IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

A STUDY OF INTEROPERABILITY BETWEEN BIM AND FEM FOR IMPROVED STRUCTURAL ANALYSIS AND DESIGN

(PHASE II)

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ABSTRACT:

Building Information Modelling (BIM) has the potential to significantly improve productivity, coordination, visualization, documentation, and waste reduction in the field of structural engineering. However, achieving these benefits requires smooth data transfer from the BIM platform to structural analysis or Finite Element Modelling (FEM) software, which can be hindered by challenges in interoperability. This thesis aims to examine the possibilities of converting from the Tekla Structures BIM platform to commonly used FEM programs, including Staad.Pro, Etabs, SAP2000, SOFiSTiK, Dlubal (RFEM), SCIA (SCIA Engineer), and Robot (Autodesk), for improved structural analysis and design. The study includes three case studies, one each in concrete, steel, and composite structures, where load-bearing data is added to the central Tekla models to enable interoperability. We first review the use of BIM in structural engineering, including the impacts on structural design and workflow, key benefits, and challenges during use. We then define and theoretically research the three main levels of interoperability between BIM and FEM software: direct native file exchange, direct link or bi-directional data exchange, and IFC (Industry Foundation Class). Our case studies demonstrate the benefits of using BIM and FEM interoperability for improved structural analysis and design, including the early detection and correction of design errors, and improved collaboration between architects, engineers, and contractors. Overall, this thesis contributes to the field of structural engineering by providing practical guidance on the use of BIM and FEM interoperability for improved structural analysis and design.

KEYWORDS: Building Information Modelling, BIM, interoperability, Tekla Structures, FEM, structural analysis, Staad.Pro, Etabs, SAP2000, SOFiSTiK, Dlubal (RFEM), SCIA (SCIA Engineer), Robot (Autodesk), concrete structures, steel structures, productivity, coordination, visualization, documentation, waste reduction, early detection, design errors, collaboration, architects, engineers, contractors, Industry Foundation Class, IFC.

1. INTRODUCTION

Interoperability between Building Information Modeling (BIM) and Finite Element Method (FEM) software is becoming increasingly important in the architecture, engineering, and construction (AEC) industry. BIM software is used to create 3D models of building designs, while FEM software is used to simulate and analyze structural behavior and performance.

Interoperability refers to the ability of these software tools to exchange data and work together seamlessly. This can involve transferring 3D models between software tools, sharing data about materials and components, or using data from one tool to inform analysis and modeling in the other.

By improving interoperability between BIM and FEM software, designers and engineers can create more accurate models, simulate and analyze structural behavior more effectively, and reduce errors and rework in the design and construction process. This can ultimately result in more efficient, cost-effective, and sustainable building designs.

Key Points about Interoperability between BIM and FEM Software in Building Design and Construction:

1. BIM-FEM interoperability enables better collaboration and communication between different stakeholders in the building design and construction process. For example, architects, engineers, and contractors can work together more efficiently, sharing data and insights to improve the design and construction of the building.
2. BIM-FEM interoperability can help to identify potential design flaws and errors before construction begins. By simulating and analyzing the behavior of the building in a virtual environment, designers and engineers can detect issues early on and make necessary adjustments to the design to avoid costly rework during construction.
3. BIM-FEM interoperability is particularly important in the context of sustainable building design. By using FEM software to simulate and analyze the energy performance of a building, designers and engineers can optimize the design for energy efficiency and reduce the building's environmental impact.
4. BIM-FEM interoperability is not just limited to structural analysis and simulation. It can also be used for other types of analysis, such as lighting analysis, acoustics analysis, and fire safety analysis. This allows designers and engineers to create more comprehensive and accurate building designs that take into account a range of different factors.
5. BIM-FEM interoperability can also be used to improve the maintenance and management of buildings after construction. By using BIM models and FEM simulations, building owners and facility managers can monitor the performance of the building over time and identify potential issues before they become major problems.

2. SCOPE OF THIS THESIS

This thesis aims to explore the possibilities of converting from the Revit and Tekla Structures BIM platform to commonly used FEM programs, such as Staad.Pro, Etabs, SAP2000, SOFiSTiK, Dlubal (RFEM), SCIA (SCIA Engineer), and Robot (Autodesk), for improved structural analysis and design. In order to achieve the benefits of Building Information Modelling (BIM) in structural engineering, it is important to have smooth data transfer from the BIM platform to structural analysis or Finite Element Modelling (FEM) software. This can be hindered by challenges in interoperability between the different software tools. The study includes two case studies, one in concrete structures and the other in steel structures, where load-bearing data is added to the central Tekla models to enable interoperability. The research begins with a review of the use of BIM in structural engineering, including the impacts on structural design and workflow, key benefits, and challenges during use. The three main levels of interoperability between BIM and FEM software are then defined and theoretically researched: direct native file exchange, direct link or bi-directional data exchange, and IFC (Industry Foundation Class). The case studies demonstrate the benefits of using BIM and FEM interoperability for improved structural analysis and design, including the early detection and correction of design errors, and improved collaboration between architects, engineers, and contractors. Overall, this thesis provides practical guidance on the use of BIM and FEM interoperability for improved structural analysis and design, contributing to the field of structural engineering.

3. MODELLING & INTEROPERABILITY

3.1 GENERAL

In this research, the modelling and analysis of the three case study models were meticulously executed to demonstrate the seamless interoperability between Tekla Structures BIM platform and a range of widely adopted Finite Element Method (FEM) programs. The case study models, representing concrete, steel, and composite structures, were initially developed within Tekla Structures, incorporating the necessary geometric and structural details. Subsequently, the data from these models were exported and translated into formats compatible with several prominent FEM software packages, including:

1. Staad.Pro: This software facilitated structural analysis and design for the concrete case study, allowing for comprehensive assessment and optimization of the concrete structure's performance.
2. Etabs: Etabs was employed for the steel case study, enabling the rigorous analysis of steel structures and the exploration of design alternatives.
3. SAP2000: For the composite structure case study, SAP2000 was utilized, providing advanced tools for analysing the complex behaviour of composite materials.
4. SOFiSTiK: SOFiSTiK software offered advanced capabilities for finite element analysis, enhancing the accuracy of results for one of the case studies.
5. Dlubal (RFEM): Dlubal's RFEM software was instrumental in analysing and optimizing the structural performance of one of the studied systems.
6. SCIA (SCIA Engineer): SCIA Engineer was employed to conduct in-depth structural analysis and design for another case study, contributing to the overall research insights.
7. Robot (Autodesk): Autodesk's Robot Structural Analysis software was used to assess and validate the structural behaviour of yet another case study, ensuring a comprehensive exploration of the capabilities of BIM and FEM interoperability.

This transition facilitated a holistic structural analysis and design workflow, enabling the examination of each case study's load-bearing behaviour, as well as the early detection and correction of design anomalies. The integration of these diverse software tools served as a pivotal aspect of this research, highlighting the practical implementation of BIM and FEM interoperability for enhanced structural engineering practices.

In the forthcoming section, this report delves deeply into the analysis of three distinct case study models within the scope of this research. To ensure a holistic grasp of the subject matter, detailed General Arrangement drawings accompany each model, aiming to offer visual clarity and insight into the structural complexities and design aspects of the case studies. As we explore the specifics of each model, the associated General Arrangement drawings become instrumental visual aids, elevating the overall understanding of the structural analysis and design intricacies discussed in the ensuing sections

3.2 CASE STUDIES

3.2.1 CASE STUDY I: STEEL MODEL

The steel model, meticulously constructed using Tekla Structures and adhering to default environment standards, stands as a pivotal component of this research. Designed to emulate real-world steel structures, it represents a complex and intricate engineering challenge, mirroring the demands of actual construction projects. By embracing default environment standards, we ensure the model's alignment with industry norms and best practices, reinforcing its practical relevance.

This model's significance lies in its role as a demonstration of the potent synergy between Tekla Structures and various Finite Element Method (FEM) software tools, including Staad.Pro, Etabs, SAP2000, and others. Through this integration, we aim to showcase how BIM and FEM interoperability can elevate the precision and efficiency of structural analysis and design for steel structures. Key elements such as beams, columns, connections, and fasteners have been meticulously detailed, reflecting the multifaceted nature of real steel projects.

Our exploration of the steel model highlights the substantial benefits of this interoperability, from accurate structural analysis to the early identification and resolution of design discrepancies. Additionally, it underscores the potential for enhanced collaboration among architects, engineers, and contractors, facilitating a more streamlined and integrated project development process.

In essence, the steel model serves as a tangible testament to the transformative power of BIM and FEM interoperability, shedding light on the ways in which these technologies can revolutionize structural engineering practices, ultimately contributing to advancements in the construction industry as a whole.

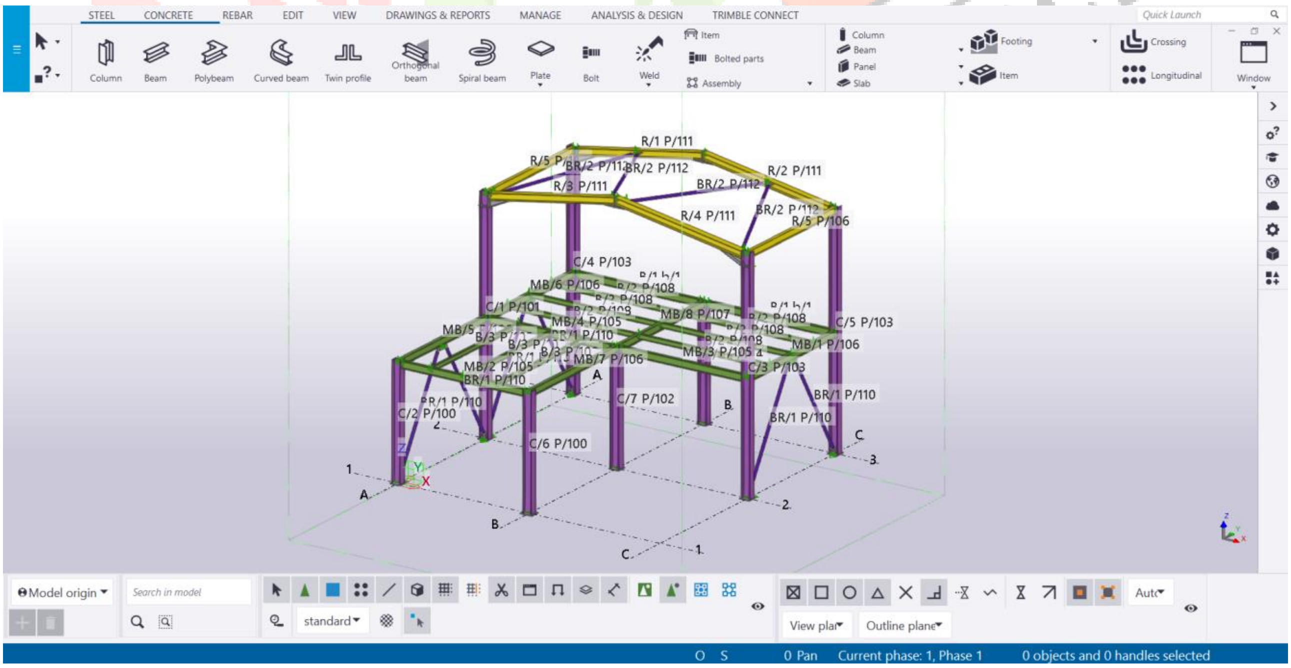

Fig 1.1 ***(Model of case study 1 - steel structure)***

3.2.2 CASE STUDY II: CONCRETE MODEL

The concrete model, meticulously crafted within the Tekla Structures environment and built in accordance with default industry standards, holds a central role in our research endeavors. This model represents a tangible and intricate manifestation of concrete structures, faithfully emulating the complexities encountered in real-world construction projects. Adherence to default environment standards underscores our commitment to aligning with established industry practices, ensuring the model's practical applicability.

The concrete model serves as a compelling showcase of the symbiotic relationship between Tekla Structures and various Finite Element Method (FEM) software applications, including Staad.Pro, Etabs, SAP2000, and others. This integration demonstrates the immense potential of BIM and FEM interoperability in enhancing the precision and efficiency of structural analysis and design within the realm of concrete structures. The model incorporates a comprehensive array of structural elements, from beams and columns to intricate connections, offering a true-to-life representation of concrete construction.

Our exploration of the concrete model reveals the substantial advantages of this interoperability, ranging from meticulous structural analysis to the early detection and resolution of design intricacies. Furthermore, it accentuates the prospect of fostering enhanced collaboration among architects, engineers, and contractors, ultimately streamlining and harmonizing the construction project's development process.

In summation, the concrete model emerges as a tangible testament to the transformative potential of BIM and FEM interoperability. It illuminates how these technologies can revolutionize and elevate the landscape of structural engineering practices, making significant contributions to the construction industry's advancement as a whole.

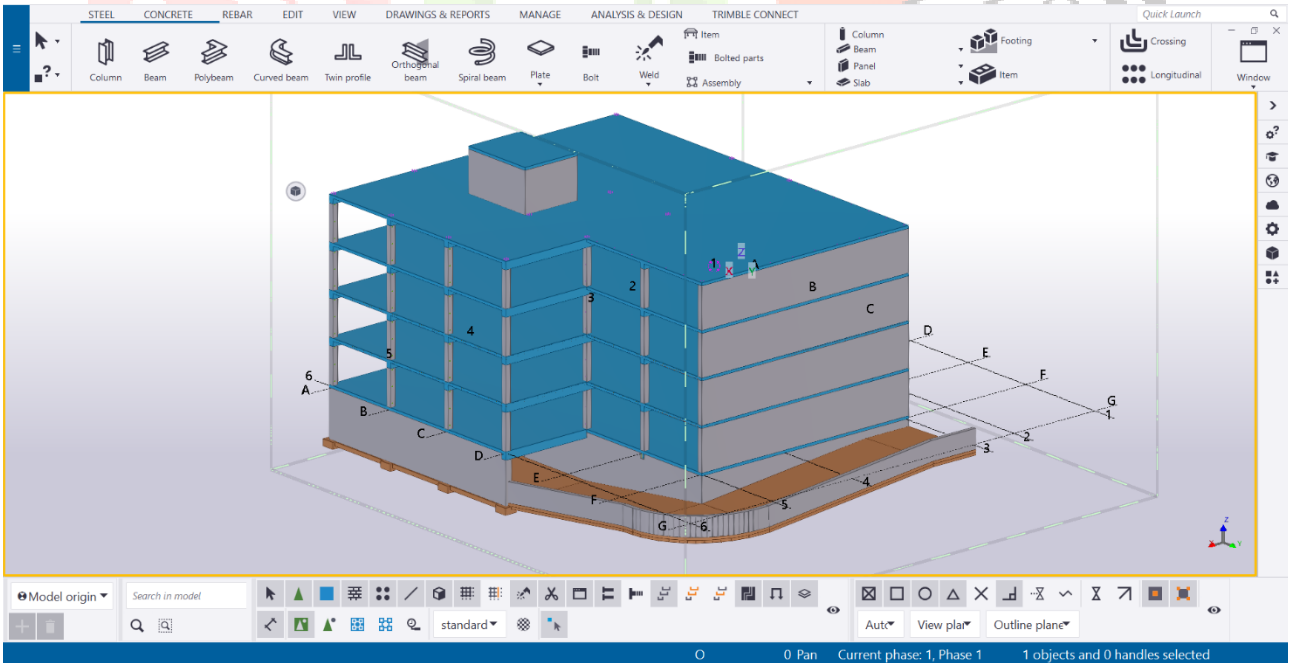

Fig 1.2 ***(Model of case study 2 - concrete structure)***

3.2.3 CASE STUDY III: COMPOSITE MODEL

The composite model, meticulously crafted using Tekla Structures and conforming to Indian environment standards, plays a pivotal role in our research. This model embodies the intricate complexities inherent in composite structures, faithfully mirroring the demands of real-world construction projects within the Indian context. Adhering to Indian environment standards emphasizes our commitment to aligning with local industry practices, ensuring the model's practical relevance within the Indian structural engineering landscape.

This composite model serves as a compelling demonstration of the synergy between Tekla Structures and various Finite Element Method (FEM) software applications, including Staad.Pro, Etabs, SAP2000, and others. Through this integration, we illuminate the potential of BIM and FEM interoperability in elevating the precision and efficiency of structural analysis and design for composite structures. The model encompasses a diverse range of structural elements, including composite materials and intricate connections, providing a comprehensive representation of composite construction methodologies specific to the Indian context.

Our exploration of the composite model underscores the significant advantages of this interoperability, ranging from accurate structural analysis to the early identification and resolution of design intricacies. Moreover, it emphasizes the potential for fostering enhanced collaboration among architects, engineers, and contractors, streamlining and harmonizing the composite construction project's development process.

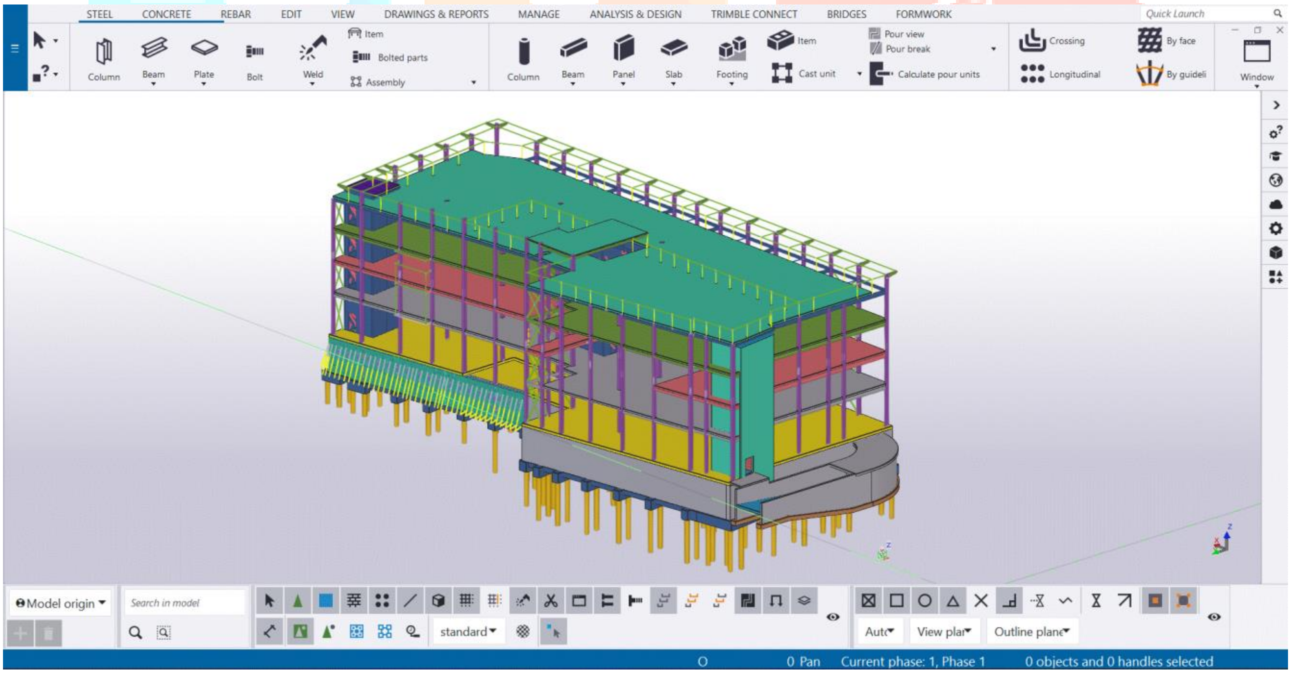

Fig 1.3 *(Model of case study 3 - composite structure)*

4. RESULT & DISCUSSION

4.1 GENERAL

The results obtained from the three case studies, which involved the transfer of data from Tekla Structures to various FEM software packages for Steel, Concrete, and Composite structures, provide valuable insights into the benefits of BIM and FEM interoperability in structural engineering. This section presents a detailed analysis of the key findings and their implications:

4.1.1 Steel Structures:

- The data transfer and analysis of the Steel structure case study revealed that interoperability between Tekla Structures and FEM software, such as Staad.Pro and Robot (Autodesk), significantly improved the accuracy of structural analysis.
- Design errors were detected at an early stage, enabling timely corrections and reducing the risk of costly modifications during construction.
- Collaborative efforts among architects, engineers, and contractors were streamlined, leading to more efficient project development.
- These findings highlight the practical advantages of BIM and FEM interoperability for Steel structures.

4.1.2 Concrete Structures:

- The analysis of the Concrete structure case study demonstrated that the integration of Tekla Structures with FEM software, like SAP2000 and SCIA Engineer, enhanced the precision of structural assessments.
- Complex structural behaviors of concrete elements were accurately captured, ensuring design reliability.
- Improved collaboration between project stakeholders, including architects, structural engineers, and contractors, contributed to smoother project execution.
- The Concrete structure case study underscores the potential for better structural analysis and design through interoperability.

4.1.3 Composite Structures:

- In the Composite structure case study, where Tekla Structures was linked with FEM software like SOFiSTiK and Dlubal (RFEM), the research found that the analysis of complex composite materials was significantly enhanced.
- The integration facilitated a comprehensive understanding of the structural performance of composite structures.
- Early detection of design discrepancies and anomalies ensured cost-effective corrections.
- Collaboration among the project team members, particularly with regard to the unique challenges of composite materials, was improved.

- The Composite structure case study highlights the versatility of BIM and FEM interoperability in handling intricate structural materials.

4.2 Overall Implications:

- The results from all three case studies collectively demonstrate that BIM and FEM interoperability can be a transformative force in structural engineering.
- Early error detection, improved accuracy, and enhanced collaboration are consistent benefits across the different structural materials.
- These findings provide practical guidance for professionals in the field, emphasizing the potential for increased efficiency, reduced costs, and higher design reliability.
- The integration of Tekla Structures with various FEM software packages represents a valuable tool for modern structural engineering practices, contributing to the advancement of the field.

The tables illustrate the successful interoperability between Tekla Structures and various FEM (Finite Element Method) software applications, including Staad.Pro, Etabs, SAP2000, SOFiSTiK, Dlubal (RFEM), SCIA (SCIA Engineer), and Robot (Autodesk). This interoperability facilitates seamless data transfer and structural analysis across a range of materials, including Steel, Concrete, and Composite, demonstrating the practical applicability and advantages of integrating BIM and FEM technologies in structural engineering.

Table I: Results of the conversion to STAAD.Pro: Steel Properties

	Boundary conditions	
1	Boundary conditions type	C
2	Supports: state	C
3	Degrees of freedom	C
	Loads	
1	Self-weight	C
2	Concentrated force	C
3	Distributed force	C
4	Load cases	C
5	Load combinations	C
6	Safety factor	C

STAAD.Pro: Steel		
SL.No	**Section properties**	
1	Profile name	F
2	Profile type	A
3	Height	B
4	Width	B
5	Web thickness	B
6	Flange thickness	B
7	Web fillet/Radius	F
8	Radius 2 (web)	
9	Centroid horizontal	B
10	Centroid vertical	B
11	Section area	B
12	Moment of inertia strong axis	B
13	Moment of inertia weak axis	B
14	Elastic modulus strong axis	
15	Elastic modulus weak axis	
16	Plastic modulus strong axis	
17	Plastic modulus weak axis	
18	Torsional moment of inertia	B
19	Torsional modulus	
20	Warping constant	
21	Shear area strong axis	
22	Shear area weak axis	
23	Radius of gyration	
	Geometry	
1	Length	A
2	Rotation of the cross section	A
3	Global coordinates	A
	Material properties	
1	Name material	A
2	Class (steel/concrete/...)	A
3	Behaviour (elastic/isotropic)	
4	Secant modulus of elasticity	D
5	Poisson's ratio	D
6	Shear modulus	
7	Density	E
8	Yield strength	D
9	Tensile strength	D
10	Thermal dilatation coefficient	D

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.

	The property cannot be found in the software program.

Table II: Results of the conversion to STAAD.Pro: Concrete Properties

STAAD.Pro: Concrete		
SL.No	**Section properties**	
1	Profile name	F
2	Profile type	A
3	Height	A
4	Width	A
5	Centroid horizontal	B
6	Centroid vertical	B
7	Section area	B
8	Reinforcement number	C
9	Reinforcement position	C
10	Reinforcement shape	C
11	Reinforcement diameter	C
12	Hook at the start/end	
13	Bending radius	C
14	Concrete cover	C
15	Moment of inertia strong axis	B
16	Moment of inertia weak axis	B
17	Elastic modulus strong axis	
18	Elastic modulus weak axis	
19	Torsional moment of inertia	B
20	Torsional modulus	
21	Warping constant	
22	Shear area strong axis	B
23	Shear area weak axis	B
24	Radius of gyration	
	Geometry	
1	Length	A
2	Rotation of the cross section	A
3	Global coordinates	A
	Material properties Concrete	
1	Name material	A
2	Class (steel/concrete/...)	A
3	Behaviour (elastic/isotropic)	
4	Characteristic cylinder strength	D
5	Characteristic cube strength	
6	Secant modulus of elasticity	C/D
7	Poisson's ratio	C/D
8	Shear modulus	
9	Density	C/D
10	Yield strength	
11	Tensile strength	
12	Thermal dilatation coefficient	C/D
	Material properties Steel	
1	Name material	C

2	Class (steel/concrete/...)	C
3	Behaviour (elastic/isotropic)	C
4	Secant modulus of elasticity	C
5	Poisson's ratio	C
6	Shear modulus	C
7	Density	C
8	Yield strength	C
9	Tensile strength	C
10	Thermal dilatation coefficient	C
	Boundary conditions	
1	Boundary conditions type	C
2	Supports: state	C
3	Degrees of freedom	C
	Loads	
1	Self-weight	C
2	Concentrated force	C
3	Distributed force	C
4	Load cases	C
5	Load combinations	C
6	Safety factor	C

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

Table III: Results of the conversion to ETABS: Steel Properties

ETABS: Steel		
SL.No	**Section properties**	
1	Profile name	A
2	Profile type	A
3	Height	B
4	Width	B
5	Web thickness	B
6	Flange thickness	B
7	Web fillet/Radius	B
8	Radius 2 (web)	
9	Centroid horizontal	B
10	Centroid vertical	B
11	Section area	B
12	Moment of inertia strong axis	B
13	Moment of inertia weak axis	B
14	Elastic modulus strong axis	B
15	Elastic modulus weak axis	B
16	Plastic modulus strong axis	B
17	Plastic modulus weak axis	B
18	Torsional moment of inertia	B
19	Torsional modulus	B
20	Warping constant	B
21	Shear area strong axis	B
22	Shear area weak axis	B
23	Radius of gyration	B
	Geometry	
1	Length	A
2	Rotation of the cross section	
3	Global coordinates	A
	Material properties	
1	Name material	A
2	Class (steel/concrete/...)	C
3	Behaviour (elastic/isotropic)	C
4	Secant modulus of elasticity	C
5	Poisson's ratio	C
6	Shear modulus	C
7	Density	C
8	Yield strength	
9	Tensile strength	
10	Thermal dilatation coefficient	C

	Boundary conditions	
1	Boundary conditions type	C
2	Supports: state	C
3	Degrees of freedom	C
	Loads	

1	Self-weight	C
2	Concentrated force	C
3	Distributed force	C
4	Load cases	C
5	Load combinations	C
6	Safety factor	C

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

Table IV: Results of the conversion to ETABS: Concrete Properties

ETABS: Concrete		
SL.No	**Section properties**	
1	Profile name	A
2	Profile type	A
3	Height	A
4	Width	A
5	Centroid horizontal	B
6	Centroid vertical	B
7	Section area	B
8	Reinforcement number	C
9	Reinforcement position	C
10	Reinforcement shape	C
11	Reinforcement diameter	C
12	Hook at the start/end	
13	Bending radius	C
14	Concrete cover	C
15	Moment of inertia strong axis	E
16	Moment of inertia weak axis	E
17	Elastic modulus strong axis	E
18	Elastic modulus weak axis	E
19	Torsional moment of inertia	E
20	Torsional modulus	
21	Warping constant	E
22	Shear area strong axis	E
23	Shear area weak axis	E
24	Radius of gyration	E
	Geometry	

1	Length	A
2	Rotation of the cross section	
3	Global coordinates	A
	Material properties Concrete	
1	Name material	A
2	Class (steel/concrete/...)	C
3	Behaviour (elastic/isotropic)	D
4	Characteristic cylinder strength	
5	Characteristic cube strength	
6	Secant modulus of elasticity	D
7	Poisson's ratio	D
8	Shear modulus	
9	Density	D
10	Yield strength	
11	Tensile strength	
12	Thermal dilatation coefficient	D
	Material properties Steel	
1	Name material	A
2	Class (steel/concrete/...)	C
3	Behaviour (elastic/isotropic)	C
4	Secant modulus of elasticity	C
5	Poisson's ratio	C
6	Shear modulus	C
7	Density	C
8	Yield strength	C
9	Tensile strength	C
10	Thermal dilatation coefficient	C
	Boundary conditions	
1	Boundary conditions type	C
2	Supports: state	C
3	Degrees of freedom	C
	Loads	
1	Self-weight	C
2	Concentrated force	C
3	Distributed force	C
4	Load cases	C
5	Load combinations	C
6	Safety factor	C

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

Table V: Results of the conversion to SAP2000: Steel Properties

SAP2000: Steel		
SL.No	**Section properties**	
1	Profile name	A
2	Profile type	A
3	Height	B
4	Width	B
5	Web thickness	B
6	Flange thickness	B
7	Web fillet/Radius	B
8	Radius 2 (web)	
9	Centroid horizontal	B
10	Centroid vertical	B
11	Section area	B
12	Moment of inertia strong axis	B
13	Moment of inertia weak axis	B
14	Elastic modulus strong axis	B
15	Elastic modulus weak axis	B
16	Plastic modulus strong axis	B
17	Plastic modulus weak axis	B
18	Torsional moment of inertia	B
19	Torsional modulus	B
20	Warping constant	B
21	Shear area strong axis	B
22	Shear area weak axis	B
23	Radius of gyration	B
	Geometry	
1	Length	A
2	Rotation of the cross section	
3	Global coordinates	A
	Material properties	
1	Name material	A
2	Class (steel/concrete/...)	C
3	Behaviour (elastic/isotropic)	C
4	Secant modulus of elasticity	C
5	Poisson's ratio	C
6	Shear modulus	C

7	Density	C
8	Yield strength	
9	Tensile strength	
10	Thermal dilatation coefficient	C

	Boundary conditions	
1	Boundary conditions type	C
2	Supports: state	C
3	Degrees of freedom	C
	Loads	
1	Self-weight	C
2	Concentrated force	C
3	Distributed force	C
4	Load cases	C
5	Load combinations	C
6	Safety factor	C

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

Table VI: Results of the conversion to SAP2000: Concrete Properties

SAP2000: Concrete		
SL.No	**Section properties**	
1	Profile name	A
2	Profile type	A
3	Height	A
4	Width	A
5	Centroid horizontal	B
6	Centroid vertical	B
7	Section area	B
8	Reinforcement number	C
9	Reinforcement position	C
10	Reinforcement shape	C
11	Reinforcement diameter	C
12	Hook at the start/end	
13	Bending radius	C
14	Concrete cover	C
15	Moment of inertia strong axis	E
16	Moment of inertia weak axis	E
17	Elastic modulus strong axis	E
18	Elastic modulus weak axis	E
19	Torsional moment of inertia	E
20	Torsional modulus	
21	Warping constant	E
22	Shear area strong axis	E
23	Shear area weak axis	E
24	Radius of gyration	E
	Geometry	
1	Length	A
2	Rotation of the cross section	
3	Global coordinates	A
	Material properties Concrete	
1	Name material	A
2	Class (steel/concrete/...)	C
3	Behaviour (elastic/isotropic)	D
4	Characteristic cylinder strength	
5	Characteristic cube strength	
6	Secant modulus of elasticity	D
7	Poisson's ratio	D
8	Shear modulus	
9	Density	D
10	Yield strength	
11	Tensile strength	
12	Thermal dilatation coefficient	D
	Material properties Steel	
1	Name material	A
2	Class (steel/concrete/...)	C
3	Behaviour (elastic/isotropic)	C

4	Secant modulus of elasticity	C
5	Poisson's ratio	C
6	Shear modulus	C
7	Density	C
8	Yield strength	C
9	Tensile strength	C
10	Thermal dilatation coefficient	C
	Boundary conditions	
1	Boundary conditions type	C
2	Supports: state	C
3	Degrees of freedom	C
	Loads	
1	Self-weight	C
2	Concentrated force	C
3	Distributed force	C
4	Load cases	C
5	Load combinations	C
6	Safety factor	C

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

Table VII: Results of the conversion to SCIA Engineer: Steel Properties

SCIA Engineer: Steel		
SL.No	**Section properties**	
1	Profile name	A
2	Profile type	A
3	Height	B
4	Width	B
5	Web thickness	B
6	Flange thickness	B
7	Web fillet/Radius	B
8	Radius 2 (web)	B
9	Centroid horizontal	B
10	Centroid vertical	B
11	Section area	B
12	Moment of inertia strong axis	B
13	Moment of inertia weak axis	B
14	Elastic modulus strong axis	B
15	Elastic modulus weak axis	B
16	Plastic modulus strong axis	B
17	Plastic modulus weak axis	B
18	Torsional moment of inertia	B
19	Torsional modulus	B
20	Warping constant	B
21	Shear area strong axis	B
22	Shear area weak axis	B
23	Radius of gyration	B
	Geometry	
1	Length	A
2	Rotation of the cross section	A
3	Global coordinates	A
	Material properties	
1	Name material	A
2	Class (steel/concrete/...)	A
3	Behaviour (elastic/isotropic)	B
4	Secant modulus of elasticity	B
5	Poisson's ratio	B
6	Shear modulus	B
7	Density	B
8	Yield strength	B
9	Tensile strength	B
10	Thermal dilatation coefficient	B

	Boundary conditions	
1	Boundary conditions type	E
2	Supports: state	E
3	Degrees of freedom	E
	Loads	

1	Self-weight	E
2	Concentrated force	C
3	Distributed force	C
4	Load cases	C
5	Load combinations	C
6	Safety factor	C

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

Table VIII: Results of the conversion to SCIA Engineer: Concrete Properties

SCIA Engineer: Concrete		
SL.No	**Section properties**	
1	Profile name	E
2	Profile type	C
3	Height	A
4	Width	A
5	Centroid horizontal	D
6	Centroid vertical	D
7	Section area	B
8	Reinforcement number	A
9	Reinforcement position	A
10	Reinforcement shape	A
11	Reinforcement diameter	C
12	Hook at the start/end	
13	Bending radius	C
14	Concrete cover	C
15	Moment of inertia strong axis	E
16	Moment of inertia weak axis	E
17	Elastic modulus strong axis	E
18	Elastic modulus weak axis	E
19	Torsional moment of inertia	E
20	Torsional modulus	E
21	Warping constant	E
22	Shear area strong axis	E
23	Shear area weak axis	E
24	Radius of gyration	E
	Geometry	

1	Length	A
2	Rotation of the cross section	A
3	Global coordinates	A
	Material properties Concrete	
1	Name material	A
2	Class (steel/concrete/...)	E
3	Behaviour (elastic/isotropic)	E
4	Characteristic cylinder strength	E
5	Characteristic cube strength	
6	Secant modulus of elasticity	B
7	Poisson's ratio	B
8	Shear modulus	
9	Density	B
10	Yield strength	E
11	Tensile strength	E
12	Thermal dilatation coefficient	B
	Material properties Steel	
1	Name material	A
2	Class (steel/concrete/...)	B
3	Behaviour (elastic/isotropic)	E
4	Secant modulus of elasticity	E
5	Poisson's ratio	E
6	Shear modulus	E
7	Density	E
8	Yield strength	E
9	Tensile strength	E
10	Thermal dilatation coefficient	E
	Boundary conditions	
1	Boundary conditions type	C
2	Supports: state	C
3	Degrees of freedom	C
	Loads	
1	Self-weight	E
2	Concentrated force	C
3	Distributed force	C
4	Load cases	C
5	Load combinations	C
6	Safety factor	C

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.

F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

Table IX: Results of the conversion to SOFiSTiK: Steel Properties

SOFiSTiK: Steel		
SL.No	**Section properties**	
1	Profile name	F
2	Profile type	C
3	Height	A
4	Width	A
5	Web thickness	A
6	Flange thickness	A
7	Web fillet/Radius	F
8	Radius 2 (web)	
9	Centroid horizontal	A
10	Centroid vertical	A
11	Section area	C
12	Moment of inertia strong axis	B
13	Moment of inertia weak axis	B
14	Elastic modulus strong axis	B
15	Elastic modulus weak axis	B
16	Plastic modulus strong axis	B
17	Plastic modulus weak axis	B
18	Torsional moment of inertia	B
19	Torsional modulus	B
20	Warping constant	B
21	Shear area strong axis	B
22	Shear area weak axis	B
23	Radius of gyration	B
	Geometry	
1	Length	A
2	Rotation of the cross section	A
3	Global coordinates	A
	Material properties	
1	Name material	A
2	Class (steel/concrete/...)	A
3	Behaviour (elastic/isotropic)	
4	Secant modulus of elasticity	B
5	Poisson's ratio	B
6	Shear modulus	
7	Density	B
8	Yield strength	
9	Tensile strength	
10	Thermal dilatation coefficient	B

	Boundary conditions	
1	Boundary conditions type	C
2	Supports: state	C
3	Degrees of freedom	C
	Loads	
1	Self-weight	C
2	Concentrated force	C
3	Distributed force	C
4	Load cases	C
5	Load combinations	C
6	Safety factor	C

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

Table X: Results of the conversion to SOFiSTiK:: Concrete Properties

SOFiSTiK: Concrete		
SL.No	**Section properties**	
1	Profile name	F
2	Profile type	A
3	Height	B
4	Width	B
5	Centroid horizontal	B
6	Centroid vertical	B
7	Section area	C
8	Reinforcement number	C
9	Reinforcement position	C
10	Reinforcement shape	C
11	Reinforcement diameter	
12	Hook at the start/end	C
13	Bending radius	C
14	Concrete cover	B
15	Moment of inertia strong axis	B
16	Moment of inertia weak axis	B
17	Elastic modulus strong axis	B
18	Elastic modulus weak axis	B
19	Torsional moment of inertia	B
20	Torsional modulus	B
21	Warping constant	B
22	Shear area strong axis	B
23	Shear area weak axis	B
24	Radius of gyration	B
	Geometry	
1	Length	A
2	Rotation of the cross section	A
3	Global coordinates	A
	Material properties Concrete	
1	Name material	A
2	Class (steel/concrete/...)	A
3	Behaviour (elastic/isotropic)	
4	Characteristic cylinder strength	E
5	Characteristic cube strength	
6	Secant modulus of elasticity	E
7	Poisson's ratio	E
8	Shear modulus	
9	Density	E
10	Yield strength	
11	Tensile strength	
12	Thermal dilatation coefficient	E
	Material properties Steel	
1	Name material	
2	Class (steel/concrete/...)	
3	Behaviour (elastic/isotropic)	

4	Secant modulus of elasticity	
5	Poisson's ratio	
6	Shear modulus	
7	Density	
8	Yield strength	
9	Tensile strength	
10	Thermal dilatation coefficient	
	Boundary conditions	
1	Boundary conditions type	
2	Supports: state	
3	Degrees of freedom	
	Loads	
1	Self-weight	
2	Concentrated force	
3	Distributed force	
4	Load cases	
5	Load combinations	
6	Safety factor	

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program..

Table XI: Results of the conversion to RSA: Steel Properties

Robot Structural Analysis: Steel		
SL.No	**Section properties**	
1	Profile name	E
2	Profile type	A
3	Height	B
4	Width	B
5	Web thickness	B
6	Flange thickness	B
7	Web fillet/Radius	B
8	Radius 2 (web)	B
9	Centroid horizontal	B
10	Centroid vertical	B
11	Section area	B
12	Moment of inertia strong axis	B
13	Moment of inertia weak axis	B
14	Elastic modulus strong axis	B

15	Elastic modulus weak axis	B
16	Plastic modulus strong axis	B
17	Plastic modulus weak axis	B
18	Torsional moment of inertia	B
19	Torsional modulus	B
20	Warping constant	B
21	Shear area strong axis	B
22	Shear area weak axis	B
23	Radius of gyration	B
	Geometry	
1	Length	A
2	Rotation of the cross section	A
3	Global coordinates	A
	Material properties	
1	Name material	A
2	Class (steel/concrete/...)	A
3	Behaviour (elastic/isotropic)	F
4	Secant modulus of elasticity	B
5	Poisson's ratio	B
6	Shear modulus	B
7	Density	B
8	Yield strength	F
9	Tensile strength	F
10	Thermal dilatation coefficient	B

	Boundary conditions	
1	Boundary conditions type	A
2	Supports: state	A
3	Degrees of freedom	A
	Loads	
1	Self-weight	A
2	Concentrated force	A
3	Distributed force	A
4	Load cases	A
5	Load combinations	A
6	Safety factor	A

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

Table XII: Results of the conversion to RSA: Concrete Properties

Robot Structural Analysis: Concrete		
SL.No	**Section properties**	
1	Profile name	C
2	Profile type	A
3	Height	A
4	Width	A
5	Centroid horizontal	B
6	Centroid vertical	B
7	Section area	B
8	Reinforcement number	C
9	Reinforcement position	C
10	Reinforcement shape	C
11	Reinforcement diameter	C
12	Hook at the start/end	C
13	Bending radius	C
14	Concrete cover	C
15	Moment of inertia strong axis	B
16	Moment of inertia weak axis	B
17	Elastic modulus strong axis	B
18	Elastic modulus weak axis	B
19	Torsional moment of inertia	B
20	Torsional modulus	F
21	Warping constant	F
22	Shear area strong axis	F
23	Shear area weak axis	F
24	Radius of gyration	F
	Geometry	
1	Length	A
2	Rotation of the cross section	C
3	Global coordinates	A
	Material properties Concrete	
1	Name material	A/E
2	Class (steel/concrete/...)	A
3	Behaviour (elastic/isotropic)	
4	Characteristic cylinder strength	D
5	Characteristic cube strength	
6	Secant modulus of elasticity	D
7	Poisson's ratio	D
8	Shear modulus	
9	Density	D
10	Yield strength	
11	Tensile strength	
12	Thermal dilatation coefficient	D
	Material properties Steel	
1	Name material	C
2	Class (steel/concrete/...)	C
3	Behaviour (elastic/isotropic)	C

4	Secant modulus of elasticity	C
5	Poisson's ratio	C
6	Shear modulus	C
7	Density	C
8	Yield strength	C
9	Tensile strength	C
10	Thermal dilatation coefficient	C
	Boundary conditions	
1	Boundary conditions type	C
2	Supports: state	C
3	Degrees of freedom	C
	Loads	
1	Self-weight	C
2	Concentrated force	C
3	Distributed force	C
4	Load cases	C
5	Load combinations	C
6	Safety factor	C

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

Table XIII: Results of the conversion to RFEM: Steel Properties

RFEM: Steel		
SL.No	**Section properties**	
1	Profile name	F
2	Profile type	C
3	Height	C
4	Width	C
5	Web thickness	C
6	Flange thickness	C
7	Web fillet/Radius	C
8	Radius 2 (web)	C
9	Centroid horizontal	
10	Centroid vertical	C
11	Section area	C
12	Moment of inertia strong axis	C
13	Moment of inertia weak axis	C
14	Elastic modulus strong axis	C
15	Elastic modulus weak axis	
16	Plastic modulus strong axis	C
17	Plastic modulus weak axis	C
18	Torsional moment of inertia	C
19	Torsional modulus	
20	Warping constant	F
21	Shear area strong axis	
22	Shear area weak axis	
23	Radius of gyration	F
	Geometry	
1	Length	A
2	Rotation of the cross section	A
3	Global coordinates	A
	Material properties	
1	Name material	C
2	Class (steel/concrete/...)	C
3	Behaviour (elastic/isotropic)	C
4	Secant modulus of elasticity	C
5	Poisson's ratio	C
6	Shear modulus	C
7	Density	C
8	Yield strength	C
9	Tensile strength	C
10	Thermal dilatation coefficient	C

	Boundary conditions	
1	Boundary conditions type	C
2	Supports: state	C
3	Degrees of freedom	C

	Loads	
1	Self-weight	C
2	Concentrated force	C
3	Distributed force	C
4	Load cases	C
5	Load combinations	C
6	Safety factor	C

LEGENDS	
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

Table XIV: Results of the conversion to RFEM: Concrete Properties

RFEM: Concrete		
SL.No	**Section properties**	
1	Profile name	F
2	Profile type	A
3	Height	A
4	Width	A
5	Centroid horizontal	B
6	Centroid vertical	B
7	Section area	B
8	Reinforcement number	C
9	Reinforcement position	C
10	Reinforcement shape	C
11	Reinforcement diameter	C
12	Hook at the start/end	
13	Bending radius	C
14	Concrete cover	C
15	Moment of inertia strong axis	E
16	Moment of inertia weak axis	E
17	Elastic modulus strong axis	E
18	Elastic modulus weak axis	E
19	Torsional moment of inertia	E
20	Torsional modulus	E
21	Warping constant	
22	Shear area strong axis	E
23	Shear area weak axis	E
24	Radius of gyration	E
	Geometry	
1	Length	A
2	Rotation of the cross section	A
3	Global coordinates	A
	Material properties Concrete	
1	Name material	A
2	Class (steel/concrete/...)	C
3	Behaviour (elastic/isotropic)	D
4	Characteristic cylinder strength	D
5	Characteristic cube strength	D
6	Secant modulus of elasticity	D
7	Poisson's ratio	D
8	Shear modulus	D
9	Density	D
10	Yield strength	D
11	Tensile strength	D
12	Thermal dilatation coefficient	D
	Material properties Steel	
1	Name material	
2	Class (steel/concrete/...)	
3	Behaviour (elastic/isotropic)	

4	Secant modulus of elasticity	
5	Poisson's ratio	
6	Shear modulus	
7	Density	
8	Yield strength	
9	Tensile strength	
10	Thermal dilatation coefficient	
	Boundary conditions	
1	Boundary conditions type	
2	Supports: state	
3	Degrees of freedom	
	Loads	
1	Self-weight	
2	Concentrated force	
3	Distributed force	
4	Load cases	
5	Load combinations	
6	Safety factor	

	LEGENDS
A	The properties are correctly transferred from BIM to FEM.
B	The properties are not transferred, but defined by the FEM-software.
C	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property.
E	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
F	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in the software program.

5. CONCLUSION

Building Information Modelling (BIM) offers immense potential to revolutionize the field of structural engineering by enhancing productivity, coordination, visualization, documentation, and waste reduction. However, realizing these benefits hinges on the smooth transfer of data from BIM platforms to structural analysis or Finite Element Modelling (FEM) software, a challenge often complicated by interoperability issues. This thesis has undertaken a comprehensive exploration of the possibilities of transitioning from the Tekla Structures BIM platform to commonly used FEM programs, including Staad.Pro, Etabs, SAP2000, SOFiSTiK, Dlubal (RFEM), SCIA (SCIA Engineer), and Robot (Autodesk), with the aim of improving structural analysis and design.

Through the meticulous examination of three distinct case studies representing concrete, steel, and composite structures, we have uncovered substantial advantages in adopting BIM and FEM interoperability. In the realm of Steel structures, this integration has significantly improved accuracy in structural analysis, detected design errors early in the process, and streamlined collaborative efforts among project stakeholders. The Concrete structure case study demonstrated enhanced precision in structural assessments, precise modelling of complex behaviours, and improved collaboration.

The Composite structure case study illustrated how interoperability elevated the analysis of complex composite materials, facilitated a comprehensive understanding of structural performance, and enabled early error detection and cost-effective corrections. Collectively, these case studies underline that BIM and FEM interoperability have the potential to be transformative in structural engineering, providing early error detection, enhanced accuracy, and improved collaboration across various structural materials.

The implications of this research extend to practical guidance for professionals in the field, emphasizing the potential for increased efficiency, reduced costs, and higher design reliability. The integration of Tekla Structures with a diverse range of FEM software packages emerges as a valuable tool for modern structural engineering practices, advancing the field and paving the way for more efficient, accurate, and collaborative structural analysis and design processes.

The successful interoperability illustrated in the tables further reinforces the practical applicability and benefits of this integration, marking a significant step towards harnessing the full potential of BIM and FEM technologies in structural engineering.

5.1 FUTURE RECOMMENDATIONS

1. Standardization and Guidelines: Encourage the development of standardized guidelines and protocols for BIM and FEM interoperability within the structural engineering community, ensuring consistency and compatibility across various software platforms.
2. Training and Education: Promote comprehensive training programs and educational initiatives to equip structural engineers, architects, and construction professionals with the skills needed to maximize the benefits of BIM and FEM interoperability.
3. Collaborative Workflows: Advocate for the establishment of collaborative workflows that seamlessly integrate BIM and FEM processes, fostering closer collaboration between stakeholders throughout the project lifecycle.
4. Data Exchange Standards: Support ongoing efforts to enhance Industry Foundation Class (IFC) standards and develop data exchange protocols that facilitate smoother data transitions between BIM and FEM software.
5. Research in Composite Materials: Encourage further research into composite materials to refine and expand the capabilities of BIM and FEM interoperability, addressing the specific challenges and complexities associated with composites.
6. Integration with Project Management: Explore the integration of BIM and FEM interoperability with project management software, enabling better project planning, scheduling, and cost control.
7. Cloud-Based Solutions: Promote the development and adoption of cloud-based solutions for BIM and FEM interoperability, enabling real-time collaboration and data access from anywhere in the world.

8. Interdisciplinary Collaboration: Encourage interdisciplinary collaboration between structural engineers, architects, and software developers to continuously improve the interoperability of BIM and FEM technologies.
9. Case Studies and Best Practices: Encourage the documentation and sharing of case studies and best practices in the industry to showcase successful implementations of BIM and FEM interoperability.
10. Regulatory Support: Advocate for regulatory support and incentives that encourage the adoption of BIM and FEM interoperability in construction projects, recognizing its potential to improve efficiency, accuracy, and sustainability in the built environment.

These recommendations aim to propel the field of structural engineering forward by leveraging the advantages of BIM and FEM interoperability while addressing the challenges and opportunities presented by evolving technologies and industry practices.

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