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TECHNOLOGY, ISLAMABAD



Addressing the Short Comings of BIM Tools for Structural Assessment of RC Tall Building

by

Usman Khalid

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degree of Master of Science

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Abstract

Building Information Modeling (BIM) technology has made structural design and analysis more efficient, coordinated, and accurate. The BIM-integrated structural analysis software offers advanced modelling, analysis and design functions for complex structures, but their capability and reliability for seismic analysis of tall reinforced concrete buildings needs to be further examined. This research investigates and compares seismic analysis capabilities of Autodesk Robot Structural Analysis Professional (RSAP) and Tekla Structural Designer (TSD) with ETABS for a 35-story reinforced concrete dual system building. The building was modeled as per ASCE 7-22 and ACI 318-19. The three software platforms were tested based on modal time period, seismic weight, base shear, roof displacement, story drift ratio, and torsional irregularity. The results from RSAP and TSD were checked against the benchmark ETABS model. The fundamental time period in ETABS, RSAP and TSD in the x-direction was 5.00 s, 4.79 s, and 4.80 s, respectively, and in the y-direction was 5.67 s, 4.29 s, and 4.60 s, respectively. The seismic weight was 195,616.739 kip in ETABS, 195,410.945 kip in RSAP, and 195,540.945 kip in TSD, which shows consistency in the mass representation between the three software. The base shear values were 7,463.14 kip, 7,470.00 kip, and 7,465.30 kip, respectively, showing good agreement in seismic load calculation. The maximum roof displacement in the x-direction in ETABS, RSAP and TSD were 29.00 in, 28.80 in and 28.00 in, respectively, and in the y-direction were 24.00 in, 23.87 in and 23.00 in, respectively. The maximum story drift ratios from the three software packages varied from 0.0019 to 0.0029, which is less than the ASCE 7-22 allowable story drift ratio of 0.0036. The torsional irregularity ratios ranged from 1.12-1.18 in ETABS, 1.04-1.09 in RSAP, and 1.09-1.13 in TSD, all within the ASCE 7-22 limit of 1.20. Overall, the results indicate that RSAP and TSD are capable of conducting seismic analysis of tall reinforced concrete structures with high level of reliability using code-based approach, and the global structural responses are in good agreement with ETABS. However, shortcomings were identified in advance performance-based seismic assessment. RSAP does not have nonlinear material modeling, P-M2-M3, P-M3 plastic hinge definitions, and

ASCE 41-17 performance evaluation procedures. Likewise, TSD does not include nonlinear material modeling, plastic hinge assignment, nonlinear static pushover analysis and performance-level evaluation. Thus, BIM-based structural analysis software can be used effectively for seismic analysis and design of tall reinforced concrete buildings, but further development is needed to include comprehensive nonlinear analysis, plastic hinge modeling, and ASCE 41-17-based performance evaluation capabilities.

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List of Abbreviations

CBD	Code-Based Design
CBDA	Code-Based Design Approach
CBF	Concentrically Braced Frame
CP	Collapse Prevention
EQGM	Earthquake Ground Motion
FEMA	Federal Emergency Management Agency
IO	Immediate Occupancy
IS	Indian Standard
LS	Life Safety
P-B EQ-RD	Performance-Based Earthquake-Resistant Design
PBD	Performance-Based Design
PBDA	Performance-Based Design Approach
PBSD	Performance-Based Seismic Design
RC	Reinforced Concrete

Chapter 1

Introduction

1.1 Background

The ongoing development of tall buildings construction as a way of making the communities all over the world to be more modern has been the cause of the rising demand towards sustainable urban habitats [1]. The vast majority of tall buildings are designed in specification-based or prescriptive approach designs that follow the construction norms and standards which are utilized to measure the stressors exerted on the structure and design the structural elements to withstand those stressors [2]. While the floor-to-floor height varies by building type, CTBUH believes that, in general, a building with 14 or more stories or 50 meters (165 feet) or more can be considered a “tall building” [3].

In this regard, the codes embrace safety and serviceability limit states. Safety or ultimate limit state is maximum limit to which a structure may sustain itself without failure or collapse (i.e. yielding with excessive deformation, lateral instability, fatigue) [4]. On the other hand, serviceability limit state is the condition in which the structure must be able to perform the intended purpose (e.g. excessive deflections, excessive sway acceleration that makes people uncomfortable, and people being comfortable near buildings) [5].

In the last few decades, performance-based approach has been implemented by a number of researchers [6]. Under the Performance-Based Design (PBD) the

structural system of any building must deliver the desired performance rather than explicitly specifying how to build it. The Federal Emergency Management Agency provides and explains examples of intended performance [7]. An example is that the level of operational performance is when the building suffers the least damage and non-essential functions are slightly impaired, whereas the level of collapse prevention is when the building stands upright but barely only and any other loss or damage is tolerable [8]. Performance Based Design (PBD) is a paradigm shift in earthquake engineering. Instead of relying on a simplified application of force reduction, it presents a design process whereby performance objectives for performance levels of Immediate Occupancy, Life Safety, and Collapse Prevention are achieved at different levels of seismic intensity [9].

Design methods can always be simpler to implement using a specified approach such as the Specification-based approach compared to the performance-based approach. The methods known as specification-based, or code-bases-design, incorporate a number of safety factors in order to take consideration of the unknown in both loading and resistance cases and of the simplifications inherent in the methods of analysis [10]. The elastic seismic forces are calculated in Code-Based Design (CBD) using the response spectra and then are reduced by response modification factors that include considerations of ductility, overstrength, and redundancy [11]. Structural engineering has been based upon methods such as Response Spectrum Analysis (RSA) since long time ago, as evidenced in standards such as UBC 97 or ASCE 7 [12].

The progress of BIM methodology in the Architectural, Engineering, and Construction (AEC) sector brings innovative and new approaches for handling both existing and new constructions [13]. Using digital design in construction through BIM methodologies has significantly contributed to reducing the construction industry's carbon footprint. The current BIM system provides a detailed computerized representation that will capture the physical attributes as well as the functionality of the building. Signify a centralized information source, allowing collaboration and decision-making among various participants throughout the building's lifecycle stages [14]. BIM allows unifying various dimensions of building data, such

as geometry, materials, schedule, cost, and sustainability data, which allows planning, tracking, and optimization of resources during construction and operation. Moreover, by facilitating early clash detection, automated quantity take-offs, and energy performance simulations, BIM reduces errors, rework, and material waste, further enhancing efficiency and environmental sustainability [15].

1.2 Research Motivation and Problem Statement

The growing adoption of Building Information Modeling (BIM) in structural engineering has encouraged engineers to rely on integrated digital platforms for both modeling and analysis of high-rise reinforced concrete buildings. Specialized software like Tekla Structures and Autodesk Robot Structural Analysis allows in-depth structural modeling and analytical assessment as a single workflow. Nevertheless, it is unclear how well BIM-based platforms could perform accurate structural evaluations, especially in comparison with proven analytical tools, like the ETABS. Since performance-based design involves the accurate estimation of nonlinear behavior and seismic response parameters, it is crucial to confirm the ability of BIM-integrated tools to provide similar and reliable outcomes. This research is motivated by the need to critically evaluate and enhance the accuracy of BIM-based structural analysis workflows for tall RC buildings in seismic regions.

The problem is “The accuracy and reliability of structural assessment of tall reinforced concrete buildings using BIM-based structural analysis platforms, such as Tekla Structures and Autodesk Robot Structural Analysis, is not well established. Seismic response parameters derived from the various differences in modelling approach, formulation of stiffness and mass, element discretization and analysis procedures may differ significantly from the existing analytical software such as ETABS. Therefore, for the seismic analysis of the tall RC building, it is necessary to conduct a systematic comparative evaluation of consistency, accuracy and reliability of the BIM-based platforms”.

1.2.1 Research Questions

This research is structured around the following key questions:

- i. What are the differences between the seismic performance results for a tall RC building modeled independently in BIM-based tools and a benchmark ETABS model?
- ii. What are the variations in the major engineering demand parameters like inter-story drift, base shear, fundamental time period, plastic hinge formation and floor acceleration among the three software platforms?
- iii. What are the inherent limitations of BIM-based structural modeling tools in performing structural analyses of tall RC buildings?
- iv. What potential improvements can be made to the BIM-based structural modeling tools to enhance their accuracy and reliability in performing structural analysis of tall reinforced concrete buildings?

1.3 Overall Goal of the Research Program and Specific Aim of this MS Thesis

The overall goal of this MS thesis is

To develop a typical tall structure built from reinforced concrete, relying on a combined lateral-resistance approach, integrating rigid frame action with wall-based shear resistance, to withstand horizontal forces using a traditional, force-based design approach per ASCE 7-22, and to thoroughly evaluate the structure's seismic behavior through a capacity-based framework, employing inelastic static (pushover) analysis in accordance with ASCE 41-17.

The particular objective of this master's thesis is to evaluate parameters including drift, formation of plastic hinges, accelerations at the floor level and residual displacement, with the ultimate goal of providing practical guidance to incorporate demand-capacity seismic design practices within tall building engineering in seismically active areas.

1.4 Scope of Work and Study Limitations

The study aims to assess the structural performance of a 35-story dual lateral system (DLS) reinforced concrete structure, which features a combination of moment-resisting frames (MRF) and shear walls. The building is modeled and analyzed independently in Tekla Structures and Autodesk Robot Structural Analysis, and results of ETABS are used as a benchmark. The study is confined to the superstructure of the building, assuming fixed-base conditions and excluding soil-structure interaction effects. The non-load-bearing components are not modeled individually; rather, their effects are represented through the use of various model parameters, including inter-story drift and floor acceleration. The main aim of the research is to assess the important seismic performance factors, such as inter-story drift ratios, floor accelerations, and other structural response parameters. Additionally, the study aims to identify BIM-related modeling and interoperability limitations within the two software platforms (Tekla Structures and Autodesk Robot Structural Analysis), and to propose an improved approach for more reliable structural assessment of tall reinforced concrete buildings.

The study limitations are:

- i. The analysis is restricted to the superstructure of the building and does not include the effects of soil structure interaction, assuming fixed-base conditions throughout.
- ii. Rather than being directly represented in the model, non-structural elements are accounted for indirectly, with their influence reflected through seismic response indicators.
- iii. The research also concentrates on one building structure, which can be studied in more detail and comparatively but might not be applicable to other building structures.
- iv. The study does not extend to transferring BIM-based analytical models to advance nonlinear analysis software for performance-based seismic assessment, only to Autodesk Robot Structural Analysis Professional and Tekla Structural Designer.

Although these constraints restrict the scope, the study provides useful information on BIM-based seismic performance assessment, and the study is likely to guide future studies with more complex modeling factors.

1.4.1 Justification for the Chosen Constraints

The research is confined to tall reinforced concrete structures with dual structural system (moment-resisting frames and shear walls) since the systems are widely utilized in high rise construction to deliver strength and ductility to the structure under seismic loads. Autodesk robot structural analysis and Tekla structures are chosen to explore the potential and shortcomings of the BIM integrated workflows, and ETABS is used as a reliable source of advanced seismic analysis. The research bridges the interoperability, modeling assumptions, and automated code compliance verification gaps by modeling the same building on such platforms and the insights gained are useful in enhancing seismic design practice in high rise reinforced concrete buildings.

1.5 Brief Methodology

The research methodology commences with an extensive review of relevant literature to establish the theoretical foundation for BIM-based performance assessment, while identifying gaps in current research related to BIM integration and response-based seismic assessment of tall RC structures. The 35-story reinforced concrete building with a combined frame-wall structural system, already modeled in ETABS, serves as the benchmark for comparison. The next step involves recreating the same building model in Robot Structural Analysis and Tekla Structures, ensuring consistency with the ETABS model for a meaningful evaluation of the BIM tools.

The design is based on ASCE 7-22 provisions and Response Spectrum Analysis is used to ensure consistency across all platforms. In the performance-based assessment, nonlinear models, which have plastic hinges in all three platforms, are

developed. Statics Pushover Analysis with various patterns of lateral loads is done to determine the inelastic seismic response.

The findings of the Robot and Tekla models are contrasted to the ETABS benchmark, in terms of performance parameters including drifts, hinge formations and accelerations. This comparison will assist in determining the limitations, differences and deficiencies of BIM-integrated tools in the execution of structural assessment. Recommendations are made based on these findings to overcome these limitations so that BIM tools may be used more effectively and accurately in the seismic analysis. Lastly, the outcomes of all models are compared and contrasted systematically. Structural assessment gaps in BIM workflow are identified and suggestions are made. These results are then summarized and generalized into the final thesis report, giving useful recommendations for the earthquake-resistant design of tall RC structures using BIM.

1.6 Research Significance and Novelty

1.6.1 Research Novelty

The study is innovative in the application of the high-level structural assessment principles to tall RC buildings with dual structural systems in Autodesk Robot Structural Analysis and Tekla Structures. In contrast to traditional studies which use only force-based design, this study combines both nonlinear static (pushover) and dynamic analyses to evaluate the real seismic performance, such as plastic hinge development, inter-story drift, and energy dissipation. The direct comparison of benchmark ETABS models and independently developed Tekla-Robot workflows offers exclusive information about the limitations of modeling, structural weaknesses, and design efficiency of high-rise RC buildings.

1.6.2 Significance

The study improves structural safety assessment, informs better design practices, and encourages resilient urban development by determining the differences between conventional and BIM-integrated performance-based analyses. It is useful

to engineers, policymakers, and academia as it gives evidence-based advice on how to adopt PBD methods in high-rise RC construction.

1.6.3 Practical Implementation

The application of this research in practice is that it can be directly applied to the Earthquake-resistant design and evaluation of tall RC buildings in professional engineering practice. The results can be used to assist structural engineers to optimize some of the critical design parameters, including lateral stiffness, inter-story drift control, the size of members, and the allocation of seismic forces in the dual structural systems. Through performance-based analysis, engineers will be in a better position to detect key areas of vulnerability, foresee probable damage patterns, and enhance the safety margins of high-rise buildings under earthquake loading. The method also helps in more effective utilization of construction materials by balancing the requirements of strength, ductility, and serviceability in a rational way.

1.6.4 National and Global Impact with Emphasis on SDGs Relevance

The research has significant national and international significance as it will help in the creation of safer, more resilient, and more sustainable high-rise structures in seismic prone areas. At national level, it can assist in enhancing urban infrastructure by encouraging better earthquake-resistant design of tall RC buildings, which is critical in saving lives, minimizing structural damage, and facilitating long-term urban development. On the international scale, the research helps in the development of performance-based design and BIM-based engineering strategies which can be implemented in most of the earthquake-prone nations. The research is also closely aligned with the Sustainable Development Goals (SDGs), especially SDG 11: Sustainable Cities and Communities, by encouraging resilient and safe construction practices, and SDG 9, which emphasizes industrial development, ingenuity, and infrastructure, accomplished through the deployment of advanced

computational tools and innovative structural analysis methods for stronger and more reliable infrastructure.

1.6.5 Research Challenges

The main issues in this study are the need to model the complicated nonlinear behavior of reinforced concrete structures, to capture the higher-mode effects which have a strong impact on the response of tall buildings, and to simulate realistic seismic loading conditions. Additional study constraints are fixed-base assumptions, simplified analysis of non-structural elements, and the high-computational demands of nonlinear time-history analysis. Moreover, the developed models should be checked with the practical and realistic structural conditions in order to make sure that the results are accurate and reliable.

1.6.6 Ethical and Management Considerations Including Risk Management

In this study, ethical considerations involve upholding academic integrity, reporting data accurately, and making responsible interpretations of findings in such a way that the findings does not misinform structural design decisions. Risk management is aimed at the creation of trustworthy analytical models, safeguarding of digital and project data and reduction of the mistake in the seismic assessment which may influence the actual structural safety. It is also necessary to manage the project properly, which implies that it should be supervised, periodically review the progress of the project, and ensure that the best practices in software use are followed during the research process.

1.6.7 Project Outcomes, Sales Viability and Promotional Scope

The project will focus on addressing the shortcomings of BIM tools for performance-based assessment of code compliance in tall RC buildings. It will provide a proven

BIM seismic analysis framework, and a comprehensive comparative performance analysis reports, indicating the shortcomings of the existing BIM capabilities in evaluating seismic resilience. It will give recommendations on how to integrate the principles of Performance-Based Design (PBD) to make BIM tools more effective in assessing code compliance. Such insights will be presented at conferences and to engineering firms, and they will provide practical solutions to the current limitations. The methodology will also be created as consultancy tools or add-ons to software, and they can be commercialized. The project will enhance the use of BIM in code compliance and seismic design standards of tall RC buildings by incorporating these tools into professional training programs.

1.7 Thesis Outline

This thesis comprises six chapters, organized as follows:

Chapter 1 - Introduction

This chapter introduces the need for performance-based seismic design in the construction of tall reinforced concrete (RC) buildings, emphasizing the shift from customary code-governed design to demand-capacity design. It highlights the limitations of current BIM tools in assessing seismic compliance for RC tall buildings, setting the stage for this research.

Chapter 2 - Literature Review

This chapter delivers a wide-ranging review of the existing research base on seismic design methodologies for tall RC structures, emphasizing the divergence between conventional code-based and behavior-based approaches. It also explores the role of BIM tools in structural analysis and evaluates their applications in seismic assessments. Knowledge gaps in BIM workflows for performance-based assessment and the need for improvements in BIM-integrated tools for high-rise buildings will be discussed.

Chapter 3 - Methodology

The research methodology is detailed in this chapter. It describes the process of selecting and modeling a 35-story RC structure utilizing an integrated lateral-resisting system merging rigid frame action with structural shear walls using BIM software (Tekla Structures and Autodesk Robot Structural Analysis). A benchmark model created in ETABS will serve as the basis for comparison. The chapter also outlines the performance-based assessment procedures, including nonlinear analysis techniques such as Static Pushover and Response Spectrum Analysis.

Chapter 4 - Results and Analysis

This chapter discusses the results of the seismic performance evaluations for both code-based and performance-based designs. It presents the comparative results from BIM-based models (Tekla and Robot Structural Analysis) and the ETABS benchmark, with a focus on core seismic performance metrics, namely inter-story drift, base shear, plastic hinge occurrence, and floor acceleration. The chapter will analyze discrepancies, identifying the limitations of BIM tools and proposing potential improvements.

Chapter 5 - Conclusion and Recommendations

The final chapter gives a summary of the main lessons learned from the study and discusses the modifications that have to be made in BIM-based seismic assessment tools. It discusses the implications of the study for the practical design of tall RC buildings and outlines recommendations for further research. Future work could focus on expanding the use of BIM in performance-based seismic evaluations and refining interoperability between different BIM tools for more accurate assessments.

The thesis concludes with a comprehensive bibliography, listed immediately following Chapter 5.

Chapter 2

Literature Review

2.1 Background

The earthquake-resisting design and evaluation of tall RC structures are still one of the challenging and complex fields of structural engineering as the high-rise buildings become more complex and vulnerable to lateral loading. Unlike low-rise structures, in addition to gravity-load design, tall buildings are also subject to dynamic response considerations, higher-mode participation, drift control, torsional stability considerations, P-Delta effects, and force redistribution due to nonlinearity during strong earthquakes. This means that the basic compliance with the code is not sufficient for the analytical evaluation of tall reinforced concrete structures, which is increasingly dependent on the level of interpretation of the structural behavior, and therefore, on depth of performance.

While earthquake engineering is making advances, another digital tool that has become prevalent in the building sector is Building Information Modeling (BIM). BIM has revolutionized the process of design coordination, documentation, visualization and information integration. It has proven to be an effective multidisciplinary coordination platform, but using it directly to advanced structural analysis is still a concern. Especially, the application of BIM based tools in the

performance-based assessment of seismic code compliance in tall reinforced concrete buildings is not completely addressed. The analytical idealisation, interoperability, and nonlinear simulation ability of BIM can be less than ideal compared to specialised structural analysis software, while its ability to improve model consistency and information flow can also be limited.

This study aims to tackle this by examining the limitations of BIM tools in the performance-based assessment of code compliance of a tall building in reinforced concrete (RC). Accordingly, this chapter examines relevant literature related to tall reinforced concrete buildings, dual structural systems, and seismic design methodologies encompassing both code-based and performance-based approaches, seismic response parameters, BIM in structural engineering, and prior studies on BIM-based structural analysis and software benchmarking. Finally, the chapter concludes by stating the gap in the literature that serves as the motivation for the current thesis.

2.2 Evolution of RC Building Analysis and Design Principles

2.2.1 Traditional Working Stress Method vs Limit State Method

The design of reinforced concrete was previously constrained by the elastic working stress approach in which service stresses in concrete and steel were limited to allowable values for unfactored service loads [16]. Although the working stress method was simple in hand calculation, it did not explicitly show the ultimate strength reserve of the members of reinforced concrete under severe loading condition [17]. Working stress design was criticized by researchers for assuming the behaviour of concrete and steel is primarily elastic although reinforced concrete members can behave nonlinearly to failure [18]. To get a more rational safety format, the limit state method was used which separately checked the ultimate limit state and the serviceability limit state [19]. The collapse, flexural failure,

shear failure, instability and excessive plastic deformations under factored design loads were considered in the ultimate limit state checks [20]. Deflection, cracking, vibration, drift, durability and user comfort under normal operating conditions were included in serviceability limit state checks [21].

The partial safety factors applied to deal with the uncertainty of material strength, load intensity and assumptions of structural modelling made in the design were seen as more realistic and therefore considered by the authors as a more realistic approach for the limit state design [19]. The probabilistic basis of limit state design made the reliability of RC structures better than the allowable-stress methods based solely on elastic design. In tall RC buildings, limit state design became more significant due to the need to check gravity load, lateral load, P-delta effects, as well as serviceability drift limits in the same time [22]. The transition to working stress to limit state design also shifted the responsibility of the structural software with the requirement of tools that efficiently can handle multiple load cases and design combinations. With this development, however, limit state design continued to be mainly code-prescriptive, and not always representative of the damage condition of a structure following a strong earthquake. This restriction was important for RC tall buildings since two buildings with equal strength requirements may exhibit various drift shape, hinge mechanism and damage patterns [23]. Previous studies thus showed that strength safety alone was not a suitable parameter to assess the seismic performance of complex RC structural systems [24].

2.2.2 Transition from Code-Based to Performance-Based Design

Performance-based design (PBD) is a major paradigm change in seismic design. The code-based design method has always been based on the use of simplified models and safety factors to calculate the seismic performance of a building. Although they provide a good overall safety criterion, these approaches do not consider the

actual nonlinear response of structures, especially tall buildings under dynamic earthquake loading [25].

However, in the case of Performance Based Design, attention is paid to the actual performance of buildings in seismic events. PBD gives the engineer the opportunity to establish specific performance goals including life safety, non-collapse and reoccupancy of the building after an earthquake. PBD differs from conventional design approaches, which work with static forces, because it considers the performance of a building subjected to dynamic seismic forces and allows engineers model a building's components based on the varying magnitudes of the earthquakes [26]. In contrast to CBD, PBD is specifically designed to achieve a defined set of performance objectives across each category, Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), under specific hazard conditions [27]. PBD can give a more realistic picture of the performance of the structure but its use is typically limited to sophisticated, high-budget projects owing to the additional expense and effort required, along with the associated advantages are deemed to be worth it [28, 29]. The following figure represents the building's performance levels Immediate Occupancy, Life Safety, and Collapse Prevention under different seismic intensities:

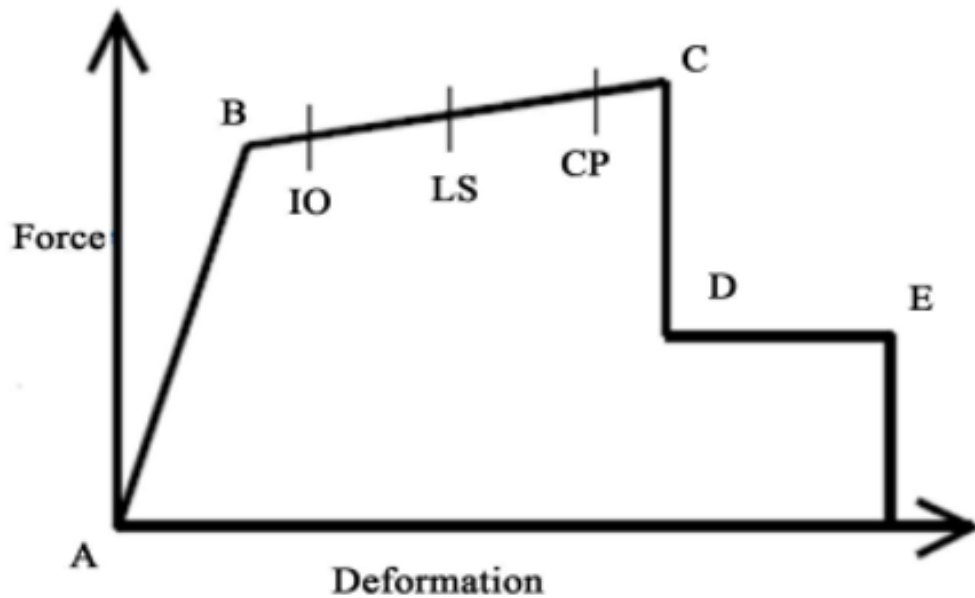


FIGURE 2.1: Seismic Performance Assessment with Performance-Based Design (PBD) [30]

While PBD is promising, it has not yet been widely adopted due to practical and theoretical hurdles. As for structural parts falling outside the primary category, such as secondary beams and joint connections, establishing clear damage states is challenging, which makes the system-level performance evaluation more difficult [31]. Structural performance evaluation may be best performed through trial-and-error modeling, which tends to be more computationally intensive and time consuming [9]. One of the other drawbacks is the mismatch between analytical studies and computational tools. There are limited numbers of structural tests for many advanced methods of PBD to validate the performance of the structures during actual earthquake shaking and therefore, limited confidence in predictions of post-earthquake load-carrying capacity and the behaviour of the system [32].

2.3 Code-Based Approaches for Gravity and Lateral Load Design

2.3.1 International Codes: ACI 318, Eurocode 2, IS 456

International RC design codes had already established standard procedures for designing beams, columns, slabs, walls, joints and foundations for gravity and lateral loads. In the design philosophy of ACI, the strength reduction factors, load combinations, member detailing, and serviceability checks were highlighted for reinforced concrete structure. The design was based on Eurocode with partial safety factors and limit state principles to control structural reliability for both ultimate and serviceability conditions [33]. Limit state concepts were also introduced into RC design in IS 456, and were incorporated for flexure, shear, compression, deflection, cracking and durability [34]. The codes enhanced the uniformity of design as the engineers were able to use the same rules for different structural systems and loading conditions. But, the code provisions in general tended to simplify real structural behavior by idealizing boundary conditions, simplified stiffness assumptions, and conservative safety factors. These simplifications may affect the lateral stiffness, drift demand, participation of walls, and frame-wall interaction in tall RC buildings [35]. The researchers noted that code-based design procedures

worked well for routine design, but were not sufficient for detailed performance prediction in strong earthquakes [36]. RC dual systems needed to be carefully coordinated in terms of frame and wall design, as walls imposed significant lateral forces on the frame, and frames offered deformation capacity and redundancy [37]. The code-based gravity design was generally simple, while the lateral design was more complicated due to the role of seismic and wind effects in controlling drift, overturning and stability in tall buildings [6].

2.3.2 Seismic Provisions: ASCE 7, UBC 97, Eurocode 8

Modern seismic design provisions had been developed to protect life safety by controlling strength, drift, ductility, redundancy, and detailing requirements in earthquake-resistant buildings [38]. ASCE type seismic procedures commonly used response spectrum analysis, equivalent lateral force procedures, modal combinations, and drift limits for building design [39]. UBC-based seismic design historically influenced many regions by introducing seismic zones, importance factors, soil coefficients, and response modification factors [40]. Eurocode 8 emphasized ductility classes, capacity design principles, behavior factors, regularity conditions, and displacement control for seismic-resistant structures [33]. These provisions simplified nonlinear seismic behavior by reducing elastic design forces according to expected ductility and overstrength. The force-reduction concept was practical, but it did not explicitly show where plastic hinges would form during severe [41]. In RC frames, local damage depended on reinforcement detailing, confinement, lap splice location, shear capacity, and plastic rotation capacity [42]. In RC shear walls, seismic performance depended on boundary element detailing, axial load ratio, wall aspect ratio, coupling action, and flexural-shear interaction [35]. Response spectrum analysis was useful for estimating modal response, base shear, and story drift, but it remained an elastic procedure unless combined with nonlinear assessment [39, 43]. Pushover analysis complemented code-based seismic design because it provided a capacity curve and approximate sequence of inelastic behavior [44]. Nonlinear time-history analysis provided more detailed performance evaluation, but it required reliable ground-motion scaling and robust nonlinear modeling assumptions [45].

2.4 BIM and Its Role in Seismic Performance Assessment

2.4.1 Role of BIM in Modern Construction

Building Information Modeling (BIM) is a revolutionary new technology that has changed the way the construction industry works, providing a single platform for managing every aspect of a building project. This technology involves combining geometric, material, scheduling, cost and performance data into a comprehensive digital model that allows all project stakeholders, architects, engineers, contractors and clients to access, modify and interact with the model in real-time [46]. In traditional construction, errors, omissions, and miscommunication are commonplace. BIM can help lower these issues. BIM also provides real-time updates and a central repository, making sure that any modifications to the design are communicated instantly to all disciplines, which facilitates decision-making, optimizes resources and prevents costly errors [47]. Furthermore, BIM helps in conducting complex simulations, such as modelling the seismic behavior of the buildings, to simulate the building performance under the different loading conditions, including the seismic forces. BIM can provide a more dynamic and accurate representation of building responses during an earthquake, as opposed to traditional methods that are based on simplified assumptions [48].

2.4.2 BIM for Structural Modeling

Building Information Modeling (BIM) is a digital process that involves the development of a building model that contains information, such as to coordinate, document, and make decisions on a building's design and construction throughout the process. In the field of structural engineering, BIM is already employed for creating geometry, detailing reinforcement, visualizing structure, quantity take-off, clash detection and multidisciplinary coordination. [49]. BIM's ability to integrate various types of data, including geometry, material properties, and load distribution, makes it a valuable tool for modeling the structural components of tall

buildings under seismic loads. For structural modeling, BIM is not only capable of visualizing the structure in 3D, but also generates data-rich models that can be used for various analyses, such as seismic performance, energy efficiency, and structural behavior during dynamic events [15].

The detailed models allow engineers to simulate the seismic loading on each part, such as the shear walls and frames, to determine how each will respond to the earthquake shaking, uncovering potential weak points of the design that are not obvious with conventional methods [50]. In addition, BIM enables the simulation of the whole building life cycle, including simulation of the structure under different loading conditions as a function of time. This is important to assure optimal building performance during its life cycle, especially in seismic regions [51]. With these simulations, the building's vulnerability can be understood, including areas where stress concentrations may occur, which may be missed with conventional design tools [52]. The major benefits and designing aspects of BIM application in reinforced concrete tall buildings as per literature is presented in Table 2.1.

TABLE 2.1: Key benefits and structural design considerations of BIM in RC tall buildings

BIM Benefit / Feature	Key Contribution in Structural Design	Reference
Parametric 3D modeling of structural systems	Allows the correct geometry, reinforcement and load paths to be represented	[53]
Improved multi disciplinary coordination	Reduces design clashes and rework through coordinated models	[54]
Automated documentation and quantities	Enhances efficiency in generating schedules and concrete/steel take offs	[55]
Parametric modification support	Allows easy updates and design iterations	[56]
Visualization for structural behaviour	Assists in visual inspection of load paths and potential weak regions	[57]
Foundation for analysis integration	Prepares structural model for export to analytical tools	[58]

Structural software comparison and validation studies often use benchmark structures because they are a reference structure that is well known and has been documented in the literature so that only the analytical and modeling capability

of the software being tested is changed, not the structure [59]. This is similar to formal verification and validation (V&V) for structural engineering, which has been used to compare the results of benchmark models to reliable reference results to check the accuracy of the analysis and design tools, and has also been applied to multi-software seismic performance comparisons of the same benchmark building [60].

2.4.3 Seismic Simulations with BIM

BIM offers an integrated platform for modeling and evaluating the performance of buildings. Seismic simulations are a key part of buildings' performance-based evaluation and BIM makes it easier to carry out simulations. By combining BIM with more sophisticated seismic analysis software engineers can assess seismic performance and consider complex seismic phenomena like plastic hinges and inter-story drift. These tools can be used to assess the building's structural system's vulnerability to seismic forces and identify weak links, such as energy dissipation components or components that are over-stressed [61]. Furthermore, BIM can be used in conjunction with seismic analysis, which enables efficiency and minimization of human error in seismic analysis when undertaking key tasks such as quantity take-off, material optimization, and clash detection [50].

2.4.4 Enhancing Collaboration and Decision Making

BIM improves collaboration by offering a single environment that's rich in information for everyone working on the project, including engineers, architects, and contractors. This collaboration is very useful for seismic performance assessment, as this process needs a multidisciplinary approach. The collaborative aspect across disciplines is one of the most powerful aspects of BIM. This allows structural engineers, architects and contractors to share and manipulate the same model to create better communication and design and analysis synergy. This is especially significant in the case of seismic evaluations where many factors will be taken into account such as material behavior, load distribution, and seismic hazard levels [26].

Working in a shared BIM environment allows for stakeholders to identify potential problems and make real time changes to the design while optimizing it for better seismic performance [62].

2.5 BIM-Based Performance-Based Design for Tall Buildings

The adoption of the BIM-based Performance Based Design (PBD) for tall buildings has increased the traditional design approach by concentrating on the actual performance of the building during seismic events, instead of depending on prescriptive codes. BIM can also be used for a simulation of nonlinear phenomena like the formation of plastic hinges and inter-story drift under various seismic loads and to create detailed models of these phenomena. The approach is a means of assessing major performance indicators like life safety and collapse prevention, and contributing to the seismic resilience goals of the building.

2.5.1 BIM's Role in PBD

Building Information Modeling (BIM) plays a crucial role in Performance-Based Design (PBD) by providing detailed, data-rich models that simulate how buildings will behave under seismic loads. BIM allows engineers to add a variety of complex nonlinear behaviors to the model, including the formation of plastic hinges, inter-story drift, and global displacement, and results in a more precise information of the structure's seismic response [61]. BIM enables the ability to incorporate seismic data, including ground motions, into the model. This allows engineers to simulate a variety of earthquakes and get a full picture of how the building would respond to an earthquake. BIM can simulate various seismic loading conditions, which can optimize the design and ensure its performance under normal and severe seismic conditions [63]. Benefits of BIM in Seismic Performance Analysis

The advantages that BIM brings to the design process, coupled with performance-based seismic analysis, are plentiful and valuable in the design and evaluation

process. The building's response to seismic loads is simulated, and the engineer can accurately predict the building's response when the building or its materials/components are subjected to extreme conditions, such as nonlinear behavior [54]. This capability is particularly important for tall buildings, where seismic performance is often complex due to large lateral displacements and high forces acting on structural elements [64]. BIM can simulate the effects of the building under different seismic conditions, which enables engineers to anticipate where failure might occur and makes the vulnerable areas more noticeable to reinforce or redesign [65].

In addition, BIM can incorporate dynamic analysis software and enhance the efficiency of the seismic analysis process, by automatically handling part of the tasks in the process, such as material optimization, energy performance evaluation and clash detection [55]. These features simplify the design process, saving time from manual calculations and provide a lower chance of error in the design and analysis process. Furthermore, BIM can accommodate large amounts of data, and can simulate various seismic scenarios simultaneously, which can provide engineers with a more comprehensive evaluation of a building's seismic resilience, helping them make more informed decisions [66].

Structural analysis workflows have been more recently associated with BIM with the aim of facilitating data exchange and minimizing repetitive modeling tasks. The applications of BIM with regard to seismic includes member co-ordination, geometric accuracy, documentation of design change and inter-disciplinary consistency [15]. Several research projects have shown that the efficiency has increased when BIM models have been introduced to the analysis platform through interoperable working procedures [67]. While these benefits exist in BIM, there are limited applications of BIM in seismic performance evaluation. Most BIM environments aren't as well developed as the geometry and coordination, and the detailed nonlinear analysis part is weaker [68]. They can support simple analytical model generation, verification by code, etc., but may not offer the same level of control over the assumptions made in the analytical models such as cracked stiffness, hinge properties, shell discretization, etc., or the definition of damping [69, 70].

2.6 Limitations of BIM Tools in Performance-Based Code Compliance Assessment of RC Tall Buildings

The potential of BIM for coordination, visualization, and information integration has been demonstrated in structural engineering, while more recent literature indicates that the use of BIM in advanced seismic assessment is limited by a few technical and methodological constraints [71, 72]. These restrictions are more apparent if BIM is to be used to create the geometric model and to document it along with the building's seismic performance, compliance with building codes, and nonlinear analysis [73, 74]. Recent investigations have thus concluded that BIM is a promising platform for seismic performance workflows but not yet fully developed in comparison to dedicated structural analysis software [75]. All of these drawbacks are significant because the stiffness, force transfer, nonlinearity, and result traceability for RC tall buildings with dual systems are important to seismic compliance [76].

2.6.1 Interoperability and Data Exchange Challenges

One of the most common complaints with BIM-based structural workflows is interoperability, as models typically are transferred from one software to another prior to the completion of seismic assessment [71]. While BIM does enable collaboration and coordination and integration in the structural design phase, the need to coordinate across tools also makes the quality of exchange a key to successful workflow. The automated generation of structural models from architectural models has been facilitated in OpenBIM but structural models still need to be translated, meaning that the workflow is not yet seamless. [72]. Standard BIM authoring workflows do not yet allow for a direct handoff to seismic analysis, as a Dynamo-based interoperability script was created to transfer geometry, section properties, material properties, support conditions and reinforcement from Revit to SeismoStruct [77]. Interoperability is therefore considered a semantic issue as

well as a geometric one: that is, the meaning of the structure can be compromised even when the visual structure is not. The literature is therefore not only geometric, but also semantic, because the meaning of the structure can be degraded, even if the visual structure is not. The automated compliance workflow was encapsulated around the IFC preparation and the translation of the rules, revealing the need for pre-processing for structural checking before the exchange of the models becomes usable [74]. Routine two-way data exchange is still insufficient, as was suggested by an IFC-based framework for reintegrating the results of structural analysis into BIM for code compliance [75]. In seismic design, it is crucial that the stiffness assumption, support conditions, and connectivity assumptions in the analysis directly affect structural period, inter-story drift, and force distribution, respectively [77]. The spread of loads between frames and shear walls is very sensitive to assumptions used in modeling, and can have more severe consequences if there are small translation errors in dual-reinforced concrete systems [78].

2.6.2 Limitations in Nonlinear Seismic Modeling

Nonlinear modeling is the basis for performance-based seismic assessment, and while BIM tools offer limited native support for nonlinear seismic idealization, there is still a long way to go. A custom Python script, called BTO, was created to configure element types, material constitutive models, load information, and analysis types and thus building BIM-to-OpenSees workflow [77]. The flexibility to address that additional program demonstrates the lack of the nonlinear constitutive and analysis definitions that were required for reliability assessment from BIM software. To apply elastic-plastic seismic analysis and damage evaluation, BIM needed to be connected to OpenSees via RevitAPI [79]. Traditional BIM work has good representation and coordination but falls short in incorporating near real-time feedback and iterative performance based design exercises [80]. This is an important restriction as it is known that geometric transfer is only a small part of the requirements of nonlinear seismic modelling [81]. Recent dual system studies do not use BIM native solvers, but nonlinear time-history, fragility or collapse

oriented procedures, showing that the current separation of digital authoring and advanced seismic assessment still exists [82].

2.6.3 Constraints in Automated Code Compliance Checking

Although automated code compliance checking has made great strides, recent literature reveals that its maturity is still unevenly distributed among the various kinds of structural checks. The application of knowledge graphs with BIM can help with automated code compliance checking, showing significant advances in computable rule interpretation [83]. A new framework based on the IFC format was created to integrate the structural analysis results generated by CAE into BIM for code compliance, which was previously a major drawback of the ACC workflows [84]. These findings are especially relevant to the use of performance-based code compliance since seismic compliance is often dependent on the results of the analysis as opposed to the attributes of the static objects. Comparatively, checking rules based on dimensions, classifications, or explicit thresholds that are directly stored in the model are easier to check [85]. It is much more difficult when the evidence that is needed is nonlinear deformation, hinge states, collapse probability or soil-structure interaction effects. Those advanced outputs are sometimes the most important for seismic compliance for tall RC buildings [8]. Current ACC systems thus seem to be more robust in terms of prescriptive checking than complete performance-based verification. There is also a growing demand for traceability, rechecking and consistency across stages in compliance processes, as indicated by the literature [86].

2.6.4 Accuracy and Reliability Issues in Seismic Response Prediction

The value of BIM for seismic assessment ultimately comes down to whether it can help to predict structural response accurately and reliably. BIM data was used as a baseline input to a reliability-analysis workflow, but not as a direct indicator

of the accuracy of responses, indicating that predictive confidence should be determined through external analysis and validation [87]. The interaction between soil foundation structure can have a significant impact on the distribution and collapse capacity in dual RC frame-wall systems [88]. The seismic response and collapse capacity of RC buildings can be significantly affected by shear wall height irregularity [89]. The studies demonstrate that there are significant uncertainties, irregularities, wall layouts and soil effects that impact seismic response prediction. The seismic outputs may be misleadingly precise if BIM transfer simplifies or eliminates any of those factors. This is particularly challenging in tall RC structures as several mechanisms can compound the impact of seemingly minor modeling assumptions [90].

2.7 Summary

This literature review aims to investigate the constraints of Building Information Modelling (BIM) tools for performance-oriented seismic evaluation of tall RC buildings. Although many advances have been made in design coordination, data integration and visualization in the application of BIM, BIM's use for seismic performance-based design (PBSD) is limited. The review points out the problems of BIM tools namely: interoperability, readiness for structural analysis and nonlinear seismic modeling problem. Although BIM is efficient in information management it doesn't necessarily have the depth required to do accurate seismic analysis and requires an external tool and other specialist software to be integrated into BIM. Data exchange problems, insufficient modeling of material properties, and lack of detailed reinforcement and section data necessary for a proper seismic analysis are some of the main drawbacks of BIM. In response to these challenges, the review suggests a more robust framework for BIM that enables performance-based compliance, including better interoperability, benchmarking and validation with reliable analysis tools. The literature reviewed generally confirms that BIM is a useful tool to support structural design, but it needs to be improved to be able to work in close collaboration with the requirements for resilient, safe and economically sound seismic design of tall RC buildings.

Chapter 3

Research Methodology

3.1 Background

While formulating tall reinforced concrete structures, horizontal force resistance, framework rigidity, and comprehensive steadiness are pivotal considerations of the structure must be considered, and the performance of the structure under earthquake load must be satisfactory. Today, code-based seismic design is the most popular method of seismic design in engineering practice because it is accepted by code and is applicable to the design. Code seismic design procedures are outlined in modern codes, including ASCE 7-22. For tall RC structures, notably ones taller than 35 story, sideways loading represents the most critical loading consideration. The combination of reinforced concrete moment resisting frames and shear walls is a common structural system to provide an optimum balance of strength, stiffness and ductility.

Advanced structural analysis software is an important part of the implementation of these design methodologies. The reference analytical model of the selected building was created in ETABS for the benchmark study. The same 35 story reinforced concrete dual system building will be used from the benchmark study as the reference building for the present research. The geometry, material grades, member sections, diaphragm assumptions, and loading conditions used in the benchmark

ETABS model will be the same in Autodesk Robot Structural Analysis Professional and Tekla Structural Designer to ensure the workflows are compared on a like for like basis.

This adaptation is consistent with the approved proposal, which is based on the need to overcome the limitations of BIM tools for the performance-based assessment of code compliance of RC tall buildings by comparing with an ETABS benchmark. The methodology in this chapter, therefore, maintains the same context of the benchmark study but expands the modeling environment to a three-platform comparative study, where the ETABS results are used as the benchmark and the results from Robot and Tekla are compared to ETABS results.

3.2 Building Description

The building under study is a benchmark 35-storey reinforced concrete high-rise building, which was taken from a previous research study. The benchmark building is a mixed-use development with parking on the basement level, commercial use on the lower floors, residential use on the upper floors and a service floor in the middle to house mechanical and utility spaces. The building relies on a combined lateral-resisting mechanism, integrating RC moment-resisting frames with shear walls, to ensure the structure has sufficient strength, stiffness, and ductility to resist gravity and seismic forces.

The total height of the building is 384 ft from the ground level. The structure is assumed to be in the area of Islamabad, Pakistan, where there is a high seismic hazard. As a result, seismic loading is the most important lateral design consideration. In the study, the geometry, material properties, member dimensions, loading conditions, seismic parameters and structural configuration of the benchmark building were established and analyzed using ETABS, which was originally modeled.

The same building is used for the present research, with no changes to the structural characteristics or design assumptions. All the modeling parameters are directly obtained from the previous research to ensure consistency and provide a

reliable basis for comparison. The building is recreated in the software packages Autodesk Robot Structural Analysis and Tekla Structural Designer, and the same input parameters are used for structural modeling, analysis and design. By using this benchmark model, the influence of the various software platforms used to analyze and design the model can be investigated without having to consider the variations resulting from different structural configurations or design criteria. The description of the benchmark 35-story RC building with a combined frame-wall building used in this study is given in Table 3.1.

TABLE 3.1: Description of Building

Parameter	Description
Building Type	RC Combined frame-wall system
Stories	35
Floor-to-Floor Height	12 ft
Top of Structure Elevation	384 ft
Floor System	Slab made of concrete, serving the role of stiff diaphragms
Earthquake Resisting System	Frames that withstand rotational forces, joined with shear wall systems
Location	Islamabad, Pakistan
Function	Multi-purpose Classification (Vehicle Storage, Housing, Business)

From ETABS, same structural members sizes are directly obtained to ensure consistency and provide a reliable basis for comparison. Same sizes will be used in Robot and Tekla Structures without any change. Table 3.2 represents the structural member sizes with concrete strength and section shapes.

The 35-storey RC dual-system building was chosen as a validated benchmark building from previous research with an established ETABS baseline; the same building was used to minimize any variability resulting from differing building configurations and to allow for the influence of BIM software capability to be isolated and

TABLE 3.2: Structural member sizes with concrete strength and section shape

Parameter	Description
B – 18×25	4500 psi, Concrete Rectangular
C – 18×24	6000 psi, Concrete Rectangular
C – 24×24	6000 psi, Concrete Rectangular
C – 30×30	6000 psi, Concrete Rectangular
C – 36×36	6000 psi, Concrete Rectangular
C – 42×42	6000 psi, Concrete Rectangular
C – 48×48	6000 psi, Concrete Rectangular
Slab – 7”	4500 psi, Concrete Rectangular
Retaining Wall – 12”	4500 psi, Concrete Rectangular
Shear Wall – 12”	6000 psi, Concrete Rectangular
Shear Wall – 24”	6000 psi, Concrete Rectangular

evaluated in relation to code-compliance and performance-based seismic assessment.

3.3 Structural Design Basis

The benchmark design criteria that has been adopted ASCE 7-22 loading and seismic provisions, together with ACI 318-19 for the design and detailing of reinforced concrete members, form the basis for structural configuration of the identified 35-floor reinforced concrete structure with its combined frameshear wall lateral system. The code-based design approach has been followed to keep the safety of life intact in the event of design level earthquake loading and to ensure that the design details are compared with the benchmark ETABS results. In accordance with the benchmark study, gravity loads applied will consist of static structural

burdens (intrinsic weight, decorative surfaces, dividing walls, and mechanical/utility demands) together with fluctuating occupant-driven forces corresponding to car-park, business, habitation, and top-level usage divisions. Considering high seismic hazard in Islamabad (Pakistan), the seismic forces will be determined. The building height is more than thirty stories, so the response spectrum method was used to conduct this dynamic analysis in the benchmark ETABS model and equivalent analysis will be created in Robot and Tekla, to produce directly comparable outputs. Equivalent lateral force procedure will be continued to be available for initial assessment and confirmation as applicable.

The benchmarked model's structural system combined special bending-resistant frames with shear walls, to give sufficient load-bearing capacity, rigidity, and deformation capacity. Design considerations included inter-story displacements, horizontal displacements, torsional asymmetries, and P-delta effects. Every floor level was assigned rigid diaphragm behavior, and Reduced stiffness factors accounting for cracking were applied in line with the benchmark assumptions and applicable code recommendations.

The same material grade, sections and loading assumptions will apply to both Robot structural analysis and Tekla structural designer, and the outputs extracted will be compared with the ETABS benchmark, for the following parameters: base shear, lateral displacement, story drift response, member design related response indicator etc. subject to software capability and output availability.

3.4 Numerical Model Development

This study uses computational modeling to assess the seismic performance of a selected 35-story RC building with a combined moment frameshear wall system, drawing on benchmark code-based seismic design data from ETABS as well as parallel analytical reproduction in Autodesk Robot Structural Analysis Professional and Tekla Structural Designer. The modeling approach is designed to enable linear elastic analysis as well as the nonlinear assessment procedures outlined in the benchmark study, and to allow for a systematic comparison between the ETABS benchmark and BIM based workflows.

The computational framework is developed to capture both system-level and member-level aspects of structural behavior such as displacement between stories, floor-level acceleration, and the emergence of plastic hinges, and is also practical for professional design work. The modelling strategy is also applied to include the properties of the benchmark material, boundary conditions and load combinations in order to compare the simulated response in the other software platforms directly to the response in ETABS. For a modal load case, ETABS solves the generalized eigenvalue problem to obtain natural circular frequencies, ω , and mode shape vectors, $\{\phi\}$:

$$[\mathbf{K}]\{\phi\} = \omega^2[\mathbf{M}]\{\phi\} \quad [91] \quad (3.1)$$

Where:

$[\mathbf{K}]$ is the stiffness matrix of the structure.

$[\mathbf{M}]$ is the mass matrix of the structure.

The eigenvalue ω^2 is the square of the natural circular frequency (ω).

The mode shape vector is denoted by $\{\phi\}$, which represents the eigenvector corresponding to ω^2 .

In robot and Tekla structural analysis software, Modal analysis is used to calculate the eigenvalues and derivative values (eigenpulsations, eigenfrequency or eigenperiods), precision, eigenvector, participation coefficient and participation mass of the problem of structure eigenvibrations. Three structure dynamic analysis modes (modal, seismic and seismic (pseudo)) are available. The following formula are used to obtain eigenvalues and eigenmodes.

$$\det(\mathbf{K} - \omega^2\mathbf{M}) = 0 \quad [92,93] \quad (3.2)$$

where:

$\mathbf{K}$ – stiffness matrix of the structure,

$\mathbf{M}$ – mass matrix of the structure,

ω – natural pulsation (natural circular frequency) of the mode.

3.4.1 Structural Modeling Using Finite Elements

The 35-storey structure's benchmark model is assembled in ETABS using a three-dimensional finite element framework, which includes beams, columns, shear walls, slabs, and diaphragms as primary components. Geometric and material properties define each member, while the combined moment-frame and shear-wall system illustrates the structure's stiffness and ductility behavior. To transfer lateral loads efficiently to vertical elements, slabs are treated as rigid diaphragms. For the inelastic static (pushover) evaluation, yield hinges are situated at pivotal locations along beams, columns, and shear walls to mirror the projected nonlinear behavior under earthquake demand. All vertical gravity forces, horizontal seismic actions, and support constraints are allocated in accordance with the reference investigation and pertinent regulatory standards. Figure 3.1 exhibits the digital ETABS model built for the 35-story reinforced concrete structure, comprising moment-capable frames, shear walls, stiff diaphragm systems, and basement-level facilities.

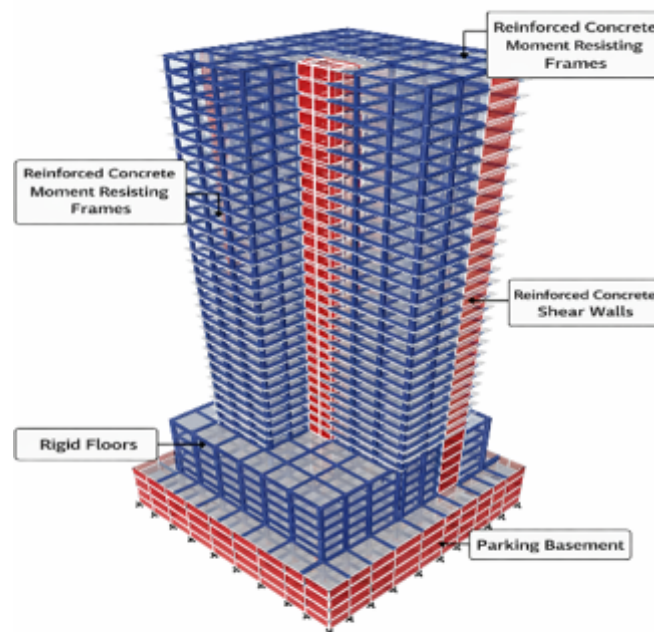


FIGURE 3.1: 3D ETABS depiction of the 35-story RC dual-system structure, showing bending-resistant frames, shear walls, rigid diaphragms, and subterranean parking

For this current study, the finite element idealization will be replicated in Robot Structural Analysis Professional and Tekla Structural Designer as much as possible within the software environment. The beams, columns, shear walls, slabs, diaphragms, restraints and loading patterns will be defined to as closely as possible match the ETABS benchmark model. If an exact one to one implementation is not feasible, the suitably chosen equivalent modelling assumption will be explicitly documented in the thesis and discussed as a potential point of discrepancy in the later comparison chapter.

3.5 Procedures for Analysis and Structural Design

3.5.1 Phase I: Code-Based Design

Within the benchmark model, a traditional prescriptive design methodology was applied using ETABS. Concrete compressive strengths of 6,000 psi and 4,500 psi were assigned to structural members, with material characteristics defined per ACI 318-19 Section 19.2.2.1 for columns, shear walls, beams, and slabs. To capture realistic structural stiffness, reduced-stiffness modifiers accounting for cracking were applied to concrete members per ACI Table 6.6.3.1.1 and the modeling guidance provided in the ETABS software manual. This method enabled the stiffness and strength degradation caused by cracking to be represented realistically in the model. The key parameters and assumptions used in the code based ETABS modelling are shown in Table 3.3.

Effective stiffness values were used for the seismic response analysis for the RC sections because ASCE 7-22 Section 12.7.3 allows the use of stiffness of cracked/-effective sections consistent with ACI 318 provisions as shown in Table 3.4.

The spectral accelerations and seismic parameters were taken from BCP 21. Per ASCE 7-22, the earthquake importance factor was taken as 1.0, the design category (SDC) was assigned as D, and the period coefficient was set at 0.02 in accordance with Table 12.8-2. A combined lateral force-resisting mechanism is present in

TABLE 3.3: ETABS Modeling Assumptions and Key Parameters for the 35-Story RC Dual-System Structure [94]

Parameter	Description	Reference
Concrete Property - Compressive Resistance	High-performance structural members were rated at 6,000 psi, while ordinary-strength members were set at 4,500 psi	ACI 318-19, Sec. 19.2.2.1
Structural Members Modeled	Columns, shear walls, beams, and slabs	ACI 318-19, Sec. 19.2.2.1
Material Property Definitions	Established per ACI 318-19 code provisions	ACI 318-19, Sec. 19.2.2.1
Cracked-Section Modifiers	Stiffness Used to account for reduced stiffness and strength resulting from concrete cracking	ETABS Manual; ACI Table 6.6.3.1.1
Modeling Objective	To realistically capture cracked-section stiffness and strength behavior in nonlinear analysis	ETABS Manual; ACI 318-19

the building, and the response modification factor, overstrength factor and the deflection amplification factor were given in Table 12.2-1. The basic combinations, such as the vertical component and minimum live load, were used per ASCE 7-22. Table 3.5 exhibits earthquake design specifications for Prescriptive Design, following ASCE 7-22 guidelines.

In the present research, Phase I involves the recreation of the benchmark code-based model in Robot and Tekla with the same material strengths, member sizes, loading assumptions, seismic parameters and code intent as presented in the ETABS benchmark. The Robot Structural Analysis Professional is a specialized software program that is used for the analysis of structural loads. RSA is software from the company, Autodesk. It helps to meet building codes and also

TABLE 3.4: Stiffness values for seismic response analysis for RC sections [94]

Structural Element	Stiffness Modifier	Effective Property
Columns	0.70	$0.70 I_g$
Beams	0.35	$0.35 I_g$
Retaining Walls	0.35	$0.35 I_g$
Slabs	0.25	$0.25 I_g$
Shear Walls	0.25	$0.25 I_g$

supports data sharing in an integrated BIM workflow. With the use of this software, designs become resilient, constructible, and precise while providing effective coordination and seamless integration within the BIM environment [95].

Tekla Structures is a powerful structural BIM software. Tekla Structures is a specialized software for structural engineering that is created for the construction industry, particularly for structural engineers. This software enables to design and model structures of various dimensions and complexity, and create information-rich 3D Building Information Modeling (BIM) models [96].

The outputs from the Robot and Tekla will then be extracted and compared directly with the outputs from ETABS for the benchmark. At this stage, the comparison will concentrate on the software consistency in the definition of the structural model, the application of the benchmark loading, generation of seismic response and reporting of design relevant demand parameters.

3.5.2 Phase II: Performance-Based Evaluation

Phase II will be the stage where the existing model developed in Phase I is re-evaluated under the advanced framework of ASCE 41-17 without changing the geometry or the size of the members. The methodology for the present study will

TABLE 3.5: Code-Based Design (CBD) Seismic Parameters as per ASCE 7-22 [94]

Parameter	Value / Description	Reference
Spectral Accelerations	S_s and S_1 obtained from BCP 21	BCP 21
Seismic Importance Factor	1.0	ASCE 7-22
Seismic Design Category (SDC)	D	ASCE 7-22, Table 11.6-1
Period Coefficient C_t	0.02	ASCE 7-22, Table 12.8-2
Earthquake Resisting System	SMRF + shear walls	ASCE 7-22
Response Factor R	7.0	ASCE 7-22, Table 12.2-1
Overstrength Coefficient Ω_0	2.5	ASCE 7-22, Table 12.2-1
Deflection Amplification Factor C_d	5.5	ASCE 7-22, Table 12.2-1
Load Combinations	Basic combinations including vertical seismic component and minimum live load	ASCE 7-22, Table 4.3-1

be based on ETABS benchmark procedures and where possible similar implementation steps will be undertaken in Robot and Tekla.

3.5.2.1 Formulation of the Inelastic Model

To perform the performance-based design (PBD) in the benchmark study, the nonlinear analysis was carried out in ETABS manual. The code-based design (CBD) output was provided to the PBD phase, Since preliminary CBD design functioned largely as a foundation for the PBD stage, true dimensions of concrete and steel components were established via ETABS' section property configurations and carried forward into the plastic hinge modeling. Member sizes and reinforcement were assigned first, followed by application of the auto-hinge feature to place hinges at beam locations governed by flexural behavior, using M3-type hinges.

Performance levels, Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), were assigned in ETABS based on Table 10.7 from ASCE 41-17. Columns were modeled with P-M2-M3 hinges, while shear walls used PM3 hinges, both in accordance with the criteria specified in ASCE 41-17 Tables 10-8 and 10-9. Table 3.6 below provides the summary of hinge types that were assigned to the elements and reference table from ASCE 41-17.

TABLE 3.6: Summary of Hinge Types, Assigned Elements, and ASCE 41-17 Reference Tables

Structural Element	Hinge Type	Purpose / Behavior	ASCE 41-17 Reference
Beams	M3	Flexural hinge used to simulate inelastic moment-rotation behavior in beams	Table 10.7
Columns	P-M2-M3	Hinge accounting for the interaction between axial force and biaxial moment demands	Table 10-8
Shear Walls	PM3	Hinge type used to represent nonlinear axial-bending behavior in shear wall elements	Table 10-9

M3 hinge section properties were defined at multiple backbone curve points (A-D) on the moment-rotation relationship, alongside other nonlinear parameters. These points map to the IO, LS, and CP performance levels, enabling ETABS to simulate the beams' increasingly inelastic response as lateral demand rises. This detailed calibration keeps plastic hinge behavior consistent with the target performance at each level. In ETABS model, M3 plastic hinge is defined in the following manner as shown in figure 3.2.

The parameters described above are based on tables specified in ASCE 41-17, and comparable, well-defined tables covering other structural elements are likewise available within the ASCE 41-17 guideline. For the present research, the same modelling purpose will be explored in Robot and Tekla based on the ETABS

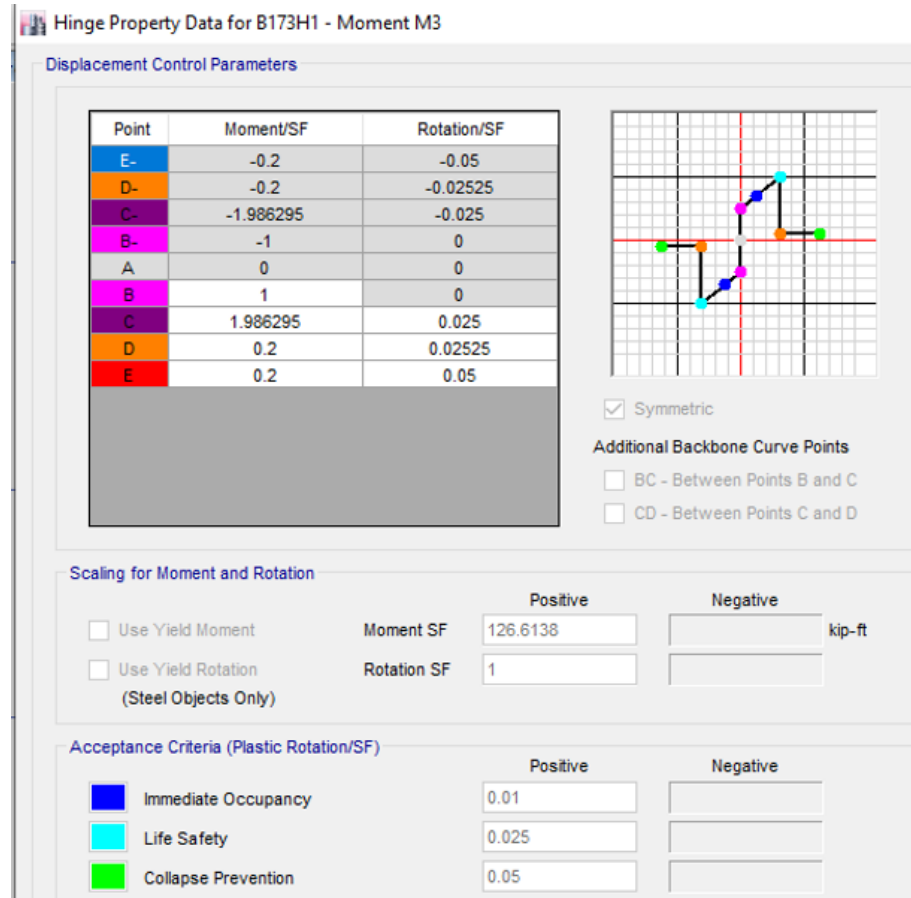


FIGURE 3.2: Definition of M3 plastic Hinge

hinge definitions and performance criteria as the reference. This objective is to check if equivalent nonlinear idealization properties can be consistently determined according to the code and if output quantities that can be compared to the ETABS benchmark can be reliably obtained.

3.5.2.2 Static Inelastic - Pushover- Analysis Framework

To assess the seismic behavior of the proposed 35-story reinforced concrete hybrid-system structure, pushover analysis was selected as the principal nonlinear static technique. This approach provides a streamlined yet robust way of capturing a structure's inelastic behavior as horizontal loads are applied progressively, continuing until a predetermined target displacement is achieved. This target value represents the anticipated peak roof-level displacement under the design-level seismic event and functions as the reference point against which structural performance

is measured. The target displacement for the reference study was calculated using ASCE 41-17, Equation 7-22, which incorporates the structure's fundamental period, seismic demand, and nonlinear structural behavior. Figure 3.3 illustrates the M3 hinges assigned to beams in the ETABS model, while Table 3.7 presents the model input parameters and numerical acceptance criteria for the nonlinear procedure applied to RC beams.

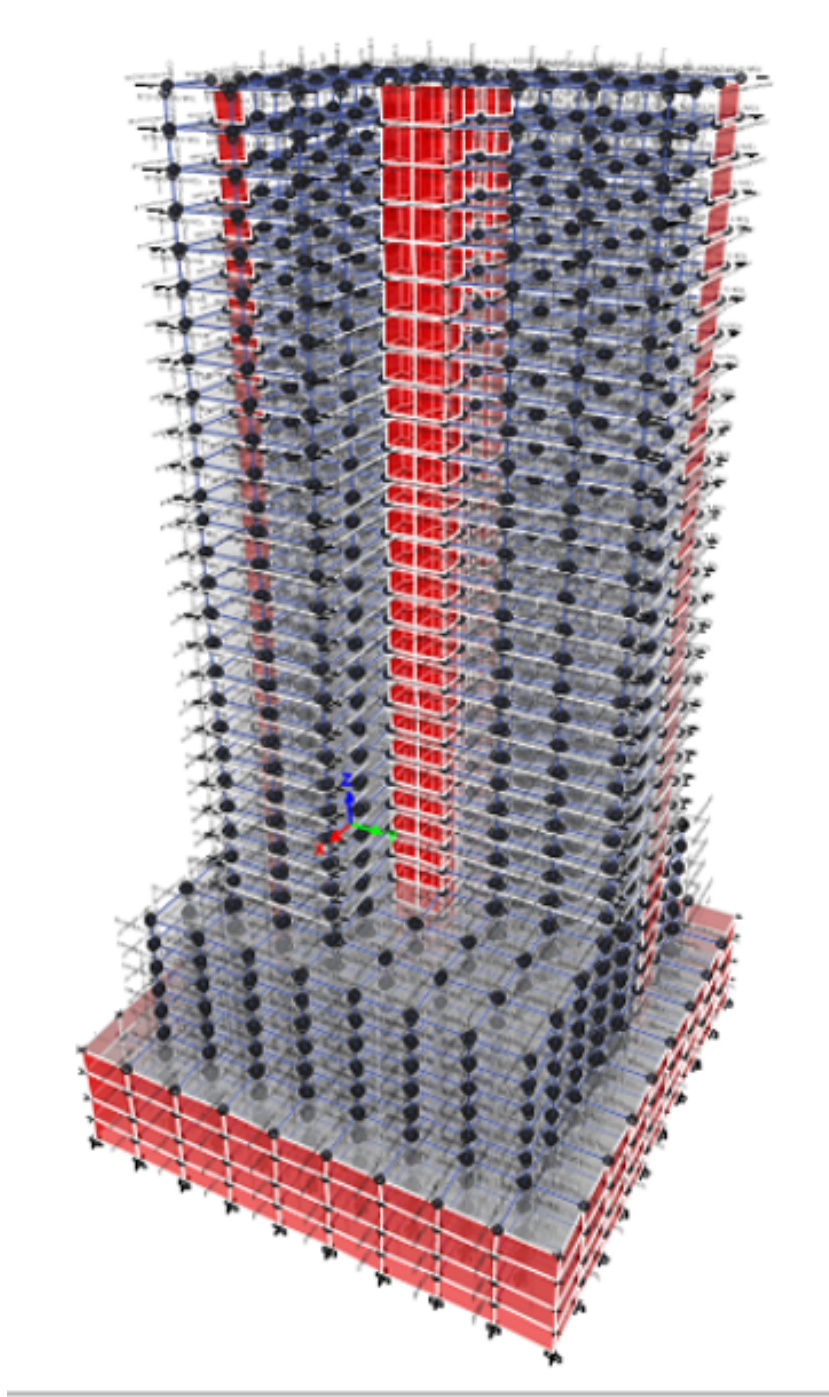


FIGURE 3.3: Beams were assigned M3-type plastic hinges [94]

TABLE 3.7: Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedure for RC Beam

Conditions	Transverse Reinforcement ^c	$V^E \text{ lock} /$ $(b_t d \sqrt{f_t^{CE}})$	Modeling Parameters ^a			Acceptance Criteria ^a		
			Plastic Rotation Angle (rad)		Residual Strength Ratio	Plastic Rotation Angle (rad)		
			a	b		Performance Level		
						IO	LS	CP
Condition i. Beams controlled by flexure ^e								
≤ 0.0	C	≤ 3 (0.25)	0.025	0.05	0.2	0.010	0.025	0.05
≤ 0.0	C	≥ 6 (0.5)	0.02	0.04	0.2	0.005	0.02	0.04
≥ 0.5	C	≤ 3 (0.25)	0.02	0.03	0.2	0.005	0.02	0.03
≥ 0.5	C	≥ 6 (0.5)	0.015	0.02	0.2	0.005	0.015	0.02
≤ 0.0	NC	≤ 3 (0.25)	0.02	0.03	0.2	0.005	0.02	0.03
≤ 0.0	NC	≥ 6 (0.5)	0.01	0.015	0.2	0.0015	0.01	0.015
≥ 0.5	NC	≤ 3 (0.25)	0.01	0.015	0.2	0.005	0.01	0.015
≥ 0.5	NC	≥ 6 (0.5)	0.005	0.01	0.2	0.0015	0.005	0.01
Condition ii. Beams controlled by shear ^e								
Stirrup spacing ≤ d/2			0.0030	0.02	0.2	0.0015	0.01	0.02
Stirrup spacing > d/2			0.0030	0.01	0.2	0.0015	0.005	0.01
Condition iii. Beams controlled by inadequate development or splicing along the span ^e								
Stirrup spacing ≤ d/2			0.0030	0.02	0.0	0.0015	0.01	0.02
Stirrup spacing > d/2			0.0030	0.01	0.0	0.0015	0.005	0.01
Condition iv. Beams controlled by inadequate embedment into beam-column joint ^e								
			0.015	0.03	0.2	0.01	0.02	0.03

The target displacement determined by ASCE 41-17 can be used to identify potential plastic hinge formations, to assess demands on inter-story drift, and to determine if structural elements achieve the performance objectives of a specific performance level, including Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). This approach ensures the inelastic static procedure aligns with prevailing capacity-based seismic design standards and delivers a dependable framework for capturing the structure's inelastic seismic response.

3.6 Design Parameters to be Considered

Gaining an in-depth understanding of the seismic performance exhibited by the 35-story reinforced concrete hybrid-system structure calls for a robust grasp of the pivotal structural elements that dictate its conduct under seismic loading. These elements constitute the underpinning of both conventional code-driven and outcome-oriented design strategies, supplying the necessary basis for credible modeling, analysis, and appraisal of the building's response to earthquakes.

The same set of parameters used in the previous research will serve as a reference point for the comparison among ETABS, Robot, and Tekla in the present research. The aim is to compare the same engineering demand parameters and the design response indicators, between all three software platforms, while documenting any parameter that cannot be extracted directly or equivalently from the BIM based tools.

3.6.1 Code-Based Design Parameters

The code-based design (CBD) approach is concerned with ensuring safety of the structure and meeting prescriptive code limits through the use of parameters. Natural period of building, dynamic response and spectral acceleration are fundamental parameters related to the building's structural response, while base shear is related to the lateral forces that must be resisted by the vertical members of the structure.

Additional vital variables consist of relative story displacement ratios and torsional inconsistencies, both of which play a role in keeping lateral deformations and

torsional effects within acceptable bounds, thus supporting overall stability and serviceability. Sizing of columns, along with their reinforcement ratios, is another critical design factor - beams, columns, and shear walls are proportioned according to expected axial loads and bending moments, while reinforcement placement is carefully managed to fulfill both strength and ductility criteria. In parallel, material qualities including concrete crushing strength and steel's tensile yield capacity form yet another essential category of parameters, directly affecting a member's stiffness, load-carrying capacity, and deformation behavior.

In general, parameters used in CBD establish a conservative foundation for structural design, helping ensure life safety during earthquakes and confirming that code-defined thresholds are respected. That said, these parameters fall short of capturing the true inelastic response or localized damage patterns that can develop during more severe seismic events.

3.6.2 Performance-Based Design Parameters

Unlike simplified approaches, performance-based design (PBD) establishes parameters that capture how a building actually responds under seismic loading. A key element of this method is the target displacement, incorporating inelastic deformation, hysteresis, and $P-\delta$ effects.

Another key parameter is the formation of plastic hinges within beams, columns, and shear walls, which indicates the sequence and magnitude of yielding experienced under seismic loading. These hinge patterns offer insight into structural performance evaluated both globally and locally. The hinge types used within ETABS, based on ASCE 41-17, are summarized in Table 3.8 PBD further depends on metrics like inter-story drift ratios, residual displacements, and floor-level accelerations, each signaling possible non-structural damage and consequences for occupant well-being. Through these parameters, PBD enables a more nuanced assessment of the building's response, shedding light on inelastic behavior, localized weaknesses, and system-level redundancy, aspects that CBD alone is unable to fully address.

TABLE 3.8: Standard Hinge Types per ETABS and ASCE 41-17

Structural Element	Hinge Type	Behavior Mode	Reference
Beam	M3	Simulates flexural yielding under pure bending	Table 10.7, ASCE 41-17
Column	P-M2/M3	Models coupled axial-biaxial bending response	Table 10.8, ASCE 41-17
Shear Wall	PM3	Represents wall behavior under combined axial and flexural effects	Table 10.9, ASCE 41-17
Beam-Column Joint	P-M2J / P-M3J	Accounts for combined flexure, shear, and moment transfer within the joint zone	Table 10.10, ASCE 41-17

Other Drift between stories, unrecovered displacement, and floor-level acceleration together form the essential PBD indicators, each hinting at probable non-structural impairment and safety implications for building occupant. PBD can be used to evaluate the buildings response based on these parameters, giving a deeper insight into inelastic response, localized weaknesses, and structural redundancy, aspects that CBD alone fails to capture.

3.7 Summary

Chapter 3 outlines the methodology for the assessment of seismic performance of a 35-story reinforced concrete building. The building has a dual structural system composed of moment-resisting frames and shear walls which are appropriate to withstand seismic challenges in a high seismic zone. The study adopts a two-stage process, first based on code-based design (CBD) and then based on performance-based design (PBD). For the CBD phase, the size of the members, material properties and seismic parameters are determined based on ASCE 7-22 in order to meet the seismic requirements. In the PBD phase, performance levels such as Immediate Occupancy, Life Safety and Collapse Prevention are evaluated by the application of nonlinear static pushover analysis, which offers a more realistic representation of inelastic response to seismic loading. Key parameters like base shear, story drift, target displacement and formation of plastic hinges are

compared between ETABS, Autodesk Robot Structural Analysis Professional and Tekla Structures. The ultimate goal is to detect differences and deficiencies in the software platforms, especially between the code-based and performance-based design evaluations. The outcome of this comparison can be used to evaluate the seismic behavior reproduction capabilities of tools integrated with BIM for tall reinforced concrete buildings. Finally, the methodology helps to improve understanding of BIM-based workflows, suggesting procedures for more reliable seismic assessment and strengthening recommendations for future high-rise building designs.

Chapter 4

Results and Analysis

4.1 Background

In this chapter, the results of structural modeling and seismic analysis had been obtained for the benchmark building, which is a 35-story RC hybrid-system structure, using the software namely Autodesk Robot Structural Analysis Professional and Tekla Structural Designer. The building was modeled following the approach described in chapter 3, with the same geometry, material properties, loadings, seismic parameters and building assumptions used with the benchmark ETABS modelling. The aim of this chapter is to assess the performance of the BIM integrated structural analysis software in the simulation of the seismic response of a high-rise RC building designed based on the provisions of ASCE 7-22 and ACI 318-19.

The chapter first summarizes the results for model development and finite element modeling performed in both software environments. Each result of the modal analysis, seismic weight calculation, base shear calculation, lateral displacement, story drift calculation and torsional response analysis is then summarized and explained. Results obtained by Robot Structural Analysis Professional, Tekla Structural Designer, and the benchmark ETABS model are compared to assess the reliability and applicability of BIM-based structural analysis flows for tall reinforced concrete structures. Furthermore, seismic performance-based assessment capabilities

of the selected BIM-based software platforms, in accordance with ASCE 41-17, is investigated.

4.2 Building Model Development Results

4.2.1 Building Model Developed in Autodesk Robot Structural Analysis Professional

A replicated model of the benchmark 35-story RC hybrid-system building was successfully created in Autodesk Robot Structural Analysis Professional. The model was a dual lateral force-resisting system comprising reinforced concrete beams, columns, slabs and shear walls. All the geometric properties, member dimensions, loading definitions, support conditions and diaphragm various assignments were picked from the benchmark ETABS model, to be consistent during the study.

In the modeling procedure, structural grids were created, floor levels defined, concrete material properties were set, the structural member cross-sections were also specified, and the seismic and gravity loading were applied. A particular effort was made to assure the analytical representation was consistent with the structure of the benchmark model, so that any discrepancies in the results obtained would be due to the software behavior and not due to differences in the representation. The plan view, elevation and roof top plan were created using the Autodesk Robot Structural Analysis Professional software, and are all displayed in Figure 4.1. The completed 3D analytical model to be used for a seismic analysis is shown in Figure 4.2.

Completed model reasonably represented benchmark building configuration, and served as a foundation for the finite element analysis and seismic response evaluation. After model development, loads were defined in RSAP including dead load, live load, wind load, wall load and finishes with load combinations. Figure 4.3 shows the load patterns for 35-story RC building.

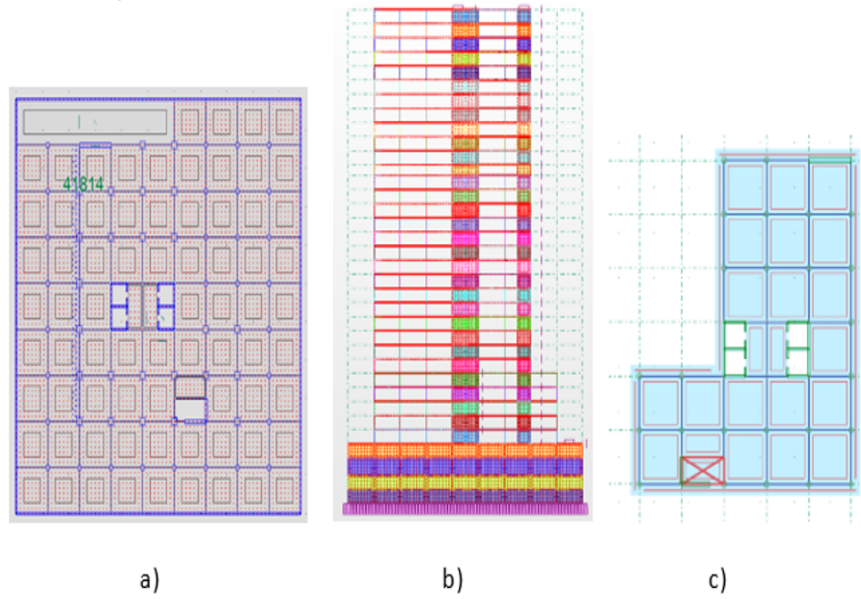


FIGURE 4.1: Robot Structural Analysis model of the building: (a) basement plan, (b) elevation view, and (c) rooftop plan

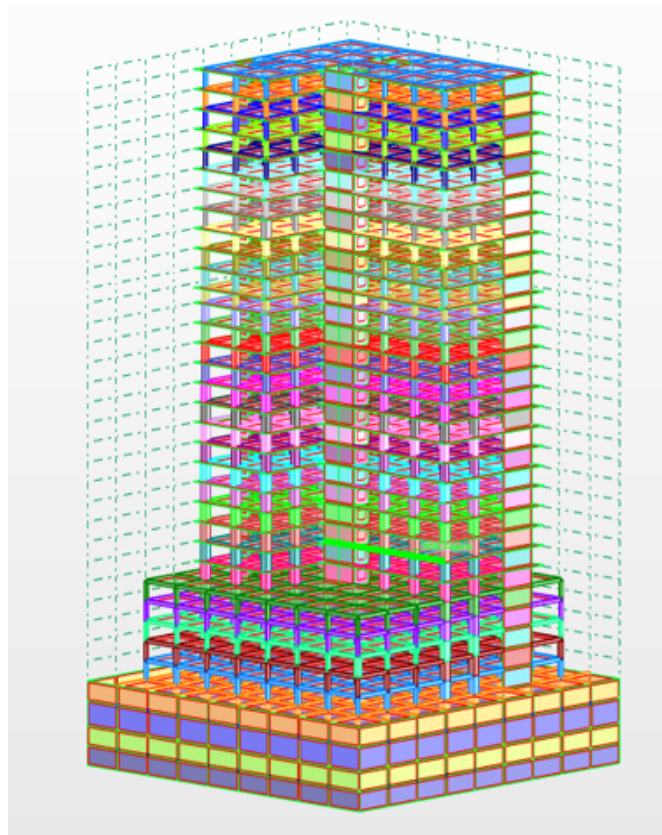


FIGURE 4.2: 3D Model of Building created in Robot Structural Analysis (RSA)

After adding the load patterns, seismic parameters according to ASCE 7-22 were added which are shown in table 3.5 in methodology chapter. Figure 4.4 represents the seismic parameters used in RSAP according to ASCE 7-22.

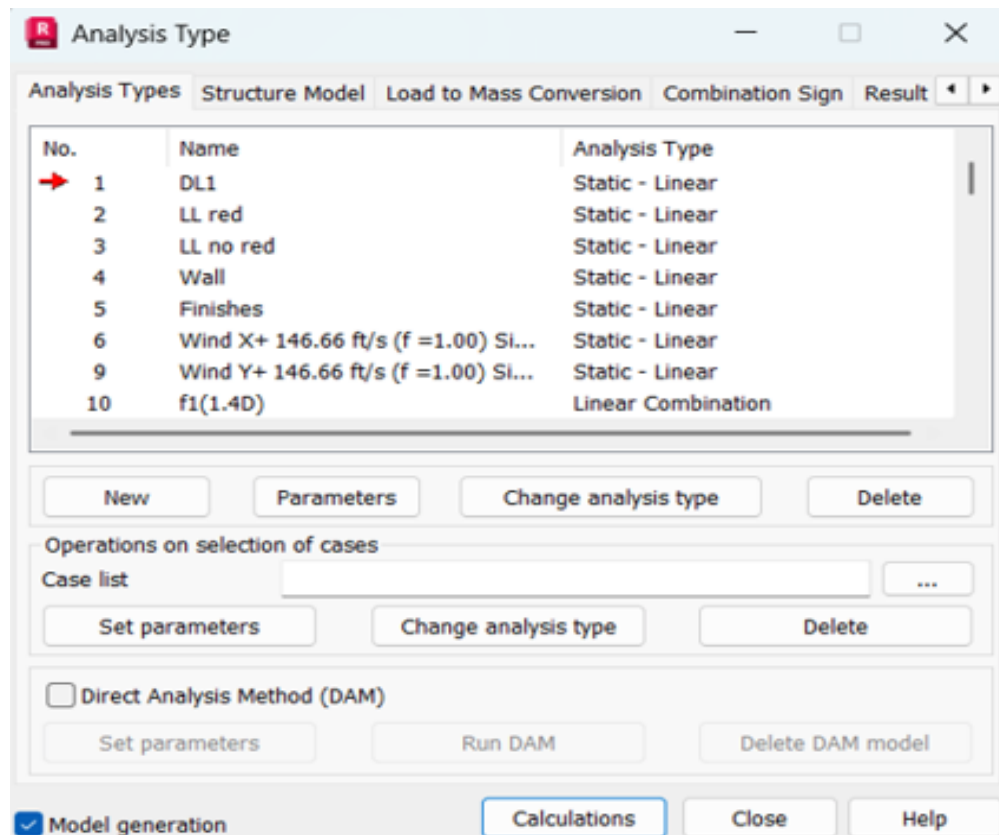


FIGURE 4.3: Load patterns used in RSAP for building analysis

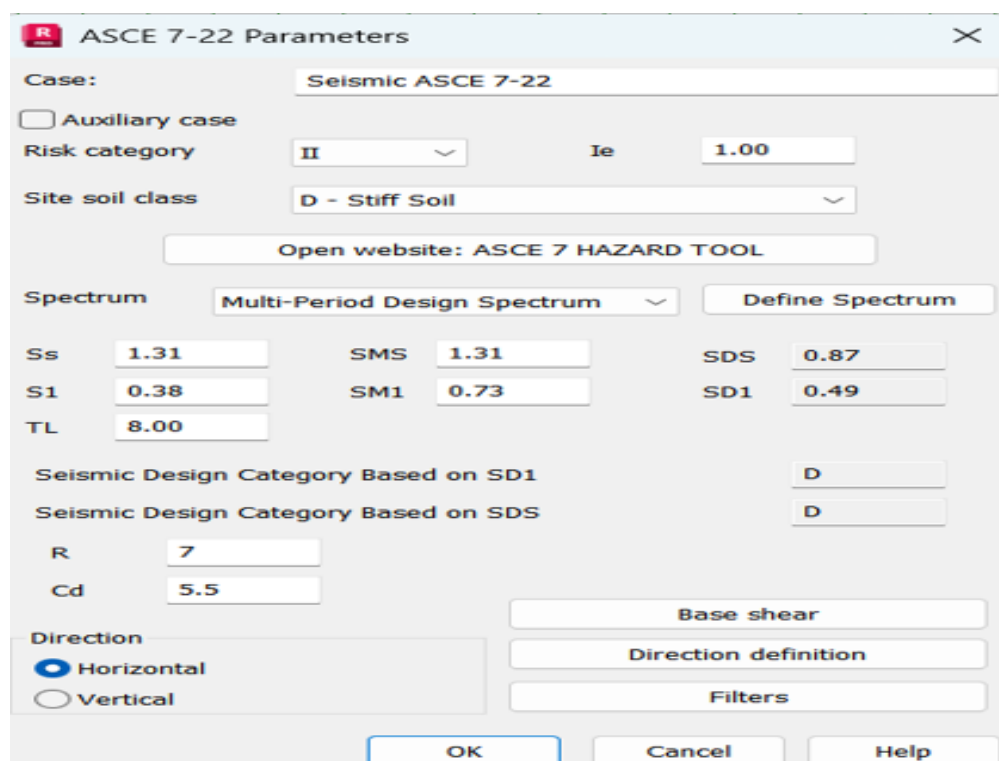


FIGURE 4.4: Seismic parameters used for building analysis in RSAP

4.2.2 Building Model Developed in Tekla Structural Designer

The geometric and structural parameters have also been applied in the Tekla Structural Designer to create the benchmark building. The model comprised reinforced concrete beams, columns, slabs and shear walls configured in accordance with the benchmark structural layout. Modeling process comprised the creation of floor levels, assignment of properties to members, material specification and loading conditions were applied. It was ensured that the analytical model generated was carefully matched with the benchmark ETABS model and the Robot Structural Analysis model. Plan view, elevation and roof plane (top plan) created in Tekla Structural Designer are presented in Figure 4.5, and the entire 3D analytical model that is to be used for seismic analysis is presented in Figure 4.6.

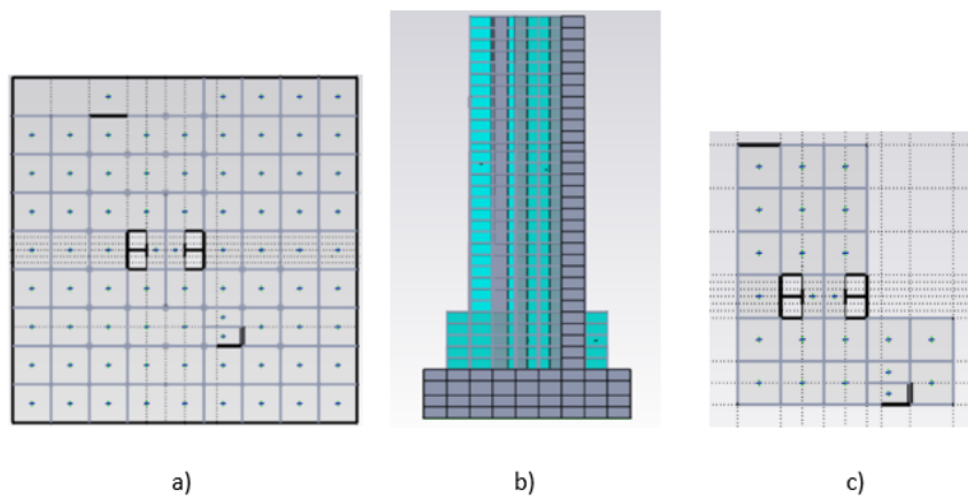


FIGURE 4.5: Tekla structures model of the building: (a) basement plan, (b) elevation view, and (c) rooftop plan

Completed model faithfully simulated the benchmark building geometry and this model was utilized for structural analysis and design evaluation. After model development, loads were defined in Tekla. Figure 4.7 shows the load patterns for 35-story RC building.

After adding the load patterns, seismic parameters according to ASCE 7-22 were added which are shown in table 3.5 in methodology chapter. Figure 4.8 represents the seismic parameters used in Tekla according to ASCE 7-22.

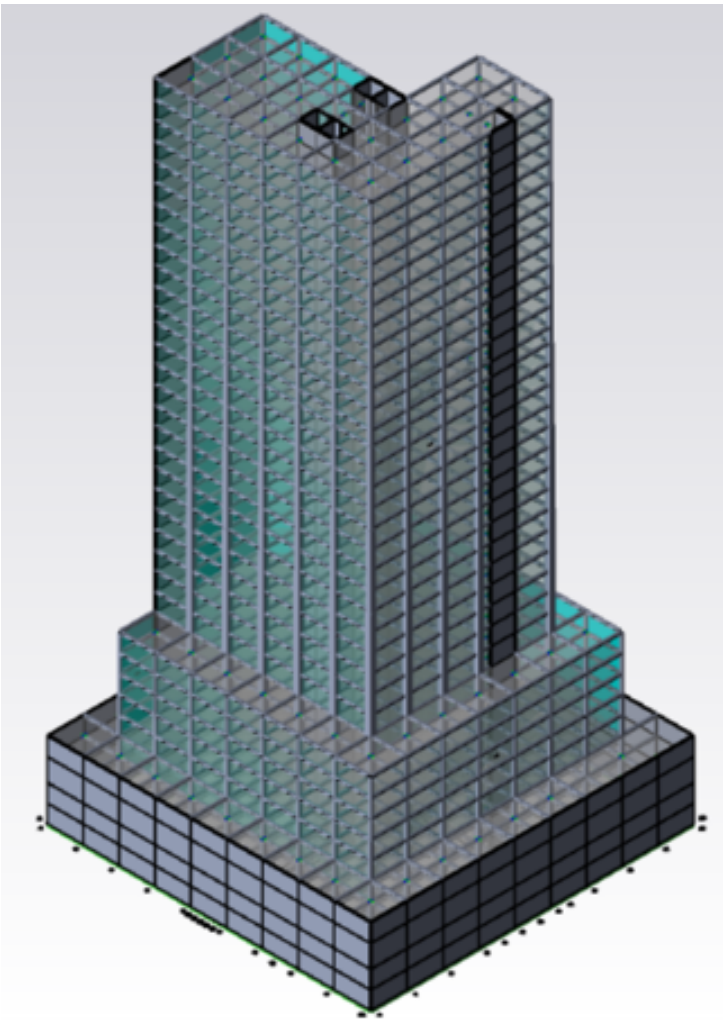


FIGURE 4.6: 3D Model of Building created in Tekla Structural Designer (TSD)

Figure 4.7 shows the 'Loading' dialog box in Tekla Structural Designer, displaying a list of load cases and their associated parameters. The dialog box has tabs for 'Loadcases', 'Load Groups', 'Combinations', and 'Envelopes'. The 'Loadcases' tab is active, showing a list of 23 load cases. The table below represents the data shown in the dialog box.

#	Loadcase Title	Type	Calc. Automatically	Include in Generator	Live Load Reductions	Pattern Load	Pattern Ecc. Moments for Precast Columns
1	Self weight - excluding slabs	SelfWeight	☒	☒			
2	Slab self weight	Slab Dry	☒	☒			
3	Dead	Dead		☒			
4	Live	Live		☒	☐	☒	☒
5	Roof Live	Roof Live		☒	☐		
6	Snow	Snow		☐			
17	Min Lateral Load $\pm 0.1\%$	MLL					
18	Min Lateral Load $\pm 0.2\%$	MLL					
19	Min Lateral Load $\pm 0.3\%$	MLL					
20	Min Lateral Load $\pm 0.5\%$	MLL					
21	Seismic Dir1	Seismic		☐			
22	Seismic Dir2	Seismic		☐			
23	Seismic Accidental Torsion	Seismic		☐			

FIGURE 4.7: Load patterns used in Tekla for building analysis

The screenshot shows the 'Seismic Wizard' dialog box, titled 'Basic Information'. It is divided into several sections for inputting seismic data:

- Structure Details:**
 - Height to the highest level: 384.000 ft
 - Ignore seismic in floor (and below): none
 - Number of stories: 35
- Site & Occupancy:**
 - Site class: D - Medium dense sand/stiff clay
 - ☐ Site specific velocity measurements made
 - Risk category: II
 - I_e - importance factor: 1.000 ☐ Override
- Seismic Design Category:**
 - Seismic design category: D
 - ☐ Alternative SDC determination - from Table 11.6-1 alone
 - ☒ User defined SDC
 - ☒ Include vertical seismic load effect
- MCE_s spectral response acceleration for site class BC:**
 - S_1 - short period (0.2s): 130.000 %g
 - S_1 - 1s period: 38.000 %g
- Design Spectral Response Acceleration:**
 - S_{DS} - short period: 86.700 %g
 - S_{D1} - 1s period: 48.600 %g
- MCE_s spectral response acceleration adjusted for site class:**
 - S_{MS} - short period: 130.050 %g
 - S_{M1} - 1s period: 72.900 %g

At the bottom, there is a 'Geodatabase ASCE Hazard Tool - Seismic' button and navigation buttons: '< Back', 'Next >', and 'Finish'. The status bar at the bottom indicates 'Cancel Step 2 of 7'.

FIGURE 4.8: Seismic parameters used for building analysis in Tekla

4.3 Finite Element Model Development Results

4.3.1 Finite Element Model Developed in Autodesk Robot Structural Analysis Professional

After the structural geometry was created, Autodesk Robot Structural Analysis Professional automatically created the finite element representation of the building. The frame elements were used to model beams and columns, and the slabs and shear walls were modeled using shell elements. The finite element meshes created by the software ensured connectivity between the building's structural elements and allowed the software to accurately represent the stiffness distribution and load transfer throughout the building. Figure 4.9 shows the meshing options in RSAP software.

The finite element model was refined to the point of providing a good representation of the interaction between the moment resisting frame system and the reinforced concrete shear walls. In dual system buildings this interaction is especially crucial since both systems play a major role in providing lateral stiffness and

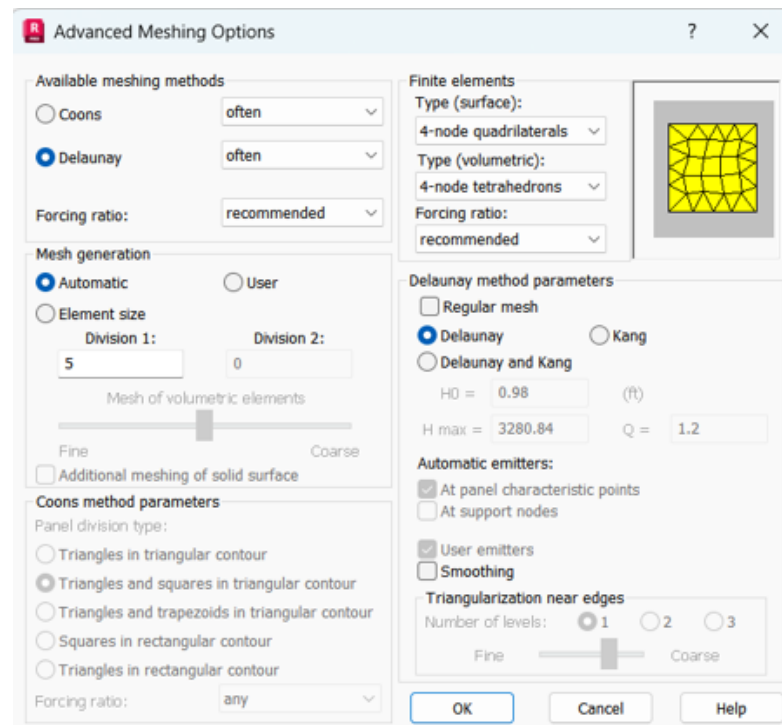


FIGURE 4.9: Advance meshing options in RSAP

seismic resistance. The finite element mesh created in Autodesk Robot Structural Analysis Professional is shown in figure 4.10.

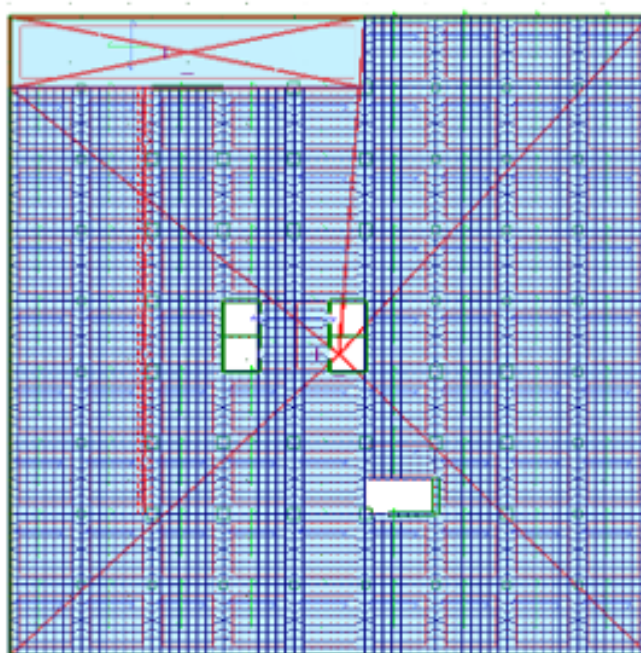


FIGURE 4.10: Finite element mesh created in Autodesk Robot Structural Analysis Professional

The created finite element model was able to represent the overall behavior of the building and was used for modal analysis and response spectrum analysis.

4.3.2 Finite Element Model Developed in Tekla Structural Designer

The analytical finite element model was automatically generated by Tekla Structural Designer from the defined structural geometry. Like Robot Structural Analysis, beams and columns were modeled as frame elements while slabs and shear walls were modeled as finite element shell elements. The analytical model was used to define the structural connectivity necessary to generate stiffness matrix and dynamic analysis. The finite element representation generated was able to accurately represent the load transfer paths and stiffness distribution within the building, and it was used to evaluate the seismic response parameters. The finite element model created in Tekla Structural Designer is shown in figure 4.11.

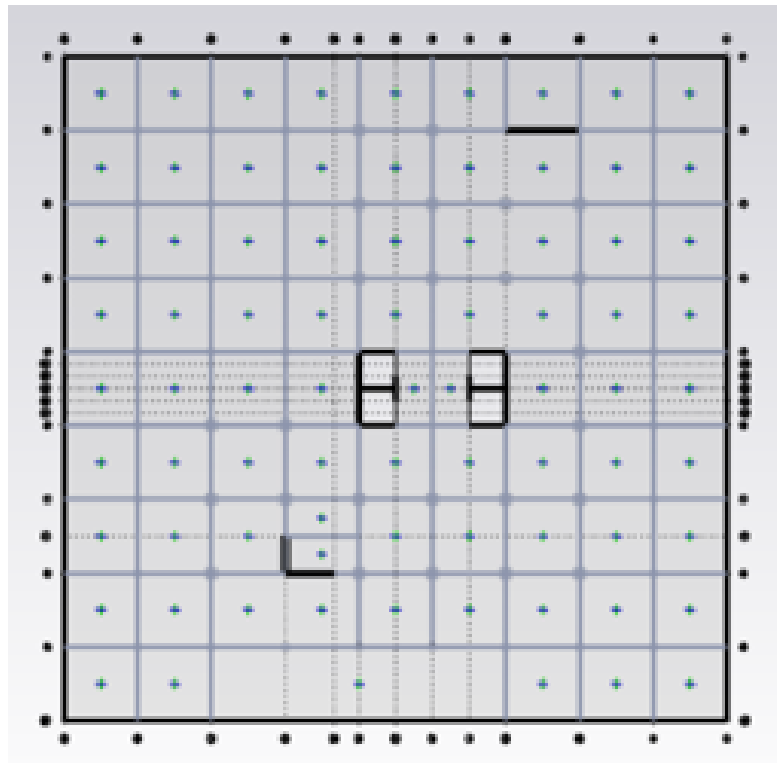


FIGURE 4.11: Finite Element Model Developed in Tekla Structural Designer

The model created was able to capture the structural system and served as a good foundation for the following seismic analysis procedures

4.4 Code-Based Design Results

4.4.1 Modal Analysis Results

The natural vibration characteristics of the structure were obtained by modal analysis. Mass and stiffness of a structure are the main factors influencing natural time period and frequency of a structure. The greater the stiffness of the structure, the more quickly the vibration will dampen out and the higher the natural frequency; the higher the mass, the longer the time period and the lower the natural frequency. The fundamental time period of a building is the duration of time (in seconds) required for the building to complete one full cycle of free vibration in the first (lowest) natural mode of vibration.

$$T_a = C_t h^x \quad (4.1)$$

T_a – Average of the fundamental periods (seconds) (Approximate)

h – Height of the building in feet or meters (depending on code) above the base

Usually, the empirical values of C_t and x are determined based on the structural system (steel moment frame, concrete frame, shear walls, etc.). Table 4.1 shows the results from both software platforms.

TABLE 4.1: Fundamental Time Period Results

Software	X Direction (s)	Y Direction (s)
Robot Structural Analysis	4.79	4.29
Tekla Structural Designer	4.80	4.60

The results show that both software platforms give comparable dynamic properties of the building. The observed differences are rather small and can be explained by differences in finite element formulation, stiffness representation and numerical solution techniques used by each software package.

4.4.2 Seismic Weight Results

The seismic weight of the structure is the sum of all the effective masses that are involved in the earthquake response. Seismic weight estimation is an important issue as it directly influences the computation of seismic forces since it is a crucial factor. Table 4.2 shows the results of both software platforms.

TABLE 4.2: Seismic Weight Results

Software	X Direction (kip)	Y Direction (kip)
Robot Structural Analysis	195,410.945	195,410.945
Tekla Structural Designer	195,540.945	195,540.945

The calculated seismic weights show good agreement between the two software platforms and good consistency in the mass source generation and load assignment procedures.

4.4.3 Base Shear Results

The design base shear is the total seismic force applied at the foundation level of the structure and is one of the important parameters that control seismic design. Table 4.3 shows the results from both software platforms.

TABLE 4.3: Base Shear Results

Software	Base Shear (kip)
Robot Structural Analysis	7,463.14
Tekla Structural Designer	7,465.30

The computed base shear values are close and this shows that both software packages apply the response spectrum procedure in a similar way.

4.4.4 Displacement Results

The maximum displacement was calculated in both directions to determine the overall flexibility of the structure under seismic loading. The results from both software are shown in Table 4.4.

TABLE 4.4: Maximum Displacement Results

Software	X Direction (in.)	Y Direction (in.)
Robot Structural Analysis	28.80	23.87
Tekla Structural Designer	28.00	23.00

The displacement values show that both software platforms have similar lateral response characteristics. The results show that the lateral stiffness of the building is sufficient to control the seismic deformations.

4.4.5 Story Drift Results

Drift ratio is a significant serviceability criterion for seismic design, and is also referred to as story drift. Even if a structure does not collapse, it can suffer structural and non-structural damage due to excessive inter-story drift. Table 4.5 displays the results of both software platforms.

TABLE 4.5: Maximum Story Drift Ratio Results

Software	X Direction	Y Direction	ASCE 7-22 Limit
Robot Structural Analysis	0.0029	0.0019	0.0036
Tekla Structural Designer	0.0028	0.0020	0.0036

The maximum drift ratios for both software platforms are still within the allowable drift ratio as specified in ASCE 7-22, which demonstrates good seismic performance and compliance to code requirements.

4.4.6 Torsional Response Results

Torsional irregularity was assessed to identify if there was excessive torsional amplification under seismic loading. Torsional irregularity is considered to be significant when the amplification ratio is greater than 1.20, per ASCE 7-22. Table 4.6 shows the results from both software platforms.

TABLE 4.6: Maximum Torsional Irregularity Ratios

Software	EqX	EqY	ASCE 7-22 Limit
Robot Structural Analysis	1.09	1.04	1.20
Tekla Structural Designer	1.13	1.09	1.20

The response of the structure in the torsional direction shows that the structure is not significantly torsional irregular and meets the code requirements in both directions.

4.5 Comparison with ETABS Benchmark Results

After the seismic analysis procedures in Robot Structural Analysis Professional and Tekla Structural Designer, the results were compared to the benchmark ETABS model. This comparison aimed to assess the capacity of BIM integrated software platforms to simulate seismic response features of a high-rise reinforced concrete dual-system building. The main seismic response parameters calculated using all three software platforms are summarized in Table 4.7.

The comparison shows that the three software platforms are very consistent. The seismic weights calculated using Robot Structural Analysis Professional and Tekla Structural Designer are slightly different from the benchmark ETABS model. The close match between the seismic weight in both BIM-based software environments suggests that the gravity loading and mass generation process were replicated effectively. Likewise, the computed base shear values are in good agreement. The

TABLE 4.7: Comparison of Seismic Analysis Results Between Software Platforms

Parameter	ETABS		Robot		Tekla	
	X	Y	X	Y	X	Y
Time Period (s)	5.00	5.67	4.79	4.29	4.80	4.60
Roof Displacement (in.)	29.00	24.00	28.80	23.87	28.00	23.00
Story Drift Ratio	0.0027	0.0021	0.0029	0.0019	0.0028	0.0020
Torsional Ratio	1.12	1.18	1.09	1.04	1.13	1.09
Seismic Weight (kip)	195,616.739	195,616.739	195,410.945	195,410.945	195,540.945	195,540.945
Base Shear (kip)	7,470.00	7,470.00	7,463.14	7,463.14	7,465.30	7,465.30

maximum difference between the software platforms is less than one percent, which suggests that the results of the response spectrum procedures performed in Robot Structural Analysis Professional and Tekla Structural Designer are similar to those in ETABS.

The time periods from ETABS (5.67 s), Robot (4.29 s) and Tekla (4.80 s) are quite different, especially in the Y-direction. The same geometry, member sizes, material properties and boundary conditions were used, but differences may be due to the finite element formulation, the generation of the mass and stiffness matrices, the assumptions for diaphragm and connectivity, the meshing, and the procedure for solving for the eigenvalues. Thus, the difference observed does not necessarily correspond to a bug in the software, but may be due to variations in numerical modelling and computation methods.

The results of the displacement also show a good correlation between the software packages. There is some variation in both directions of the main axis, but overall the displacement patterns are similar. The differences in these variations are due to the differences in the finite element formulations, stiffness assumptions and the numerical solution methods used by each software platform. The story drift results are similar. The drift ratios for all of the software platforms were below the ASCE 7-22 limit of 0.0036, so they meet the seismic serviceability requirements. The calculated drift values show that the building has sufficient lateral stiffness, and all three software packages give similar estimates of deformation demand.

The three software platforms also yield very similar torsional irregularity ratios that are less than the threshold value of 1.20 from ASCE 7-22. Thus, the building

has no significant torsional irregularity for any software platform used for analysis. In general, the findings suggest that the results of seismic analysis performed with Autodesk Robot Structural Analysis Professional and Tekla Structural Designer can be reproduced with acceptable engineering accuracy for the seismic analysis results obtained from the benchmark ETABS code. The results indicate that the study is replicable to tall RC buildings as long as the same modelling assumptions and validations are adopted.

4.6 Performance-Based Assessment Capability

4.6.1 Assessment of Autodesk Robot Structural Analysis Professional

To explore the possibility of integrating the Performance Based Design (PBD) procedures into the BIM-integrated structural analysis platforms was also the part of research. As mentioned in Chapter 3, the methodology suggested was to use static nonlinear pushover technique as per ASCE 41-17 for the seismic performance evaluation of the benchmark building. But in the implementation phase, a few software restrictions were found in Autodesk Robot Structural Analysis Professional.

While Robot Structural Analysis Professional offers a wide range of features for linear static analysis, response spectrum analysis, modal analysis, and structural design verification, it does not contain pre-defined ASCE 41-17 plastic hinge properties for reinforced concrete members, and does not contain P-M2-M3 plastic hinges for reinforced concrete columns. In addition, there are no P-M3 hinge definitions for reinforced concrete shear walls.

Another major drawback that was found in the course of the investigation was the lack of nonlinear material constitutive models for the behavior of reinforced concrete. The absence of material nonlinearity for reinforced concrete members makes it challenging for performance-based seismic assessment, which relies on nonlinear material properties.

Due to these restrictions, the nonlinear static pushover analysis presented in Chapter 3 was not possible with Autodesk Robot Structural Analysis Professional. Thus, the software was only tested against code-based seismic design procedures. Table 4.8 shows Performance-based design capabilities of Robot Structural Analysis Professional software.

TABLE 4.8: Performance-Based Design Capabilities of Robot Structural Analysis Professional

Capability	Status
Response Spectrum Analysis	Built-in
Modal Analysis	Built-in
Nonlinear Material Definition	Not Available
P-M2-M3 Plastic Hinges	Not Available
PM3 Plastic Hinges	Not Available
ASCE 41-17 Performance Evaluation	Not Available
Nonlinear Static Pushover Analysis	Not Available

The results show that the Robot Structural Analysis Professional software is appropriate for code-based seismic analysis, but the software has limited functions for the performance-based seismic analysis of reinforced concrete high-rise structures.

4.6.2 Assessment of Tekla Structural Designer

The performance-based seismic assessment procedures were also tested with Tekla Structural Designer. The investigation found that the software is mainly used for conventional code-based structural analysis and design and lacks the ability to perform nonlinear seismic performance evaluation. Unlike ETABS, Tekla Structural Designer does not have a module for nonlinear static pushover analysis, plastic hinge generation, nonlinear material modeling or ASCE 41-17 performance assessment.

As a result, the software is unable to assess structural performance levels like Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). The lack of nonlinear analysis tools greatly restricts the use of Tekla Structural Designer for advanced seismic assessment of high-rise reinforced concrete structures. While

the software offers effective workflows for BIM integration and code-based design procedures, it is not yet possible to use it for performance-based design procedures. Table 4.9 shows Performance-based design capabilities of Tekla Structural Designer software.

TABLE 4.9: Performance-Based Design Capabilities of Tekla Structural Designer

Capability	Status
Response Spectrum Analysis	Available
Modal Analysis	Available
Nonlinear Material Definition	Not Available
Plastic Hinge Assignment	Not Available
ASCE 41-17 Performance Evaluation	Not Available
Performance Level Assessment	Not Available
Nonlinear Static Pushover Analysis	Not Available

The results of this study indicate that Tekla Structural Designer can be used for code-based seismic design but not for performance-based seismic assessment.

4.7 Limitations of BIM Tools and Mitigation Measures

4.7.1 Limitations and Mitigation Measures of Autodesk Robot Structural Analysis Professional

Autodesk Robot Structural Analysis Professional (RSA) does not provide the same level of nonlinear modeling capabilities as is needed for advanced seismic assessment and performance-based evaluation. Although it is useful for linear analysis and traditional design processes, RSA does not provide the necessary tools for material nonlinearity, plastic hinge definition, and performance evaluation based on ASCE 41-17. To overcome these constraints, engineers use interoperability with specialized nonlinear analysis software and better BIM data exchange processes. The limitations and mitigation measures are summarized in Table 4.10.

TABLE 4.10: Limitations and Mitigation Measures for RSA

Limitations	Mitigation Measures
1. Does not support nonlinear material constitutive models for reinforced concrete.	1. Export models to ETABS, SAP2000, Perform-3D, OpenSees, or Abaqus.
2. Cannot define P-M2-M3 plastic hinges for RC columns required by ASCE 41-17. Does not provide PM3 hinge definitions for RC shear walls.	2. Improve BIM interoperability workflows.
3. Lacks ASCE 41-17 performance evaluation procedures.	3. Incorporate nonlinear material properties, hinge libraries, and ASCE 41-17 modules in future versions.

4.7.2 Limitations of Tekla Structural Designer

Nonlinear material modeling, hinge formation, and explicit consideration of performance levels (Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP)) are required for advanced performance-based seismic design. However, Tekla Structural Designer (TSD) is mainly designed for linear elastic analysis and code-based design, which restricts its capability in advanced nonlinear and ASCE 41-17 based assessment. Thus, it is required to integrate with specialized nonlinear analysis software from the outside to get full performance-based evaluation. The limitations and mitigation strategies are summarized in Table 4.11.

TABLE 4.11: Limitations and Mitigation Measures for Tekla Structural Designer

Limitations	Mitigation Measures
1. Does not support nonlinear material modeling.	1. Integrate Tekla models with advanced nonlinear software.
2. Does not allow plastic hinge assignment.	2. Use external platforms for pushover and response-history analyses.
3. Lacks nonlinear static pushover analysis capabilities.	3. Develop future modules for nonlinear behavior and performance assessment.
4. Cannot perform ASCE 41-17 performance evaluation.	
5. Cannot assess IO, LS, and CP performance levels.	

4.8 Summary

The results of seismic analysis and comparative evaluation of a 35-story RC hybrid-system structure were presented in this chapter with the use of Autodesk Robot Structural Analysis Professional (RSA), Tekla Structural Designer (TSD), and ETABS as the benchmark reference. The study was directed towards the evaluation of the important structural response parameters under the same loading conditions and seismic provisions as specified in ASCE 7-22 and ACI 318-19. The results of modal analysis revealed that the fundamental time periods derived from all three software packages were well correlated, which means that the dynamic characteristics of the structure were well predicted. Likewise, seismic weight and base shear values showed very small differences between the three programs, RSA, TSD, and ETABS, which indicates that the mass distribution and the implementation of the response spectrum were consistent. The results of lateral displacement and story drift ratio were also determined to be in good agreement between the three software tools. The computed drift values were all within the acceptable limits specified in ASCE 7-22, which means that the seismic performance in terms of serviceability was satisfactory. Furthermore, the torsional irregularity ratios obtained from all the software packages were found to be below the code defined value, indicating that the structure is not sensitive to torsional effects under seismic loading. A comparative evaluation also showed that the differences between the results obtained from RSA, TSD and ETABS are very small and are mainly attributed to the differences in finite element formulations, stiffness assumptions and numerical solution procedures. In general, both BIM-based structural analysis tools were able to produce seismic response results that are in good agreement with the code-based results for high-rise reinforced concrete structures, as compared to the benchmark ETABS model. But there were major drawbacks in the seismic assessment based on performance. Autodesk Robot Structural Analysis Professional does not include nonlinear material modeling and the necessary plastic hinge definitions for reinforced concrete members, and Tekla Structural Designer does not include functionality for nonlinear seismic performance evaluation. As a result, both software packages were unable to conduct the proposed nonlinear

static pushover analysis outlined in Chapter 3. The limitations underscore the need for specialized software like ETABS to implement the performance-based seismic design procedures in high-rise reinforced concrete structures. The results of this chapter are used to draw conclusions and make recommendations in Chapter 5.

Chapter 5

Conclusion and Recommendations

5.1 General

In this research, the ability of the BIM-integrated structural analysis software to analyze and assess the seismic response and structural behavior of a 35-storey RC structure employing a joint frame-wall system was evaluated. The results showed that Autodesk Robot Structural Analysis Professional and Tekla Structural Designer were capable of conducting code-based seismic analysis and yielding results similar to that of the benchmark ETABS model. Seismic response parameters such as fundamental time period, seismic weight, base shear, displacement, story drift, and torsional response were compared and found to be in good agreement for all software platforms. The calculated drift ratios and torsional irregularity values were within acceptable limits as stated in ASCE 7-22, indicating good seismic performance of the structure. But it was found that both BIM based platforms have shortcomings in nonlinear material modeling, plastic hinge definition, pushover analysis and ASCE 41-17 performance evaluation. Thus, these tools are suitable for traditional code-based seismic design, but need to be integrated with advanced nonlinear analysis software to enable full performance-based seismic evaluation of high-rise RC structures.

5.2 Conclusion

The main purpose of this research was to examine the capacity of BIM integrated structural analysis software to perform seismic analysis of a 35-story reinforced concrete dual-system building and to compare the results with a benchmark ETABS model created based on the ASCE 7-22 and ACI 318-19 requirements. The following conclusions can be drawn from the results presented in Chapter 4.

5.2.1 Code-Based Seismic Analysis Conclusions

- i. All software platforms agreed very closely in the fundamental time period results. The time period calculated in the x-direction was 5.00 seconds in ETABS, 4.79 seconds in Autodesk Robot Structural Analysis Professional and 4.80 seconds in Tekla Structural Designer, and in the y-direction, it was 5.67 seconds in ETABS, 4.29 seconds in RSA and 4.60 seconds in TSD. The results show that the dynamic characteristics of the structure are well predicted.
- ii. The seismic weights determined by all software platforms were in good agreement. The seismic weight in ETABS was 195,616.739 kip, in RSA was 195,410.945 kip and in TSD was 195,540.945 kip, showing that the mass source generation and load assignment procedures were reliable.
- iii. The calculated base shear values were very similar with 7,470.00 kip in ETABS, 7,463.14 kip in RSA and 7,465.30 kip in TSD, showing similar implementation of response spectrum in all the software platforms.
- iv. Close correlation of the maximum roof displacement results was obtained. The displacement in the x-direction in ETABS was 29.00 inches, in RSA was 28.80 inches, and in TSD was 28.00 inches; the displacement in the y-direction in ETABS was 24.00 inches, in RSA was 23.87 inches, and in TSD was 23.00 inches.

- v. Maximum story drift ratios from all software platforms were below the ASCE 7-22 limit of 0.0036. The drift ratios were within the range of 0.0019 to 0.0029, which is considered satisfactory seismic serviceability performance.
- vi. All software platforms produced torsional irregularity ratios that were less than the ASCE 7-22 limit of 1.20. The values range from 1.12 to 1.18 for ETABS, 1.04 to 1.09 for RSA, and 1.09 to 1.13 for TSD, which are not significant enough to indicate that the building is significantly torsional irregular.
- vii. The comparison with ETABS showed that the two software packages Autodesk Robot Structural Analysis Professional and Tekla Structural Designer are capable of producing acceptable engineering accuracy in seismic analysis results as per the codes. The differences observed were generally within 1-3%, primarily because of differences in finite element formulation, stiffness assumptions and numerical solution methods.

5.2.2 Performance-Based Seismic Assessment Conclusion

- i. The performance-based seismic assessment was shown to be limited in Autodesk Robot Structural Analysis Professional due to the absence of nonlinear material modeling of reinforced concrete, P-M2-M3 plastic hinges for RC columns, PM3 plastic hinges for RC shear walls, and automated ASCE 41-17 performance evaluation procedures.
- ii. The Tekla Structural Designer also does not have the necessary nonlinear analysis features such as nonlinear material modelling, plastic hinge assignment, nonlinear static pushover analysis, ASCE 41-17 performance evaluation, or performance level assessment (Immediate Occupancy (IO), Life Safety (LS), Collapse Prevention (CP)).
- iii. Because of these software restrictions, nonlinear static pushover analysis and ASCE 41-17-based performance evaluation were not possible with Autodesk Robot Structural Analysis Professional and Tekla Structural Designer.

- iv. The study showed that BIM-based analytical workflows created with RSA and TSD can be exported to advance nonlinear analysis software, including ETABS, SAP2000, Perform-3D, OpenSees, and Abaqus, for future performance-based seismic assessment.
- v. In general, Autodesk Robot Structural Analysis Professional and Tekla Structural Designer can be used for code-based seismic analysis and design for high-rise reinforced concrete buildings, but certain nonlinear analysis software is still required for more in-depth performance-based seismic evaluation.

5.3 Recommendations and Future Work

The following recommendations for further research are suggested based on the results of this study:

- i. Further research is needed to assess the accuracy and effectiveness of transferring structural models from BIM software to advanced analysis software for nonlinear analysis.
- ii. Future studies need to be conducted on effective interoperability techniques between the BIM-based structural analysis software and advanced nonlinear analysis software. The models should be imported into software like ETABS, SAP2000, Perform-3D, OpenSees or Abaqus for detailed performance-based seismic evaluation.
- iii. Non-linear material modeling, plastic hinge definition, pushover analysis and ASCE 41-17 performance evaluation features should be incorporated into future enhancements of BIM-based structural analysis software to facilitate full performance-based seismic design.
- iv. Further research is recommended to establish automated BIM-to-performance-based-design workflows that can facilitate data exchange, minimize modelling time, and advance the use of BIM technology in seismic engineering.

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