Integration of digital models and real data for the forecast and validation of seismic behavior of tall building

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Abstract

This research evaluates the reliability of numerical methods to analyse skyscrapers subjected to extreme actions based on ETABS model, that model have ten story tower excited by an earthquake of magnitude MW 9.5 the research combines finite element modeling, model analyses and verification of inter-stage deviation complemented by a review of artificial intelligence methods based on neural networks for the automatic characterization of building from urban images, the results show participatory mass ratios close to 0.9 on short periods, indicating a generally rigid and well mobilized structure, but also reveal a very high maximum drift ratio at the last level in one direction, sign of unevenness in rigidity and possible concentration of damage, strengthening strategies are proposed (additional sails, increase in sections, consideration of the soil structure interaction) in order to bring the response within the regulatory limits, the research concludes that the numerical model calibrated and validated by real data and complemented by probabilistic and AI approaches provides is a good approaches for skyscrapers analyses.

Introduction

The skyscrapers are a big challenge for civil engineering, the project combines architectural design elements with technical building skills, which also need to meet high standards of safety and durability protection and performance efficiency, these complex vertical structures are subject to various stresses, notably seismic and aerodynamic numerical modeling via approaches such as the finite element method fluid dynamics simulations or digital twins is now an essential tool for predicting and analyzing their behavior, these methods push the traditional limits of sizing by integrating complex phenomena into precise and personalized simulations. [1],[2] Despite these advances, the absolute reliability of digital models remains contested for such sensitive projects. Ultra physics complex interactions non-linear phenomena and the effects of heterogeneous materials introduce uncertainties that models must integrate.The Numerical errors emerge from more specific issues which include method stability, method meshing (action of transforming something continuous into separate elements) and method simplification, the main difficulty lies in the lack of experimental validation especially for extreme scenarios that are difficult to reproduce in the laboratory as well as in the uncertainty about material and environmental data [3], [4], [5] this work aims to demonstrate the reliability of numerical methods in the calculation and sizing of skyscrapers based on rigorous validation via sensor data and real-world tests, it identifies current limitation while highlighting the benefits and recent advances of digital tools providing a sound scientific framework to justify their reliance in common practice, the main hypothesis is that despite their limitations, these models offer sufficiently accurate and reliable predictions to ensure the safety and durability of the structures provided appropriate calibration and validation, it also questions their ability to integrate non-linear effects and their robustness in the face of uncertainties [6] To address this an approach combining advanced numerical modeling, calibration by experimental data (sensors, wind tunnel tests), probabilistic analysis of uncertainties and comparison with construction standards is adopted. The article is structured as follows, literature review on digital tools and experimental validation, methodological presentation, results and analyses illustrating precision and limits, then discussion on challenges and opportunities.

Literature review envelop numerical tools and experimental validations for skyscrapers confronting predictions of numerical models with real data, it highlights the evolution of approaches towards AI-digital crossbreeding, validated by labeled data-sets (accuracy, recall, F1-acore).The research shows that digital methods can produce trustworthy results because they have been tested with actual data from the field, which enables designers to build secure systems, although they face challenges from images resolution issues and urban environmental factors, seismic modeling of high building (RSA, NLTHA,IDA) [7],[8],[9] Digital models for skyscrapers integrate advanced seismic analyses: (ASR) Adaptive Spectral Response, (NLTHA) Non-Linear Temporal Analyses and (IDA) Incremental Dynamic Analyses. The software applications ETABS (MEF) use these methods to create simulations of how soil and structures interact with each other together with the thermal and mechanical effects and all complicated phenomena, they are calibrated by real data (Wind tunnel, sensors) to minimize discrepancies, strengthening the digital twins and linking structural inventories to standardized fragility models (GEM taxonomy) AI approaches (DCNN, GSV, GEM, 2020-2025 works) AI approaches automate the extraction of structural features (SBST GEM seismic types, lateral systems, height) from Google Street View (GSV) images, via deep deterministic achieve a precision k>0.81 surpassing manual surveys in cost and spatial coverage for large-scale seismic vulnerability assessment.

Works cited (2020-2025), clearly separated:

- Building typology by automation (Earthquake spectra 2025):automated classification (floors, structural system, construction period), experimentally validated [11]
- Deep learning framework for building damage (JDR 2025): post-earthquake segmentation in Lima (>90% accuracy CEM) [12]
- Deep learning in seismic engineering (arXiv 2024): CNN/RNN review for hybrrid skyscraper validation [13]

Own contributions: development of a hybrid methodology DCNN+GSV+GEM, validated on data sets Santiago (Chile) with K>0.81

Integrating heterogeneous defining bulk classification and link to GEM models.improvements via fine-tuning (e.g Lima.Peru) and sensor integration (accelerometer, Li-DAR) for continuous validation minimizing dependencies on image quality and bias.

Methodology and Materials

Structural modeling was executed through ETABS software which modeled a reinforced concrete structure, seismic data used for this study represents the strongest earthquake ever recorded o Earth which reached a magnitude of MW 9.5.

Model was made in ETABS software which served as the main tool for conducting digital simulations research concentrated on studying the 10th floor to evaluate how the model would perform during an earthquake after completing optimization and thorough analysis work.

Analysis seismic considered multiple key parameters which included the building’s natural periods and frequencies together with the participating mass also, and we took into account the 10th floor seismic assessment element enabled exact measurement of how the model would react to extreme earthquake loads focused approach of this study enables better identification of critical areas which need special examination document contains an in-depth analysis which includes suggestions to enhance model earthquake, resistance through better structural design recommendations include model security enhancements through structural optimization methods and model design changes for better protection against potential dangers study produced a comprehensive conclusion which presented all findings together with the main study results about how the building design for earthquake zones because it considers both actual limitations and expected performance outcomes.

Materials used include steel reinforcement and load- bearing tendons concrete used in this study is ordinary concrete with a high tensile strength that meets the standard of 400 pis or B25 because it behaves non uniformly (in a way that is uniform in all directions) while supporting heavy compression loads, building system depends on its mechanical strength and rigidity because it is the main structural element, properties of concrete make it unable to provide enough protection against dynamic forces that during an actual earthquake.

Building design incorporate grade 60 steel (A615Gr60) reinforcing bar to extend its structural reinforcement capabilities bars provide the structural system with substantial resistance against tensile and bending forces which results in improved overall flexibility of the building system enables engineers to redistribute structural forces while eliminating the risk of fragile failures which protects the building during seismic events design team introduced grade 270 steel load-bearing tendons (A41Gr270) into the building design to establish stronger support structures for the concrete sections.

The induced post-tension creates controlled concrete cracking which improves the structure’s ability to handle dynamic loads while extending its lifespan, the system increases seismic performance by enhancing the building’s ability to return to its preceded performance state after experiencing structural changes, engineers establish precise structural measurements which include all materials needed to build beams and columns while they study how withholding will affect their performance throughout the study.

Table 1 - Material Properties - General

Material	Type	SymType	Grade
4000Psi	Concrete	Isotropic	f'c 4000 psi
A416Gr270	Tendon	Uniaxial	Grade 270
A615Gr60	Rebar	Uniaxial	Grade 60
B25	Concrete	Isotropic	B25

Frame Sections

Table 2 - Frame Section Property Definitions - Summary

Name	**Material**	**Shape**	**Color**	**Area mm2**	**J mm4**	**I33 mm4**	**I22 mm4**	**I23 mm4**
BEAM	B25	Concrete Rectangular	Green	60000	470746119.3	450000000	200000000	-
CLM	B25	Concrete Rectangular	Gray8Dark	87500	1024249272.2	893229166.7	455729166.7	-

Table 3 - Frame Section Property Definitions - Summary

Name	**As2 mm2**	**As3 mm2**	**S33Pos mm3**	**S33Neg mm3**	**S22Pos mm3**	**S22Neg mm3**	**Z33 mm3**	**Z22 mm3**	**R33 mm**	**R22 mm**
BEAM	50000	50000	3000000	3000000	2000000	2000000	4500000	3000000	86.6	57.7
CLM	72916.7	72916.7	5104166.7	5104166.7	3645833.3	3645833.3	7656250	5468750	101	72.2

Table 4 - Frame Section Property Definitions - Summary

Name	**CG Offset 3 mm**	**CG Offset 2 mm**	**PNA Offset 3 mm**	**PNA Offset 2 mm**	**Area Modifier**	**As2 Modifier**	**As3 Modifier**	**J Modifier**	**I33 Modifier**	**I22 Modifier**	**Mass Modifier**
BEAM	-	-	-	-	1	1	1	1	1	1	1
CLM	-	-	-	-	1	1	1	1	1	1	1

Table 5 - Frame Section Property Definitions - Summary

Name	**Weight Modifier**
BEAM	1
CLM	1

Shell Sections

Table 6 - Area Section Property Definitions - Summary

Name	**Type**	**Element Type**	**Material**	**Total Thickness mm**	**Deck Material**	**Deck Depth mm**
SLAB	Slab	Shell-Thin	B25	150		
Wall1	Wall	Shell-Thin	4000Psi	250		

Renforcement Sizes

Table 7 - Reinforcing Bar Sizes

Name	**Diameter mm**	**Area mm2**
10	10	78.5
18	18	254.5
20	20	314.2

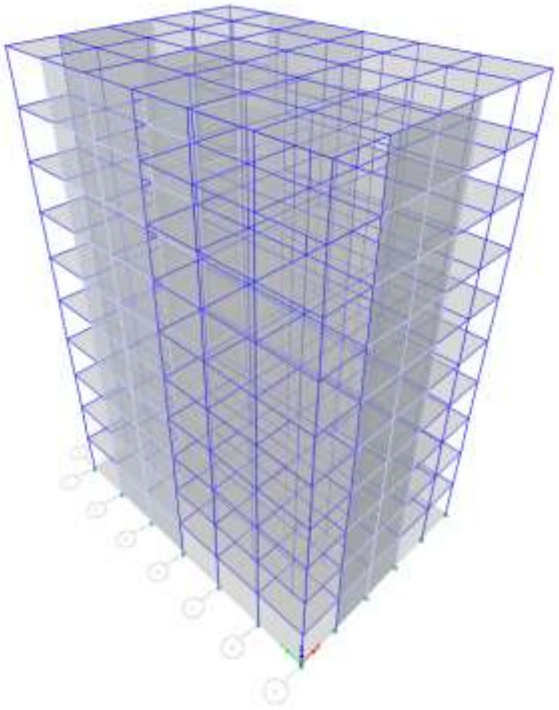

Figure 1. analysis

The analysis of procedures (modal analysis, drifts performance criteria) is made in 12 modes analyzed with cumulative mass participation > 90% (Sum RX is 0.81, Sum RY is 0.84, Sum RZ is 0.91) and periods are 0.029 to 0.522 with a frequency that lies between 1.915 to 34.649 Hz (high rigidity) and the criteria according to ASCE 7-16 must be lower than 2.5 of ratios for the rigidity regularity and acceleration limit and the hybrid validation will be done by deep deterministic networks (DCNN) on Google view images (GSV) for automatic extraction characteristics SBST-GEM.

The results

1. Participating mass ratio

The participating mass ratio is the representation of the total fraction mass of the building that actually participates in the movement (the higher this ratio are better the structure is likely to behave under seismic solicitations)
After 12 modes capture > 90% of the cumulative participatory mass (Sum RX is 0.81, Sum RY is 0.84, Sum RZ is 0.91 at the 12 model) that confirming a good structural mobilization.

Table 8 - Participation Weight ratio

Case	Mode	SumRX	SumRY	SumRZ
Modal	1	0.3884	0.0008	0.0003
Modal	2	0.3893	0.3101	0.1194
Modal	3	0.3893	0.3758	0.6499
Modal	4	0.6241	0.3835	0.6507
Modal	5	0.6323	0.6213	0.6665
Modal	6	0.6323	0.6485	0.8412
Modal	7	0.6447	0.7413	0.8448
Modal	8	0.747	0.7528	0.8452
Modal	9	0.7471	0.7676	0.8996
Modal	10	0.7499	0.8116	0.9075
Modal	11	0.8086	0.8142	0.9077

Case	Mode	SumRX	SumRY	SumRZ
Modal	12	0.8093	0.8398	0.9077

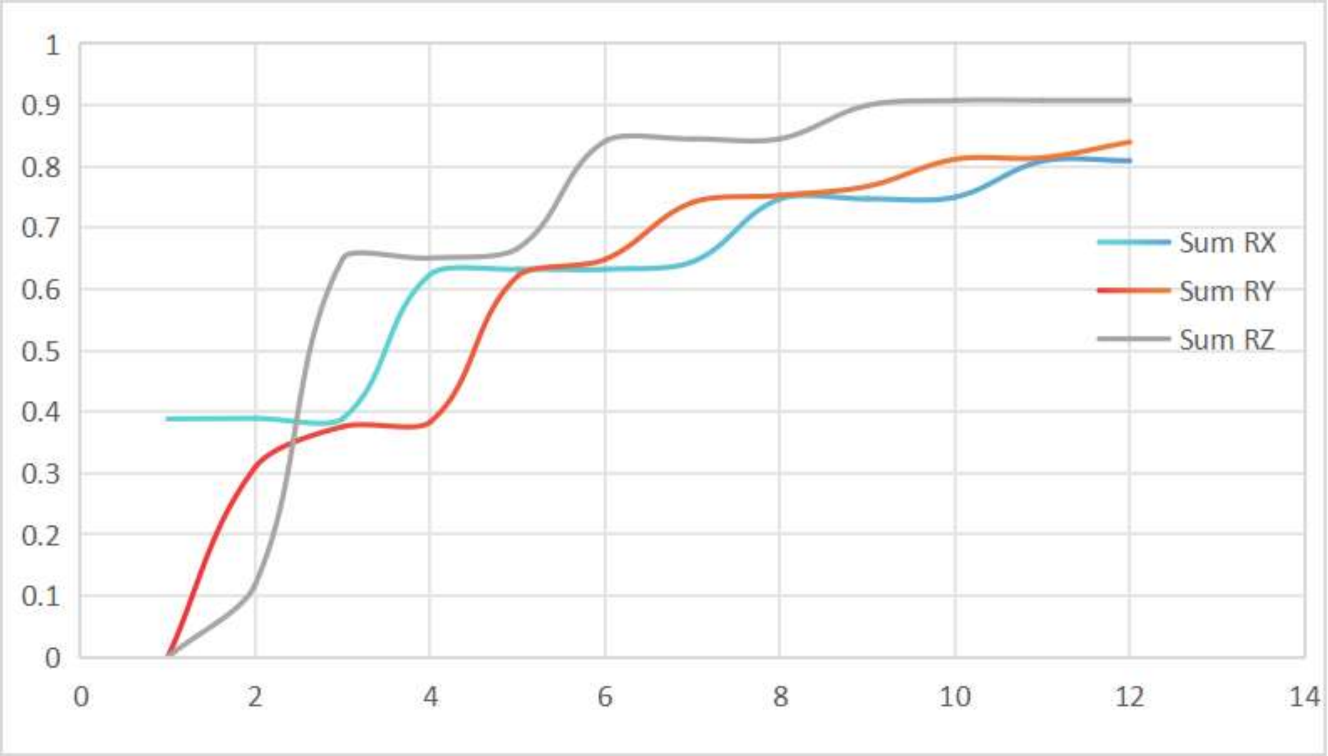

Figure 2. mass ratio

Modal periods and frequencies

The graph shows different modes of deformations that could be taken up by the structure during an earthquake, frequency is a measure of how many vibrations occur in a second and is determined by the stiffness and weight of the structure, the graph and table provide herein represent changes in the form of deformation and the frequency of vibrations (cycles per second) of a building as per the horizontal axis of the graph.

Table 9 - Modal Periods And Frequencies

Case	Mode	Period sec	Frequency cyc/sec	CircFreq rad/sec	Eigenvalue rad2/sec2
Modal	1	0.522	1.915	12.0319	144.7673
Modal	2	0.479	2.088	13.1173	172.0626
Modal	3	0.366	2.732	17.1645	294.6188
Modal	4	0.112	8.96	56.2952	3169.1517
Modal	5	0.109	9.139	57.4217	3297.2523
Modal	6	0.081	12.32	77.4117	5992.5665
Modal	7	0.051	19.433	122.1027	14909.076
Modal	8	0.051	19.779	124.2757	15444.4619
Modal	9	0.037	27.145	170.5571	29089.7267
Modal	10	0.035	28.446	178.7285	31943.8843
Modal	11	0.034	29.574	185.8219	34529.7614
Modal	12	0.029	34.649	217.7045	47395.2442

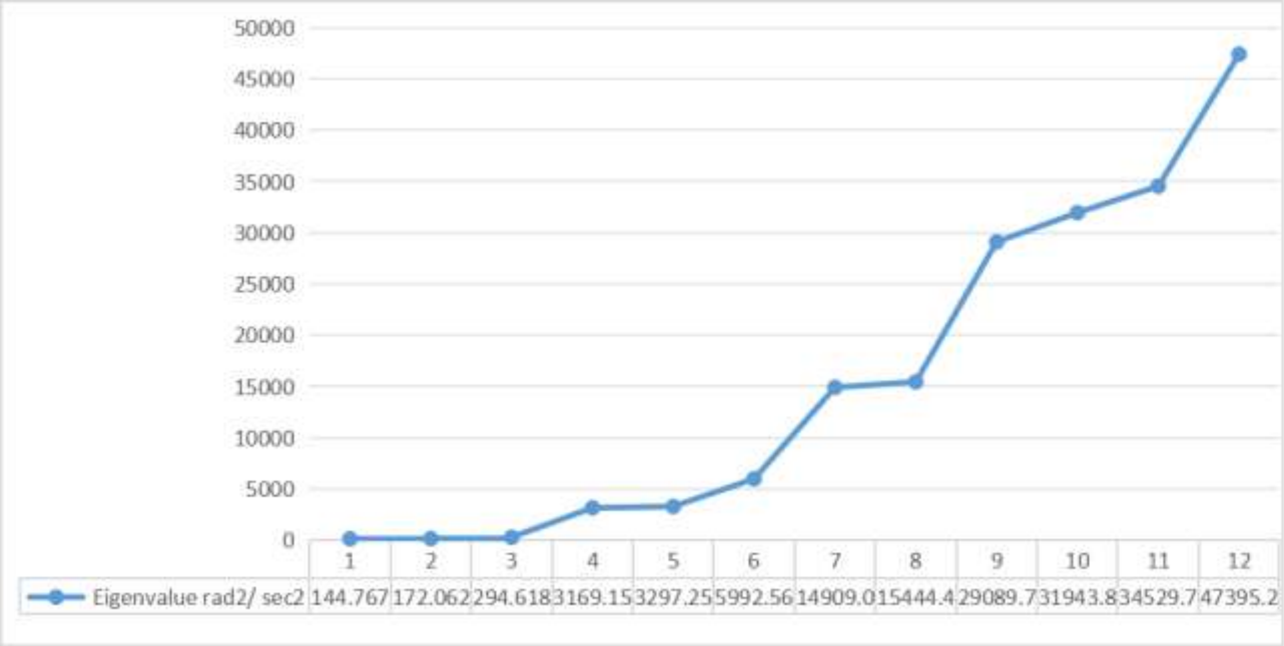

Figure 3. Periods And Frequencies

Seismic results for the tenth floor

The graph provided presents the results of a seismic analysis of a building .the detailed interpretation of the information it contains.

The graph shows the maximum (orange curve), average (blue curve) and ratio (green curve). the movements of the building on the 10th floor in X and Y direction as a function of the horizontal pivot.

Tableau.10- seismic for the tenth floor

Story	Output Case	Case Type	Step Type	Direction	Max Drift mm	Avg Drift mm	Ratio
Story10	SEISMIC	Lin-static	Max	X	6.707	5.328	1.259
Story10	SEISMIC	Lin-static	Max	Y	7.322	7.244	1.011
Story10	SEISMIC	Lin-static	Min	X	0.092	0.057	1.609
Story10	SEISMIC	Lin-static	Min	Y	1.085	0.075	14.542

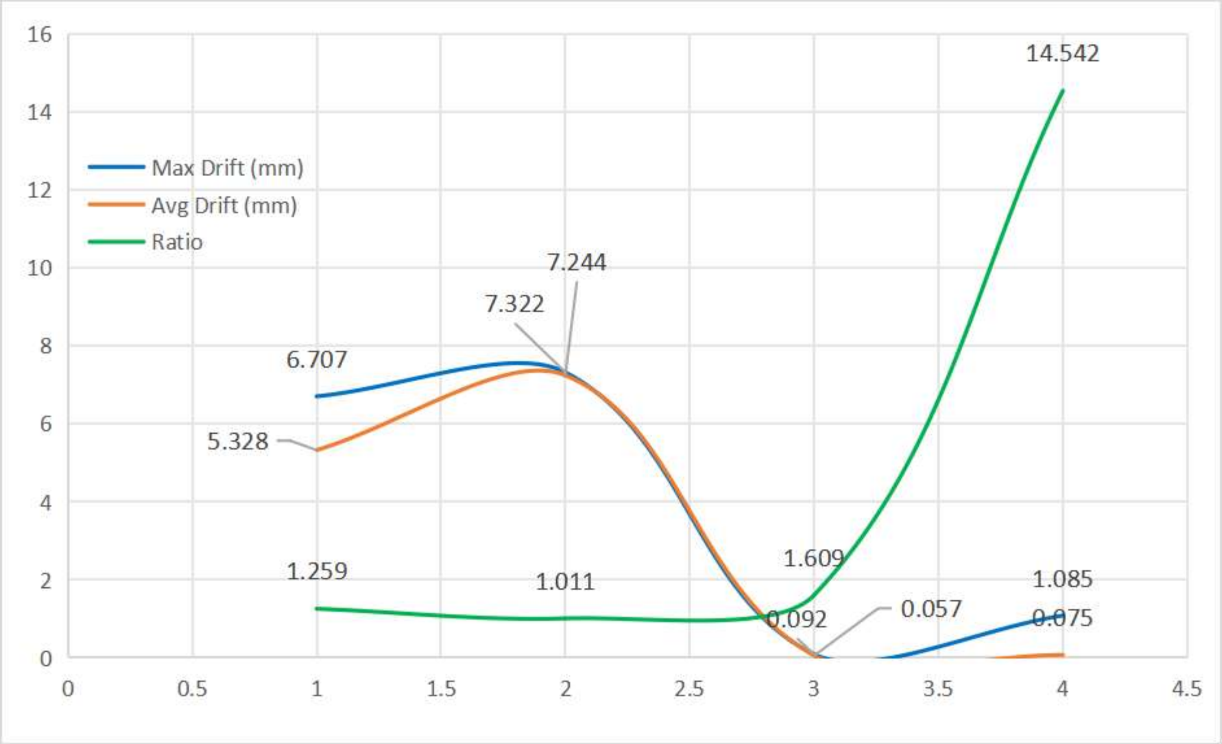

Figure 4. seismic

Discussion

1. Analysis and interpretation of the results of preparatory mass

The shows tree curves that shows the participating mass ratios in the x,y and z directions of a 10 storey building (respectively Sum RX, Sum RY and Sum RZ) and in this graph we observe that ration increases gradually with the horizontal axis indicating that the participation of the mass of the building in seismic movements is becoming more and more important and the curves reach maximum values of about 0.9, this means that nearly 90% of total mass of the building participates in seismic movements.

High participating mass ratio are to land this indicates that the structure is well designing to withstand seismic solicitations and capable of mobilizing a large part of its mass to dissipate seismic energy which limits the movements and efforts of the structural elements. [14], [15]

This analysis allows for the validation according to standard (ASCE 7-16) that shown the seismic design of this building is well mastered and we can have confidence in it ability to withstand earthquakes.

2. **Modal periods and frequencies**

The graph shows a curve that represents the evolution of the mode as a function of the horizontal axis but one can be inclined by observing well we notice the mode gradually increasing from 1.915 to 34.649 cycles in point 12 on the horizontal axis. in conclusion and according to the standards this increase in mode indicates that the structure is becoming increasingly rigid and tends to vibrate at higher frequencies regarding for a 10 story building. A very rigid structure attracts and amplified seismic accelerations, On the other hand it is necessary to strengthen the lateral rigidity in ETABS model by adding additional bracing sails in the Y direction to balance the rigidity with the X direction or increase the dimensions of the posts or use more robust section in the critical areas of direction Y and integrate rigid gantries (moment resisting frames) and it is necessary to know that the vibration modes and associated frequencies are key parameters in the seismic design of buildings because they guide engineers in the choice of structural systems (beams, columns, slab,..) in order to optimize the dynamic response of the model.

Interpretation of the results for 10th floor and analysis

The maximum ratio reaches is 14.5mm which means that the maximum displacements are 14.5 times higher.

According to typical allowable limits which are generally around 1.5 to 2.5 for most seismic codes (such as ASCE 7-16 or Euro-code 8), this indicates localized weakness unevenness of rigidity or significant twisting effect in the structure, Such a high ratio means that the displacements are not uniform which can lead to severe non structural damage and potentially structural failure under strong seismic load.

To improve resistance to deformations and mitigate excessive rigidity (too short periods and high frequencies) it is necessary to model the soil-structure if the model assumes a rigid recessed base it will reduce the rigidity because a

flexible floor reduces the rigidity we must also check the rigidity of the links (posts-slabs, beams-columns) to avoid overestimation of rigidity
To strengthen monitoring we need digital twin integration with real-time sensors ML ETABS hybridization.

Conclusion

The results of the research conform the ability of the ETABS numerical to faithfully reproduce the dynamic behavior of a 10 story tower under extreme earthquake MW 9.5 modal analyses capture 90%[16] of the participating mass with short periods (0.029 to 0.522s), which means that the tower is very rigid and good for global drift, However,critical drift ratios (14.542 on Y direction) show local irregularities that don't match ASCE 7-16 and ACI 318-14. the results confirm the overall reliability of digital tools for skyscrapers while highlighting the importance of response regularity and compliance with normative criteria to correct the identified weaknesses, it is necessary to add bracing sail in the direction Y to balance the the rigidity X/Y also increase the column sections (CLM) and integrate the resistant moment gantries also model the soil structure interaction (flexible or recessed base) and finally check the stiffness of the connections (columns-slabs, beams-columns) and attenuate excessive frequencies (>30 Hz), digital models offer sufficient reliability for secure skyscraper designs, combined with AI validations (DCNN+GSV+GEM) and probabilistic analyses. Digital twin integration with real-time sensors, ML ETABS hybridization for automatic calibration and extension to many physics scenarios (seismic) a critical approach persists in the face of material and environmental favoring safe and efficient structures.

Reference

1. Mega-tall buildings: current trends, challenges and future prospects

July 2025,authors: Tanmoy konar

2. Performance-Based Wind Design of High-Rise Buildings Using Generated Time-History Wind Loads

Authors: Seung yong jeong, Hamidreza Alinejad, Thomas H.-K.Kang

3. Validity, Verifiability, and Confirmability: A Critique of Multiphase Packed Bed Modeling, by Masood OtarodORCID, Department of Mathematics, University of Scranton, Scranton, PA 18510, USA, Modelling 2024, 5(3), 720-736;https://doi.org/10.3390/modelling5030038,Submission received: 1 May 2024 / Revised: 14 June 2024 / Accepted: 24 June 2024 / Published: 29 June 2024

4. Advances in the discrete elements method applied to soil, rock and concrete mechanics, January 2009Electronic Journal of Geotechnical Engineering 8, Authors: Frederic Victor Donze, Vincent Richefeu, Sophie-Adelaide Magnier

5. Data-based scheme for a coupled chemo-mechanical problem at two scales for heterogeneous materials under transient chemical diffusion

The author's links open the overlay panel

Xinwei Yang has, Chunwang He has, Jie Yang b, Yikun Wu c, The Yang a, Hao-Sen Chen has

6. Modal testing and finite element model updating of full-scale hybrid timber-concrete building

August 2023Engineering Structures 289(3):116250, DOI:10.1016/j.engstruct.2023.116250, LicenseCC BY 4.0, Authors:Blaz Kurent, University of Ljubljana, Wai Kei Ao, The Hong Kong Polytechnic University, Aleksandar Pavic, Fernando Pérez Pérez, ETH Zurich

7. Dynamic Behavior of the Palazzo Lombardia Tower: Comparison of Numerical Models and Experimental Results

June 2014Journal of Performance of Constructed Facilities 28(3):491-501

DOI:10.1061/(ASCE)CF.1943-5509.0000431

Authors:Alfredo Cigada, Politecnico di Milano, Elena Mola, Franco Mola, Gianfranco Stella

8. A new real-time aeroelastic hybrid simulation system for wind tunnel testing on adaptive extended Kalman filter based section model

The author's links open the overlay panel, Wenkai Du, Guangzhong Gao, Suhan Li, Bo Fu , Jiawu , Ledong Zhu

9. Recognition of the identity of cities: how does representation bias influence the predictability and reproducibility of the model?

November 2025Computers Environment and Urban Systems 123:102370

DOI:10.1016/j.compenvurbsys.2025.102370

Authors:Xiang Zhang, Sun Yat-sen University, Fan Yang, Zongze He, Weijia Li

10. Automated characterization of buildings for seismic risk assessment using street-level images and deep learning

The author's links open the overlay panel, Patrick Aravena Pelizari, Christian Geiß, Paula Aguirre, Hernán Santa Maria, Yvonne Merino Peña, Hannes Taubenböck

11. Automation of building typology identification for seismic risk assessment using deep learning.

Daniel Gomez, Daniela Charris, Winston Percybrooks, Carlos A Arteta

First publication: April 12, 2025

12. Automated Building Structural Parameters Extraction for Seismic Risk Assessment in Villa El Salvador Area

December 2025Journal of Disaster Research 20(6):959-974

DOI:10.20965/jdr.2025.p0959

Authors:Jhianpiere Salinas, Miguel Diaz; National University of Engineering, Carlos Zavala; National University of Engineering, Masashi Matsuoka;Tokyo Institute of Technology

13. Deep learning in earthquake engineering: a comprehensive review.

Yazhou Xie

14. A comparative study of "missing mass" correction methods for response spectrum method of seismic analysis

Author links open overlay panel, M. Dhileep, P.R. Bose

Department of Civil Engineering, Delhi College of Engineering, Delhi-42, India

Received 25 May 2007, Accepted 7 April 2008, Available online 21 May 2008.

15. SEISMIC ANALYSIS OF A MULTI-STORY TIMBER-CONCRETE BUILDING AND DESIGNING FOR REUSE

Author: Sivert Lie1, Themistoklis Tsalkatidis

16. A new method to estimate the input energy of MDOF structures

December 2019Digital Patterns in Civil Engineering 4(2):36-43

DOI:10.52547/nmce.4.2.36

Authors:Daniel Davarnia; University of Tabriz, Bahman Farahmand Azar; University of Tabriz