, which simulates energy systems [25]. Finally, collaborative simulation environments have been developed to allow the integration of various simulation tools through hierarchical architectures, facilitating cross-disciplinary and cross-locational collaboration in global-scale projects [26].

Figure 3. Overview of consultation supported by BIM at different project stages.

This figure 3. illustrates how *Building Information Modeling (BIM)* facilitates multi-stage project consultations—from design and tendering to planning, construction, and operational handover. BIM enables efficient data integration among stakeholders, accelerates communication, and supports virtual project condition simulations.

Figure 4. Integration of simulation and BIM

This figure 4. illustrates the integration of simulation and BIM is increasingly crucial in creating real-time, transparent collaborative environments—especially for decision-making and comprehensive project management.

4. Conclusion

Simulation has become a critical component in the transformation of the architecture, engineering, and construction (AEC) industry due to its ability to enhance efficiency, accuracy, and collaboration throughout the design and execution phases of a project. By incorporating simulation from the early stages of design, stakeholders can predict and evaluate structural performance, energy efficiency, and potential failure risks—allowing for design improvements before construction begins.

The implementation of simulation extends beyond technical analysis to include conceptual design and organizational strategy. It enables the visualization of design alternatives, more accurate cost estimation, and data-driven decision-making. The use of digital platforms and simulation methods—such as agent-based or complex modeling—provides the flexibility needed to address the increasingly diverse and integrated challenges of modern design.

In both education and professional practice, simulation plays a vital role in skill development, understanding construction law, and fostering interdisciplinary collaboration. Simulation games and virtual learning environments offer innovative approaches to training and capacity building in the construction sector. Moreover, the development of collaborative simulation environments and the application of technologies like *Building Information Modeling (BIM)* have paved the way for more effective and transparent project coordination.

Simulation technology also promotes material efficiency and waste reduction through more precise design. This contributes not only to environmental sustainability but also to long-term cost savings. At a broader scale, simulation architecture enables the integration of multiple systems and technologies, creating an adaptive ecosystem that keeps pace with the evolving dynamics of the industry.

Overall, the use of simulation in AEC is no longer merely a technical aid—it has become an inseparable part of design innovation, risk management, and the development of sustainable construction strategies. This approach paves the way toward a smarter, more efficient, and highly competitive future for the built environment.

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