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Analysis of Structural Response Spectrum Under Walking Loads

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Abstract - In structural engineering and vibration analysis, the dynamic response of structures to pedestrian loads especially those caused by individual walking has grown to be a major focus. Digitalize civil structures such as pedestrian footbridges, building floor systems, and stadium stands are increasingly susceptible to human-induced vibrations due to the widespread use of lightweight materials, longer spans, and slender structural forms. While these structures often satisfy conventional strength and safety requirements, vibrations generated by everyday human activities—including walking, exercising, and synchronized crowd movement—can significantly affect occupant comfort, perception, and confidence. This research investigates human-induced vibrations with a particular emphasis on serviceability and human experience rather than structural failure. The study adopts an integrated methodology combining analytical modeling, computational simulation, and experimental validation. Single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) analytical models are developed to describe the dynamic response of structures subjected to pedestrian loading. These models are implemented in MATLAB and Python to simulate various activity scenarios, structural properties, and damping conditions. Response spectra and time-history analyses are used to identify critical frequencies, resonance effects, and amplification mechanisms associated with human motion. To bridge the gap between theory and practice, field experiments are conducted using accelerometers installed on real structures, including footbridges, gym floors, and stadium seating systems. Experimental results validate many analytical predictions while also revealing limitations of simplified models, particularly in capturing human behavioral adaptation and perceptual response to vibration. Based on these findings, the research proposes practical, structure-specific design guidelines that promote early-stage vibration assessment, realistic human loading models, and effective damping strategies. Overall, this thesis advocates a human-centered approach to vibration-sensitive design, demonstrating that occupant comfort is a measurable and essential performance criterion. By integrating technical accuracy with experiential understanding, the study contributes toward creating built environments that are not only structurally safe, but also comfortable, trusted, and responsive to human use.

Keywords - ***Structural vibrations,Walking load, Response spectrum, Footbridges, Human comfort, Resonance, Vibration control strategies, Dynamic analysis, MATLAB.***

1. INTRODUCTION

Modern civil structures, including pedestrian footbridges, building floor systems, and stadium stands, should not be regarded as static entities but as dynamically responsive systems that continuously interact with their occupants. Contemporary architectural and structural design trends increasingly favor longer spans, reduced structural mass, and slender forms in pursuit of material efficiency, sustainability, and visual transparency. While these developments have significantly enhanced the functionality and aesthetics of the built environment, they have simultaneously increased vulnerability to human-induced vibrations generated by everyday activities such as walking, running, jumping, and synchronized crowd movement. Under typical operating conditions, these vibrations may remain unnoticed; however, when excitation frequencies associated with human motion align with a structure's natural frequencies, resonance phenomena can occur, resulting in amplified vibration responses that adversely affect serviceability and occupant comfort, even when structural safety is not compromised.

The importance of human-induced vibration lies primarily in serviceability and human perception rather than ultimate strength or collapse prevention. Numerous investigations reported in high-impact structural engineering journals have demonstrated that occupants are highly sensitive to motion, and discomfort may arise at vibration levels far below those associated with structural damage. Well-documented cases of excessive vibrations in open-plan office floors, gymnasiums, and pedestrian bridges illustrate the limitations of traditional

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Vol. 15 Issue 02 , February - 2026

design approaches that prioritize static loading and strength criteria. The lateral oscillations observed on the London Millennium Bridge serve as a particularly influential example, highlighting the role of human–structure interaction and pedestrian synchronization in amplifying structural response. Subsequent studies have shown that typical human excitation frequencies, ranging from approximately 1.6 to 2.4 Hz for walking and extending beyond 3 Hz for rhythmic activities, frequently overlap with the fundamental frequencies of lightweight and long-span structures, making resonance a realistic and recurrent design concern.When these human-induced frequencies match with a structure's intrinsic frequency, a harmful phenomenon called resonance monitors tremble or desks sway slightly. The science behind this is rooted in vibration dynamics.

As mentioned in the background, the general equation that governs these dynamics is:

$$m\,x(t) + cx(t) + kx(t) = F0\,\sin(2\pi ft)$$

Where: m is the structure's effective mass, c is the damping coefficient, K is the stiffness, F0 is the applied force amplitude, f is the frequency of the applied force, and x(t) is the displacement. This equation exposes a vital insight: when the forcing frequency f is equal to the natural frequency fn, defined as: $fn = (1 / 2\pi)\sqrt{(k / m)}$

the system can experience increased vibrations, especially if damping is minimal. This is precisely why footbridges, floors, and stadiums are high risk candidates for undesired vibrations because their inherent frequencies often lie within the range of human movement frequencies.

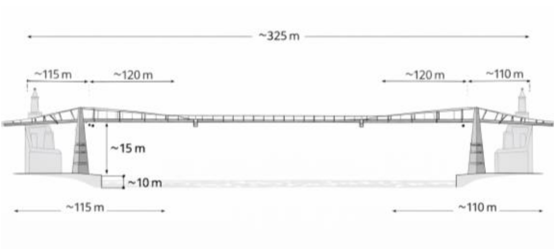

Figure 1: Elevation view of the Millennium Bridge illustrating structural dimensions.

After recognizing the hidden yet significant effects of human-induced vibrations on structures such as footbridges, floors, and stadium stands, this research aims to propose practical and reliable mitigation strategies. The ultimate goal is to ensure that these structures feel safe, remain structurally sound, and support the people who rely on them in daily activities—from walking to work and exercising in gyms to celebrating in crowded stadiums. This challenge is not only technical but fundamentally human-centered.

The first main objective of this study is to develop reliable analytical and mathematical models that describe the dynamic behavior of such structures. These models represent the relationship between mass, stiffness, damping, and external excitation forces. A fundamental starting point is the Single Degree of Freedom (SDOF) equation:

$$mx(t)+cx(t)+kx(t)=F0\sin(2\pi ft)$$

This equation provides a first approximation of how structural elements, such as bridge decks or floor slabs, vibrate under human footfall. Proper calibration of these models allows engineers to predict problematic behavior before it occurs.

However, analytical models alone are insufficient to capture the complexity of real structures. Therefore, the second objective is to implement these models in simulation environments such as MATLAB or Python. These tools enable virtual testing of different designs, loading scenarios, and human activity patterns, such as synchronized walking on footbridges or collective jumping in stadiums. Engineering, at its essence, is not simply about solving problems; it is about enhancing human capability and improving quality of life. Through the thoughtful application of science, mathematics, and creativity, engineering transforms abstract ideas into practical solutions that promote safety, efficiency, and sustainability.

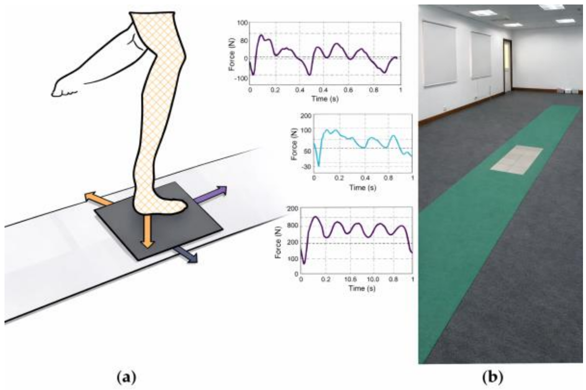

Figure 2: Human-Induced Vibration Serviceability

Research published in leading top journals further indicates that vibration perception is influenced not only by peak response amplitudes but also by factors such as vibration duration, frequency content, and damping characteristics. For floor systems, especially those constructed using steel or composite materials with minimal partitions, occupant complaints have often arisen despite compliance with strength-based design codes. In such cases, excessive vibration has led to loss of user confidence and costly post-construction retrofitting.

Despite considerable advances in vibration theory, experimental techniques, and numerical modeling, a persistent gap remains between analytical predictions and real-world human experience. Many existing studies rely on simplified

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representations of human loading or focus on isolated structural typologies without fully integrating analytical modeling, computational simulation, and experimental validation into a unified framework. Although multi-degree-of-freedom models and full-scale measurements have improved understanding of dynamic behavior, their practical application during routine design stages remains limited. In particular, the interaction between structural motion and human behavioral adaptation is often neglected, reducing the accuracy of vibration performance predictions.

This work seeks to contribute to addressing these limitations by synthesizing analytical and computational approaches for the assessment of human-induced vibrations in structures that directly accommodate occupants. Building upon classical vibration theory, including single-degree-of-freedom and extended dynamic formulations, the study aims to establish predictive models that relate structural properties such as mass, stiffness, and damping to characteristic human excitation mechanisms. These models are further implemented within numerical simulation environments to allow systematic evaluation of different structural configurations and activity scenarios. Through this integrated approach, the research supports a human-centered design philosophy in which comfort, usability, and perceived safety are treated as essential performance criteria rather than secondary considerations.

The scope of the study is intentionally focused on structural systems known to be particularly sensitive to human-induced vibrations, namely pedestrian footbridges, building floor systems, and stadium seating structures. These systems are examined within realistic geometric, material, and frequency ranges commonly encountered in practice, with emphasis placed on serviceability operating conditions. Extreme loading events, material nonlinearities, and failure mechanisms are excluded to maintain focus on vibration performance relevant to everyday use. By adopting this targeted approach, the study aims to provide practical insights and design-oriented guidance that enhance the comfort and confidence of occupants while supporting efficient and reliable structural design.

Table 1: Typical span ranges and frequency ranges for different structures under human-induced loading

Structure Type	**Span Range**	**Frequency Range**	**Example Activities**
Footbridges	20 - 100 m	1.5 - 2.5 Hz	Walking, jogging
Floor Systems	5 - 12 m	3 - 5 Hz	Fast walking, group exercises
Stadium Stands	10 - 30 m	2 - 3 Hz	Jumping, synchronized chanting

Note: *The frequency ranges shown are typical values associated with human-induced dynamic loading and may vary depending on structural stiffness, damping, and boundary conditions.*

Human-induced vibration issues in footbridges, floor systems, and stadium structures extend beyond theoretical formulations and demand a systematic approach supported by experimental evidence.

This research follows a three-stage methodology. First, analytical modeling is used to describe structural vibration behavior under human-induced dynamic loads using physics-based equations. Second, these models are extended into computational simulations using platforms such as MATLAB and Python, enabling efficient evaluation of structural responses under varying conditions, including changes in crowd behavior, damping, and geometry. Finally, experimental validation is employed to compare simulated results with measured data obtained from laboratory tests or in-situ monitoring of real structures. By integrating analytical rigor, numerical simulation, and experimental observation, this study aims to provide reliable predictions and enhance the safety, comfort, and trustworthiness of structures subjected to human-induced vibrations.

With the advancement of modern engineering, the consideration of human-induced vibrations in structures such as footbridges, floors, and stadiums has become increasingly important. The growing use of lighter materials and longer spans has made structures more susceptible to dynamic actions generated by activities such as walking and jumping. A notable example is the Millennium Bridge in London, where unexpected lateral vibrations occurred due to pedestrian synchronization, highlighting the need to account for human–structure interaction in design. To address such challenges, engineers employ analytical models such as single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) systems to predict structural responses under dynamic loading. While SDOF models offer simplicity, MDOF models provide a more detailed representation of complex structures by capturing higher vibration modes. Importantly, structures may satisfy strength requirements yet still cause discomfort to users. Therefore, modern structural engineering must consider not only safety but also vibration control to enhance occupant comfort and overall user experience.

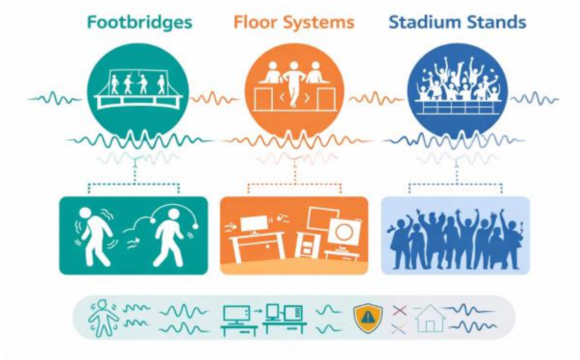

Figure 3: Human-Induced Vibration Effects in Footbridges, Floors, and Stadium Stands

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2. LITERATURE REVIEW

Nowadays civil structures, including pedestrian footbridges, building floor systems, and stadium stands should not be regarded as static entities but as dynamically responsive systems that continuously interact with their occupants. Contemporary architectural and structural design trends increasingly favor longer spans, reduced structural mass, and slender forms in pursuit of material efficiency, sustainability, and visual transparency. While these developments have significantly enhanced the functionality and aesthetics of the built environment, they have simultaneously increased vulnerability to human-induced vibrations generated by everyday activities such as walking, running, jumping, and synchronized crowd movement. Under typical operating conditions, these vibrations may remain unnoticed; however, when excitation frequencies associated with human motion align with a structure's natural frequencies, resonance phenomena can occur, resulting in amplified vibration responses that adversely affect serviceability and occupant comfort, even when structural safety is not compromised.

The importance of human-induced vibration lies primarily in serviceability and human perception rather than ultimate strength or collapse prevention. Numerous investigations reported in high-impact structural engineering journals have demonstrated that occupants are highly sensitive to motion, and discomfort may arise at vibration levels far below those associated with structural damage. Well-documented cases of excessive vibrations in open-plan office floors, gymnasiums, and pedestrian bridges illustrate the limitations of traditional design approaches that prioritize static loading and strength criteria. The lateral oscillations observed on the London Millennium Bridge serve as a particularly influential example, highlighting the role of human–structure interaction and pedestrian synchronization in amplifying structural response. Subsequent studies have shown that typical human excitation frequencies, ranging from approximately 1.6 to 2.4 Hz for walking and extending beyond 3 Hz for rhythmic activities, frequently overlap with the fundamental frequencies of lightweight and long-span structures, making resonance a realistic and recurrent design concern.

Research published in leading quartile journals further indicates that vibration perception is influenced not only by peak response amplitudes but also by factors such as vibration duration, frequency content, and damping characteristics. For floor systems, especially those constructed using steel or composite materials with minimal partitions, occupant complaints have often arisen despite compliance with strength-based design codes. In such cases, excessive vibration has led to loss of user confidence and costly post-construction retrofitting. Similarly, stadium structures present additional challenges due to large crowd densities and the potential for synchronized movement, which can excite multiple vibration modes and produce complex dynamic behavior. These findings emphasize the necessity of considering human comfort as a primary design objective alongside structural safety.

Despite considerable advances in vibration theory, experimental techniques, and numerical modeling, a persistent gap remains between analytical predictions and real-world human experience. Many existing studies rely on simplified representations of human loading or focus on isolated structural typologies without fully integrating analytical modeling, computational simulation, and experimental validation into a unified framework. Although multi-degree-of-freedom models and full-scale measurements have improved understanding of dynamic behavior, their practical application during routine design stages remains limited. In particular, the interaction between structural motion and human behavioral adaptation is often neglected, reducing the accuracy of vibration performance predictions.

This work seeks to contribute to addressing these limitations by synthesizing analytical and computational approaches for the assessment of human-induced vibrations in structures that directly accommodate occupants. Building upon classical vibration theory, including single-degree-of-freedom and extended dynamic formulations, the study aims to establish predictive models that relate structural properties such as mass, stiffness, and damping to characteristic human excitation mechanisms. These models are further implemented within numerical simulation environments to allow systematic evaluation of different structural configurations and activity scenarios. Through this integrated approach, the research supports a human-centered design philosophy in which comfort, usability, and perceived safety are treated as essential performance criteria rather than secondary considerations.

The scope of the study is intentionally focused on structural systems known to be particularly sensitive to human-induced vibrations, namely pedestrian footbridges, building floor systems, and stadium seating structures. These systems are examined within realistic geometric, material, and frequency ranges commonly encountered in practice, with emphasis placed on serviceability behavior under normal operating conditions. Extreme loading events, material nonlinearities, and failure mechanisms are excluded to maintain focus on vibration performance relevant to everyday use. By adopting this targeted approach, the study aims to provide practical insights and design-oriented guidance that enhance the comfort and confidence of occupants while supporting efficient and reliable structural design.

3. ANALYTICAL MODELING

3.1 Introduction to Analytical Modeling

Analytical modeling serves as the key-point in structural vibration analysis. It works for that theoretical mechanics bridge to real world engineering and helps provide insights into how structures respond to dynamic loading such as human induced activities.While with sophisticated numerical computation technologies, able for advanced numerical simulations, the method of analytical modeling is crucial because it emphasizes the clarity of mathematical formulation, conceptual understanding, and answers in a closed form that gives insights in both conceptual design and engineering education. The essential purpose of analytical modeling is to

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establish a simplified mathematical representation of the difficult structural systems. Mostly they are models with idealized assumptions like linear material behavior, mass concentrated on one point, or simplified support conditions to gain the use of established dynamics and mechanics principles. For instance, the well-known Equation of Motions read mx(t)+c x(t)+k x(t)=F(t) It portrays the dynamic behavior of a vibrating system with a mass m, damping c, stiffness k, and a changing force F(t) with time. Still, such a simple equation marks the basis for understanding a vast capacity of responses, from a gymnasium floor with minimal vibration to extreme sway of a footbridge. One of the biggest contributions from the analytical model are correlations between physical parameters and structure behavior.Mathematical modeling is very important today for understanding and predicting the vibratory behavior of structures, especially at the preliminary stages of design. It will enable engineers to easily determine the displacement, acceleration, and natural frequency responses of a structure using mathematical relationships with parameters such as mass stiffness and damping. These simplified designs provide benchmarks to develop more complex numerical simulations. Numerical methods such as the finite element analysis may give an exhaustive answer to design simulations. Still because of their extensive computations and their sensitivity to the mesh density and solver settings analytical models are excellent means to cross check simulation results and therefore increase the confidence level in design decisions. In those cases when snap decisions must be made such as in selecting materials or defining the geometry of a structure-analytical means give instant responses. For example if a floor system has a natural frequency of around 2-3 Hz and is close to the typical one associated with human activities, then the engineer probably would select a stiffer beam with good damping without making extensive simulations. analytical models also assist in educational purposes, giving an immediate intuitive sense

of dynamic behavior among engineers. This is a very important value for performance analyses of

structures with respect to the human occupant-induced vibrations. Analytical models serve the purpose of being the first line of attack to determine any possible resonance conditions or extreme motions early in the design process, in applications where vibration comfort is of utmost importance footbridges steps in a stadium, or open flooring. The more complex the architectural design becomes, the more critical it turns out to maintain a link to these very basic principles about which engineers can stand secure in the knowledge of the physics involved in reality, which governs structural behavior. Overview of the Equation of Motion. In the study of structural vibrations, the Equation of Motion is the fundamental mathematical formula that determines how structures respond to time varying forces. Whether a person is strolling on a footbridge, bouncing on a gym floor, or dancing in a stadium crowd, their activities generate dynamic loads that interact with the structural system. These interactions are best understood through the ideas of vibration dynamics, where the equation of motion provides the foundation for both theoretical insight and practical design decisions. The general form of the second order differential equation applied in structural dynamics is mx(t)+cx(t)+kx(t)=F(t) Imagine a simple structural element like a suspended beam or bridge modeled as a mass spring damper system. When an external dynamic force is applied, the structure: First opposes motion due to its inertia, Then loses energy due to internal and material friction And ultimately, seeks to return to its prior position due to elasticity or restoring force. The combination of these three forces must equal the applied external load F(t), leading to the complete dynamic equilibrium given in the equation. This intuitive yet mathematically straightforward relationship allows engineers to define, anticipate, and regulate the structural response to a wide range of time dependent demands.

The relevance of this equation in civil engineering cannot be overstated. Whether engineers are analyzing a footbridge, an office floor, or a stadium stand, this equation enables them to, Predict natural frequencies and avoid resonance, Estimate maximum displacement or acceleration under a given load, Evaluate whether vibrations will remain within acceptable comfort thresholds. For example, if a footbridge has a natural frequency close to the pace of pedestrian footsteps, engineers can immediately use this equation to simulate the resulting motion and determine whether additional damping or stiffness is needed. Similarly, in a gymnasium, the same formula helps assess whether synchronized jumping will cause the floor to amplify motion in a way that feels unstable.Even in more complex

scenarios involving MDOF systems, the same principles apply, though the equation is expanded into matrix form. Still, the heart of the dynamic analysis remains rooted in this single expression, making it one of the most powerful tools in the engineer's toolkit.

Although the equation of motion is a mathematical calculation, its ramifications are profoundly human. When the vibration response is not effectively regulated, it can contribute to discomfort, distraction, and loss of confidence even in structures that are technically safe. Therefore, comprehending this equation is not merely a theoretical necessity but a practical, ethical obligation. By applying it efficiently, engineers can build settings that move with life, but never against comfort. It is this delicate balance between flexibility and stability, reaction and resistance, that makes the Equation of Motion important to this thesis and to every structure where human interaction and motion matter.

3.2 Free Vibration Analysis

In vibration engineering, the simplest and most fundamental situation of structural motion is the scenario of free vibration, when the structure is sent into motion and then allowed to vibrate without any continuing external force. This case is described quantitatively by setting the applied load to zero: F(t)=0 Thus, the Equation of Motion reduces to: mx(t)+cx(t)+kx(t)=0 This form represents the normal behavior of the system it shows us how the structure wants to move on its own, depending simply on its intrinsic properties: mass (m), stiffness (k), and damping (c). Free vibration analysis is particularly useful in early design and diagnostics because it helps engineers to estimate natural frequencies, identify resonance concerns, and understand how energy dissipates over time owing to damping.

International Journal of Engineering Research & Technology (IJERT)
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Footbridges are among the most widely referenced structures in vibration research because they are slender, lightweight, and frequently subjected to rhythmic pedestrian activity. Their behavior under human loading is commonly modeled using a Single Degree of Freedom (SDOF) approach to analyze the first mode of vibration, which is often the primary contributor to vertical motion. In early-stage analysis, a vertical SDOF model is formulated as mx(t)+cx(t)+kx(t)=F0sin(2πft) Lateral motion has become a significant concern after the Millennium Bridge incident in London, where lateral synchrony among people led to unanticipated swaying. For lateral analysis, engineers employ similar models but account for decreased lateral stiffness and the potential for human synchronization, commonly modeled by a lateral force component applied at walking frequency Vertical displacement and acceleration, which affect comfort. Natural frequency, which must be designed to avoid matching regular walking or jogging patterns.Resonance circumstances, where modest rhythmic pressures can lead to huge amplitude responses.These models offer the initial estimations that inform whether more complex finite element or field measurements are necessary.

Floor systems, particularly in modern open plan buildings, are increasingly versatile due to the desire for broad spans, few columns, and lightweight construction. In gymnasiums, fitness studios, or event spaces, these floors are exposed to synchronized activity, such as jumping or running, which results to vertical vibration that can be uncomfortable or even alarming. A popular analytical approach is to represent the floor as a simply supported beam under dynamic loading. For example w(x,t)=n=1∑∞ϕn(x)qn(t) Where: ϕn(x) is the nth mode shape of the beam, qn(t) is the time dependent modal coordinate (response amplitude), Human forces are applied as periodic functions: F(t)=F0sin(2πft) In analytical terms, we often reduce the system to an equivalent SDOF oscillator in the vertical direction, particularly when only the fundamental mode contributes significantly to motion.

Different structural systems have different responses to the human-induced vibrations. They all demand different analytical models about how they will behave in real conditions. Footbridges are slender, lightweight structures and are known to be immensely susceptible to vibrations caused by pedestrian activities, such as walking, jogging, or synchronous movements. Engineers make use of single-degree-of-freedom (SDOF) models for doing these initial assessments fast for vertical or lateral responses, to assess potential for discomfort or instability, as in the example of the Millennium Bridge in London. Real residential floor systems, such as those in open-plan offices or gyms, have different problems. These expansive, flexible floors sit atop minimum column supports for open- space advantages and yield some very different-seeming vertical vibrations as they are made to absorb and impinge the kinetic energy caused by such activities as walking or jumping. So, modeling them as beams or slabs with end supports by engineers, performing elementary calculations to see whether vibrations will affect user comfort or not. In cases where synchronized movement occurs in most gym-like set-ups or in a studio, further amplification of floor effects is assured, and hence, important vibration predictions will be necessary. Stadium structures indeed add to that complexity more, being multi-tiered constructions that can all have huge crowds attending and all moving as one. Such scenarios hence can lead to vertical and lateral movement sways, especially with collective actions such as cheering or jumping. An analytical model for a stadium will also necessarily cover many interacting components and therefore require MDOF systems for proper predictions of different responses for different sections and the locations of concern in building vibration without compromising structural integrity. While none of these analytical models will catch all the details, they are extremely useful tools for the early hazard watch, guiding decisions in design, and ensuring that those designs will not just be stable, but provide a safety feeling for their users.

3.4 Human Loading Models

It is just as important in the discipline of structural vibration analysis to accurately model how humans apply forces to a structure as it is to model the structure itself. Although human movement can not be random, it can be rhythmic, patterned, and somewhat predictable depending on the task. Whether someone is walking on a footbridge, jogging on a floor slab, or jumping in a crowded stadium, they are creating dynamic forces on the move, and these are time-varying forces that are going to be able to interact with the natural impulses of the structure to move. Engineers refer to these conditions as human loading models. These patterns are surprisingly constant, which is why walking-induced vibrations can be reasonably accurately anticipated. if you transfer the same situation to jumping or sprinting, it gets more complicated: the forces are sharper, stronger, and often more synchronized, for example, in fitness classes, concerts, or sports stadiums, where lots of people move together. In a synchronized way, the so called resonance occurs in which the frequency of human motions corresponds with that of the structure loves to vibrate. In those cases, even minute recurrent loads could easily cause the structure to sway or bounce in ways that are perceptively sensed by the users. To get an accurate estimation of these forces, most engineers refer to motion profiles generated from actual world data. This profiles how load varies with time and how and where the load is distributed through the structure. For instance, an individual's jump in a gym floor scenario might appear minor but dozens of people jumping simultaneously make it a dominating force acting on the entire floor system. Such models of human loading are significant because they serve to concrete some ethereal quality such as movement into solid entry for technical studies. With these models, one can simulate the actual way people behave in spaces, and even help engineers answer questions such as: Will this floor feel bouncy; will this footbridge sway uncomfortably when used by a crowd; and can this stadium tier manage the energy of 5,000 supporters jumping in unison without provoking dread or anxiety? It is not just the numbers generated that give such models significance but the capacity they offer to drive safer, smarter, and more humane design decisions.. When engineers employ human loading models early in the design process, they may proactively change the structure to manage those forces either by changing materials, adding stiffness, or inserting damping features that absorb energy.

International Journal of Engineering Research & Technology (IJERT)
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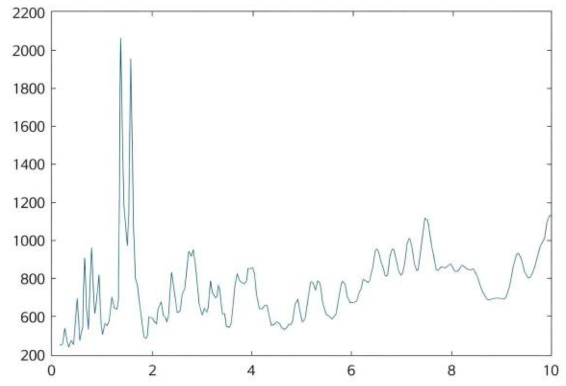

Figure 4: Time History of Individual Walking Load

The image above displays a time history plot of an individual walking load which shows how the force exerted by a person walking varies over a period of 10 seconds. The x-axis represents time in seconds, while the y-axis represents the magnitude of the walking load, likely measured in Newtons. The plot reveals significant fluctuations in the load with prominent peaks occurring around 1.5 to 2 seconds, indicating moments of higher force application, possibly corresponding to heel strikes during walking. After these peaks, the load demonstrates periodic variations reflecting the repetitive nature of human gait. This type of plot is essential for analyzing how walking loads change over time and is commonly used as input data for structural vibration and response spectrum analyses.The image above displays a time history plot of an individual walking load, which shows how the force exerted by a person walking varies over a period of 10 seconds1. The x-axis represents time in seconds, while the y-axis represents the magnitude of the walking load, likely measured in Newtons. The plot reveals significant fluctuations in the load,with prominent peaks occurring around 1.5 to 2 seconds, indicating moments of higher force application, possibly corresponding to heel strikes during walking. After these peaks the load demonstrates periodic variations, reflecting the repetitive nature of human gait. This type of plot is essential for analyzing how walking loads change over time and is commonly used as input data for structural vibration and response spectrum analyses.

3.5 Comparison of Analytical Models

Appropriate analytical modeling selection is paramount in structural vibration analysis. SDOF models stand out because of their simplicity and speed and thus can be incorporated in such an early assessment on structures like footbridges or isolated floor sections. Such a

model typically provides a reasonable notion of the fundamental frequency and acceleration responses of the structure. SDOF results tend to average out the responses of the structure, thus ignoring local issues. Multi-degrees of freedom (MDOF) models become essential for more complex structures. The structure is modeled as an assembly of interlinked masses for the performance of relative movement analysis between separations within a structure. This way, localized vibrations and phase differences that single degree of freedom methods might overlook are captured. In addition, MDOF models are capable of generating highly resolved analysis concerning the distribution of mass, stiffness, and damping effects along the structure to assess how alterations in such parameters are reflected on the dynamic responses of the structure.The decision on the SDOF or MDOF modeling depends primarily on the complexity of the structure and the objectives pursued in the analysis. According to the professionals, they often adopt the SDOF structure-first approach for better preliminary results and end up using MDOF structure models for an exhaustive analysis of the dynamic behavior thereby serving both purposes.

4. COMPUTATIONAL SIMULATION

4.1 Introduction to Computational Simulation

In structural vibration research, computational modeling serves a significant and increasingly indispensable function. While analytical models help us grasp the theoretical underpinning of how structures respond to forces they often rely on simplifications that don’t necessarily reflect the messiness and unpredictability of the real world. Simulation helps us to move beyond these restrictions and study how a building will genuinely respond when faced to time varying, human produced pressures. It enables engineers to experiment with a wide range of situations modifying the mass, the stiffness, the type of human activity, or the shape of the building all in a controlled, virtual environment before anything is created or modified in the real world.Computational simulation is the one connecting term between mathematics and experience. It is then possible for an engineer to envisage not only numbers but motion: through a footbridge swaying with rhythmic steps a gym floor responding to a jumping class, an exhibit stand vibrating under the combined energy of applauding spectators. These are not merely academic curiosities but are actual cases where comfort safety and public confidence are at stake. With simulation we can emulate structures, visualize forces and even eavesdrop on the stories that those structures are attempting to tell us, which mathematics alone may not provide. Thus, this thesis principally uses Python and MATLAB as the main.simulation tools because they offer flexibility and visibility. Python, with its open source libraries, is ideally suited for dynamic model development, parametric experimentation, and clearly visual results delivery. It enables us to design and customize simulations in a way that it is accessible and adaptive, particularly in academic institutions. MATLAB, on the other hand, encompasses strong central functions for numerical integration, system modeling, and data ostentation. Its strength rests on its engineering orientation, rendering it superior for the simulation of dynamic systems with variable inputs and outputs. This thesis, therefore, merges flexibility with accuracy. Components were collected to prepare individuals for experimenting mindfully, while being able to depend on outcomes. Within that context of computer simulation, it totally does not concern replacing physical testing or theoretical analysis; it is all about completing the picture. It allows the room to explore test the impact of architectural changes, and predict how comfortable or not someone would feel in a new project before any construction actually occurs. It even gives assurance that when a person

International Journal of Engineering Research & Technology (IJERT)
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Vol. 15 Issue 02 , February - 2026

walks, jumps, or dances on a floor or bridge, the motion they are feeling is intentional, not accidental.

The act of simulating real world human behaviour on structures is more than running software it is a process of emulating real life structural responses to human activities. This thesis documents a workflow that involves setting up a model applying loads inputting parameters running numerical integration and interpreting results.This process starts with the definition of any physical structure a floor a bridge a stadium by combining simplified elements to model most essential aspects of dynamic behaviors with high efficiency. Specific structural parameters for mass, stiffness, and damping tell how the object should translate when in movement: these elements help in obtaining a structures response towards an input movement.Modeling activities of load induced by human beings, such as going or jumping by functions dependent on time so that these will shadow forming attacks in real life. Such inputs are necessary in simulating the structure behavior's dynamic activities.Methods of numerically integrating determine the structural response over time using a means like Python and MATLAB. These are also quite flexible and rich in libraries that deal with complex simulations.Simulation results, such as displacements, accelerations, and time histories, are all finally subject to the analysis for structural performance evaluation and comfort levels of the human occupant. This ensures that practical measures are taken on how structures behave under human induced vibrations.This holistic approach, with a broad understanding of the application of engineering and human considerations, creates possibilities for structures that are safe and comfortable

4.2 Model Setup for Structural Components

This is important because accurate modeling of structural components can provide a valid analysis of dynamic human loads. The thrust of this thesis is modeling structures like footbridges floor systems and stadiums which have unique vibration characteristics for efficiency and realism in digital representations.For footbridges models are primarily flexible spans defined at both ends allowing vertical and lateral movements. Important dynamic characteristics such as swaying and bouncing are aimed to be represented without going into detail of every structural element so that computation will be efficient yet the essential behaviors are captured.Floor systems are to be modeled with extensive slab or beam networks, as are found in gyms or open plan offices such systems accommodate dispersed loading with localized vibrations. Simulated activity zones and boundary conditions are varied to study comfort levels for different sections of floor.Stadium structures must create several complexities in their modeling. Due to their erecting height and crowd dynamics, the seat zones are partitioned into extensive and interconnected areas that respond to the dynamic load differently. Internal partitioning should be taken into account besides the correct mass distribution and boundary conditions, especially in cases where cantilever sections can sway differently.All models consider the support conditions fixed roller or partly constrained joints.These support conditions significantly affect the energy transmission and structural response. The digital twin serves as the test ground where engineers predict the behavior of a structure and the impact on its occupants due to different loading scenarios well before the actual implementation occurs.

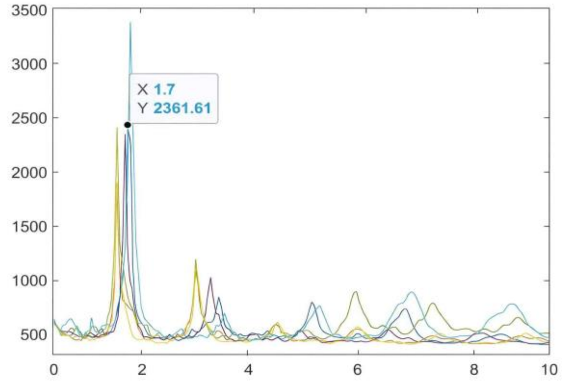

Figure 5: Peak Dynamic Response Spectrum of Individual Walking Load

Figure 5 illustrates the response spectrum of an individual walking load, as obtained from

MATLAB simulations. The x-axis represents time (in seconds), while the y-axis shows the

magnitude of the dynamic response which could be displacement, acceleration, or force depending on the context of the analysis. Each colored line in the plot corresponds to the peak response of a single degree of freedom (SDOF) system with a different natural frequency or damping ratio, subjected to the same walking load input.The most prominent feature in the plot is a sharp peak at approximately 1.7 seconds, where the response magnitude reaches as high as 2361.61 units. This peak indicates a moment of resonance or maximum dynamic amplification, likely caused by the synchronization of the walking load frequency with the natural frequency of one of the SDOF systems. After this peak the response values decrease but continue to exhibit smaller oscillations, reflecting the periodic nature of the walking excitation and the varying dynamic characteristics of the SDOF systems. This response spectrum is crucial for understanding how different structural systems might react to walking induced vibrations. High peaks in the spectrum highlight critical frequencies where the structure is more susceptible to large dynamic responses, which is essential information for safe and comfortable structural design.

4.3 Implementing Human Induced Dynamic Loads

Effectively simulating the structural vibrations is to precisely converting human activities walking running jumping into dynamic load patterns specifying their time and intensity variation. The forces induced by such activities are rhythmic and fluctuating but not static on this basis one simulates use of time varying load functions which describe the developing and weakening forces related to use of a structure by a human.Walking has repetitive vertical impacts running creates sharp quick forces. Group activities such as synchronized jumping can synchronize body movements within a group to manifest the effect more intensively causing responses that amplify structural response. The synchronization of load input often creates huge vibrations compared with single

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

actions.The Dynamic Load Factor (DLF) is employed to scale up or down the intensity of loads in relation to activities and crowds. A single person will apply some minimum load due to his/her movement, but synchronized group action can produce much higher loads since their rhythm is common to the natural frequency of the structure.The simulation employs time-stepping simulations such as a small increment of time, at each new human pulse, when modeling reaction in the structure. The difference between transient response such as a bounce and steady state vibrations from continuous activity is thus made clear.It is more in applying 'force' for simulation in integrating human induced

dynamic loads than that it is in getting well the energy and rhythm of the movement of real human behavior and seeing how that energy interacts with structural materials. The very process allows engineers not just to forecast structural performance, but also human comfort and experience.

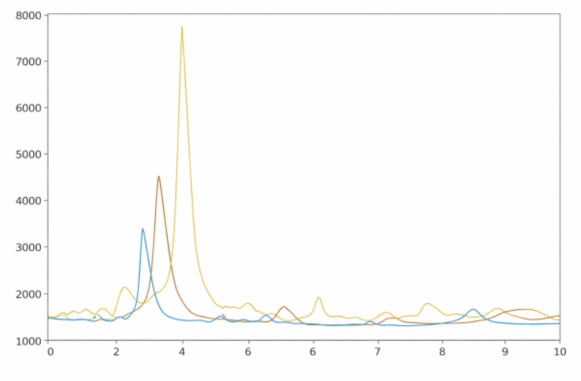

Figure 6: Time History of Maximum Response to Individual Walking Load

4.4 Solving the Equation of Motion Numerically

The human induced loading would be modeled first followed by numerical integration to simulate the temporal response of the system. The effects of such loading to induce motion within the structure, such as walking or jumping, translate into a time theory whereby movement evolves and decays-a very important stage for evaluating human comfort and operational safety for the structure.The numerical solvers discrete the time domain into very small intervals in order to compute the position velocity and acceleration of the structure in each time step. This procedure takes reservation of the time-sequenced nature of human activities and the cumulative impact that they induce on structures. The accuracy and efficiency of the whole simulation are considerably affected by choice of solvers. Some solvers are faster but may yield false results in complex models while others provide better stability at enhanced costs. The flexibility of numerical methods is one of its main benefits. Load patterns damping conditions or material properties can be modified without redoing the entire model by simply changing parameters of interest for quick assessments of different scenarios. numerical time integration offers information about human activities acting on structures, thus helping engineers get to a point of designing spaces that are comfortable and safe under dynamic

considerations.

4.6 Output Interpretation and Visualization

Results interpretation is crucial at the end of a vibration simulation. Raw data such as displacements velocities and response time histories becomes valuable upon being analyzed and transformed into real world intended use. This phase connects abstracted movements to real world meaning.Displacement over time forms the main thrust. It identifies how far and how long a structure moves under a given load. While movement is anticipated oscillations that last for a little too long can prove discomforting to the user. Such motion histories are clear graphical presentations evaluated not on amplitude only but also on the effect of perceived stability.Acceleration data too is very important given that humankind would be more sensitive to rapid than large slow movements. Small sudden vibrations might seem quite unsettling compared to larger albeit steady ones. Thus to be evaluated become frequency and peak acceleration with reference to comfort thresholds defined by building regulations and those deriving from human reaction studies. The vibrations from typical rhythmic loads may intensify during simulation for instance synchronized jumping wherein resonance is suspected. Animated plots and color maps are visualization tools that help identify all these conditions and subsequently help improve designs. Engineer Latest.one may simulate a basic footbridge and a footbridge that now has damping or has other modifications to support. In that comparison, it can now easily spell out how by design the expected differences are seen by the output data and visualization. What output means is connecting actually humanizing those digital simulations in terms of experience. Meaning vibration is no longer a figure but also a tangible perception to look forward to and improve on.

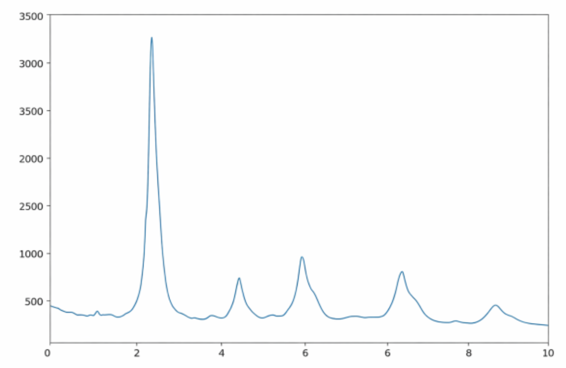

Figure 7: Amplification of Structural Response from Pedestrian Walking Load

Sensitivity analysis is an important element in the simulation process because it helps us understand how slight changes in a structure’s attributes can lead to major alterations in how it performs under real world settings. In the context of human caused vibrations, this is especially essential because the border between comfortable and uncomfortable can be extremely thin. A structure that feels strong with one group of users could feel unstable when another group with slightly different timing or weight enters the room. Sensitivity analysis gives engineers the tools to anticipate these transitions and design with a deeper level of confidence.sensitivity analysis

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

entails methodically modifying important structural characteristics like as stiffness damping, and mass and evaluating how such changes affect the structure's dynamic response. The technique doesn't try to create a single optimal design but instead analyzes how adaptable or fragile the system is to variation. For instance, increasing stiffness may reduce displacement but also enhance the system's inherent frequency, putting it closer to the rhythm of walking or jumping. Likewise, increasing damping can assist absorb energy more effectively, but too much damping could damage structural responsiveness or increase material costs. Sensitivity analysis allows us to assess these trade offs in a controlled, virtual setting, long before any changes are made to a real structure.This strategy is particularly effective when dealing with different loading circumstances. A floor planned for routine office use may need to accommodate unforeseen events, like a group meeting or a temporary fitness class. A stadium intended for regular match day conditions could respond differently during a concert where dancing and jumping are common. Through simulation, the model is exposed to varying crowd sizes, loading rhythms, and motion intensities. By altering factors one at a time or in combination engineers can assess how near the structure is to crossing a threshold where comfort changes into concern.sensitivity analysis also helps uncover crucial zones within the structural locations that are especially vulnerable to dynamic changes. In a large gym, it can be the central span that's most prone to bouncing. In a stadium, it could be the higher tiers that wobble most under synchronized cheering. Recognizing these zones allows engineers to focus reinforcements or dampening solutions where they will have the most impact, rather than applying costly design changes uniformly over the entire structure. Another benefit of this strategy is that it makes design decisions more transparent. When discussing changes with architects, clients, or other engineers, the study can be presented visually, showing exactly how alternative design adjustments improve or decrease vibration performance. This makes the design process more collaborative and evidence driven, which is especially helpful in large projects involving several

Verification and comparison are critical final steps in simulation that account for the nearness of a digital model to the reality of structural behavior. The simulation is credible when its results can be aligned to analytical theory published research work and observed data being the start point when the results are compared to earlier analytical model solutions.While a perfect match is never expected due to complexities in the physical world alignment in trends provides confidence in the simulations predictions. Moving beyond analytical comparisons, results of simulation are examined against real world measurements taken from published case studies on footbridge floors and stadiums. This introduces uncertainties in user behavior and variability in materials things that may not appear in the theoretical modeling. If the simulations obtain responses correlating with real life ones then this validates the simulations as reliable and applicable to future scenarios.Considering various changes within the same model say changing damping or dividing groups shows how sensitive structures are to changes. These internal comparisons lead to making design decisions indicating where most reinforcement or damping is needed. it is verification and comparison that make the simulations into reliable tools for decision making. They join the world of digital experimentation with that of practice, ensuring that engineering ideas maintain an underlying mathematically sound logic along with operationally practical meaning.

While the simulations of this thesis do provide insights into human induced structural vibrations it must be borne in mind that such studies have their limitations. They offer models to replicate situations which despite being well conceptualized use idealized inputs and defined boundary conditions to simplify reality. Such simplifications may not include localized effects like joint flexibility or construction imperfections which tend to control the vibration behavior. they have generalized damping values apart from material properties which will dynamically vary while in service because of wear temperature or

level of occupancy.human loading remains a challenge. Time varying load functions for human activities such as walking or jumping are included but are average behavior functions. In fact human movement shows a high degree of variability and randomization depending on person group and environmental influences. Besides most models ignore that part of the feedback loop which lets structural vibrations determine human behavior in turn, changing the load patterns induced by these people.For model fidelity improvement future research can integrate detailed finite element methods nonlinearities and material heterogeneity. Real time sensor feedback and motion capture data from real human subjects will definitely lead to load profiles which are more dynamic and personalized. The gap between engineering measurements and human experience may be bridged by incorporating user feedback in simulations through perceived vibration surveys.A statement of limitations, if made can bring out the potential for further insight and brighter design, and ultimately lead to structures that can adjust better to human interaction and comfort.

5. EXPERIMENTAL VALIDATION AND CASE STUDIES

5.1 Introduction to Experimental Validation

Experimental validation is the ultimate and most critical reality check in the process of structural vibration analysis. While analytical and simulation models allow us to forecast how a building should respond under human activity, real reality often has its own designs.People don't move exactly as we expect, materials don't behave flawlessly, and structures respond in subtle ways that can't always be expressed in code. That's why testing those models against real world behavior is not just good practice it's critically vital. It's where engineering theory meets living experience, and where we find out whether our designs truly operate under the footfall, cheers, and motions of ordinary life. The fundamental goal of validation is to examine how well the predicted reactions coincide with what really happens in physical structures. This could be as basic as measuring how much a floor deflects during a leaping exercise, or as complex as detecting the lateral sway of a stadium tier during a synchronized chant

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

from thousands of people. These measurements help engineers to enhance their models, rectify overly simple assumptions, and reveal aspects of vibration behavior that may have been overlooked entirely. Without this real-world feedback loop, even the most thorough simulation runs the risk of being theoretical accurate in statistics, perhaps, but divorced from how humans actually experience space.What makes experimental validation especially significant in vibration analysis is that it tackles not just structural performance, but human perception. A floor might move only slightly but still feel uneasy. A bridge could meet every safety standard but wobble in a way that discourages use. These experiences can't be fully understood without measuring actual vibrations and comparing them with what people feel. By collecting motion data under real loading situations such as walking, jumping, or crowd movement engineers can comprehend how the structure behaves moment by moment, and how that motion could affect trust, comfort, and usage.Field measurements assist bridge the gap between theory and practice. They anchor abstract ideas like damping ratios and natural frequencies in the tactile reality of bolts, beams, footfall, and crowds. When models are confirmed by data obtained from real structures, the confidence in their predictive potential grows. When disparities develop, they become chances to learn and improve. Experimental validation is not simply a tool for showing something is proper it's a tool for growth, insight, and evolution in the design process. In this thesis, experimental validation is used not as a final stamp, but as a living feedback system. It directs the improvement of models, provides a greater knowledge of how different structures function, and integrates the digital with the physical.

Ultimately, the purpose of our effort isn't only to imitate vibration it's to comprehend it as humans feel it, in actual buildings, under real settings, with real effects. That comprehension can only occur when we move away from the screen, into the space, and listen intently to what the building is telling us.

5.3 Field Study Setup

Setting up a field study for vibration measurement is not simply a technical task, it's a logistical and strategic operation that requires careful attention to detail. Before a single sensor is put, engineers must completely understand the structure in question, how it is utilized by people, when it is most active, and where its weaknesses can lie. The setup is the bridge between theoretical curiosity and practical insight. In this thesis, field investigations were planned to capture the actual world behavior of three important structural types a lightweight footbridge, an open plan floor in a gym like atmosphere, and a section of stadium seating during live movement. Each brought its own unique issues, and each necessitated a distinct technique for capturing motion in a way that was accurate, relevant, and non disruptive to users.For the footbridge investigation, the setup began by identifying parts most susceptible to vibration often the mid-span, where bending and displacement are greatest. Accelerometers were positioned at this area, as well as near the supports, to compare how energy traveled across the structure. The studies were scheduled during periods of mild to moderate pedestrian flow, allowing a balance between controlled and natural movement. Volunteers were also instructed to walk, jog, or pause in position to examine how each form of movement altered the bridge's behavior. The structure's environment such as wind conditions, temperature, and surface materials was also noted, since even modest external influences might influence vibration.In the floor system scenario, the arrangement required to imitate genuine conditions of a gym or flexible workspace. Portable vibration sensors were put in the center of the span, as well as near known high use regions like treadmill zones or free weight parts. One test comprised synchronized hopping by a small group, designed to replicate group fitness activity, while

another captured the uneven footfalls of persons leisurely wandering around. The building's own sound system was employed to coordinate timing, ensuring that the movement patterns had enough rhythm and repetition to activate the floor's natural modes. Because floor vibration is often quite mild, particularly in vertical direction, the sensitivity and sample rate of the sensors have to be properly tuned to detect low-amplitude, high frequency signals.The stadium construction offered a far more challenging challenge. Here, the arrangement was coordinated to coincide with a controlled event with a medium-sized group exhibiting crowd behavior cheering, applauding, and bouncing in rhythm. Vibration sensors were put along the risers and beam connections of the seating structure, notably in the higher levels, which tend to endure the highest dynamic amplification. Capturing genuine motion in such a huge and linked structure required that several sensors had to work in coordination to track phase shifts and sway. Crowd management, safety, and timing were important. Unlike the footbridge or floor, the stadium setting introduced additional environmental noise people chatting, moving weight, entering and exiting which made data filtering and post-processing extremely crucial. Across all three sites, setting up the field study entailed balancing realism with measurement precision. It included not just deploying equipment, but anticipating human behavior, coordinating volunteers, adapting to site limits, and ensuring the test would not interfere with the structure's routine use. Cables had to be secured, power supplies checked, data recorders synchronized, and safety procedures followed properly. Often, the biggest problem wasn't the technology it was the unpredictability of real people moving through real settings in real time.But that's precisely what makes field study so valuable. It captures reality as it is not as we assume it to be. It exposes how buildings genuinely respond to life, and how minor structural motions may influence how people feel about the spaces they occupy.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

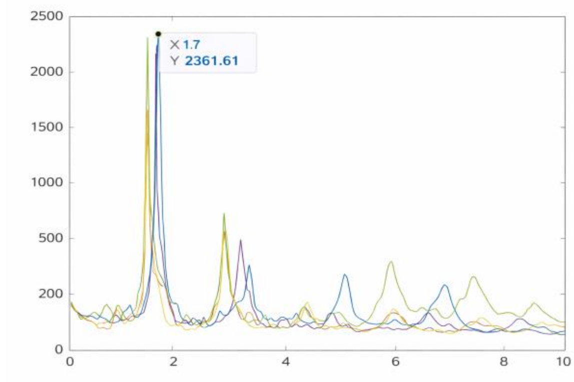

Figure 8: Structural Response Spectrum Due to Walking Load

5.4 Data Collection and Measurement Strategy

Measuring the vibrations accurately in real life conditions demands more than just switching on the sensors. It essentially requires a careful plan to record the subtle nuances between human activity and structural response. In this research study the measurement method has been designed keeping in mind that the data should not be representative only from a technical aspect but also in terms of how people meaningfully interact with built environments.A major consideration was in the sampling frequency. Walking or jumping tends to generate human-induced vibration measurements somewhere within the 1 to 10 Hz range. To record these motions high resolution data logging was established to identify fast changes and extremely transient peaks such as those caused by a loud stomp or synchronized group movements.

Figure 9: Crowd-Induced Vibrations in Stadium Stands During Synchronized Cheering

This was critical because stadium environments tended to have quick intense spikes in vibration during activities where groups were involved. Duration was equally vital. Measures extended well beyond a snapshot, allowing immediate reactions and long term effects to be captured. after people stopped jumping or cheering in a group, data would still be collected regarding how long it takes for a structure to stabilize because this would reflect damping characteristics and real time comfort levels. Such longer measurement duration also captured natural fluctuations, such as differences in the distribution of foot traffic or slight de-synchronizations within groups which reflect realistic usage patterns.Incorporate varied activity scenarios that represent authentic use. Single walking subjects established a low-amplitude baseline group walking subjects added coordination effects and individual and cluster jumping created relatively high and dynamic impact patterns. A few short spurts of running or stomping would mimic sudden changes due to loads. All such exercises would also be safe consensual and repeatable. All the activities would be thoroughly documented to correlate sensor data with the activity itself. Environmental and contextual factors were assiduously recorded to accompany the field measurements. Temperature humidity time of day occupancy ambient noise all of these variables might exert some influence on the behavior of the structure and more importantly, on humans perception. A bridge would behave differently on a hot afternoon compared to a cool morning and a gym floor somehow develops a different feel according to what happens elsewhere in the building. All of these observations enriched the dataset with a much broader view of the testing environment.Human observation forms part of the measurement process. In addition to technical data brief informal interviews captured first hand users subjective experience whether or not they felt the floor vibrations or if they felt different with more people. Though not quantified as formal data these subjective insights were valuable in contextualizing numerical results with human perception that types of

structures resonate with users' comfort and confidence rather than merely meeting technical standards.

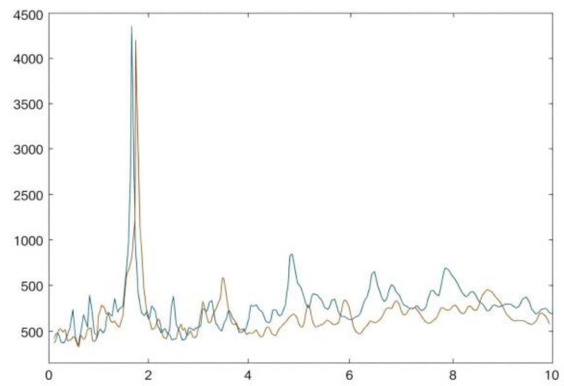

Figure 10: Resonant Peak in Structural Response Spectrum Due to Walking Load

5.6 Comparison with Simulation Results

A footbridge within a university campus made of lightweight steel construction and pretty much predominantly used for pedestrian purposes by students and faculties was selected for vibration study due to complaints of a slight shudder at peak usage times. To evaluate this high sensitivity accelerometers were mounted at mid-span and near the supports to record the motion suffered under different pedestrian activities like solitary walking group crossings and controlled walking and jogging tests.during light-use conditions, the acceleration and the displacement of the bridge were within acceptable comfort levels while paired with synchronized group movements there were noticeable lateral movements and vertical oscillations. Even if these oscillations are structurally safe they changed pedestrian behaviors who subconsciously adjusted their gait to

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

reduce discomfort. Although there was good correspondence between empirical data and simulated models in terms of frequency and amplitude behaviour the models did not include the adaptability of pedestrians' response to movement of the bridge thus revealing lack of consideration in the current simulation approaches concerning the feedback loop between human behaviour with structural response.The conclusions of the research were that the bridge is indeed structurally safe under normal conditions but can further improve users' comfort during heavy pedestrian congestion by the incorporation of some damping devices which could prove to include tuned mass dampers.the study emphasized the importance of including human behavior adaptations into vibration modeling so that prediction and remedial measures of comfort issues become more accurate in the pedestrian bridge design process.

5.7 Case Study : Lightweight Footbridge Vibration

A slender pedestrian footbridge located within the corridor of a university campus primarily recognized for its lightweight steel construction is subjected to frequent foot traffic by students and faculty alike. Despite passing structural safety tests users claimed that discomfort inducing sensation due to vibration is mostly felt during peak traffic periods. Hence the need to investigate the bridge vibration characteristics. High-sensitivity accelerometers were installed at mid-span and near the supports to capture motion data when pedestrians performed various activities such as solitary walking group crossings

and jogging or walking through controlled tests. According to data collected the acceleration and displacement of the bridge are within comfort limits during light use but noticeable lateral sway and vertical oscillations were observed during synchronized group movements. Although those vibrations were not dangerous for any structure they interfered with human behavior with pedestrians constantly instinctively changing their gait to reduce their feeling of discomfort. Some models matched fairly well in terms of frequency and amplitude of vibrations with the experimental data.they completely neglected the adaptive responses of pedestrians to the vibrations of the bridge. This has shown a limitation in current simulation approaches that do not provide for feedback between human behavior and structural response.The study concludes that while the bridge is safe in an engineering sense adding additional damping including tuned mass dampers will improve comfort for users during high pedestrian flow periods. Furthermore, the necessity of including human behavioral adaptations in vibration modeling was emphasized to predict and deal with comfort problems in pedestrian bridge design more reliably.

6. DIGN RECOMMENDATIONS

6.1 Introduction to Design Guidance

This chapter provides design guidance for engineers based on analytical, computational, and experimental findings of this study. It emphasizes that addressing human-induced vibrations requires not only technical accuracy but also consideration of human comfort and perception from the early stages of design. Although structures may satisfy safety requirements, vibration-related discomfort can still occur, highlighting the need for a proactive design approach.

The chapter presents tailored recommendations for structures prone to vibration issues, including footbridges, gym floors, and stadium stands, acknowledging their distinct dynamic characteristics. Rather than promoting a one-size-fits-all solution, the guidelines encourage adaptable, evidence-based strategies supported by simulation and empirical research. The ultimate aim is to bridge the gap between research and practice, enhancing user comfort, confidence, and trust in built environments.

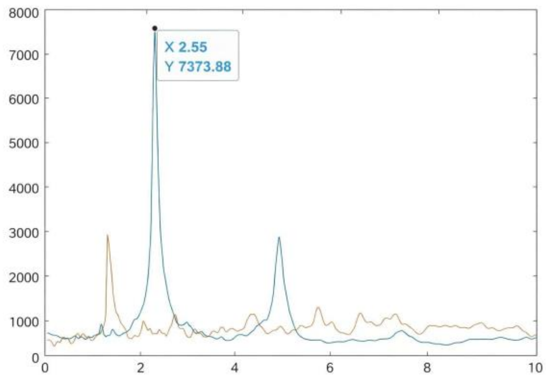

Figure 11: Transient Response Spectrum of Structure Subjected to Walking Load

6.2 Guidelines for Footbridge Design

Design pedestrian bridges that are not only functional and attractive but also comfortable and reassuring for users. Footbridges often face vibration issues not due to structural failure, but because people feel the motion. Even lightweight bridges that meet code can visibly bounce or sway especially when people walk in sync or in crowds. While these movements may be safe they can reduce public confidence discourage use and harm the bridge’s reputation over time.To prevent this vibration control must be a core part of footbridge design focusing on user comfort and psychological safety from the start. Key decisions include choosing the right shape and span length. Longer narrow spans with lightweight decks are more flexible and prone to vibrations. Though these designs look good and are cost effective they require careful dynamic assessment.Design strategies include shortening spans increasing deck stiffness adjusting support condition, or adding passive dampers like tuned mass dampers or viscous devices early on to absorb vibrations. These solutions are more cost effective when integrated during initial design rather than retrofitted later. Material choices also matter—softer surfaces can mask small vibrations, while hard surfaces may amplify them. Finally, engaging with stakeholders and planning post-construction testing helps build public trust and ensures lasting comfort.

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Vol. 15 Issue 02 , February - 2026

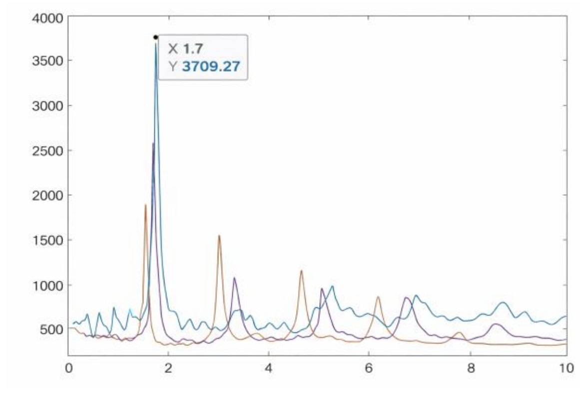

Figure 12: Time History Response of SDOF System under Individual Walking Load

6.3 Guidelines for Floor Systems

The design of floor systems for spaces such as gyms, fitness centers, and open plan offices need consideration for human induced vibrations. Jumping running, and synchronized activities cause noticeable floor vibrations, especially in areas with large uninterrupted spans. These vibrations do not endanger the structural integrity of the system yet they can work against comfort and confidence of users.Addressing these vibration issues should become an aim of consideration from the engineers' point of view. Longer floor spans in general will have lower natural frequencies and therefore will be more prone to vibrations. Intermediate support or increased floor system stiffness can help lift these natural frequencies and thus reduce the chances of resonance with activities performed by humans. The choice of materials can significantly govern vibrating behavior. Using composite or multilayered floor systems can help to balance weight and stiffness, providing a damping effect without adding excessive weight. Damping systems such as tuned-mass dampers or resilient sub layers can dissipate a good portion of the vibration energy. They will give good service in high-impact activity areas reducing the duration and amplitude of vibrations for overall comfort. Floor covering materials also play a role in the perception and transmission of vibrations. Soft floor coverings such as rubber mats or foam layering can absorb impact energy and minimize tactile and audible feedback. This aspect becomes more significant in areas where noise and vibration must be controlled. The inclusion of vibration analysis during design would facilitate an assessment of the problem areas before construction. Simulations would predict empathetic floor responses to a variety of

activities thereby giving designers an avenue to make informed decisions concerning structural modifications or choice of materials. Post occupancy evaluation ensures that spaces remain comfortable over time.When integrated into any designs, these considerations give professionals the opportunity to create conditions that not only fulfill structural function but also serve with an air of comfort and assurance to the user.

6.4 Integrating Human Comfort into Structural Codes

One of the most important specifics found through this study is the difference between how structures are rated by codes of design and the actual experience of those structures by end users. Most of the codes are biased from strength and stability in view of vibration, treating it as a secondary issue or only coming up when it is fatal or has high risks. human-induced vibrations especially in stadium, footbridges and floor scan significantly affect people's feelings of safety comfort and trust. Comfort should not be an option nor something anecdotal because it should be formally included into structural regulations. Certainly, present-day standards such as ISO 10137 and BS 6472 offer useful guidance on vibration limits; unfortunately, at present, the applicability of these standards differs country to country and structure by structure. Usually, designers adopt conservative assumptions or check vibrations just after design leaving a lost window for better comfort improvement. To this end, comfort, and vibration criteria should be standardized alongside strength check, deflection, and fatigue.Achieving this will mean three main changes: all structures with induced human rhythmic loading should undergo vibration assessment; metrics for human-centeredness would require a focus on such terms as exposure time and perceived disturbance use, rather than objective measures of disturbance; and a multi-phase assessment that wraps early modeling debates and simulations with post-occupancy monitoring can characterize the assessment posture. This is true because better effects related to vibration change with time; hence, continuous evaluation is required. Comfort from vibration concerns subject areas such as psychology, acoustics, biomechanics, and architecture. Thus, structural engineers must work with these experts to create standards reflecting how the affected human should really perceive motions rather than how much a structure can withstand. By including comfort in building codes, the purpose of engineering is completed. Future buildings will build not only heights or rocks but very much also comfort and coziness, supporting the people that would be using them every day in real terms.

This chapter brings close to theoretical and practical insights of the entire thesis into simple straightforward actionable guidance for structural designers and stakeholders. It emphasizes that vibration cannot just be treated as something mechanical; rather, it is something to be experienced deeply humanly at the earliest stage of design.Here, for footbridges, one needs to check natural frequencies, use passive dampers, and model well the rhythmic pedestrian loads long before construction. It would point out the significance of layout in structure damping surface materials and user perception for gym floors and spaces with flexible use. Other stadium design aspects would include dynamics of crowd, torsional effects, and the management of public perception during emotionally charged events. Beyond all technical considerations, the chapter advocates a complete shift in the engineering mindset on the general scheme from purely performance-based to one in which comfort, usability, and trust are prioritized. Modeling early realistic load simulations with stakeholder involvement and embedding comfort criteria into codes are important ways to avoid expensive fixes after construction. the chapter reminds that great design is intentional anticipatory and user focused. Structures should inspire confidence and security with comfort built-in from the start not added later. With these lessons, the thesis now moves toward its last chapter

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ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

conclusions and future directions for human-centered vibration design.

7. CONCLUSION

This thesis has highlighted human-induced vibration as a critical design consideration that extends beyond structural safety to include human comfort, perception, and confidence. Through analytical modeling, numerical simulation, and experimental validation, the study demonstrated that everyday activities such as walking, exercising, or crowd movement can significantly influence how structures are experienced, even when safety limits are satisfied.

Investigations of footbridges, gym floors, and stadium stands showed that vibration behavior is shaped not only by stiffness and damping but also by human interaction and synchronization, which are not always fully captured by conventional models. Field measurements confirmed many theoretical predictions while revealing additional perceptual effects, emphasizing the importance of validation and user-centered evaluation.

Overall, this work supports a shift toward human-centered vibration design, where comfort is treated as a measurable performance objective rather than a secondary concern. By integrating technical rigor with experiential understanding, the thesis offers a holistic framework that encourages proactive, empathetic engineering and promotes built environments that are not only safe, but also trusted and comfortable for their users.

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