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FULL LENGTH ARTICLE

BIM-Enabled Interpretation of Saudi Building Code Shear Wall Requirements for Mixed-Use Buildings

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ABSTRACT

Purpose: This study develops a Building Information Modeling (BIM)-enabled methodology that integrates Saudi Building Code (SBC) seismic detailing provisions for reinforced concrete shear walls into a rule-based parametric modeling environment. The research enhances compliance traceability, automates code interpretation, and improves quantity accuracy for mixed-use high-rise buildings with significant vertical zoning effects. Approach: Selected SBC shear wall provisions were translated into computable IF–THEN engineering rules linked to BIM parameters. The methodology incorporates vertical zoning, axial load ratio evaluation, rule-based reinforcement detailing, and automated quantity extraction. The framework was validated using a large-scale Saudi healthcare mixed-use case study by comparing BIM-derived quantities with independent SBC-consistent reference calculations on a zone-by-zone basis. Findings: Axial load ratio governs boundary element activation and confinement reinforcement demand. BIM-generated reinforcement distributions aligned closely with SBC intent, with average differences of 2–4% for concrete volume, 3–6% for longitudinal reinforcement, and 4–8% for confinement reinforcement. Boundary confinement was concentrated within the lower 30–40% of building height, while zone-based detailing reduced upper-zone reinforcement by approximately 15–25%. Practical Implications: The methodology improves automated compliance verification, reduces overdesign, enhances reproducibility, and supports efficient structural modeling for complex mixed-use buildings. Originality/Value: The study establishes a direct digital linkage between SBC provisions, parametric BIM modeling, and automated structural quantity outputs.

Keywords: Parametric compliance ▪ Rule-based modeling ▪ Axial load interaction ▪ Vertical zoning ▪ Digital structural workflow

1. INTRODUCTION

Reinforced concrete (RC) shear walls are widely used as primary lateral load –resisting systems in medium - and high-rise buildings because their axial –flexural response governs strength, d uctility, and seismic performance. Modern design standards [1] therefore prescribe minimum wall thickness, axial -load limits, boundary element requirements, and confinement reinforcement to achieve ductile behavior and avoid brittle compression failures. In parallel, Building Information Modeling (BIM) has enabled parametric modeling, multidisciplinary coordination, and automated quantity extraction, and has been reported to improve design efficiency and reduce errors [2-3]. Despite these advances, most BIM-based structural workflows still depend on manual interpretation of code provisions before modeling, creating a disconnect between code requirements and the digital model. This gap is particularly critical for SBC seismic detailing of shear walls in mixed-use high-rise buildings, where vertical zoning causes significant variations in axial demand along the height. As a result, manually applying code triggers can be time - consuming and highly dependent on engineering judgment, often leading to conservative o r

inconsistent detailing and inefficient material use. More broadly, prior work indicates that shear -wall behavior research, code-based design, and BIM automation have largely evolved independently, limiting traceability between code clauses, detailing decisions, and quantity outputs. To address these limitations, this study proposes a BIM -enabled methodology that integrates SBC shear -wall provisions into a parametric modeling environment by translating code clauses into computable IF–THEN rules directly linked to BIM parameters. The objectives are to: (1) automate interpretation of relevant SBC provisions, (2) implement zone -dependent reinforcement detailing that accounts for mixed-use vertical zoning, and (3) integrate axial load ratio effects while enabli ng automated and traceable quantity extraction that connects "code → rule → BIM parameter → design output." The research is motivated by the need for a consistent, auditable, and efficient compliance workflow, especially where axial load ratio changes substantially between podium and tower levels. The proposed approach follows a rule-based BIM workflow: defining zoning, selecting and abstracting SBC provisions, translating clauses into engineering rules, encoding these rules into BIM parameters, and validating automated quantity outputs. The framework is demonstrated on a large - scale Saudi healthcare mixed - use project (≈165,000 m2,

>18 storeys plus basements), with validation performed by comparing BIM -derived quantities against independent SBC-consistent reference calculations on a zone-by-zone basis. Results indicate that SBC detailing demands vary markedly with height: axial load ratio governs boundary-region activation and confinement intensity, and the BIM implementation produces reinforcement distributions consistent with SBC intent. Agreement with reference calculations is strong, with average differences of 2 –4% (concrete), 3–6% (longitudinal reinforcement), and 4 –8% (confinement reinforcement). Boundary confinement is concentrated within the lower 30–40% of the building height, and zone-based detailing can reduce reinforcement in upper zones by approximately 15 -25% compared with uniform conservative assumptions. These findings suggest that linking SBC provisions to BIM parameters improves compliance traceability, reduces overdesign, and supports more reproducible design decisions. The remainder of this paper review s related literature, presents the proposed methodology and case -study implementation, reports validation and key findings, and concludes with implications and future research directions.

2. LITERATURE REVIEW

2.1 Structural Behavior of Reinforced Concrete Shear Walls

Reinforced concrete shear walls are widely used as primary lateral load –resisting systems in medium - and high- rise buildings because their axial –flexural response directly governs strength, ductility, and seismic Performance [4]. The performance of these walls is governed by axial –flexural interaction, since gravity - induced axial forces significantly al-ter compression - zone stresses, neutral -axis depth, boundary -element reinforcement demands, and the initiation of con-crete crushing or longitudinal bar instability [5]. Extensive experimental and analytical investigations have demonstrated that axial load ratio plays a critical role in determining wall ductility and failure mode. Early experimental studies by [6] showed that increasing axial compression significantly increases confinement demand and may lead to premature compression failure if boundary regions are not adequately detailed. Similarly, [7] emphasized that ductile seismic per-formance of shear walls depends strongly on confinement reinforcement and boundary element detailing in compres-sion - controlled regions. Later analytical and fiber -based modeling studies further confirmed that axial load ratio gov-erns strength degradation, curvature capacity, and ultimate failure mechanisms of structural wall s [8-9]. These studies provided valuable insight into nonlinear behavior of shear walls and highlighted the need for accurate characterization of axial–flexural interaction during design. Figure (1) illustrates the influence of axial load ratio on shear wall confinement demand, showing that increasing axial load activates bound-ary confinement reinforcement and shifts structural behavior from tension -controlled to compression-controlled response. While these studies provide strong theoretical and experimental understanding of shear wall behavior, they primarily focus on analytical modeling and laboratory testing rather than integration with digital design workflows. Strengths of previous studies • Strong experimental validation • Detailed analytical modeling • Reliable prediction of failure mechanisms

Limitations. • Limited linkage to design automation • No integration with BIM environments • Manual interpretation required in practice

2.2 Code-Based Shear Wall Design and SBC Requirements

Modern structural design codes such as these codes [1-15-16] provide comprehensive provisions governing shear wall design, including minimum wall thickness, axial load limits, boundary element requirements, and confinement reinforce-ment ratios. The Saudi Building Code adopts performance -based s eismic design principles that require enhanced detailing when axial load ratios exceed prescribed limits. These provisions ensure adequate ductility and prevent brittle fail-ure in compression -controlled regions. However, implementation of such provisions depends heavily on engineering judgment and manual interpretation.

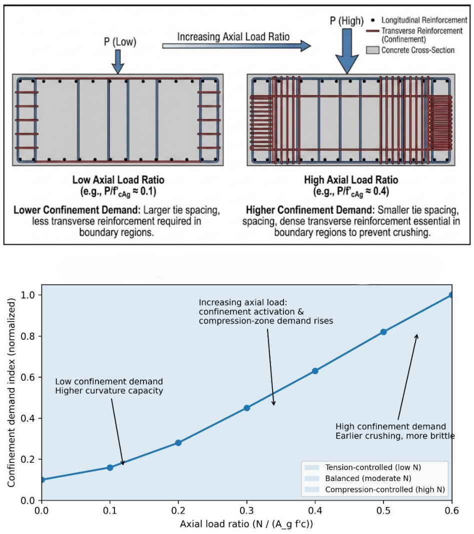

Figure 1. Influence of Axial Load Ratio on Confinement Demand.

Several researchers have highlighted challenges associated with manual application of design codes. Studies indicate that manual interpretation may lead to conservative detailing, inconsistent reinforcement distribution, and inefficient material usage, particularly in mixed-use buildings where axial load distribution varies significantly along the height [10 -11].As shown in Figure(2) illustrates the conventional workflow of structural code implementation, highlighting how manual interpretation of design provisions can lead to conservative detailing, inefficiencies, and inconsistent reinforcement distribution, particularly in mi xed-use buildings with varying axial load demands.

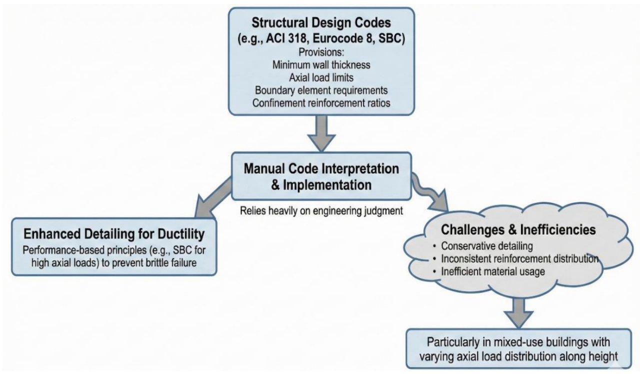

Figure 2. Traditional Manual Code Interpretation Process.

Although design codes provide reliable safety guidelines, their manual implementation limits efficiency and traceability within digital modeling environments. Strengths • Robust safety-based design rules • Well-established detailing provisions • Consistent performance objectives Weaknesses • Manual interpretation required • No automated compliance verification • Limited linkage with BIM-based modeling

2.3 BIM Applications in Structural Engineering

Building Information Modeling (BIM) has transformed design and construction processes by enabling parametric modeling, multidisciplinary coordination, and automated quantity extraction. Research by [2-3] demonstrated that BIM improves project efficiency, reduces errors, and enhances visualization. Subsequent studies explored BIM applications

Table 1. Strengths and limitations of existing research domains related to shear wall design and BIM integration.

Domain	Strength	Limitation
Shear wall behavior research	Accurate analytical understanding	No BIM integration
Code-based design	Reliable safety provisions	Manual implementation
BIM research	Automation and modeling	Limited structural code linkage

in structural engineering, including automated reinforcement detailing, cost estimation, and structural optimization [12]. Rule -based BIM systems have also been proposed to support automated code checking and compliance verification. [13] introduced automated rule -checking frameworks capable of verifying design constraints within BIM models. Despite these advancements, integration between structural design codes and BIM environments remains limited. Most BIM-based structural workflows rely on manual interpretation of code provisions before modeling, resulting in a disconnect between code requirements and digital representation. Strengths • Automated quantity takeoff • Parametric modeling capability • Improved coordination Weaknesses • Limited integration with structural codes • No automated SBC interpretation • Minimal focus on shear wall detailing

2.4 Integration of Structural Codes and BIM

Recent research has attempted to bridge the gap between structural design codes and BIM through rule-based and parametric modeling approaches. Studies on automated compliance checking demonstrated that textual code provisions can be translated into computable rules u sing logical IF–THEN relationships [14]. Other studies explored integration of BIM with structural analysis tools for performance-based design and quantity optimization. However, these approaches mainly focused on general building components rather than de tailed structural elements such as shear walls and boundary regions. Furthermore, limited research addressed integration of seismic detailing requirements into BIM environments, particularly within the context of the Saudi Building Code and mixed-use high-rise buildings.

2.5 Identified limitations, inconsistencies, and knowledge gaps

A critical comparison of previous research reveals that three major domains have evolved independently as shown in Table (1):

Despite extensive research in each domain, integration between structural code provisions and BIM-based parametric modeling remains limited. Key gaps identified: • Absence of automated translation of SBC shear wall provisions into BIM parameters • Limited integration between axial load effects and parametric modeling • Lack of zone-based detailing logic for mixed-use buildings • No direct linkage between code clauses and automated quantity extraction • Limited traceability between design requirements and structural quantities

2.6 Research Contribution

To address these limitations, this study proposes a BIM - enabled methodology that integrates SBC shear wall provisions into a parametric modeling environment, as illustrated in Figure (3). The proposed framework translates code clauses into computable engineering rules directly linked to BIM parameters. The methodology enables: • Automated interpretation of SBC provisions • Zone-dependent reinforcement detailing • Integration of axial load ratio effects • Automated quantity extraction • Traceable linkage between code requirements and design outputs

linkage

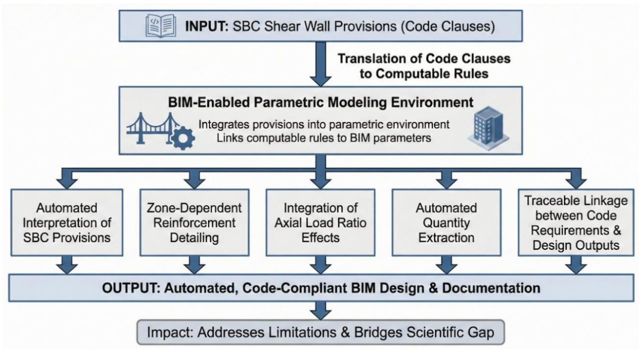

Figure 3. Proposed Framework Bridging the Gap

3. METHODOLOGY

This study employs a BIM -enabled, rule-based methodology to interpret reinf orced concrete shear wall requirements prescribed by the Saudi Building Code for mixed-use buildings. The approach translates SBC seismic and detailing provisions traditionally implemented through manual structural calculations into explicit BIM parameters, enabling consistent shear wall modeling, zone-specific interpretation, and automated quantity takeoff across vertically heterogeneous building configurations. The proposed methodology consists of five main stages: 1. Definition of mixed-use vertical zoning and structural context 2. Identification and abstraction of SBC shear wall provisions 3. Translation of SBC provisions into engineering rules 4. BIM-based rule encoding and parametric modeling 5. Automated quantity extraction and validation The overall methodological workflow is illustrated in Figure (4), which summarizes the transformation process from SBC textual provisions to BIM-based quantity outputs.

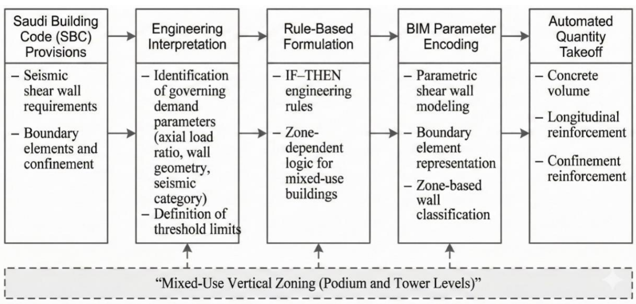

Figure 4. Workflow for BIM-based translation of SBC shear wall provisions into rule-based parameters and automated quantity extraction for mixed-use buildings.

3.1 Methodology Workflow Overview

As shown in Figure (1), the methodology begins with the identification of relevant SBC shear wall provisions and proceeds through a sequence of interpretation, rule formulation, and BIM parameterization. SBC clauses are first translated into engineering rules, which are then encoded into BIM elements through parametric constraints and zone-based classification. The final stage involves automated quantity takeoff, enabling objective comparison of shear wall quantities across different functional zones within the mixed-use building.

3.2 Mixed-Use Building Zoning and Structural Characteristics

Mixed-use buildings are characterized by vertical functional heterogeneity, typically comprisin g podium levels with commercial or public functions and upper levels designated for residential, office, or hospitality use. These functional transitions introduce abrupt variations in axial load demand, stiffness distribution, and seismic force participation, which directly influence RC shear wall detailing requirements under SBC. To explicitly capture these effects, the building is discretized into vertical structural zones, defined based on: • Functional occupancy, • Gravity load intensity, • Tributary height contributing to axial force in shear walls. The zoning concept adopted in this study is illustrated in Figure (5), which depicts a representative mixed-use building divided into podium and tower zones, with corresponding segmentation of shear wall elements along the building height. For each zone z, a characteristic axial load ratio $\nu z$is evaluated as: νz = Pz fc' Ag,z (1) where: Pzis the factored axial load acting on the shear wall segment in zone z, fc 'is the specified concrete compressive strength, and Ag,zis the gross cross-sectional area of the wall in zone z. This zoning strategy enables zone -specific interpretation of SBC detailing requirements, avoiding the unrealistic assumption of uniform detailing along the entire building height.

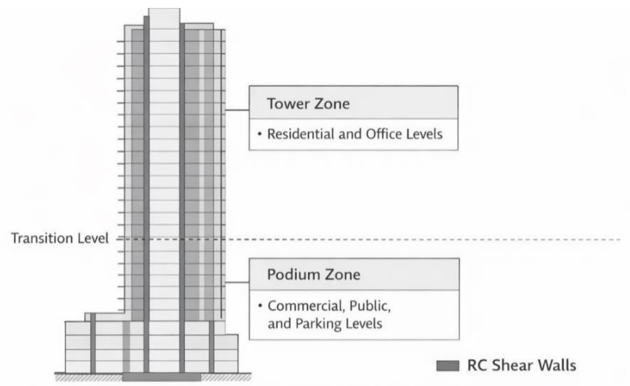

Figure 5. BIM-based translation of SBC shear wall provisions using mixed-use vertical zoning.

3.3 Selection of SBC Shear Wall Provisions

Only SBC provisions that directly affect wall geometry as shown in Table (2), rein forcement detailing, and quantity outcomes are considered in this study. Provisions related exclusively to global analysis procedures or load combinations are excluded, as the objective is not to verify structural safety but to interpret code requirements for modeling and quantification purposes. The selected SBC provisions are grouped

into four categories: 1. Geometric requirements
2. Boundary element criteria 3. Longitudinal reinforcement requirements 4. Transverse confinement requirements

Table 2. SBC provisions considered and their structural implications.

Category	SBC Design Intent	Structural Implication	Quantity Impact
Minimum wall thickness	Ensure stiffness and stability	Controls rigidity and slenderness	Concrete volume
Boundary element requirement	Prevent premature crushing	Confined boundary regions	Confined concrete and reinforcement
Axial load ratio limits	Regulate compression demand	Activates boundary elements	Longitudinal/ transverse reinforcement
Minimum longitudinal reinforcement	Ensure flexural strength	Minimum vertical steel	Longitudinal reinforcement
Transverse confinement	Enhance ductility	Dense boundary ties	Confinement reinforcement
Seismic detailing applicability	Ensure seismic performance	Seismic-specific detailing	Detailing intensity
Vertical irregularity	Address height demand changes	Zone-dependent interpretation	Zone quantity variation

3.4 Engineering Interpretation of SBC Provisions

Each selected SBC provision is reformulated as an explicit engineering rule suitable for BIM-based implementation. This translation represents a critical step in moving from descriptive code language to computable logic. Rules are expressed in conditional IF–THEN format, enabling direct linkage between structural demand parameters and detailing outcomes. For example: • Boundary element rule IF $\nu z > \nu\text{lim}$ (2) THEN boundary elements with confinement reinforcement are required at wall ends in zone z. These rules provide the logical foundation for BIM-based differentiation of shear wall detailing across mixed-use zones.

Computational Significance of Rule-Based Formulation. The explicit rule formulation enables differentiation of shear wall detailing along the height of a mixed-use building, where axial load demand varies significan tly between podium and upper residential or office levels. Rather than enforcing uniform boundary elements throughout the wall height, the rule-based approach allows: RC Shear Walls on Quantities Minimum wall thickness Ensure adequate stiffness and stability under seismic actions Controls wall rigidity and limits slenderness effects Concrete volume Boundary eleme nt requirement Prevent premature concrete crushing at highly compressed wall ends Introduction of confined boundary regions with increased reinforcement Confined concrete and reinforcement Axial load ratio limits Regulate compression demand and ductility capacity Governs activation of boundary elements and confinement Longitudinal and transverse reinforcement Minimum longitudinal reinforcement ratio Ensure flexural strength and crack control Sets lower bound on vertical reinforcement content Longitudinal reinforcement Transverse confinement reinforcement Enhance ductility and energy dissipation in seismic regions Dense transverse reinforcement in boundary elements Confinement reinforcement Seismic detailing applicability Ensure consistent seismic performance Activates seismic -specific detailing rules Reinforcement detailing intensity Vertical irregularity considerations Address changes in demand along building height Requires zone - dependent interpretation of detailing Zone-dependent quantity variation

- Activation of boundary elements only in zones where compression demand exceeds SBC limits , • Concentration of confinement reinforcement where ductility demand is critical, • Reduction of unnecessary reinforcement in zones with lower axial demand. From a BIM perspective, the THEN - clause of each rule triggers the assignment of zone -dependent parameters, such as: • Boundary element presence flags, • Confined concrete region dimensions, • Confinement reinforcement ratios. These parameters directly control quantity takeoff outputs, enabling automated calculation of confined concrete volume and transverse reinforcement weight associated with SBC compliance.

3.5 BIM Modeling Environment and Parametric Assumptions

A parametric BIM model is developed using a commercial BIM platform. RC shear walls are modeled as structural wall elements with embedded parameters representing: wall thickness, • Effective height per zone, • Boundary element presence, • Reinforcement ratios. The model is developed to LOD 300–350, which is sufficient for: • Rule-based differentiation of wall segments, • Automated quantity takeoff, • Comparative assessment of detailing requirements across zones.

3.6 Encoding SBC Rules into BIM Parameters

Translated SBC engineering rules are encoded into the BIM model through a combination of: • Wall type definitions, • Shared parameters, • Zone-based wall classification. Each shear wall instance is assigned a zone identifier, allowing SBC rules to be applied selectively depending on vertical location. Boundary elements are represented explicitly within the BIM model as distinct end regions, as illustrated in Figure (6). Boundary elements are modeled either through: • Localized increases in wall end thickness, or parametric end regions assigned enhanced confinement attributes.

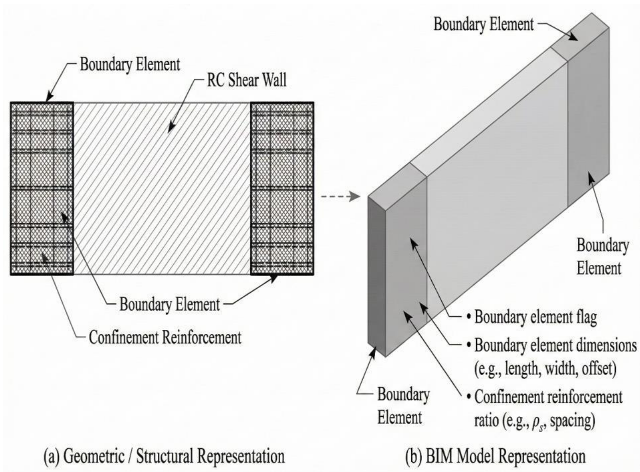

Figure 6. Representation of shear wall boundary elements and confinement reinforcement in structural design and corresponding BIM parametric modeling.

This representation enables the differentiation between boundary and web regions during quantity extraction without requiring construction-level bar modeling. As presented in Table (3), SBC design provisions are linked directly to BIM parameters through rule-based interpretation to support automated code-compliant shear wall detailing.

Table 3. Presents the mapping between SBC rules and BIM parameters.

SBC Requirement Category	SBC Structural Trigger/Condition	Engineering Interpretation	BIM Parameter	Parameter Type	Zone Dependency
Boundary element requirement	Axial load ratio exceeding the limit ($\nu_z > \nu_{lim}$)	Compression-controlled wall ends require enhanced confinement	Boundary element flag	Boolean	Yes
Boundary element geometry	Boundary element required	Increased end-region width and/or thickness	Boundary element width/thickness	Numeric	Yes
Confinement reinforcement	Boundary element activated	Dense transverse reinforcement to ensure ductility	Confinement reinforcement ratio (ρ_t)	Numeric	Yes
Minimum wall thickness	Wall height and seismic category	Control of stiffness and stability	Wall thickness	Numeric	Yes
Minimum longitudinal reinforcement	Wall geometry and detailing limits	Ensure minimum flexural capacity	Longitudinal reinforcement ratio (ρ_l)	Numeric	Yes
Vertical zoning classification	Change in functional use or axial demand	Zone-dependent detailing interpretation	Vertical zone ID	Categorical	Yes
Seismic detailing applicability	SBC seismic classification	Activation of seismic detailing rules	Seismic detailing flag	Boolean	Global

3.7 Quantity Takeoff Formulation

Automated quantity takeoff is performed directly from the BIM model using rule-consistent schedules. Quantities are extracted per vertical zone, enabling assessment of the effect of mixed-use functional transitions on shear wall quantities.

3.7.1 Concrete Quantity

Vc,z = ∑ Aw,i nz i=1 · hz,iEi(N) = ΔM M ΔXi Xi (3)

3.7.2 Longitudinal Reinforcement Quantity

Wl,z = ρl,z · Ag,z · hz · γs (4)

3.7.3 Transverse Confinement Reinforcement

Wt,z = ρt,z · Aconf,z · hz · γs (5)

3.8 Validation Strategy

The quantities derived from the BIM-based rule implementation are validated against independent reference quantities obtained through hand calculations performed in accordance with SBC -compliant sectional assumptions. The primary ob-jective of the validation is to verify the logical correctness and structural consistency of the proposed BIM -enabled interpre-tation of Saudi Building Code shear wall requirements, rather than to demonstrate exact numerical equivalence. Validation is conducted on a zone -by-zone basis to reflect the vertical heterogeneity inherent in mixed-use buildings. Emphasis is placed on: • The consistency of quantity trends across verti-cal zones, • The proportional concentration of longitudinal and confinement reinforcement in podium levels, where axial load demand and seismic requirements are highest, and • The traceability between SBC rule activation and resulting quan-tity outputs. To support the qualitative validation, a simplified quantitative indicator is introduced to measure the relative difference between BIM-derived and reference quantities for each vertical zone. The validation metric is defined as: ΔQz = QBIM,z - QRef,z QRef,z × 100% (6) where: QBIM,zdenotes the quantity extracted from the rule -encoded BIM model for zone z, and QRef,zrepresents the corresponding reference quantity obtained from SBC-compliant hand calculations for the same zone. This metric is used to contextualize discrep-ancies between BIM-derived and reference with-out implying design-level accuracy. Acceptable variations are interpreted in light of modeling discretization, parameter rounding, and abstraction of reinforcement detailing withinthe BIM environment. By combining trend-based assess-ment with a transparent quantitative indicator, the validation strategy ensures that the proposed methodology reliably cap-tures the structural intent of SBC shear wall provisions, while maintaining auditability and reproducibility across different mixed-use building configurations.

3.9 Case Study Demonstration

To validate the proposed BIM -enabled methodology for in-terpreting Saudi Building Code (SBC) shear wall provisions, an actual large-scale Saudi healthcare building was selected as a representative mixed-use case study. The project consists of a multi -storey reinforced concrete hospital complex with an approximate built -up area exceeding 165,000 m2, com-prising basement levels, podium floors, and high-rise medical towers exceeding 18 floors. The structural system is primarily composed of reinforced concrete cores and distributed shear walls acting as the main lateral load -resisting system. Due to the mixed-use functional configuration (basements, public podium, inpatient floors, and technical levels), the building exhibits clear vertical structur al zoning, leading to significant variation in axial loads along the height. These variations directly affect shear wall design parameters including such as wall thickness, boundary element activation, and reinforce-ment concentration as required by SBC provisions.

3.9.1 Structural and Modeling Characteristics

A parametric BIM-based structural model was developed to represent the building and integrate SBC shear wall re-quirements within a unified digital environment as shown in Table (4). Key modeling inputs included: • Shear wall core locations and geometry • Wall thickness and boundary zones • Vertical zoning based on functional use • Axial load distribution along height • SBC design parameters and constraints

Table 4. Case study building characteristics.

Characteristic	Description
Building type	Healthcare mixed-use high-rise
Approximate area	165,000 m^2
Vertical composition	Basements, podium, and tower levels
Structural system	Reinforced concrete shear wall core
BIM scope	Rule-based SBC detailing and quantity takeoff

3.9.2 BIM-Based SBC Integration

SBC shear wall provisions were translated into parametric BIM rules to allow automated compliance assessment and visualization. These rules included minimum wall thickness limits, axial load ratio checks, and boundary element requirements as shown in Table (5).

Table 5. Mapping of SBC requirements into BIM parameters.

SBC Require-ment	BIM Parameter	Output
Minimum wall thickness	Wall type/thickness	Geometry com-pliance
Axial load ratio check	Zone axial ratio	Boundary trigger
Boundary element requirement	Boundary element flag	Confined regions
Reinforcement limits	Longitudinal/ transve ratios	Steel quantities

This integration enabled real-time verification of SBC com-pliance directly within the BIM environment.

3.9.3 Implementation of the Proposed Framework

The methodology was applied through three main stages: Stage 1 — Structural Zoning and Load Mapping The building was divided into vertical zones based on structural demand and functional use as shown in Figure (7). BIM visualization enabled identification of critical shear wall regions subjected to higher axial forces.

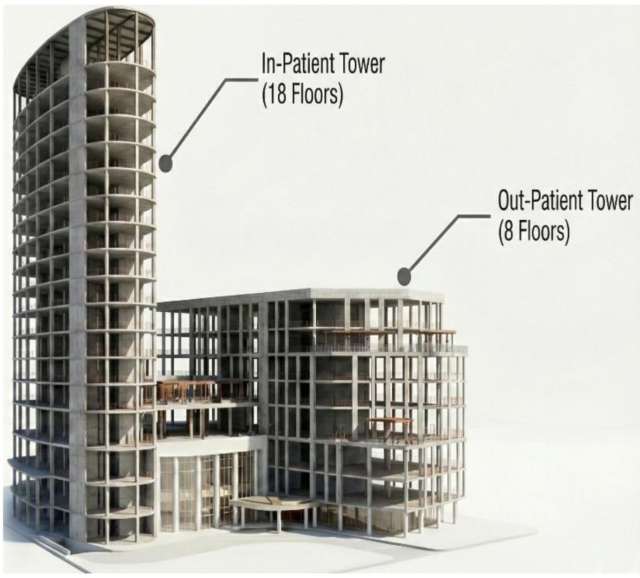

Figure 7. Vertical structural zoning of the case study building showing basement, podium, and tower zones.

Parameter Description Building type High-rise healthcare (mixed-use) Structural system RC cores and shear walls Num-ber of floors >18 storeys + basements Built-up area >150,000 m2 Structural zoning Basement, podium, tower Design code Saudi Building Code (SBC) Minimum wall thickness Para-metric wall constraint Axial load ratio limits Analytical load parameter Boundary element requirement Automated zone detection Reinforcement limits Rebar family constraints Com-pliance verification Embedded rule-based checks used for SBC-based shear wall analysis. Stage 2 — Rule-Based SBC Interpretation SBC provisions governing shear wall design were embedded into the BIM model as parametric rules.

This allowed automated detection of: • Non-compliant wall thickness • Boundary element requirements • High axial load regions The translation of SBC shear wall provisions into BIM-based parameters is illustrated in Figure (8). The framework demonstrates how key code requirements, includ-ing minimum wall thickness, axial load ratio limits, boundary element criteria, and reinforcement limi ts, are interpreted through rule-based logic and mapped directly to BIM model parameters. This process enables automated verification of wall thickness constraints, activation of boundary elements based on axial load demand, and enforcement of reinforce-ment detailing requirements, thereby ensuring consistent and traceable code-compliant shear wall modeling across differ-ent structural zones.

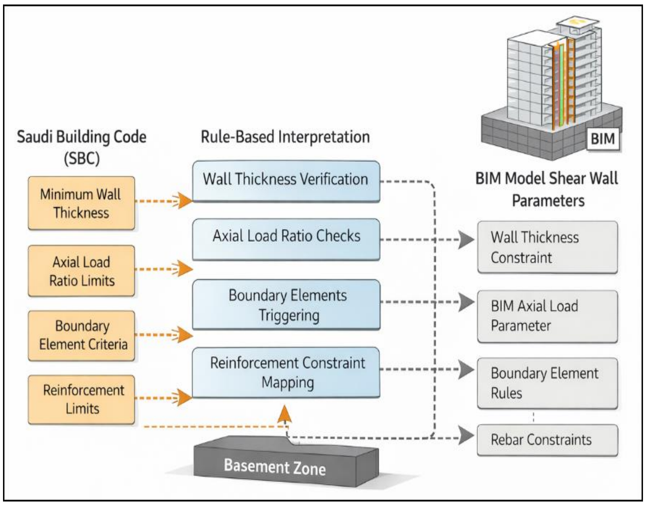

Figure 8. BIM-based translation of SBC shear wall provisions into parametric design rules for automated compliance.

Stage 3 — Reinforcement and Sensitivity Evaluation Para-metric analysis was conducted to evaluate reinforcement dis-tribution and wall efficiency across building zones. The BIM-linked model enabled visualization of reinforcement demand variation due to ax ial load changes and SBC design con-straints. The variation of reinforcement demand along the building height is illustrated in Figure (9). The results indi-cate that reinforcement concentration is significantly higher in the lower structural zones, where sh ear forces and bending moments are dominant, resulting in increased confinement and longitudinal reinforcement requirements. As the building height increases, reinforcement demand gradually decreases due to reduced lateral load effects and the predominance of gravity loading. This trend confirms the importance of zone-based detailing strategies for optimizing reinforcement distribution and improving material efficiency in high-rise shear wall systems.

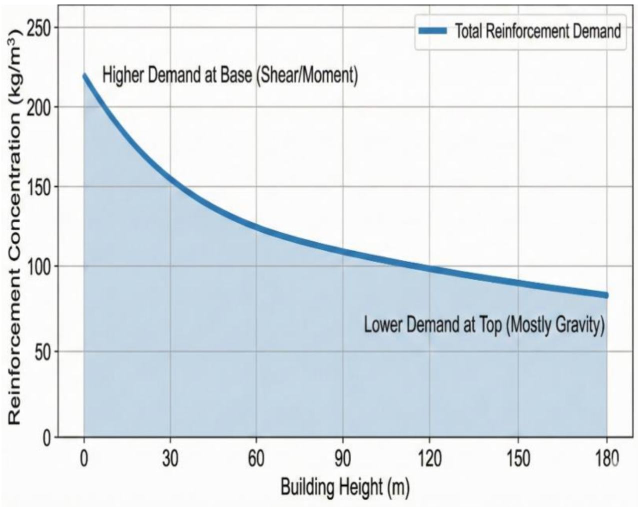

Figure 9. Variation of shear wall reinforcement demand along building height based on SBC-driven axial load effects and vertical zoning.

3.9.4 Key Observations

Application of the proposed methodology to the real building demonstrated that: • Shear wall demand varies significantly across vertical zones due to axial load changes. • SBC boundary element requirements are primarily triggered in lower and mid -height zones. • Conventional manual interpretation may lead to reinforcement overdesign. • BIM-enabled rule integration improves compliance verification and design efficiency. The case study confirms that integrating SBC shear wall provisions into BIM-based workflows provides a practical and efficient approach for analyzing and optimizing shear wall systems in Saudi mixed-use high-rise buildings.

4. RESULTS AND DISCUSSION

4.1 Performance of the BIM–SBC Integration Framework

The proposed BIM-enabled framework successfully translated Saudi Building Code (SBC) shear wall provisions into explicit parametric engineering rules and produced automated quantity outputs consis tent with structural design intent. Results confirm that shear wall detailing requirements vary significantly along the height of mixed-use buildings due to axial load ratio variation and functional zoning. The BIM-based interpretation enabled direct linka ge between SBC clauses, modeling parameters, and extracted quantities, ensuring traceability and reproducibility. Unlike conventional manual interpretation, which often applies uniform detailing along the wall height, the proposed approach produced zone-dependent reinforcement distributions aligned with SBC intent.

4.2 Variation of Axial Load Ratio across Building Height

The analysis revealed that axial load ratio is the governing parameter influencing SBC detailing activation. Lower structural zones (basement and podium) exhibited significantly higher axial load ratios due to accumulated gravity loads from upper floors. As height increased, axial load ratios decreased progressively, reducing confinement and boundary element demand as shown in Table (6).

Table 6. Typical axial load ratio variation by zone.

Zone	Relative Axial Load	SBC Detailing Implication
Basement	Very high	Boundary elements required
Podium	High	Increased confinement reinforcement
Mid-tower	Moderate	Reduced confinement
Upper tower	Low	Minimum reinforcement

Boundary element activation occurred primarily in zones where: $vz > v\text{lim}$ (7)

This confirms that SBC detailing requirements are strongly dependent on vertical load distribution rather than uniform wall geometry.

4.3 Reinforcement Quantity Distribution

Automated BIM-based quantity extraction revealed clear trends in reinforcement demand across building height.

Key observations. • Confinement reinforcement concentrated in lower zones • Longitudinal reinforcement highest in podium levels • Upper tower zones required minimum confinement • Uniform manual detailing would result in overdesign

This confirms the necessity of zone-based SBC interpretation in mixed-use buildings as shown in Table (7).

Table 7. Relative reinforcement demand by zone.

Zone	Concrete	Long. Steel	Conf. Steel
Basement	High	High	Very high
Podium	High	High	High
Tower mid-level	Medium	Medium	Low
Upper tower	Low	Low	Minimal

4.4 BIM vs Reference Calculation Validation

Quantities derived from the BIM model in Table (8) were validated against independent SBC-compliant reference calculations.

Validation focused on. • Concrete volume • Longitudinal reinforcement • Confinement reinforcement • Boundary element zones A simplified validation metric was used: reinforcement Basement High High Very high Podium High High High

$\Delta Q = \mid QBIM - Qref \mid Qref \times 100$ (8)

Table 8. Validation results.

Quantity Type	Average Difference
Concrete volume	2–4%
Longitudinal reinforcement	3–6%
Confinement reinforcement	4–8%

Differences remain within acceptable modeling tolerance due to: • BIM abstraction level • Rounding of reinforcement ratios • Parametric representation of boundary regions The strong agreement confirms reliability of the proposed frame-work.

4.5 Sensitivity of Reinforcement to Axial Load

A parametric evaluation was conducted to examine the sensi-tivity of reinforcement demand to axial load ratio as shown in Figure (10).

Results indicate. • Reinforcement demand increases non-linearly beyond SBC axial threshold • Boundary confinement rises sharply after limit activation • Upper zones show mini-mal sensitivity

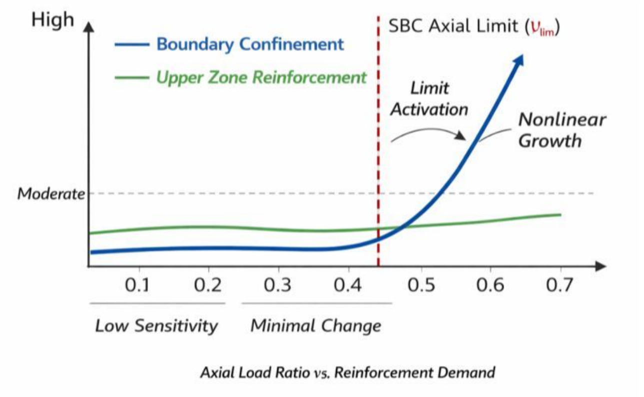

Figure 10. Axial load ratio versus reinforcement demand showing sharp increase after the SBC limit.

Interpretation. The curve confirms that SBC confinement requirements are activated only when c ompression demand exceeds prescribed limits, validating the rule-based imple-mentation.

4.6 Scientific Gap Bridging

The results confirm that the proposed methodology success-fully bridges a key gap between structural codes and BIM-based modeling.

Quantity Type Average Difference Concrete volume 2–4% Longitudinal reinforcement 3–6% Confinement reinforce-ment 4–8%

Traditional approach limitations. • Manual interpretation of SBC provisions • Lack of integration with BIM • No automated quantity linkage • Uniform detailing assumptions

Achievements of proposed method. ✓ Translation of SBC clauses into computable rules ✓ Zone-based detailing automation ✓ Automated quantity takeoff ✓ Traceable link: Code → Rule → BIM → Quantity ✓ Reduction of reinforcement overdesign ✓ Improved reproducibility

4.7 Key Quantitative Outcomes

The study demonstrates that: • Boundary element con-finement c oncentrates w ithin l ower 3 0–40% o f building height • Reinforcement reduction of approximately 15–25% achieved in upper zones • Automated BIM interpretation maintains compliance with SBC • Quantity outputs remain fully traceable to code provisions These findings confirm the practical applicability of the BIM-enabled methodology for mixed-use Saudi buildings.

5. CONCLUSION

This study presented a BIM -enabled methodology for inte-grating Saudi Building Code (SBC) provisions for reinforced concrete (RC) shear walls into a rule-based parametric mod-elling environment. The primary objective was to ove rcome the disconnect between structural code interpretation and BIM-based design workflows by automating the translation of SBC detailing requirements into computable engineering rules. The research specifically addressed mixed-use high-rise buildings, where vertical zoning creates substantial varia-tions in axial load demand and consequently influences shear wall detailing requirements.

Key Findings. The results confirmed that axial load ratio represents the governing parameter controlling boundary ele-ment activation and confinement reinforcement demand along the building height. The BIM-based implementation success-fully reproduced SBC detailing intent by generating reinforce-ment distributions consistent with structural demand varia-tions. Validation against i ndependent SBC-consistent refer-ence calculations demonstrated strong agreement, with aver-age differences ranging between 2 –4% for concrete volume, 3 –6% for longitudinal reinforcement, and 4 –8% for con-finement reinforcement. Furthermore, the study revealed that confinement reinforcement is primarily concentrated within the lower 30 –40% of the building height, while zone-based detailing enables reinforcement reduction in upper zones by approximately 15 –25% compared with conventional uniform detailing assumptions.

Research Contributions. The study contributes to struc-tural engineering and digital construction research by estab-lishing a traceable workflow linking code provisions, en-gineering rules, BIM parameters, and automated quantity outputs. The proposed meth odology enhances compliance transparency, improves reproducibility of detailing decisions, reduces conservative overdesign, and supports efficient struc-tural modelling of complex mixed-use buildings. Addition-ally, the research bridges an important gap betwe en code-based structural design and BIM automation, which have traditionally evolved independently.

Limitations. Despite its contributions, the study has sev-eral limitations. The proposed framework primarily addresses SBC provisions related to shear wall geometry and reinforce-ment detailing and does not include full structural perfor-mance verification or nonlinear se ismic behaviour assess-ment. The methodology was validated using a single case -study project, which may limit generalization across dif-ferent building typologies, seismic hazard levels, or struc-tural systems. Moreover, reinforcement detailing was imple-mented through parametric abstraction rather than detailed construction-level reinforcement modelling.

Future Work. Future research should focus on integrating performance -based seismic assessment within the BIM -rule framework, extending rule-based automation to a dditional structural components, incorporating real -time structural analysis and optimization, and validating the methodology across diverse building configurations and international design codes. Expanding the framework toward construction-level reinforcement detailing and digital twin integration also represents promising research directions. Overall, the findings demonstrate that BIM-enabled interpretation of SBC shear wall provisions provides a reliable, transparent, and efficient approach for improving structural compliance, quantity accuracy, and design automation in modern high-rise building projects.

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