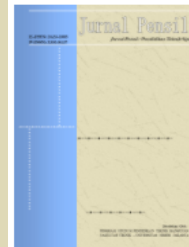


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EVALUATION OF BIM INTEROPERABILITY FOR STRUCTURAL ANALYSIS AND DESIGN OF MULTI-STOREY BUILDINGS

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Abstract

Interoperability between software platforms represents a significant challenge in Building Information Modeling (BIM) implementation for structural design and analysis of multi-storey buildings. This research evaluates the effectiveness of BIM interoperability between Autodesk Revit and ETABS through a case study of a four-story office building with Special Moment Resisting Frame System (SMRFS) located in Jakarta, Indonesia. Structural model transfer was performed from Revit to ETABS using CSiXRevit plugin with EXR format, followed by evaluation of data consistency in bidirectional transfer processes. Results demonstrate that initial transfer from Revit to ETABS successfully maintained all major structural parameters, although support type changes from fixed to pinned occurred requiring manual correction. In the reverse transfer from ETABS to Revit, data inconsistencies were found including 10% reduction in column dimensions (from 500×500 mm to 500×450 mm) and inaccuracies in reinforcement placement. The structural model successfully meets seismic requirements according to SNI 1726:2019 for mass participation parameters, base shear forces, and story drift. This research confirms that while EXR format can maintain relatively good structural data integrity, validation and manual corrections remain necessary to ensure model consistency in integrated BIM workflows.

Keywords: Autodesk Revit, Building Information Modeling (BIM), CSiXRevit, Data Loss, ETABS, Interoperability, Structural Analysis

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Introduction

The global construction industry is undergoing a significant digital transformation through the implementation of Building Information Modeling (BIM), which has revolutionized project management approaches from traditional methods to integrated data systems that enhance productivity and enable multidisciplinary collaboration (Telaga, 2018; Ullah et al., 2019). As a digital platform that combines three-dimensional models with comprehensive information about structural elements, materials, and project schedules, BIM enables data-driven decision making, reduces design errors, and optimizes project outcomes through more efficient workflows (Chi et al., 2015; Varouqa & Alnsour, 2024; Yilmaz et al., 2023). In the context of structural design, BIM implementation has become a catalyst for significant change, particularly for high-rise building projects with high complexity (Ullah et al., 2019). The integration of BIM with structural analysis software such as ETABS enables early detection of potential clashes between elements, simulation of dynamic responses to seismic loads, and design optimization through faster and more accurate iterations (Sampaio et al., 2023; Hu et al., 2016; Tohho et al., 2024). Modern BIM platforms such as Autodesk Revit integrated with ETABS have demonstrated the ability to improve design accuracy by up to 43% compared to conventional methods, while accelerating the structural validation process (Hadi et al., 2021; Omrany et al., 2023; Sulistian et al., 2022).

Through BIM-based workflows, structural models can be efficiently transferred to analysis software such as ETABS, enabling comprehensive simulation of building responses to dynamic loads, including seismic forces, wind pressure, and temperature changes (Jia et al., 2022). This process enables seamless transfer of structural models from Revit to analysis software such as Robot Structural Analysis and ETABS, allowing engineers to simulate various structural scenarios and select the safest and most economical design (Hadi et al., 2021). Additionally, BIM digital models assist in more accurate material volume calculations and precise structural deformation analysis, ensuring structural reliability, safety, and optimal performance throughout the building's operational lifespan (Gomes et al., 2022). Research demonstrates that BIM integration significantly enhances structural design workflows. A ten-story building model created in Revit and then integrated into ETABS for response spectrum and linear time history analysis showcases BIM's capability to improve design accuracy and simplify complex structural design processes (Alfredo et al., 2024). These integrated workflows enable structural engineers to maintain model consistency while conducting comprehensive analysis that meets current building codes and standards.

Despite these significant advantages, the main challenge in BIM implementation is interoperability between design and structural analysis software (Habte & Guyo, 2021; Torkhani et al., 2019). This issue frequently arises during data exchange between modeling software such as Autodesk Revit and structural analysis tools such as CSI ETABS and Robot Structural Analysis (Sampaio et al., 2023; Yousaf et al., 2024). These interoperability problems primarily stem from incompatible data formats, data loss during transfer, and mismatches in design parameters, all of which hinder effective collaboration and project efficiency (Sampaio & Gomes, 2021; Wu et al., 2021). Consequently, construction projects often face increased costs and delays due to time-consuming manual adjustments required to resolve these differences (Abdelhameed & Ismaeil, 2024; Sampaio et al., 2023). For example, a case study on an eight-story reinforced concrete building showed significant differences in design results between traditional and BIM methods, with differences of up to 43% in reinforcement requirements for structural walls, indicating challenges in data consistency across platforms (Hadi et al., 2021). Furthermore, in high-rise building projects, differences in data formats and limitations in cross-platform compatibility can cause structural analysis model inconsistencies, further complicating project workflows (Sampaio & Gomes, 2021). Minor differences in coordinates or changes in design parameters due to data conversion can significantly affect force calculations, deformations, and structural responses to loads (Jia et al., 2022). These challenges are particularly pronounced in projects with complex geometry and irregular structural elements such as curved floor slabs or intricate structural connections (Singh et al., 2024).

In Indonesia, BIM implementation has become a government priority to accelerate infrastructure development, as outlined in Regulation No. 22/2018 issued by the Ministry of Public Works and Public Housing (Aditya et al., 2024; Sopaheluwakan & Adi, 2021). However, despite these regulatory efforts, the use of BIM in the national construction industry continues to face challenges, particularly in software integration. Incompatibilities between Revit and ETABS file formats, as well as mismatches in design parameters, often create barriers to efficient data exchange (Tohho et al., 2024b). To address these integration barriers, several studies have been explored various solutions, particularly the application of neutral data exchange standards such as Industry Foundation Classes (IFC), which are specifically designed to improve data capability and consistency across various BIM platforms (Fitrah et al., 2024; Muller et al., 2017). Additionally, Application Programming Interface (API)-based approaches have been developed to enhance software compatibility and enable more accurate bidirectional data transfer (Matarneh et al., 2022).

However, technical challenges remain, particularly in maintaining data integrity, addressing data inconsistencies, and ensuring that generated models remain accurate after cross-platform integration (Amoah & Nguyen, 2019; Fitrah et al., 2024; Rostamiasl & Jrade, 2024). Previous studies have generally focused on evaluating interoperability using the IFC format or one-way data transfer from modeling software to structural analysis programs (Muller et al., 2017; Sampaio & Gomes, 2021). Although some research has explored the integration of Revit with structural analysis software such as ETABS and Robot Structural Analysis, most studies have only assessed the initial data transfer without analyzing data consistency during the reverse transfer process (Hadi et al., 2021; Yousaf et al., 2024). This limitation represents a gap in understanding the complete BIM workflow, particularly regarding the bidirectional data exchange that is essential for effective collaborative design processes.

Furthermore, while IFC serves as a global interoperability standard, native software formats such as RVT from Revit often demonstrate higher model accuracy in maintaining design details and structural parameters (Muller et al., 2024; Sampaio & Gomes, 2021). Evidence shows that while IFC plays a role in enabling cross-platform collaboration, software-specific file formats typically maintain greater geometric and parametric precision during integration, a variation that critically affects the completeness of the final model and the accuracy of structural analysis results (Matarneh et al., 2022). In the Indonesian context, although BIM implementation has become a government priority, comprehensive evaluations of BIM software interoperability based on the latest national standards are still limited (Tohho et al., 2024b).

However, several research gaps remain unaddressed in current literature. Most existing studies focus on unidirectional data transfer from modeling to analysis software, with limited evaluation of bidirectional data exchange that is essential for collaborative design workflows (Hadi et al., 2021; Yousaf et al., 2024). Additionally, quantitative assessment of data loss during BIM integration remains limited, particularly for native software formats such as EXR in structural design applications (Fitrah et al., 2024; Wu et al., 2021). In the Indonesian context, comprehensive BIM interoperability evaluations aligned with current national standards are scarce (Sjah et al., 2024; Tohho et al., 2024a). This research addresses these gaps by providing systematic quantitative evaluation of bidirectional BIM interoperability and its impact on structural design consistency.

The main objective of this research is to evaluate the effectiveness of BIM interoperability in structural analysis and design of high-rise buildings, by quantifying the level of data loss levels, analyzing model consistency and identifying validation requirements for integrated BIM workflows. The context of this research becomes increasingly relevant in Indonesia, where BIM adoption in construction projects shows potential for efficiency improvements, particularly in projects with high complexity levels (Sjah et al., 2024; Vittori et al., 2023). The results of this research are expected to contribute to practitioners and academics in optimizing BIM implementation and supporting the development of more effective interoperability standards.

Research Methods

This research evaluates BIM interoperability between Revit 2025 and ETABS v21.0.0 through a case study of a four-story office building located in Jakarta. The building measures 24 m x 30 m. Each floor has a height of 4 m, resulting in a total building height of 16 m, utilizing a Special Moment Resisting Frame System (SMRFS).

The structural components consist of 500 x 500 mm columns (f_c' 30 MPa), 300 x 600 mm main beams, 200 x 400 mm secondary beams, 140 mm floor slabs, and 120 mm roof slabs, all using concrete with compressive strength f_c' 25 MPa. Loading refers to SNI 1727:2020 and includes live loads (LL) of 2.5 kN/m², roof live loads (LR) of 0.96 kN/m², superimposed dead load (SIDL) of 1.5 kN/m², and wall loads of 3.98 kN/m. The geometric and analytical models in Revit are shown in Figure 1 and Figure 2.

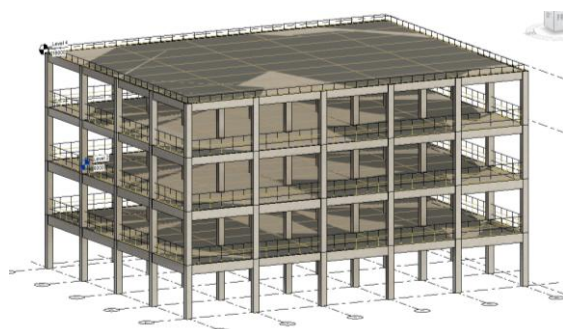


Figure 1. Geometric Model in Revit

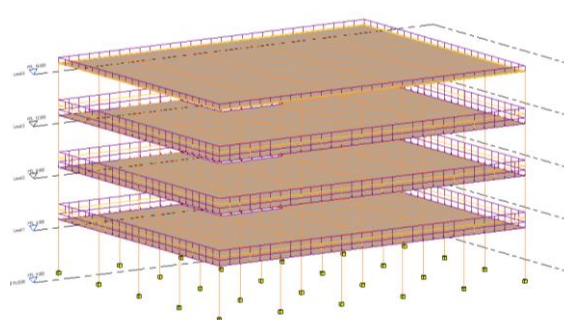


Figure 2. Analytical Model in Revit

Data transfer between Revit and ETABS was performed using the CSIXRevit plugin with the EXR file format. Data was collected by examining and comparing parameters on both platforms, documenting any differences found. The export process and the imported model results are shown in Figure 3 and Figure 4.

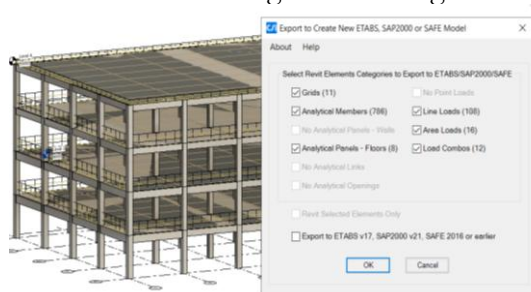


Figure 3. Export Model between Revit and ETABS

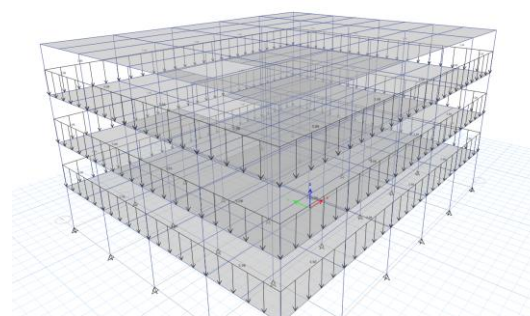


Figure 4. Structural Model Imported into ETABS

The model imported into ETABS was then analyzed for lateral and vertical loads using the Response Spectrum Method in accordance with SNI 1726:2019, with seismic parameters including risk category II with importance factor (I_e) of 1.0, site class SE (soft soil), spectral acceleration parameters (S_s) of 0.79 and (S_1) of 0.39, modification response coefficient (R) of 8 for the Special Moment Resisting Frame system, and redundancy factor (ρ) of 1.3. The results were compared with SNI 2847:2019 and SNI 1726:2019 standards to verify structural elements' compliance with code provisions. To assess interoperability, data consistency was calculated using the formula :

$$Data Loss = \frac{(B - A)}{A} \times 100\% \tag{1}$$

Where :

A : Source Value

B : Target Value

All differences found in geometric parameters, material properties, and analytical characteristics between the two platforms were recorded in detail. The structural analysis results were then verified for compliance with SNI 2847:2019 and SNI 1726:2019 requirements to ensure the structure meets applicable standards. This approach enabled systematic documentation of data integrity and model consistency throughout the BIM integration process

Research Results and Discussion

Mass Participation Ratio

Mass participation is a measure of how much mass of the structure is involved in each vibration mode. According to article 7.9.1.1 of SNI 1726:2019, the cumulative total mass participation must reach at least 90% to ensure that significant dynamic responses have been considered (Albertini et al., 2021; Nurasih & Erizal, 2022). **Table 1** presents the mass participation results for the building.

Table 1. Mass Participation Ratio

Mode	Period (S)	UX	UY	UZ	SumUX	SumUY
1	0.845	0.8488	5.48E-07	0	0.8488	5.48E-07
2	0.842	5.37E-07	0.8489	0	0.8488	0.8489
3	0.731	0.0005	0	0	0.8493	0.8489
4	0.282	0	0.1058	0	0.8493	0.9547
5	0.281	0.1055	0	0	0.9548	0.9547
6	0.251	0.0001	0	0	0.955	0.9547
7	0.163	0	0.036	0	0.955	0.9907
8	0.163	0.0357	0	0	0.9907	0.9907
9	0.146	0.0002	0	0	0.9909	0.9907
10	0.121	0.0087	0.0003	0	0.9996	0.991
11	0.121	0.0003	0.009	0	0.9999	1
12	0.11	0.0001	0	0	1	1

Source : ETABS v21

As shown in Table 1, the mass participation indicates that the first mode contributes 84.88% to the total mass in the X direction, while the second mode contributes 84.89% in the Y direction. By the 12th mode, the cumulative mass participation reaches 100% in both directions, far exceeding the minimum requirement of 90%. This confirms that the analysis has accounted for all critical vibration modes, in accordance with the provisions of Article 7.9.1.1 of SNI 1726:2019.

Base Shear

Base shear scaling is applied to ensures that the dynamic base shear force calculated using the response spectrum method meets the requirements of SNI 1726:2019. As stated in Article 7.9.1.4.1, if the base shear from the dynamic analysis (Vt) is less than 100% of the static base shear

(V), it should be scaled by a factor (V/V_t) , to meet the minimum lateral forces required for structural stability (Albertini et al., 2021; Ardian Putra & Nur Arini, 2023).

Table 2. Base Shear Forces

Story	Output Case	Case Type	Location	VX	VY
				kN	kN
Level 1	RSX	LinRespSpec	Bottom	1903.8376	0.104
Level 1	RSY	LinRespSpec	Bottom	0.104	1903.7856
Level 1	EQX	LinStatic	Bottom	-1893.764	0
Level 1	EQX	LinStatic	Bottom	-1893.764	0
Level 1	EQX	LinStatic	Bottom	-1893.764	0
Level 1	EQY	LinStatic	Bottom	0	-1893.7638

Source : ETABS v21

Based on the results in Table 2, the dynamic shear forces in both X direction (RSX = 1903.84 kN) and Y direction (RSY = 1903.79 kN) exceeded the static shear forces (EQX = 1893.76 kN and EQY = 1893.76 kN). According to article 7.9.1.4.1 of SNI 1726:2019, this condition indicates that no scaling is required, as the dynamic shear values have already met the minimum code requirements. Therefore, the structure can be considered compliant with seismic design provisions without the need for further adjustment to the analysis results.

Story Drift

Story drift is refers to the lateral displacement that occurs between two consecutive floors as a result of seismic forces.. The limitation of inter-story drift in a structure aims to prevent non-structural damage. According to SNI 1726:2019 Article 7.12.1, for seismic design categories D-F, the design story drift (Δ) shall not exceed Drift limit ($\Delta a/\rho$) for all stories (Albertini et al., 2021; Zhafira et al., 2023). Story drift Calculation control is as follows:

$$Hsx = 4000 \text{ mm}, \rho = 1,3$$

$$\Delta a = 0,020 \times Hsx$$

$$\Delta a = 0,020 \times 4000 = 80 \text{ mm}$$

$$\frac{\Delta a}{\rho} = \frac{80}{1,3} = 61,538 \text{ mm}$$

Table 3. Story Drift X and Y Direction

Story	Displacement		Elastic Drift		h	Inelastic Drift		Drift Limit	Check
	δe_x	δe_y	δe_x	δe_y		Δ_x	Δ_y		
	(mm)	(mm)	(mm)	(mm)		(mm)	(mm)	(mm)	
4	22.475	22.412	3.264	3.432	4000	17.952	18.876	61.538	OK
3	19.211	18.980	5.826	5.759	4000	32.043	31.675	61.538	OK
2	13.385	13.221	7.429	7.321	4000	40.860	40.266	61.538	OK
1	5.956	5.900	5.956	5.900	4000	32.758	32.450	61.538	OK

Source : ETABS v21

Based on Table 3 above, it is known that no inter-story drift exceeds the allowable limits in either the X or Y direction, so this structure has met the requirements and is safe with the condition.

Design Optimization

Further evaluation of structural elements is required to ensure compliance with standards. Structural analysis using ETABS showed that 34 beams with dimensions of 300×600 mm did not meet the requirements of ACI 318-14 (which has been adopted as SNI 2847), when loaded with combined gravity and lateral loads. The non-compliant elements included 16 beams on the first floor, 16 beams on the second floor, and 2 beams on the third floor. To address this issue, optimization was performed by increasing the cross-section dimensions to 400×700 mm, which improved the flexural capacity of the beams. This modification successfully ensured all structural elements met the design criteria.

Design Consistency

During data transfer from Revit to ETABS, several differences were found in the model. One important change occurred in the support type, which changed from Fixed supports in Revit (Figure 5) to Pinned supports in ETABS (Figure 6). This change resulted in columns being unable to resist bending moments, making the structure more flexible but potentially less stable (Faoji & Sambowo, 2019) . Therefore, manual adjustments were required to restore the support type according to the original design.

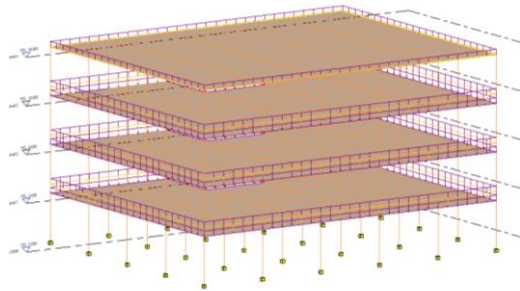


Figure 5. Fixed Support in Revit

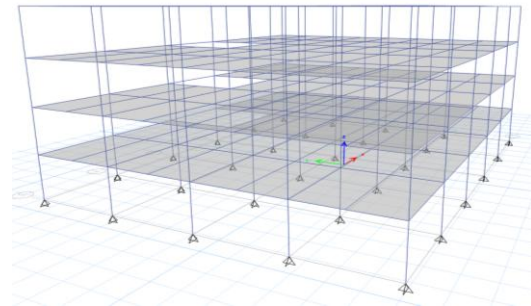


Figure 6. Pinned Support in ETABS

After structural analysis in ETABS, changes in column dimensions were observed, which initially measured 500×500 mm in ETABS (Figure 7) but changed to 500×450 mm when imported back to Revit (Figure 8).

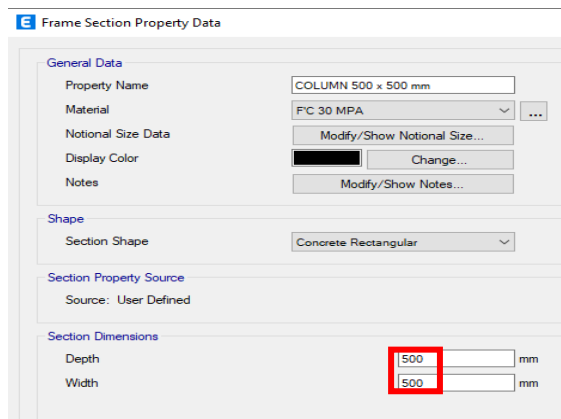


Figure 7. Column Dimensions in ETABS (500×500 mm)

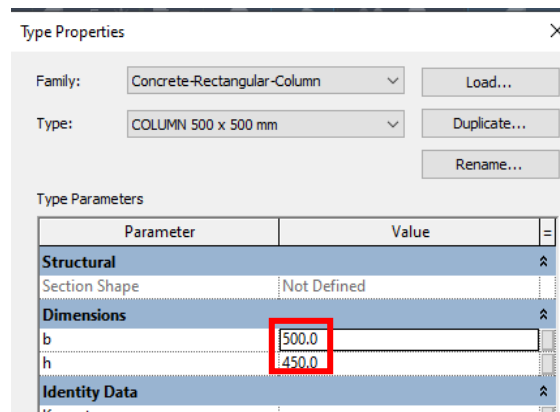


Figure 8. Column Dimensions in Revit (500×450 mm)

This dimensional change caused a significant reduction in width, which can affect material volume calculations for structural elements. Additionally, there were issues with reinforcement placement when data was transferred from ETABS to Revit, where reinforcement bars were positioned outside the structural elements (Figure 10). These issues required manual adjustments to maintain model consistency and accuracy.

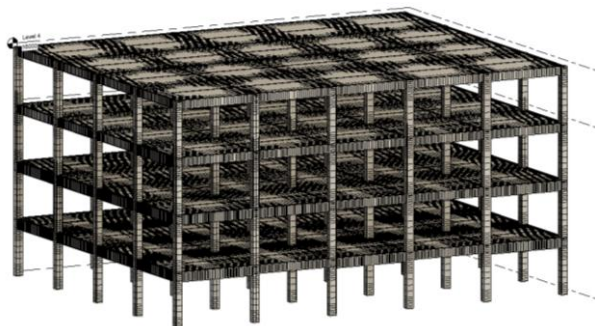


Figure 9. Reinforcement exported from ETABS

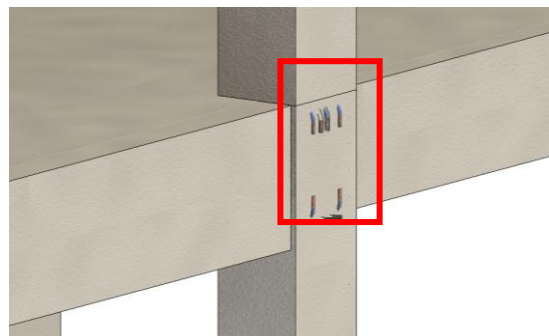


Figure 10. Overlapping Beam Rebars in Revit

The overlapping rebars in the beam element indicates a difference between reinforcement data from ETABS and the Revit model, requiring manual adjustment to ensure the reinforcement is properly placed within the structural element.

Data Accuracy

The interoperability between Revit and ETABS was evaluated to determine the effectiveness of data transfer between two platforms. This assessment focused on data accuracy, design consistency, and the identification of potential issues affecting BIM workflow efficiency. Data transfer from Revit to ETABS showed that most structural design parameters were successfully transferred without significant data inconsistencies, as shown in Table 4. Key parameters such as element geometry, material properties, and loads remained consistent during the data transfer process.

Table 4. Data Integrity Assessment on Revit to ETABS Transfer

Parameter Category	Revit (A)	ETABS (B)	Data Loss
Grid Spacing	6 m	6 m	0.00%
Level	4 m	4 m	0.00%
Column	500×500 mm	500×500 mm	0.00%
Slab Thickness	140 mm	140 mm	0.00%
Roof Slab Thickness	120 mm	120 mm	0.00%
Beam 1	300×600 mm	300×600 mm	0.00%
Beam 2	200×400 mm	200×400 mm	0.00%
Beam Concrete Strength	25 MPa	25 MPa	0.00%
Column Concrete Strength	30 MPa	30 MPa	0.00%
Superimposed Dead Load (SIDL)	1.5 kN/m ²	1.5 kN/m ²	0.00%
Live Load (LL)	2.5 kN/m ²	2.5 kN/m ²	0.00%
Live Load Roof (LR)	0.25 kN/m ²	0.25 kN/m ²	0.00%
Wall Load	3.98 kN/m ²	3.98 kN/m ²	0.00%

As shown in Table 4, data transfer from Revit to ETABS demonstrated that all measured dimensional parameters were successfully transferred without visible data loss on these elements. However, when transferring data from ETABS back to Revit after structural analysis, several data inconsistencies were found as shown in Table 5. The reverse integration process revealed

challenges in data transfer, particularly in maintaining data parameters from structural element components.

Table 5. Data Integrity Assessment on ETABS to Revit Transfer

Parameter Category	ETABS (A)	Revit (B)	Data Loss
Grid Spacing	6 m	6 m	0.00%
Level	4 m	4 m	0.00%
Column	500×500 mm	500×450 mm	-10.00%
Slab Thickness	140 mm	140 mm	0.00%
Roof Slab Thickness	120 mm	120 mm	0.00%
Beam 1	300×600 mm	300×600 mm	0.00%
Beam 2	200×400 mm	200×400 mm	0.00%
Beam 3	400×700 mm	400×700 mm	0.00%
Beam Concrete Strength	25 MPa	25 MPa	0.00%
Column Concrete Strength	30 MPa	30 MPa	0.00%
Reinforcement Steel Strength	420 MPa	420 MPa	0.00%
Superimposed Dead Load (SIDL)	1.5 kN/m ²	1.5 kN/m ²	0.00%
Live Load (LL)	2.5 kN/m ²	2.5 kN/m ²	0.00%
Live Load Roof (LR)	0.25 kN/m ²	0.25 kN/m ²	0.00%
Wall Load	3.98 kN/m ²	3.98 kN/m ²	0.00%

As shown in Table 5, data transfer from ETABS back to Revit resulted in a reduction in column width, which changed from 500×500 mm to 500×450 mm. This dimensional inconsistency can be quantified using formula (1).

The negative value indicates a reduction in dimension during the transfer process. This finding reveals limitations in two-way interoperability between ETABS and Revit, particularly regarding geometric data of structural elements.

Impact on BIM Workflow

Data changes during the bidirectional transfer process have a significant impact on BIM workflows, especially in structural design and analysis phases. The change in support conditions from fixed to pinned, if not corrected, would cause alterations in structural behavior and force distribution patterns (Russell et al., 2015). The 10% reduction in column dimensions (from 500×500 mm to 500×450 mm) affects structural element volume calculations and subsequently impacts material quantities and cost estimation (Naderi et al., 2025). Additionally, misplacement of reinforcement issues compromise detailing accuracy may results in construction errors if not properly addressed (Widjaja et al., 2025). During the integration process, structural elements demonstrated a relatively high level of model consistency. Most parameters, such as floor heights, grid spacing, slab thickness, element dimensions, material properties, and load definitions, remained consistent throughout the transfer. Although interoperability between Revit and ETABS still presents some limitations, the overall data and model integrity was largely maintained. Nevertheless, the results indicate that BIM workflows still face challenges in data exchange, requiring manual corrections to ensure overall model accuracy. The identified inconsistencies highlight the importance of implementing quality control and validation procedures at every stage of the integration process. These measures are essential to minimize the negative impact of bidirectional data transfers within an integrated BIM workflow.

The interoperability challenges identified in this study align with findings from previous BIM research. Support condition changes from fixed to pinned requiring manual correction have also been reported by Sampaio & Gomes (2021) in their Revit-ETABS integration evaluation, indicating this is a recurring issue in structural BIM workflows. The dimensional inconsistencies

and reinforcement placement errors found in bidirectional transfer are consistent with findings by Alfredo et al. (2024) and Tohho et al. (2024b), who reported similar challenges in modeling and structural analysis software integration. The need for validation procedures and quality control identified in this research has also been emphasized by Hadi et al. (2021) and Torkhani et al. (2019), who stated that manual oversight remains necessary to maintain model accuracy in BIM implementation. The consistency of these findings indicates that EXR format limitations and plugin integration issues identified are systematic problems in current BIM data exchange protocols, as also identified by Fitrah et al. (2024) and Sampaio et al. (2023). This reinforces the importance of developing better interoperability standards and validation procedures in integrated structural design workflows.

Conclusion

This study demonstrates that interoperability between Autodesk Revit and ETABS using the CSiXRevit plugin with EXR format is generally effective in preserving key structural parameters such as element geometry, material properties, and loading definitions. However, several data inconsistencies were identified during the bidirectional transfer process, including changes in support conditions from fixed to pinned, a significant 10% reduction in column dimensions (specifically from 500×500 mm in ETABS to 500×450 mm when transferred back to Revit, representing a 50 mm width reduction that affects both structural capacity and material volume calculations), and systematic inaccuracies in reinforcement placement where rebars were positioned outside structural elements. The dimensional inconsistency calculation using the formula $((450-500)/500) \times 100\% = -10\%$ confirms a substantial geometric data loss that could impact structural performance and cost estimation. The measurement of data loss and model consistency confirms that BIM workflows can still be applied to structural design that complies with SNI 1726:2019 and SNI 2847:2019, provided that validation and manual correction are conducted at each stage of the integration process.

This research acknowledges several important limitations that should be considered when interpreting the findings. First, the research is based on a single case study of a four-story office building, which may limit the generalizability of results to other building typologies, heights, or structural systems. Different building geometries, irregular floor plans, or alternative structural systems such as shear walls or composite structures may exhibit different interoperability characteristics. Second, the evaluation focuses exclusively on the integration between Revit and ETABS using the CSiXRevit plugin, while other structural analysis software or different data exchange methods may demonstrate varying levels of data integrity. Third, the assessment is limited to static structural parameters and does not extensively evaluate dynamic properties or complex loading scenarios that may be critical in more sophisticated structural designs. Fourth, the study is conducted within the specific regulatory context of Indonesian building codes (SNI standards), and results may not be directly applicable to projects governed by other international standards.

These findings are expected to offer an initial contribution toward a better understanding of technical challenges in BIM interoperability, particularly within the context of structural design practices in Indonesia. The authors recommend future research to explore interoperability with other structural analysis software and more complex building typologies, as well as to develop automated validation tools aligned with national standards, and conduct multiple case studies across different building types to provide more comprehensive insights into BIM workflow optimization.

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