Structural Analysis Ready Building Information Modelling: A Requirement Analysis

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Abstract

Structural analysis is utilised to evaluate the behaviour of structures under applied loads to ensure their safety and stability. It is crucial in designing, assessing, and retrofitting buildings and structures. With the growing adoption of Building Information Modelling (BIM) in the Architecture, Engineering, and Construction (AEC) industry, using BIM for conducting structural analysis enables professionals from different disciplines to collaborate efficiently throughout a building's lifecycle. When no BIM is available from a structure, scan-to-BIM can be employed to produce a BIM from point clouds generated through laser scanning or photogrammetry approaches. An essential step in scan-to-BIM is requirement analysis which optimizes scan-to-BIM by identifying essential data and avoiding the inclusion of unnecessary information. This study conducts a comprehensive requirement analysis, identifying five essential structural elements namely, columns, primary beams, secondary beams, floor systems, and shear walls that must be included in a Structural Analysis Ready BIM (SARBIM) for Reinforced Concrete (RC) structures. Additionally, three critical information categories - Material Mechanical Properties (MMP), Reinforcement Content (RCo), and Cross-Section Information (CSI) - are outlined as key information for these elements. Furthermore, this study presents essential modelling considerations to enhance the accuracy and reliability of SARBIM models. By refining BIM models for structural analysis, this research contributes to the advancement of SARBIM in the field.

1. Introduction

Structural analysis involves predicting a structure's performance under different loads and external effects such as the structure's weight, wind, and earthquakes. Structural analysis is essential for protecting lives and assets by identifying vulnerabilities in structures and ensuring their stability against disasters like earthquakes, which cause an estimated $4.4 billion annual loss in the US (Li, 2012). Conducting structural analysis demands information on the geometry and material mechanical properties of the structural elements that can be stored in 2D floor plans, structural drawings, simple 3D models (e.g. Finite Element Model (FEM)), or Building Information Modelling (BIM). Among these, BIM has become the most widely used data standard across the Architecture, Engineering, and Construction (AEC) industry, throughout the entire lifecycle of a building, from design to demolition. Through BIM professionals from different disciplines can cooperate and share information effectively (Habte and Guyo, 2021).

For many existing buildings, neither BIM models nor structural drawings are available. In such cases, laser scanning and photogrammetry can be employed to capture a point cloud of the structure, which can then be converted into a BIM through a workflow that is called scan-to-BIM. A critical preliminary step in this workflow is requirement analysis, during which the essential information for the BIM is identified. This analysis ensures that the scan-to-BIM process is efficient, avoiding the inclusion of redundant information that could waste resources.

For a Structural Analysis Ready BIM (SARBIM), it is crucial to include structural components such as columns, beams, and their material mechanical properties e.g. modulus of elasticity. However, to the best of the authors' knowledge, no comprehensive requirements have been identified for structural analysis based on BIM to answer the following questions (these questions are adapted from the requirement analysis method used in (Wang et al., 2019)):

1. Which classes of elements, as defined by the Industry Foundation Class (IFC) standard, need to be included in the model?
2. What Level of Detail/Development (LOD) is required for the selected elements?
3. What attributes and information should the model include for instances of a class?
4. What specific considerations should be made during the modelling process?

Accordingly, existing scan-to-BIM frameworks designed for structural analysis have not systematically enriched models with all the essential information needed. Instead, they assigned a limited set of features to the model's elements (Shu et al., 2023; Zouaoui et al., 2020). This research addresses this gap by providing a comprehensive list of the information that should be included in a SARBIM. Considering that different construction types may have unique SARBIM requirements, this study focuses on Reinforced Concrete (RC) buildings. Besides, the integration of damages (e.g. cracks) to SARBIM is neglected.

2. Literature Review

2.1 BIM Structural Requirements Analysis

The lack of guidelines and standards for BIM implementation is one of the challenges faced repeatedly (Habte and Guyo, 2021). Several studies have been conducted to address this gap. (Jeong and Eastman, 2009) provided BIM functional requirements for cast-in-place RC constructions. These requirements are introduced to address special geometries, parametric manipulation, overlapping concrete volumes, and management aspects associated with concrete pouring. (Mobasher et al., 2016) proposed a standard BIM for automatic structural design and analysis of RC plates using the Boundary Element Method (BEM). They focused on developing BIM standards for the preprocessing and postprocessing of BEM analysis, as well as for structural slab and beam design, with an emphasis on software extensibility and applicability across diverse research and practical applications. Despite the availability of such documents, no comprehensive requirements for structural analysis based on BIM have been identified to date.

2.2 Scan-to-BIM for Structural Applications

A common way to generate structural BIM is to use the existing structural drawings e.g. Computer Aided Design (CAD) documents and convert them into a structural BIM (Byun and Sohn; Yang et al., 2020). Although this has shown promising results, they are impractical when such records are unavailable for a structure. To address this gap, scan-to-BIM workflows can be employed to generate a SARBIM. After the requirements for the target BIM are identified, the scan-to-BIM process continues with three steps namely, data acquisition, geometric modelling, and BIM enrichment.

2.2.1 Data Acquisition: Data acquisition for geometric modelling is done using laser scanners or photogrammetric techniques. Latter is cheaper but cannot work properly in poor lighting or visibility conditions. Laser scanners used for geometric modelling purposes are classified into Terrestrial Laser Scanners (TLS) and Mobile Laser Scanners (MLS) where TLS offers denser and more accurate point cloud but in higher acquisition time which makes it not suitable for large acquisition sites. An in details comparison of the mentioned data acquisition methods is provided in (Abreu et al., 2023). In addition to point clouds, structural information can be collected using Destructive Tests (DT) e.g. rebound hammer, Knocking, and drilling, and non-DT that uses advanced equipment e.g. ultrasonic and Ground-Penetrating Radar (GPR) devices (Malek and Kaouther, 2014; Honic et al., 2021). The former causes damage to construction but demands cheaper equipment.

2.2.2 Geometric Modelling: Typically, geometric models are generated manually with the help of software packages. Once the point cloud is imported into a software package, an operator starts drawing the geometric model. Autodesk Revit, Autodesk AutoCAD, and Rhinoceros are among the software widely used for modelling purposes. Manual modelling of a typical building demands days or even months of work, so advanced modelling software packages offer semi-automatic tools that can facilitate modelling procedures. (Drobnyi et al., 2023b) Provides information on the level of automation in modelling software packages.
Automatic and semi-automatic geometric modelling procedures rely on detecting shape primitives (plane, cubes, cylinder, circles, e.g.) and objects (walls, ceilings, floors, columns, beams, and openings), segmentation (grouping the points belonging to a specific object) and fitting predefined shapes and models to the segmented instances. Typically, primitive shape detection and segmentation are conducted utilizing model-driven methods e.g. (RANdom SAmple Consensus (RANSAC), region growing, and hough transform), and data-driven methods e.g. (machine learning and deep learning algorithms) (Drobnyi et al., 2023a). Shape fittings are mainly conducted using least square techniques (Honti et al., 2022), Principal Component Analysis (PCA) (Cui et al., 2019), or learning based techniques (Xu et al., 2021).

2.2.3 BIM Enrichment: This section merges non-geometric information into the geometric models generated previously. This includes information introduced in section 4 namely Material Mechanical Properties (MMP), Reinforcement Content (RCO), Cross-Sectional Information (CSI).
While material information can be extracted from RGB images using CNN networks (Bunrit et al., 2020; Bunrit et al., 2019; Kim et al., 2023), GPR enables the extraction of subsurface elements, including rebars (Xiang et al., 2021; Xiang et al., 2023b). Besides, (Mirzaei et al., 2022) trained PointNet on synthetic point clouds classify the cross-sections of steel structural elements.

3. Methodology

This research follows a two-step methodology: 1) requirement gathering and 2) requirement analysis. Figure 1 shows the proposed methodology.

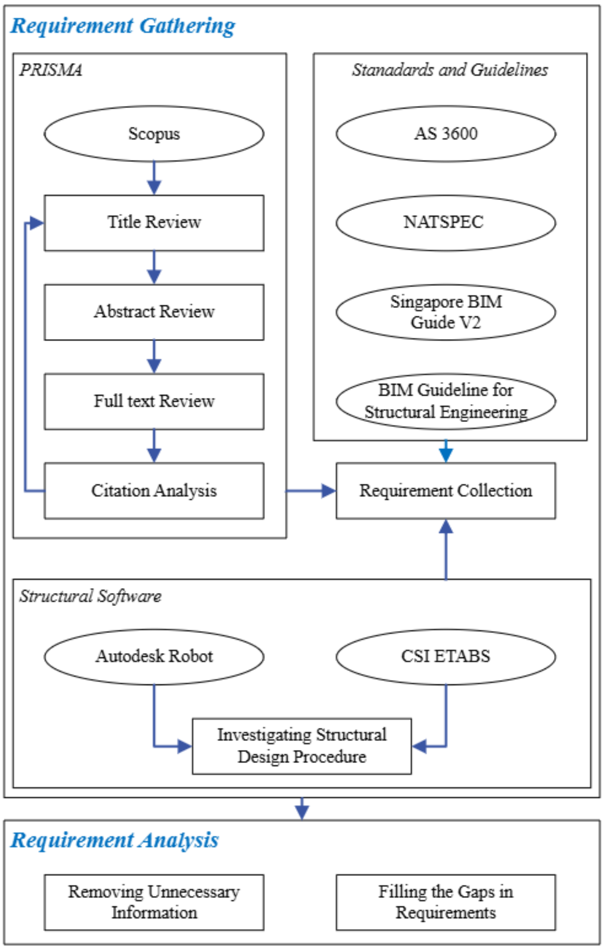

Figure 1. Research methodology

3.1 Requirement Gathering

The first step focuses on collecting SARBIM requirements by reviewing and analysing three sources:
1- National/international standards and guidelines are valuable sources of information regarding different topics as they are provided by professionals in their fields. Considering this, the BIM guideline (2022) and AS 3600:2018 standard for concrete structures (Standards, 2018) issued by Australian authorities are considered the primary source of information for this. In addition to them, BIM guidelines offered by the governments of Singapore (2013) and Hong Kong (Bimwg, 2023), are used as

complementary data because the authors found them highly relevant to the purpose of this study. In case of disagreement among different countries' guidelines, the Australian standards are given priority.

2- A systematic search was conducted in the Scopus database on 21/11/2024 to extract papers that conducted BIM-based structural analysis. The search criterion considers that the papers should meet three conditions:

- They are related to BIM
- They are related to either structural analysis or structural design
- The proposed method in papers is tested on RC structures

Considering these conditions the search criterion is as follows:

"(TITLE-ABS-KEY (BIM OR "Building Information Modelling" OR "Building Information Modeling" OR "Scan-to-BIM" OR "Scan2BIM") AND TITLE-ABS-KEY ("Structural analysis" OR "Structural Design" OR "Numeric analysis" OR "Seismic Analysis" OR "Dynamic Analysis" OR "Static Analysis" OR "Finite Element Model" OR "Finite Element Analysis" OR "FEA" OR "FEM")) AND TITLE-ABS-KEY ("Reinforced Concrete" OR "RC" OR ("Reinforcement" AND "Concrete")) AND PUBYEAR>2013 AND PUBYEAR<2026 (LIMIT-TO (LANGUAGE, "English"))"

Then, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, eligible papers that provide information on structural analysis procedure e.g. (required elements and their essential attributes) are identified. This can be offered through conducting structural analysis, enriching the geometric models with structural information, and facilitating the interoperability between BIM and structural analysis platforms.

93 items were extracted from the database, among which three could not be accessed. 29 and 26 documents are excluded after reviewing the titles and abstracts, respectively. Then, the full papers of the remaining items are read. After the exclusion of 11 documents, 24 remained. Then, by searching the cited references in the accepted documents, 29 new relevant items were identified, among which seven were accepted after full-text review. Table 1 introduces the accepted paper.

Reference	Topic
(Singh et al., 2024)	Automatically obtaining structural models directly from architectural models
(Russo et al., 2024)	Using Heritage BIM (HBIM), archival research and numerical structural analysis to preserve thin shells
(Shi et al., 2023)	Intelligent earthquake damage prediction and seismic performance evaluation
(Sampaio et al., 2023)	Interoperability between Revit and Robot
(Bourahla et al., 2023)	Optimization of structural design using hill climbing and genetic algorithm
(Shu et al., 2023)	Modelling of a damaged RC beam using point clouds
(Xiang et al., 2023a)	Transformation of BIM to structural analysis model using semantics and artificial neural networks
(Abbate et al., 2022)	FEM of heritage structures using HBIM from point clouds
(Wang and Chen, 2022)	Extraction of geometric and material information from BIM for conducting Finite Element Analysis (FEA)

Table 1. Accepted papers

Reference	Topic
(Zimmert and Braml, 2022)	Utilizing non-uniform rational BSplines (NURBS) for parametric modeling and analysis of a structural concrete beam
(Sherif et al., 2022)	BIM based structural optimization to reduce construction costs
(Gomes et al., 2022)	Explored BIM's benefits and limitations in structural design workflows
(Minafò et al., 2022)	Seismic vulnerability in a mixed RC-masonry historical structure using a multidisciplinary approach
(Rajčić et al., 2021)	Generation of architectural and structural BIM based models using laser scanning and photogrammetry techniques
(Mangal et al., 2021)	Design optimisation of clash-free steel reinforcement.
(Hamidavi et al., 2020)	Optimization of the structural design
(Nasybullin et al., 2021)	Optimising glass-fiber reinforced plastic bars placement in concrete structures
(Sampaio and Gomes, 2021)	Evaluating the interoperability between three modelling and three structural analysis software
(Habte and Guyo, 2021)	Demonstrating BIM integration for structural design using Revit, ETABS, and SAFE
(Gerbino et al., 2021)	Evaluating IFC-based interoperability issues between CAD and Computer Aided Engineering (CAE) software
(Blandini and Nieri, 2020)	Provide information on the fabrication of Kuwait International Airport Terminal 2
(Park et al., 2020)	Proposing a meshfree analysis framework integrated with IFC
(Tsay, 2019)	Generating a BIM including geometry and reinforcement and importing it into ETABS
(Ede et al., 2019)	Designing an iconic museum using BIM tools
(Tafraout et al., 2019)	Using genetic algorithm for optimization of structural design
(Ren et al., 2018)	Reviewing the literature to explore BIM interoperability challenges for structural analysis
(Da Silva, 2017)	Automatic structural design of a 3D concrete frame
(Pukl et al., 2016)	Interoperability between IFC format and ATENA software
(Mobasher et al., 2016)	Proposing a standard BIM for automatic structural design and analysis of RC plates
(Anil et al., 2016)	Developed a BIM-based approach integrating damage information for analysis of RC structure
(Barbato, 2014)	Evaluating BIM interoperability by analysing data exchange between ArchiCAD, Revit Architecture, and Robot Structural Analysis

Table 1. Cont.

3- Autodesk Robot and ETABS are used as supplementary materials to include essential information that might be neglected. According to the systematic search conducted, Autodesk Robot is the most widely used platform for BIM-based structural design (Gomes et al., 2022; Sampaio et al., 2023; Mangal et al., 2021). It offers good interoperability with Revit as they both are provided by the same company, Autodesk (Sampaio and Gomes, 2021). For example, no loss of data is reported in (Barbato, 2014), during exchanging a model of beams and columns between Revit and Robot. In addition, ETABS is one of the most widely used structural design platforms that offers interoperability with BIM authoring platforms through IFC format (Singh et al., 2024).

3.2 Requirement Analysis

The collected information on the requirement gathering can include both redundant and missed information. In the requirement analysis step, the outcome of the previous step will be reviewed to identify potential errors, correlations, gaps, and redundancies and apply any required modification. Table 2 shows a few samples of the changes applied to the results in the requirement analysis step and their justifications. The requirement analysis step aims to ensure the results meet the requirements for structural analysis.

Sample Change	Justification
Spacing of rebars is removed from attributes required for reinforcement details.	Rebars in the cross-section of a structural element typically follow a uniform spacing. Therefore, the spacing between rebars can be calculated using the reinforcement cover, rebar number, and cross-sectional dimension. The uniform spacing will only be disrupted if design requirements necessitate it.
Connections are removed from the essential elements. Instead, they are mentioned as considerations.	Connections are not considered separate from other structural elements. However, according to the types of connections used in structures some attributes are added to the model.
Attributes are grouped into two groups, essential and optional attributes.	Some attributes are required for almost all sorts of structural analysis. These attributes are considered essential. The optional attributes may be required for specific types of structural analysis e.g. FEA

Table 2. Sample changes applied to the results during the requirement analysis step

4. Results & Discussion

4.1 Essential Information

BIM models are widely produced and utilized for many applications. This means they can include a variety of information. Conducting structural analysis demands a simplified version of the model that only keeps the mechanical meaning of the structure (Chi et al., 2015). This includes both geometry and structural information of elements including their topological and semantic relationships (Abbate et al., 2022). According to the results, five classes of elements are essential to be included in the model during the scan-to-BIM workflow. It is worth noting the classes of elements that cannot be captured using photogrammetry or laser scanning techniques e.g. (foundations) are excluded from the list. Load-bearing walls are also neglected as they are rarely used in modern RC structures. The essential elements should be defined according to a unique building element classification system e.g. MasterFormat, UniClass, and OmniClass. This research follows the OmniClass classification system. The IFC Objects and OmniClass numbers of the essential classes of elements are introduced in Table 3. The required classes of elements are as follows:

- ***Column:*** Vertically support beams and transfer load to the foundation
- ***Primary Beam:*** Support and transfer loads from secondary beams to columns
- ***Secondary Beams:*** Transfer loads across horizontal spans, typically supporting floors or roofs
- ***Floor System:*** Distribute gravity and lateral (dead and live) loads across a wide surface and transfer them to beams
- ***Shear Walls:*** Resist lateral forces (e.g., wind or earthquakes)

Class	Ifc Object	OmniClass	Details
Column	IfcColumn	23-13 35 11 13 11	
Primary Beam	IfcBeam	23-13 35 11 13 13	IfcBeamType = BEAM
Secondary Beam	IfcBeam	23-13 35 11 13 13	IfcBeamType = JOIST
Floor System	IfcSlab	23-13 35 11 13	
Shear Walls	IfcWall	23-13 35 21	IfcWallType = SHEAR

Table 3. Essential classes of elements

Some types of structural analysis e.g. (linear analysis) are started with an idealization step which is conducted to replace the precise geometry of structural elements with simpler shapes. Considering this, LOD 200 is considered satisfactory for the simplest versions of structural analysis. Even in these situations, the dimensions of idealized structural elements should be considered accurately. Table 4 shows the definition introduced by (Bimforum, 2024) for different LODs.

LOD	Description
100	Generic representation of elements like symbols
200	Graphical representation of elements with approximate quantity, size, shape, location and orientation
300	Graphical representation of elements with measurable quantity, size, shape, location and orientation
350	Graphical representation of elements with measurable quantity, size, shape, location, orientation, and includes interference between adjacent and dependent elements
400	Graphical representation of elements with enough detail to support fabrication, assembly, and installation processes.
500	The Model Element represents an existing or as-built condition, created using observation, field verification, or interpolation

Table 4. Different LODs

For more advanced types of structural analysis e.g. FEA that demands a more accurate geometrical model, utilization of LOD 300 or even higher might be necessary to ensure the geometry of the elements is accurately preserved in the generated BIM. The mentioned classes do not describe the performance of a structure unless they are enriched with the information required to model their mechanical meanings. This essential information can be categorized into three classes namely, MMP, RCo, and CSI as shown in Table 5. In this table, the information required for conducting linear analysis is introduced essential. Optional information is needed when more advanced analysis e.g. FEA is required.

- ***MMP:*** Material mechanical properties like modulus of elasticity determine how materials interact under applied loads, influencing deformation, stability, and overall structural performance. These properties are crucial for accurately modelling, simulating, and designing structural systems to meet safety and performance requirements. While the material itself can be stored using IfcMaterial, the relevant attributes should be stored using IfcPropertySingleValue which is managed by IfcMaterialProperties (Park et al., 2020).

• ***RCo:*** The main usage of reinforcement in RC structures is to resist tensile forces and to strengthen the concrete in areas under compression (Nasybullin et al., 2021). IfcReinforcingElement can be used for adding the reinforcement into a model. It includes four types of objects, IfcReinforcingBar (one or many of actual rebars), IfcReinforcingMesh (a series of longitudinal and transverse wires or bars), IfcTendon, and IfcTendonAnchor.

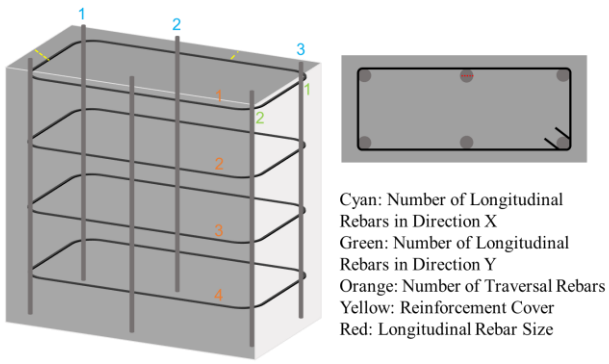

Figure 2. Information provided in the cross-section of a structural column, 3D View (Left), 2D View (Right)

• ***CSI:*** Cross-sectional information is fundamental in structural analysis as the cross-sections of structural elements can store the geometry, material distribution, and reinforcement inside the elements that can describe the response of a structure to the applied loads. For example, the magnitude and distribution of stresses and strains, and the determination of forces and displacements depend on the dimensions of the cross-sections (Da Silva, 2017). Figure 2 shows an RC column and some of the information that can be extracted from the cross-sections of structural elements.

Information	What to Include
CSI	Shape and Geometry, MMP, RCo
MMP	***Essential:*** Density (Weight/Mass per Unit Volume), Modulus of Elasticity, Poisson's Ratio, Shear Modulus, Yield Strength ***Optional:*** Characteristic Strength, Compressive strength, Reduction Coefficient for Long Lasting Resistances, Tensile Strength, Thermal Expansion Coefficient, Total Elongation, Shear Factor, Strain Hardening Coefficient
RCo	***Essential:*** Reinforcement MMP, Reinforcement Ratio, Yield Strength ***Optional:*** Number of Rebars in each Direction, Reinforcement Configuration, Reinforcement Cover, Reinforcement Diameter and Area, Thermal Expansion Coefficient (It is particularly essential when iron is not used as the reinforcing material)

Table 5. SARBIM required information specification

4.2 Considerations

In this section, any essential considerations during modelling steps are described as a list.

- There are several factors associated with the construction site including ground type, seismic zone, bedrock acceleration ratio, and other factors regarding the structure itself including structural type, regularity in elevation and plan, and fundamental period of vibration that are important for conducting seismic design and analysis (Habte and Guyo, 2021). The information mentioned, in addition to other environmental parameters like wind speed and corrosion, are defined as attributes for the model.
- Although applied loads to the structure are vital for conducting structural analysis, this paper does not consider them part of the SARBIM model except for dead loads. Dead loads include the weight of structural and non-structural components. The structural part can be calculated using the parameters introduced previously, but the approximate weight of non-structural parts should be considered as an attribute of the model. Other applied loads such as live loads are decided during the analysis step and are not included in SARBIM.
- To evaluate a concrete structure's behaviour, the age of concrete that affects material properties variations, and the rate of loading shall be taken into account (2018). So, it is recommended to include construction time for each structural element as an attribute for them.
- The structural elements should be divided into smaller pieces upon intersecting with other structural elements (see Figure 3). So:
  - Each column is defined between stories. For example, a column that connects the first storey's floor to the third storey's ceiling is divided into three pieces.
  - Primary beams are divided into small pieces at their connections with a vertical support
  - Secondary beams are divided into small pieces at their connections to primary beams
  - Floor systems e.g. (slabs) are divided into small pieces at their connections to beams.

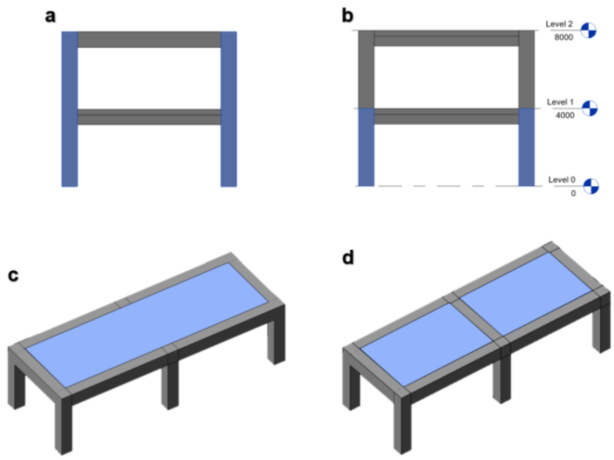

Figure 3. How columns and slabs should be included in the model. Incorrect way of representation of columns (a) and slabs (c), Correct way of representation of columns (b) and slabs (d)

- "Openings" are empty spaces inside a structural element and their corresponding IFC object is IfcRelVoidsElement. The presence of openings inside walls and other structural elements can affect the structural behaviour of the walls. They can affect the distribution of rebars inside structural elements as well.

Although the effects of small openings can be neglected, depending on the analysis that is being conducted, the structural elements with large openings may be required to be divided into smaller ones (Anil et al., 2016). There are existing thresholds in construction standards describing when the effects of opening can be neglected. For example, AS 3600 standard mentions that the openings can be neglected on walls that are laterally supported on four sides if the total area of openings is less than 1/10 of the wall area, and the height of any openings in the wall is less than 1/3 of the wall's height (Standards Australia, 2018).

- Connections are crucial in the structural assessment of constructions, and they represent the topology of structural elements, describing how different structural elements interact and transfer forces. This is particularly crucial for prefabricated structures, as their structural stability relies heavily on the connections' quality of adjacent components (Liu et al., 2023). The connections are not considered separate from other structural elements. However, depending on the type of connections used in structures, some attributes may be required for their structural assessment. Connections between the structural elements can be introduced by IfcStructuralPointConnection IFC object. Considering the importance of connections for structural analysis, it is important to verify their consistency in the data exchange process before exporting data into a structural analysis platform (Sampaio and Gomes, 2021).

4.3 Limitations and Future Works

The requirement analysis conducted in this paper targets a typical RC structure and provides an overview of the information needed for conducting structural analysis. Different types of RC structures and structural analysis may demand modification to the information provided in this paper.
Besides, the mentioned requirements need to be validated comprehensively. In their future works, the authors will evaluate the requirements identified using two techniques:

1- Interviews with the structural engineers as the users of SARBIM will be conducted to validate the requirements identified previously.
2- According to the requirements identified, a SARBIM will be generated and will be used for conducting different types of structural analysis. The results of the analysis conducted will be compared with the results expected.

5. Conclusion

This study focuses on defining the essential components and attributes of SARBIM to optimise scan-to-BIM processes. By reviewing guidelines, literature, and structural software, it identified five key classes of structural elements and their required attributes. The proposed framework aims to guide researchers in systematically enriching BIM models with the necessary structural information for accurate analysis. By addressing key considerations in structural modelling and data exchange, the framework facilitates the development of more reliable and efficient BIM models for structural analysis, contributing to the ongoing evolution of SARBIM in the field.

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