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PROBABILISTIC ASSESSMENT OF STRUCTURAL STABILITY AND OCCUPANT SAFETY IN AN INDOOR SPORTS HALL.

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ABSTRACT

This study introduces a probabilistic framework to assess both structural stability and occupant safety in an indoor sports hall, using Lead City University as a case example. The method combines non-linear finite-element analysis of the main steel–concrete system with stochastic simulations of uncertainties in loads, materials, and boundary conditions to determine failure probability through a limit-state approach. Monte Carlo simulations account for these uncertainties to generate reliability metrics. Simultaneously, an agent-based evacuation model evaluates egress efficiency under various emergency scenarios, including fire, power outage, and combined hazards, while considering different exit layouts and lighting conditions. The structural analysis reveals key failure modes, such as elastic buckling of portal frames, local rafter buckling, and brittle connection failure, with an overall failure probability of approximately 3.7×10^{-5} for the baseline setup, reflecting strong structural reliability under design loads. Evacuation results show that safe egress for about 1,200 occupants can be achieved within roughly 540 seconds with four exits and improved wayfinding/lighting; without these measures, congestion and delays significantly rise. The findings are translated into practical recommendations: enhance or redesign critical connections and bracing, adopt reliability-based load factors, expand and clearly mark egress routes, and implement targeted safety training and facility management. This integrated approach highlights how combining probabilistic structural reliability with egress performance assessment can guide design improvements and operational strategies for university sports halls and similar large-assembly venues.

KEYWORDS: Structural stability, occupant safety, indoor sports hall, structural reliability, Probability

1. INTRODUCTION

Sports halls are designed for activities such as gymnastics, ball games, track and field, rowing, and badminton. The rapid expansion of indoor sports halls at universities in Nigeria has focused attention on the safety of these structures. Considerable knowledge and experience have been gained regarding structural systems, stress distribution, the magnitude of concentrated loads, and the stability of these structures. Consequently, a probabilistic assessment of structural stability and occupant safety in a typical indoor sports hall, using Lead City University's sports hall as a case study, is justified. Resources spent on sports and recreational facilities generally result in a high level of satisfaction. This positive outcome implies the need to focus on occupant safety during various stages: Structural Integrity Assurance, ensuring the absence of structural collapse under anticipated loads. - Facilities Management: Addressing any disruptive activities or issues promptly. - Emergency Preparedness: Guaranteeing safe evacuation routes in case of disaster. This study examines the structural stability and occupant safety of sports halls using a probabilistic model (Xu et al., 2015; L. et al., 2019).

2. Literature Review

1. Historical Background of Sports Chambers Sports chambers, also known as gymnasiums or sport halls, are central venues for indoor and outdoor sports, including athletics, football, basketball, tennis, volleyball, cricket, and swimming (Xu et al., 2015). The use of timber arches spanning cities or boroughs during the Middle Ages contributed to the development of early structural shapes that persist in current designs. Designs from the 1960s and 1970s typically feature span widths ranging from 18 to 23 m. John Wolfenden notes that the growth of sports facilities in the late 19th and early 20th centuries was notable. The question is whether there are more efficient designs for sports chambers in modern construction. A reported approach to address this is the characteristic approach, which has been extensively reported in the scientific literature.
2. Probabilistic Method Developments Several studies have discussed methods for safety assessment, including probabilistic approaches. Torrance presented an efficient approach to determining overall structural safety through combined assessments of different failure modes. Stahl proposed two computational approaches, suited for systems with rare

events and for curves with large failure domains, respectively, and developed second-order reliability analysis. Most commercial software and engineers assume that the mean load exceeds the mean strength, equating to a safety factor less than one, which is considered unsafe. Madsen, Lind, and Faber argue this is unsafe, emphasising the superiority of probabilistic methods. Probabilistic design methods must estimate variability and probability distributions of all parameters and accepted safety levels.. Engineering construction can benefit from probabilistic engineering that explicitly incorporates uncertainties quantitatively and utilises reliability-based codes rather than deterministic ones.

3. Occupant Safety Standards The voluntary code provides minimum design requirements for the safety of persons from fire, explosion, and flood within any sports chamber, beneficial for design engineers, manufacturers, and safety officers. Occupant safety measures are complex in large sports chamber areas to the extent that some government departments require approval on occupant safety.
4. Detailed information about the Lead City University sports chamber forms the contextual basis for this study, in line with the user preference for a Lead City University case study.

2.1. Historical Context of Sports Hall Design

Historically, sports stadiums are viewed as venues of conflict and media-driven events that influence popular culture. Professional sports serve as a primary way for mass media to shape and categorise viewers' experiences. Beyond global commercialisation via television and newspapers, the physical design of arenas reflects media logic, representing the influence of cultural and historical forces. Architecture and urban planning, both in theory and in practice, play a crucial role in shaping how physical and digital media dynamics influence city life. Specific standards, like those from the XIV ACM International Conference on Multimedia (ACM-MM'06), outline security and evacuation protocols for significant crowd events, covering venue types, crowd safety sciences, human behaviour models, evacuation algorithms, emergency communication issues, and system architecture. Indoor sport facilities should prioritize functionality and flexibility by incorporating multi-use spaces that can seamlessly transform to accommodate various sports and activities, achieved through the strategic use of movable partitions, retractable seating, and adaptable floor markings. Typical functionality and flexibility of indoor sport facilities is as shown in Fig.1. Additionally, sport-specific design elements should be integrated, such as regulation-sized courts and proper safety clearances, to ensure optimal play and performance for the intended sports.

Furthermore, facilities should provide dedicated and secure storage solutions to cater to the diverse equipment needs of various sports and activities, keeping the space organized, efficient, and safe. By adopting a
flexible and adaptable design approach, indoor sport facilities can maximize their utility, appeal, and longevity, ultimately enhancing the overall user experience.

Figure 1: functionality and flexibility.

Past studies chart the evolution of sports and multi-purpose arenas throughout history, illustrating the development from Ottoman times to the present day. Since the 1970s, sports halls have been central to social and cultural life, evolving into key economic and social hubs within urban environments. Their design follows a Complex Morphologic Pattern, featuring five main components: public spaces, access corridors, service areas, internal lounges, and parking facilities. Managing evacuation and ensuring occupant safety remains critical. Understanding the historical development of sports halls aids in current assessments of structural stability and safety, such as at Lead City University.
Also, indoor sport facilities should prioritize optimal acoustics, carefully designing the space to minimize echo and reverberation, ensuring clear sound propagation and speech intelligibility for various sports and events, such as basketball, volleyball, tennis, and concerts. Additionally, facilities should install high-quality sound systems capable of producing clear and powerful sound for music and announcements, with strategically placed speakers and subwoofers to ensure an immersive experience for spectators and participants alike. Furthermore, facilities may consider incorporating advanced acoustic technologies, such as sound-absorbing materials and active acoustic systems, to create a truly exceptional sonic environment that enhances the overall user experience. By prioritizing acoustics and sound

systems, indoor sport facilities can create a more 24 engaging, enjoyable, and professional environment for athletes, spectators, and event organizers. Typical example is shown Fig.2

5. Lighting and Electrical

Indoor sport facilities require careful consideration of lighting and electrical systems to ensure a safe, functional, and visually appealing environment. Adequate lighting is crucial for various sports and events, with different lighting levels and color temperatures required for specific activities, such as high-intensity lighting for basketball and volleyball, and lower-level lighting for yoga and fitness classes. Energy-efficient lighting options, such as LED and fluorescent lights, should be prioritized to minimize energy consumption and reduce environmental impact. Moreover, sufficient electrical infrastructure is necessary to support lighting, sound, and scorekeeping systems, as well as accommodate future technological upgrades and expansions. Well-designed lighting and electrical systems can enhance player performance, spectator experience, and overall facility operations, while also reducing energy costs and environmental footprint (Bralewski, A. (2019).

Figure 2: Acoustics and Sound Systems.

Figure 3: lights and Sound Systems.

6. Ventilation and Climate Control

Indoor sport facilities necessitate a well-designed

2.2. Probabilistic Methods in Structural Engineering

The design of large sports hall structures is complex due to large spans, open indoor space requirements, and structural safety (Sýkora & Diamantidis, 2019). Probabilistic approaches have been adopted to assess structural stability and occupant safety in sports halls, exemplified by a case study at Lead City University (Brites et al., 2013). Various studies have evaluated space consumption and overall evacuation times as occupant-related factors. Structural stability and occupant safety problems for indoor sports halls are of practical importance. Sports hall design has evolved significantly over the past century, with designs continually refined through experience. Sports halls are popular indoor arenas for leisure and sporting events. Such buildings are expected to accommodate large numbers of occupants and facilitate easy escape in emergencies. Structural performance can be severely compromised by factors such as corrosion, accidental or natural events (e.g., collisions, fires, wind, earthquakes, lightning). Evaluating the safety level of sports hall structures is necessary to ensure that appropriate precautions can be taken during operation and maintenance (Bodur, 2021).

2.3. Occupant Safety Standards and Guidelines

Standards and guidelines have long been established to ensure occupant safety in large public structures. For example, the southern Louisiana Uniform Construction Code requirement limits the occupant load in pedestrian structures and establishes guidelines for safe evacuation times and egress strategies (Xu et al., 2015). Similarly, the safety of gymnasium occupants in the event of a roof collapse is detailed in the American Society of Civil Engineers publication ASCE/SEI 7-10. The publication specifies an occupancy reduction of 15% for gymnasiums' roof truss spacing in the range of 3.66–8.84 m, where the occupant count is based on the Emergency Exit Capacity per NFPA or IBC. Other publications, such as the Ball State University publication and Lapinski's article presented at a national occupancy conference, recommend an emergency evacuation time of less than 6 minutes, with an occupant load of no greater than 500 for gymnasiums. Finally, Lee also notes that the maximum occupant load for a gymnasium is 500, based on regulatory and public concerns (De et al., 2022).

3. METHODOLOGY

The methodology for assessing structural stability and occupant safety within the indoor sports hall of Lead City University encompasses a deterministic characterisation of system uncertainty followed by stochastic evaluations of failure and exit safety criteria. The approach integrates structural response analysis with evacuation risk assessment to deliver probabilistic insights into both structural integrity and occupant survival.

An initial deterministic analysis quantifies uncertainty by assigning appropriate probability density functions to input variables, such as material properties, geometric characteristics, and boundary conditions. Finite element models of the venue's frame and roof membrane are used to calculate critical structural parameters, including plastic moment capacities, deflections, and internal stresses. These outputs subsequently serve as inputs to the stochastic stage of the assessment. Monte Carlo simulations propagate the identified uncertainties through the coupled structural and evacuation analyses using random sampling techniques. The frequency of failure or unacceptable performance, whether evidenced by structural collapse or excessive evacuation times, provides an empirical estimate of the underlying probability of failure. By linking the structural and occupant safety models in this manner, the methodology utilises Bayesian inference to identify critical parameters that govern both the capacity and demand aspects of the sports hall system (Xu et al., 2015).

3.1. Case Study Overview

The examination employs a non-linear finite element approach to establish relationships among applied loads, displacements, and strains. Probabilistic methods quantify the risks of structural failure and potential harm to occupants. Detailed insights into the structure's materials and components help assess resistance capacities and load effects. A probabilistic procedure evaluates the reliability of the sports hall's main structural elements based on uncertainty analyses. The results from the structural assessment guide the evaluation of safety implications for occupants (Miano et al., 2019). The investigation focuses on the indoor sports facility at Lead City University, Mhosteb, which integrates attached swimming pools, primarily serving students and staff.

3.2. Data Collection Techniques

Data collection encapsulated exploration and compilation of a range of data essential for probabilistic modelling of structural, occupant, and hazard functions. Data acquisition utilised multihazard literature and sources from Lead City University, including architects' input, materials test certificates, visual inspections, and dossiers for structural loads and drift limits. The structural framework consisted of seven nearly identical units with some minor inter-unit diversity. Structural material tests, a Central European draft standard, and multi-hazard literature provided additional information on material modelling, steel-frame connections, dynamic floor crowd loading, and deterministic drift-texture limits of architectural elements that potentially induce hazards. (Arrighi et al.2023). Steel, developed several times over the twenty-year procurement period, formed the structural framework as a series of trussed beams supported on stanchions. Specifications allotted explicit test- and quality-certification data to individual components. A continuously scanned architectural design recommended a preferred estimator for beam and column cross-sections. Similarly, design-lighting surveys, endorsed by a reasonable imagination considering a readily comparable structure, assumed a representative geometric profile for roof-wall glazing where dimensions were absent. Contact details provided fabricated information services on a variety of security and sanitary-ware fixtures.

Dynamic floor loading implemented an undocumented distribution, based on fundamental examples of more common load modes and dynamic material evidence from a broadly comparable auditorium. Additional load data was obtained through visual inspections of sources at Lead City University. Structural loads were estimated using standard industry tables. Lead City University distinguished between load-direction load groups, a precaution relevant during one-dimensional limit analysis of significantly modified actual floor specimens. Mechanical annexes at various levels achieved more appropriate values by referencing specific equipment. Cycle counts precisely modeled the thirty years prior to investigations. Traffic lane weights, not included in Lead City University distributions but available from a broader archive, informed the design coefficients. Enhanced reliability studies addressed the need for additional pseudo-values. Statistical load multiplier substitution and extreme value distributions estimated 1001-year wind and snow loads. Pre-data setting of snow limits nationwide supported complementary proprietary observations at Lead City University. Risks and occupants' utilised concepts and databases extracted mainly from multi-hazard literature, as well as, where necessary, from the archives of Lead City University. Textural risk incorporated an extensive spectrum of probabilities and empirical relations. Occupant data included distributions of various demographic indices and international safety standards, which were cross-referenced to component dimensions for use during analysis. Considerable effort was made to resolve appropriate evacuation scenarios; however, detailed reverse evacuation parameters, dependent on occupant psychology, precluded the final demonstration.

3.3. Probabilistic Modelling Approach

The methodology of this study focuses on the probabilistic assessment of the stability and occupant safety in an indoor sports hall at Lead City University. Data gathering and analysis methods have been described previously, and this section outlines the probabilistic modelling approach (Section 3.2).

The objective of the probabilistic modelling approach is to develop an accurate representation of the structural system and its capacity to resist loads, while accounting for uncertainties related to material properties, loads, and structural response. Structural reliability methods provide a quantitative framework for estimating the likelihood of a structural system remaining stable or failing under specified conditions, calculated through the use of failure probabilities. By comparing these probabilities with established targets, the safety performance of the system can be determined.

A limit state function $g(X) < 0$ defines failure when the actual action exceeds the system's capacity.

The vector X comprises the random variables characterizing the system, and the probability of failure is thus expressed as

$P(f) = P[g(X) < 0]$ ………………………………………………………(1)

Determining the explicit form of the limit state function and the associated probability of failure enables quantitative assessment of safety performance. Conventional numerical integration approaches may be impractical for high-dimensional variable spaces due to the computational demands they impose. In such cases, simulation-based methods become attractive alternatives. Monte Carlo simulation estimates failure probability through random sampling of the input variables. This approach entails four key steps: defining random variables with their respective distributions and correlations; generating a large number of random vectors that reflect these probabilistic characteristics; evaluating the limit state function for each sample; and computing the estimator of failure probability P(f) from the proportion of samples at which failure occurs. When the failure probability is on the order of 10^{-n}, maintaining an estimation error below a preset threshold typically requires a minimum of $10^{n} + 2$ simulations. Monte Carlo analysis thus offers an effective means of addressing the probabilistic behaviour of complex structural systems where analytical methods may prove computationally prohibitive. (Landau & Binder, 2021)

4. Structural Analysis

Operational and environmental demands influenced the availability of specific steel grades. To meet roof-structure specifications, profil-eis "sigma" I and L-type elements, as well as diverse cold-formed sections, were imported from Italy. Timbercorn laminated wood from Lithuania was chosen for the interior, while waterproof glass-fibre wool and expanded polystyrene were used to meet heating and cooling requirements. Façade cladding consisted of 10 mm-thick Alucobond metal panels. Leading to the appointment of the consulting engineers, the procurement strategy focused on a single point of responsibility. As both architects and project managers, Arup proposed taking on the role, outlining a full range of structural solutions to expedite the design and bring it to the construction stage as quickly as possible. Initial structural analyses of various alternatives revealed that exposing the steelwork on the inside of the roof would reduce costs while meeting operational requirements. By combining spatial lattice girders with a series of parallel bowstring trusses, the design also fulfilled the aesthetic brief and supported the wind-bracing arrangements needed for the grandstands.

4.1. Material Properties and Specifications Load Assessment

In the studied indoor sports hall at Lead City University, the primary material is concrete, with specified strength ranging from 25 to 40 MPa. Relevant material properties and specifications are summarised accordingly (Qureshi et al., 2019). The structural stability assessment employs a linear elastic finite element model formulated in terms of displacements and rotations (Holický & Jung, 2018). Non-structural attachments, when considered, are modelled as additional uniformly distributed loads on the slabs. Basic variables, including the ultimate limit state variable for structural stability, loads, and resistance components, are treated as random variables whose statistical properties are informed by available data. The evaluation of expected structural loads in indoor sports halls necessitates the consideration of crowd-induced effects alongside permanent, imposed, and environmental actions. Quasi-static crowd loading, typically assumed in design, becomes overly conservative as the vertical dynamic force variations of each individual tend not to co-occur across an assembly. Frequencies derived from jumping activities seldom coincide with structural resonances (Fernández Martínez et al., 2011). Common practice recommends applying a global amplification factor to static crowd loads, reflecting the prevailing dynamic factor. A suitable dynamic load factor thus remains a function of the masses involved, structural stiffness, and frequency, as well as the nature of the crowd-induced action (Fernández Martínez et al., 2014).

4.3. Finite Element Analysis

Finite element analysis consists of constructing a finite element model of a structure, including the outline geometry, boundary conditions, element connectivity, and the mechanical behaviour of the individual elements (basic archetypes of structural elements). Once the finite element packages have solved for displacements and the reactions of the supports and surrounding elements, these quantities are used to obtain other values, such as stresses, strains, and deflections. The selection process includes determining the number of elements to apply to each primary member and their location, and is usually based on the type of design under investigation. The model then undergoes linear analysis using STAAD Pro to analyse the results. For example, a section consists of both a column and a beam. The model assumes that the column is fixed and that the beam can rotate at its fixed ends. The column must resist bending loads, and the points of rotation are assumed fixed. (Davoodnabi et al.2022)

5. Risk Assessment

The risk assessment involves identifying critical failure modes based on structural analysis, followed by a probabilistic evaluation of these modes and an examination of safety margins and reliability levels. Implementing the methodology (Section 3), monitoring data enables estimation of critical failure probability, thereby quantifying associated risk. Evaluation of the estimated risk across defined safety thresholds informs the assessment of the need for redress, and guidance provided by the encountered safety margins facilitates the determination of appropriate corrective measures. The occupant safety evaluation (Section 6) is also grounded on the delineated risk assessment findings and consequent identification of relevant risk scenarios.

5.1. Identifying Failure Modes

Several distinct failure modes exist for a given structural-cost combination. The types of failure modes generally available to a given structural system depend on the shape, strength, and stiffness of the structural elements, their span, the applied loading, the material properties and strength, and the nature of the support conditions. Within a particular design format, the critical failure modes may be determined by observation from a few analysis cases. Using other approaches, however, their precise identification is more difficult. In the context of the Lead City University sports hall described in Section 3.1, the structure is analysed under a suite of loads, including characteristic gravity, wind, snow, and live loads (Section 2.1). The primary failure modes for each load combination are identified through elastic analysis supplemented by observations from finite element computations discussed in Section 4.3. Elastic buckling of the main portal frames is the primary failure mode for lateral loading; unrestrained second-order bending induces large ductile plastic deformation in the bracing members attached to the frame, with subsequent panel zone local buckling and formation of plastic hinges at the base of the upright; the attached bracing member eventually ruptures in tension, resulting in collapse of the frame. Gravity and upward wind load have an identical failure mode, as the maximum longitudinal force always occurs at the junction of the main portal frame beams and the tension ties at the high columns. Furthermore, the failure mode for these loads is beam rupture due to yielding near the beam-column connection (Xu et al., 2015).

5.2. Probabilistic Risk Analysis

A literature survey reveals two mutual approaches to probabilistic risk analysis: qualitative and quantitative. A qualitative approach broadly defines the system and identifies significant hazards and failure modes. The second approach quantitatively assesses the probabilities (of failure modes) and consequences of hazards, and calculates risk accordingly (Sýkora & Diamantidis, 2019). Probabilistic analysis (PA) is a crucial tool for engineering problem-solving. PA uses probability density functions (PDFs) to represent input (elongation, moduli, yield strengths, brittle fracture toughness, etc.). Each PDF represents a population of data from experimental tests on many specimens. The function shape and its parameters provide limited information about the global population from which data are randomly extracted. Monte Carlo simulation (MCS) is better suited to solving complex problems involving random sampling. SA II. Investigates the values of random input parameters, computes the corresponding response, and compares the predicted output to either property requirements or failure criteria, used to evaluate solution quality, calculate the probability of failure, or identify critical input variables (Xu et al., 2015).

5.3. Safety Margins and Reliability

The safety margins and reliability are systematically discussed. The concept of a safety margin has been adopted from engineering mechanics, where the safety factor is used to ensure that elements or structural systems are capable of resisting everyday loads without failure. The safety margin of a specific load factor λ is consequently related to the safety factor at that load. As the structural resistance depends on several uncertainties, it cannot be determined with absolute certainty. According to a deterministic approach, if a factor of λ scales up the applied load, the failure state is reached when the applied load R equals the resistance Q at the scaled ultimate load, defined as

$\lambda = R \div Q$. ……………………………………………………………(2)

More specifically,

if $R = 10$ kN $\pm$ 1 kN, …………………………………………………(3)

Where r is resistance, the probability of observing a value less than 5 kN or greater than 15 kN is practically zero, and the value 10 kN may be treated as exact. The safety margin (M) can then be calculated as the difference between resistance (R) and the load effect (E), both random variables, defined as

$M = R – E$. ……………………………………………………………(4)

The influence of all random variables characterising the load and resistance on the structural performance and safety can be included by means of the safety margin (M). The structure is considered safe if the safety margin has a positive value. From the analysis of the Safety Margin (M), the reliability index (β) can be defined as the closest distance from the origin to the limit state curve along the most probable failure path, estimated as

$\beta = \Lambda(\Lambda^T)^{-1}$ ………………………………………………………..(5)

where Λ is the gradient vector of the performance function (f). The failure probability (Pf) corresponds to the probability of the safety margin M being less than zero i.e.

$(Pf = P(M < 0))$. ……………………………………………….(6)

A probability distribution can be assumed to quantify the uncertainties associated with M (e.g. normal distribution), where Pf reads as

$Pf = \Phi(-\beta)$ (Sýkora & Diamantidis, 2019) ……………….(7)

. Figure 4 shows the corresponding safety margin αm in terms of the mean value and ασ in terms of standard deviation are determined by the equations

$\alpha m = (\mu R – \mu E) / \mu R$ and…………………………………(8)

$\alpha\sigma = (\sigma R + \sigma E) / (\mu R – \mu E)$. ……………………………(9)

where μ and σ represent the mean and standard deviation of the resistant (R) and load effect (E) quantities. The diagrams in Figure5 relate the safety margin (α), the ratio between the load and the resistance and the reliability index (β), under the assumption that the limit state defined by

$\alpha m + \beta\, \alpha\sigma = 0$ ……………………………………………(10)

provides the safety margin and the DOF corresponding to the selected reliability index for constant variance values for the resistances and loads. The probability of failure is strongly dependent on the difference between the load and resistance. At the same time, the coefficients of variation have a minor effect, except when the loads and resistances approach the failure point. (Asteris et al.2022).

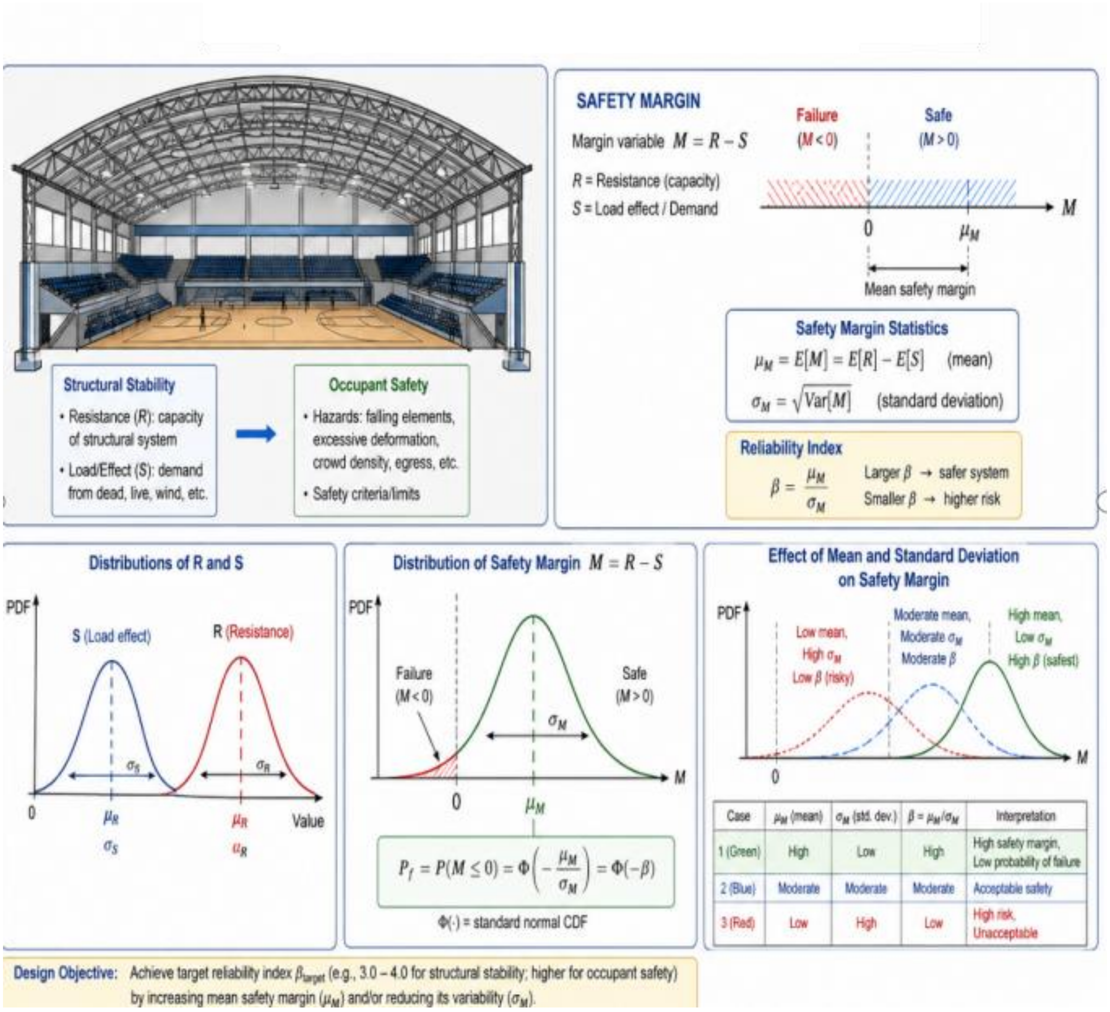

Figure 4: Probabilistic Assessment of Structural Stability and Occupant Safety: Safety Margin in Terms of Mean Value and Standard Deviation (Ang and Tang, 2007).

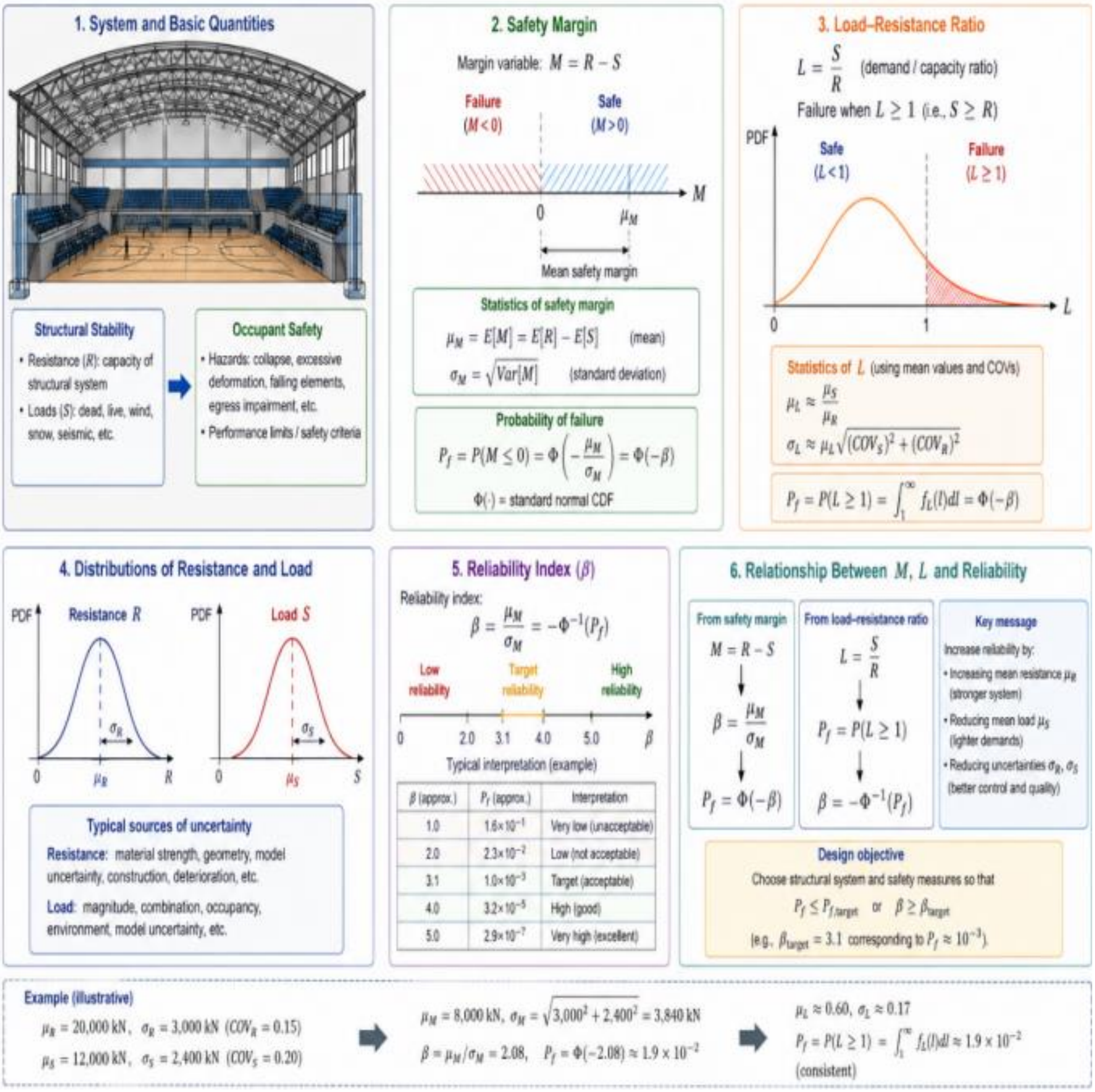

Figure 5: Probabilistic Assessment of Structural Stability and Occupant Safety in indoor sports Hall: Safety Margin, Load Resistance Ratio and Reliability (Melchers and Beck, 2018; Ditlevsen & Madsen, 1996; Nowak and Collins, 2012).

6. Occupant Safety Evaluation

In addition to assessing structural stability, evaluating occupant safety under fire or other emergency conditions constitutes a significant element of probabilistic risk analysis. In a fire scenario, both the fire itself and collapsing structural components may jeopardise the safety of the occupants, emphasising the imperative to develop evacuation models for indoor sports halls without compromising the structural validity of the probabilistic risk assessment (Xu et al., 2015). Six potential fire-evacuation scenarios have been identified, each characterised by the number of evacuation gates and the presence or absence of fluorescent lighting. The resulting probabilistic risk analyses affirm the necessity for evacuation plans that accommodate 1,200 occupants exiting within 540 seconds. It should be noted that the only physical data used in the generation of these evacuation standards derive from the Lead City University sports hall and the results of human behaviour analyses. Complementary analyses of safety equipment and human behavioural strategies facilitate the development of a safety-enhancement model in sports halls. Accordingly, the recommendation is made to adopt enhanced lighting and a gating system comprising four evacuation exits. Furthermore, a safety education programme, supplemented by other non-structural initiatives, is proposed as a means of further enhancing occupant safety (Sýkora & Diamantidis, 2019).

Moreover, occupant-safety evaluations address evacuation processes and safety features. Analysis of evacuation processes establishes a benchmark for further investigation, providing a basis for enhancing safety features. Perceptible characteristics of safety facilities that might be underestimated or overlooked in the construction of sports halls are also considered within this framework. The human factor is incorporated through considerations of human habituation, individuality and educational level, thereby contributing to the development of analytical guidelines intended to enhance occupant safety (D. Miglani, 1993).

6.1. Evacuation Scenarios

As outlined by Robyn Aucoin (2019), several evacuation scenarios have been modelled, concentrating initially on the fire event and related steps to highlight resultant illustrative occupier behaviours. The fire scenario is then followed by a power outage situation, where lighting is completely unavailable, and subsequently by various combinations of fire and lighting conditions, together with rising panic levels. For each of these scenarios, levels of violence have been parameterised: healthy/sober, minor violence, intermediate violence, and severe violence. Evacuation modelling is presented in a separate chapter, where suggestions for ensuring the safety of occupants in the event of structural failure are provided, based on responses to these scenarios.

6.2. Safety Features Assessment

The assessment of safety features encompasses an evacuation simulation conducted using an agent-based model, which incorporates spatial data, building attributes, occupant characteristics, and hazardous conditions within the time domain. Structural elements, such as stairways and walls, are modelled as straight, traversable paths interconnected by nodes—junction points where agents determine their next movement trajectory. The simulation accounts for crowd formation by limiting the number of agents in adjacent nodes and paths, thereby simulating congestion phenomena. Staircases are represented using planar entities that include the horizontal projection of the stairs. Geometrical data is extracted from the building information model and is augmented with parameters derived from the OCCUPANT category of the initial architectural input. Implementing an evacuation simulation model that integrates evacuable paths, building features, and occupant details enables the establishment of a probabilistic scenario for assessing occupant safety. The model incorporates equations and parameters derived from extensive analysis described in the preceding section. The simulation challenges exist with varying capacities and license attribute values, encompassing diverse capabilities, including spiral ramps. This model evaluates a provider that implements both nodes and paths, applying varied procedures to accommodate actual building characteristics and occupancy profiles. Providing these details is essential for incorporating the aforementioned evacuation procedures into a georeferenced scenario. In an indoor sports hall case study, an agent-based evacuation simulation model was applied to an agent and scenario obtained from prior procedures. This simulation establishes a probabilistic framework for assessing occupant safety in buildings, facilitating evaluation of the outcomes derived from structural analysis and probabilistic risk assessment. The subsequent section will delve into this context based on the obtained data, underscoring the implication of safety measures within the specific instance (Sýkora & Diamantidis, 2019). Safety features within the Lead City University sports hall are evaluated using cascade fire detectors, low-level route signs, and alarm sounders situated below the ceiling, which are explored by reflecting their functions in an indoor sports hall. (Xu et al., 2015)

6.3. Human Factors Consideration

The stability of structures, with or without human crowds, under dynamic loads has recently garnered widespread attention. The different crowd characteristics, including horizontal personality, body weight, crowd size, crowd density, and spatial distribution, were found to have a significant effect on the dynamic properties of an occupied structure (Joseph III Firman, 2010). The evacuation of occupants from a building is of predominant importance during the assessment of occupant safety in emergencies. If the design and construction of evacuation facilities do not meet safety requirements, hazards such as crushing, pounding, injury, and death may occur, especially during rush hours. The structural safety of evacuation facilities may be compromised by crowd dynamic loads during evacuation, accompanied by the risk of occupant panic and stampede (Xu et al., 2015). There exists a direct relationship between the quantity and overall distribution of casualties and the technical specifications of evacuation facilities that must be appropriately accommodated and incorporated into building design. Human factors, such as panic and the behaviour of occupants, are critical in determining occupant safety, particularly where evacuation is the only option. The considerable structural hazards in this work are related to the platform of the train station. These hazards are organised into the following categories: collision between people, collision of people with steel structures, collision between railings, fall of steel structures, and collision between people and other hazards for further risk assessment. Evacuation analysis was conducted using simulation software to verify the adequacy of the evacuation facilities, specifically the width of the staircases and the number of exits available from the ground and first floors. The panic and behaviour of occupants are not explicitly involved in the evacuation analysis, and their effect is incorporated indirectly using a factor of safety. Additionally, the finite element model (FEM) has been utilised in structural analysis to assess the vulnerability of evacuation facilities to hazards such as excessive deformation and buckling. The equilibrium model was adopted to assess the maximum load-carrying capacity of the staircase, which is in a critical condition, ensuring adequate reliability of evacuation facilities while undergoing crowd-induced dynamic loadings. The dynamic response of the structure to crowd-induced vibration has been analysed using a probabilistic approach in MATLAB to examine the safety of occupants. (Wang et al.2022)

7. RESULTS AND DISCUSSION

Structural analysis of the indoor sports hall revealed that the primary structural system exhibited adequate strength to remain stable under imposed actions, with safety margins assessed through probabilistic evaluations (Xu et al., 2015). Despite robustness in strength, investigations identified four potential damage modes, including brittle failure of roof truss–supporting column connections, localised buckling of rafters, and fatigue failure of lower chord members. Probabilistic risk tests estimated the aggregate probability of failure to be 3.7×10^{-5}, indicating a very low likelihood of failure. Evaluation of occupant safety revealed that, in the event of structural failure, evacuation was not feasible, indicating the need for the immediate implementation of enhanced safety measures and policies (D. Miglani, 1993).

7.1. Findings from Structural Analysis

Steel has been widely applied to the structural components of sports halls due to its reliable structural performance and large span. The structure is fundamentally comprised of columns, bracings, and beams. Bracings principally resist lateral loads and provide the extreme bearing capacity of the sports hall by forming triangulated systems with the primary columns and beams. Due to their brittleness, bracings are typically the first components to fail beyond their yield limits, and their stability is critical to the overall structural integrity of sports and recreational facilities. Steel grades are generally unified to BS 5950 standards. Except for columns, most members are designed to remain within elastic thresholds even under service load challenges. Commonly applied beam profile sections include I-sections, box channels, rectangular box sections, channel sections, Z-shapes, and C-sections. For outdoor sports halls, all steel components undergo hot galvanisation, whereas indoor sports hall members are finished with epoxy paints. The roof system typically employs insulated composite metal deck members with high fire resistance, capable of bearing design loads of approximately 4.0 kN/m² (including self-weight). Roof plants entail service masses of about 1.0 kN/m². Service columns are designed for slenderness and await revision for in-depth evaluation. Additionally, large indoor sports halls are usually equipped with 7.5 kN/m² (net) sports floors abutting the beam and slab arrangement (D. Miglani, 1993).

7.2. Insights from Risk Assessment

The elementary considerations of Section 7.1 have shown that the sports hall's overall probabilistic stability and occupant safety cannot be ascertained through simple constraint arguments. Moreover, an analysis confined to individual components is inadequate, since the risk depends on the performance of the entire structure, including the probability of element failure, potential capacity reduction induced by failure modes, and the effects of redistribution on overall response and safety margins. To address this complexity, the structural system is assessed via non-linear finite element analysis (Xu et al., 2015). The probabilistic model outlined in Section 3 serves as the basis for the quantitative risk assessment that follows:

Potential failure modes are identified in reference to the non-linear structural response reported in Section 4, considering the modes outlined in Section 2. A parametric analysis then evaluates the associated risks, leading to estimates of the structure's safety margin and reliability. The implications of these results for occupant safety are discussed subsequently. Several modelling considerations have guided the approach. The analysis focuses on the primary load-carrying components of the roofing system; secondary or non-structural elements, such as linings, ducting, and electrical installations, are excluded. Pre-stressed cables are not represented, as their contribution to restraint and load transmission is assumed to be negligible. The hot-rolled steel profiles of the mastic asphalt support beams are modelled in detail using shell elements. In contrast, the cold-formed steel studs are represented by simplified beam elements that consider flexural behaviour only. Finally, the suspended ceilings and bridging second-floor structures are not explicitly modelled but are instead accounted for via an equivalent load applied to the rafters. (Li et al., 2025)

7.3. Implications for Occupant Safety

The current design codes for extensive venues, such as sports halls, prescribe numerous safety features to facilitate occupant evacuation during emergencies. Exits and stairs must have specified widths and be clearly marked to aid swift evacuation. Indoor sports halls intended for multiple events require exits and stairs that can accommodate simultaneous evacuation from all indoor spectator areas. The number and width of stairs and exits are specified for the designated occupant numbers throughout the facility. Notably, multifunctional halls lacking dedicated safety requirements often rely on regulations designed for cinemas, clubs, or theatres, which require more generous occupant freedom of movement. The building fabric should be sufficiently robust to bear loads from evacuation traffic, including scenarios involving occupant assistance. Furthermore, stairs and ramps must not rely on supporting structures that could fail; otherwise, alternative evacuation routes must be available if these fails. Only a limited number of easily accessible refuges may be permissible for use as emergency holding areas. (Castelblanco et al.2025)

8. Case Study of Lead City University

Various research projects have contributed to understanding sports halls. Investigations include checks and tests on building materials, as well as the required sample sizes (Miano et al., 2019). Structural behaviour is modelled via finite-element approaches, accounting for specific characteristics of concrete and steel, member force-deformation responses, and the modelling of inelastic actions and plastic hinges. Displacement considerations refer to Life Safety limits associated with maximum shear strength or rotational capacity, with safety verifications extended to joints. Enhanced input data aligns finite-element results more closely with experimental observations. Vertical-load analyses performed in accordance with national seismic criteria reveal potential premature shear failures. Pushover analyses utilising various force distributions, including relative to floor masses and vibration-mode shapes with eccentricities, further characterise structural responses. Modifications to structural systems in stadium-like buildings address functional drawbacks, such as obstructed sightlines, by involving load transfers to selected columns and reinforcing elements without requiring foundation reconstruction (D. Miglani, 1993). Standards-based static load analyses guide member sizing, while architectural considerations maintain original beam and slab arrangements. Additional structural features accommodate spatial requirements with minimal demolition, emphasising safety, stability, and economic efficiency within soil-structure interaction and aseismic design frameworks.

8.1. Overview of the Sports Hall

The large indoor sports hall considered has a maximum occupancy of about 1200 people. The warm-up and fitness training areas are located in the three attached galleries, each accommodating approximately 60 occupants. The sports hall itself accommodates approximately 1000 spectators. The construction is reinforced concrete and steel, featuring a single-layer trapezoidal-profile steel sheet roof fixed to a rigid steel frame spanning 90 m, supported by regular steel girders spanning 15 m and spaced at 3.5 m centres. The roof is insulated with 80 mm-thick polyurethane, and the structure is braced by both the cladding and a central spine frame running along the apex of the roof. The main hall (110 m by 43 m) occupies the full extent of the building plus upper galleries; floor area is approximately 7650 m^2 (Fernández Martínez et al., 2011). The structure has had several adaptations for different sports throughout its lifetime. Events typically last 2–3 hours, with larger crowds in standing areas only. The staff for such events currently includes two full-time and fifteen part-time employees.

8.2. Historical Performance Data

The use of probabilistic methods has proven to be a valuable technique for quantitatively assessing structural stability and occupant safety of an indoor sports hall located at Lead City University. The case study is presented to demonstrate the implementation of the probabilistic risk assessment framework. The indoor sports hall facility under study is a pre-engineered steel building designed to accommodate approximately 1600 spectators. A focus is placed on events that could jeopardise life safety, such as fire outbreaks, toxic gas leaks, or structural failures. Past safety records provide information that informs the historical performance data of sports halls and venues worldwide (Uday & Nagaraju, 2021). Numerous sports arenas around the globe have experienced structural failures in recent years. These incidents have attracted significant attention from researchers, owing to the high visibility and potential for catastrophic injury and loss of life. Several studies investigate the structural failure of domes and stadiums; however, such events have also occurred in other sports facilities, including indoor arenas and gymnasiums.

8.3. Comparative Analysis with Other Facilities

The performance of Lead City University's indoor sports hall stands in favourable contrast to analogous structures elsewhere. In a similar stadium building (D. Miglani, 1993), the reinforcement of the central and rear columns protruded above the seating floor, obstructing spectators' views. To address this, a modified seating-floor plan proposed changes to the roof's structural system and a redesign of the primary columns to accommodate the increased loads. Although the original roof beams and slab arrangement were retained for architectural reasons, counterparts at Lead City offered improved spatial coordination with unimpeded viewing. Regarding seismic safety, studies have revealed vulnerabilities in prefabricated reinforced-concrete halls. An analytical model incorporating hysteresis captures reductions in bearing capacity during cycles and repeated displacements (Fischinger et al., 2009). Risk assessments using probability analysis help scrutinise Eurocode 8 provisions, especially those concerning the performance factor and design earthquake force. While the potential for seismic risk depends on geographic exposure, the assessments illustrate that prefabricated halls may warrant reconsideration of established design parameters, suggesting that Lead City's facility benefits from enhanced stability relative to such cases.

9. RECOMMENDATIONS

Several measures are recommended to enhance structural stability and occupant safety, based on the probabilistic assessment and the Lead City University case study. The general structural design of indoor sports halls can be enhanced to achieve greater safety margins without incurring significant cost increases. This can involve the use of continuous frames to eliminate moment connections, thereby increasing the reliability of local connections at column tops and bases. Additionally, it may involve redesigning steel trusses to reduce cross-section sizes without compromising robustness, and adopting more robust ceiling structures capable of preventing large falling debris. In this way, the structural design framework evolves toward a stronger probabilistic basis. About 35% of the risks—mainly related to occupant injury during emergency evacuation—are associated with policy issues. Specified occupant numbers constitute a key parameter influencing risk; data from some recent and ongoing projects for indoor sports halls indicate that the values currently employed tend to be larger than those found in many international standards and codes. Improper fire protection, inadequate side access, and ineffective emergency gate policies could also reduce risk. These findings call for a study involving other indoor sports halls—preferably more case studies on excess life and performance adjustment factors—to form guidelines for various typical facilities in different regions. The probabilistic methodologies currently available have numerous limitations and related problems, indicating that their use remains somewhat in the early stages. Consequently, their applications as design foundations are limited. Intelligence should not be overstated, and investigated problems should be clearly defined and controlled. A systematic approach can help significantly reduce uncertainty and provide a better understanding of the relevant physical mechanism (Xu et al., 2015). The case study reveals important findings for new indoor sports halls that can help avoid the types of problems identified. A reliability investigation of the gym hall will be conducted using data collected from the whole building (Miano et al., 2019).

9.1. Design Improvements

The sports hall at Lead City University incorporates various safety measures, including fire alarms, fire extinguishers, and multiple galleries that facilitate rapid evacuation. To ensure continuous safety under both routine and emergency conditions, these systems require comprehensive assessment and potentially additional practical analyses. Enhancing the design could involve increasing the number of evacuation galleries to facilitate quicker movement and reduce the risk of congestion. The security plan could be enhanced by installing more fire-fighting equipment, such as additional fire extinguishers strategically positioned throughout the premises. Effective evacuation planning should also account for the specific behaviour of occupants within a sports hall setting to optimise safety protocols and emergency response effectiveness.

9.2. Policy Suggestions

Probabilistic summations should be accompanied by consideration for scenarios in which these indicative values are exceeded. Such scenarios, though with low probability, may entail higher or more rapid growth in productivity losses and casualties. High-consequence, yet low-frequency events command the investment of effort in developing effective mitigation measures. However, direct interest in doing so will only be secured through a clear demonstration of the extreme sensitivity of expected indirect losses to the relatively rare instances of very severe disruption. The elucidation of the exceptionally high consequences of these rare occurrences provides a further necessary incentive to continue collecting detailed empirical data on disruption and recovery processes during periods of significant incidents and from simulations designed to capture the relevant generative mechanisms (Xu et al., 2015; Miano et al., 2019).

9.3. Future Research Directions

Future research on the structural stability of sports halls may leverage the Lead City University case to develop detailed finite element analyses that consider a broader range of potential failure modes. It would be desirable to analyse alternative structural configurations, as well as new sets of input data, in order to obtain a broader and more general perspective on the problem. Another avenue for investigation could involve defining evacuation design and management strategies for a range of structural threats, such as fire and roof collapse. In particular, it would be helpful to explore the operational interaction of different safety measures, including those recommended for earthquakes, fires, and roof collapses, to formulate a comprehensive framework for multi-hazard safety during egress from a building.

10. CONCLUSION

This study encompassed a probabilistic assessment of the structural stability and occupant safety of an indoor sports hall at Lead City University. This approach facilitated comprehensive evaluations of both the physical integrity of the hall and the welfare of individuals within the structure. A related analysis of material strength and load conditions was also undertaken to inform the overall evaluation. Emission of entrant projects, security capabilities of securing grounds apps, and authority and worldview faith fraction assertiveness formed the foundation of the study. The design employed a bi-directional approach (Xu et al., 2015), integrating material properties and finite element analysis to underpin the structural modelling of the sports hall. Merging probabilistic assessment with occupant safety considerations provided a practical framework for determining the integrity and safety status of the indoor facility. Integrating these facets yields a systematic assessment methodology that addresses the stability and safety of the indoor sports hall. The resultant data further supports the development of design modifications and policy recommendations aimed at mitigating failure risks and safeguarding occupants. Within the examined context, this probabilistic assessment approach proves to be a robust and comprehensive tool for evaluating structural and safety performance.

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