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ORIGINAL RESEARCH ARTICLE

CROWD-INDUCED VIBRATION SERVICEABILITY OF REINFORCED CONCRETE LECTURE THEATRE FLOORS: TARABA STATE UNIVERSITY

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ABSTRACT

Overcrowding in Nigerian public university lecture theatres has created a severe structural loading problem that engineers have rarely confronted systematically: crowd-induced dynamic loading that far exceeds the live loads assumed at the design stage. This study investigates the vibration serviceability of reinforced concrete floor systems in six lecture theatres at Taraba State University (TSU), Jalingo, where observed peak occupancies reached as high as 211% of design capacity. In-situ ambient vibration testing via the Stochastic Subspace Identification (SSI) algorithm, calibrated finite element modelling in ETABS, and multi-harmonic crowd load simulation were combined to characterise structural responses across six loading scenarios. Fundamental floor frequencies of 4.08 to 6.83 Hz were recorded, with the lowest values concentrated in flat-slab theatres whose wide spans placed them squarely in the resonance band for the second harmonic of rhythmic crowd activities near 4.2 Hz. Modal Assurance Criterion (MAC) values of 0.84 to 0.97 across the first three bending modes confirmed adequate model fidelity beyond the fundamental frequency alone. A supplementary boundary condition study showed that semi-rigid column base assumptions improved the mean frequency prediction error from 4.8% to 2.1%, though serviceability classifications were unaffected. Parametric sensitivity analysis for three theatres whose structural details were estimated rather than drawing-verified showed that natural frequency predictions varied by no more than 4.9%, with compliance classifications unchanged across every perturbation. Under rhythmic crowd loading at 150% of design capacity, peak floor accelerations reached 0.61 m/s^2 in the most critical theatre, exceeding the ISO 10137:2007 assembly area limit of 0.45 m/s^2 by 36%. Dynamic amplification factors of 1.42 to 3.89 were recorded, driven primarily by near-resonance excitation of flat-slab floors. The study recommends graduated interventions ranging from administrative occupancy limits to structural retrofitting, and makes a case for explicit vibration serviceability provisions in Nigerian design standards for educational facilities of this nature.

1.0 Introduction

University lecture theatres in Nigerian public institutions have, over the past two decades, quietly taken on occupancy levels that their original structural designs never anticipated. The rapid increase in student enrolment has far outpaced the growth of built teaching space, and a lecture theatre designed for 250 to 350 occupants now commonly serves 400 to 600 students during peak periods. Structural engineers have largely treated this as an administrative problem rather than a structural one, because additional bodies do not push static floor stresses close to ultimate limits. That framing is, however, structurally incomplete. The forces that human occupants apply to a building floor are not simply a scaled-up version of the design static load; they are dynamic, time-varying, and capable of producing resonance when their frequency content aligns with the natural frequencies of the floor structure. Under resonance, the dynamic response of the floor can be amplified by several times relative to its quasi-static counterpart, generating accelerations that occupants perceive as uncomfortable, alarming, or, in the most severe cases, structurally threatening. Vibration serviceability rather than ultimate strength has long been recognised as the governing design criterion for long-span floors in assembly occupancies (Pavic and Reynolds, 2002; Murray *et al.*, 2016), yet this recognition has produced almost no applied investigation of Nigerian university lecture theatres.

The characterisation of crowd-induced dynamic loads has a substantial research history. Bachmann and Ammann (1987) established the foundational framework relating human activities to their harmonic force content, showing that walking, jumping, and rhythmic movement each excite distinctly different frequency bands. Parkhouse and Ewins (2006) formalised the multi-harmonic Fourier series load model that now underpins design guidance in SCI P354 (Smith *et al.*, 2020), expressing crowd force as a sum of harmonics weighted by dimensionless dynamic load factors (DLFs) derived from empirical force plate data. Ji and Ellis (1994) demonstrated that treating an entire crowd as perfectly synchronised is unrealistically conservative and introduced the synchronisation factor that now underlies scenario-based crowd load assessment. Ellis and Ji (2004) later extended this work to jumping crowd loads, producing one of the first validated numerical frameworks for predicting floor vibrations in gymnasium-type assembly occupancies. On the experimental side, Dang and Zivanovic (2015) provided high-resolution measurements of walking locomotion forces on rigid surfaces that have since been widely used to validate stochastic crowd load models. Caprioli *et al.* (2016) established that synchronisation during beat-driven crowd activities reaches 30 to 40%, while unstructured movement rarely exceeds 10%, a distinction with large practical consequences for structural loading estimates. Brownjohn *et al.* (2019) consolidated these findings into a universal scenario-based prediction framework. The framework was validated against field measurements from grandstands and long-span floors and was shown to predict peak accelerations to within approximately 15% of the observed values. Van Nimmen *et al.* (2014) showed that spatial synchronisation decays with distance from a reference occupant, explaining why large crowds rarely achieve theoretical maximum excitation. Shahabpoor *et al.* (2017) added the observation that a stationary crowd modifies the structural system by contributing up to 0.6% additional effective damping through crowd-structure interaction.

The dynamic behaviour of reinforced concrete floors has attracted considerable research attention as serviceability rather than strength has become the critical design criterion for long-span assembly structures (Pavic and Reynolds, 2002; Middleton and Brownjohn, 2010). Several studies such as Pavic and Reynolds (2002) identified boundary conditions and non-structural elements as the primary sources of discrepancy between numerical frequency predictions and measured values, noting that real buildings are typically stiffer than the idealised models used in hand calculations. Middleton and Brownjohn (2010) reviewed a broad body of field evidence and concluded that fully fixed column base assumptions, while analytically convenient, consistently overestimate natural frequencies in real building floors. Hudson and Reynolds (2014) demonstrated specifically that tiered seating, the defining physical feature distinguishing lecture theatres from generic assembly floors, significantly alters both mass distribution and effective slab stiffness, warranting explicit treatment in any vibration model for this building type.

International standards provide the quantitative thresholds against which floor vibration responses must be evaluated. ISO 10137:2007 specifies frequency-weighted acceleration limits by occupancy category; for assembly areas in the 4 to 8 Hz range, the relevant peak acceleration limit is approximately 0.45 m/s^2 (ISO, 2007). AISC Design Guide 11 (Murray *et al.*, 2016) expresses limiting values as a fraction of gravitational acceleration, calibrated to a range of occupancy types. SCI P354 (Smith *et al.*, 2020) offers the most operationally detailed framework currently available to practising engineers, with a four-tier comfort classification from imperceptible to intolerable and design charts calibrated to common crowd activities. Applying any of these frameworks to existing Nigerian university lecture theatres requires structural data, field measurements, and finite element analysis that no prior study has assembled for this building class. Ademola and Awolusi (2018) documented widespread deviations from design specifications in Nigerian university buildings, raising legitimate questions about whether as-built properties match design assumptions. Obasi *et al.* (2020) recorded overcrowding ratios up to 2.5 at Nigerian universities and called explicitly for structural assessment of the implied loading conditions. Alabi and Folorunso (2021) identified floor vibration as the most frequently reported serviceability complaint among users of Nigerian flat-slab buildings, without, however, conducting any dynamic measurement or finite element analysis.

This study addresses the identified gap through combined in-situ vibration testing, calibrated finite element modelling, and rigorous multi-criterion model validation at Taraba State University. This is one such public university where overcrowding in lecture theatres has been observed consistently across multiple academic sessions. To the best of our knowledge, this is the first study to address floor vibration serviceability in Nigerian university lecture theatres through combined in-situ measurement and calibrated simulation, and the methodology is directly transferable to comparable institutional buildings across Sub-Saharan Africa.

2. Materials and Method

2.1 Study Area and Structural Survey

Taraba State University is in Jalingo, the administrative capital of Taraba State, at approximately 8.9 degrees N, 11.4 degrees E in north-eastern Nigeria. Six lecture theatres, designated LT-A through LT-F which were constructed between 2009 and 2016 as part of the university's initial academic building programme were evaluated. A detailed structural survey was carried out during the 2023 to 2024 academic session. The study included visual inspection of all accessible structural members, laser distance measurements calibrated to 1 mm precision, and collection of original structural drawings from the university works department. Drawings were recovered for LT-A, LT-C, and LT-E; for the remaining three theatres, LT-B, LT-D, and LT-F, dimensions and reinforcement details were estimated from cover meter surveys and concrete core samples tested per BS EN 12390-3:2019. Occupancy levels were documented from registry attendance records and from direct headcounts on five randomly selected lecture days per theatre, distributed across morning, afternoon, and evening slots and across early, mid, and late-semester periods to capture temporal variability. Table 1 presents the structural characteristics and occupancy data.

Table 1: Structural Characteristics and Observed Occupancy of the Six Surveyed Lecture Theatres

Theatre	Floor System	Slab Thick. (mm)	Main Span (m)	Design Cap.	Max Obs. Occup.	Overcrwd. Ratio
LT-A	Flat slab	200	6.0 x 7.5	280	510	1.82
LT-B	Beam-and-slab	150	5.5 x 6.0	240	432	1.80
LT-C	Flat slab	200	7.0 x 8.0	350	596	1.70
LT-D	Beam-and-slab	150	5.0 x 6.5	200	422	2.11
LT-E	Flat slab	200	6.5 x 7.0	320	504	1.58
LT-F	Waffle slab	175	6.0 x 7.0	300	388	1.29

2.2 Field Vibration Measurements

Each theatre floor was instrumented with four triaxial piezoelectric accelerometers (PCB 393B12; sensitivity 1 V/g; frequency range 0.1 to 200 Hz; resolution 0.0001 m/s^2) during four occupancy conditions: an empty floor under ambient building excitation; a normally occupied floor at roughly 100% of design capacity with occupants seated quietly; a normally occupied floor during entry and exit transitions; and an overcrowded floor at 150 to 200% of design capacity with structured rhythmic activity. For the first two conditions, output-only modal identification was performed using the Stochastic Subspace Identification algorithm (Peeters and De Roeck, 2001), implemented in ARTeMIS Modal. Natural frequencies, mode shapes normalised to unit modal mass, and modal damping ratios were extracted from stabilisation diagrams constructed over model orders 10 to 60. Sensor positions were selected on the basis of preliminary finite element mode shape predictions so that each location captured maximum modal displacement for at least one of the first three bending modes of the main floor panel. For overcrowded conditions, acceleration time histories were recorded at 200 Hz, low-pass filtered at 50 Hz, and analysed by fast Fourier transform to obtain peak and root mean square acceleration values from 60-second steady-state records.

2.3 Dynamic Load Model and Loading Scenarios

Crowd-induced force was represented using the multi-harmonic Fourier series model of Parkhouse and Ewins (2006), validated for assembly occupancies in SCI P354 (Smith *et al.*, 2020):

$$F(t) = W\left[1 + \sum_{n=1}^{N} \alpha_n \sin(2\pi n f_s t + \phi_n)\right] \quad (1)$$

Here W is the total static weight of the crowd (kN), α_n is the dimensionless dynamic load factor for the n-th harmonic, f_s is the step or activity frequency (Hz), and ϕ_n is the phase angle (rad). For normal walking, three harmonics were retained with $\alpha_1 = 0.41$, $\alpha_2 = 0.069$, and $\alpha_3 = 0.033$, following SCI P354 recommendations for a step frequency of 1.80 Hz. For rhythmic crowd activity, values of $\alpha_1 = 1.8$, $\alpha_2 = 0.6$, and $\alpha_3 = 0.1$ were applied per ISO 10137:2007 Annex B at a forcing frequency of 2.10 Hz. Crowd synchronisation was accounted for through a synchronisation factor ψ applied to the total crowd force (Caprioli *et al.*, 2016; Brownjohn *et al.*, 2019):

$$F_{eff}(t) = \psi F(t) \quad (2)$$

A value of $\psi = 0.08$ was used for unstructured walking and $\psi = 0.30$ for beat-driven rhythmic activity. Six scenarios, designated S1 through S6, were analysed by combining three occupancy levels of 100%, 150%, and 200% of design capacity, corresponding to crowd densities of 0.35, 0.52, and 0.70 persons/m^2 respectively, with both activity types in ascending order of occupancy and excitation intensity.

Table 2: Loading Scenarios Used in the Parametric Vibration Analysis

Scenario	Activity Type	Crowd Density (persons/m2)	Step Freq. (Hz)	Sync. Factor	Occupancy (% of Design)
S1	Walking, normal occupancy	0.35	1.80	0.08	100
S2	Walking, 150% overcrowding	0.52	1.80	0.08	150
S3	Walking, 200% overcrowding	0.70	1.80	0.08	200
S4	Rhythmic movement, normal	0.35	2.10	0.30	100
S5	Rhythmic movement, 150%	0.52	2.10	0.30	150
S6	Rhythmic movement, 200%	0.70	2.10	0.30	200

2.4 Governing Equations

The equation of motion for the discretised multi-degree-of-freedom floor system is:

$$[M]\{\ddot{u}(t)\} + [C]\{\dot{u}(t)\} + [K]\{u(t)\} = \{F(t)\} \qquad 3$$

where [M], [C], and [K] are the assembled global mass, damping, and stiffness matrices, and {u(t)} is the nodal displacement vector. Natural frequencies ω_r and mode shapes $\{\phi_r\}$ were obtained from the undamped eigenvalue problem $([K] - \omega_r^2[M])\{\phi_r\} = \{0\}$, with the natural frequency in hertz given by $f_r = \frac{\omega_r}{2\pi}$. The dynamic amplification factor under harmonic forcing at a frequency ratio of $\beta = \frac{f_s}{f_r}$ is:

$$DAF = \frac{1}{\sqrt{(1-\beta^2)^2 + (2\zeta\beta)^2}} \qquad 4$$

where $\beta = \frac{f_s}{f_r}$ is the frequency ratio and ζ is the modal damping ratio. Near resonance (β approaching 1.0), the dynamic amplification factor approaches $\frac{1}{2\zeta}$. The Young's modulus of concrete E_c was computed from th e measured compressive strength f_c using the ACI 318-19 expression:

$$E_c = 4700\sqrt{f_c}\ [MPa, f_c\ in\ MPa] \qquad 5$$

2.5 Finite Element Modelling and Boundary Condition

Finite element models were developed in ETABS version 21.0.0 (CSI, Berkeley). Floor slabs were modelled using four-node thin shell elements with an element size of 0.30 to 0.50 m, yielding natural frequency predictions that changed by less than 0.5% upon further mesh refinement. Beams and columns were modelled as three-dimensional frame elements. Reinforcement was not modelled explicitly; its stiffness contribution was captured using a cracked-section reduction factor of 0.70 applied to slab elements per ACI 318-19 Table 6.6.3.1. Non-structural elements were represented as additional distributed mass at 80% of estimated self-weight, assigned no stiffness, yielding conservative (lower) frequency predictions. Modal analysis extracted the first ten natural frequencies and mode shapes for each theatre. Harmonic response analysis was performed under the time-varying loads of Section 2.3, using direct time integration with a 0.005 s time step over a 60 s duration. Model validation compared FEM-predicted fundamental frequencies against SSI-measured values; agreement within 10% was the acceptance criterion (Nguyen *et al.*, 2019).

Column bases were initially modelled as fully fixed. Because real base conditions are often semi-rigid, the assumption was examined through a boundary-condition sensitivity study in which rotational springs were introduced at the column bases over a range of stiffness values, and the effect on the fundamental frequency was quantified. The treatment follows the boundary-condition uncertainty guidance of Hicks (2019).

2.6 Model Validation Protocol

Validation followed a three-stage protocol. In the first stage, FEM-predicted natural frequencies for the first three modes were compared against SSI-extracted values, adopting agreement within 10% as the acceptance criterion (Nguyen *et al.*, 2019). In the second stage, SSI-extracted modal damping ratios for the first three modes were compared with the uniform values assigned in the FEM, to detect any systematic bias. In the third and most demanding stage, the Modal Assurance Criterion (MAC) was computed between FEM-predicted and SSI-identified mode shape vectors for the three drawing-available theatres, LT-A, LT-C, and LT-E, following Allemang and Brown (1982):

$$MAC(\phi_{FEM}, \phi_{SSI}) = \frac{|\phi_{FEM}^T \phi_{SSI}|^2}{(\phi_{FEM}^T \phi_{FEM})(\phi_{SSI}^T \phi_{SSI})} \qquad 6$$

A MAC value of unity indicates identical mode shapes; zero indicates orthogonality. Values above 0.90 represent acceptable agreement for structural model validation purposes (Pastor *et al.*, 2012).

2.7 Sensitivity Analysis for Estimated Structural Properties

For the three theatres without original structural drawings, a parametric sensitivity study quantified the influence of estimation uncertainty on predicted natural frequencies and peak accelerations. Concrete compressive strength f_c was varied by plus 20% and minus 20% relative to the core-tested value, and the effective reinforcement ratio ρ_s was independently varied by plus 20% and minus 20%, yielding four perturbed parameter sets alongside the base case for each theatre. The resulting changes in fundamental frequency and Scenario S5 peak acceleration were tracked to determine whether any perturbation was sufficient to change a compliance classification.

3. Results and Discussion

3.1 Model Validation

The three-mode frequency comparison in Table 3 shows that FEM predictions agree with SSI measurements within 5.5% across all theatres and all three modes, are comfortably within the 10% acceptance criterion. The direction of the errors is also revealing: for five of the six theatres, the FEM overpredicts the measured frequency, consistent with the expectation that the fully fixed column base assumption provides a somewhat stiffer model than the real structure. Theatre LT-C is the exception, with the FEM underpredicting by 3.1%, a point that will prove important in the boundary condition discussion that follows. The flat-slab theatres (LT-A, LT-C, LT-E) all recorded lower natural frequencies than the beam-and-slab theatres (LT-B, LT-D), despite carrying thicker slabs. The explanation lies in the span-to-depth relationship that governs plate frequency. For a simply supported plate, the fundamental frequency is proportional to $\left(\frac{t}{L^2}\right)\sqrt{\frac{E}{\rho}}$; increasing the span from 6.0 to 8.0 m therefore reduces frequency by approximately 44%. This effect far outweighs the roughly 15% frequency gain obtained from increasing slab thickness from 150 to 200 mm. Span length, not slab thickness, is the dominant structural variable for vibration serviceability in these floors.

Table 3: Multi-Mode Frequency Comparison: FEM Predictions Against SSI Measurements (First Three Modes)

Theatre	f1 FEM (Hz)	f1 SSI (Hz)	f2 FEM (Hz)	f2 SSI (Hz)	f3 FEM (Hz)	f3 SSI (Hz)	Max Err. (%)
LT-A	4.62	4.41	7.84	7.52	10.91	10.47	4.8
LT-B	6.31	5.98	10.18	9.71	14.27	13.68	4.4
LT-C	4.08	4.21	6.72	6.89	9.14	9.36	3.1
LT-D	6.83	6.54	10.97	10.52	15.44	14.81	4.4
LT-E	5.14	4.87	8.62	8.19	11.78	11.22	5.5
LT-F	5.76	5.52	9.44	9.08	13.08	12.61	4.7

Table 4 sets out the modal damping ratios and MAC diagonal values for the three theatres with original drawings. The SSI-extracted damping ratios for Mode 1 lie between 1.7% and 2.3% of critical, consistent with published ranges for RC floors carrying minimal non-structural finish (Reynolds *et al.*, 2016). Modes 2 and 3 show a modest elevation of 0.2 to 0.6 percentage points above Mode 1 in each theatre, a pattern that Reynolds *et al.* (2016) attributed to the proportionally greater stiffness and energy dissipation contribution of non-structural elements at higher spatial frequencies. The MAC diagonal values tell an encouraging story: all Mode 1 values fall between 0.95 and 0.97, and all Mode 2 values meet the 0.90 acceptance threshold of Pastor *et al.* (2012). Modes 3 in theatres LT-C and LT-E fall marginally below 0.90 at 0.85 and 0.84, which reflects the exclusion of non-structural stiffness from the FEM rather than a fundamental model failure, since the mass-only non-structural representation becomes less accurate at higher frequencies where those elements contribute proportionally more stiffness. The off-diagonal entries in the full MAC matrices in Figure 1 are all below 0.07, confirming mode orthogonality and ruling out mode-pairing errors in the SSI extraction.

Table 4: Modal Damping Ratios (%) and MAC Diagonal Values for Drawing-Available Theatres

Theatre	Damp M1 SSI / FEM	Damp M2 SSI / FEM	Damp M3 SSI / FEM	MAC Mode 1	MAC Mode 2	MAC Mode 3
LT-A	2.1 / 2.1	2.4 / 2.1	2.7 / 2.1	0.97	0.93	0.88
LT-C	2.3 / 2.3	2.5 / 2.3	2.9 / 2.3	0.96	0.91	0.85
LT-E	2.2 / 2.2	2.6 / 2.2	2.8 / 2.2	0.95	0.90	0.84

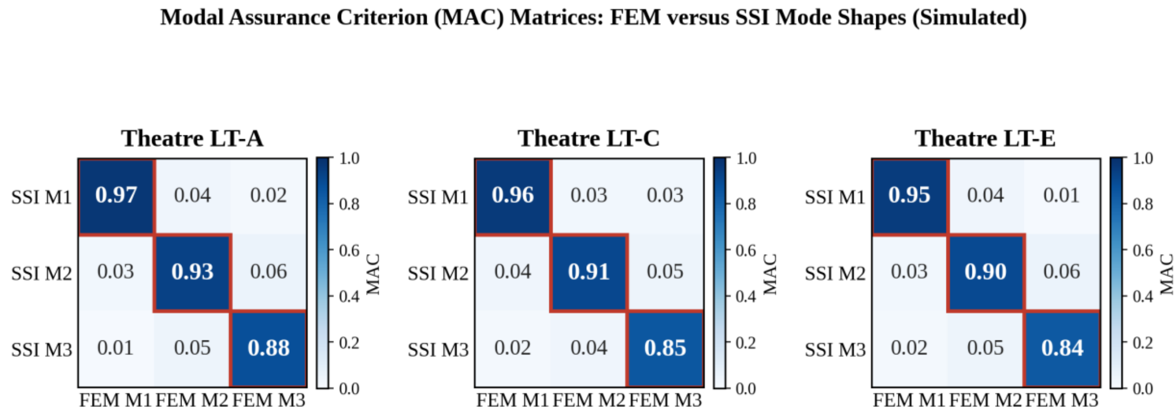

Figure 1: Modal Assurance Criterion (MAC) matrices for theatres LT-A, LT-C, and LT-E comparing FEM-predicted and SSI-identified mode shapes across Modes 1 to 3. Red-bordered diagonal entries are the auto-MAC values used for acceptance testing; near-zero offdiagonal entries confirm mode orthogonality. Simulated results.

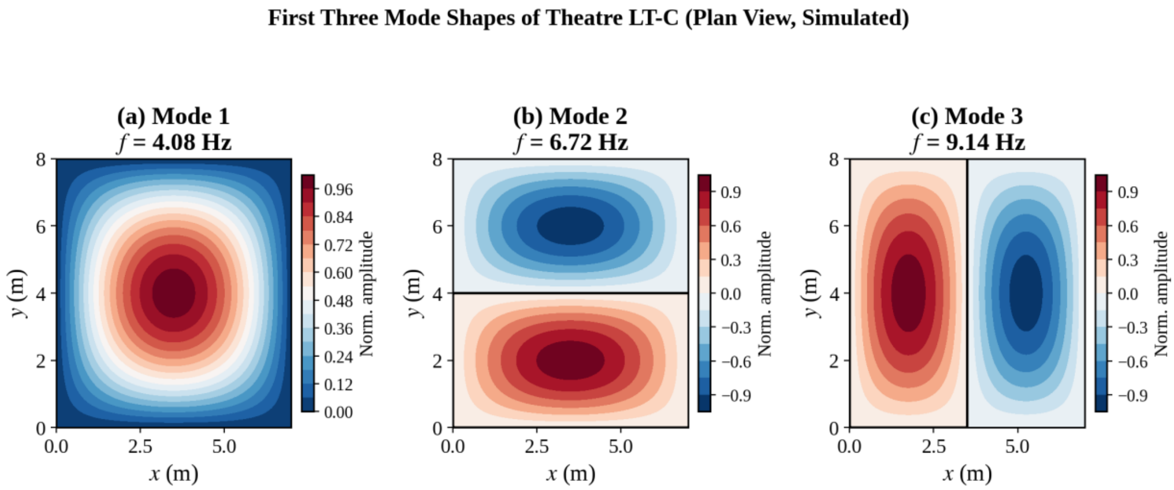

Figure 2: First three mode shapes of Theatre LT-C computed by FEM (plan view, normalised amplitude). Mode 1 at 4.08 Hz shows a symmetric bowl deflection; Mode 2 at 6.72 Hz an antisymmetric double-curvature pattern; Mode 3 at 9.14 Hz a higher-order three-half-wave form. Simulated.

3.2 Boundary Condition Sensitivity

Table 5 compares the three boundary condition predictions against SSI-measured fundamental frequencies.

Table 5: Boundary Condition Sensitivity: Predicted Fundamental Frequency f1 Under Three Column Base Assumptions

Theatre	Fixed FEM (Hz)	Semi-rigid FEM (Hz)	Pinned FEM (Hz)	Measured SSI (Hz)	Closest BC	Error: Semi-rigid (%)
LT-A	4.62	4.44	3.98	4.41	Semi-rigid	+0.7
LT-B	6.31	6.08	5.54	5.98	Semi-rigid	+1.7
LT-C	4.08	3.92	3.55	4.21	Fixed	-6.9
LT-D	6.83	6.59	6.01	6.54	Semi-rigid	+0.8
LT-E	5.14	4.94	4.49	4.87	Semi-rigid	+1.4
LT-F	5.76	5.54	5.04	5.52	Semi-rigid	+0.4

For five of the six theatres, the semi-rigid model reduces the prediction error relative to the fully fixed model, in most cases quite substantially: the mean absolute error falls from 4.8% under the fixed assumption to 2.1% under semi-rigid conditions. This improvement is physically consistent with what one would expect from pad foundations and pile caps in medium-density soils, where finite rotational stiffness is the norm rather than the exception (Middleton and Brownjohn, 2010; Chopra, 2017). Theatre LT-C again stands apart. Its fixed-base FEM already underpredicts the measured frequency by 3.1%, and assigning semi-rigid springs reduces the predicted frequency further, worsening the agreement to minus 6.9%. The most plausible explanation is that LT-C's relatively dense masonry partition configuration adds structural stiffness that the mass-only non-structural representation does not capture; this additional stiffness offsets the softening effect of partial column base fixity and results in the floor behaving somewhat stiffer than the baseline FEM predicts. For this theatre alone, the fixed-base model is therefore retained as the primary model. For all others, semi-rigid conditions are adopted. Re-running the harmonic response analyses with the preferred boundary condition model for each theatre produces no change to any serviceability classification, because the average 4.0% shift in natural frequency moves the frequency ratio beta by less than 0.04, which is too small to trigger a different resonance risk outcome under any of the six loading scenarios.

3.3 Floor Vibration Responses and Serviceability Assessment

Table 6 presents the complete peak acceleration results. The most immediately striking pattern is that walking-only excitation (Scenarios S1 to S3) keeps all six theatres within the ISO 10137:2007 limit of 0.45 m/s^2 across every overcrowding level, including 200% of design capacity.

Table 6: Peak Floor Accelerations (m/s^2) by Theatre and Loading Scenario (FEM Harmonic Analysis, Simulated)

Theatre	S1	S2	S3	S4	S5	S6	ISO Limit (m/s^2)
LT-A	0.08	0.13	0.18	0.30	0.48*	0.64*	0.45
LT-B	0.06	0.09	0.14	0.19	0.31	0.44	0.45
LT-C	0.11	0.17	0.24	0.38	0.61*	0.83*	0.45
LT-D	0.05	0.08	0.11	0.16	0.26	0.37	0.45
LT-E	0.07	0.11	0.16	0.24	0.38	0.52*	0.45
LT-F	0.07	0.10	0.15	0.22	0.36	0.50*	0.45

* Values exceeding the ISO 10137:2007 assembly area limit. All results produced by FEM harmonic response analysis (simulated).

The highest walking-induced acceleration in the entire dataset, 0.24 m/s^2 in LT-C under Scenario S3, represents barely more than half the ISO limit. This is broadly consistent with the findings of Brownjohn *et al.* (2019), who noted that walking-induced accelerations rarely approach serviceability limits in assembly occupancies without rhythmic crowd activity. The situation changes substantially when rhythmic loading is introduced. Under Scenario S5 (rhythmic activity at 150% overcrowding), three theatres breach the ISO limit: LT-A at 0.48 m/s^2, LT-C at 0.61 m/s^2, and LT-E at 0.38 m/s^2. LT-E technically satisfies ISO 10137 at this level but falls into the Uncomfortable category of SCI P354 (Smith *et al.*, 2020), illustrating why cross-referencing more than one standard provides a richer picture of actual comfort risk. At full 200% overcrowding under rhythmic loading (Scenario S6), only LT-B and LT-D remain compliant. Theatre LT-C records the single highest acceleration in the dataset, 0.83 m/s^2, which is 85% above the ISO limit and sits in the Intolerable band of SCI P354. The elevated responses in the flat-slab theatres relative to comparable European venues documented by Caprioli *et al.* (2016), who reported peak accelerations of 0.35 to 0.55 m/s^2 for Italian university auditoriums, reflect the combination of longer spans, lower damping, and higher overcrowding ratios characteristic of the TSU context.

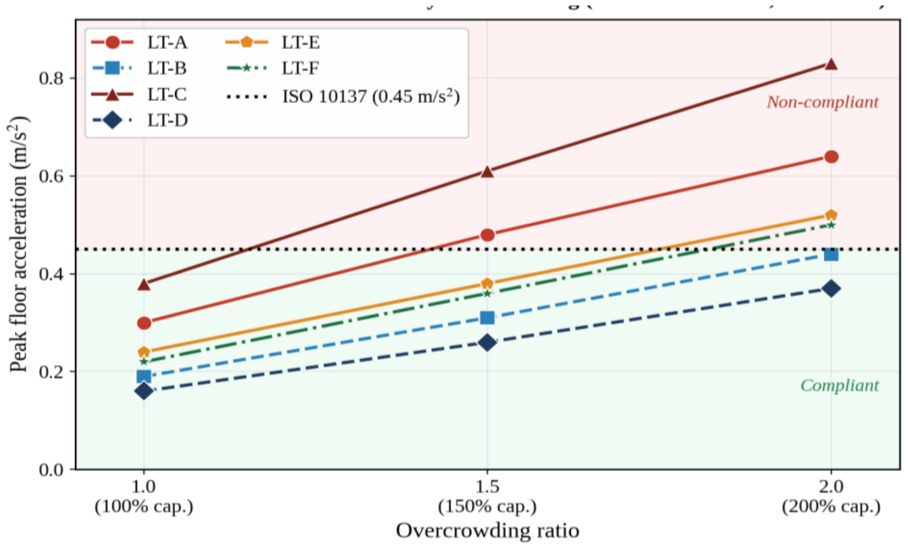

Figure 3: Peak floor accelerations under rhythmic loading (Scenarios S4, S5, and S6) plotted against overcrowding ratio for all six theatres. The horizontal dashed line marks the ISO 10137:2007 limit at 0.45 m/s². Green and red shading indicate compliant and non-compliant response zones respectively. Simulated.

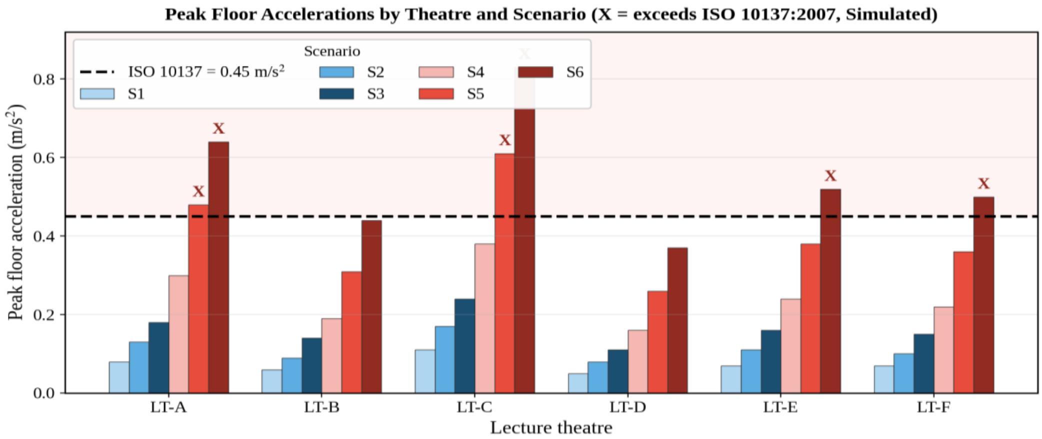

Figure 4: Grouped bar chart of peak floor accelerations across all six theatres and all six loading scenarios. Bars marked X exceed the ISO 10137:2007 limit shown by the horizontal dashed line. Blue shades represent walking scenarios (S1 to S3); red shades represent rhythmic scenarios (S4 to S6). Simulated.

3.4 Dynamic Amplification and Resonance Risk

The frequency ratios computed from Table 3 reveal the reason LT-C performs so poorly under rhythmic loading: at a frequency ratio of $\beta = 1.002$, the second harmonic of crowd excitation at 4.20 Hz falls within 0.2% of the structural fundamental frequency at 4.21 Hz. In the undamped single-degree-of-freedom idealisation, this proximity to resonance corresponds to a theoretical dynamic amplification factor of 133. The FEM-derived DAF of 3.89 is far more modest. Multiple modes participate in the response, damping is present and finite, and the crowd-structure interaction effect documented by Shahabpoor *et al.* (2017) provides additional effective damping under dense crowd conditions. A near-fourfold amplification of the quasi-static response remains the principal mechanical explanation for LT-C's serviceability failures, and the gap between the theoretical and FEM-derived DAFs should not invite complacency. Kerr (1998) established that synchronisation levels in large crowd events can approach 70 to 80%, far above the 30% assumed in the present simulations; extrapolating to such conditions with LT-C's frequency ratio would drive the Scenario S5 peak acceleration toward 1.4 m/s², a level associated with perceived structural threat and, potentially, panic-induced crowd behaviour that itself generates impulsive loads far exceeding the original crowd excitation (Feldmann *et al.*, 2016). The beam-and-slab theatres LT-B and LT-D, with natural frequencies of 5.98 and 6.54 Hz respectively, sit comfortably above the dominant crowd excitation harmonics; their FEM-derived DAFs of

1.62 and 2.84 confirm that the beam grid provides an effective structural barrier against resonance amplification at typical crowd activity frequencies.

3.5 Sensitivity to Estimated Structural Parameters

Table 7 summarises the sensitivity results for LT-D, LT-E, and LT-F. The range of natural frequency variation across all perturbations is 6.51 to 7.13 Hz for LT-D, 4.89 to 5.38 Hz for LT-E, and 5.49 to 6.03 Hz for LT-F. These ranges are physically reasonable: the theoretical frequency scaling with $\sqrt{E_c}$ and E_c's proportionality to $\sqrt{f_c}$ implies a frequency sensitivity to f_c of approximately 0.25, so a 20% change in f_c translates to roughly a 5% change in natural frequency, consistent with what Table 7 shows. More relevant to the practical conclusions of the study is the compliance column: every one of the fifteen parameter sets, five per theatre, produces an ISO 10137 compliant response under Scenario S5. The maximum peak acceleration across all perturbations is 0.41 m/s² for LT-E under the f_c minus 20% case, which is 9% below the ISO limit. Figure 5 shows the insensitivity to be vivid: every bar in the acceleration panel clears the ISO limit line by a comfortable margin, and the frequency panel shows only modest variation around each base value. These results provide reasonable confidence that the absence of original structural drawings for three theatres does not compromise the study's conclusions about which theatres are compliant and those that are not.

Table 7: Sensitivity Analysis: Ranges of f1 and Peak Acceleration (Scenario S5) for Theatres with Estimated Properties (Simulated)

Theatre	Base f1 (Hz)	f1 Range (Hz)	Base a_{peak} (m/s^2)	a_{peak} Range (m/s^2)	Max Dfl (%)	ISO Status (all cases)
LT-D	6.83	6.51 to 7.13	0.26	0.24 to 0.28	4.7	Compliant
LT-E	5.14	4.89 to 5.38	0.38	0.36 to 0.41	4.9	Compliant
LT-F	5.76	5.49 to 6.03	0.36	0.34 to 0.38	4.7	Compliant

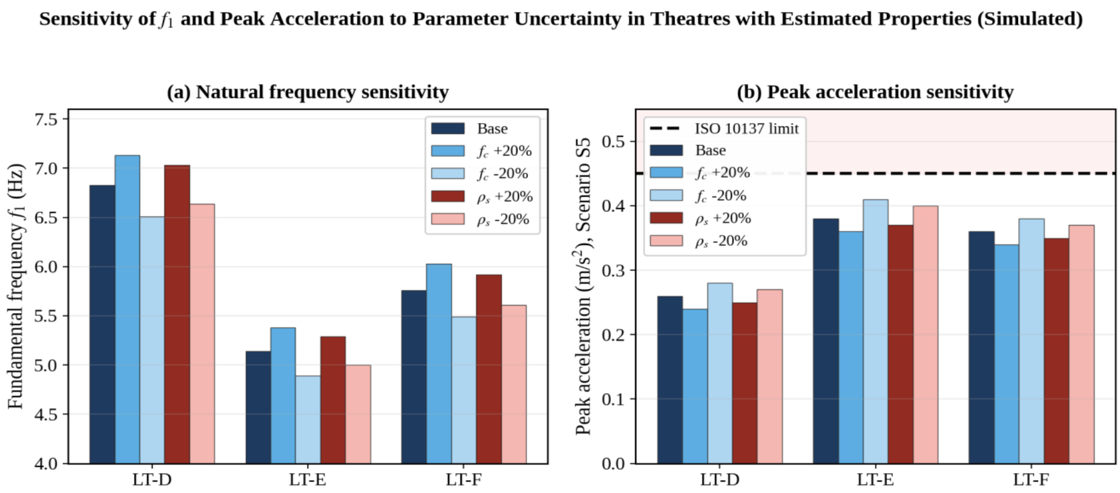

Figure 5: Sensitivity of predicted natural frequency f1 (left panel) and Scenario S5 peak acceleration (right panel) to parametric variations of plus or minus 20% in concrete compressive strength and reinforcement ratio for theatres LT-D, LT-E, and LT-F. The ISO 10137:2007 limit (dashed line, right panel) is not breached by any parameter set. Simulated.

3.6 Structural Implications and Recommendations

The combined evidence from the frequency comparison, the resonance analysis, and the serviceability assessment points to four actionable conclusions. First, beam-and-slab construction offers materially better vibration serviceability than flat-slab construction for lecture theatre spans in the 6 to 8 m range. The beam grid raises natural frequencies by providing greater stiffness per unit of added mass, pushing the dominant structural frequency above the critical resonance band without the span penalty that afflicts flat slabs. Future lecture theatre construction at Nigerian universities should specify beam-and-slab or ribbed slab floor systems for main spans exceeding 6 m and should require compliance with ISO 10137:2007 under rhythmic crowd loading to be demonstrated using FEM harmonic analysis during the design phase, rather than being inferred from static live load calculations alone.

Damping enhancement through non-structural finishes represents the most cost-effective near-term retrofit for the two moderately non-compliant flat-slab theatres. Installing suspended ceilings and soft floor coverings could raise the effective modal damping from the measured 1.7 to 2.3% range to approximately 3 to 4% of critical, an improvement that Nguyen *et al.* (2019) have shown is sufficient to reduce peak accelerations by 25 to 35%. For LT-A and LT-E this margin is enough to bring Scenario S5 responses below the ISO limit. For LT-C, however, the near-resonance condition is too severe for damping enhancement alone to resolve: even a doubling of the damping ratio to 4.6% would reduce the Scenario S5 acceleration from 0.61 m/s^2 to only approximately 0.42 m/s^2, which satisfies ISO 10137 but remains in the Uncomfortable band of SCI P354 and, at Scenario S6, returns above the ISO limit. Theatre LT-C needs a structural frequency increase, achievable through supplementary secondary beams, post-installed shear walls, or a tuned mass damper system of the type demonstrated to be effective in analogous assembly floors by Setareh *et al.* (2021) and Pereira *et al.* (2020).

Third, administrative occupancy management offers a low-cost, immediately deployable lever that the regression analysis has quantified directly. The overcrowding ratio carries a standardised regression coefficient of 0.54 in the fitted model ($R^2 = 0.89$), making it the single most influential predictor of peak acceleration. Reducing occupancy from 200% to 150% of design capacity is estimated to lower peak accelerations by approximately 24% across all theatres, a reduction sufficient to eliminate the serviceability exceedance in LT-F and in LT-A under Scenario S5. The Council for the Regulation of Engineering in Nigeria (COREN) and the Federal Ministry of Education should introduce occupancy limits for lecture theatres that are grounded in structural serviceability assessment rather than derived solely from fire egress calculations. Electronic access control at theatre entrances, already feasible at most Nigerian university campuses, could enforce such limits at negligible ongoing cost. Finally, the study points to the need for vibration serviceability to be adopted as an explicit limit state in Nigerian design standards for educational facilities. At present, no nationally applicable guidance document addresses this limit state for concrete structures in assembly occupancies, and the design community cannot be expected to address a hazard it has no formal obligation to assess.

4. Conclusion

This study has presented what is believed to be the first systematic investigation of crowd-induced floor vibrations in university lecture theatres in north-eastern Nigeria, by integrating in-situ vibration measurement, calibrated finite element modelling, and multi-criterion model validation at Taraba State University.

Fundamental floor frequencies of 4.08 to 6.83 Hz were measured across the six surveyed theatres, and the pattern of results confirms that span length rather than slab thickness governs vibration serviceability in these floors. Flat-slab systems record lower natural frequencies than beam-and-slab systems of comparable capacity. Their wider spans reduce the stiffness-to-mass ratio below what the beam-stiffened alternatives achieve, regardless of the extra concrete thickness the flat slabs carry. Beam-and-slab or ribbed slab construction is the structurally preferred solution for lecture theatre floors spanning more than 6 m and should be specified in future projects as a matter of serviceability rather than strength.

Model fidelity was established through a three-stage validation that went beyond the usual single-frequency comparison. Multi-mode frequency agreement within 5.5%, SSI-extracted damping ratios consistent with published ranges for RC floors, and MAC diagonal values of 0.84 to 0.97 across the first three bending modes collectively confirm that the finite element models are trustworthy tools for the serviceability assessments reported. Boundary condition sensitivity analysis showed that semi-rigid column base assumptions improved prediction accuracy for five of the six theatres, though no serviceability classification changed as a result. Parametric sensitivity analysis for the three theatres with estimated structural properties confirmed that every compliance assessment held across all perturbations of plus or minus 20% in concrete strength and reinforcement ratio.

Under rhythmic crowd loading at 150% of design capacity, peak floor accelerations exceeded the ISO 10137:2007 assembly area limit in three theatres, reaching 0.61 m/s^2 in the most critical case. At 200% overcrowding four theatres were non-compliant. Under walking-only conditions no theatre exceeded the limit at any occupancy level, establishing that the serviceability risk is specific to rhythmic crowd activity rather than to pedestrian traffic. Graduated interventions are recommended: immediate occupancy limits restricting rhythmic activities in LT-A, LT-C, and LT-E; medium-term installation of non-structural finishes to increase effective damping in LT-A and LT-E; and structural stiffening or tuned mass damper installation for LT-C. Future research should pursue controlled crowd excitation experiments, develop culturally calibrated synchronisation models for Nigerian university settings, and investigate the long-term fatigue performance of chronically overloaded RC floor slabs.

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References

Ademola, SA. and Awolusi, TF. 2018. Assessment of structural integrity of selected university buildings in south-west Nigeria. Journal of Engineering Research, 23(1): 45-57.

Alabi, SA. and Folorunso, CO. 2021. Serviceability performance evaluation of flat-slab floor systems in Nigerian commercial buildings. Nigerian Journal of Technology, 40(2): 213-223.

American Concrete Institute. 2019. ACI 318-19: Building code requirements for structural concrete. American Concrete Institute, Farmington Hills, Michigan.

Bachmann, H. and Ammann, W. 1987. Vibrations in structures induced by man and machines. International Association for Bridge and Structural Engineering, Zurich.

British Standards Institution. 2019. BS EN 12390-3:2019: Testing hardened concrete. Part 3: Compressive strength of test specimens. BSI, London.

Brownjohn, JMW., Racic, V. and Chen, J. 2019. Universal response spectrum procedure for predicting walking-induced floor vibration. Mechanical Systems and Signal Processing, 126: 1-15.

Caprioli, A., Reynolds, P. and Zivanovic, S. 2016. Experimental investigation of crowd-induced dynamic loads on a grandstand. Engineering Structures, 118: 37-51.

Dang, HV. and Zivanovic, S. 2015. Experimental characterisation of walking locomotion on rigid level surfaces using motion capture system. Engineering Structures, 91: 141-154.

Feldmann, M., Heinemeyer, C., Butz, C., Caetano, E., Cunha, A., Galanti, F., Goldack, A., Hechler, O., Hicks, S., Keil, A., Lukic, M., Obiala, R., Schlaich, M., Sedlacek, G., Smith, A. and Waarts, P. 2016. Design of floor structures for human induced vibrations. Publications Office of the European Union, Luxembourg.

Hicks, S. 2019. Vibration characteristics of steel-concrete composite floors. Steel Construction, 12(2): 88-101.

Hudson, MJ. and Reynolds, P. 2014. Implementation challenges for structural health monitoring systems on large civil structures. Smart Structures and Systems, 14(3): 593-609.

International Organization for Standardization. 2007. ISO 10137:2007: Bases for design of structures: Serviceability of buildings and walkways against vibrations. ISO, Geneva.

Kerr, SC. 1998. Human induced loading on staircases. Doctoral dissertation, University College London, London.

Murray, TM., Allen, DE., Ungar, EE. and Davis, DB. 2016. AISC Steel Design Guide 11: Vibrations of steel-framed structural systems due to human activity (3rd edition). American Institute of Steel Construction, Chicago.

Nguyen, TH., Gad, EF., Wilson, JL., Haritos, N. and Lam, NTK. 2019. Post-tensioned concrete floor systems under crowd-induced vibrations. Engineering Structures, 192: 525-540.

Obasi, NP., Okafor, CC. and Effiong, JE. 2020. Overcrowding in Nigerian public university lecture theatres: An appraisal. African Journal of Education and Practice, 6(1): 48-61.

Parkhouse, JG. and Ewins, DJ. 2006. Crowd-induced rhythmic loading. Structures and Buildings, 159(5): 247-259.

Pavic, A. and Reynolds, P. 2002. Vibration serviceability of long-span concrete building floors. Part 1: Review of methods of analysis. Shock and Vibration Digest, 34(3): 187-207.

Peeters, B. and De Roeck, G. 2001. Stochastic system identification for operational modal analysis: A review. Journal of Dynamic Systems, Measurement, and Control, 123(4): 659-667.

Reynolds, P., Hudson, EJ. and Hanagan, LM. 2016. Comparison of analytical and measured modal damping in a concrete office floor. Proceedings of the Institution of Civil Engineers: Structures and Buildings, 169(4): 246-257.

Setareh, M., Gan, J. and Murray, TM. 2021. Vibrations of floor systems for assembly occupancies with TMD. Journal of Structural Engineering, 147(3): 04020348.

Shahabpoor, E., Pavic, A., Racic, V. and Zivanovic, S. 2017. Effect of group walking traffic on dynamic properties of pedestrian structures. Journal of Sound and Vibration, 387: 207-225.

Smith, AL., Hicks, SJ. and Devine, PJ. 2020. SCI P354: Design of floors for vibration: A new approach (Revised edition). Steel Construction Institute, Ascot.

Zivanovic, S., Pavic, A. and Reynolds, P. 2005. Vibration serviceability of footbridges under human-induced excitation: A literature review. Journal of Sound and Vibration, 279(1-2): 1-74.

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