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MUNIRU NYEI

BIM IN STRUCTURAL ENGINEERING: A STUDY OF INTEROPERABILITY BETWEEN BIM PLATFORM AND FEM SOFTWARE ON STRUCTURAL MODELLING, ANALYSIS AND DESIGN

BIM V KONSTRUKCIJSKEM INŽENIRSTVU: ŠTUDIJA INTEROPERABILNOSTI BIM ORODIJ PRI MODELIRANJU, ANALIZI IN PROJEKTIRANJU

BIM A+ European Master in Building Information Modelling

Master thesis No.:

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Izvleček:

Informacijsko modeliranje zgradb BIM (angl. Building Information Modelling) kaže izjemne prednosti in potenciale tudi na področju konstrukcijskega inženirstva. Teh potencialov kot so npr. produktivnost, koordinacija, vizualizacija, dokumentiranje in zmanjšanje količine odpadkov ni mogoče doseči, če ni ustreznega mehanizma, ki zagotavlja nemoten prenos podatkov iz BIM platforme v programsko opremo za analizo konstrukcij in modeliranje konstrukcij s končnimi elementi (angl. FEM). Izzivi pri prenosu podatkov ali interoperabilnosti naj bi bili med ključnimi dejavniki, ki ovirajo polno sodelovanje projektantov (gradbenih inženirjev).

Ta študija skuša preveriti možnosti pretvorbe iz platforme Revit BIM v programsko opremo FEM z izmenjavo osrednjih podatkov modela Revit, dopolnjenih z ustreznimi konstrukcijskimi lastnostmi, z vsakim od naslednjih pogosto uporabljenih FEM programov: SOFiSTiK, Dlubal (RFEM) in SCIA Engineer. Podrobno smo pregledali uporabo BIM v konstrukcijskem inženirstvu, s poudarkom na vplivih na konstrukcijsko zasnovo in potek dela, ključnih prednostih in nekaterih izzivih med uporabo. Nato so opredeljene in teoretično raziskane ter podrobno razložene tri glavne ravni interoperabilnosti med programsko opremo BIM in FEM. Te stopnje interoperabilnosti so: neposredna izmenjava izvornih datotek (izmenjava med istimi komercialnimi ponudniki programske opreme), neposredna povezava ali dvosmerna izmenjava in IFC (Industry Foundation Class).V podporo zaključkom te teze sta na primerih izvedeni dve študiji. S prvo študijo so preizkušene zmožnosti neposredne izmenjave podatkov med platformo Revit BIM in programsko opremo FEM . V drugi študiji je uporabljen vmesnik Revit-SOFiSTiK s ciljem, da se analizira učinkovitost BIM delovnih procesov v konstrukcijskem inženirstvu S to študijo je bilo ugotovljeno, da je izmenjava podatkov preko tega vmesnika dobro sinhronizirana in učinkovita. Učinkovitost vmesnika glede delovnih procesov v konstrukcijskem inženirstvu je dokazana z visoko stopnjo zanesljivosti.

Rezultati te naloge zagotavljajo ustrezne informacije o interoperabilnosti BIM v konstrukcijskem inženirstvu. Poleg tega potrjujejo rezultate prejšnjih študij, ki kažejo, da je interoperabilnost najučinkovitejše sredstvo za sporočanje podatkov med platformo Revit BIM in programsko opremo za konstrukcijsko inženirstvo.

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Abstract:

Building Information Modelling (BIM) shows exceptional advantages and potentials in the field of structural engineering as well. These potentials, e.g., productivity, coordination, visualization, documentation, and waste reduction, cannot be achieved without an appropriate mechanism to ensure the smooth transfer of data from the BIM platform to structural analysis or Finite Element Modelling (FEM) software. Challenges in data transfer or interoperability to be among the key factors hindering the full participation of structural engineers in BIM workflow.

This thesis seeks to examine the possibilities of conversion from the Revit BIM platform to FEM software by exchanging a central Revit model, supplemented by appropriate load-bearing data, with each of the following commonly used FEM programs: SOFiSTiK, Dlubal (RFEM) and SCIA (SCIA Engineer). We first reviewed in detail the use of BIM in structural engineering, focusing on the impacts on structural design and workflow, key benefits, and some challenges during use. The three main levels of interoperability between BIM and FEM software are then defined and theoretically researched and explained in detail. These interoperability levels are direct native file exchange (exchange between the same commercial software providers), direct link or bi-directional data exchange, and IFC (Industry Foundation Class). Two case studies are conducted to support the conclusions of this thesis. The first case study tests the capability of direct link interoperability (data exchange via add-on/plug-in) between the Revit BIM platform and the FEM software. The second case study uses the Revit-SOFiSTiK interface to analyse the efficiency of BIM workflows in structural engineering. This study found that the exchange of data via this interface is well synchronized and efficient. The efficiency of the interface in terms of structural engineering BIM workflow is proven with a high degree of reliability.

The results of this thesis provide relevant information on the interoperability of BIM in structural engineering. In addition, the study confirms the results of previous studies showing that interoperability (most especially direct link interoperability level) is the most effective means of communicating data between the Revit BIM platform and structural engineering software.

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1   INTRODUCTION

The introduction of Building Information Modelling methodology in planning, design, and construction processes is increasing the effectiveness, efficiency, and productivity of structural engineers. By employing the 3D modelling design approach, a structural engineer can understand the complexities of his model and facilitate seamless collaboration with design team members and other relevant project stakeholders. However, despite these potential benefits, the BIM application in structural engineering is faced with 'interoperability' challenges. For a structural engineer, this means challenges arising from exchanging his central BIM model from a BIM platform to an analysis tool or Finite Element Analysis software (FEM) [1]. Interoperability difficulties as the main inhibitor of BIM adoption in AEC sectors have been elaborated extensively in many studies [2]. To overcome these obstacles, appropriate data exchange mechanisms from the BIM platform to a Finite Element Modelling or FEM (structural analysis and design) software is required. This will ensure the full participation of structural engineers in the real-time 3D modelling design approach that is currently revolutionizing the AEC industry.

There are three key levels of establishing data exchange interoperability in BIM structural engineering. Namely; direct native file exchange-- wish ensures data exchange between same software vendor; direct link or bi-directional interoperability-- which considers a one-to-one data exchange between two suits; and IFC (Industry Foundation Class) -- which relies on open and common format data exchange. In this thesis, the direct link interoperability, identified as one of the widely used levels and the most effective interoperability for structural engineering practice, will be extensively examined.

1.1   Problem Statement

As BIM adoption is gradually becoming the new standard in the AEC industry, structural engineers are adjusting their workflows and software tools to adapt to the opportunities and challenges that this real-time 3D innovative methodology presents.

For good exchange of data to take place between BIM and FEM tools, there must be a good coherence in the interoperability of BIM data. Hence, this thesis seeks to find answers to the following questions:

- Which efficient and effective means of interoperability are available for structural engineers to exchange data?
- How does FEM software interpret structural model from a BIM tool?
- How to perform and document BIM workflow in structural engineering?
- What are the benefits and challenges in interoperability in BIM structural engineering?

1.2   Thesis Objectives

This thesis exams interoperability in BIM structural engineering, focusing on modelling, analysis, design, result documentation, and coordination. The AEC sector relies heavily on collaboration, and it usually involves many stakeholders with different software and file format requirements; data exchange capability is key to a successful BIM implementation [3]. Thus, the objectives of the thesis are:

- present an overview of BIM in the construction sector and how it provides an innovative platform to improve the workflow for structural engineers
- examine the application of BIM in structural engineering workflow, from modelling to analysis, design and documentation
- examine the three main levels of interoperability or data exchange in structural engineering which includes, direct native file, direct link, open BIM format or IFC
- access interoperability capability, quality, and problems, through the application of two case studies

The overall goal of the thesis is to gain insightful knowledge in the application of BIM in structural engineering with a particular focus on understanding the technical capabilities and challenges regarding exchanging structural model data between mainstream BIM Platforms and FEM software.

1.3   Scope of Thesis

Building Information Modelling is still an evolving and complex topic; hence, appropriate context and boundaries are needed to deal with the topic adequately. Therefore, this thesis covers the interoperability aspect of BIM data in structural engineering employing the direct link data exchange method. The three main levels of interoperability in BIM structural engineering are discussed in details. Two practical case studies which focus on data exchange in the reinforced concrete structure are presented. In the first case study, a central Revit BIM model is populated with all relevant structural data and exchanged with the following widely used FEM software: SOFiSTiK, RFEM, and SCIA Engineer. The second case study employs the well-integrated Revit-SOFiSTiK platform to access BIM workflow in structural engineering, from modelling, analysis, design and documentation.

1.4   Methodology

An extensive literature review was conducted to understand the theories, concepts and main arguments of the thesis subject, followed by a detailed study of the interoperability from data exchange perspectives. The method employed to arrive at the conclusions of this thesis is based on a data analysis experiment. Two detailed case studies presented. Revit was used as a central platform for all BIM data. The Revit BIM model was exchanged (see Figure 1) with FEM software to examine and describe what happens to structural parameters in the data exchange process. The structural model geometry was created in Dynamo; modifications and additional metadata added in Revit. The model is a reinforced concrete structure, and the tests are based on direct link interoperability level.
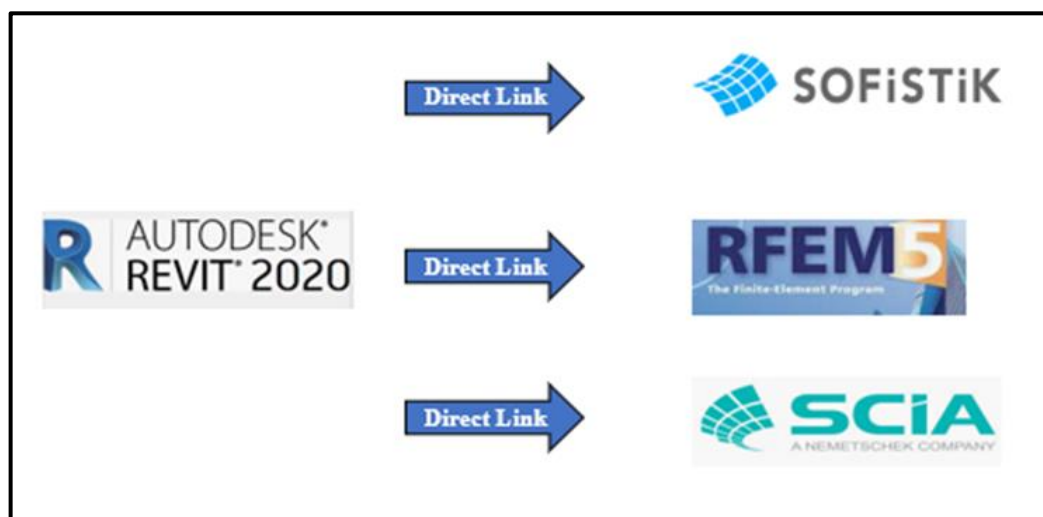
Figure 1: Exchange scenarios implemented in the case studies: Revit vs. FEM software

The transfer scenarios investigated and assigned score marks. The highest scores achieved much more data transfer efficacy than the lowest. A comparison of internal forces is presented, further demonstrating the fidelity of data transfer from Revit to FEM programs.

1.5   Thesis Outlines

The thesis contains Seven chapters, a bibliographic reference, and three appendices.

The first chapter justifies the research. The second chapter presents an overview of BIM.

The third chapter presents an extensive discourse on BIM in structural engineering. It highlights the technical background, BIM workflow in structural engineering and process map, benefits, and challenges.

The fourth chapter delves deeply into assessing the various types and levels of interoperability. The fifth chapter presents two simplified case studies model for the practical evaluation of direct link interoperability. Case studies results are compared, thus providing the basis for the conclusion of this thesis. In Chapter Six, the results of Chapter five are compared and discussed in detail. Chapter Seven concludes the thesis with a summary of key findings and outcomes.

2   BIM OVIEW

Built-environment practitioners, design engineers, and government institutions are fast adopting a novel planning process called Building Information Modelling or BIM. BIM is a process that increases efficiency and supports competitiveness in challenging business climate; encourages innovation across construction industry disciplines. As industrial practitioners, it would be right to say that digitization in construction is the modern version of the industrial revolution in the construction industry [4]. Jerry Laiserin, a digital construction enthusiast, provides one of the most up to date, comprehensive, and versatile definition of BIM: "BIM creates and maintains in real-time multidimensional, data-rich views through a project lifecycle to support communication (sharing of data), collaboration (acting on shared data), simulation (using shared data for prediction), optimization (using feedback on shared data to improve the design), documentation and delivery" [5]. BIM facilitates collaboration and project information sharing through the intelligent 3D digital environment [6]. Figure 2 graphically summarizes these definitions.
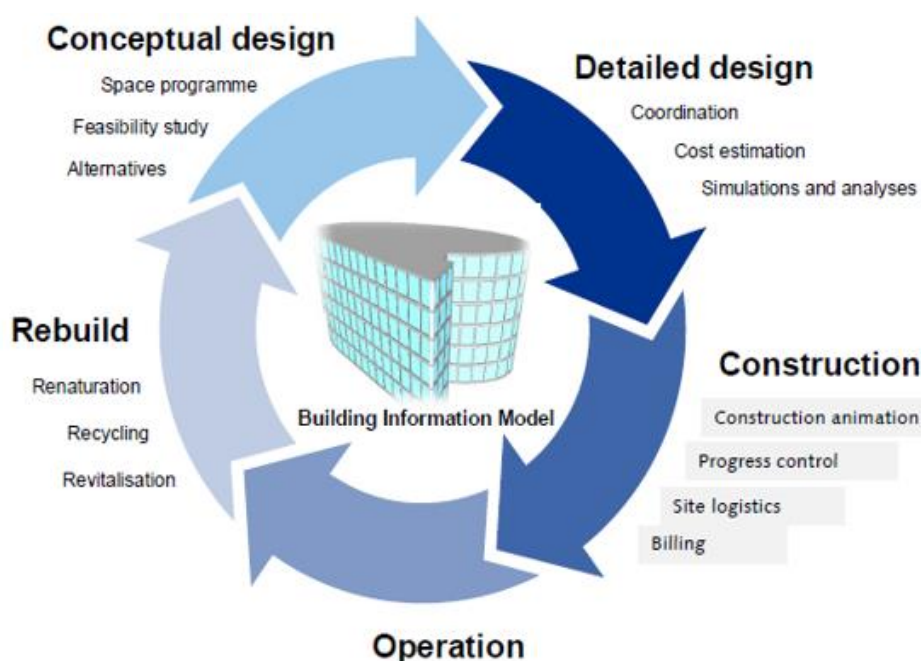
Figure 2 : BIM defined graphically [7]

The 3D modelling approach gradually being adopted in structural design companies improves decision supports and coordination.

In most developing countries, where the construction industry is seen as one of the major sources of graft and theft, the application of the real-time 3D modelling approach has the potential to improve planning processes and communications. This promises a significant contribution to the fight against waste, corruption, and abuse of meagre public resources.

This innovative 3D model-based design methodology was introduced by Autodesk in 2002. It has provided professionals in the AEC sector a positive outlook on the application of advanced and innovative technology in the built environment. Some of the key advantages BIM provides as cited by Autodesk [8]:

- project deliver time significantly reduced
- better coordination
- project cost minimization
- very high productivity

- better project quality
- windows of opportunities in terms of innovation, growth and business

The building lifecycle has three major phases: design, construction, and Management. Outlined below is how BIM provides critical information to each phase in the building lifecycle [8]:

- Design phase— provides data on analysis and design model, project schedule, and cost
- Construction phase—provides data on construction sequence/schedules, cost, and quality
- Management phase—provides data on facility management, utilities, finance, performance, and utilization

The worldwide embrace of BIM adoption and processes does not go without its misconception. While BIM is widely adopted and considered by many in the AEC sectors as an innovative approach for project design and implementation, others still view it from the lenses of a mere technological tool. Hence, while the application of BIM heavily relies on suitable technology, it should in no way be misconstrued as a technological tool; but rather a methodological approach intended to enhance project planning, design and implementation. Some technical terms and technologies that are very common in BIM applications are [8]:

- CAD
- Object CAD
- Parametric Building Modelling

2.1   BIM vs CAD
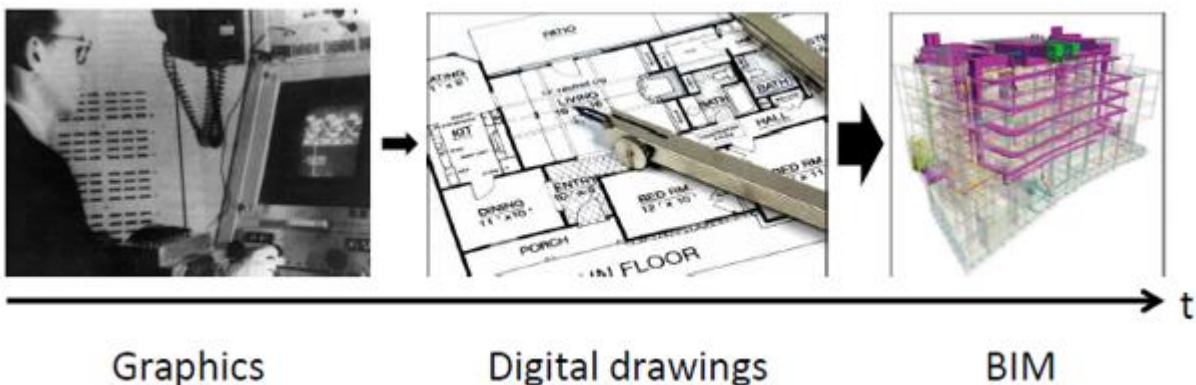
Figure 3: Evolution of digital support in construction industry [9]

Figure 3 demonstrates the evolution of digital support in the construction industry. CAD is a computer-aided technical drafting tool that sometimes provides inconsistent information, requires manual updates and stands the risk of data misinterpretations. It also cannot be used for advanced analysis and simulations. CAD (Computer-Aided Design) represents merely 2D linework; properties such as the grade of concrete, materials, and other parameters are not included within the 2D environment; specific reference is required for these data (see Figure 4). On the other hand, in addition to going from 2D to 3D, BIM objects have additional properties or metadata. It provides information on the type of component, the material properties and shows the relationship between components in a model. In Figure 5, for example, a dialog box from Revit Structure (BIM) shows a column property that includes size, grade, etc. Hence, an intelligent 3D representation of a model informs and communicate project decisions well.
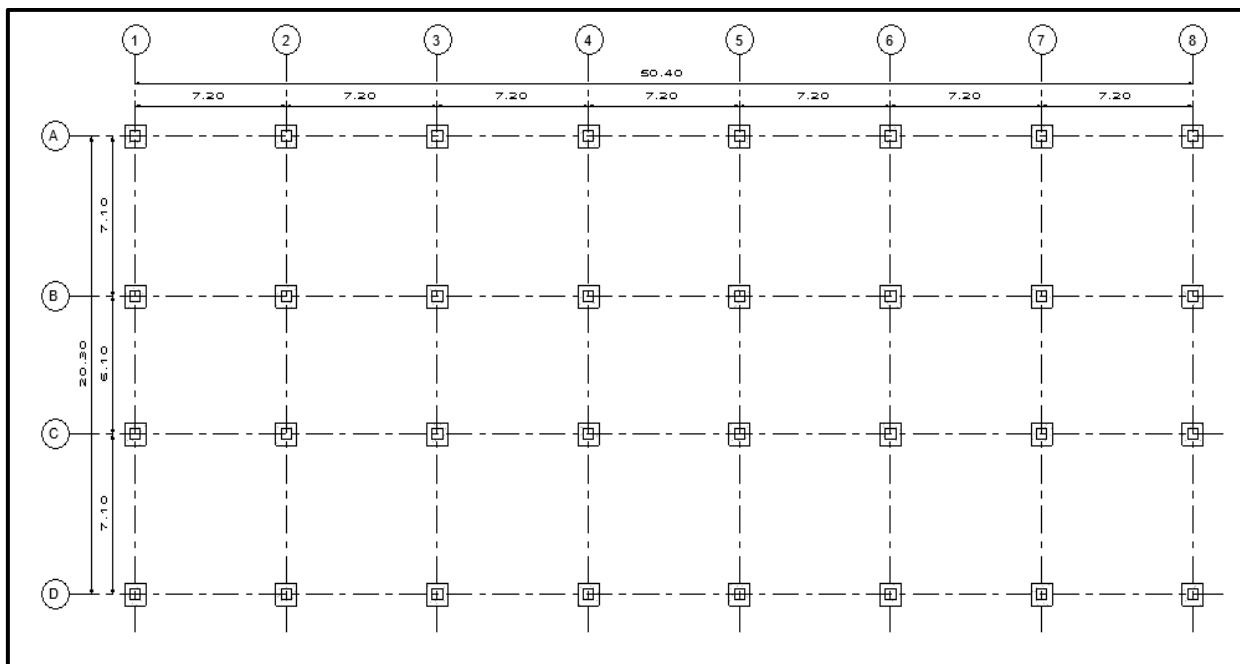
Figure 4: CAD drawing representing a floor plan with no intelligent properties attached
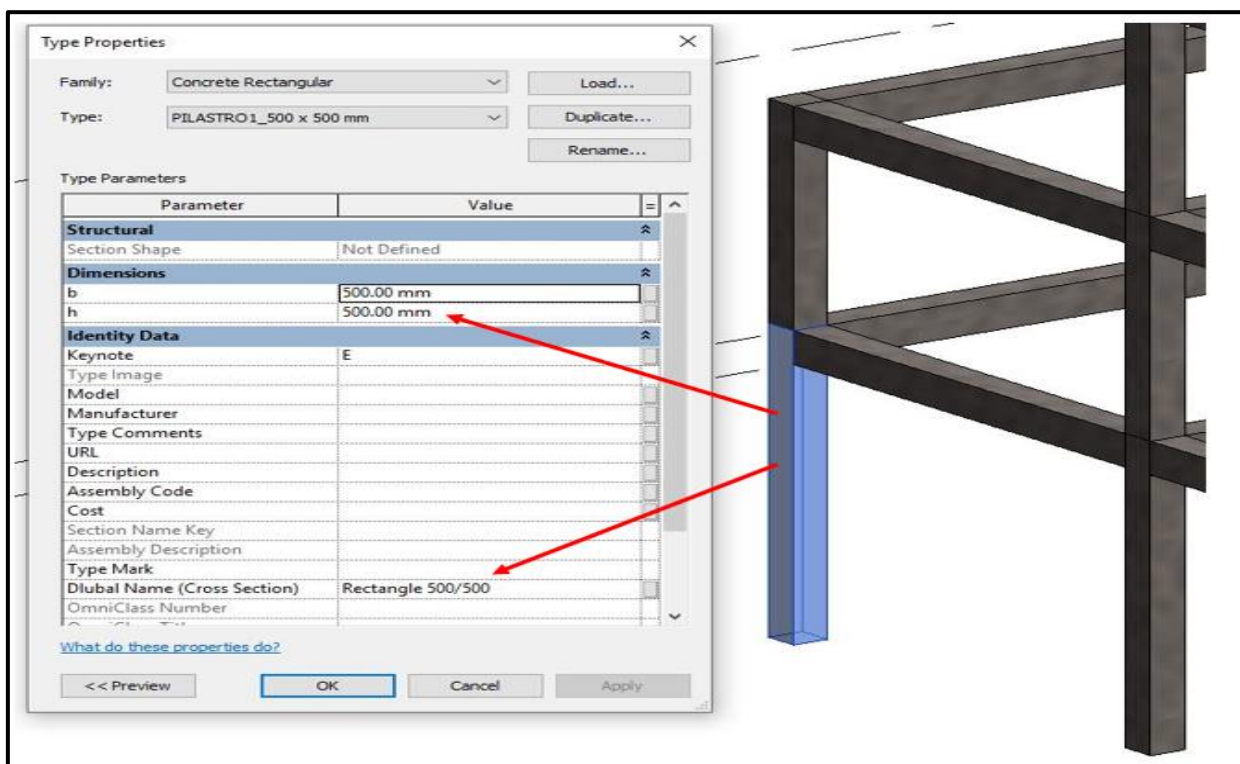
Figure 5: Intelligent data and properties attached to the 3D column in a BIM model

2.2   BIM Maturity Level

The transition from implementing BIM projects from CAD to BIM requires steps and standards set by various industries or government institutions. These standards ensure model capabilities, and not all companies pass through these transitions smoothly. The BIM maturity is a yardstick used by BIM practitioners to measure how well information within BIM collaborative environment is structured,

which, to an extent, helps to reduce error and avoid data misinterpretation. Figure 6 illustrates the BIM maturity level model due to the British standard.
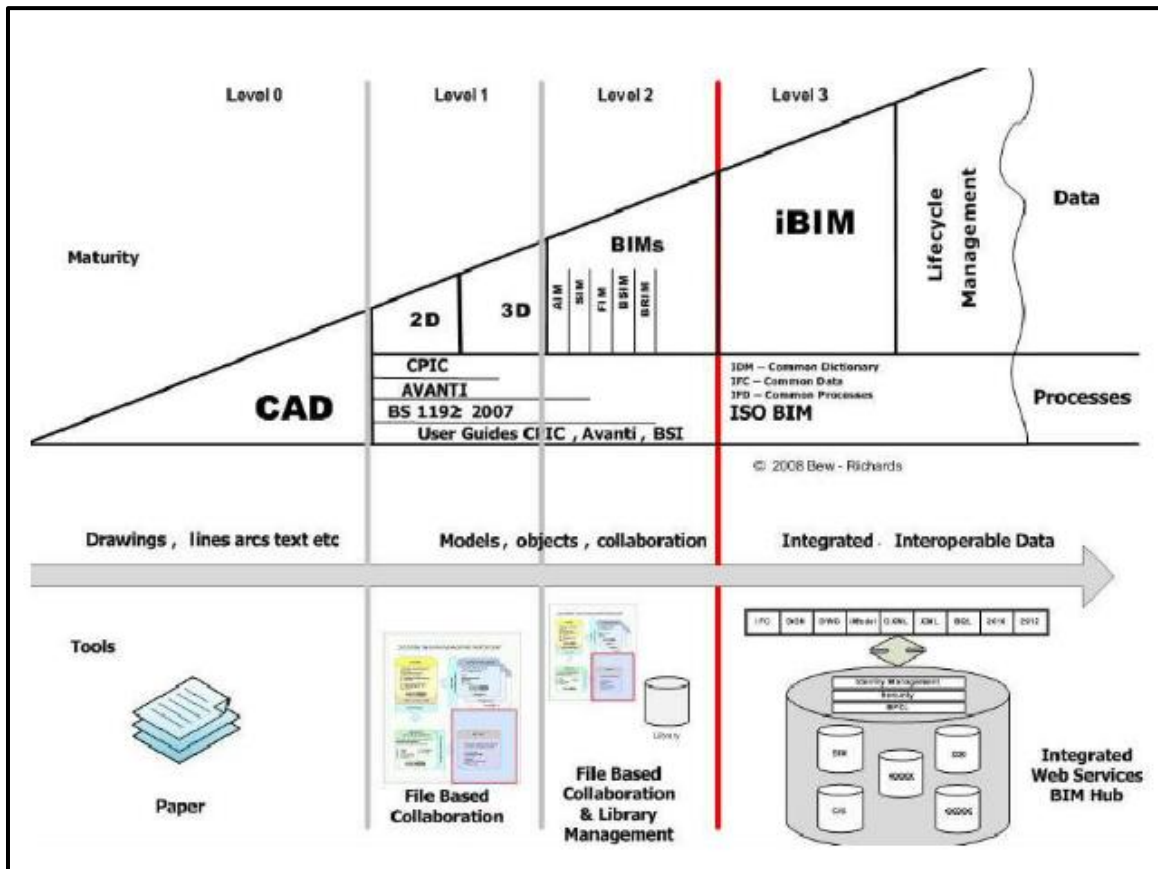
Figure 6: BIM Maturity model [10]

The four stages of BIM maturity level as define in the British BIM standard documents are briefly explained below [11]:

- Level 0 – This level represents a no BIM level. The initial phase of using Computer-Aided Design is represented at this level, and there are no 3D elements. It is reportedly undefined, no trace of coordination between project teams electronically, and an entirely paper-based model.
- Level 1 – This level represents partially structured and un-federated model data. It uses a standardized and file-based approach. It is a closed BIM model where the application of both 2D and 3D model elements are possible. The closed nature of this level means that BIM model elements are generated and shared locally.
- Level 2 – This level represents collaborative BIM, where various project participants in the construction process assembled. Here project information is structured, file-based collaboration, and library management enabled. Project stakeholders utilize a common data environment to exchange and coordinate project information [5]. This level is already being implemented in some developed countries, where BIM adoption is prescribed by legally binding national standards.
- Level 3 – This level is the highest level of BIM driven by OpenBIM and server-based object information models. One of the main characteristics of this level is the full integration of all aspects of the construction process into one connected and common data environment. Here, multiple project models are replaced by a single model and access to all stakeholders involved within a construction process. Participation in this level requires agreed formal definitions of model exchange requirements. The

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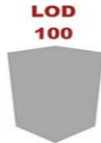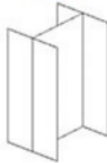
introduction of this level represents a significant change in the ways construction planning, design, and management are carried out. Its success, in terms of implementation, would require improvements in a company's organizational and managerial structures, human resources capacity building, and the introduction of new technologies.

As per standard practice, a minimum of maturity level 2 is highly recommended for BIM adoption [12]. Maturity levels 1 to 2 can easily be recognized in structural engineering BIM practices.

2.3   Level of Development

Every element within the construction model contains some key information relevant to the construction process at a specific point in time. Such detailed information is termed the level of development (LOD). Not only does the LOD helps to improve the quality of communication among project members within a BIM environment, but it also provides detailed information about the BIM model at every stage of the project. It is a very useful reference document for BIM implementation [12]. The specifications and definitions of LOD are based on the definition developed by the American Institute of Architect or AIA G202-2013 Building Information Modelling Protocol Form [12]. As briefly summarized in Table 1, the level of development ranges from LOD 100 to LOD 500.

Table 1: Level of Development in BIM

Level	Definition	Example
100	The most basic level; generic information; Conceptual stage of design; important for feasibility and cost estimation studies.	LOD 100
200	graphically representation of model content; some detail view available such as orientation, size, shape and location	LOD 200
300	Model contains reason degree of specifications and definitions; Construction model	LOD 300
400	High degree of details available; information about installation, fabrication and all-important model data available	

500	As-Built design and actual conditions; important for field validation	As-built model

2.4   BIM Execution Plan (BEP)

A successful BIM implementation does not occur in isolation from a comprehensive planning process. It involves the complex implementation of varying technology; hence, to ensure a successful BIM implementation, project stakeholders require a well-structured and comprehensive document outlining who, what, how and when a BIM project is to be executed. This document or plan is what is referred to as the BIM Execution Plan (BEP or BxP). BEP is a plan that articulates how a BIM service provider model and implement a BIM project. It provides sequential information on how the information modelling aspects of a project will be conducted. Detailed information on organizational setup, project content, vision, execution, and information exchange requirements; are all contained in a BEP [13].

It is only through a well-developed execution plan; a project team would be able to [14]:

- better understand why a project should be implemented using BIM
- layout clear implementation strategies and processes for project participants
- establish criteria to measure progress
- define responsibilities, duties and roles

A typical BEP comprises information on project objective; list of team members and their contacts; design milestones; BIM uses; design model use and requirements; coordination process; coordination sign-off; model requirements; software programs; file naming convention; coordination milestones; coordination meeting schedules; document history; and an appendix for further information. Figure 7 shows a BEP procedure format developed by Penn State University BIM research group [15].
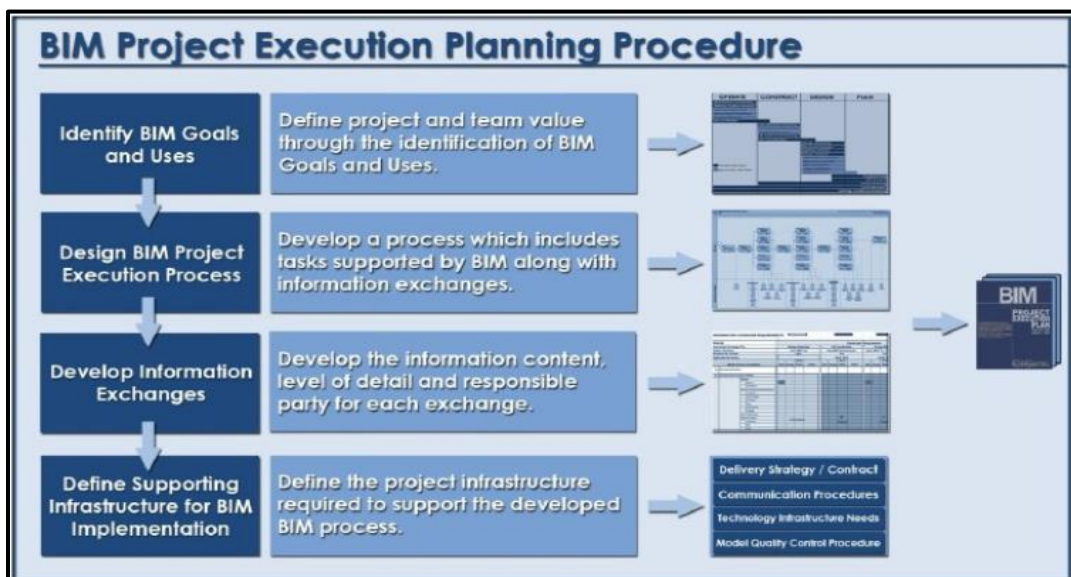
Figure 7: A template of BIM Project Execution Planning Procedure proposed by Penn State University [15]

2.5   Summary

This chapter presents a recap and a brief overview of some concepts, principles, main arguments, and implementation strategies in Building Information Modelling. Some principal difference between BIM and CAD are highlighted through practical examples. A brief elaboration on the various stages of BIM implementation is discussed. The concept of level of development is briefly presented, and some information on BIM execution plans provided.

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3   BIM IN STRUCTURAL ENGINEERING

3.1   Introduction

Construction of load-bearing structures (horizontal or vertical) is very demanding in terms of safety requirements, and a specialist skill of a professional structural engineer is required to design them. A structural engineer must possess adequate knowledge and skills in the analysis, design and construction of load-bearing structures and at the same time ensures that his/her design is economically feasible and safe [16]. The Structural engineer's role within BIM workflow is to create an error-free clean structural BIM model. His/her model should contain the necessary information to facilitate structural analysis and design: material properties, boundary condition, loads, section properties, load combinations, etc. He/she plays a very influential role in the BIM workflow by ensuring the cost and construction sequence of structural elements are under control. Therefore, this chapter will explore BIM uses relevant to the structural engineering domain and types of structural BIM model and workflow; and it will further highlight benefits accrued from the application of BIM in structural engineering and outline some challenges. Figure 8 illustrates the thought process of a structural engineer during the design stage of a project.
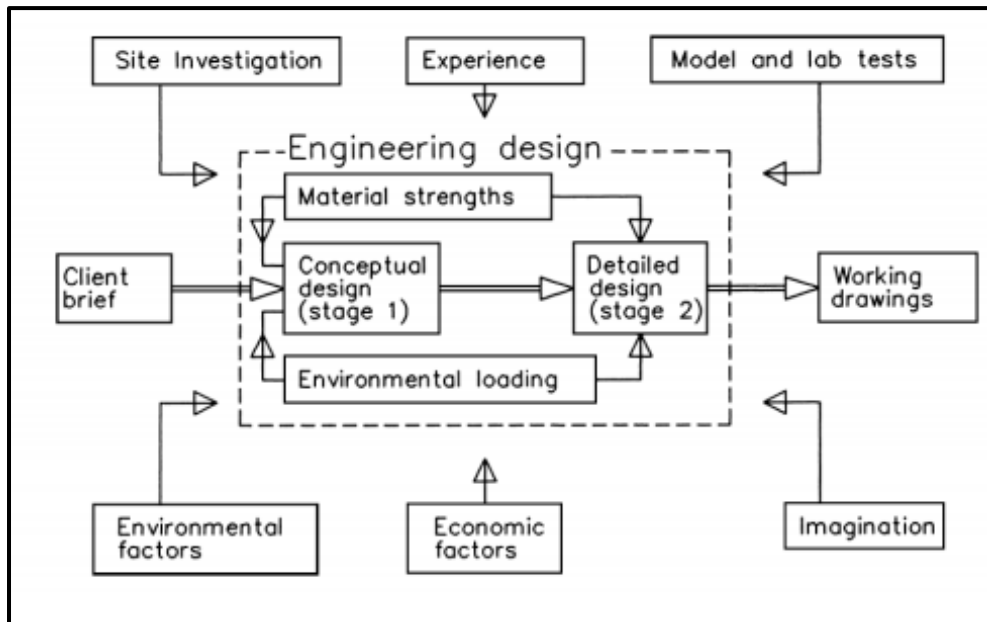
Figure 8: A look into a structural engineer's mind during design stage [17]

3.2   Technical Background

3.2.1   Structural BIM Uses

BIM Use refers to how the concept of Building Information Modelling is applied or used in each specialist domain within a project lifecycle. For example, facility management, the construction phase of the project, structural analysis and design, cost estimations, etc., all have different BIM uses tailored toward meeting specific BIM's goals and objective within a project. Currently, literature studies identify several BIM Uses, including Penn State BIM Uses, BIMessential or BIMe, etc. [18] [19]. The Penn State BIM Use looks at BIM Use from discipline perspectives based on four main phases of a construction process: plan, design, construct and operate. While BIMessential or BIMe, considers BIM Use from a model use perspective which includes general model uses, domain model uses, and custom model uses [18][19]. As previously stated, these BIM Uses are intended to tailor the implementation of BIM to specific needs and purposes. A study from McGraw Hill concludes that, after energy performance analysis, structural analysis has the lowest value/difficulty ratio among different

engineering analysis BIM Uses, and it also has the highest frequency index (representing higher BIM use) [20].

A 2008 research conducted in the United States of America; finds interdisciplinary coordination, project documentation (producing construction drawings), structural analysis and design (through third party analysis plugin or direct link); as the three most important BIM uses in structural engineering. Based on the ranking criteria employed by the survey, which investigated BIM uses in selected companies, the use of BIM for project documentation was graded 87%; BIM use for project coordination took 47%, and the application of BIM in the analysis and design graded 25% [21].

BIM Uses in structural engineering practices is ever-increasing and fast becoming a standard operating procedure. When BIM Uses, when appropriately implemented on a project, time and cost are save, project quality and higher performance ensure. A discussion on these three widely known BIM Uses in structural engineering practice is presented in the below section.

Coordination (inter-discipline)

Coordination is one of the key factors encouraging BIM adoption across the AEC industry. It helps project team members, including architect, cost estimators, structural and MEP engineers, to share project data using a single prototype model containing all aspects of the building. This way, project stakeholders can effectively coordinate and make reliable design decisions, which are enabled by accurate 3D geometries and data. The coordination view in structural engineering-based BIM projects is mainly created to allow for a smooth flow of communication between the structural design team and other project participants. It cannot, however, be used for structural analysis or design purposes. It communicates only geometric information about the structure and other data relevant for architectural purposes [20].

During the construction phase, the coordination model is also very important; it provides information to contractors about cost estimation, schedules, and phasing of the project. For project owners also do use it for managing facilities [21]. Unlike structural analysis view, coordination view can be easily shared via an open file format like IFC or a multi-discipline platform like Revit across disciplines. Figure 9 shows the same model in both coordination and analysis view.
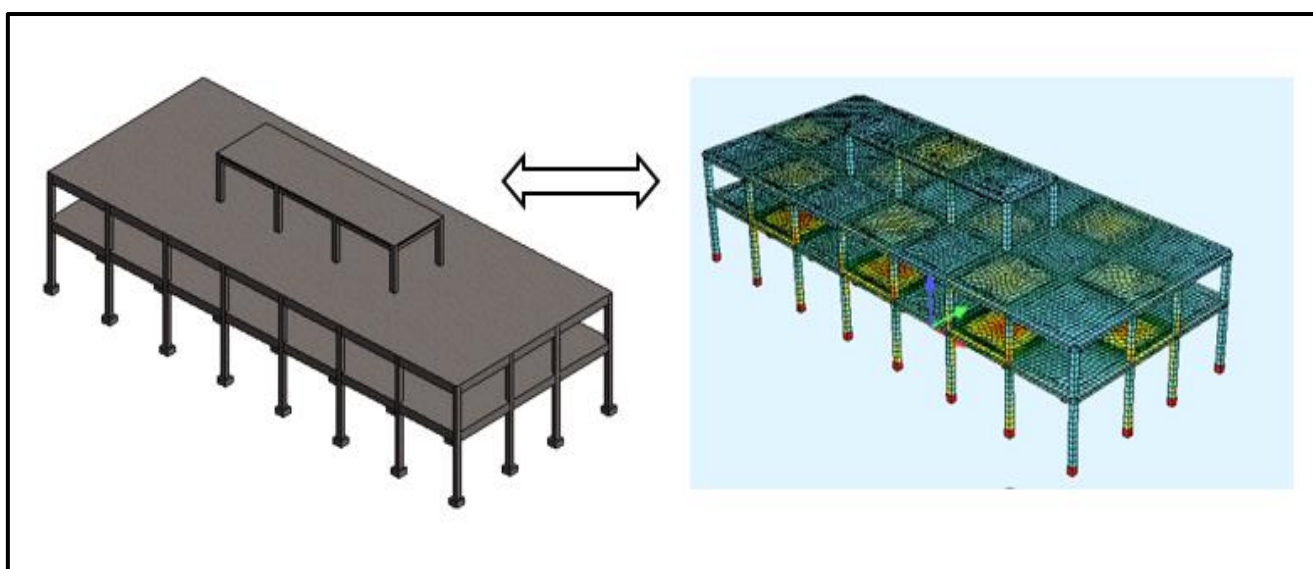
Figure 9: Identical model in both coordination and structural analysis views

Some challenges in coordinating a BIM model are [21]:

- interoperability problems

- elements ownership within a coordinated model--who owns what and from which discipline
- model exchange requirement challenges across participating disciplines
- resources, time, and BIM complexities

Documentation

One of the final stages within structural engineering BIM workflow is to make details, annotations, and schedules of structural members. This is a very challenging task that involves using the results from a 3D model to generate 2D rebar drawings and schedules. SOFiSTiK (a German structural engineering software vendor that provides well-integrated solutions for structural BIM workflow) allows for automatic generation of a 3D rebar from a FEM model through its robust interface with Revit. It gives structural engineers leverage over the design process, and it represents a complete departure from the past where rebars are manually created following FEM analysis. The possibility for engineers to detail, annotate, and schedule structural members from the same design and analysis platform, represents a significant milestone toward the documentation of structural engineering BIM workflow, made possible by Autodesk and SOFiSTiK. Figure 10 illustrates sample documentation and schedules of rebars in the Revit-SOFiSTiK platform.

Figure 10: Sample of rebar documentation in SOFISTIK

Analysis and Design

Analysis and design aspect of BIM Uses is the sole responsibility of a structural engineer or one with appreciable knowledge in a structural engineer or static computation. It is one of the most complex and challenging phases of the structural engineering BIM workflow. It takes a skilled structural engineer to understand the numbers generated, the stresses and deformation of structural members, the behaviour of each structural element in a model, and their relation to each other within a BIM and FEM environment. It would come at a high cost to the project; to allow someone without specialist skills in structural engineering to perform this task because the reliability, safety, and quality of the structure are based on this phase.

However, analysis and design within BIM workflow have greatly improved, thanks to the milestones innovative research and development by FEM software vendors like SOFiSTiK, Dlubal, SCIA Engineer, SAP2000, etc. A few years back, it was almost impossible to achieve a seamless transfer of intelligent model data between mainstream BIM platforms and analysis tools. In Revit and ARCHICAD BIM platforms, exchange of analysis model is possible via IFC link, but in coordination views only. Model exchanged through Coordination views cannot be edited or authored within an analysis software. With the bi-directional link introduced by Autodesk Revit in collaboration with these FEM vendors, it is now possible to create the structural model in Revit, populate it with all relevant structural data, and send such model to analysis and design software. This saves a tremendous amount of time, eliminates the need for manually exchanging different files of the same model or creates a parallel model, and allow designers to share customized objects through the interface. An example of an analysis model in SOFiSTiK is shown in Figure 11.
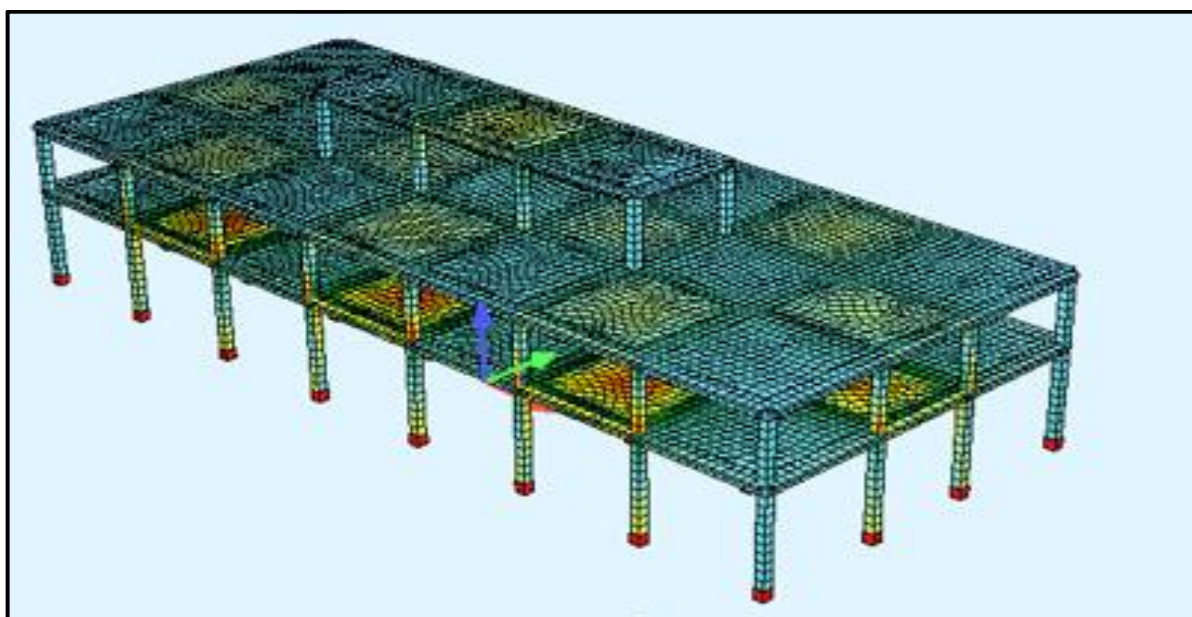
Figure 11: Example of an analysis model in SOFiSTiK

3.2.2   Structural BIM Model

The structural model represents the load-bearing components of a multi-disciplinary BIM model. The structural BIM model contains two parts: the physical structural model and the analytical model. The structural model contains all relevant components that interest a structural engineer within a BIM workflow, such as vertical and lateral load-bearing elements. The non-load-bearing parts of the model are less important to a structural engineer, as far as analysis and design are concerned. Some non-load-bearing components of a building include windows, doors, floor system, MEP and HVAC installations, and ceiling [22]. One main advantage of a 3D-BIM model to a structural engineer is that all relevant information is centrally available in a database.

Physical structural model

The geometry of structural members within a central BIM model is represented by a solid model geometry referred to as a physical model [23]. This model is available When we extract the load-bearing structural components from the central BIM model as a stand-alone model, that is, a model without architectural, mechanical, electrical, and plumbing components [23]. A physical model can also be single-handedly created or initiated by the BIM modeller without the architect being involved. As the physical model is created in the Autodesk Revit BIM platform through the structural template, the analytical element of a building structure, such as analytical beams, braces, columns, floors and walls, are automatically created. Figure 12 shows a physical and an analytical model.
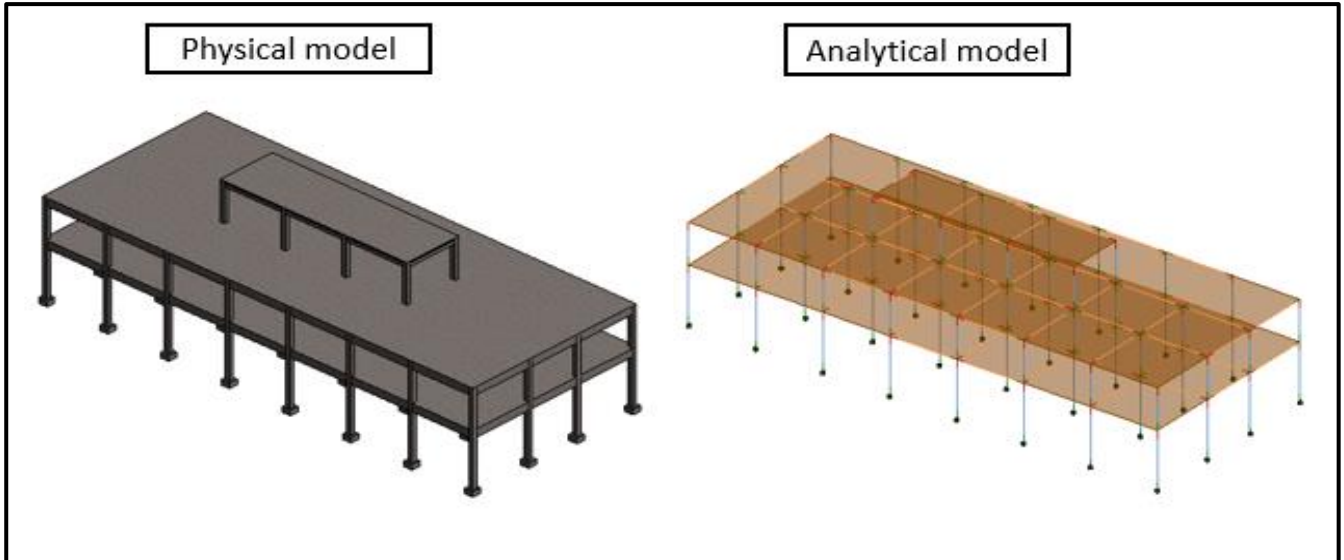
Figure 12: Example of physical and analytical models

Analytical model

As mentioned above, the analytical model is an inherent property of the physical model. This means the analytical model inherits properties like the section, the material properties, and the general geometry from the physical model [24]. The analytical model is automatically generated when creating the physical model in Revit. It is, in other words, a structurally simplified version of the physical model, where load-bearing elements such as columns and slabs are represented by lines, a slab is represented by a surface, etc. (see Figure 13). This model forms the basis for structural calculation, analysis and design during exchange scenarios. In other words, the analytical model facilitates finite element analysis, and it is the transition between BIM and FEM software, without which interoperability is impossible. For example, the bi-direction links between Revit and the FEM programs use the analytical model to perform structural analysis.

Based on the kind of model you wish to create or analysis of interest; Revit provides an option to enable or disable the analytical model while creating the physical model. Boundary conditions and structural loads are added only to the analytical model. Figure 13 shows an analytical model with relevant structural properties, including loads and boundary conditions.
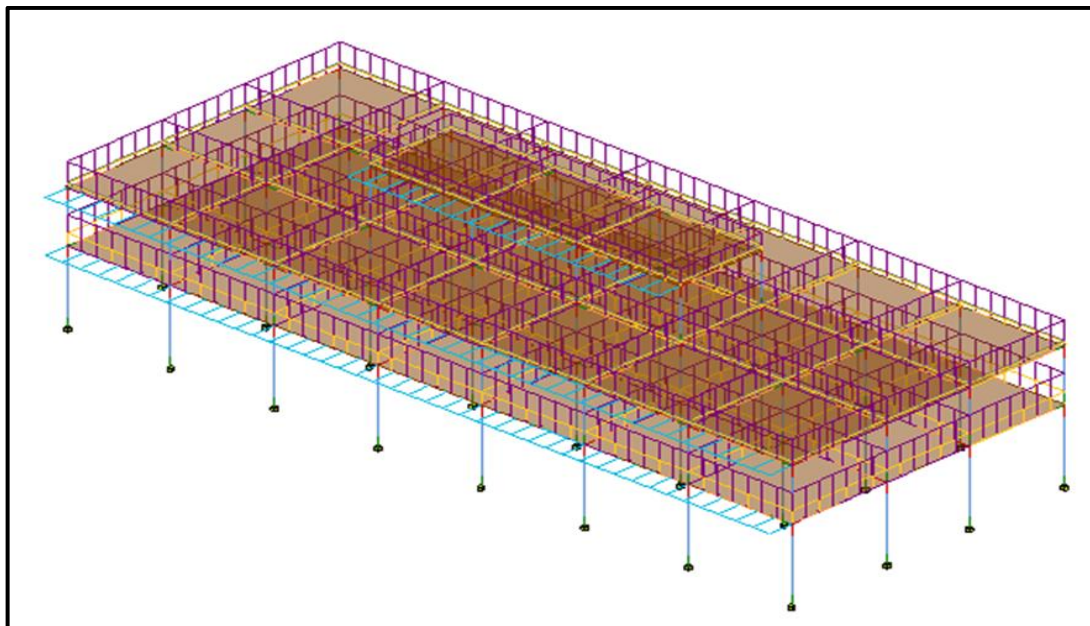
Figure 13: Analytical model with loads and boundary conditions ready for structural analysis

3.2.3   Structural Template

Templates are a starting point for the creation of a BIM model. The Revit software package comes with templates that address the needs of some specialist disciplines within the AEC sector, such as architecture, structural, construction, and MEP (mechanical, electrical and plumbing. These templates activate discipline-specific families, libraries, and views during the modelling process [25]. For example, in the structural discipline view, non-load-bearing elements such as walls, windows, and insulation panels do not show up. The disciple templates use the file extension RTE.

3.3   Structural Engineering BIM Workflow

In this section, we demonstrate the application of BIM in structural engineering by presenting and explaining possible workflow based on literature reviews and current industry practice, which shows how BIM has introduced a novel design methodology which has significantly increase the productivity of structural engineers. A demonstration of how a single central BIM model is round-tripped (see Figure 14) between various specialities within the structural design cycle is discussed below.
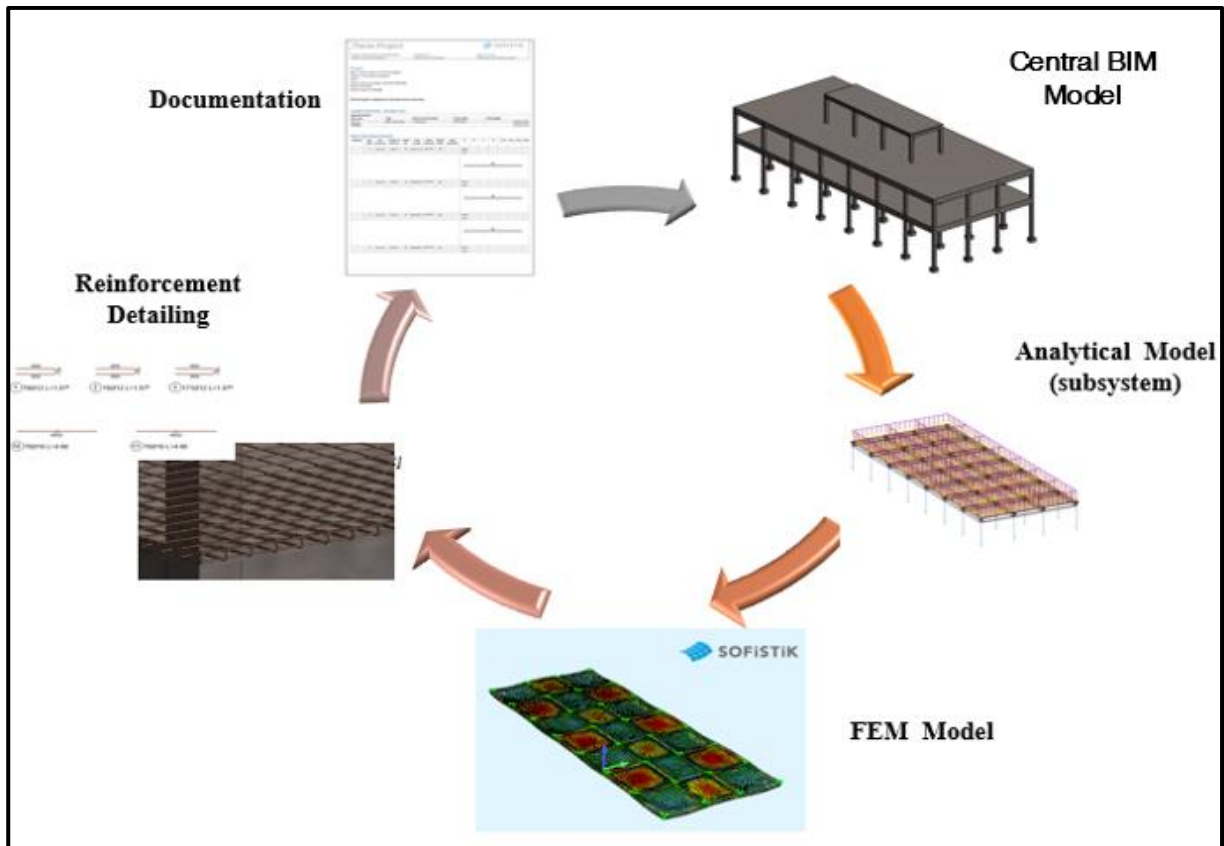
Figure 14: An example of a BIM workflow in Structural engineering design

3.3.1   Central BIM Model

The structural engineering BIM workflow as shown in the above Figure starts the creation of a BIM model. Figures 15 to 16 demonstrate how the BIM model is initiated in Revit by populating it with structural parameters, properties, and metadata. In other words, Revit serves as a medium or platform to centrally create, manage and update BIM model data, as seen in Figure 16, where the material parameters for the column and the load cases and combination are illustrated.

The structural BIM model is usually initiated, created or started by the architect or a BIM modeller, depending on the scope of work. Sometimes, an architect's perception of geometry, member size or material could be completely different from what ought to be for a structural engineer. Hence, enough care is needed when the architect is creating a structural model; for example, architectural levels are usually different from structural levels as well as the settings and templates. Based on the capacity of the firm, sometimes such as Dynamo or Grasshopper (visual scripting environment) can be employed as an innovative method of creating models parametrically to avoid repetition and allow for easy adjustments without having to click individually.

In structural engineering BIM practice, it must be said that there is no specifically defined and mandatory BIM workflow to follow. However, it would be technically prudent if the project team were to create and customize a convenient workflow based on design necessity. Such workflow should be easy to access, follow-through, placed query or audit [26].
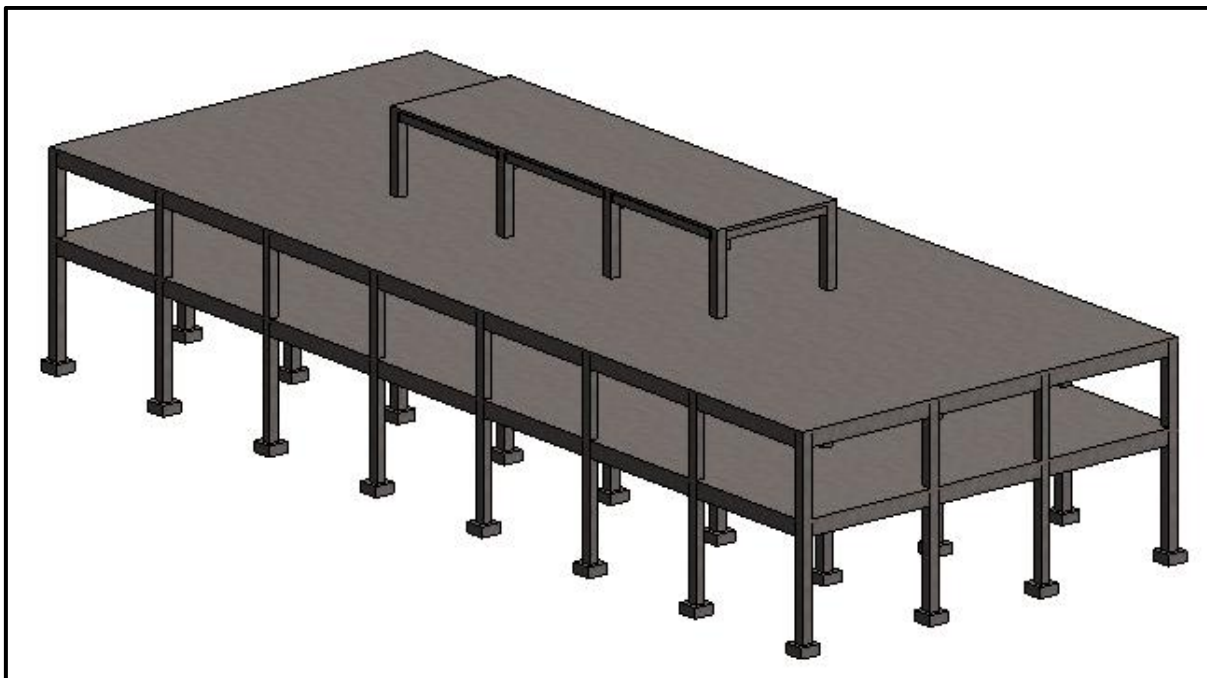
Figure 15: Central BIM model
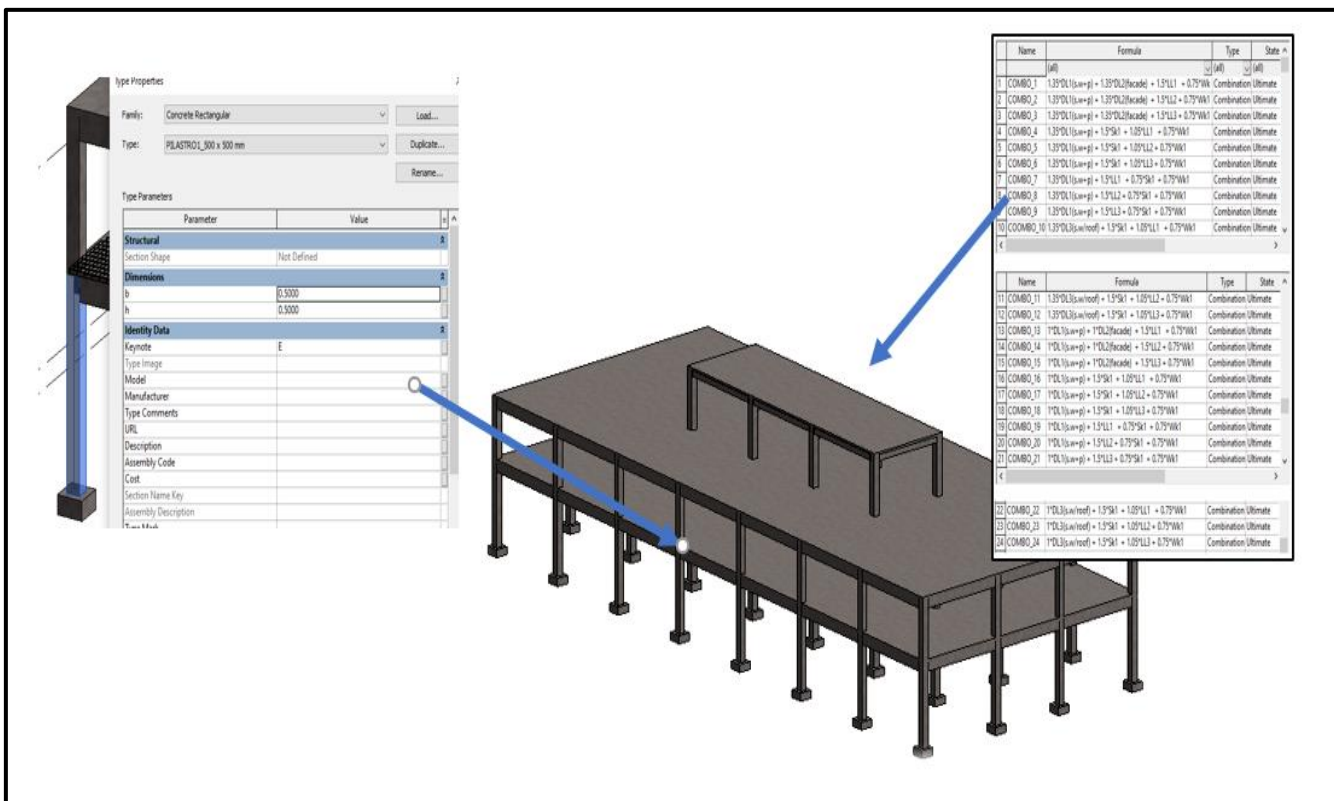
Figure 16: Central BIM model populated with data

3.3.2   Analytical Model

As already mentioned above, the analytical model (see Figure 12 and 13) is inherently connected to the physical model in Revit. It is a sort of model Revit relies on for exchange scenarios when finite element analysis is required. In other words, it serves as a transition between BIM software and Finite element (FEM) software and the medium through which interoperability is facilitated. For example, the bi-

directional link between Revit and FEM programs (SOFiSTiK, Dlubal, etc.) utilizes the analytical model to facilitate structural analysis.

3.3.3 Finite Element Model

Most structural engineering software is based on the principles of the Finite Element Method or FEM. As a user of these software tools, it is very fundamental to understand the underlining principles, mathematics, and mechanics behind the governing equations and how internal forces are computed. Hence, without a deeper understanding of the basic principles behind the computational method of these analysis tools, a critical assessment of computed results is not possible, which might otherwise lead to an unreliable and unsafe design.

In static analysis, the force method, reduction method, and displacement method are the three methods widely employed by structural engineers to investigate internal forces, moments and assess the deformation capacity of structures. FEM software often uses the displacement or deformation method due to its effective computational power in modern computer programs. By utilizing numerical approximation technique, the FEM performance the calculation as follows [27]:

1. Mesh or divide a structure member into several finite elements.
2. Compute stiffness matrix for each element.
3. The loads acting on each finite element is transformed into nodal loads or load vector.
4. Summation of the element stiffness matrix
5. The loads at each node are summed to form a vector of total load for the entire system
6. Support and restraint conditions are then considered in both the total stiffness matrix and total load vector
7. The displacement vectors and internal forces at each node are then determined based on the results of previous steps

When the analytical model is properly cross-checked and ready in Revit, it is then exported to a FEM software connected to Revit for analysis and design purposes. Figure 17 shows how a Finite Element Model looks like in a SOFiSTiK environment, and Figures 18 and 19 show the ribbons that link a Revit model to a SOFiSTiK analysis environment. It is also possible in SOFiSTiK to generate subsystem for separate analysis such as a slab of a particular level, columns, portion of a frame, etc.
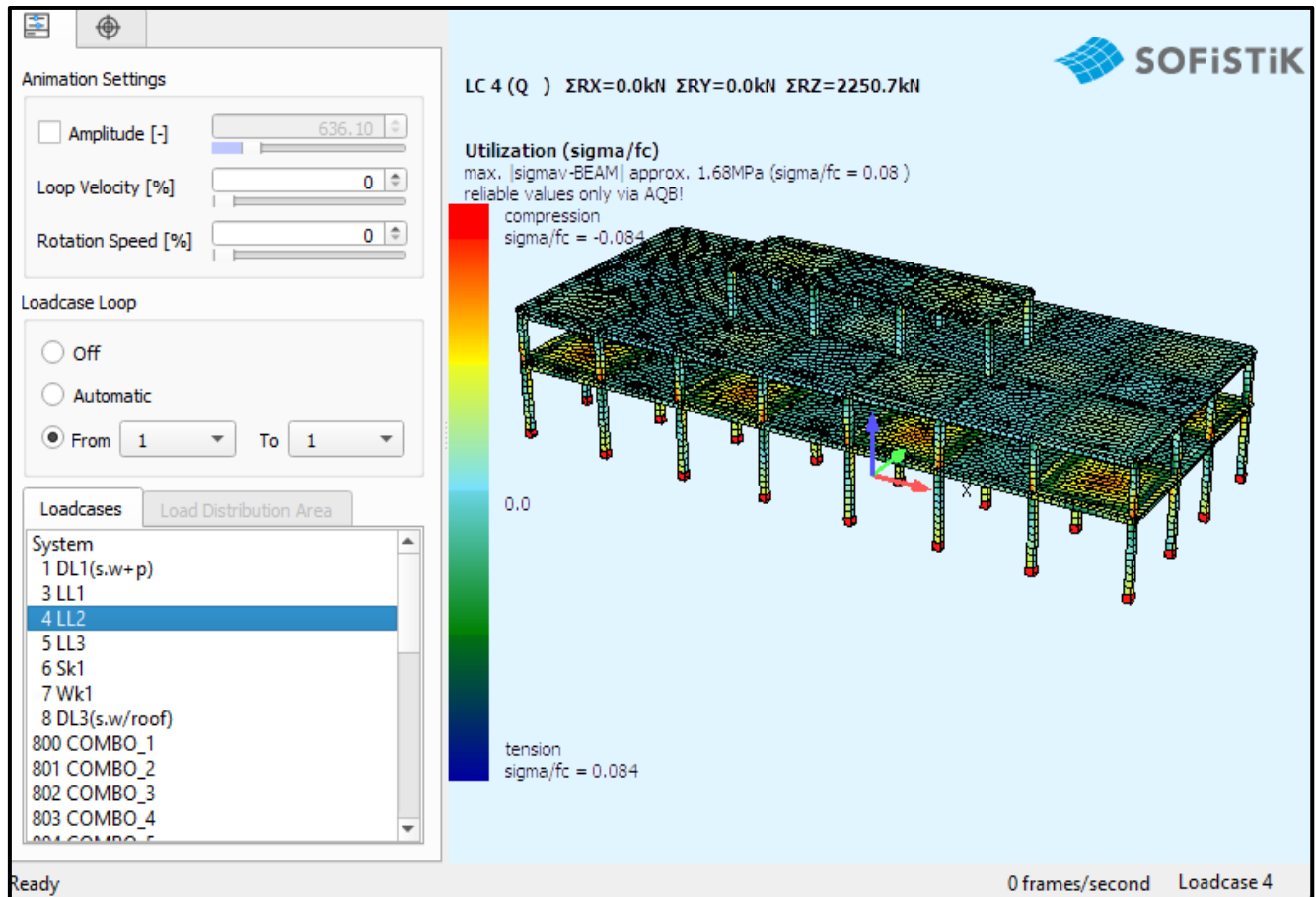
Figure 17: FEM model generated by the case study
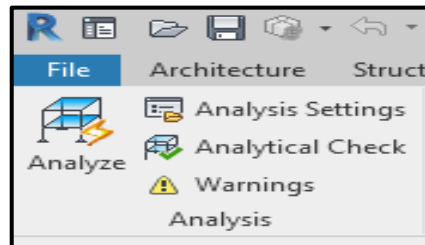
Figure 18: Analyse ribbon in Revit SOFiSTiK interface
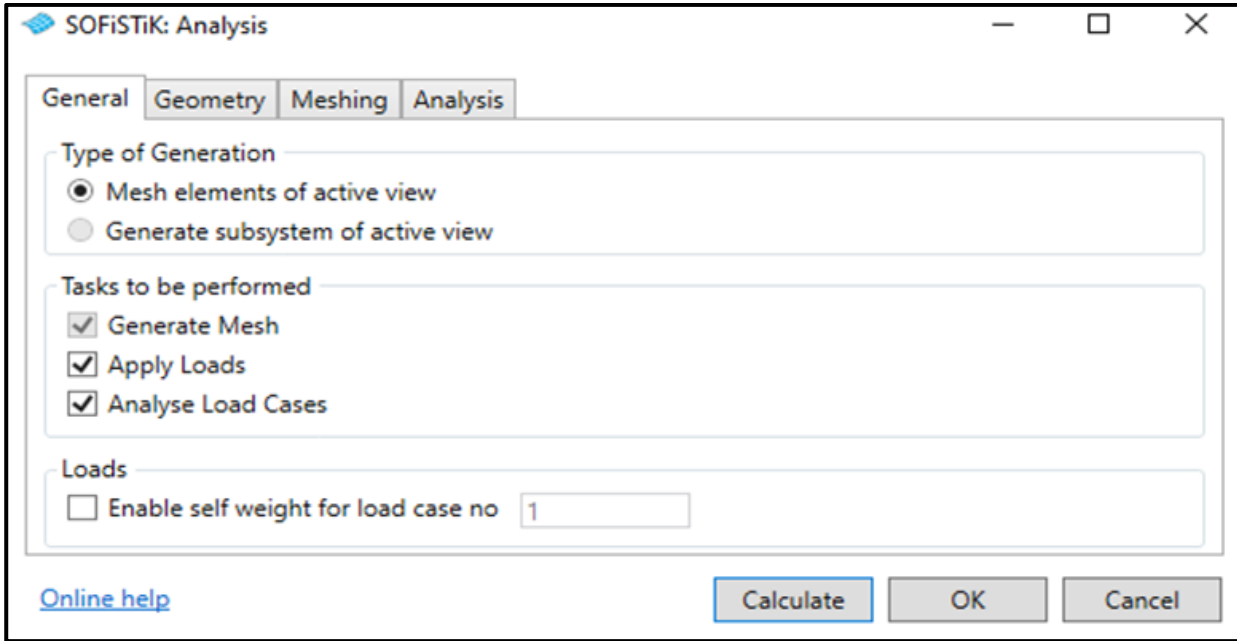
Figure 19: Analysis setting in SOFiSTiK

3.3.4   Reinforcement Detailing

BIM application has made it possible for structural engineering to visualize the reinforcement layout, locations, spacing and identify conflicts. This level of BIM Use has greatly enhanced structural engineers design performance, saves time, minimizes errors and rework. It is also possible for engineers to visualize and adjust the reinforcement model based on existing reinforcement and required reinforcement. In SOFiSTiK, for example, based on analysis and design results, one can automatically generate a 3D rebar model and use it to obtain a 2D reinforcement plan. As an example, Figure 20 shows a 3D rebar model generated for the slab in one of the case studies; from this 3D rebar model, it was possible to obtain a 2D reinforcement plan, as seen in Figure 21. Figure 22 shows the window in SOFISTIK where reinforcement parameters are controlled.
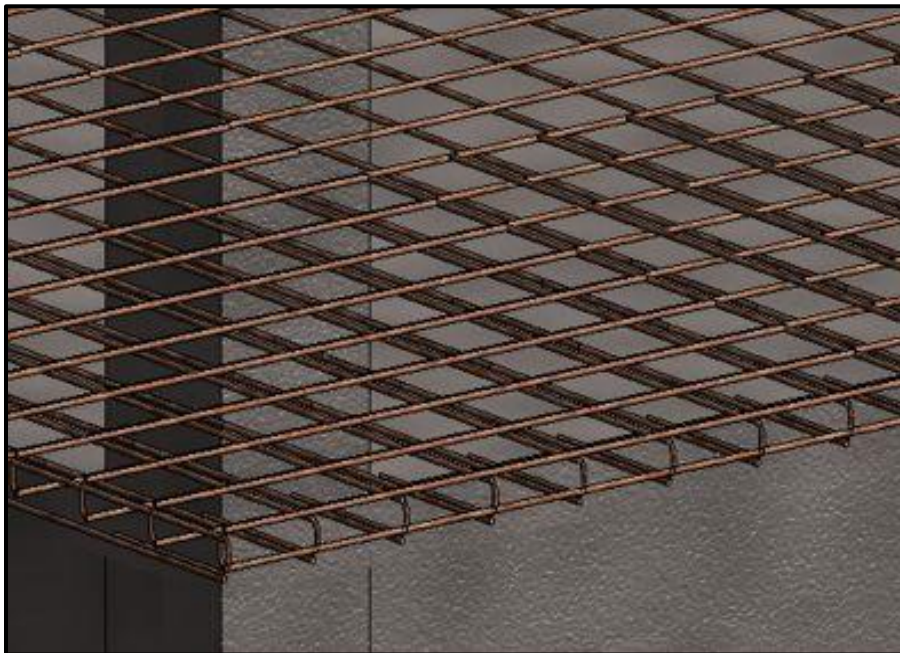
Figure 20: An example of a 3D rebar model
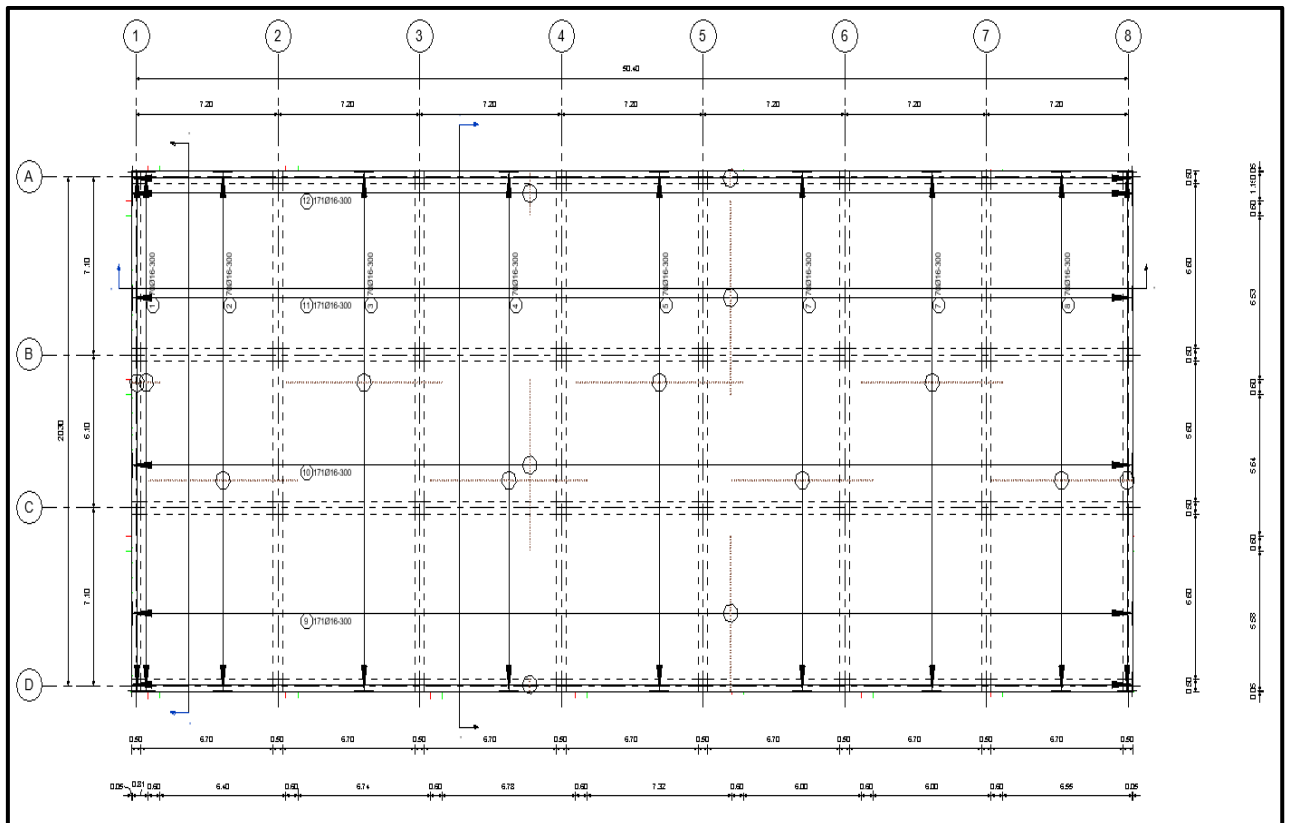
Figure 21: An example of a 2D rebar detail plan extracted from 3D rebar model
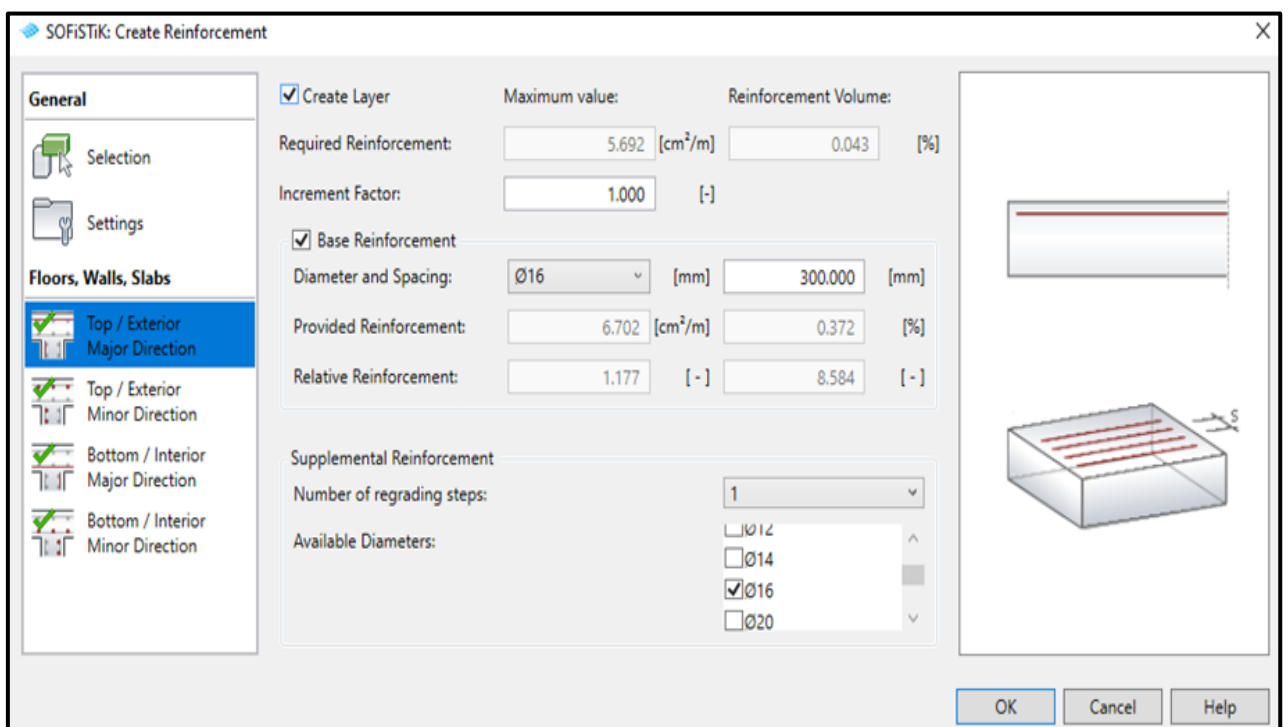
Figure 22: Window in SOFiSTiK reinforcement generation where reinforcement parameters are controlled

3.3.5   Documentation

After analysis and design, detailing and scheduling structural members are the final stages of a structural engineer's task in a BIM workflow. The innovative approach to documenting and creating quantity or material schedules available within the Revit-SOFiSTiK environment gives structural engineers

leverage over the design process; it represents a complete departure from the past. Being able to detail, annotate, and schedule structural members from the same design and analysis platform is one of the milestone contributions made by Autodesk and SOFiSTiK toward the documentation of BIM workflow. SOFiSTiK provides several ways to document and report reinforcing schedules, such as word OpenXML (.docx) document, report browser (.plb), or Revit schedule and quantity toolbar. See Appendix 1 for full detail on documentation and scheduling of rebars.

3.3.6   AutoConverter: an innovative tool for BIM workflow

For structural engineering companies implementing BIM projects, either of the two cases is imminently possible in their workflows [28]:

A) A client sends a physical model to an engineering company for analysis or/and design purposes.
B) A client places a request to an engineering company for a complete structural engineering BIM-based project that involves creating a physical model from scratch and performing analysis or/and design.

Each of the above cases comes with drawbacks that affect the BIM workflow, some of which are [28] (cite): time; collaboration; a non-engineer creating an analysis model that requires somewhat complicated engineering details; misalignment of elements (structural members not in the same plane, eccentrically misplaced or wrongly connected); complex structures are demanding—required a different set of models in some cases; inconsistencies between the physical and analysis model of the same BIM workflow; etc.

It is technically obvious that some optimizations and innovations are needed to enhance structural engineers' performance in a BIM workflow. Hence, on account of these, a key industry competitor, SCIA Engineers, launched the innovative AutoConverter in June 2020 to improve the workflow in cases A and B; by taking any structural model and automatically cleaning it for analysis and design purposes. See the example in Figure 23 how the AutoConverter corrects misaligned elements in a structural model and transformed them into a clean analysis model. A link to the AutoConverter: (https://www.scia.net/en/software/scia-autoconverter/key-features).

(1)   (2)   (3)
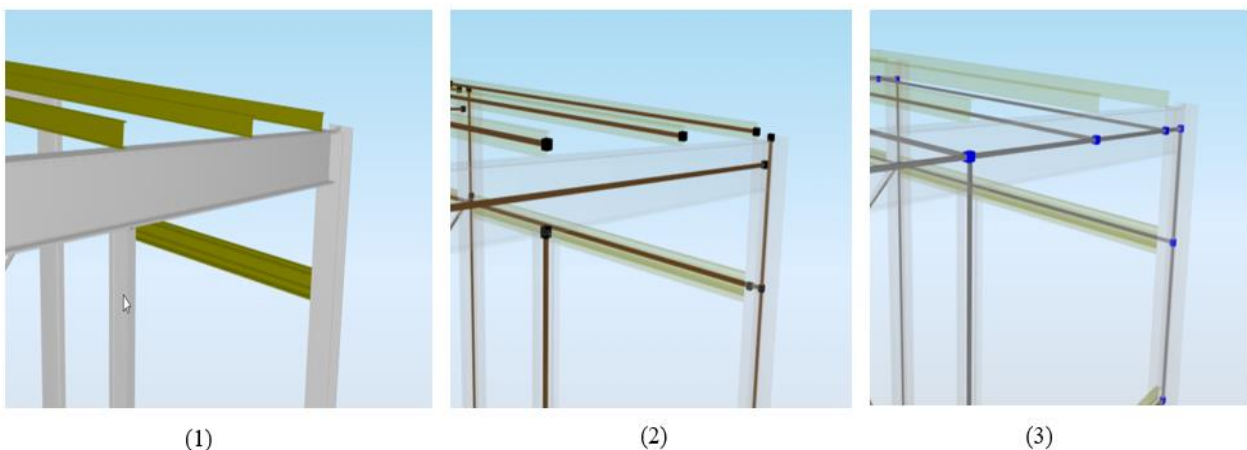
Figure 23: An example of how AutoConverter automatically corrects a faulted structural model: (1) Structural model (purlins on top of the rafters); (2) Transferred analysis model (structural elements purlins and rafters not in same plane); (3) Aligned analysis model (purlins and rafters moved to same plane) [28]

3.4 Structural Engineering Business Process Modelling

3.4.1 Process maps

A process map uses the graphical-based language (diagrams) of a Business Process Model and Notation (BPMN) procedures to show how the workflow of Building Information Modelling is executed, managed; and how information is exchanged among project team members.

Through a graphical communication plan, questions regarding what task is to be performed, who is responsible, what tool is employed in executing such task, and what sequence; is mapped and outlined. There are several process maps proposed by researchers showing traditional structural engineering design workflow for both without BIM implementation and for when BIM is introduced in a company [2][29]. Based on these process maps and the experience gained from the case studies of this thesis, a further suggestion or improvement to these process maps in BIM structural engineering is proposed.

Figure 24 shows a process map in a company without the implementation of BIM in structural design [2]. As seen in Figure 25, the author provides a modification to the process map of Figure 24; this new map shows the introduction of BIM workflow in a structural design process.
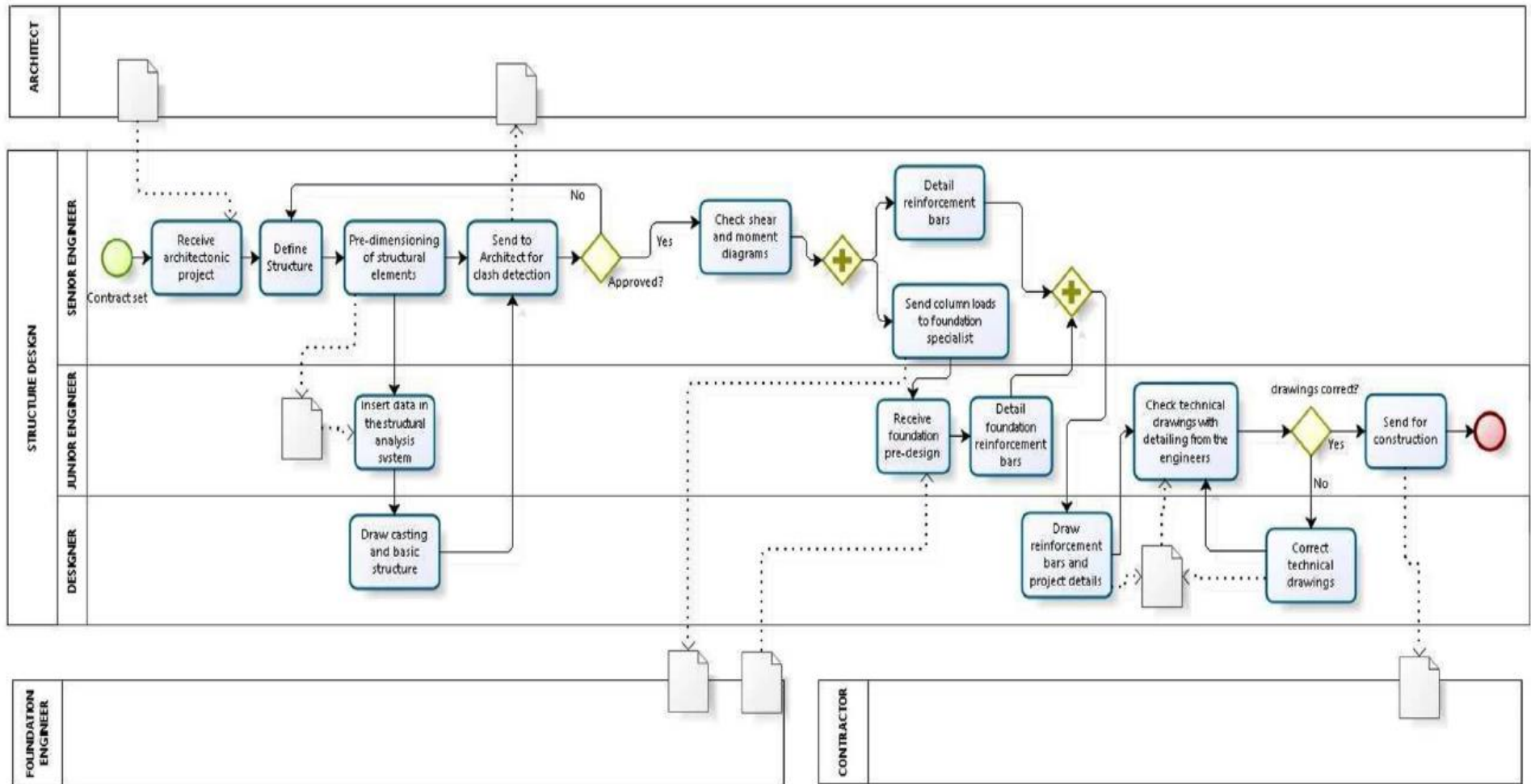
Figure 24: Process map without BIM in structural design company [2]
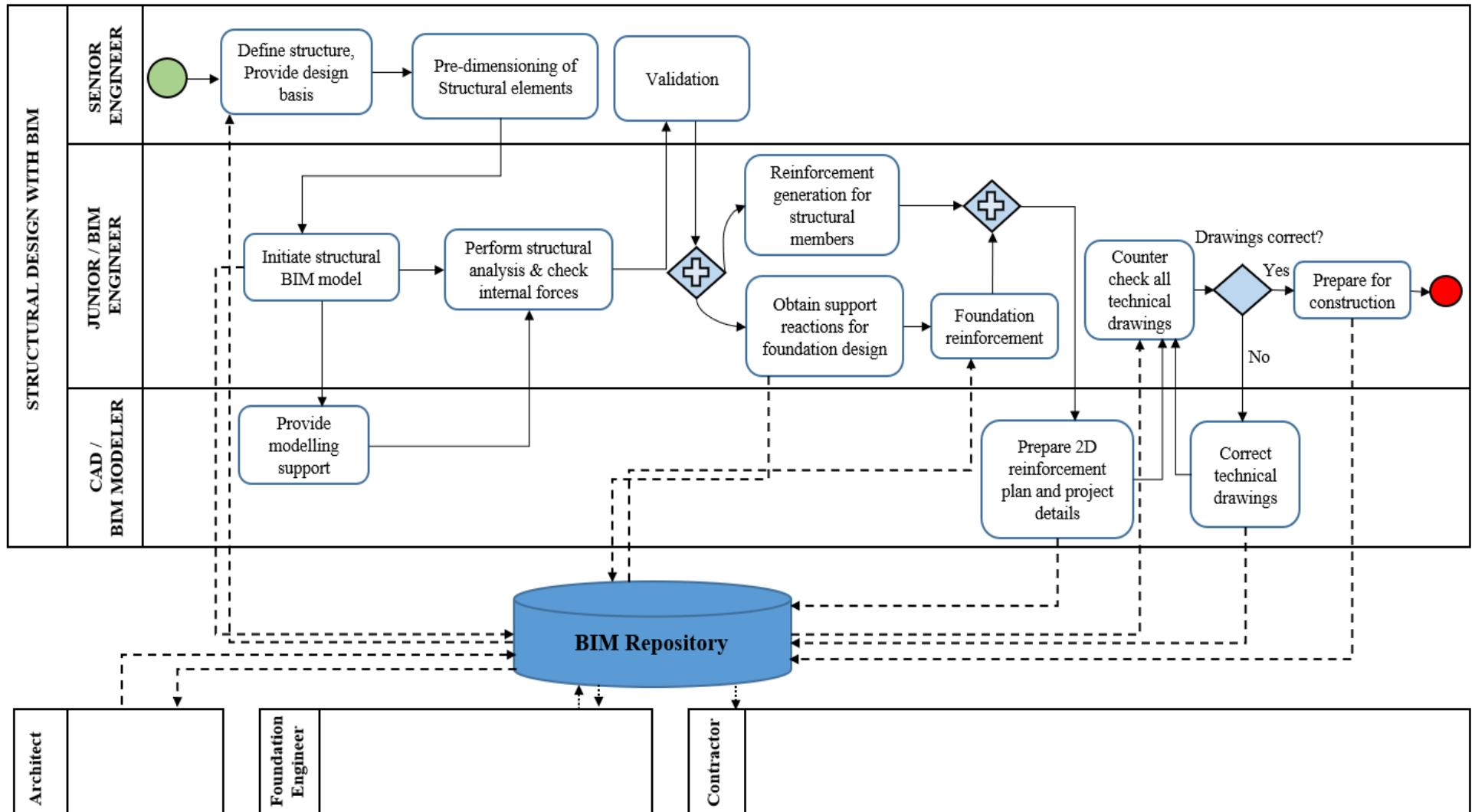
Figure 25: Modified process map when BIM is implemented in structural design (source: author)

3.5   Benefits of BIM in Structural Engineering

The application of BIM in structural engineering is making a tremendous impact in an industry that, until recently, heavily relies on traditional design workflow. Today structural engineering software solution providers are taking advantage of the breakthrough in technological advancement to enhance their workflow. BIM is transforming how structural design teams work together seamlessly to produce optimal solutions for small and large-scale projects.

Applying BIM in structural engineering means structural engineers are creating an easily verifiable accurate model, which allows for the extraction of material or quantity schedules for procurement or bidding purposes to be just a matter of few clicks. Hence, Productivity, coordination and data consistency, visualization and model simulation, and documentation; are identified as the main potential benefits gained when BIM is implemented in structural engineering [30]. Quantity or material take-offs is considered as one of the hidden benefits as well. In the below section, some of the most important benefits of BIM in structural engineering is discussed.

Productivity

BIM is already working and helping engineers to increase productivity and efficiency. Considering the wave at which the adoption of BIM by companies is moving, there is sufficient evidence to support the fact that BIM implementation brings more advantages than disadvantages to companies. Producing a 2D construction document is labour-intensive and time-consuming for a structural engineer [31]. The fact that BIM allows a structural engineer to automate this process significantly increases his productivity.

Well-integrated BIM structural engineering software programs now enable instant reinforcement generation upon the design of structural members. This gives the designer or detailer much flexibility to detail structural members according to his needs and code provisions.

All BIM software come with discipline-specific object libraries and capacities; this gives users the flexibility to have a more standardized and customized workflow [32]. Enhanced communication facilitated by the application of BIM in large infrastructural project also leads to productivity. This means large capital-intensive projects designed and implemented in different geographical locations can utilize a centralized data-rich model to communicate and meet project goals across varying teams. A proof of how engineering companies are already benefiting from this innovative 3D design methodology is manifested in a McGraw Hill Construction (see Figure 26), which identified project design and construction phases as the two most important phases where the benefits of BIM are very high [30].
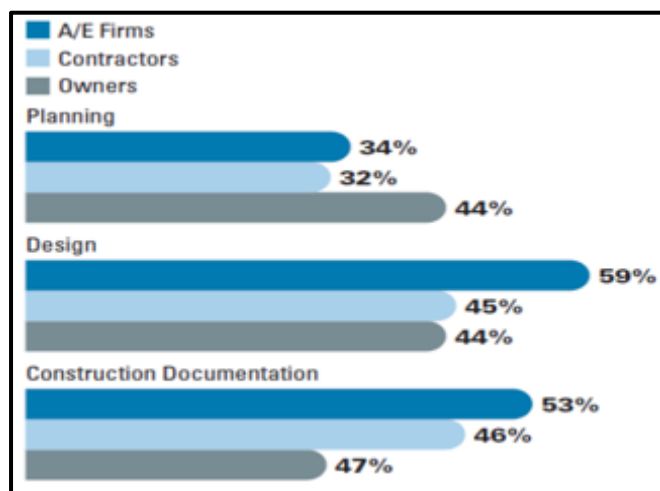
Figure 26: BIM Value according to project phase [30]

Coordination and Consistency of Data

Coordination is one of the key factors encouraging BIM adoption across the industry. It helps project team members such as architects, cost estimators, structural and MEP engineers to share project data using a single prototype model containing all aspects of the building. This way, project stakeholders can effectively coordinate and make reliable design decisions, enabled by accurate 3D geometries and data.

Coordination as a key benefit of BIM is very helpful during conception design; it helps the project team to examine alternative design solutions, review the cost and explore optimized solutions. It is also useful when communicating the intent of the structural engineers to the fabrication and construction team. Lack of coordination in a BIM environment renders BIM adoption irrelevant [33].

Mainstream BIM platforms such as Bentley, Revit, and Tekla, have improved their platforms by not only handling project modelling but also coordinating and documenting results obtained through FEM analysis programs [21]. Figures 27 illustrate data exchange challenges and coordination between a structural engineer and an architect in the absence of a robust digital model workflow, and Figure 28, on the other hand, demonstrates how structural BIM workflow is optimized by reducing the cumbersome repetitions and enabling smooth flow of information. Such level of seamless exchange of data is dealt with in the concept of interoperability, which is one of the main topics of this thesis [34].
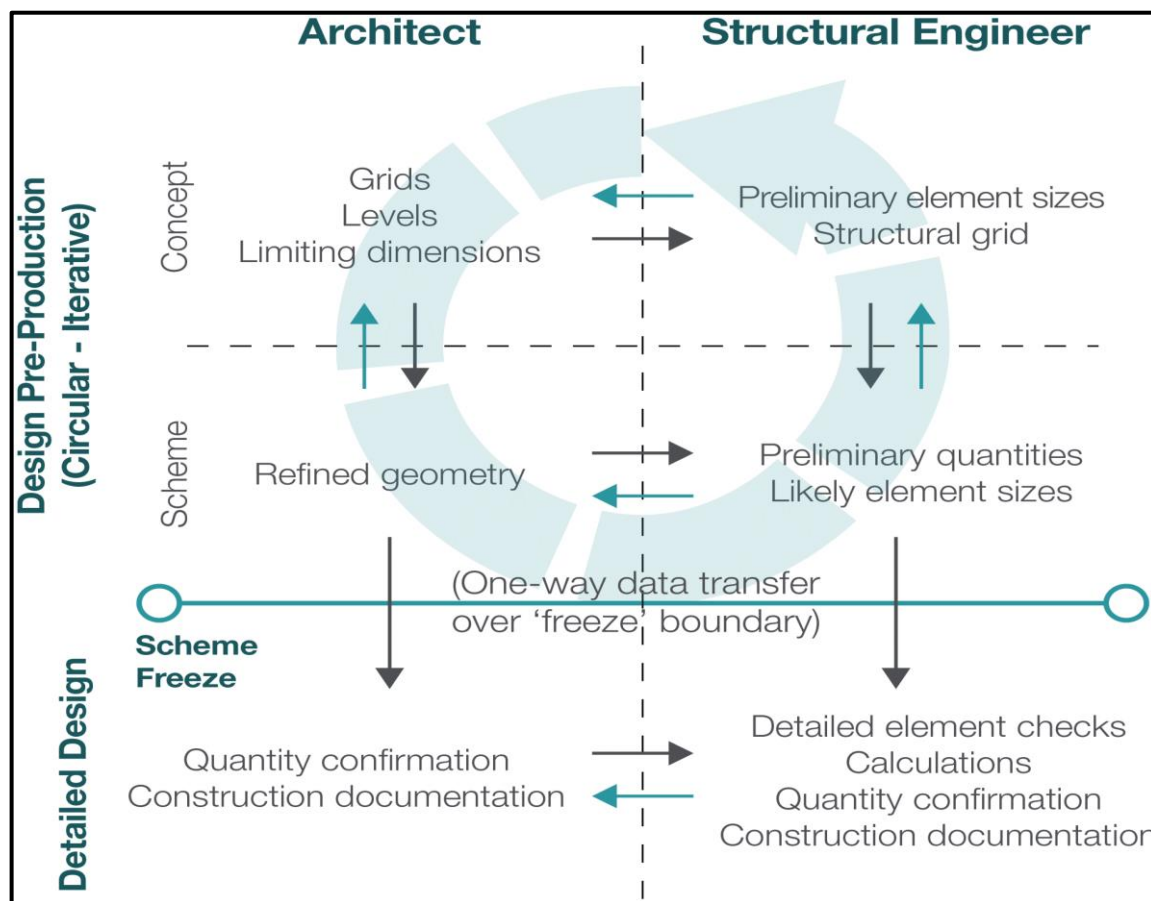
Figure 27: Example of a workflow between a Structural engineer and an architect without a robust workflow [1]
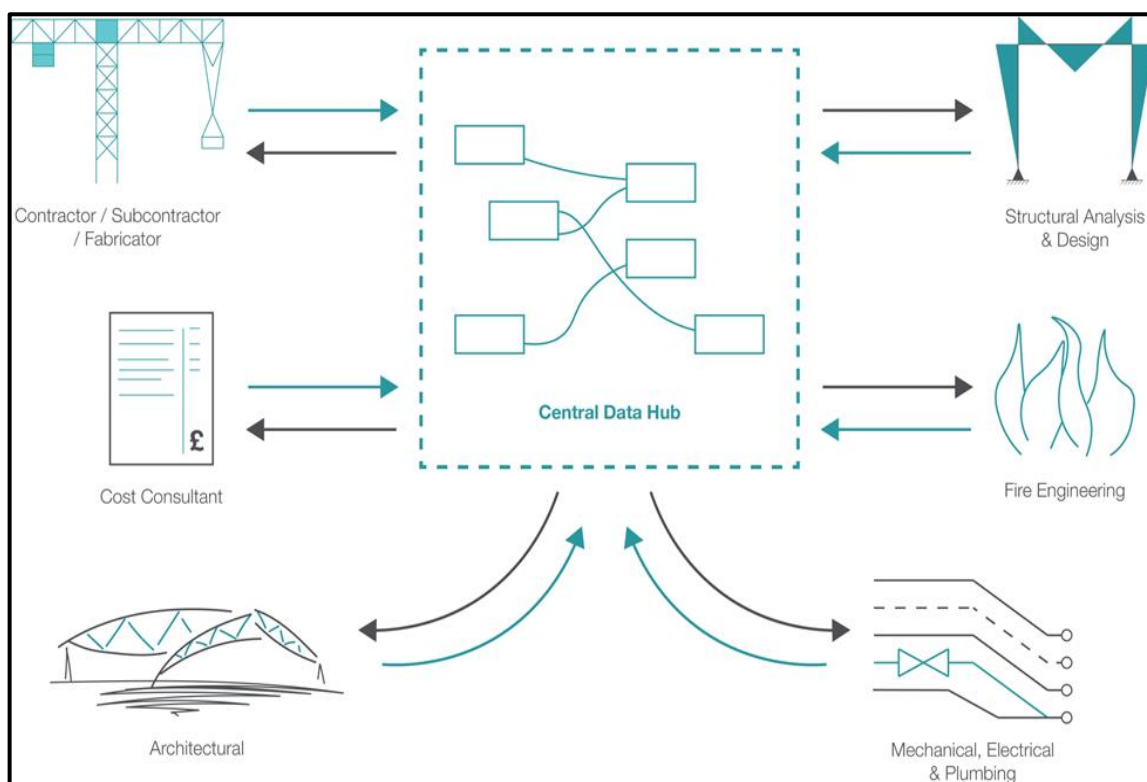
Figure 27: Example of a robust data enabled in a multi-disciplinary project team [1]

Visualization and Simulation

Structural engineers familiar with BIM project can attest to the power of visualization in BIM workflow. For example, with a few click, one can visualize the geometry and position of loads on selected structural elements; this way, the limitations of a model are easily seen, and potential clashes can be detected [32].

A simulated model enables better visualization — it allows the modeller or designer to understand the physical meaning of the behaviour of his/her model and enables a good prediction of its performance; thus, allowing for informed decision-making during analysis and design phases [30]. In the Revit-SOFiSTiK integrated platform, for example, a good simulated model helps to visualize structural behaviour and performance; and quickly offer the opportunity to correct potential deficiencies. Figure 29 demonstrates how I filtered and visualized mistakes in the application of loads in my case study.
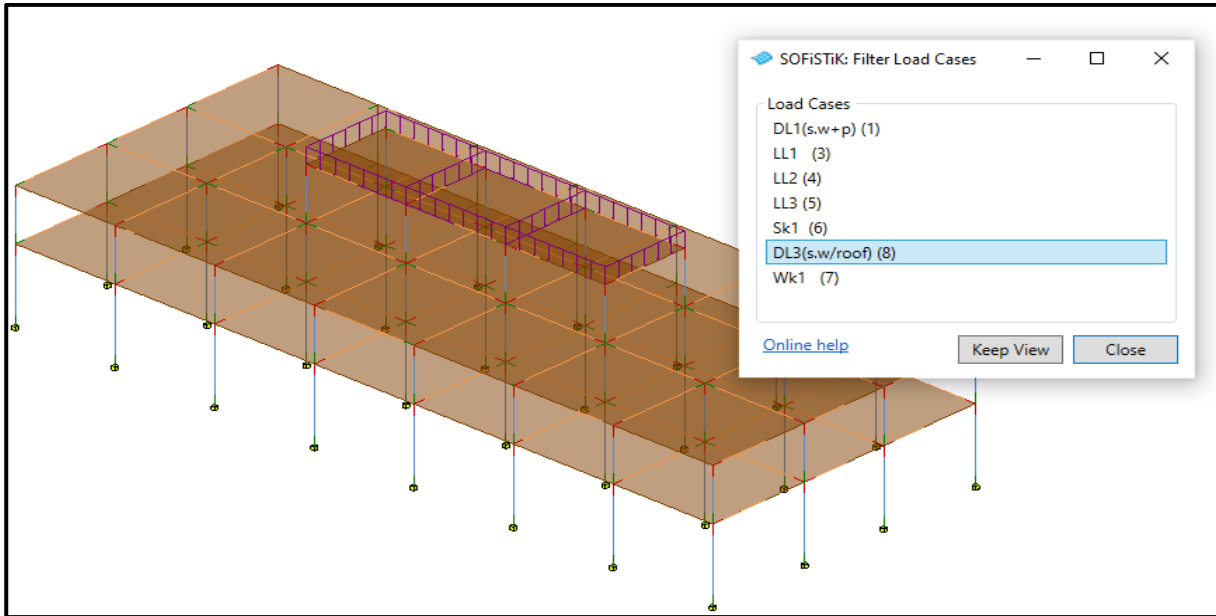
Figure 28: In SOFiSTiK BIM workflow, load can be filtered and visualized

Visualization also helps project designer to correct conflicts in reinforcement detailing and adhere to standard code rules governing structural detailing. As seen in Figure 30, structural engineers can use a 3D reinforcement model to correct potential clashes at Beam-column joint following detailing rules in international codes such as Eurocode 2 and ACI. BIM has shown significant potential in seismic retrofit efforts as well [30]. For example; a scanned model of a structure can be created and analysed in order to enhance structural diagnostic and retrofits efforts; all this is made possible due to the power of visualization and simulation.
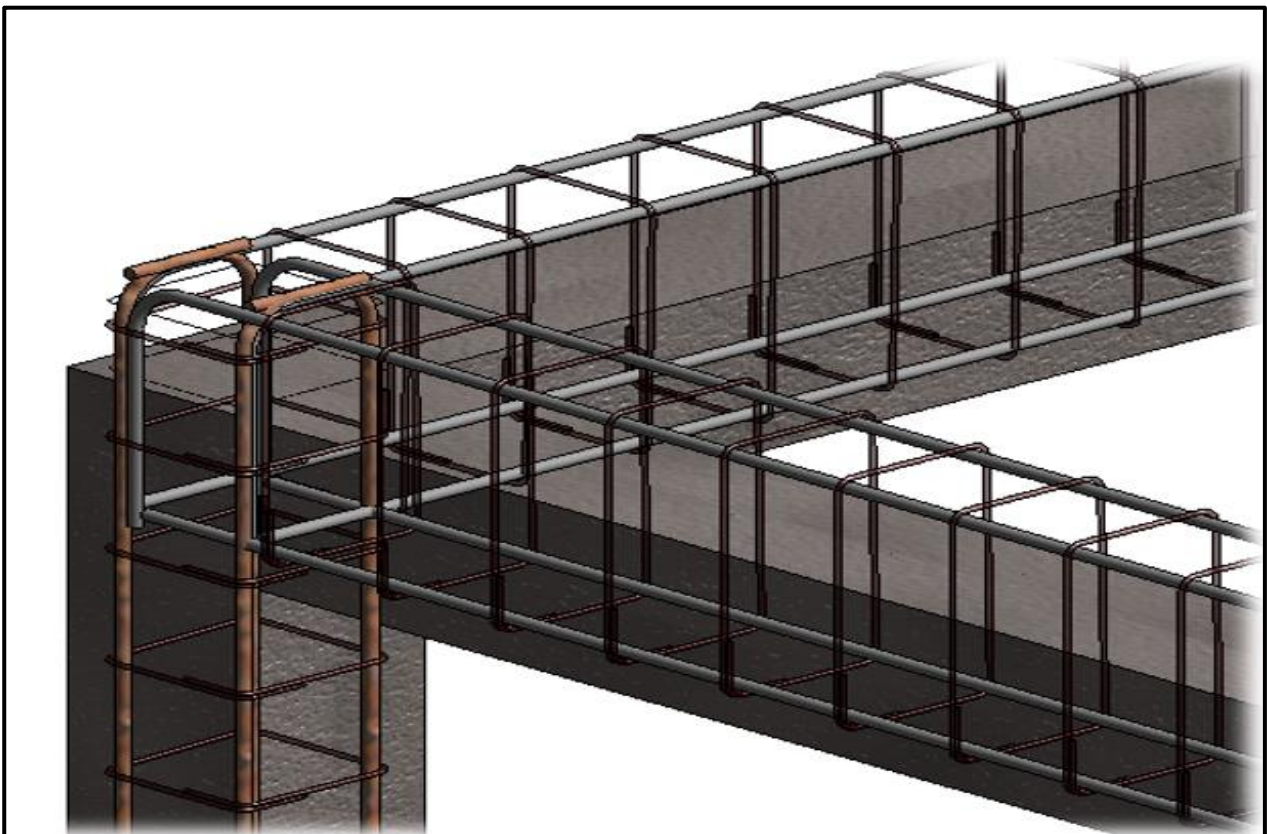
Figure 29: Potential clashes in Beam-Column joint can be easily detected and modified based on provisions in national codes and standards regarding anchorage, lap length, and spacing

Documentation

BIM allows for integrated documentation of structural analysis and design results. With the integration between BIM and structural engineering software, you can design a structural member in a FEM program and seamlessly export the results back to the BIM tool for detailing, scheduling and quantity take-off of the same member, all possible using one platform. The Revit-SOFiSTiK link is capable enough to handle such a seamless exchange of data without creating any parallel file.

Analytical Model

As mentioned earlier, in BIM software, the analytical model is created parallel to the creation of the physical model. It is the backbone for structural analysis in BIM workflow, and it serves as the transition from BIM software to FEM tool. This transition facilitates direct link interoperability. The bi-directional links between Revit and FEM programs (SOFiSTiK, Dlubal, SAP2000, SCIA Engineer, etc.) utilizes the analytical model to facilitate structural analysis. Therefore, the benefits and impacts of the analytical model on structural engineering BIM workflow are tremendous. Figure 31 shows the analytical model with loads ready to be exported to the FEM software for analysis.
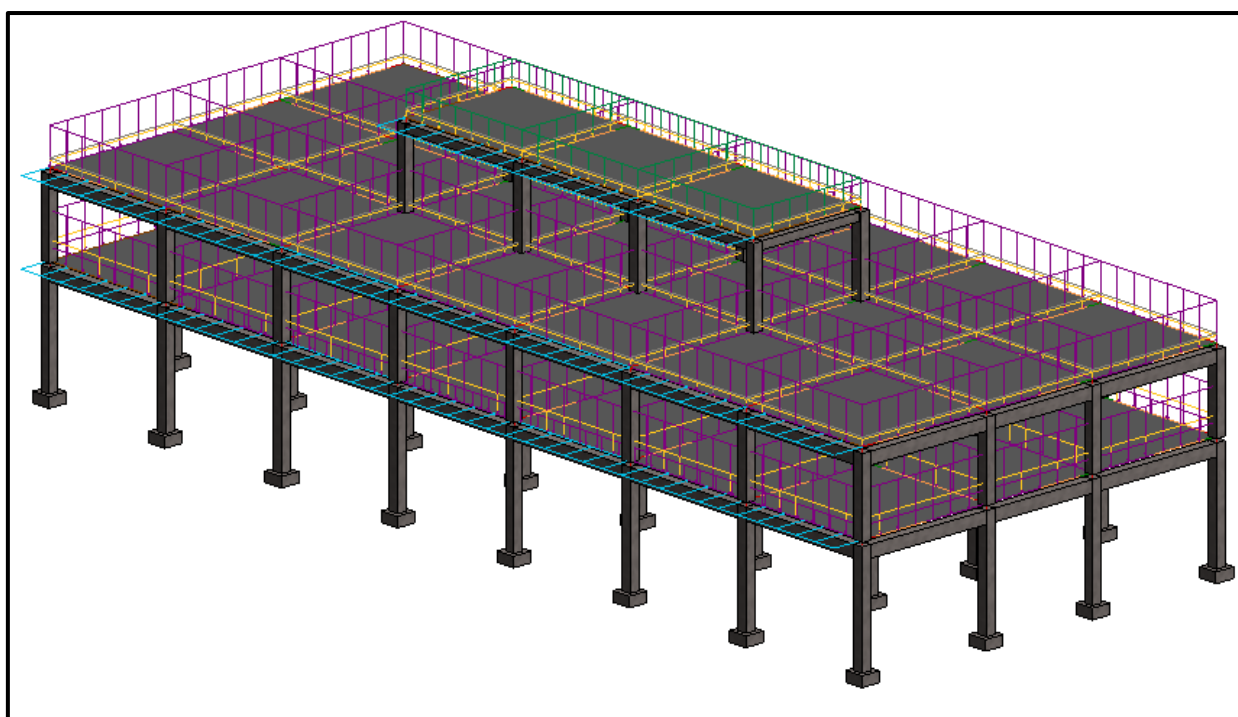
Figure 30: Analytical model with loads

The Rise of Third-Party Developers and Downstream Innovations

BIM has made it possible for third-party developers or downstream digital innovations in the built environment to flourish. These emerging innovations are moving parallel to BIM adoptions and have created vistas of opportunities and benefits, thereby improving the ways structural engineering offices perform complex design and analysis. Tasks that once take countless hours with multi-stakeholders' involvement can now be accomplished in less than a few hours with fewer people. Some examples of downstream technologies that are greatly benefiting structural engineers: Using Dynamo in parallel with Revit or applying grasshopper to create BIM model with complex geometry; application of Autodesk Revit Refinery Beta for generative design workflow, which aims to create design options and optimization to achieve better design solution; utilizing Dynamo- SOFiSTiK Add-in to create complex bridge geometry; SCIA engineer's newly-introduced auto-converter which automatically refines and analyses structures for computation.

3.6   Challenges

While the adoption of BIM presents good opportunities for structural engineering solution providers to grow and enhance their productivities, there are also a few challenges that cannot be ignored. Some of these challenges are discussed below briefly.

Time and Resources

BIM is an approach; to reap its key benefits requires a series of methodologies and procedures. It requires time and considerable investment in resources. Hence, rather than automatically subjecting the entire company's workflow to a BIM process, most companies prefer to do it gradually but; yet strategically on a small-scale basis.

Structural Engineering is Challenging

A good structural engineering BIM model requires that the modeller has appropriate knowledge or experience in structural engineering, particularly having a good grasp of the basic concepts behind structural engineering data like materials, cross-section, loads, stresses and deformations. This will enable him/her to consider structural-specific aspects at the very early phase of creating the model. But in reality, this is not always the case in the traditional planning process where the structural engineer will have to rely on the model provided him/her by the draftsman, BIM modeller or architect. A structural engineer, for example, can easily detect a conflict between the slab and columns in Revit even before seeing the analytical model or performing clash detection. Therefore, the involvement of a structural engineer in the conceptual and planning phases helps to minimize, to a great extent, future challenges in the BIM workflow [35].

Constant Modifications

BIM software solution providers often update their software settings, adding new interfaces and commands; based on trends in the industry. This constant modification means that structural engineering teams have to be on the look for updates and trends. When a company's workflow is on a smooth and comfortable course with a particular Revit version, a new client could be demanding that they switch to ArchiCAD or Tekla because it suits that client's workflow. Also, compatibility issues of various versions and getting analysis links to work are still present [21].

Interdisciplinary Knowledge is Required

The intelligent model-based process is very demanding; it requires a lot of knowledge and a high level of technical skills in both structural engineering and computer programming. The advent of new accompanying technologies makes the learning curve even steeper for engineers. Before BIM, structural engineers would only concern themselves with improving their skills in analysis tools. In the age of increasing technologies and innovations, this is no longer the case as modern engineers are now expected to have basic knowledge in most of the accompanying technologies to remain competitive. Tools like Dynamo, Rhino Grasshopper, and other downstream BIM platforms; are just a few examples.

Analysis Links

There are still some difficulties regarding exchange scenarios between BIM and structural analysis tools. The prospect of realistic data exchange between Revit and some FEM software still requires time and technological advancement to come to full maturity or success. Though a BIM-FEM data exchange works very well in a few programs, as established in this thesis, there still exists a few challenges. For example, in some cases, manual modifications of structural properties with the FEM software (e.g., loads, cross-section, material mapping, etc.) are required for a successful exchange of data to take place.

3.7   Summary

An in-depth overview of the theoretical studies underpinning the application of BIM in structural engineering is provided in this chapter. A discussion of important topics regarding the application of BIM in structural engineering, such as technical implications, BIM workflow, process map, benefits, and some challenges, are discussed.

4   INTEROPERABILITY

4.1   Introduction

BIM's potential benefits are achieved only if appropriate data transfer mechanism between platforms and tools are put in place. The process ensuring that this takes place is called interoperability. Interoperability, as the central theme of this thesis, is examined in detail. In this chapter, a detailed discussion on the three levels of interoperability in BIM structural engineering is presented; the level mostly applicable in structural engineering explained. These interoperability levels are direct native file exchange (exchange between the same commercial software providers), direct link or bi-directional data exchange, and IFC (Industry Foundation Class). Factors contributing to data exchange in structural BIM workflow is provided, and some benefits and challenges of interoperability discussed. Figure 31 graphically defined interoperability, where one system exchanged data with another system and then re-use the exchanged information. Figure 32 in section 3.6 illustrates how interoperability supports robust multi-disciplinary by reducing cumbersome repetitions and enabling integration and seamless flow of information.
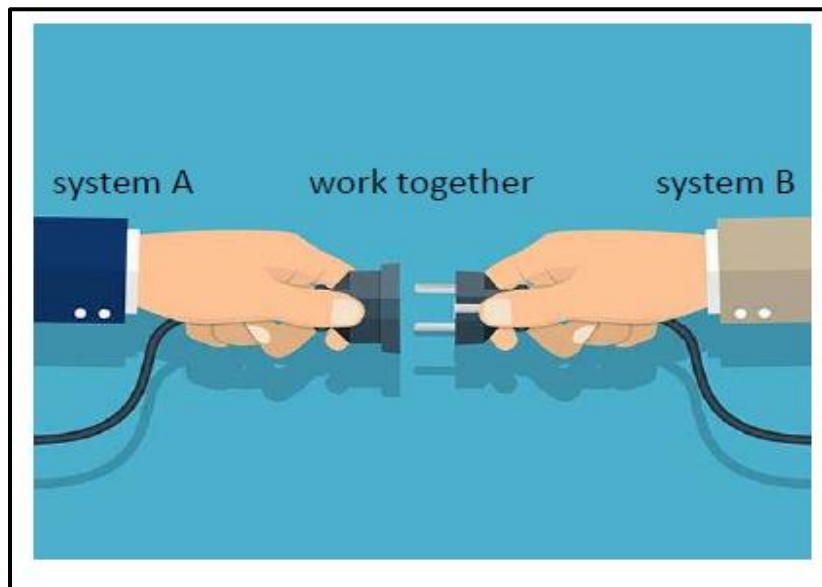
Figure 31: A Graphical representation of Interoperability

4.2   Definition

Building projects often involve many participants, including external consultants with different degree of expertise; these participants often do not use the same software to plan or design their projects. For instance, an architect may use architecture-based software to model the general layout of his/her building's geometry and levels, while a structural engineer, on the other hand, may use specialized software to determine the internal forces of his building. Thus, the need for data exchange from one software package to another is ever-present.

The ISO standard (ISO/IEC 33001:2015) defines interoperability as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" [36]. For structural engineering BIM workflow, this is simply interpreted as the seamless exchange of relevant structural model data between a mainstream BIM platform and a FEM software to enable analysis, design and documentation. For example, when Autodesk Revit seamlessly exchange model data with SOFiSTiK (FEM/structural analysis software) for structural engineering purposes, this is considered interoperability. And interoperability is considered successful when these participating applications' internal data are mapped well [29].

According to studies, data exchange tools, standardization and software technologies are two categories in which interoperability has been classified [20]. In the first classification, the exchange of data or project

information is made possible through software tools. Tools such as Add-ons, stand-alone programs, and plug-in used in BIM-based platforms to enhance interfaces with FEM software are prime examples [20]. Specific examples of structural engineering plug-ins or add-on; having direct links with Revit are SOFiSTiK, Dlubal, SAP2000, SCIA Engineers, etc. The second classification relates to how stakeholders are smoothly sharing important project information in all phases. This level of classification requires an exchange requirement and standard format for data exchange. Typical examples of this category are Model View Definitions (MVDs), Information Delivery Manuals (IDMs), etc.

Due to the high necessity for interoperability in engineering practice in recent times, many structural engineering software solution providers are directing their research in developing strong interoperability links with BIM platforms. Figure 33 illustrates the current existing level of interoperability between some analysis and design software and BIM platforms, where BIM platforms (Tekla Structures, Bentley Structures, and Autodesk Revit Structure) exchange model information with analysis software (in light grey colours) and vice versa.
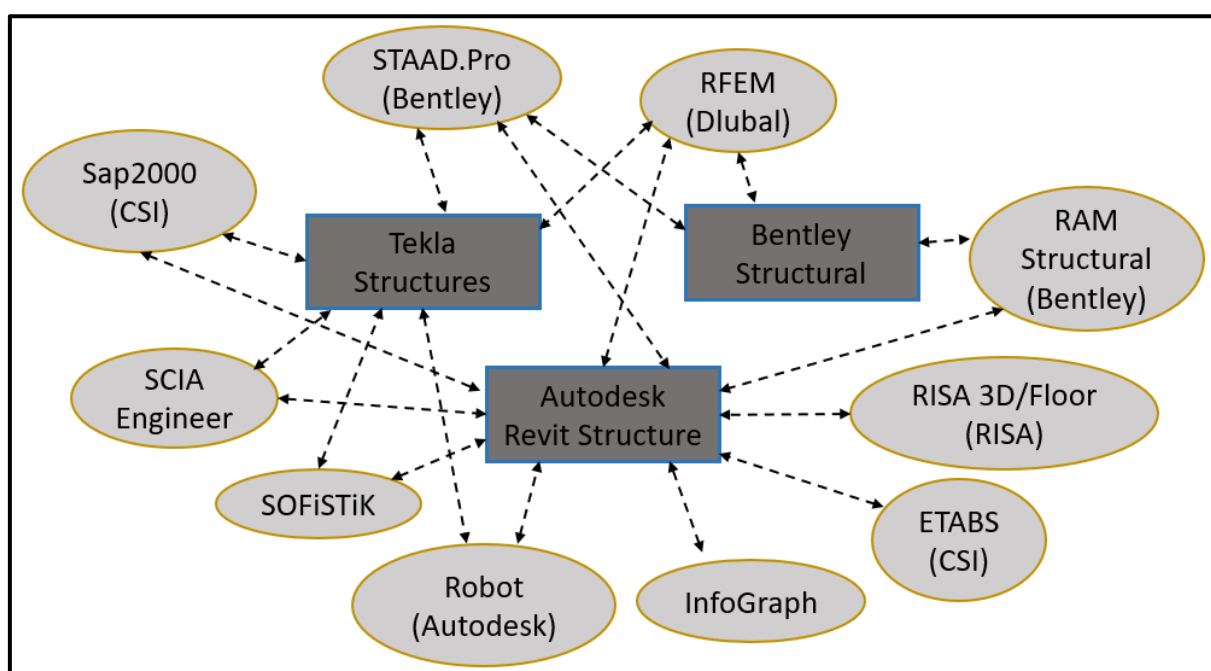
Figure 32: Some currently available interoperability between BIM platforms and analysis and design software (Source: Author)

4.3   General Overview of Interoperability

The topic of interoperability is very diverse. In this section, we take a brief look at some definitions of interoperability discussed by scholars and researchers in the AEC sectors.

4.3.1   The Three Dimensions of Interoperability
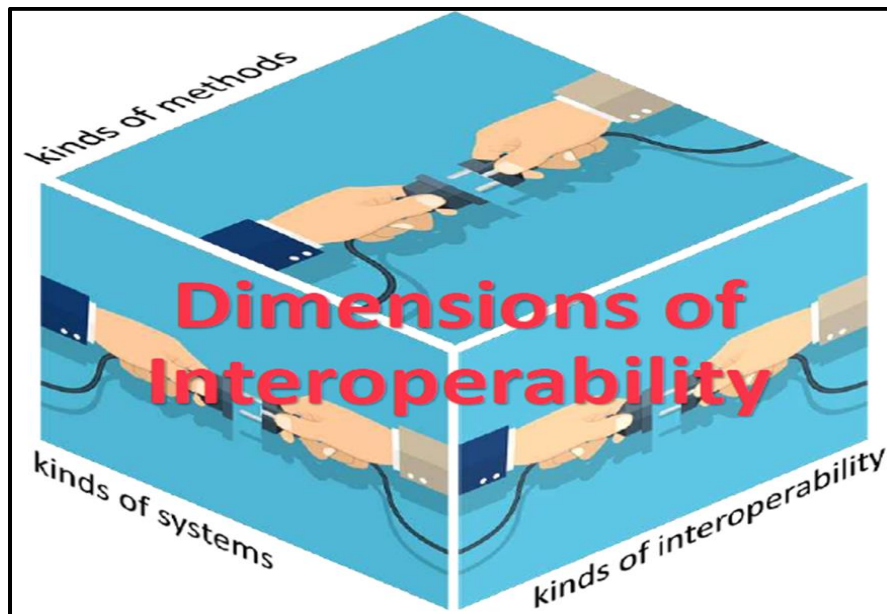
Figure 33: Dimensions of interoperability

The three dimensions of interoperability (see Figure 34) are classified in terms of kind of system, kind of interoperability, and kind of methods. Interoperability based on kind of system divides interoperability into two categories: technical and non-technical interoperability.

Non-technical interoperability is concerned with interoperability taking place within the domain of Business (sharing of information between businesses), organization (exchange of data between various organization units), projects (how projects stakeholders interact), and people (the connection between people).

Technical interoperability deals with information system interoperability (common in the AEC industry). This kind of interoperability is related to semantic (meaningful data exchange), structural (data exchange through models or schema), syntactic (data sharing by way of common format and language), connective (transportation of data due to the connectivity of systems) data exchange. The interoperability dimension due to the kind of method is concerned with openness (open standards and specifications) and machine readability (standards can be read through machines, e.g., XML, LEX, YACC). Others are protocols such as industry standards (based on agreed protocol set by the industry, e.g., PDF, DOCX, IFC, OpenBIM) and standards through international bodies (e.g., ISO-STEP).

4.3.2   Characterization of Interoperability
Different researchers defined ways in which BIM interoperability is characterized based on Value levels of Interoperability and Interoperability concerns [37][29].

Value levels of Interoperability

One of the main values and principles of interoperability is the reusability of shared information. This open data approach facilitates the reuse of shared data assets both at intra and inter-agency levels. Further, a brief overview of some value levels of interoperability is provided below. As shown in Figure 35, five model levels are proposed to characterize the evolution of BIM interoperability [29]. These levels show how much BIM interoperability is essential to companies' competitiveness:

- Communication is the first value level of BIM interoperability. At this level, 3D models are used to visualize the project, which facilitate better project communication.

- Coordination level is the level where coordination view model is used to detect and correct conflicts, and if possible, predict future problems.
- In the third level (cooperation), a full 3D BIM is used to enhance cooperation. This interaction type interoperability enjoys benefits by sharing tasks among project participants. This level does not only increase project efficiency but also saves time and reduces costs [29]. An example of this level is supply chain visibility, where manufacturers and distributors have a platform to share information.
- Collaboration represents the fourth interaction type level. As the name implies, project participants collaborate to reach project goals utilizing innovative solutions.
- The final level, that is, channel, which is Service-oriented architecture (SOA) based, relies on the internet and web as the main medium to communicate and distribute project information [29].
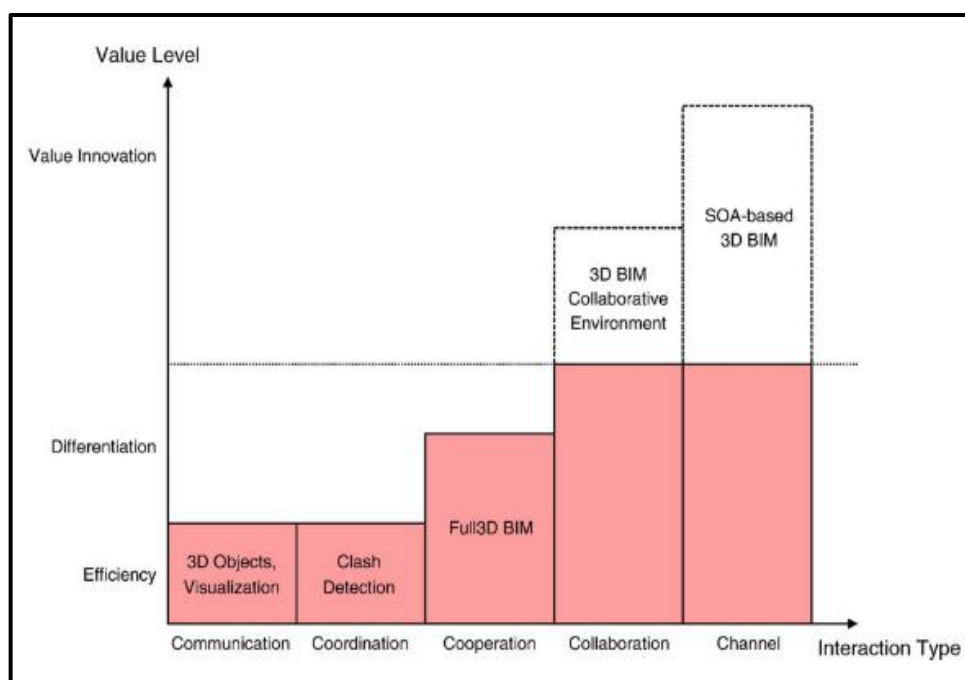
Figure 34: Value level of interoperability for BIM [29]

4.1 Types/Level of Interoperability in BIM Structural Engineering

Interoperability between software tools is achieved through several means or level. In this section, a detailed discussion aimed at answering one of the key questions of this thesis−the Interoperability of data in BIM structural engineering (domain-specific) is presented. The three levels that are most common in structural engineering practice are elaborated. These interoperability levels are direct native file exchange, direct link data exchange, and IFC. These levels address how data exchange scenarios between mainstream BIM platforms and FEM tools are made possible. Direct link interoperability is discussed in more detail since it is the focus of this thesis.

4.1.1 Direct Native File Exchange

The **direct native file exchange** level of interoperability exists between software from the same vendor. It is the most basic level of data exchange available for users to exchange data in their application software [16]. It is based on propriety format; wherein, software applications from the same company allow to exchange data seamlessly. A good number of examples are; data transfer between Microsoft Excel spreadsheet and Microsoft Word document; file exchange between Autodesk and Revit; File exchange between Allplan (Nemetschek) products; sharing of 3D Revit model with Navisworks for clash detection, scheduling, and cost estimation purposes; links between Bentley products (Integrated

Structural Modelling), etc. Some main disadvantages of this kind of exchange method are that the quality of data exchange is often less intelligent compared to direct link, and making changes to the model or data often involved repetitive process. It is also challenging to apply this level when implementing large scale projects that involved several teams and data sources [16].

4.1.2   Direct Link Data Exchange (Bi-direction or Roundtrip Engineering)

This **direct link data exchange or bi-directional** level of interoperability is possible when two software exchange information in real-time. It is considered the most advanced level of data exchange in BIM structural engineering: data is shared between a BIM authoring tool and a FEM software solution [16]. From practical experience coupled with literature review, this method of data exchange is regarded as the most effective and efficient method for BIM structural engineering up to date. Some typical examples of direct link data exchange are as follows: structural data exchange between Revit and FEM software such as SOFiSTiK, RFEM, SAP200, SCIA Engineer (see Figure 36); 'Round-Trip Engineering' between SCIA Engineer and Nemetschek Allplan; Revit and Robot Structural Analysis bi-directional interface; Revit and Tekla interface; Autodesk Revit and Bentley structures; etc.
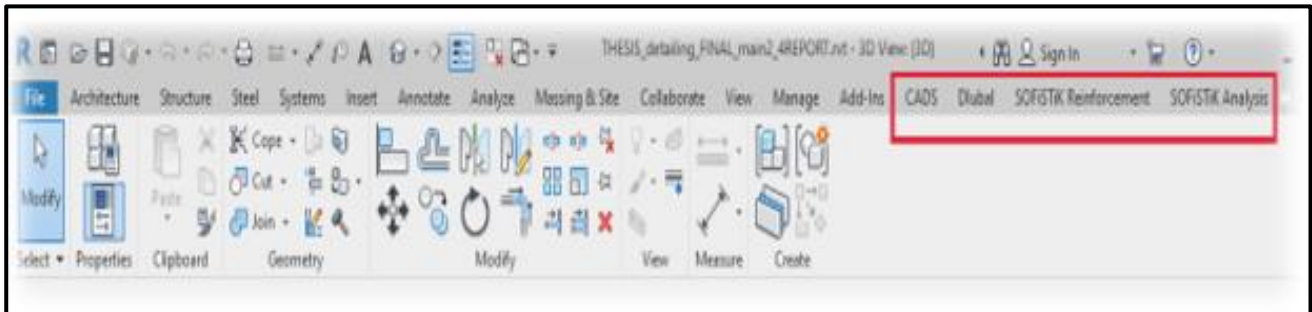
Figure 35: Revit Tab showing direct link add-ins for SOFiSTiK, Dlubal (RFEM) and SCIA Engineer

What makes the direct link powerful is the fact that it provides an interface for two independent software programs to exchange construction data in real-time. How data is transferred is hidden from the user, a complete departure from the file-based system. The way it works is that; a source system (e.g., Autodesk Revit) will provide the information for the operation; and the analysis and design performed, and the results shown in the destination system (e.g., SOFiSTiK or RFEM). Some of its main advantages are faster data exchange and consistency, smooth integration of workflow and avoidance of parallel files, the capability to assess analysis results in BIM authoring tools, and project collaboration. The main disadvantage of this level is that both software solutions are required to be installed on the same computer, which could be a costly venture for small companies.

4.1.3   IFC (Open format)

Figure 36: IFC logo

Industry Foundation Class commonly referred to as IFC, is a primary standard for open BIM data exchange for the built environment. It is an Open, object-oriented, and standardized Product Data Model (schema) for exchanging data in the AEC and Facility management industry. Simply, it is correct to refer to IFC as the pdf of BIM. IFC files can be read by any CAD software with IFC export and import functionalities. In structural engineer BIM workflow, IFC has several limitations in performing structural analysis because of its low capabilities in transferring important structural data; hence, it is mainly used for coordination purposes.

The IFC, launched in 1995, came about to correct interoperability challenges faced by built-environment professionals [38]. Figures 37 and 38 illustrate the IFC logo and the historical timelines of IFC formats development, respectively. Below is a brief description of the current available IFC formats or schema release in order, starting from the most recent version to the older version [39]:

- **IFC4.3 (**current status- candidate) — it concerned with infrastructure specifically related to Roads, Waterways, Ports and Railways;
- **IFC4.2** (current status-withdrawn) — an extension of the IFC schema to cover bridge constructions
- **IFC4.1** (current status- official) —it serves as a basis for extensions to ongoing infrastructure domain such as Tunnel, Road, Railways, Ports & Waterways, currently undergoing development.
- **IFC4** (current status- retired) — it contained three addendums (Add1, Add2, & Add2 TC1). This schema was meant to correct the limitations of previous IFC versions such as IFC2x3
- **IFC2x3** (current status- retired) — It was the immediate successor to IFC2x2; it was introduced mainly to improve the quality of previously released IFC.
- **IFC2x2** (current status- retired) — meant to improve the quality of previous IFC editions on building the facility and structural domain. For example, it provided the first sub-model for structural analysis and provided schema data on electrical, plumbing and other building definitions.
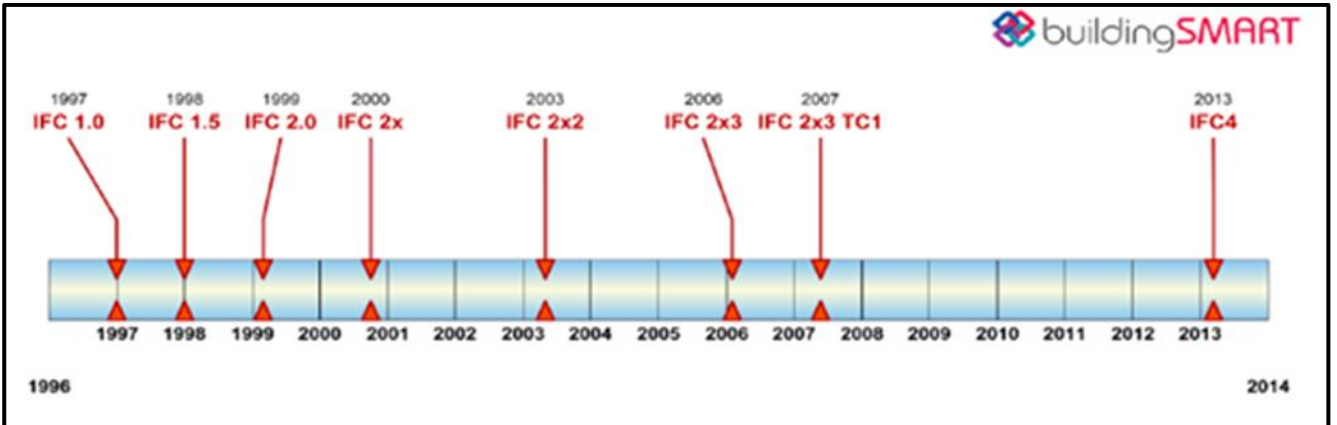
Figure 37: IFC historical timelines [39]

As shown in Figure 38, IFC architecture is divided into four layers of the data schema. The Resource layer (Domain layer) is the highest and consists of definitions of specialist disciplines in the AEC sector. The Interoperability layer represents the shared element data schemas; it consists of intermediate specializations of entities. The Core layer contains both kernel and the core extension schemas; it is the most generic definition of entities and provides the basis and concepts for models. The Resource layer is the last layer on the IFC architecture and represents resource definitions for individual schemas; the definitions have no global unique identifier and cannot be applied independently [39]. The main layers and domain of interest to structural engineer within the IFC data schema are highlighted in red (see Figure 39). It is worth noting that, currently, IFC does not have in scope data schema for dynamic analysis, topology results on stress and strains, mesh generation for finite element analysis, and loads description of pre-stressed structures.
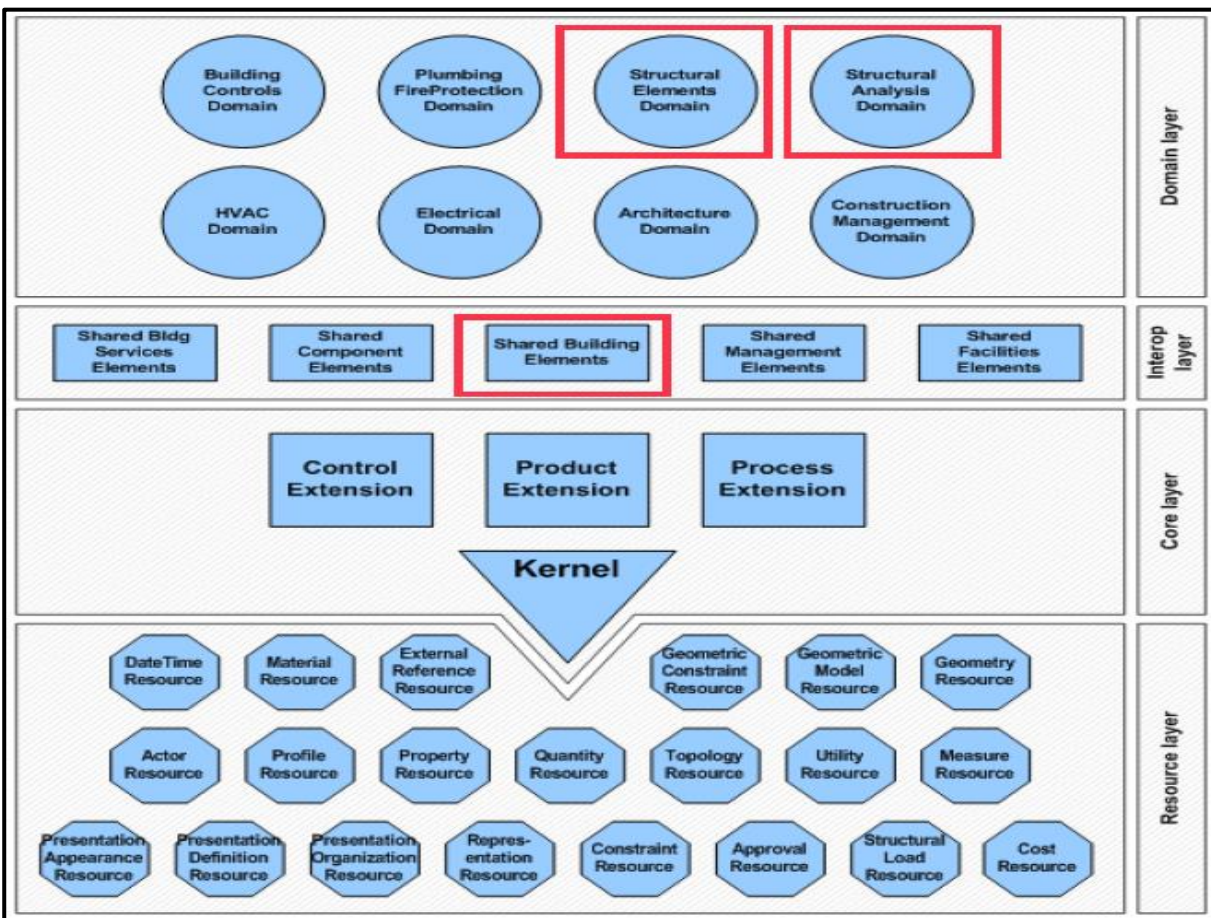
Figure 38: IFC data schema relevant to structural engineering are highlighted in red [39]

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Master Th. Ljubljana, UL FGG, Second Cycle Master Study Programme Building Information Modelling — BIM A+

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4.2 Structural Analysis Format (SAF)

The lack of effective openBIM format in handling structural analysis model is one of the contributing factors limiting structural engineers' full participation in BIM. The current IFC has several limitations and low capabilities in handling structural analysis data within a BIM workflow. To correct this, the Structural Analysis Format (SAF) is a new initiative from the Nemetschek Group and supported already by a big group of structural analysis software vendors, who aim to improve customer satisfaction in BIM-based design based on market feedback. SAF is an openBIM format which allows modellers to exchange structural model via Excel-based file type with any structural analysis software that supports its format. This level of neutral exchange of files gives modellers and engineers the needed flexibility to use the software of their choosing. In addition to helping engineers seamlessly exchange BIM model data with analysis software through an easy-to-use, practical open format, it also improves collaboration between structural engineers. The SAF initiative is currently coordinated by SCIA from the Nemetschek Group, with support from other companies such as Graphisoft, Allplan, RISA, FRILO, Strusoft, Axis VM, Dlubal, Sofistik, SCAD, LIRA land, Radimpex and IDEA StatiCa [40].

SAF remains very promising as far as overcoming the challenges structural engineers are faced with in fully participating in BIM. It currently covers most BIM objects needed for structural analysis; developers aiming to introduce non-linear and dynamics analysis by next year [41]. Figure 40 shows an Archicad BIM model exchanged with FEM-Design via a SAF file format.
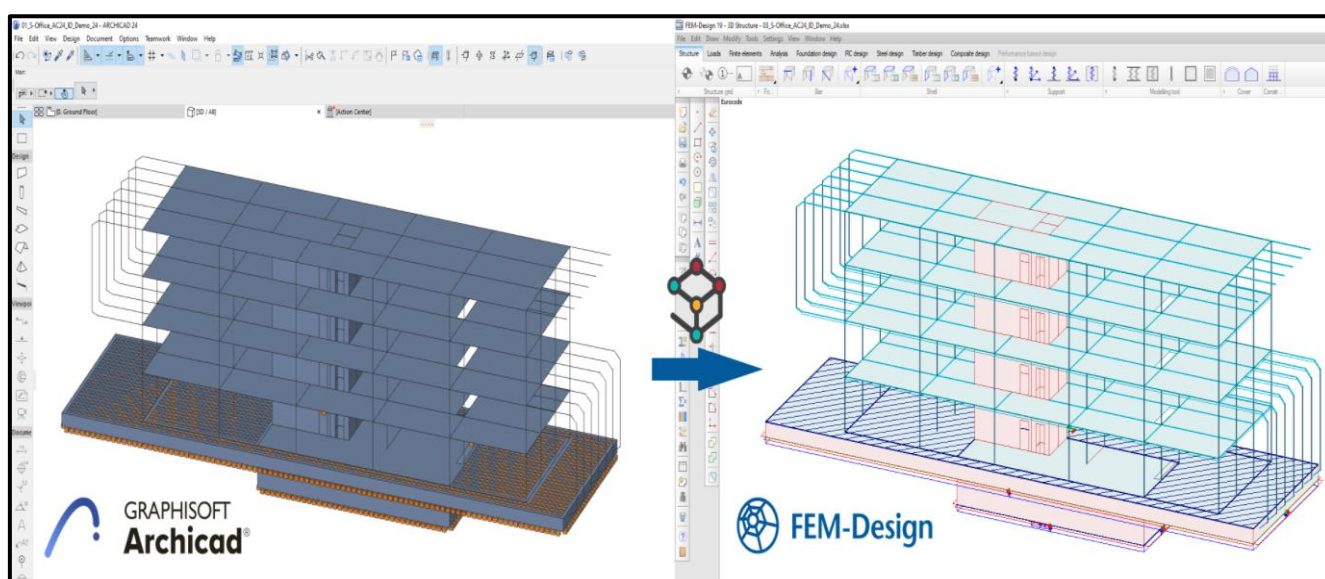
Figure 39: An Archicad model is being transfer to FEM-Design software via a SAF file [42]

4.3 Summary

This chapter assesses the concept of interoperability in the context of data exchange in BIM structural engineering, which seeks to provide answers to one of the main questions of this thesis. Several types and levels of interoperability are discussed in details. A theoretical overview of the three levels of interoperability widely implemented in BIM structural engineering, direct native file exchange, direct link data exchange, and IFC, is presented. Direct link data exchange is considered the most effective and convenient interoperability level for structural engineers. A brief review of the recently launched promising openBIM format for structural engineers, Structural Analysis Format or SAF, is also provided. SAF is based on a neutral file format that aims to help structural engineers overcome interoperability challenges.

5   CASE STUDIES

5.1   Introduction

This chapter presents two case studies that informed the conclusion of this thesis. The first case study tests the direct link exchange capabilities between Revit and selected FEM software. Case study one is divided into part A and part B.

Part A focuses on reporting the data exchange scenarios between the Revit BIM platform and the following FEM software: SOFiSTiK, RFEM, and SCIA Engineer. Part B focuses on the comparison of internal forces generated from exchange scenarios in part A. The second case study uses the Revit-SOFiSTiK interface to examine the efficacy of structural engineering BIM-workflow by designing the first-floor slab as a subsystem from the main system. The design of the slab follows the entire structural engineering design workflow, as outlined in section 6.4, from scripting in Dynamo to modelling, analysis, design, detailing and documentation. The methodologies outlined in section 1.4 recapped, the case studies model described, the process outlined, and results presented. More detailed results of each exchange scenario are reported and discussed.

5.1.1   Description of the Case Study Model

The structural model data implemented in the case studies have been provided by Politecnica Ingegneria e Architettura *(www.politecnica.it)*, one of the collaborating partners of this thesis project. Politecnica is one of the top Italian AEC companies providing integrated service in architecture, engineering and urban planning. The model is based on design data from a manufacturing plant and office building project that Politecnica executed in recent years for a multinational company. For a thesis-based project, some slight modifications to the model were necessary to make room for flexibilities in the workflow.

SOFiSTiK AG, a leading German-based software vendor for FEM and BIM solution packages, provided extensive technical supports in terms of the application of BIM workflow in structural engineering throughout the implementation of this thesis.

5.1.2   Description of the Structure, Material Properties, and loads

Geometry

The structural model is a reinforced concrete frame building consisting of two-story and a penthouse. The model spans 50.4 m in the longitudinal direction and **20.3 m** in the transversal direction, and a total building height of **13.52 m**. The cross-section dimensions of structural members are as follows: the first and the second floor contained a **500×600 mm** beam cross-section and a **500×500 mm** column cross-section; cross-section for both beams and columns in the penthouse is **400×400 mm.** Figures 41 to 46 show the architectural rendition of the completed building, the structural design model provided by the company, the modified model developed for the thesis case studies, the plan view (ground floor), elevation views, respectively.

Figure 40: Architectural rendition of the completed project used for the case studies
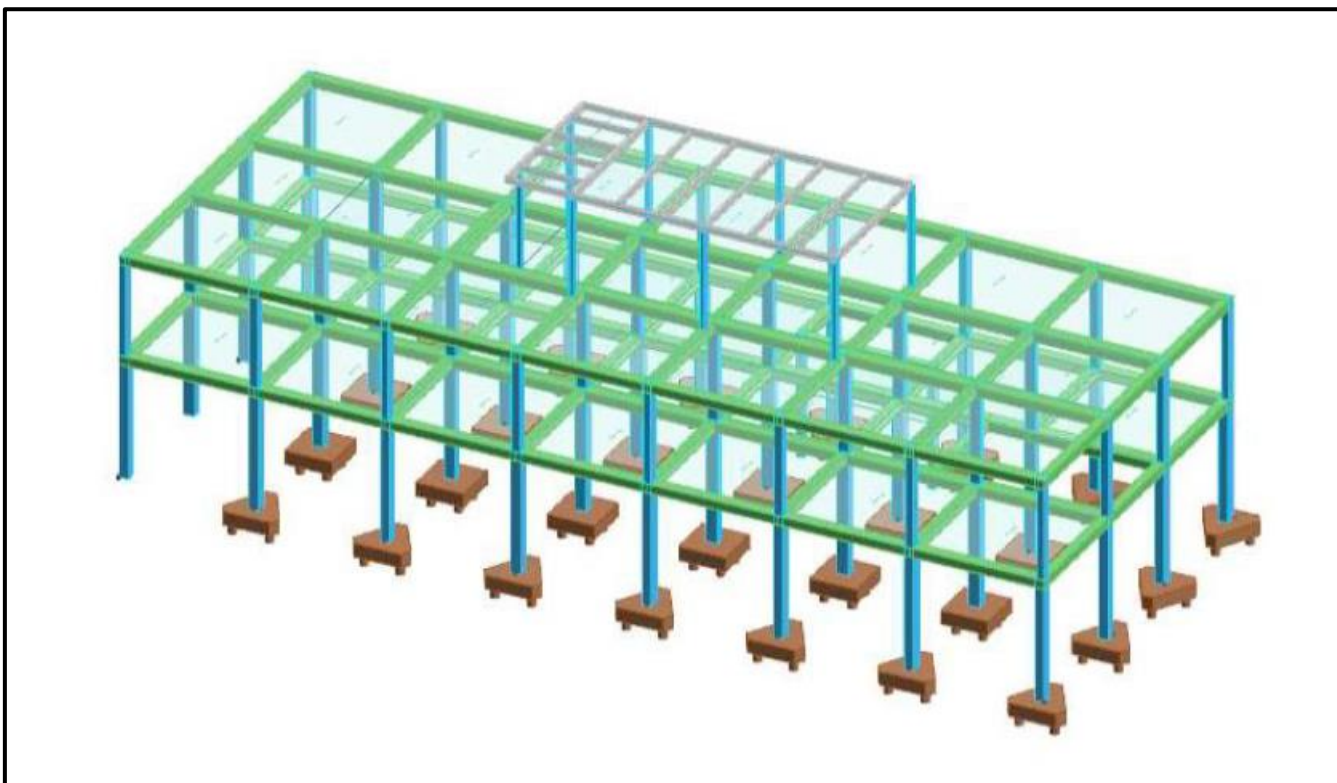
Figure 41: Structural model as prepared by Politecnica Ingegneria
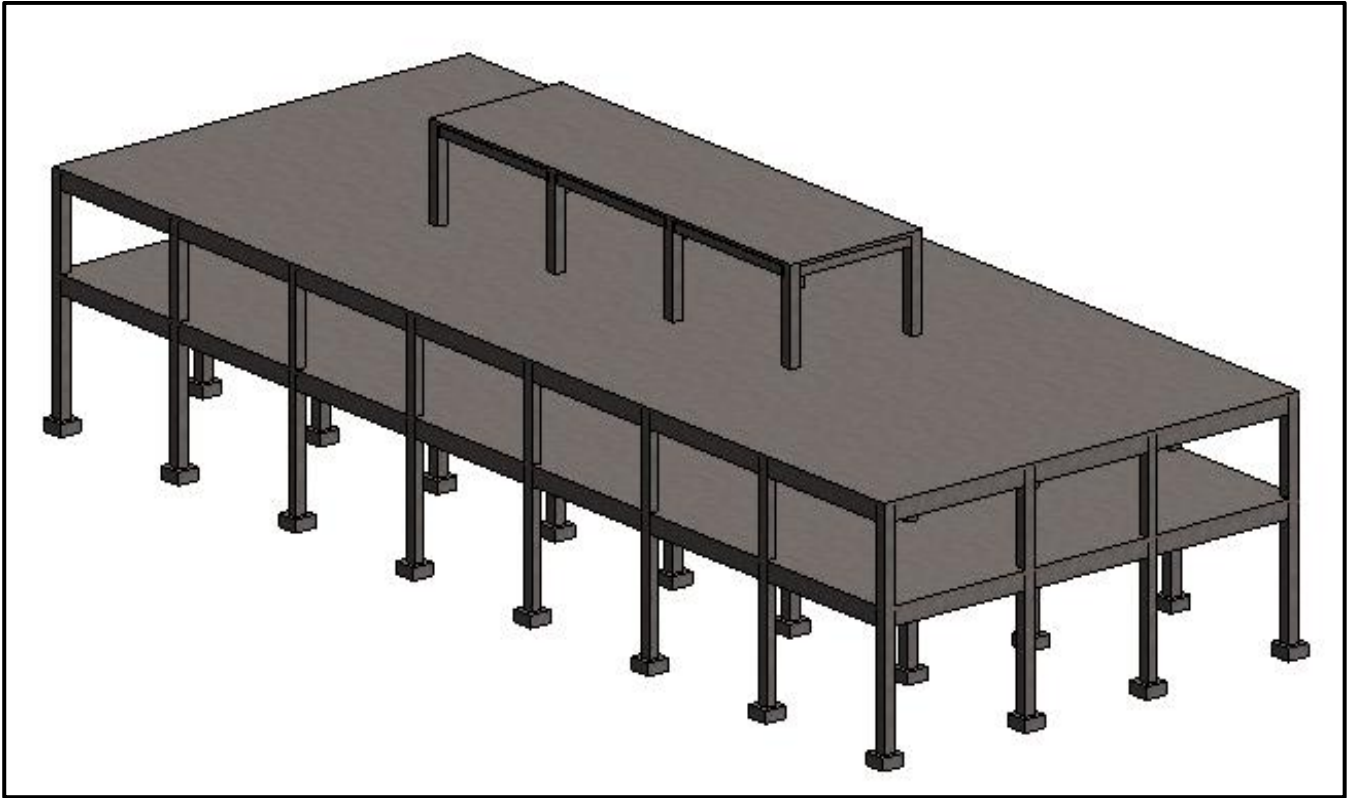
Figure 42: The structural model as developed in this thesis
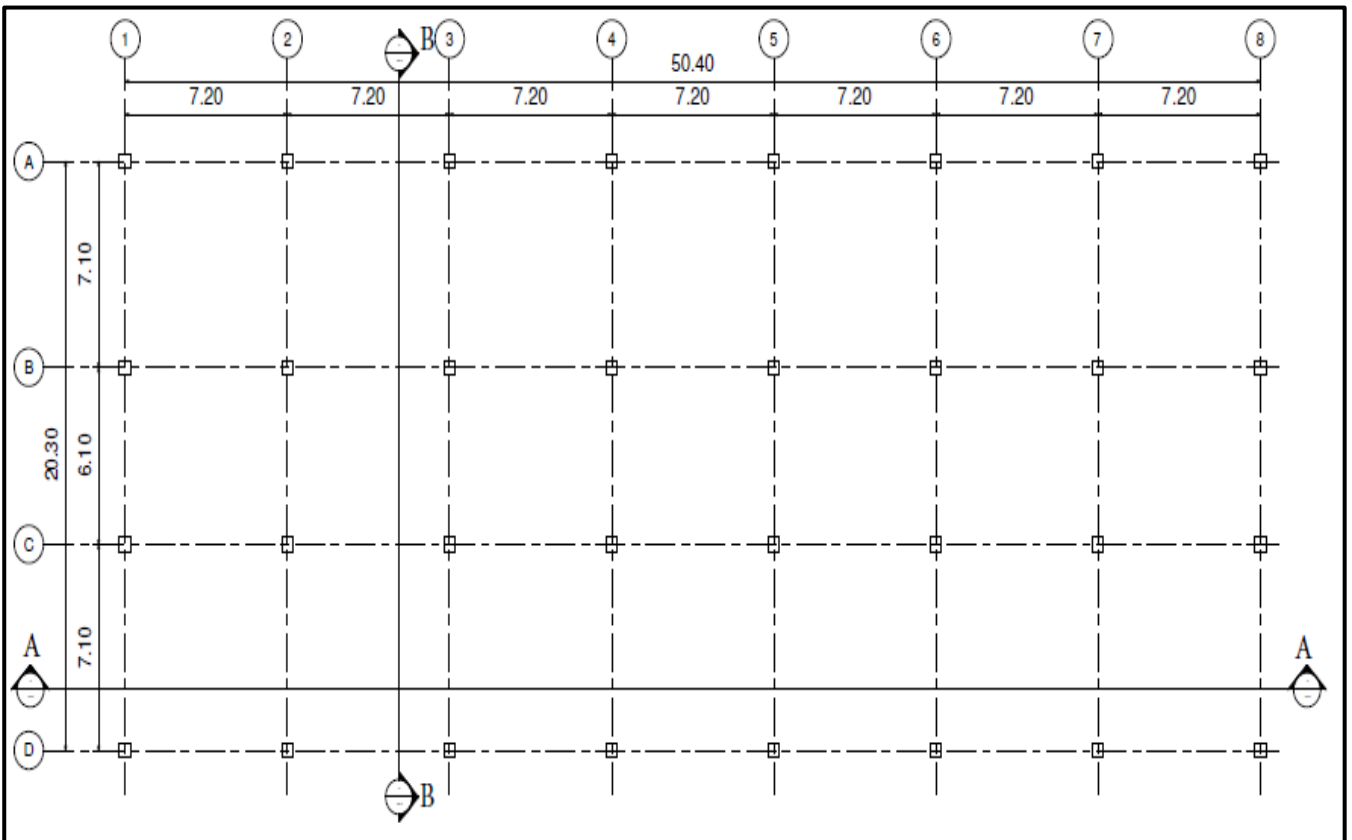
Figure 43: Figure: Ground floor plan view of the model
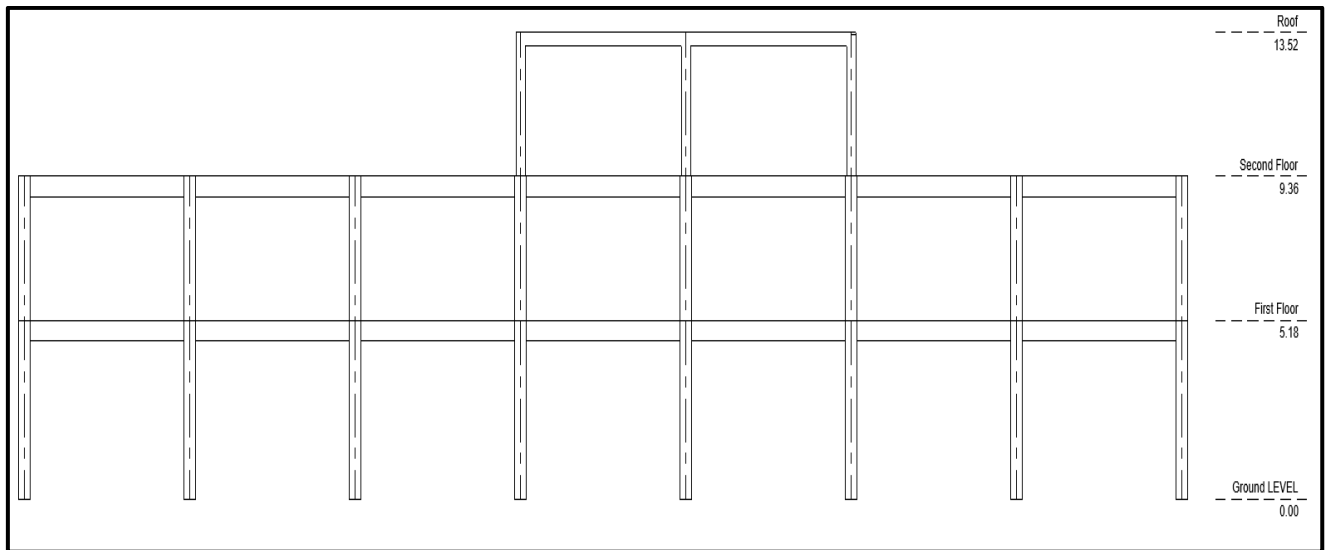
Figure 44: Elevation section A-A
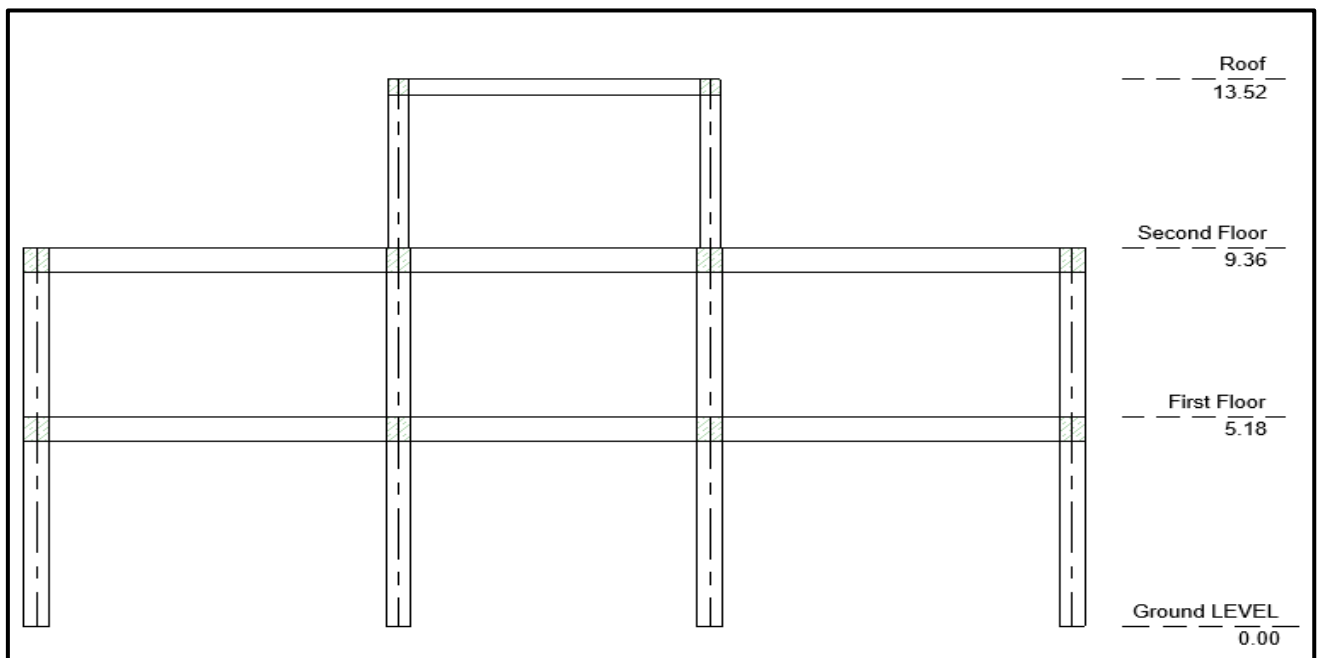
Figure 45: Elevation view section B-B

The below structural data is valid for all case studies in this thesis.

Material Properties

<u>Concrete C30/37</u>

According to EC2, the following material parameters are considered:

- Compressive strength f_{ck} = 30 MPa
- Tensile strength f_{ctm} = 2.9 MPa
- Modulus of Elasticity E_{c0m} = 32.8 GPa
- Weight (reinforced concrete)   = 25 kN/m³
- Partial safety factor γ_c = 1.50
- Design strength f_{cd} = 20 MPa = 2.0 kN/cm²

<u>Reinforcing steel</u>

Steel grade B 450 C in accordance with EC2 is chosen for all reinforcing steel.

- Yield strength f_{yk} = 450 MPa
- Partial safety factor γ_S = 1.15
- Design strength f_{yd} = 391 MPa = 39.1 kN/cm²

Loads

Loads considered in the study are summarized in Table 2.

Table 2: Loads considered in the case study

Floor	Dead Load (kN/m²)		Live Loads (kN/m²)	Wind load (windward) (kN/m²)	Snow Load (kN/m²)
	Self. wt.	Perm. load			
First Floor	4.5	2.7	3	+0.75	
Second Floor	1.5	4.5	1	+0.75	1.35
First floor (roof)	4	0	1	+0.75	1.35

For simplicity, only the external wind pressure on the windward side is considered to be acting on the structure. This is the minimum value provided in the project document for the windward side, calculated based on Eurocode1, part 1-4. As a low-rise building, a constant wind load is considered to act on the total height of the building. A facade load of 2.00 kN/m²) is considered for only the second storey.

Load Combination

The model has been statically analysed based on the ultimate limit state design situation. The ultimate limit state analysis provides adequate strength of the structure. The design combination and partial safety factors were all considered based on equation 6.10 (see Figure 47) of Eurocode 2 provisions [43]. The load combination table is shown in Table 3, as exported from the Revit model.

Design values of actions, ultimate limit state - persistent and transient design situations (Table A1.2(B) Eurocode)

Comb'tion expression reference	Permanent actions		Leading variable action	Accompanying variable actions	
	Unfavourable	Favourable		Main(if any)	Others
Eqn (6.10)	$1.35\,G_k$	$1.0\,G_k$	$1.5\,Q_{k,1}$		$1.5\,\Psi_{0,i}\,Q_{k,i}$
Eqn (6.10a)	$1.35\,G_k$	$1.0\,G_k$		$1.5\,\Psi_{0,1}\,Q_k$	$1.5\,\Psi_{0,i}\,Q_{k,i}$
Eqn (6.10b)	$0.925 \times 1.35 G_k$	$1.0\,G_k$	$1.5\,Q_{k,1}$		$1.5\,\Psi_{0,i}\,Q_{k,i}$

For buildings Exp (6.10) is usually used: $1.35\,G_k + 1.5\,Q_k$

But Exp (6.10b) could be used and for one variable action: $1.25\,G_k + 1.5\,Q_k$

Provided:
1. Permanent actions < 4.5 x variable actions
2. Excludes storage loads

Figure 46: Combination of actions equations, Table A1.28(B), Eurocode 2 [43]

Table 3: Customized load combination table in Revit as exported to FEM Software

	Name	Formula
		(all)
1	COMBO_1	1.35*DL1(s.w+p) + 1.35*DL2(facade) + 1.35*DL3(s.w/roof) + 1.5*LL1 + 0.75*Sk1 + 0.75*
2	COMBO_2	1.35*DL1(s.w+p) + 1.35*DL2(facade) + 1.35*DL3(s.w/roof) + 1.5*LL2 + 0.75*Sk1 + 0.75*
3	COMBO_3	1.35*DL1(s.w+p) + 1.35*DL2(facade) + 1.35*DL3(s.w/roof) + 1.5*LL3 + 0.75*Sk1 + 0.75*
4	COMBO_4	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL1 + 0.75*Wk1
5	COMBO_5	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL2 + 0.75*Wk1
6	COMBO_6	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL3 + 0.75*Wk1
7	COMBO_7	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*LL1 + 0.75*Sk1 + 0.75*Wk1
8	COMBO_8	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*LL2 + 0.75*Sk1 + 0.75*Wk1
9	COMBO_9	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*LL3 + 0.75*Sk1 + 0.75*Wk1
10	COOMBO_1	1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL1 + 0.75*Wk1

	Name	Formula
11	COMBO_11	1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL2 + 0.75*Wk1
12	COMBO_12	1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL3 + 0.75*Wk1
13	COMBO_13	1*DL1(s.w+p) + 1*DL2(facade) + 1*DL3(s.w/roof) + 1.5*LL1 + 0.75*Sk1 + 0.75*Wk1
14	COMBO_14	1*DL1(s.w+p) + 1*DL2(facade) + 1*DL3(s.w/roof) + 1.5*LL2 + 0.75*Sk1 + 0.75*Wk1
15	COMBO_15	1*DL1(s.w+p) + 1*DL2(facade) + 1*DL3(s.w/roof) + 1.5*LL3 + 0.75*Sk1 + 0.75*Wk1
16	COMBO_16	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL1 + 0.75*Wk1
17	COMBO_17	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL2 + 0.75*Wk1
18	COMBO_18	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL3 + 0.75*Wk1
19	COMBO_19	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*LL1 + 0.75*Sk1 + 0.75*Wk1
20	COMBO_20	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*LL2 + 0.75*Sk1 + 0.75*Wk1
21	COMBO_21	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*LL3 + 0.75*Sk1 + 0.75*Wk1
22	COMBO_22	1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL1 + 0.75*Wk1
23	COMBO_23	1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL2 + 0.75*Wk1
24	COMBO_24	1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL3 + 0.75*Wk1

5.1.3 Software Implemented in the Exchange Scenarios

Figure 48 illustrates the FEM software products implemented in the case studies. As seen in the Figure, a BIM authoring tool (Autodesk Revit) and three FEM software programs are listed. Autodesk Revit is a multidisciplinary BIM authoring platform where structural models are created and populated with relevant metadata and properties, where project coordination and documentation takes place. The FEM tools, on the other hand, serve as the source for performing structural analysis and design. In the case studies, the direct link interoperability exchange method (see Figure 48) is implemented. The models are authored in Revit and exchange with FEM tools through their add-in or interface links to Revit.
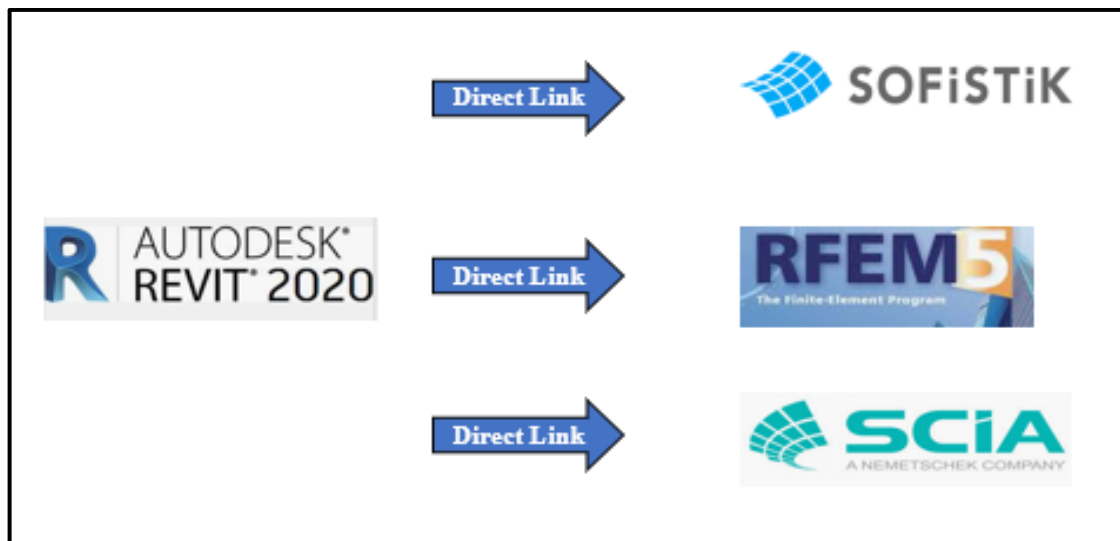
Figure 47: Direct link interoperability scenarios implemented in the case studies

SOFiSTiK is a leading German-based software producing company with a specialization in FEM and BIM solution packages for analysis, design and detailing of civil structures. Its German counterpart, REFM, owned by Dlubal, also provides similar services; for concrete, steel, and wood structures. It also has a well-integrated platform for BIM workflow.

SCIA (SCIA Engineer) is a Belgium based structural engineering software solutions company. It provides well-integrated analysis and design tools for all kinds of civil structures. Its bi-directional link or Revit interface provides an excellent platform to facilitate BIM workflow.

5.2 Method of Analysis

The method employed in these case studies is based on a data analysis experiment where structural data is exchanged through the existing direct links between Revit and each of the mentioned FEM software solutions. The method seeks to understand how seamlessly structural data in REVIT is exchanged with each of these analysis programs and how well these programs map and interpret BIM data. A comparison of internal forces is then made to evaluate each exchange scenario. This method aims to provide sufficient information to support the conclusion of this thesis.

5.3 Case Study 1A: Direct Link

As mention earlier, direct link or bi-directional interface is the central theme of this thesis; hence, case study one entirely focuses on this interoperability. Subsections 5.3.1 to 5.3.3 provide a detailed explanation of the three exchange scenarios implemented in this case study.

5.3.1 Revit-SOFiSTiK Direct Link Interface
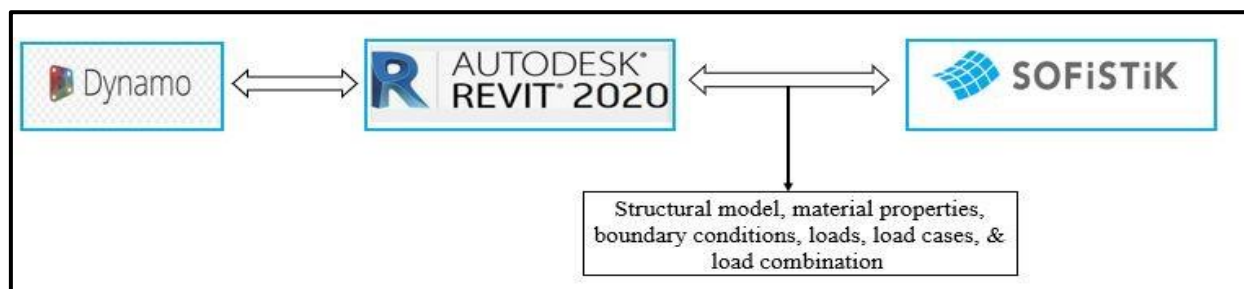
Figure 48: Data exchange between Revit and SOFiSTiK

The Revit-SOFiSTiK Interface allows for the seamless exchange of modelling, analysis, and design data. It facilitates project coordination and documentation as well. The well-integrated interface has shown strong fidelity in transferring key structural parameters such as material properties, loads and load cases, load combinations, and boundary conditions. Figure 49 shows the nature of the direct link exchange scenario between Revit and SOFiSTiK, where the model is first created in dynamo parametrically, sent to Revit for further analysis, data input, cross-section checks, and modifications. The modified Revit structural model (analytical) is then transferred to SOFiSTiK (FEM) through the bi-direction links. As shown in the figure, all structural properties and data necessary for the SOFiSTiK to perform structural analysis are listed.
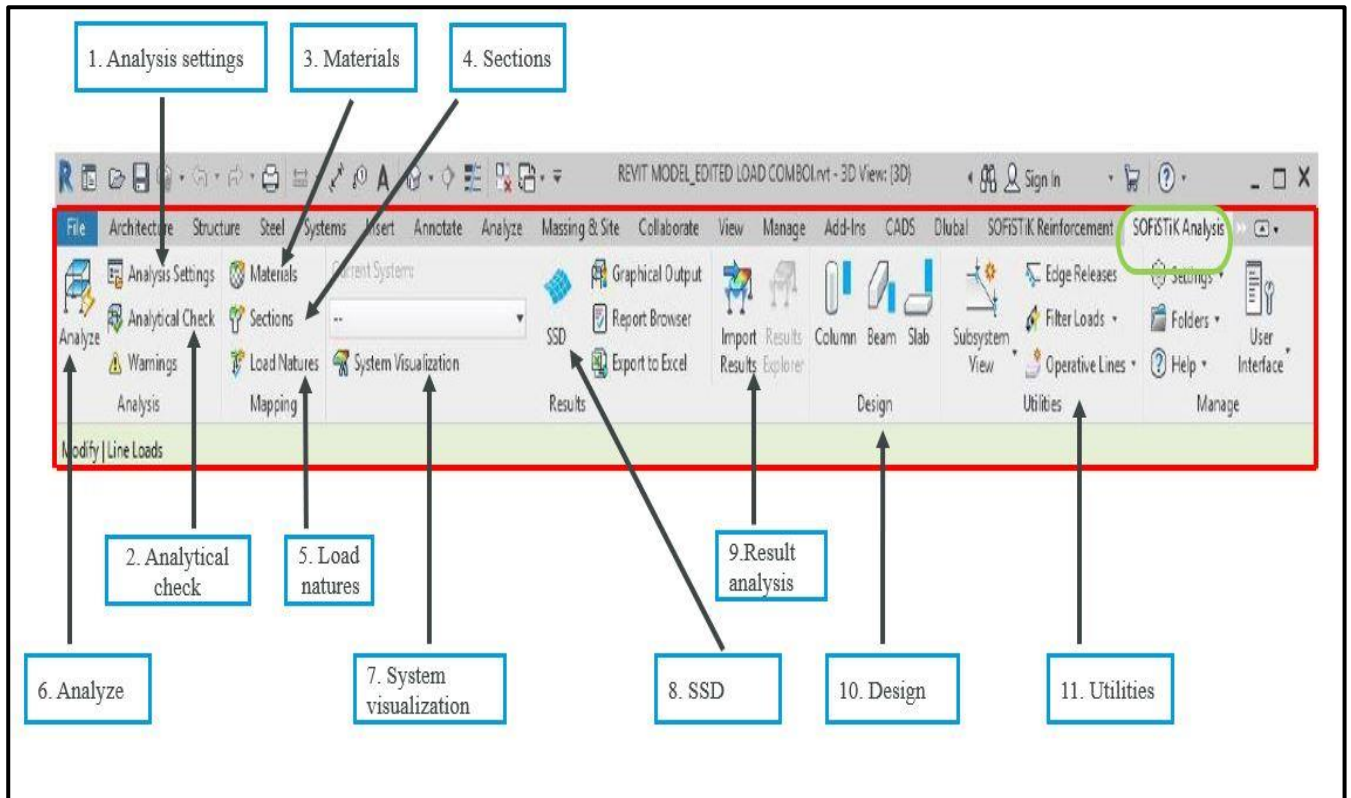
Figure 49: Revit- SOFiSTiK direct link user interface and command panel in Autodesk Revit platform

When a BIM model is ready, a click on the add-on link (green) will open up the ribbon containing several commands, as seen in Figure 50. A brief description of each of these commands is presented below:

1. Analysis settings— project settings such as file tiles, project design code, type of FEM model, language, etc., are adjusted here.

2. Analytical check— this command checks for inconsistencies in the Revit analytical structural model before calculation commences. It checks for failure in mapping, overlapping, support, and misalignment of structural elements and properties.

3. Materials— this command provides a table to compare Revit material and SOFiSTiK material.

4. Section— it displays the mapping table for cross-section parameters for Revit against SOFiSTiK cross-sections.

5. Load nature— it compares Revit Load Natures mapping table and load nature provided by SOFiSTiK.

6. Analyse— this is the main command that facilitates the export of the Revit analytical model to SOFiSTiK (FEM) platform. It provides the settings to analyse the model, loads, generate mesh before exporting the model.

7. System visualization— it displays 3D and animated views of the imported Finite Element Model. It the user to visualize some important information as load cases and load combination, node and element numbers, and structural analysis results.

8. SSD— SSD stands for SOFiSTiK structure desktop. SSD stands for SOFiSTiK structure desktop. Clicking this command provides access to the entire SOFiSTiK structural analysis and design suite, where rigorous analysis, design, and post-processing of results take place.

9. Result analysis—this command enables you to visualize Finite Element analysis (FEA) and design results in a Revit environment. Upon completion of analysis and design in the SOFiSTiK environment, the user can visualize and query results in the Revit environment utilizing this command. To facilitate the import of FEA results in Revit through this command, it requires the installation of the free Autodesk add-in "Structural Analysis Toolkit".

10. Design—This command enables you to perform a check or design required reinforcement for selected structural members.

11. Utilities— it contains commands for subsystem (subsystem view of the model can be created in Revit manually or by levels); edge releases (adjust the edge conditions of walls and slabs); filter loads (allows user to visualize loads in his/her model); etc.

Workflow

The process map in Figure 51 illustrates the workflow of the exchange scenario, clearly explaining how the modelling process originates from the BIM platform to the FEM software for analysis and design purposes, and vice versa.
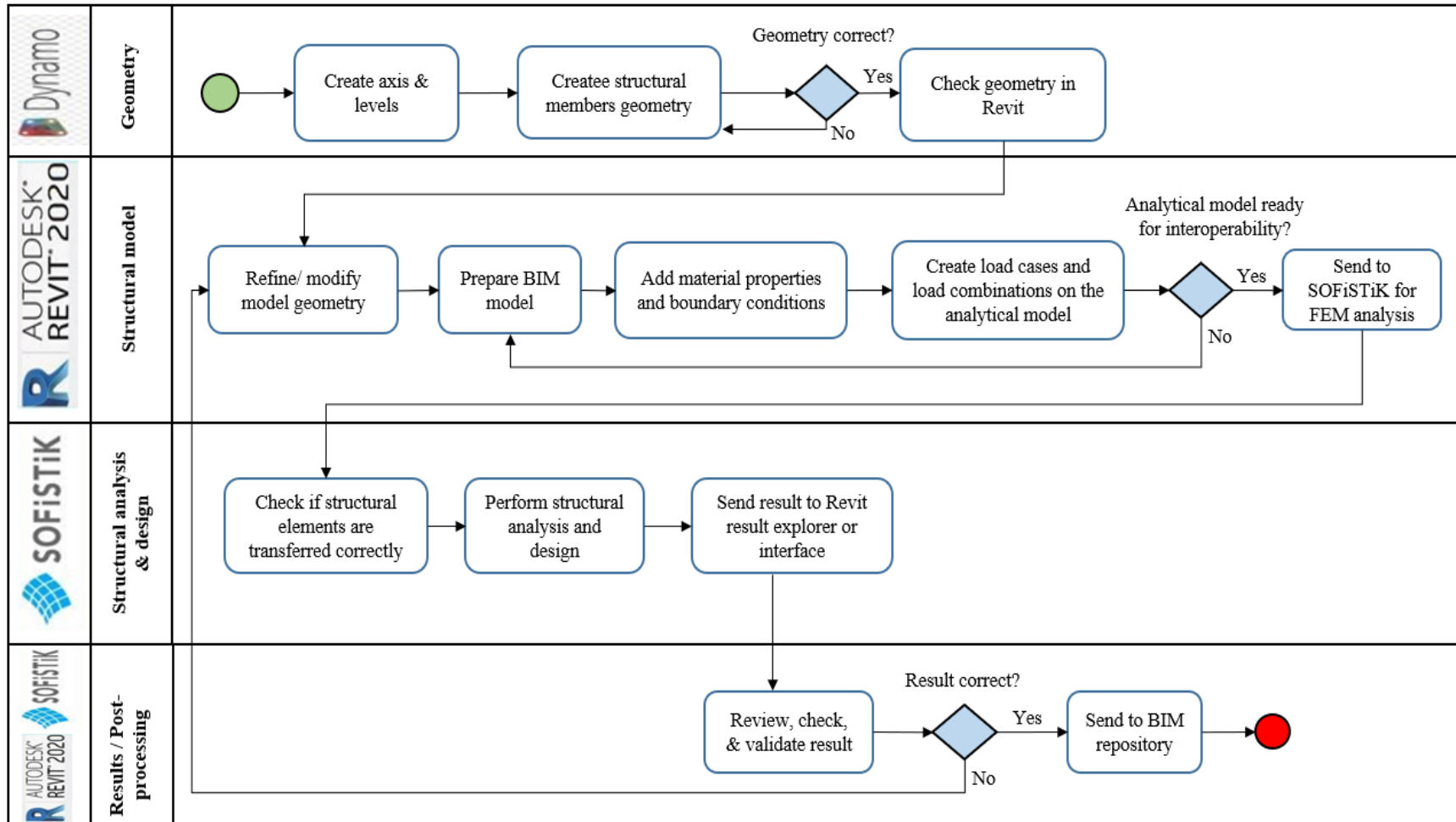
Figure 50: Workflow diagram for the exchange scenario in the Revit-SOFiSTiK case study

Dynamo is a plug-in connected to Revit with excellent visual programming capabilities. As clearly illustrated in the process map or workflow diagram above, the model geometry created in Dynamo parametrically, some refinements or modification made in Revit, plus a full initiation of the central BIM model. The parametric creation of the model in Dynamo enables easy adjustments to the model during structural calculations; it eliminates manual modelling, thus saving time. In the central Revit model, these load-bearing structural data are then added: material properties, boundary conditions, load cases, and load combinations.

As shown in the workflow chart, the Revit BIM model is transferred to SOFiSTiK for analysis and design purposes. When the design or analysis is complete, the structural model is now available for code checking and verification purposes. Request for any updates in the model is referred back to Revit. After checking the SOFiSTiK design results, it was possible to generate a 3D reinforcement of the model, from which 2D reinforcement plans, quantity and material take-offs, and documentation are extracted—all done in Revit-SOFiSTiK interface.

Results

Results obtained from Revit-SOFiSTiK exchange scenario are summarized in Table 4.

Legend	
√	The structural properties are correctly transfer from BIM to FEM tool
ₓ√	Minor medications in the FEM tool are required before properties are correctly transferred.
×	No transfer is possible

Table 4:Exchange results from Revit to SOFiSTiK.

Structural Data	Revit ⟷ SOFiSTiK
Geometry	
Overall model	√
Beam (Length)	√
Beam (cross sections)	√
Column (Length)	√
Column (cross sections)	√
Slab	√
Floor plan (axis)	√
Material Properties	
Material type (concrete)	√
Material Strength	√
Material type (reinforcing steel)	√
Material strength	√
Boundary Condition	
Fix support	√
Load	
Dead load	√
Live load	√

Snow load	√
Wind load	√
Load Combination	
All combinations	√
Result Exploration	
Calculated results back to Revit	√

5.3.2   Revit-Dlubal Direct Link Interface

Figure 51: Data exchange scenario between Revit and RFEM

Figure 52 illustrates the nature of the direct link exchange scenario between Revit and Dlubal (RFEM), implemented in this case study with all relevant data of interest. Similar to the Revit-SOFiSTiK Interface, Revit interacts with RFEM through a plug-in or add-on to facilitate seamless exchange of BIM model data for analysis and design purposes. This interface allows for an intelligent exchange of structural model information between a parametric based model (Revit) and an object-oriented model (RFEM) [44].

Figure 52: Revit- RFEM direct link user interface and command panel in Autodesk Revit Platform

When a BIM model is ready, a click on the add-on link (green) will open up the ribbon containing several commands (see Figure 53). A brief description of these commands is presented below:

1. Export model— this command initiates the data export from Revit to RFEM. A click opens up a dialog box (see Figure 54) to enable the user to define, adjust, or modified export parameters.

2. Import model— this command initiates the data import from RFEM to Revit. A click opens up a dialog box to enable the user to define, adjust, or modify import parameters.

3. Export-calculation-import— it provides settings to export-import calculated results in both directions.

4. Dlubal parameters— through this command, users can define Dlubal parameters to facilitate the exchange of cross-section or material data from Revit to RFEM. It maps user-defined parameters in Revit to parameters in Dlubal during the exchange process. For example, as seen in Figure 55, to facilitate the transfer of my cross-section, I had to create a Dlubal parameter within the properties section in Revit.
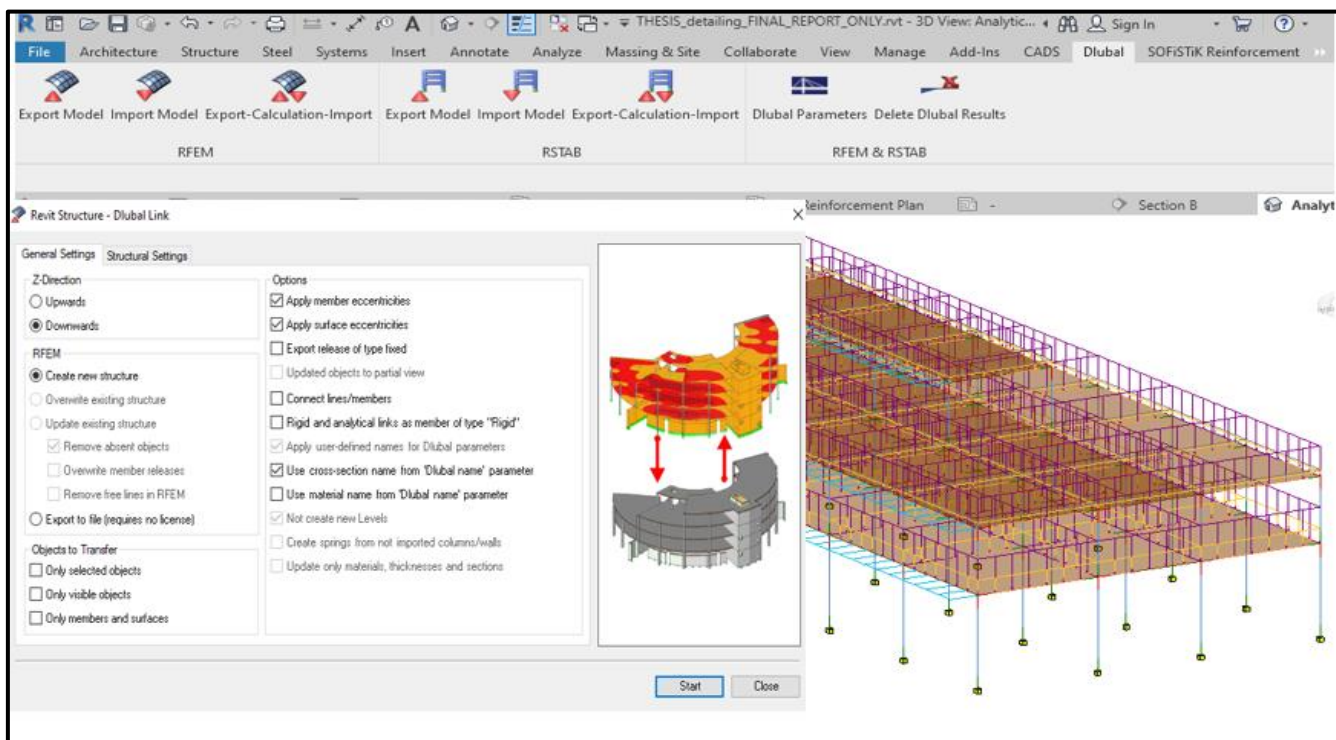
Figure 53: Dialog box which controls import and export functions in Revit-RFEM interface
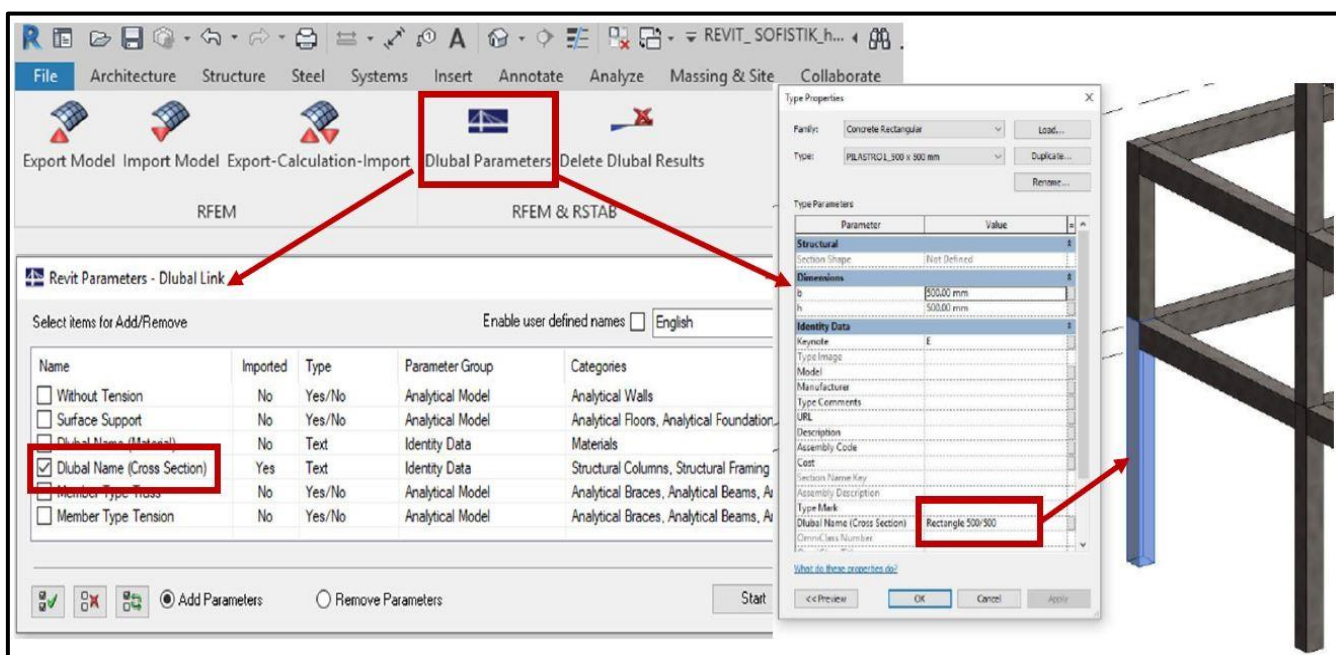
Figure 54: Dlubal parameter setting showing how cross sections are mapped

Workflow

The process map for Revit-RFEM workflow is shown in Figure 56 and follows a similar pattern as the Revit-SOFiSTiK workflow in Figure 51.

Figure 55: Workflow diagram for the exchange scenario in the Revit-RFEM case study

Figures 57 to 58 show the 3D and FEM models after the model is transferred to RFEM platform.

Figure 56: 3D View in RFEM

Figure 57: FEM view in RFEM

Results

Results obtained from Revit-RFEM exchange scenario are summarized in Table 5.

Legend	
√	The structural properties are correctly transfer from BIM to FEM tool
ₓ√	Minor medications in the FEM tool are required before properties are correctly transferred.
×	No transfer is possible

Table 5: Exchange results from Revit to RFEM.

Structural Data	Revit ⟷ RFEM
Geometry	
Overall model	√
Beam (Length)	√
Beam (cross sections)	√
Column (Length)	√
Column (cross sections)	√
Slab	√
Floor plan (axis)	√
Material Properties	
Material type (concrete)	√
Material Strength	ₓ√
Material type (reinforcing steel)	ₓ√
Material strength	×
Boundary Condition	
Fix support	√
Load	
Dead load	√
Live load	√
Snow load	√
Wind load	√
Load Combination	
All combinations	√
Result Exploration	
Calculated results back to Revit	√

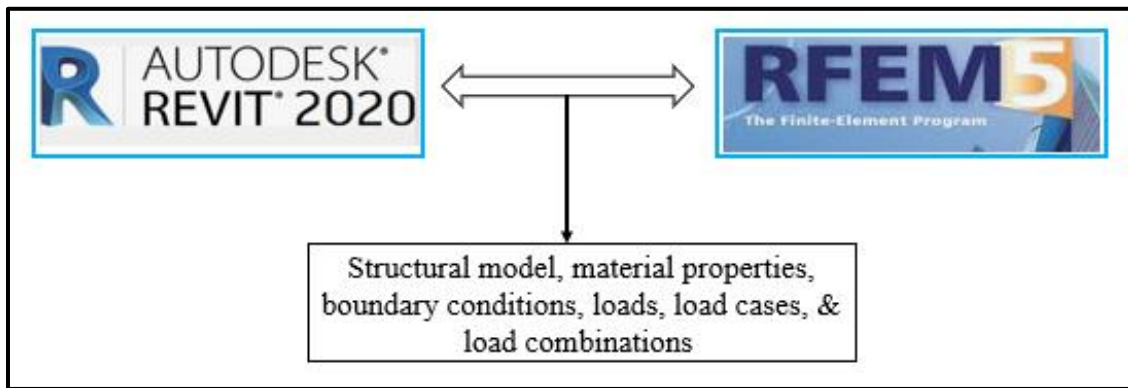### 5.3.3   Revit-SCIA Engineer Direct Link Interface
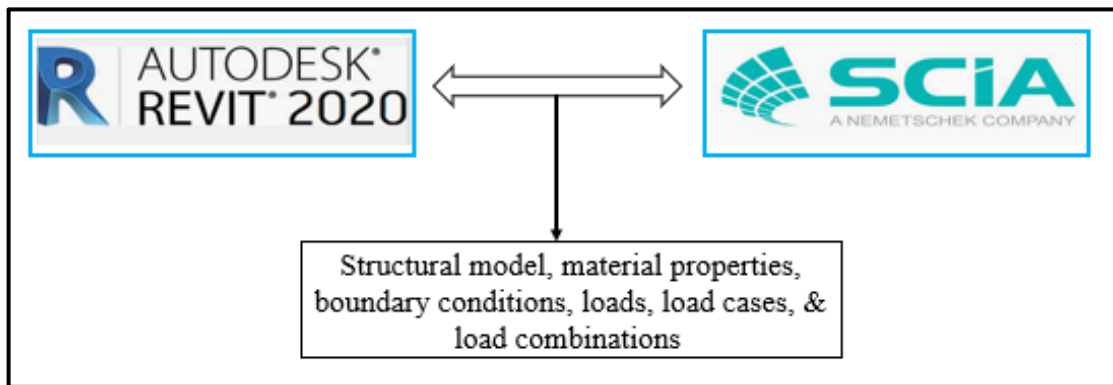
Figure 58: Data exchange scenario between Revit and SCIA Engineer

Figure 59 illustrates the nature of the direct link exchange scenario between Revit and SCIA Engineer, implemented in this case study with all relevant data of interest. The exchange of data between Revit-SCIA Engineer is done through the CAD Revit SCIA Engineer link. This link or add-on ensures the bi-directional exchange of structural engineering data between both programs through its export and import settings. Similar to the exchange scenarios mentioned supra, a Revit structural model is sent to SCIA via the direct link; when the model is analysed and designed in SCIA, the updated model is then sent back to Revit. Revit-SCIA link or interface first reads the Revit model and sort out the structural elements into categories before exporting. The Revit model is then ready for export to the SCIA Engineer based on the sorted lists provided in the "Options" dialog (see Figure 61). When the export is complete, a log dialog box (see Figure 59) will show a list of mapped and exported structural data [45].
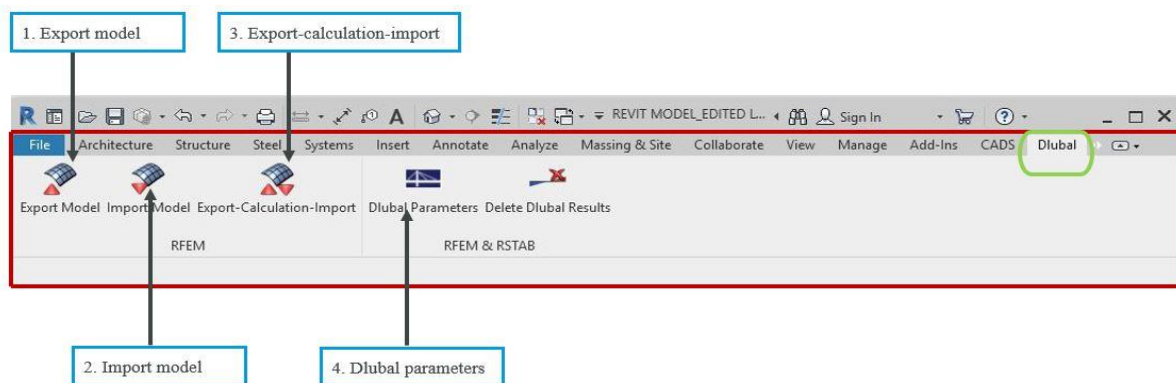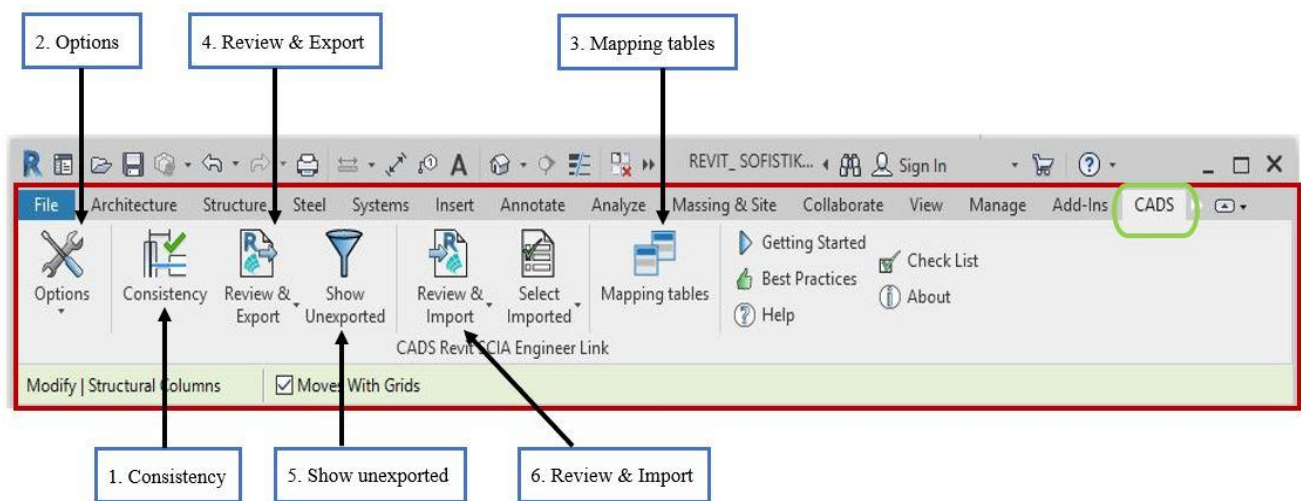

Figure 59: Revit- SCIA Engineer direct link user interface and command panel in Autodesk Revit

When a BIM model is ready, a click on the add-on link (green) will open up the ribbon containing several commands (see Figure 60). A brief description of these commands is presented below:

1. Consistency— this command checks for model consistency before commencing calculation. It checks for failure in mapping, overlapping, support, and misalignment of structural elements and properties.

2. Options— selecting this command leads you to the dialog box shown in Figure 61, where national code, mode of export (direct or file exchange), SCIA Engineer version are selected. This dialog box also controls the export and import functionalities.

3. Mapping tables— the cross-sections and material properties in Revit and SCIA Engineer vary in terms of naming conventions. The mapping table in the Revit-SCIA Engineer interface allows users to match user-defined parameters or properties between both programs when exporting or importing the model.

4. Review & Export— this command enables users to review the model carefully before exporting.

5. Show unexported— when the export is complete, some structural members are unexported due to geometric inconsistency in the Revit model; this command enables users to identify unexported elements in the model.

6. Review & Import— this command allows users to review the model carefully before importing.
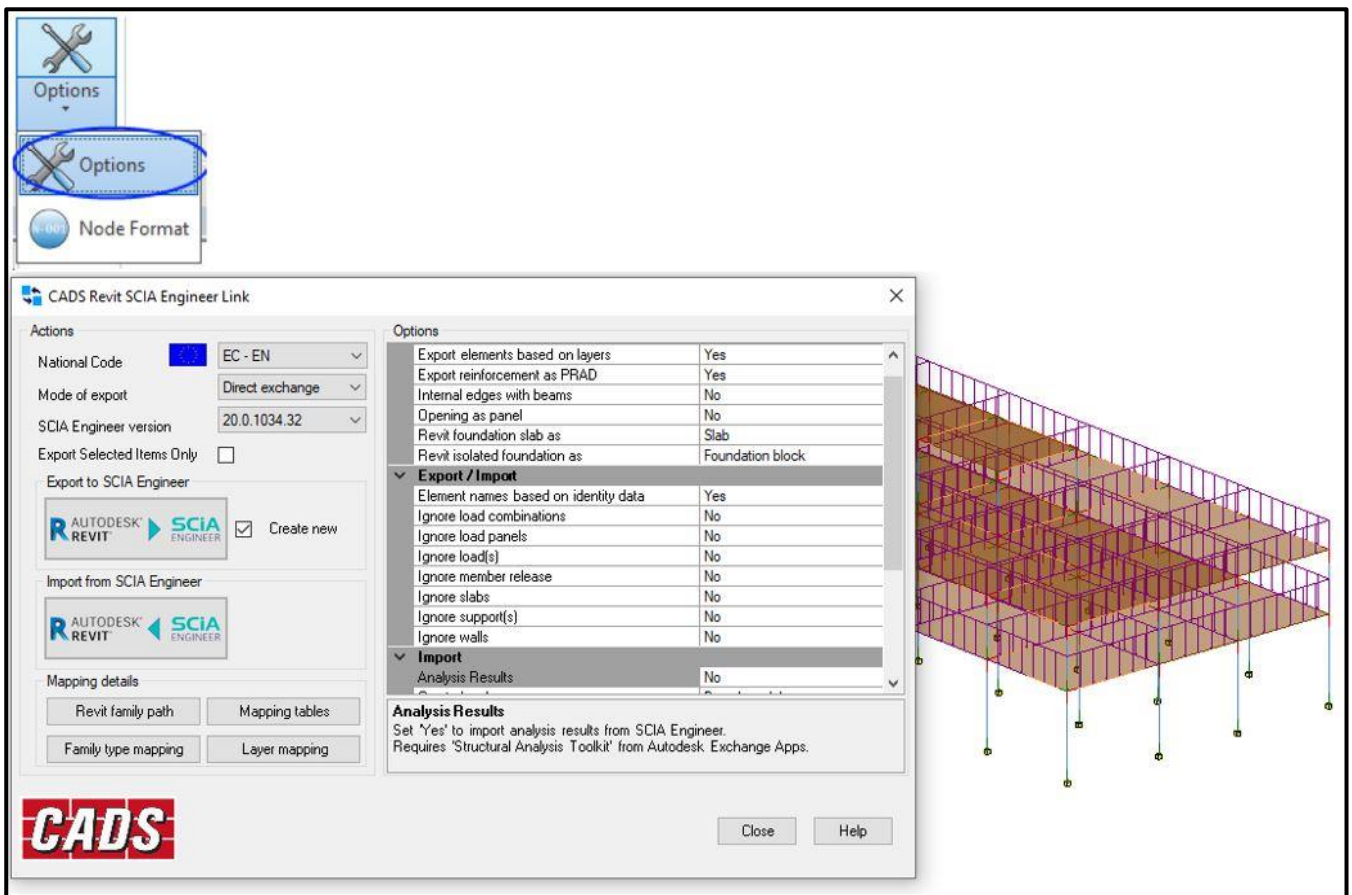
Figure 60: Dialog box which controls import and export functions in Revit-SCIA Engineer interface

Workflow

The process map for Revit-SCIA Engineer workflow is shown in Figure 62 and follows a similar pattern as the Revit-SOFiSTiK workflow in Figure 51.
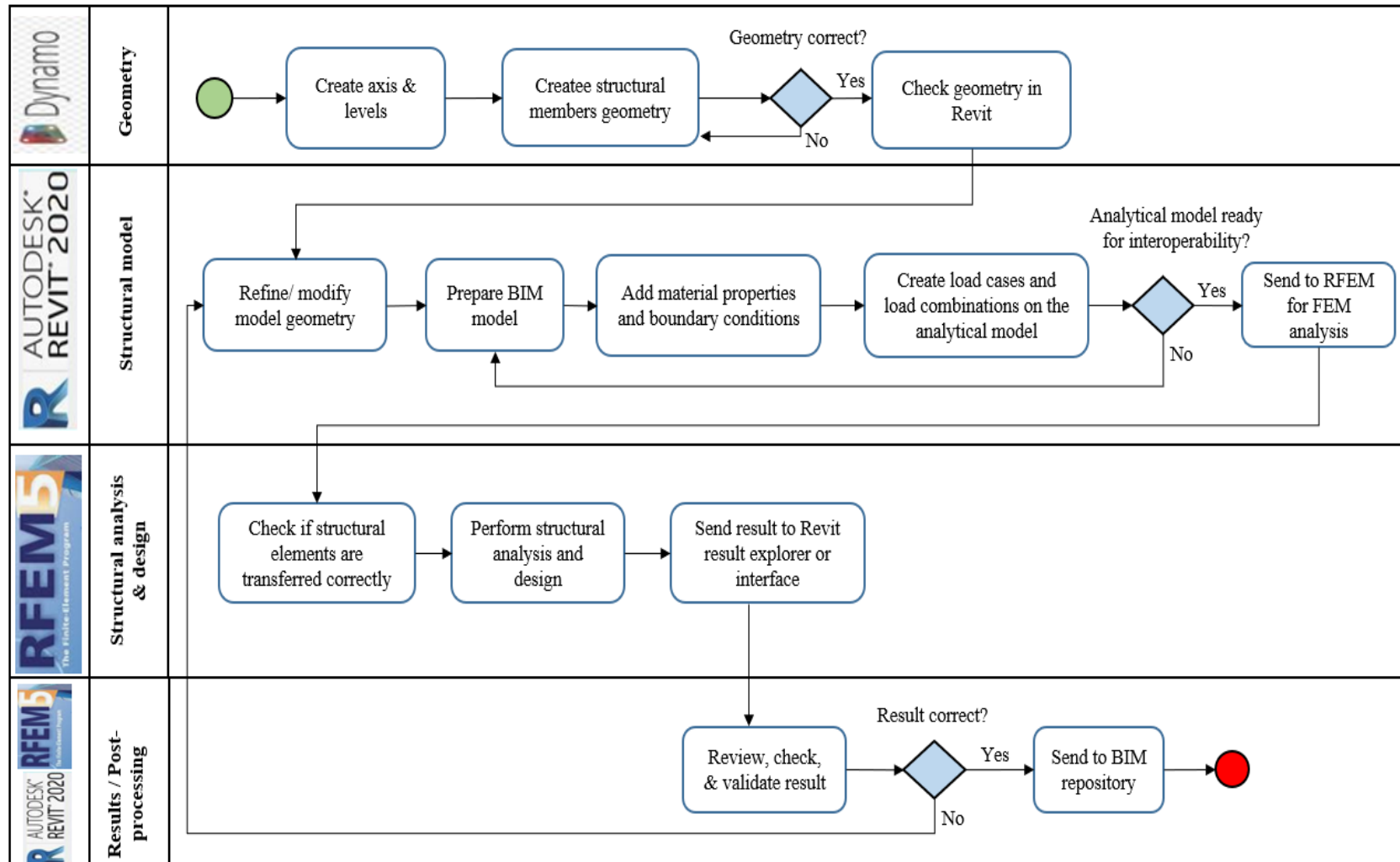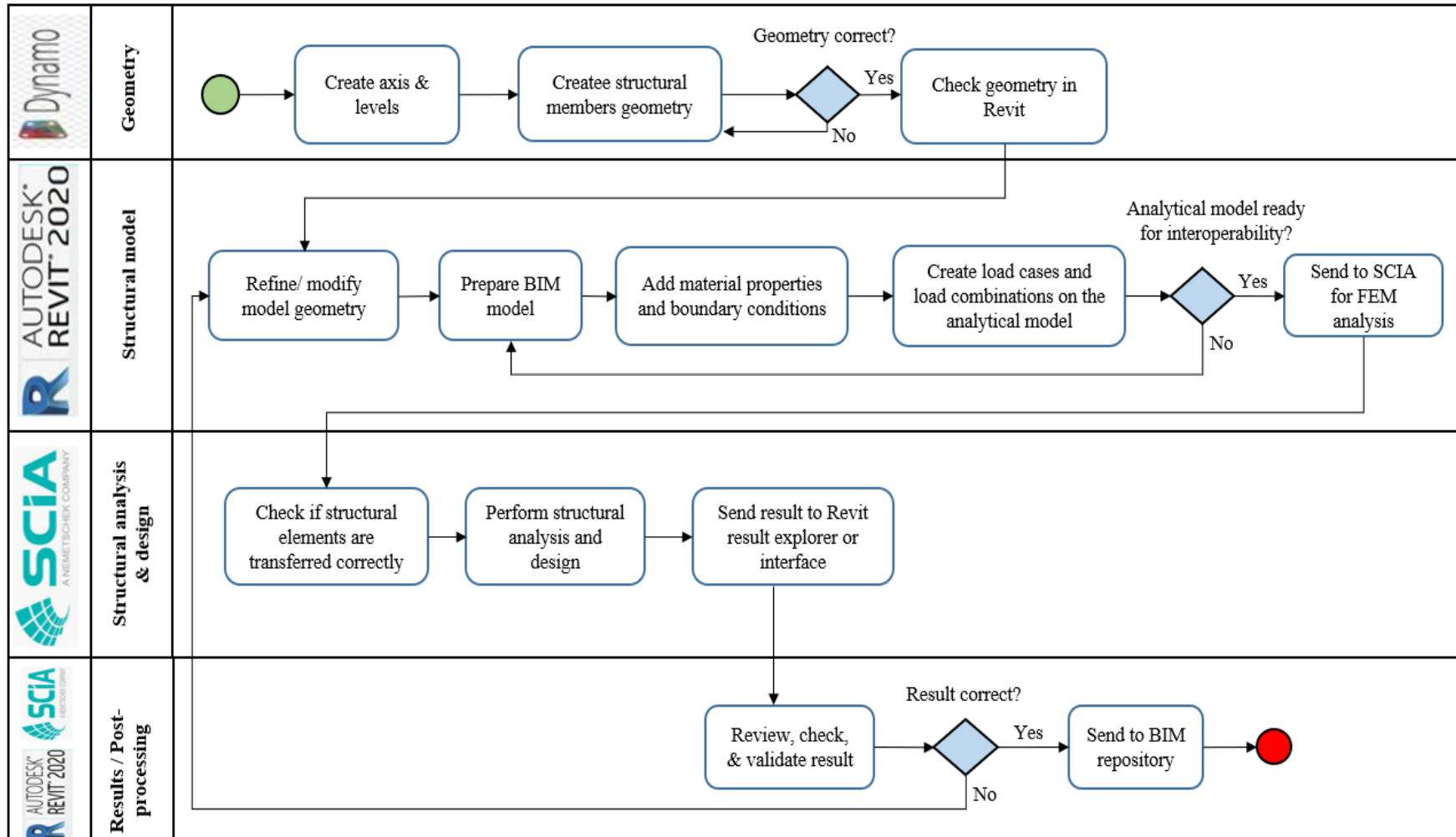

Figure 61: Workflow diagram for the exchange scenario in the Revit-SCIA Engineer case study

Figures 63 to 64 show the 3D and FEM models after the model is transferred to RFEM platform.
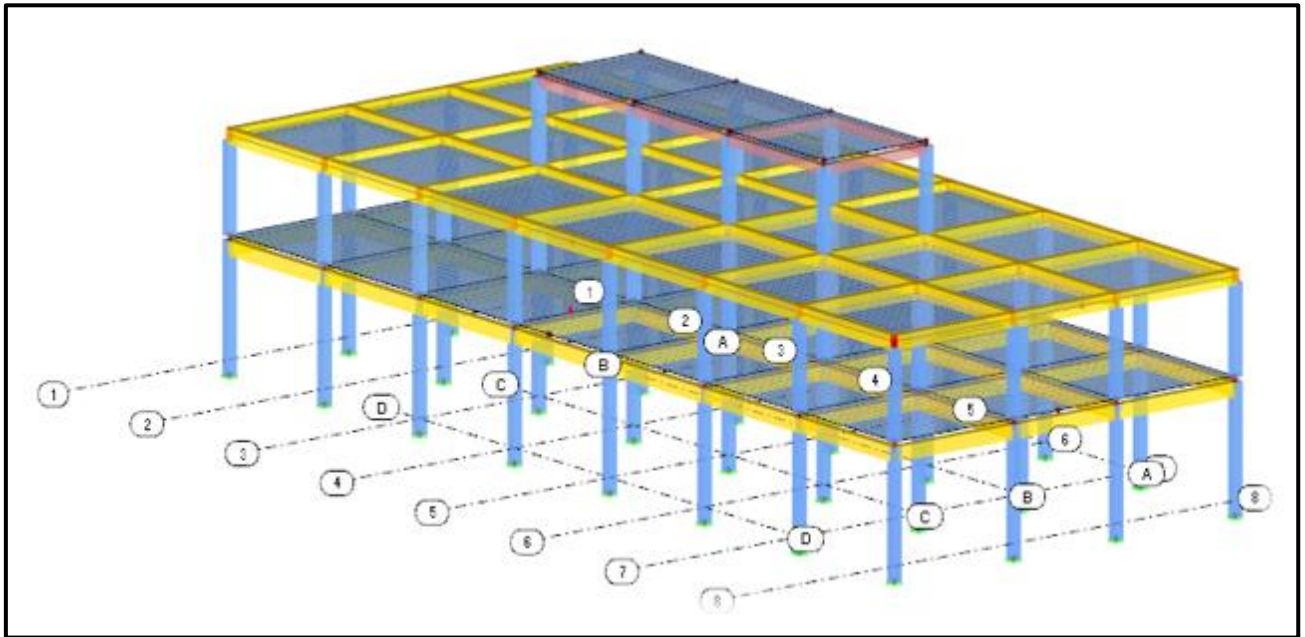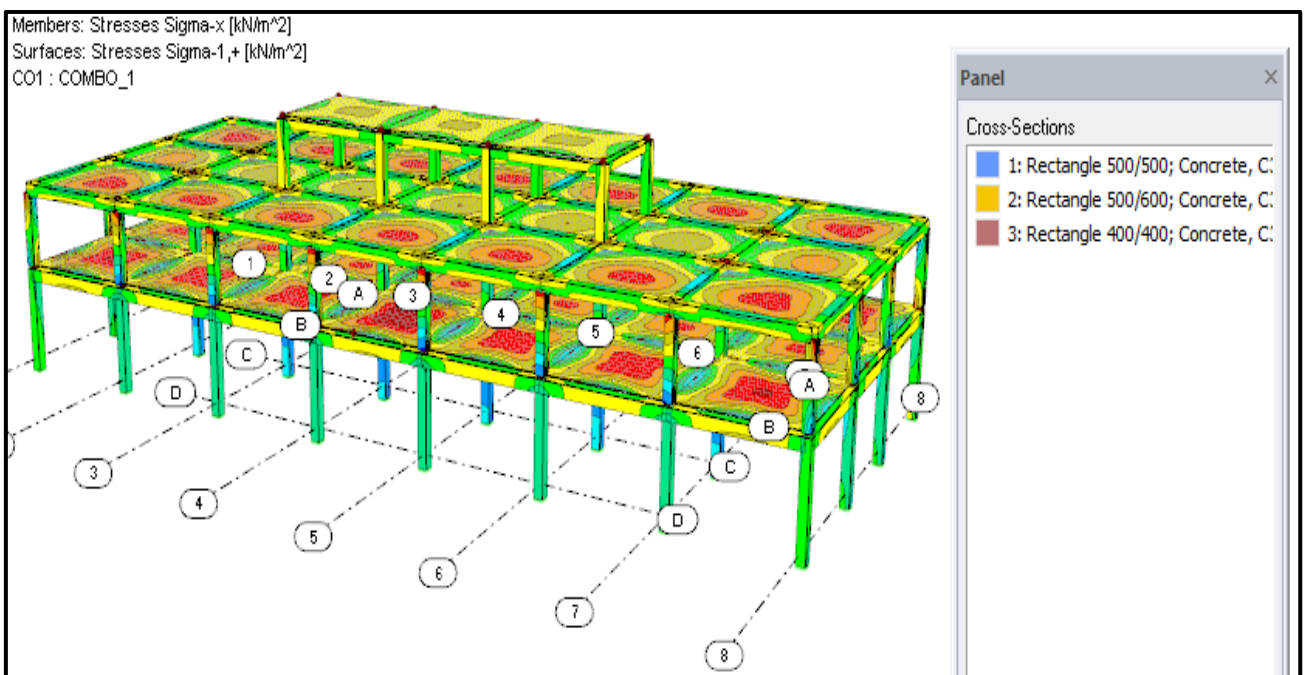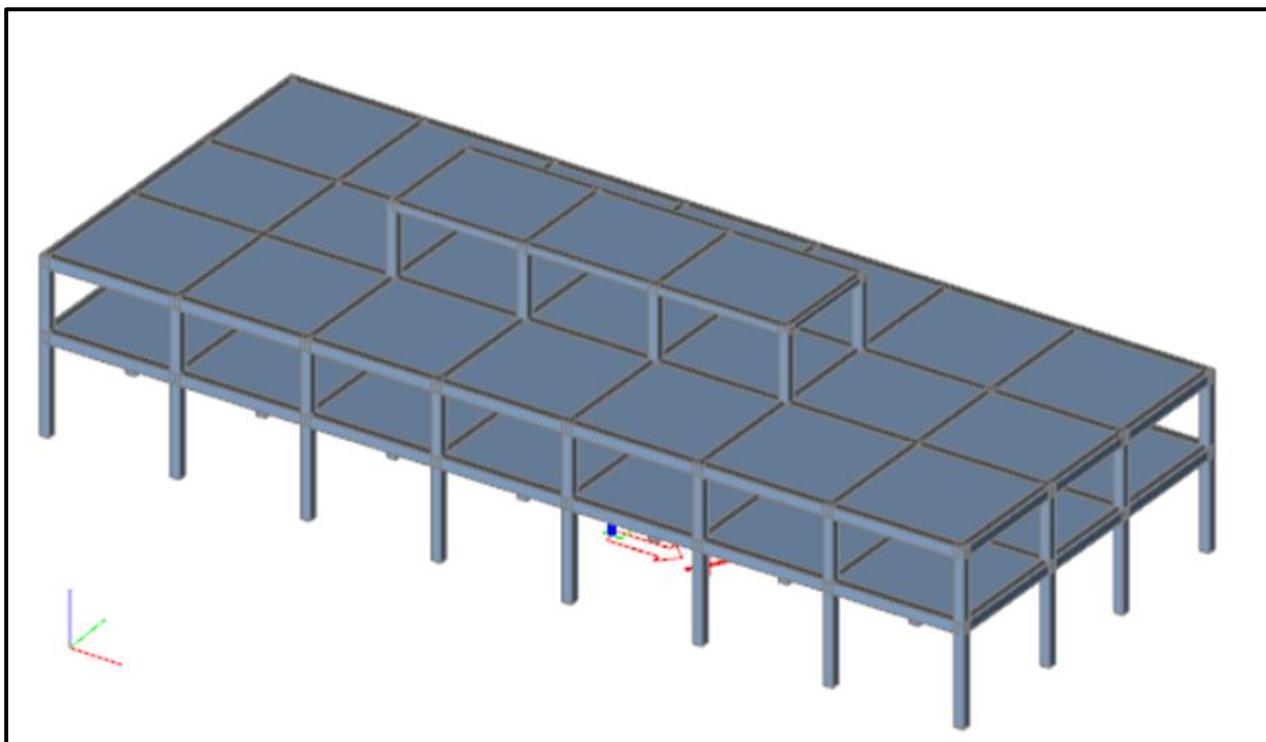

Figure 62: 3D view in SCIA Engineer
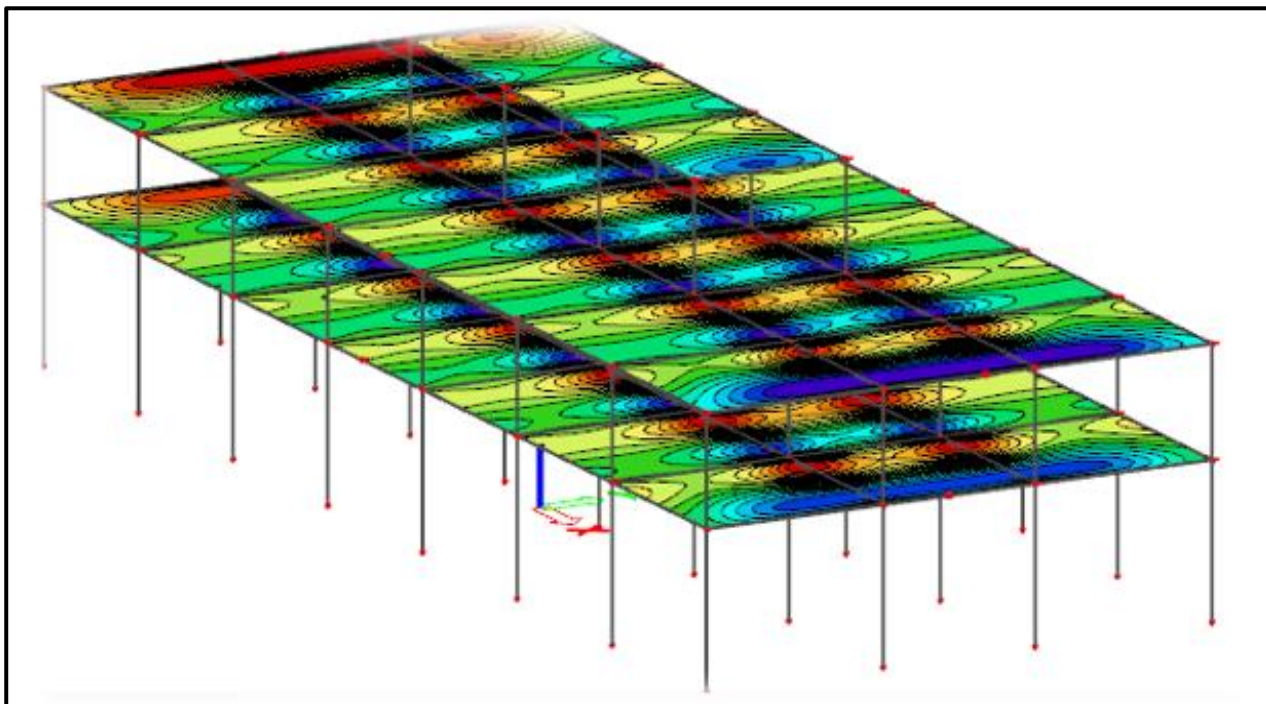
Figure 63: FEM model in SCIA Engineer

Results

Results obtained from Revit-RFEM exchange scenario are summarized in Table 6.

Legend	
√	The structural properties are correctly transfer from BIM to FEM tool
ₓ√	Minor medications in the FEM tool are required before properties are correctly transferred.
×	No transfer is possible

Table 6: Exchange results from Revit to SCIA Engineer.

Structural Data	Revit ⟷ SCIA Engineer
Geometry	
Overall model	√
Beam (Length)	√
Beam (cross sections)	√
Column (Length)	√
Column (cross sections)	√
Slab	√
Floor plan (axis)	√
Material Properties	
Material type (concrete)	√
Material Strength	ₓ√
Material type (reinforcing steel)	×
Material strength	×
Boundary Condition	
Fix support	√
Load	
Dead load	√
Live load	√
Snow load	√
Wind load	√
Load Combination	
All combinations	√
Result Exploration	
Calculated results back to Revit	√

Disclaimer

It is worth mentioning that the case study (Revit-SCIA Engineer Interface) was developed based on the 2020 version of SCIA (SCIA Engineer), as well the work is exclusively based on the personal experience and know-how of the author as it regards exchanging CAD model (Revit) data with SCIA Engineer. The preparation of the case study also coincides with the launch of SCIA's innovative AutoConverter— a neutral web-based app that automatically converts any structural model (physical load-bearing model) into a valid analytical model to be used by any structural or FEM software for analysis and design purposes [41]. Hence, to keep the focus on the central theme of the thesis (direct conversion from Revit to FEM), the author did not find the need to apply the AutoConverter, as it would be to the disadvantage of the other two FEM software selected for the case studies (SOFiSTiK and RFEM). However, it is worth mentioning that most of the challenges faced during the direct link conversions can be easily corrected using the AutoConverter. The AutoConverter facilitates structural engineers' transition in OpenBIM initiatives; it helps engineers save time, eliminate remodelling, reduce model errors, enhance project collaboration, improve model quality, and shows a high degree of flexibility.

5.4   Case Study 1B: Comparisons of Internal Forces of the 3 FEM Software Programs

To test the quality and correctness of structural analysis done via the direct link interface (as opposed to being done via standalone FEM program), a linear static analysis was performed on a portion of the model (grids A-C and 3-4), as shown in Figure 65. The loads in table 2 were applied linearly on the beams. The ultimate limit state load combination in Table 3 was considered, and the self-weight for each program was activated. Figure 66 shows the extracted frame and the 3D analytical model in Revit, under consideration (highlighted in red). This specific case study contains no wind load.
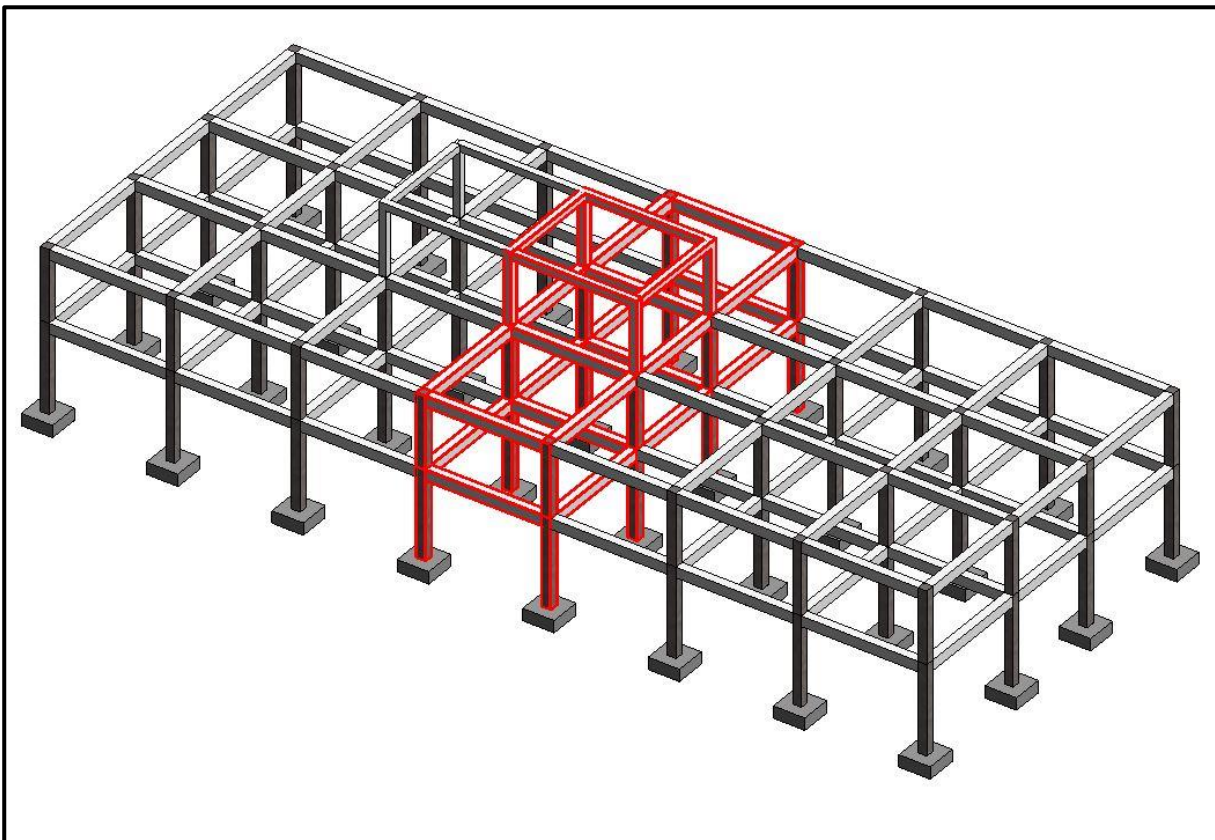
Figure 64: The highlighted (red) frame extracted as a subsystem for case study 1B analysis
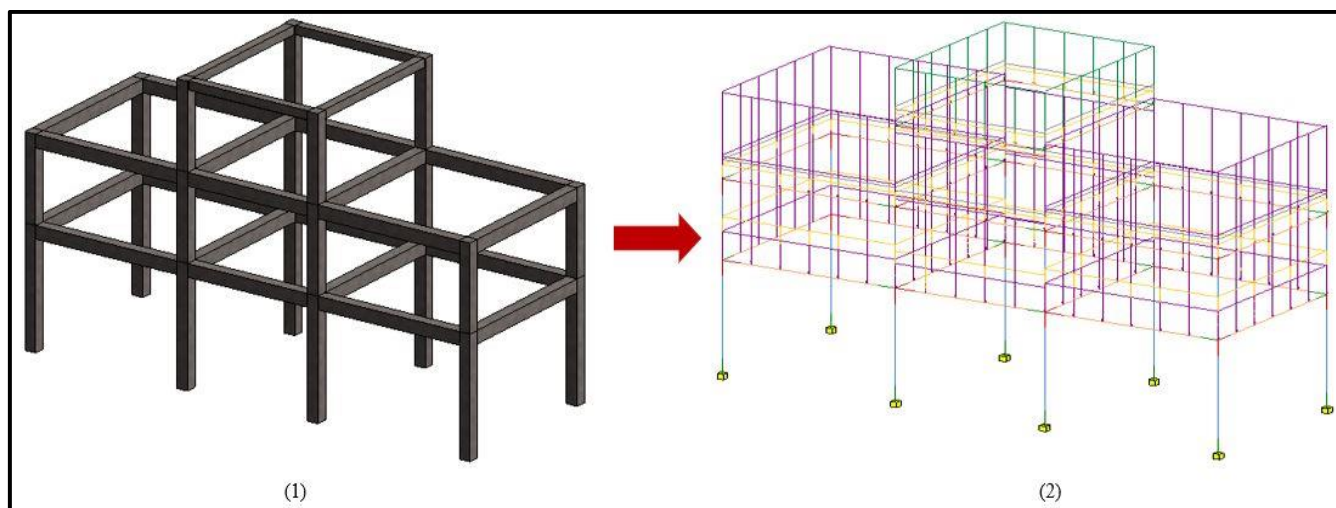
Figure 65: (1) 3D model of the frame; (2) Analytical model with applied loads

Table 7 presents a summary of internal forces obtained from the analysis. Please refer to Appendix 1 for a detailed result of internal forces diagrams for each software program. The maximum internal force values are reported for each software program. The closed proximity of these results shows that once the structural data is correctly entered in Revit, the BIM structural engineering links would produce credible, consistent, and quality results. The outcome of this case study represents an important finding of this thesis.

Table 7: Comparison of internal forces

Internal Forces						
FEM Program	Max. Bending Moment -Beam (kNm)		Max. Shear Force -Beam (kN)	Max. Axial Force (kN)	Max. Support Reaction (kN)	Max. Global Deformation -u_z (mm)
	M^+	M^-				
SOFiSTiK	404	547	481	-2661	2661	11.4
RFEM	396	545	478	-2645	2645	11.7
SCIA	398	546	479	-2656	2656	11.7

5.5   Case Study 2: BIM Workflow in Structural Engineering with SOFiSTiK

In this case study, the slab on the first floor of the model is chosen and designed as a subsystem from the main model. SOFiSTiK allows for a portion of a building structure to be designed as a subsystem. This specific case study intends to test the capabilities of the Revit-SOFiSTiK BIM workflow. This was achieved by subjecting the model to a structural engineering design cycle, including visual scripting of the structural geometry in Dynamo (open-source plug-in linked with Revit); modelling; analysis; design; detailing; and documentation. The case study utilizes the same structural model data and follows the design standards as in previous cases. Figure 67 demonstrates the BIM workflow. As seen in this figure, the BIM and analytical model are created in Revit, followed by transferring the model to SOFiSTiK for finite element analysis and design; the model is then brought back to the interface (Revit-SOFiSTiK) for reinforcement generation, detailing and documentation. Detailed discussion and the main results of the workflow are provided below. Please refer to Appendix 3 for a detailed report of results obtained using SOFiSTiK.
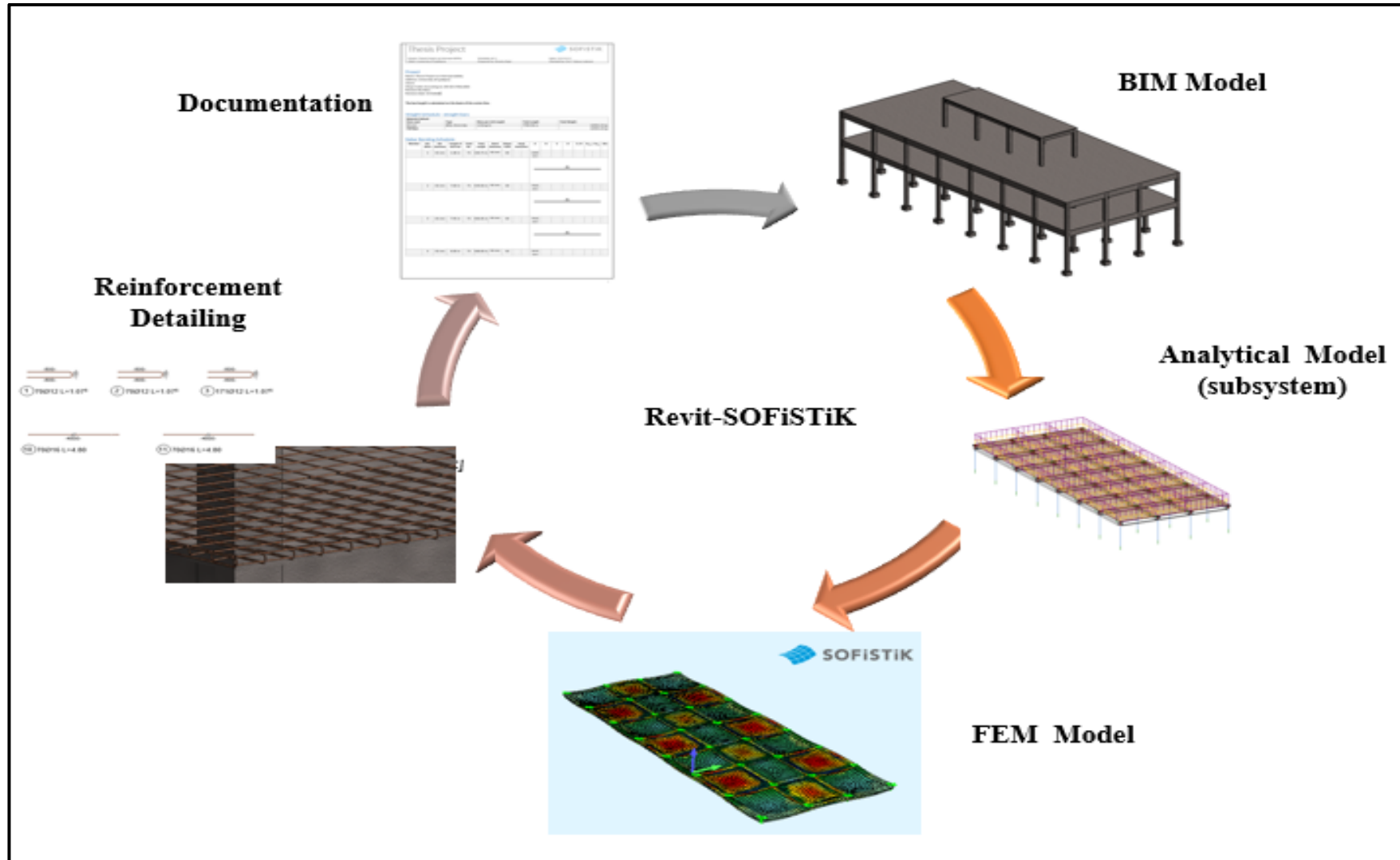
Figure 66: Structural Engineering BIM workflow in case study 2

5.5.1   3D Model

The BIM model is shown in Figure 68 with an attached Dynamo script environment. Parametric-based geometric model in Dynamo allows for easy adjustments to be made to the model during structural analysis by simply changing the script lines in dynamo nodes. In Revit, relevant BIM-based meta-data is added along with structural data, including loads and load cases, load combinations, and boundary conditions. Figure 69 to 71 show the complete dynamo scripts and Revit model, Dynamo nodes for grids, interception points, and levels.

Figure 67: BIM model geometry created with Dynamo

Figure 68: Dynamo nodes for grids creation
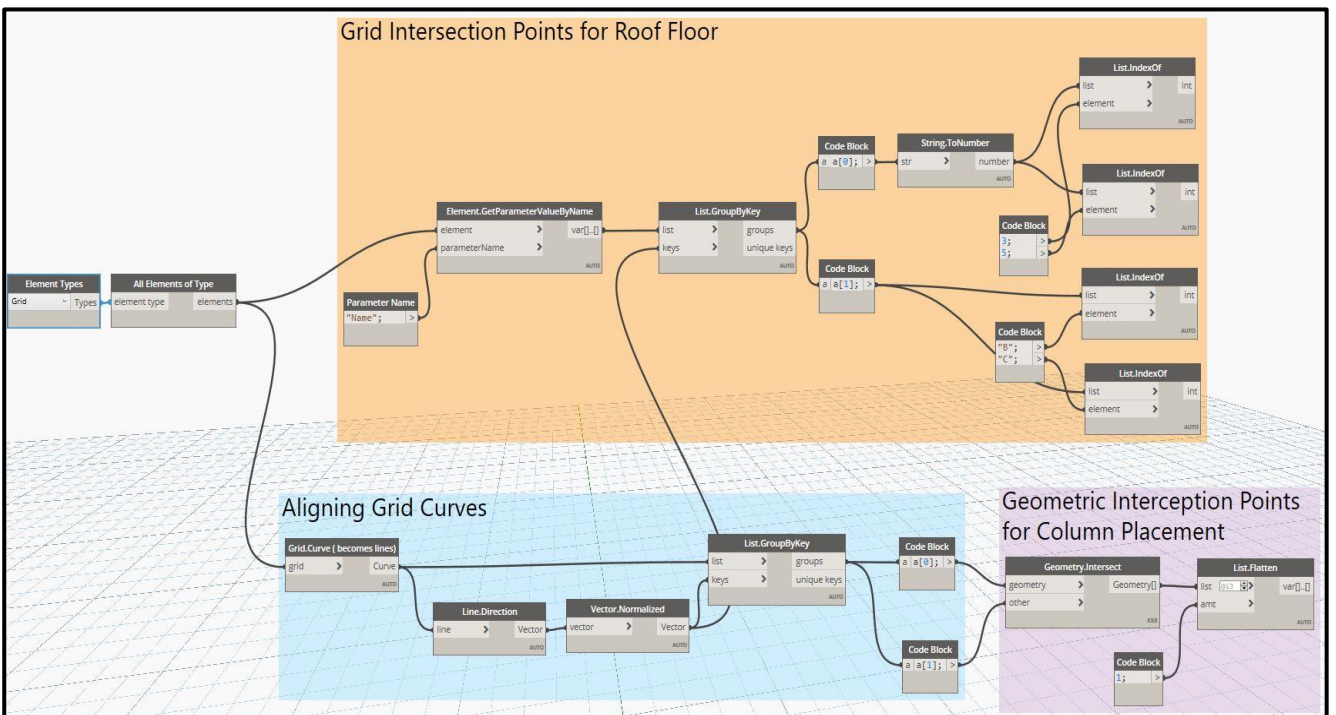
Figure 69: Dynamo nodes for interception points for columns and beams creation
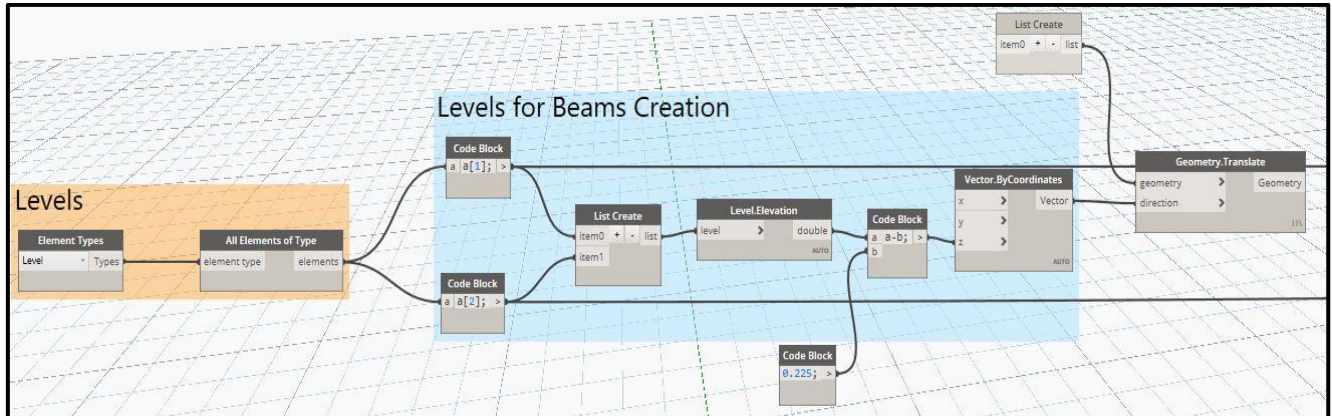
Figure 70: Dynamo nodes for level creation for beam

5.5.2   Analytical Model

A descriptive presentation of analytical models in a BIM environment is dealt with in chapter three. In Figure 72, the analytical model of a slab is shown in a Revit environment with applied loads; and ready to be exchanged with SOFiSTiK for structural analysis purposes through the existing bi-directional link.
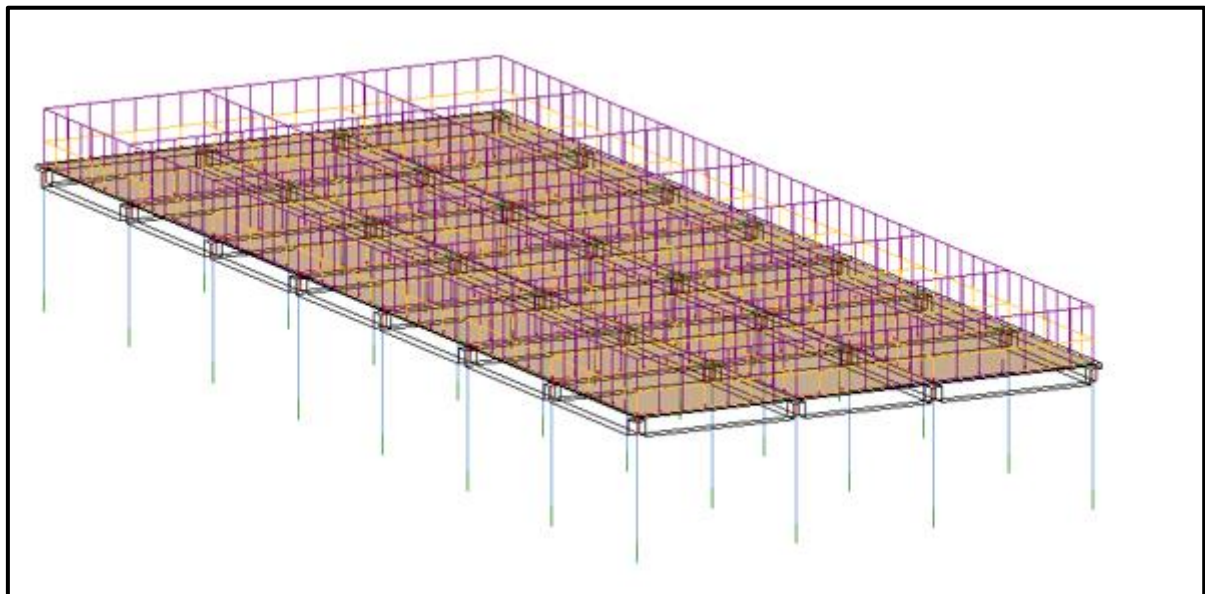
Figure 71: The analytical model for the slab (subsystem) in the case study

5.5.3   Finite Element Model

After cross-checking the analytical model in Revit, the model is exported to SOFiSTiK for finite element analysis, as shown in Figure 73.
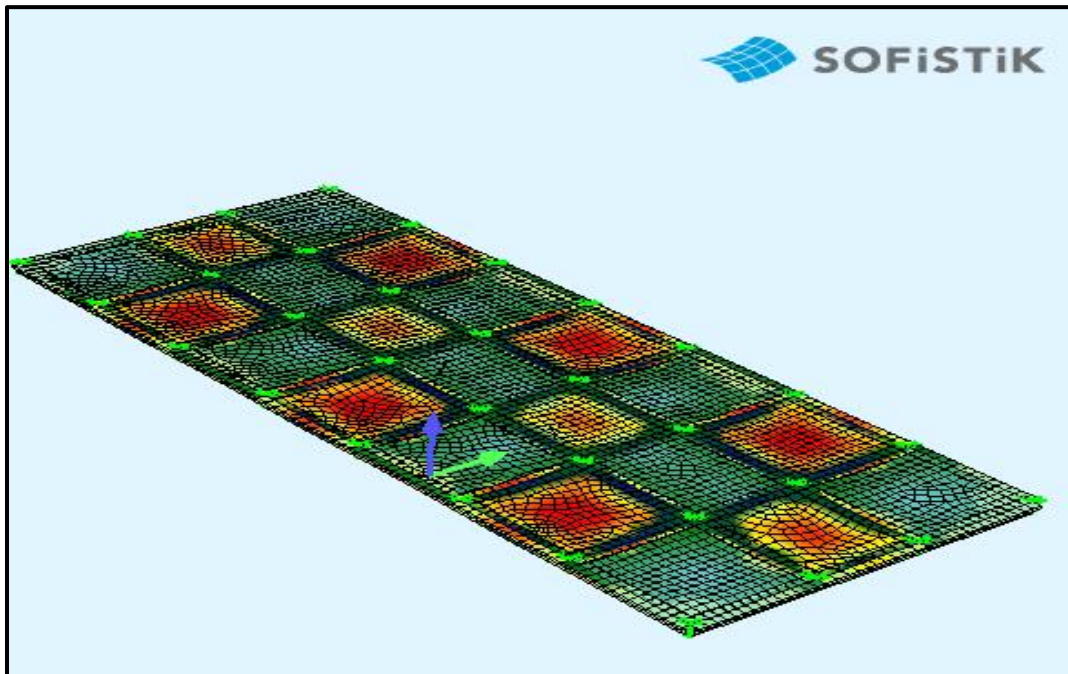
Figure 72: FEM model of the slab (subsystem)

5.5.4   Reinforcement Detailing

Based on the analysis and design results obtained in SOFiSTiK, a 3D rebar model was generated (see Appendix 3) in Revit, where it was possible to extract 2D reinforcement drawings, schedules, and documentation. It is also possible to visualize and adjust the rebar model based on existing versus required reinforcement. For this case study, only the first-floor slab is designed and detailed based on the ultimate limit state in Eurocode 2 [43]. See Appendix 3 for more details on reinforcement.

Reinforcement area

Appendix 3.D and 3.E show the maximum design reinforcement area generated at both the bottom and top of the slab. Based on these values (for simplicity), bar diameter **16 mm** and spacing of **300 mm,** were chosen for both the bottom and top reinforcement.

Detailing

Based on the chosen reinforcement diameter, the strength of reinforcing steel, and material parameters, following Eurocode 2 provisions on detailing of members in chapter 8 (section 8.4 and section 8.7), the design anchorage length and lap length were defined accordingly (see Appendix 3 - reinforcement drawings).

5.5.5   Documentation

See Appendix 3 for a full detail on documentation and scheduling of rebars for this case study.

5.5.6   Verification Procedure

As a way of verifying the results obtained from the FEM analysis, a hand calculation was performed. As shown in Figure 74, I analysed the slab bounded by grids 3-4 and B-C. The internal forces of the

Nyei, M. 2021. BIM in Structural Engineering:
A Study of Interoperability Between BIM Platform and FEM Software on Structural Modelling, Analysis and Design.
Master Th. Ljubljana, UL FGG, Second Cycle Master Study Programme Building Information Modelling — BIM A+

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slab are obtained using the coefficient method, based on the tables of Nilson and Winter's Design of Concrete Structures - 10th edition [46]. See Appendix 2 for more detailed results on the hand calculation.
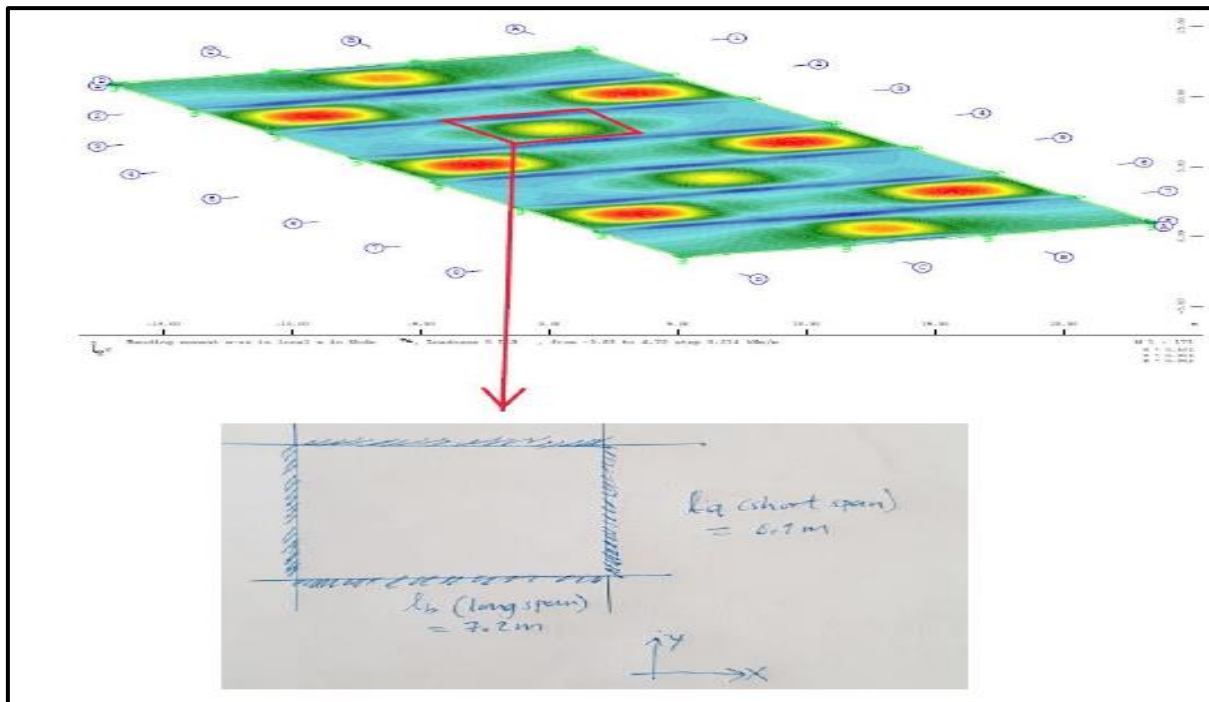
Figure 73: Portion of the slab (middle) analysed with hand calculation —all sides assumed fixed (Case 2 in Nilson and Winter) [46].

Tables 8 and 9 compare the results of internal forces and reinforcement areas obtained from hand calculation and SOFiSTiK. These results demonstrate fairly good proximity, thus the confidence to proceed with detailing of the slab. The slight difference noticed in some of the figures in table 9 is because unlike the hand calculation, where the slab element (axis B-C and 3-4) was modelled as an isolated system, SOFiSTiK, on the other hand, the entire floor slab was modelled. Based on the hand calculations results, I was able to control the following parameters (see Appendix 3) from the SOFiSTiK reinforcement generation ribbon: the required amount of reinforcement, diameters, number, and spacing of bars.

Table 8: Comparison of internal forces results obtained by hand calculation and SOFiSTiK

Method Of Analysis	Short Span (Ma)		Long Span (Mb)		DL+LL		Negative Moment (gd+qd)	
	$M_{a,dl}$ [kNm]	$M_{a,ll}$ [kNm]	$M_{b,dl}$ [kNm]	$M_{b,ll}$ [kNm]	M^{dl+ll}_{a}, [kNm/m]	M^{dl+ll}_{b}, [kNm/m]	M^-_a [kNm]	M^-_b, [kNm]
Hand Calculation	8.68	6.2	6.04	4.43	14.88	10.47	33.22	22.85
SOFiSTiK	6.71	2.8	5.32	2.21	13.4	12	26.6	24.9

Table 9: Comparison of required reinforcement areas obtained by hand calculations and SOFiSTiK

Method of Analysis	Bottom reinforcement area- short span (cm²/m)	Bottom reinforcement area-long span (cm²/m)	Top reinforcement area above support -short span (cm²/m)	Top reinforcement area above support-long span (cm²/m)
Hand Calculation	2.38	1.84	5.38	3.66
SOFiSTiK	2.4	2.34	6.3	5.7

5.6   Summary

With the aid of the case studies, this chapter demonstrates that the direct link method of interoperability is the most effective and efficient means of exchanging structural data in a BIM structural engineering workflow. Case study 1 compares the effectiveness of data exchange via bi-directional links as well as compares internal forces generated as a result of these exchanges. The closeness of the results demonstrates the quality of structural analysis performed via BIM platforms. The fidelity and quality of the bi-directional or round-tripping link (Revit-SOFiSTiK) for BIM structural engineering workflow have also been proven. Results obtained from the structural analysis performed in SOFiSTiK and the hand calculation also show convincing proximity, further demonstrating an important finding. Throughout these case studies, the need for a BIM modeller or designer to have some degree of competence and knowledge in structural engineering was identified. This way, the modeller will have the capability and understanding in identifying potential problems in his/her model and make the necessary changes as possible.

6   DISCUSSION OF RESULTS

This chapter presents summary discussions of key findings of this thesis. Results of various exchange scenarios are discussed and compared. A summary result table, with score marks showing how each structural parameter or data is transferred, is presented.

6.1   Case Study 1

As mentioned earlier, this thesis studies the effectiveness and seamlessness of data exchange between Revit and the following FEM tools: SOFiSTiK, RFEM, SCIA Engineer. This case study highlights those findings. Results obtained from all three exchange scenarios in case study 1A are presented in Table 10, while case study 1B results are further recapped.

6.1.1   Revit-SOFiSTiK Link
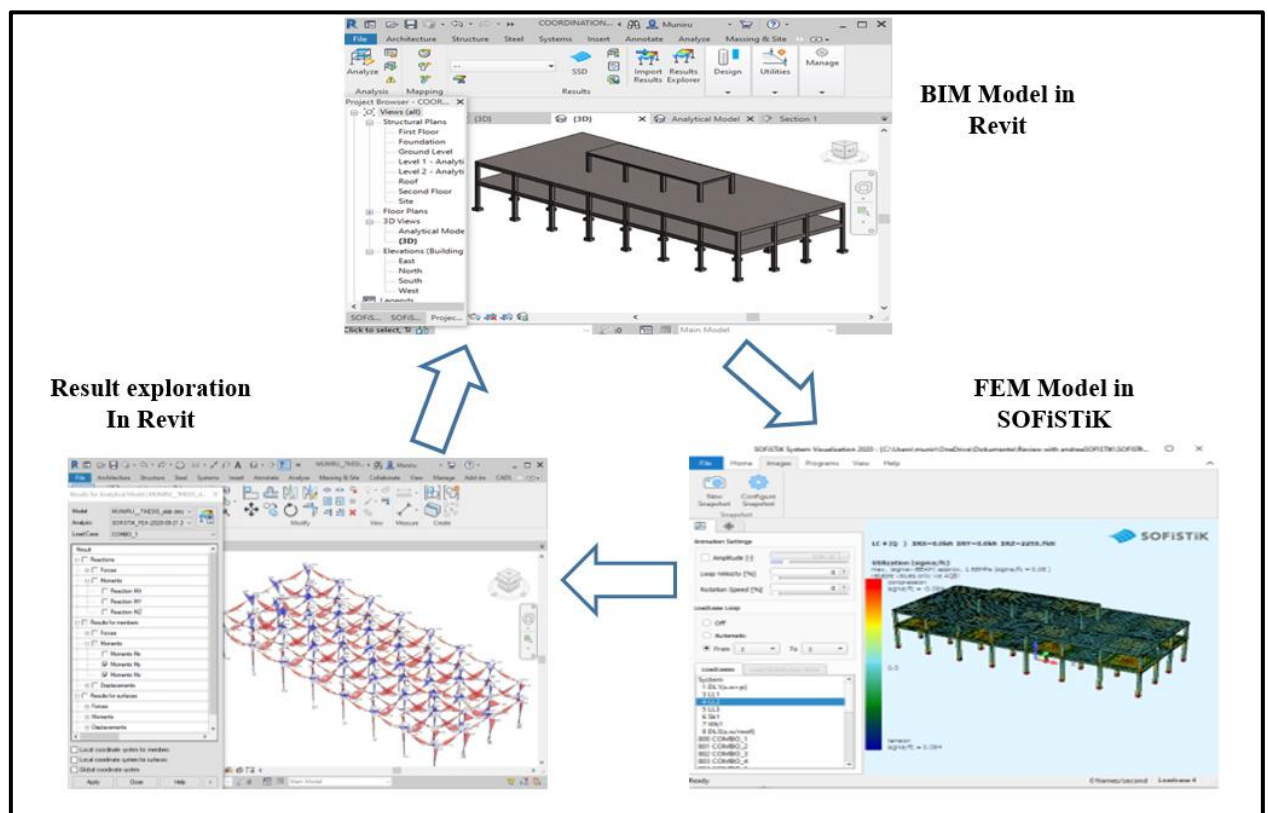
Figure 74: The round-tripping process: modelled in Revit, analysed in FEM and result checked back in Revit

Figure 75 graphically illustrates the concept of round-tripping in direct Link Interoperability: one interface, multiple analysis. As seen in the workflow, the BIM model is developed in the Rivet platform, passed onto SOFiSTiK for Finite Element Analysis. The analysed or designed model is then sent back to Revit for result exploration, detailing, and further investigation.

Geometry

The model geometry was created in Dynamo and modified in Revit. All geometry of the model, including beams, columns, slabs, were successfully exchanged between both software and verse versa. During the test, there were no difficulties or challenges established in handling the model back and forth. When model geometry is transfer to SOFiSTiK for analysis, SOFiSTiK allows for editing or transforming a rectangular beam to a T- beam based on structural analysis necessity.

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Material Properties

Material properties are essential components for any structural design and analysis, without which, analysis is impossible. A material mapping table is automatically generated in SOFiSTiK when a Revit model is exchanged via the direct link. Based on the code or chosen standard in Revit, each Revit material (e.g., concrete or steel) is mapped with the corresponding material in the SOFiSTiK environment. A correct material mapping ensures seamless exchange structural; hence, quality design and analysis results. In the Revit-SOFiSTiK interface, material and cross-section mapping capabilities are very effective and require no additional editing after the structural model is exchanged from one software to another [47]. Figure 76 shows how well both programs mapped the concrete material (C30/37).
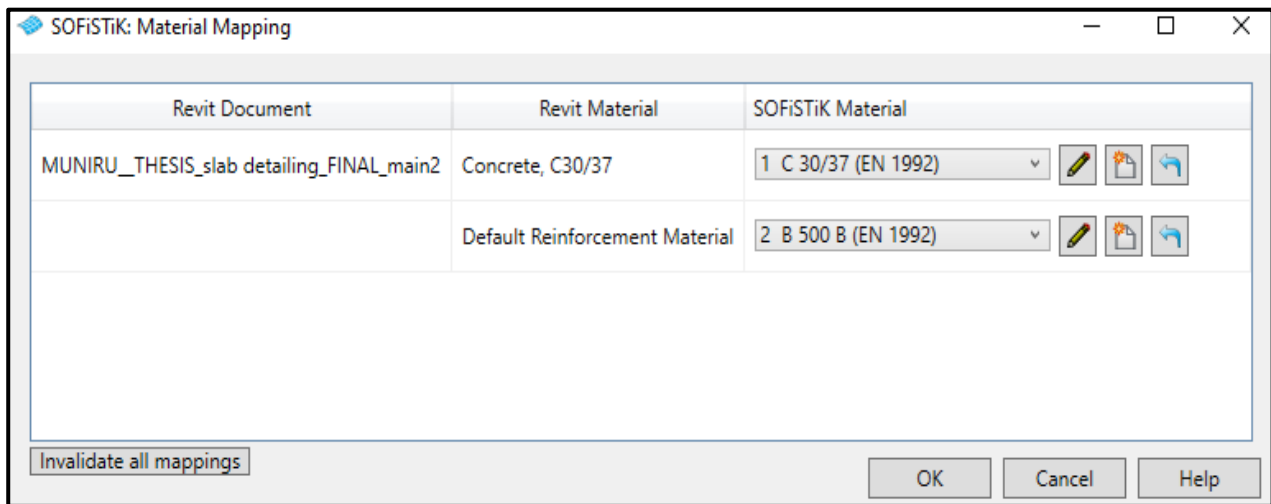
Figure 75: Mapping table between Revit structural materials and SOFiSTiK materials for verification and modification in case study

Boundary Conditions

Boundary conditions are necessary to communicate to the Finite Element analysis software about the support (fixed, pinned, roller, etc.). The Exchange of a structural model from the Revit BIM platform to an analysis software cannot proceed without first assigning the support or boundary conditions, where necessary. In Revit, boundary conditions (e.g., point, line, and area) are applied only on the analytical model. The exchange scenario showed that the model is capable of exchanging boundary conditions seamlessly.

Loads and Load Cases

This investigative case study considers four load cases, including dead, live, snow, and wind loads. In Revit, structural loads such as points, line, and area loads, were applied to the analytical model to assess possible deformations and internal forces. All load and load cases were successfully transferred from Revit to SOFiSTiK without further modifications. Figure 77 shows settings for load and load cases in Revit structure, displaying load cases adopted for this case study. See Table 2 for the values of these load cases.
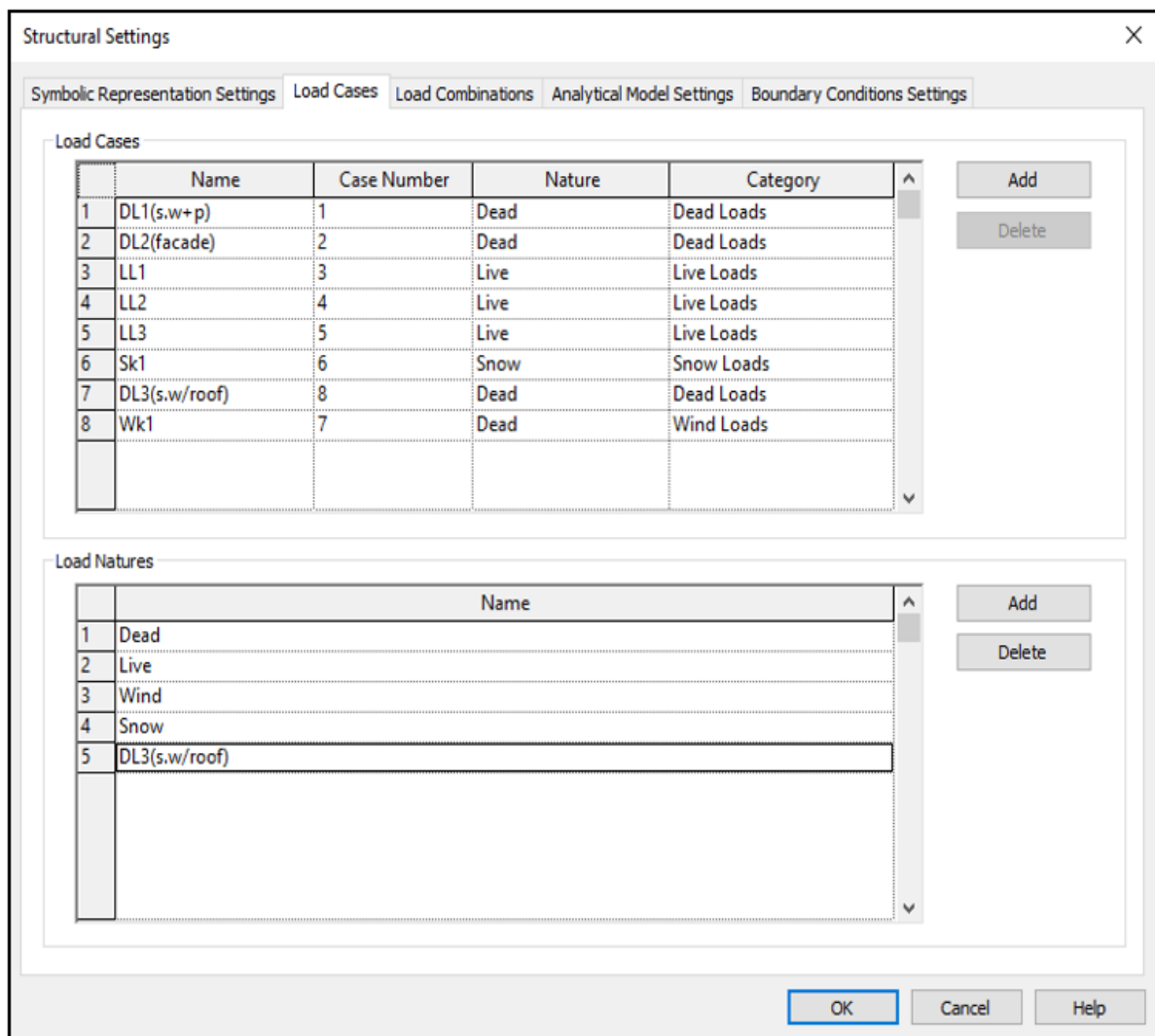
Figure 76: All load cases defined in Revit were seamlessly transfer to SOFiSTiK

Load Combination

In structural analysis, dead and live loads are combined to estimate the worst effects of actions on the structure, which induce maximum internal forces. In this case study, 24 load combinations are adopted considering both favourable and unfavourable design situations. For the simplification purpose of this case study, only the ultimate limit state is considered. The design combination and partial safety factors are adopted based on the requirements of Eurocode 2, as mentioned in section 5.1.2 [43].

This thesis demonstrates that it is possible to transfer successfully complex data like load combinations. With this, one can customize and control load combinations without allowing the structural software to do so. This enables users to share the central BIM model (Revit) with multiple structural analysis and design platforms that support BIM workflow. Such workflow saves a tremendous amount of time in terms of rework.

Figure 78 shows the load combination settings in Revit, while Figures 79 shows how the same combination is interpreted in SOFiSTiK.

	Name	Formula	
		(all)	
1	COMBO_1	1.35*DL1(s.w+p) + 1.35*DL2(facade) + 1.35*DL3(s.w/roof) + 1.5*LL1 + 0.75*Sk1 + 0.75*	
2	COMBO_2	1.35*DL1(s.w+p) + 1.35*DL2(facade) + 1.35*DL3(s.w/roof) + 1.5*LL2 + 0.75*Sk1 + 0.75*	
3	COMBO_3	1.35*DL1(s.w+p) + 1.35*DL2(facade) + 1.35*DL3(s.w/roof) + 1.5*LL3 + 0.75*Sk1 + 0.75*	
4	COMBO_4	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL1 + 0.75*Wk1	
5	COMBO_5	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL2 + 0.75*Wk1	
6	COMBO_6	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL3 + 0.75*Wk1	
7	COMBO_7	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*LL1 + 0.75*Sk1 + 0.75*Wk1	
8	COMBO_8	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*LL2 + 0.75*Sk1 + 0.75*Wk1	
9	COMBO_9	1.35*DL1(s.w+p) + 1.35*DL3(s.w/roof) + 1.5*LL3 + 0.75*Sk1 + 0.75*Wk1	
10	COOMBO_1	1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL1 + 0.75*Wk1	

	Name	Formula	
11	COMBO_11	1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL2 + 0.75*Wk1	
12	COMBO_12	1.35*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL3 + 0.75*Wk1	
13	COMBO_13	1*DL1(s.w+p) + 1*DL2(facade) + 1*DL3(s.w/roof) + 1.5*LL1 + 0.75*Sk1 + 0.75*Wk1	
14	COMBO_14	1*DL1(s.w+p) + 1*DL2(facade) + 1*DL3(s.w/roof) + 1.5*LL2 + 0.75*Sk1 + 0.75*Wk1	
15	COMBO_15	1*DL1(s.w+p) + 1*DL2(facade) + 1*DL3(s.w/roof) + 1.5*LL3 + 0.75*Sk1 + 0.75*Wk1	
16	COMBO_16	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL1 + 0.75*Wk1	
17	COMBO_17	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL2 + 0.75*Wk1	
18	COMBO_18	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL3 + 0.75*Wk1	
19	COMBO_19	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*LL1 + 0.75*Sk1 + 0.75*Wk1	
20	COMBO_20	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*LL2 + 0.75*Sk1 + 0.75*Wk1	
21	COMBO_21	1*DL1(s.w+p) + 1*DL3(s.w/roof) + 1.5*LL3 + 0.75*Sk1 + 0.75*Wk1	

	Name	Formula
22	COMBO_22	1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL1 + 0.75*Wk1
23	COMBO_23	1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL2 + 0.75*Wk1
24	COMBO_24	1*DL3(s.w/roof) + 1.5*Sk1 + 1.05*LL3 + 0.75*Wk1

Figure 77: A Revit setting showing load combinations adopted for the case study

Figure 78: SOFiSTiK load combination setting, showing exact translation of load combinations from Revit

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6.1.2   Revit-RFEM Link

Figure 79: *The round-tripping process: modelled in Revit, analysed in RFEM and result checked back in Revit*

Figure 80 graphically illustrates the concept of round-tripping in direct Link Interoperability, as mentioned in the previous case.

Geometry

The model geometry is created similarly as in the above section. All model geometry, including beams, columns, slabs, were reportedly exchanged successfully between both software and vice versa. During the test, there were no difficulties or challenges established in handling the model in both directions. RFEM, however, has a powerful visualization for cross-sections. Unlike SOFiSTiK, some adjustments are necessary to map the Revit cross-sections before a successful transfer (see Figure 81).

Material Properties

The concrete material mapping between Revit and RFEM is almost the same as in SOFiSTiK. However, some adjustments are necessary to change the Revit parameters to "Dlubal name parameters" to facilitate a correct exchange of material data (see Figure 82).
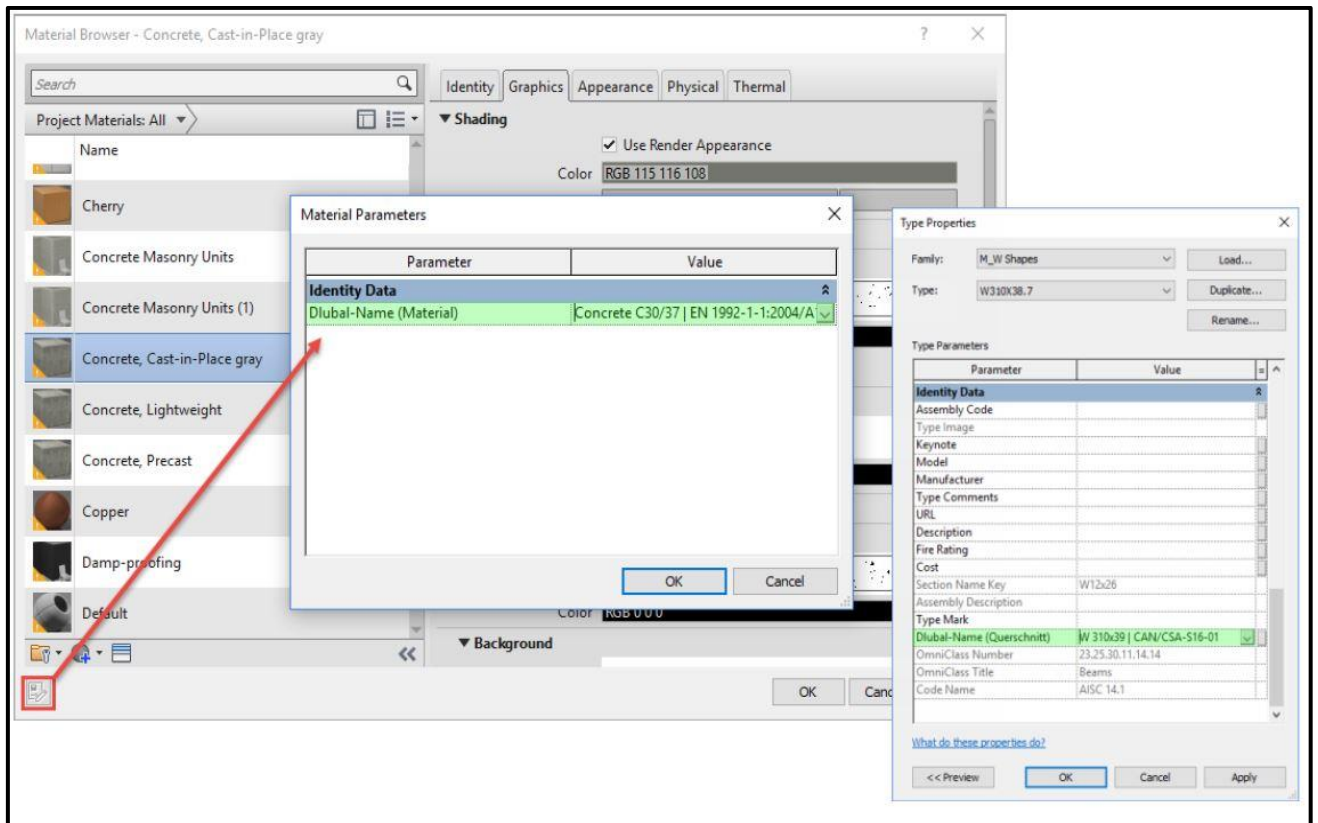
Figure 80: Conversion of Revit name parameter to Dlubal name parameter for the exchange
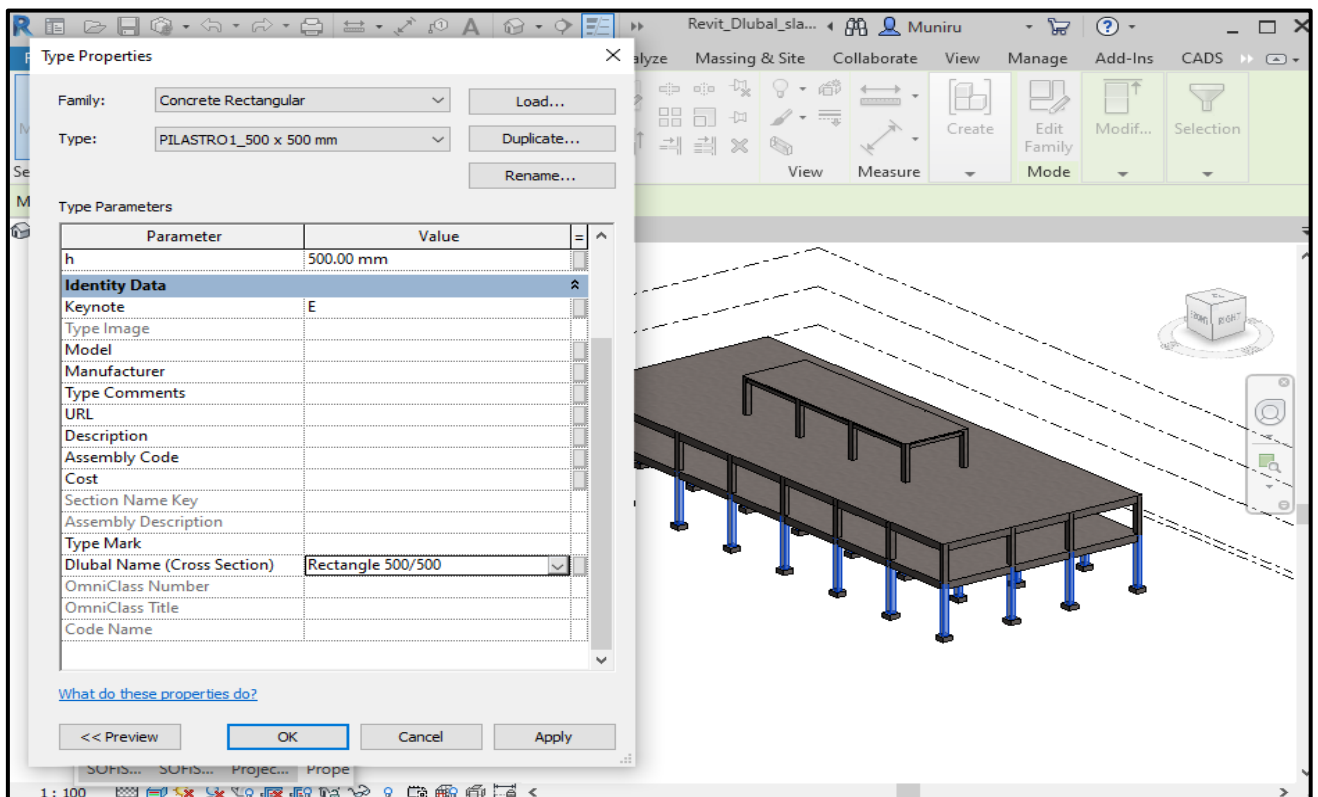
Figure 81: Conversion of Revit name parameter to Dlubal name parameter for cross section

Boundary Conditions

There were no issues found in transferring boundaries conditions from Revit to RFEM and verse versa. The exchange scenario works well, as in the case of Revit-SOFiSTiK.

Loads and Load Cases

As in the above section, load and load cases were successfully transferred from Revit to RFEM without the need for any further modifications. This finding is also considered very important.

Load Combination

The transfer of load combination was also very successful in the Revit-RFEM link. As seen in Figure 83, the RFEM load combination is on the left, and Revit is on the right side.

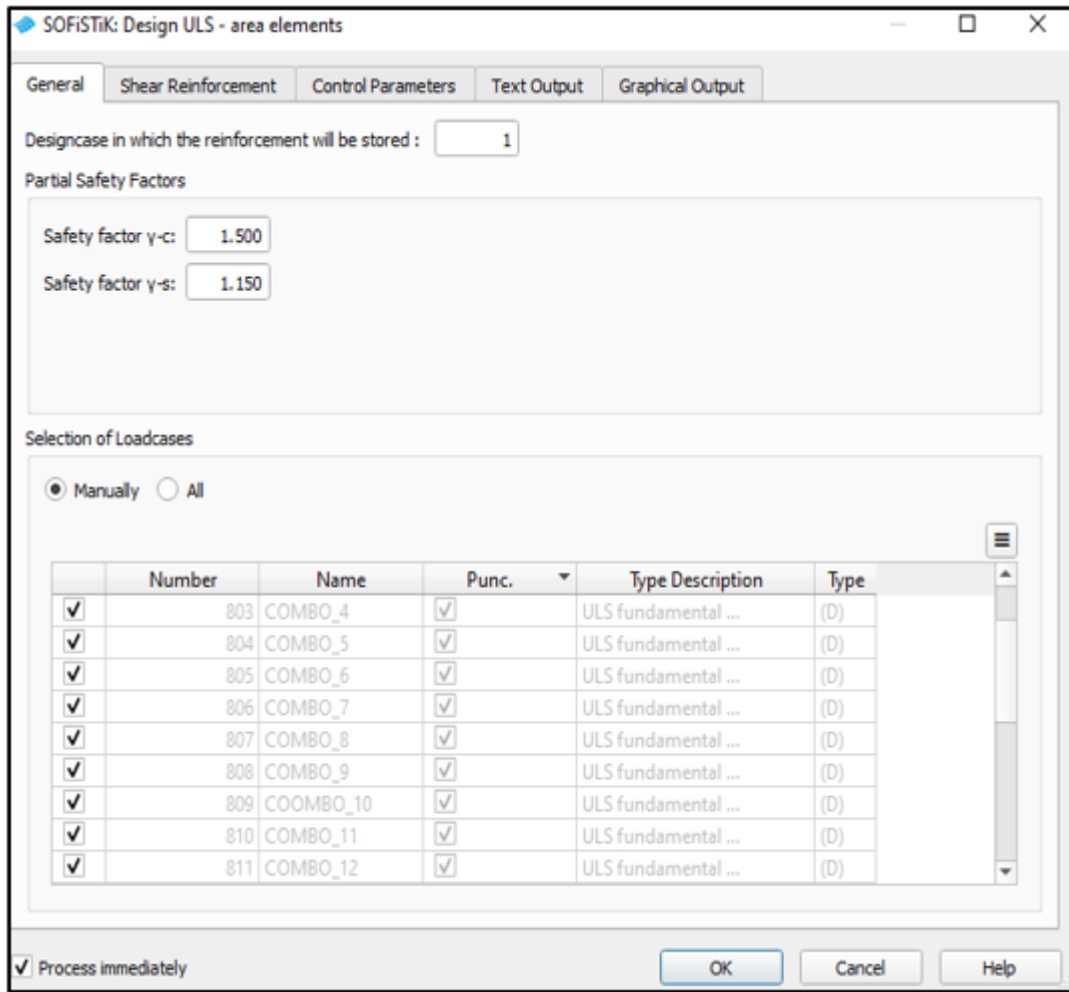| Existing Load Combinations	
CO1	COMBO_1
CO2	COMBO_2
CO3	COMBO_3
CO4	COMBO_4
CO5	COMBO_5
CO6	COMBO_6
CO7	COMBO_7
CO8	COMBO_8
CO9	COMBO_9
CO10	COOMBO_10
CO11	COMBO_11
CO12	COMBO_12
CO13	COMBO_13
CO14	COMBO_14
CO15	COMBO_15
CO16	COMBO_16
CO17	COMBO_17
CO18	COMBO_18
CO19	COMBO_19
CO20	COMBO_20
CO21	COMBO_21
CO22	COMBO_22
CO23	COMBO_23
CO24	COMBO_24

Figure 82: RFEM load combination setting showing exact translation of load combinations from Revit
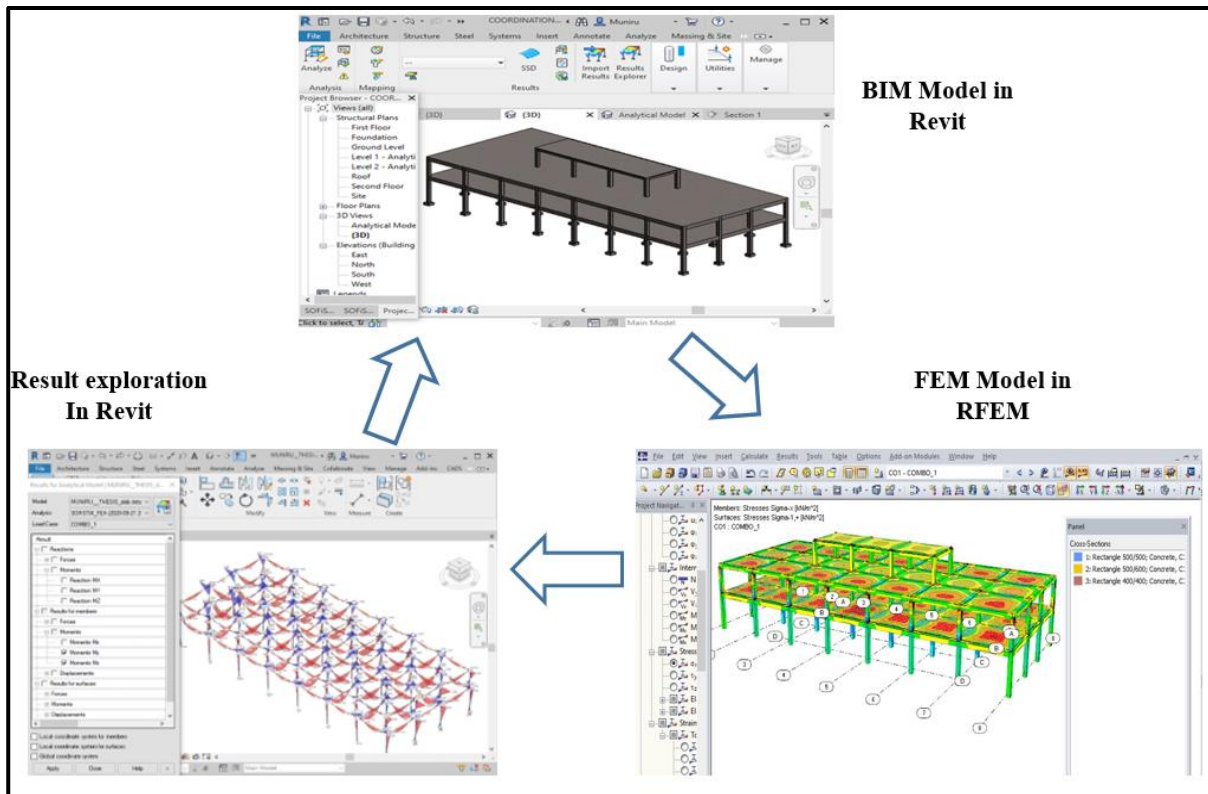
6.1.3   Revit-SCIA Engineer Link
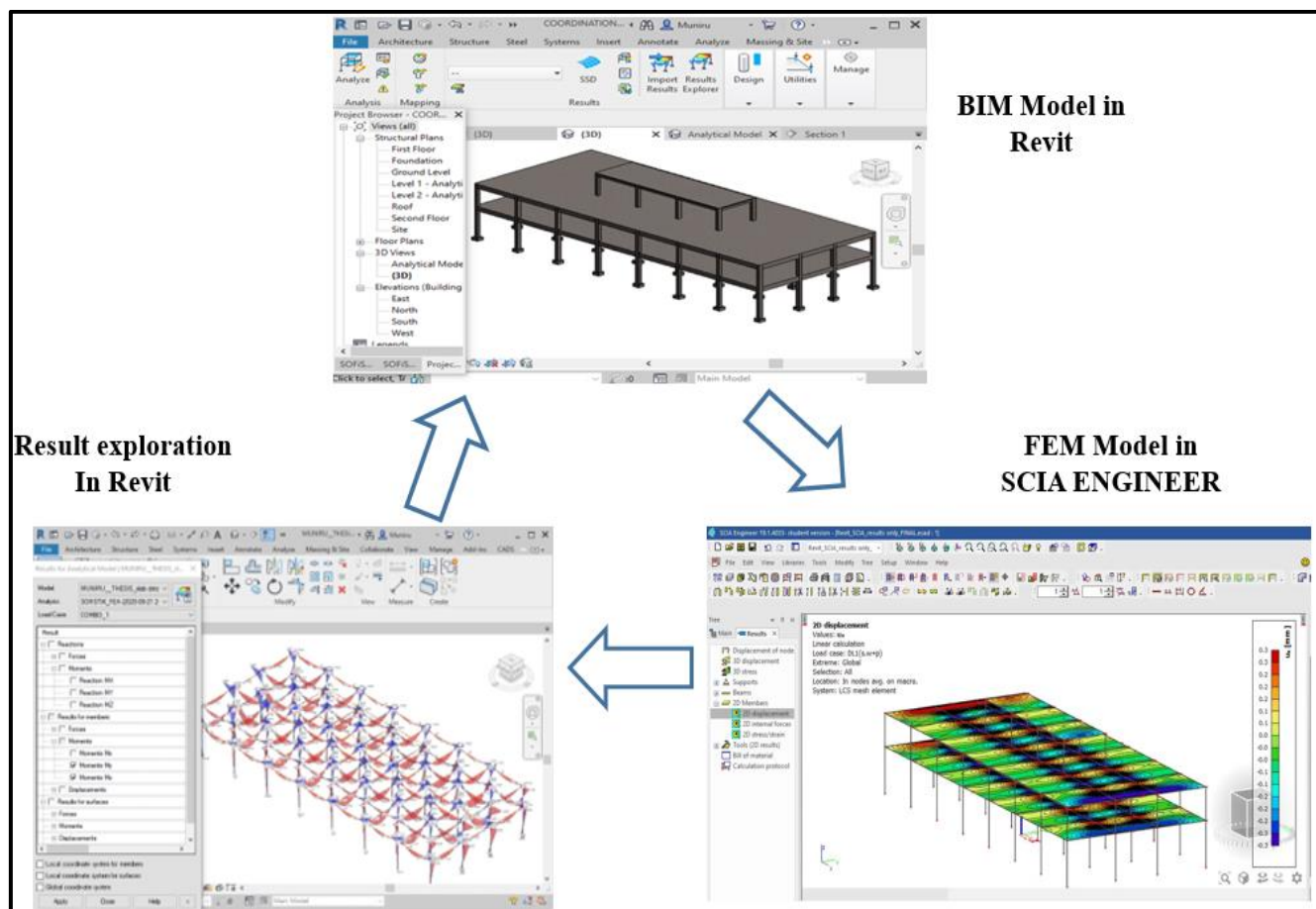
Figure 83: The round-tripping process: modelled in Revit, analysed in SCIA Engineer and result checked back

in Revit

Figure 84 graphically illustrates the concept of round-tripping in direct Link Interoperability, as demonstrated in the previous case.

Geometry

The model geometry was created similarly as in the above section. All geometry of the model, including beams, columns, slabs, were reportedly exchanged successfully between both software and vice versa. During the test, there were no difficulties or challenges established in handling the model in both directions. However, it is recommended to select the appropriate building Code or standard you wish to use in SCIA Engineer before exporting a BIM model; this will allow for easy processing and creation of the model in SCIA Engineer. Unlike SOFiSTiK, some adjustments, such as material mapping, are necessary to facilitate a successful transfer.

Material Properties

The concrete material mapping between Revit and SCIA Engineer is almost the same as in RFEM. The libraries in both Revit and SCIA Engineer do not use the same naming convention entirely. The CADS Revit SCIA Engineer link comes with a material mapping table to rectify this problem. Therefore, for my case study model to be successfully transferred to SCIA Engineer, I had to manually map Revit material families to correspond to that of SCIA Engineer materials/ sections, as shown in the material mapping table in Figure 85.
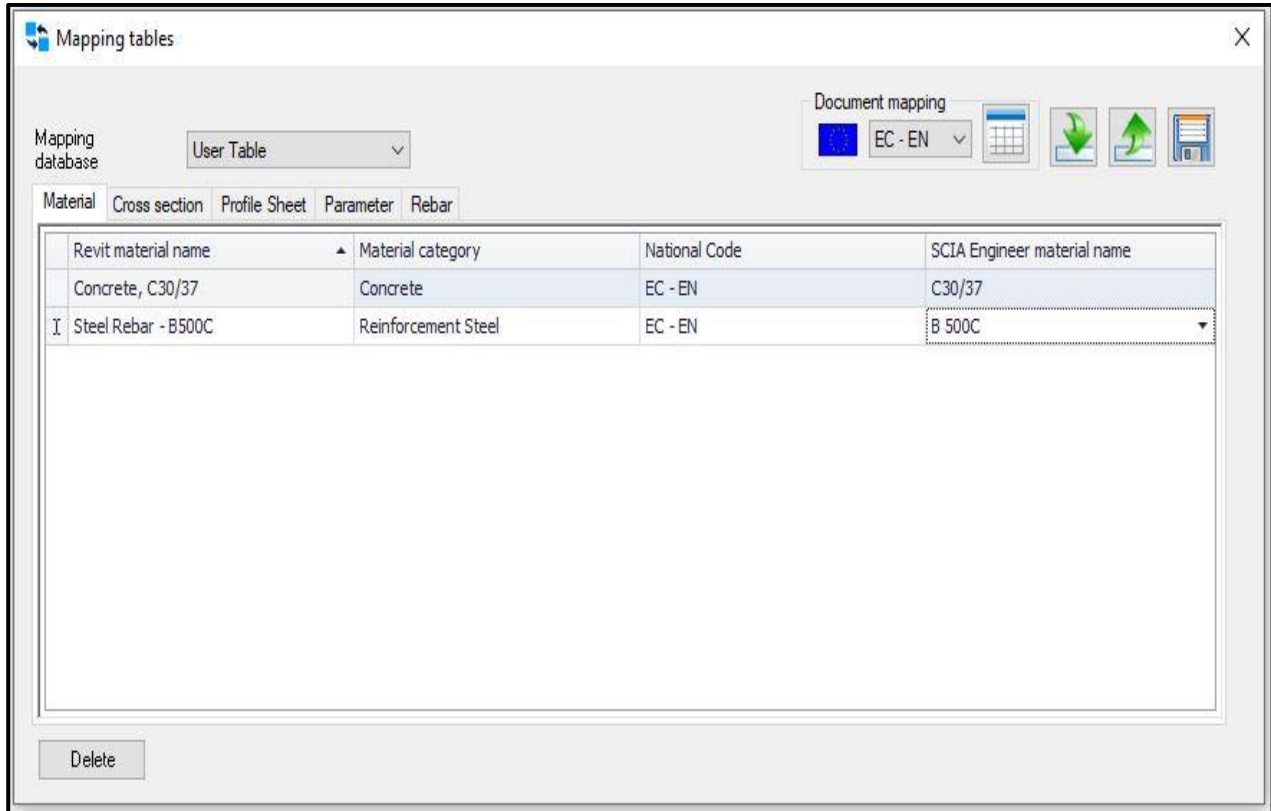
Figure 84: CADS Revit SCIA Engineer Link- Mapping tables

Boundary Conditions

There were no issues found in transferring boundaries conditions from Revit to SCIA Engineer and verse versa. The exchange scenario works well, as in the case of Revit-SOFiSTiK.

Loads and Load Cases

Loads transfer to SCIA pose some challenges because the CAD program which SCIA uses for bi-directional exchange is out-sourced to another vendor who uses a different software platform. This poses some challenges when exporting the load and load cases. However, the load export was mostly successful as in previous exchange scenarios.

Load Combination

The transfer of load combination was also very successful in Revit-SCIA Engineer, as shown in Figure 86.
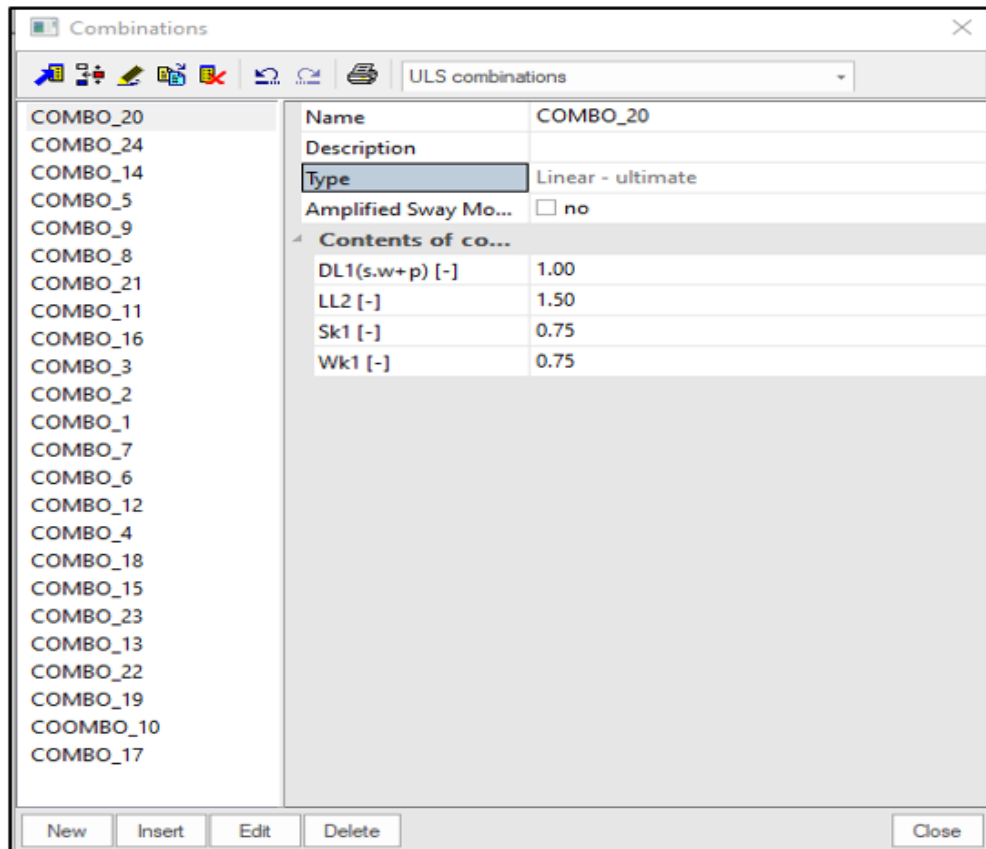
Figure 85: SCIA Engineer load combination setting showing exact translation of load combinations from Revit

6.2   Case Study 1A: Comparison of Results

Table 10 compares the results obtained from all three exchange scenarios in case study 1A with corresponding grades or score marks. The transfers are graded based on the percentage system (i.e., number of structural element/properties correctly transferred divided by the total number of elements in each category, multiply by a hundred per cent). Each structural element transfer is graded from 0 to 1 point. The grades are assigned based on the following criteria: a correctly transferred element/ property from BIM to FEM amounts to 1 point (full mark); when minor modifications are required before the model is transferred correctly, the score is 0.5; and, when no transfer is possible, the score is zero. Based on the analysis of all exchanged data, the Revit-SOFiSTiK link obtained a score of **100%** data transfer fidelity, followed by Revit-RFEM with **95%** and Revit-SCIA Engineer with **90%.**

Legend	
√	The structural elements/ properties are correctly transfer from BIM to FEM tool= 1
ₓ√	Minor medications in the FEM tool are required before properties are correctly transferred = 0.5
×	No transfer is possible = 0

Table 10: Comparative results of the 3 exchange scenarios

| Structural Data	Revit ⟷ SOFiSTiK	Revit ⟷ RFEM	Revit ⟷ SCIA
Geometry			
Overall model	√	√	√
Beam (Length)	√	√	√
Beam (cross sections)	√	√	√
Column (Length)	√	√	√
Column (cross sections)	√	√	√
Slab	√	√	√
Floor plan (axis)	√	√	√
Scores	**100%**	**100%**	**100%**
Material Properties			
Material type (concrete)	√	√	√
Material Strength	√	ₓ√	ₓ√
Material type (reinf. steel)	√	ₓ√	×
Material strength	√	×	×
Scores	**100%**	**50%**	**37.5%**
Boundary Condition			
Fix support	√	√	√
Scores	**100%**	**100%**	**100%**
Load			
Dead load	√	√	√
Live load	√	√	√
Snow load	√	√	√
Wind load	√	√	√
Scores	**100%**	**100%**	**100%**
Load Combination			
All combinations	√	√	√
Scores	**100%**	**100%**	**100%**
Result Exploration			
Calculated results back to Revit	√	√	√
Scores	**100%**	**100%**	**100%**
TOTAL SCORE	**100%**	**90%**	**88%**

6.3   Case Study 2

The collaboration between Autodesk Revit and SOFiSTiK in bringing BIM to the doorstep of structural engineering discipline through their bi-directional link—Revit-SOFiSTiK interface— has proven to be promising. The workflow of case study 2 (see Figure 65) demonstrated the technical capabilities of this well-integrated interface, wherein an entire structural engineering design workflow was implemented via this interface, from BIM data input to modelling, analysis, design, post-processing of results. The outcomes of this study were overall very impressive.

The findings further show impressive outcomes regarding generating a 3D reinforcement model from which detailed 2D reinforcement plans are extracted for scheduling and documentation. Also, the study shows that, by utilizing the Revit-SOFiSTiK interface in structural design practices, time and project efficiency can be optimized. For example, in the design of a reinforced concrete structure, to have the possibility to detail, annotate, and create schedules for structural members utilizing a single platform, is considered a milestone contribution made by Autodesk and SOFiSTiK toward documentation of structural engineering BIM workflow.

7   CONCLUSION

Literature review and case studies performed to analyse the interoperability capabilities of three different FEM software: SOFiSTiK, RFEM, and SCIA, with respect to Revit BIM software.

The study verified that the interoperability level due to the direct link is a widely accepted method by structural engineers to enhance their workflow in a BIM environment. The direct link interoperability level or bi-directional data exchange is effective; it ensures the correct transfer of structural data from a BIM platform to structural engineering software and performs well compared to other mentioned levels.

Two case studies (cases studies 1 and 2) are employed to understand interoperability challenges. Case study one is sub-divided into part A and part B. Case study 1A reports on the direct link exchange capabilities between the Revit BIM platform and the FEM software mentioned above. The study shows that the Revit-SOFiSTiK link achieved the best result in terms of a direct link or bi-directional interoperability. Table 10 shows the results obtained during the exchange process. A percentage score is used to evaluate the correctness and quality of data exchange or transfer. The grades range from 0 to 1 (lowest to highest mark). Grades are assigned based on the following criteria: correctly transferred element/ property from BIM to FEM amounts to 1 point (highest), while data transfer that requires minor modifications in the link before the correct exchange takes place is graded 0.5; and, when no transfer is possible, the score is zero. Based on the analysis of all exchanged data, the Revit-SOFiSTiK link obtained the highest score of 100% data transfer fidelity, followed by Revit-RFEM with 95%; and Revit-SCIA with 90%. However, these grades or ratings are assigned based on the personal experience and know-how of the author. As well, the case studies are implemented with the 2020 version of both BIM and FEM software. Worthy to note also, at the time of publication of this thesis, some of the software companies have already jump-started the process of improving their product performance as far as BIM workflow is concerned. Emerging tools like SCIA's AutoConverter and neutral file sharing format (e.g., Structural Analysis Format or SAF) have industry professionals on the lookout because of their promising features in facilitating interoperability through OpenBIM initiatives.

Case study 1B compares internal forces generated from the FEM analysis; with the intent to examine the quality of the structural analysis result obtained via direct link interoperability. It tries to provide answers to the question: is the FEM analysis providing reliable results when the structural modelling process is initiated via a BIM platform? Hence, to provide a scientifically based answer to this question, a linear static ultimate limit state analysis is performed on a portion of the model (grids A_C and 3-4). The same structural data in previous cases were used as input data in Revit and exchanged with the three FEM programs mentioned supra. Table 7 shows a comparison of internal forces. The closed similarity of these results provides evidence that the quality of structural analysis performed via the direct link in Revit has been proven. The closeness of these results further indicates that, with correct handling of the structural data from the initial stage, any structural analysis initiated via the Revit BIM platform will lead to a credible and quality result.

In case study two, the effectiveness, efficacy, and technical capabilities of Revit-SOFiSTiK BIM workflow, starting from modelling, analysis, and design, detailing to documentation, was tested. It was found that the exchange of data is well synchronized, effective, and time-efficient.

It was also found that in small to medium enterprises, the entire structural engineering BIM workflow could be performed by a trained and experienced structural engineer. In the case of a larger enterprise, it is recommended for a BIM-based structural engineering project team to be composed of a BIM modeller, BIM structural engineer, and BIM coordinator or manager. The amended organization scheme of BIM in a structural engineering company, the role and the collaboration of project team members and stakeholders, has been proposed in Chapter 3.

The knowledge gained while conducting these case studies provides meaningful insights into understanding the levels of complexities involved in a BIM-based structural engineering design workflow. Hence, it is highly recommended that the BIM modeller/ BIM engineer has adequate

knowledge about structural engineering to ensure a clean and reliable structural model. This fact was underscored during the implementation of the case study of the RC slab design.

Lastly, this study contributes to international knowledge and current discourse surrounding the intelligent data-reached 3D construction methodology taking the built environment by storm. It provides the basis for the application of BIM in structural engineering; it highlights benefits and challenges. The study provides an in-depth review of the various levels of interoperability and identifies the most effective interoperability level available to enhance the application of BIM in structural engineering. With case studies specifically tailored toward answering key questions regarding the application of the smart-3D modelling approach, the study offers significant insights for structural engineers or companies considering integrating BIM in their workflow, on how to link their structural or FEM models to a BIM platform, and on the approach employed to extract detailed 2D reinforcement plans, schedules, and documentation from a 3D model.

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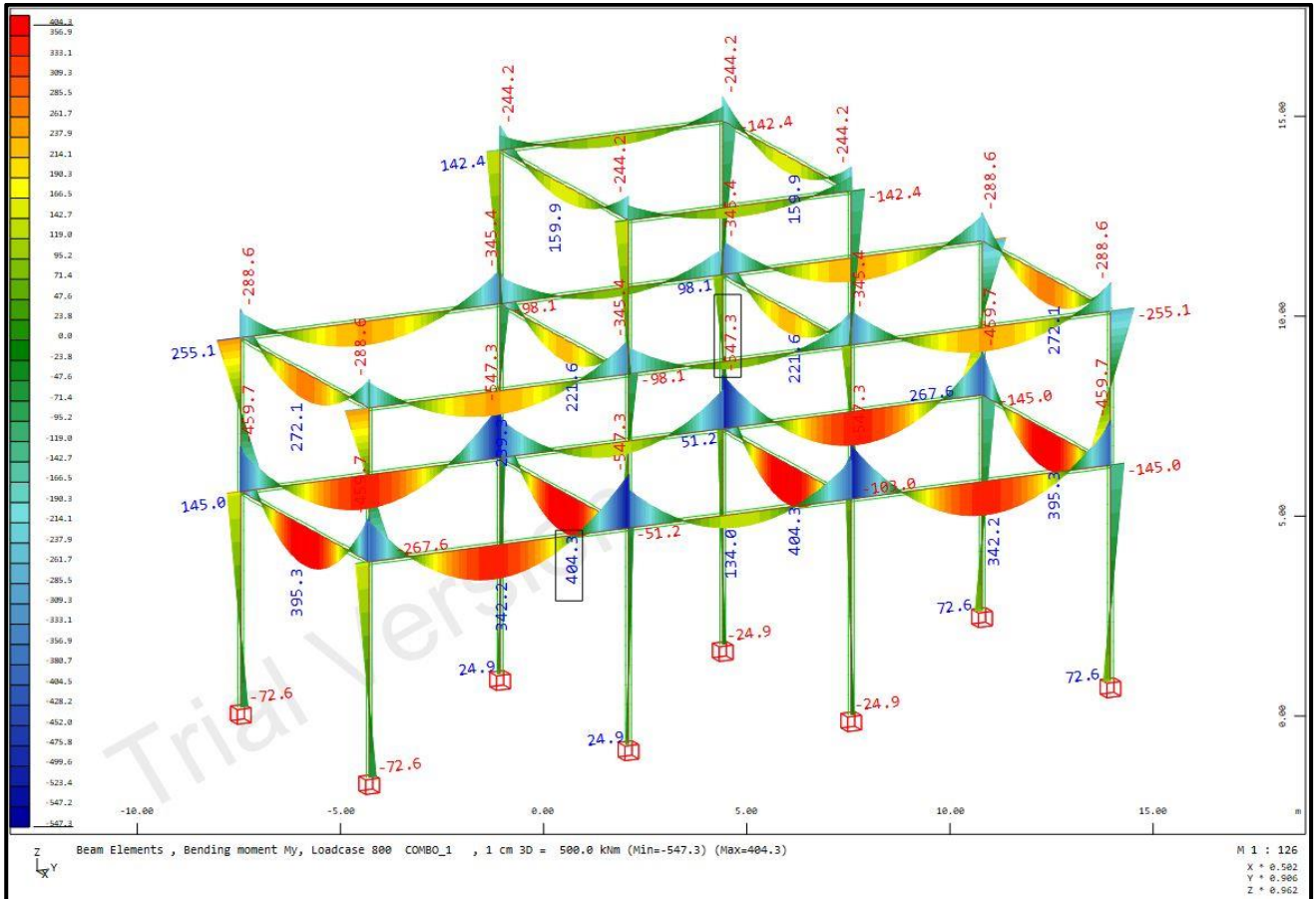
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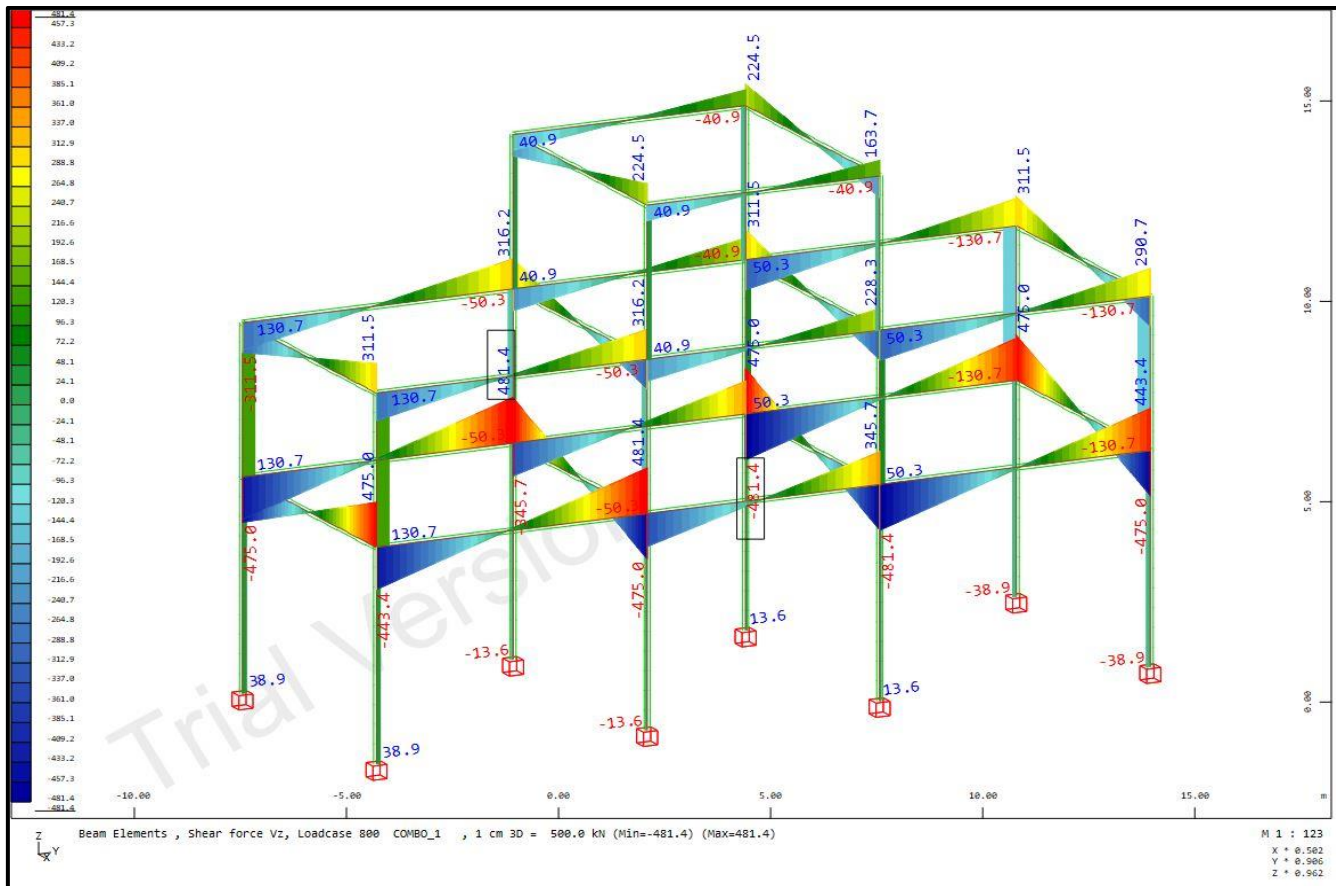
APPENDIX 1:   CASE STUDY 1B

Maximum Internal Forces Diagrams for the 3 FEM Software

Maximum values of bending moment, shear force, axial force, and displacement diagrams obtained when the model is exchanged with the following FEM programs are presented: SOFiSTiK, RFEM, SCIA Engineer. These results are taken from the most critical combination effect, combination 1.
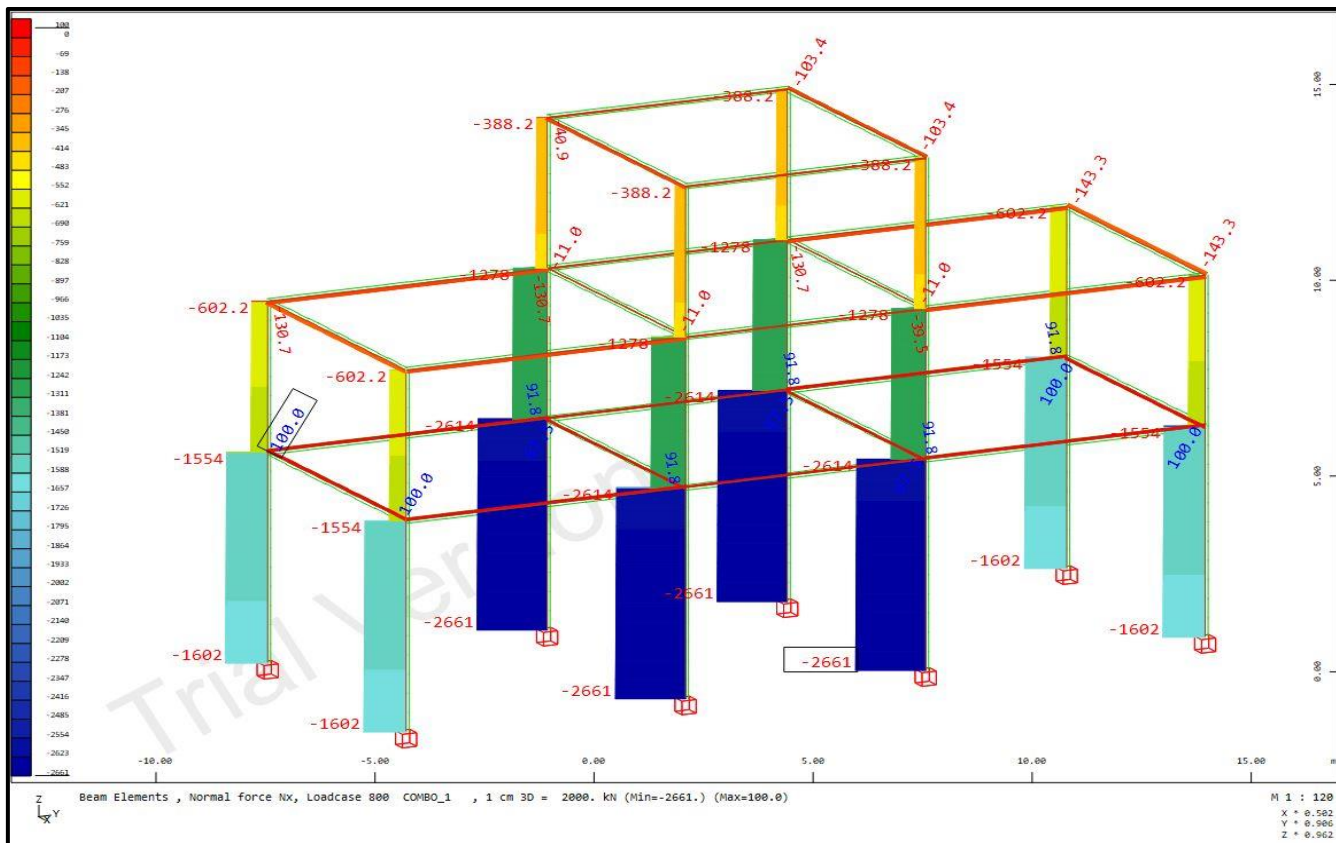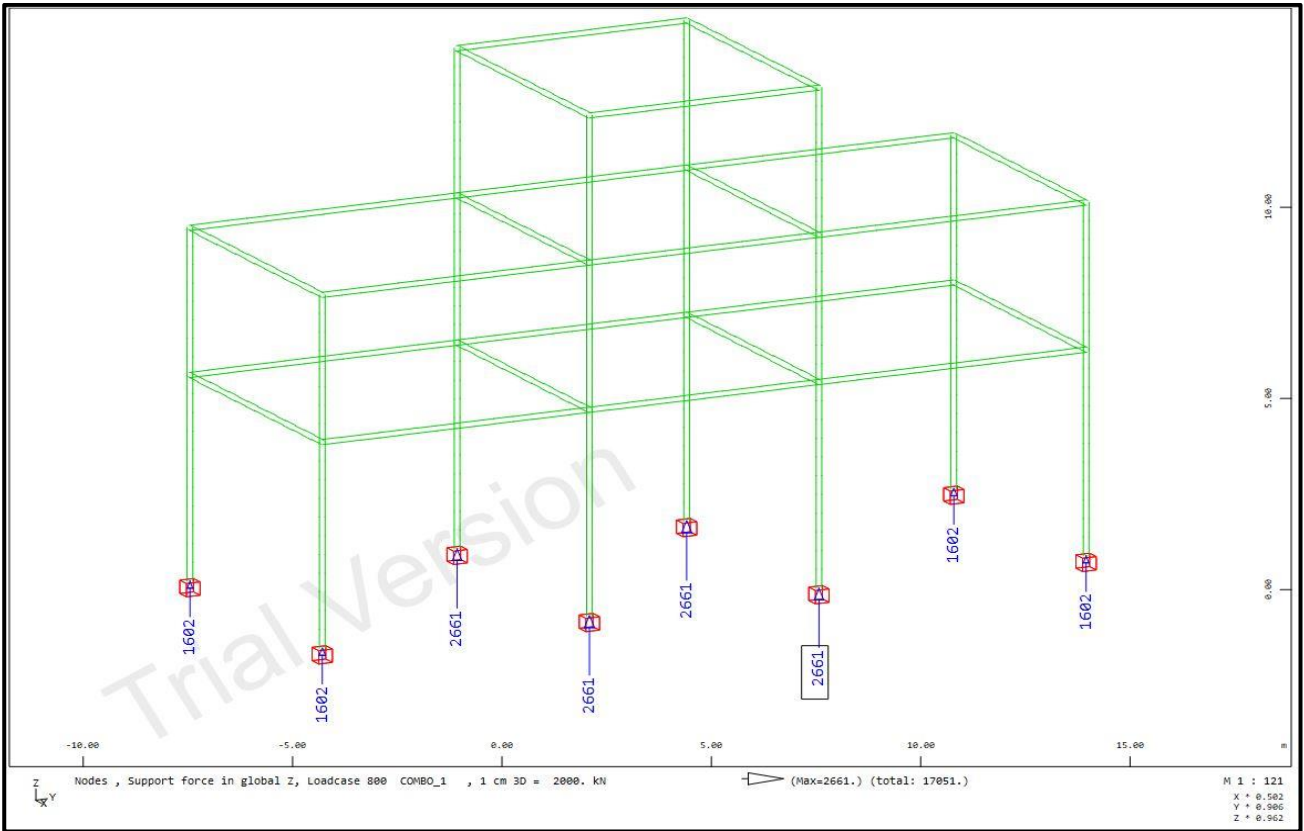
SOFiSTiK

Appendix 1. A: Maximum bending moment obtained from SOFiSTiK (in square bracket)

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Appendix 1. B: Maximum shear force obtained from SOFiSTiK (in square bracket)

Appendix 1. C: Maximum axial force obtained from SOFiSTiK (in square bracket)
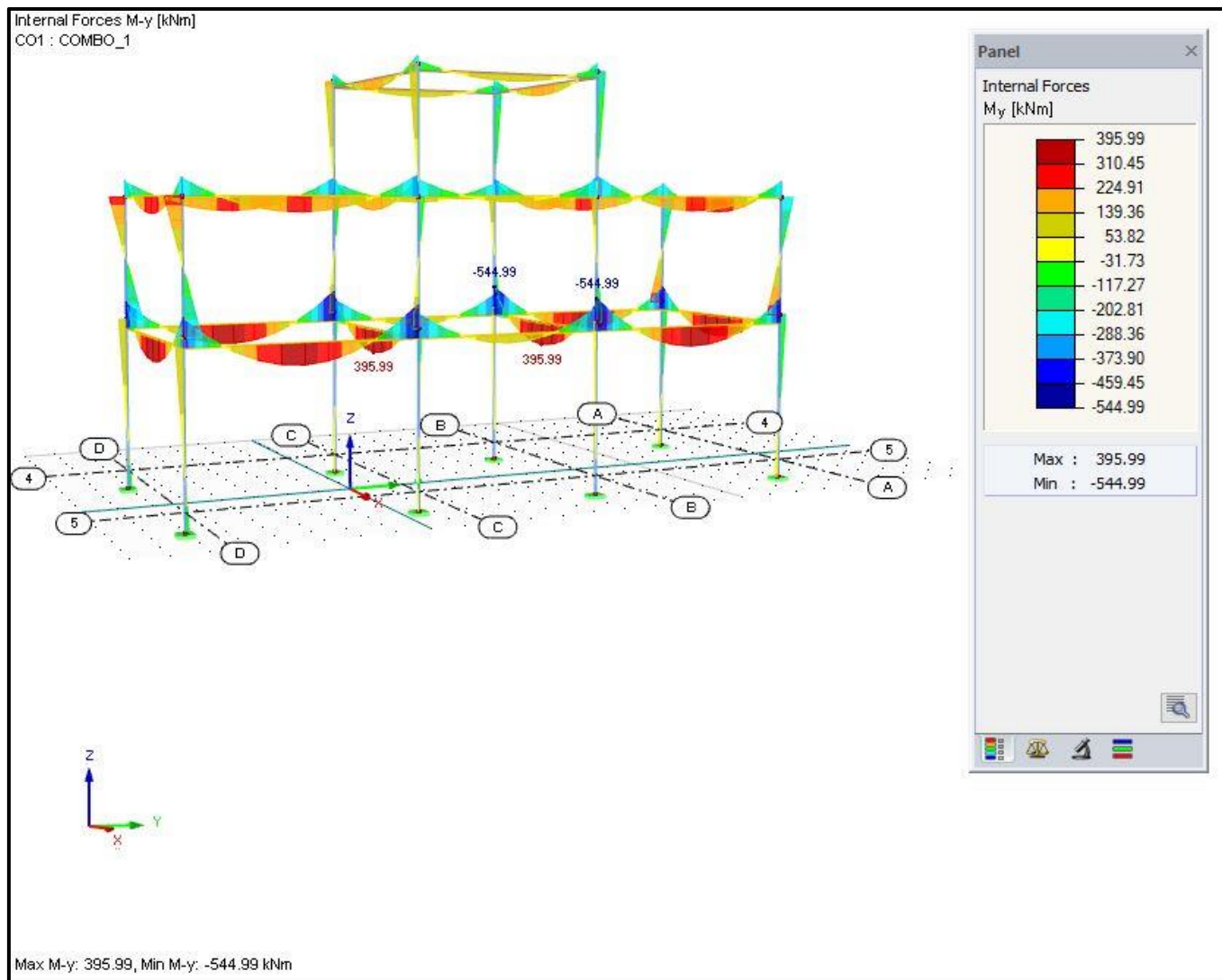
Appendix 1. D: Maximum support reaction obtained from SOFiSTiK (in square bracket)
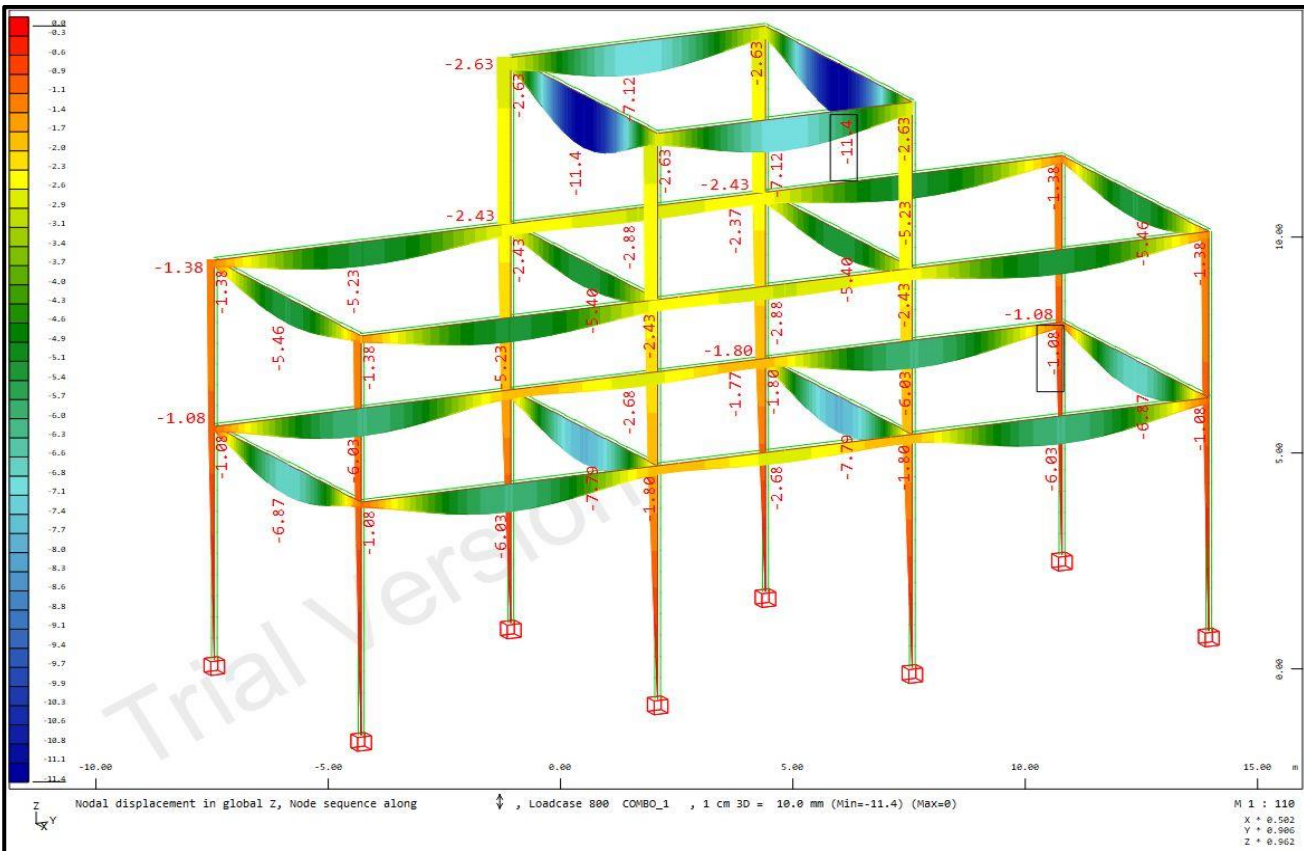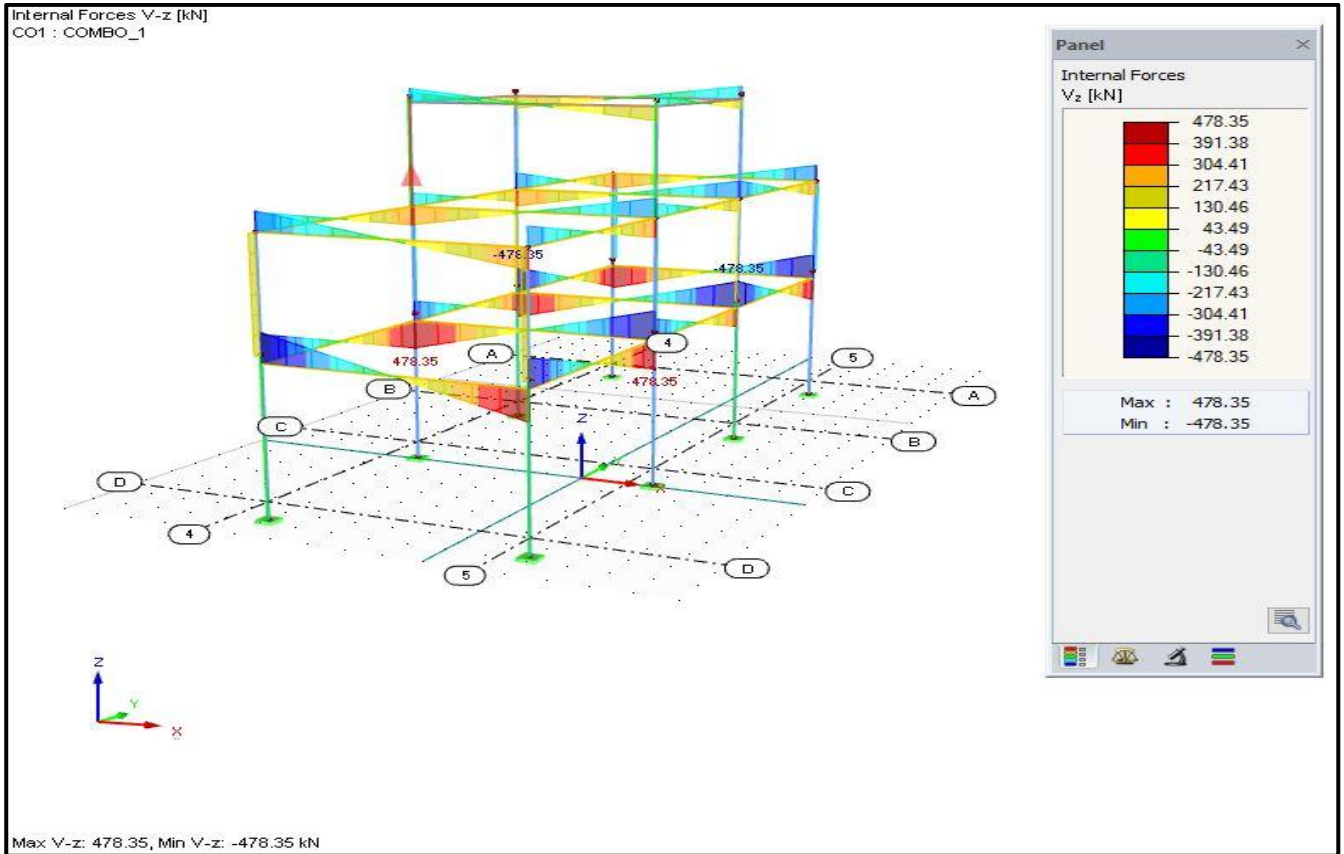

Appendix 1. E: Maximum displacement or global deformation obtained from SOFiSTiK (in square bracket)
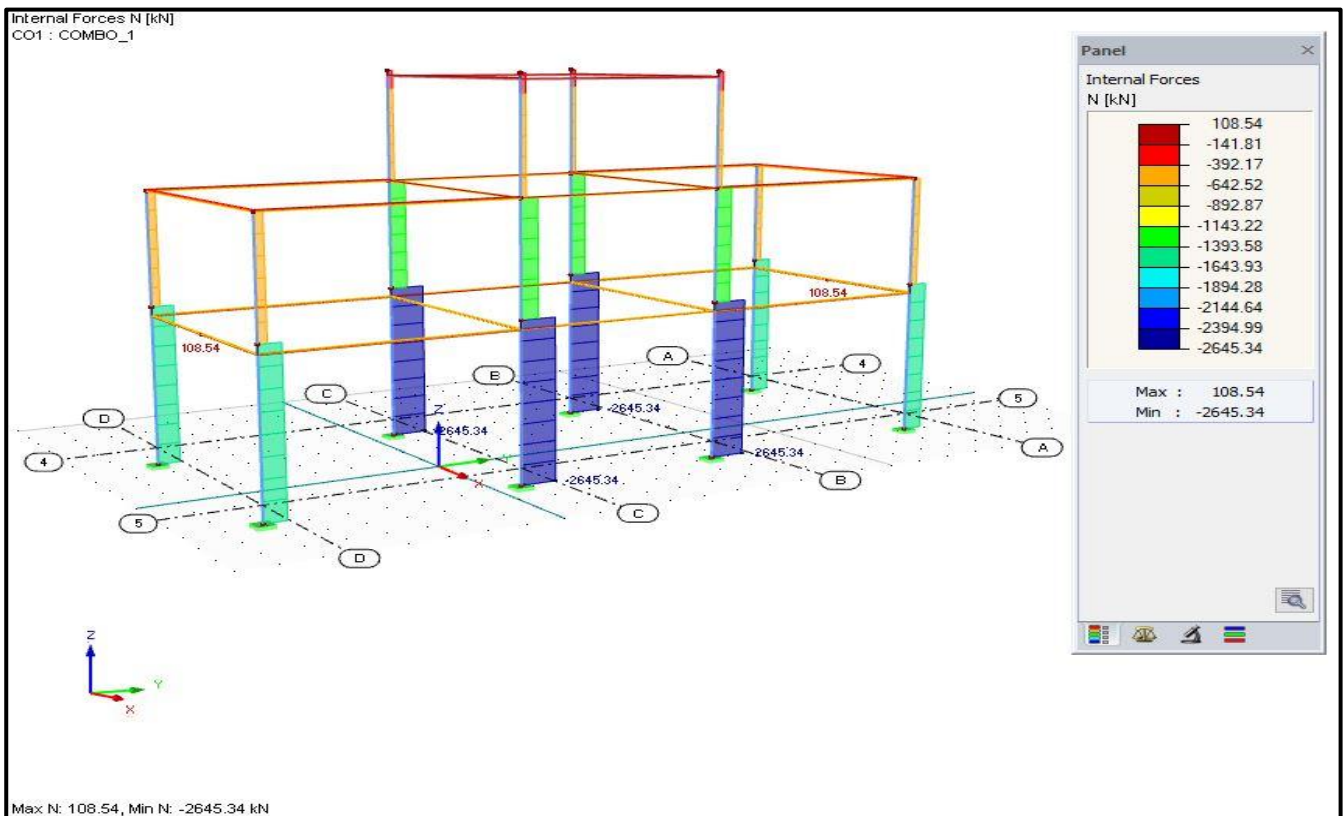
RFEM

Appendix 1. F: Maximum bending moment obtained from RFEM

Appendix 1. G: Maximum shear force obtained from RFEM

Appendix 1. H: Maximum axial force obtained from RFEM
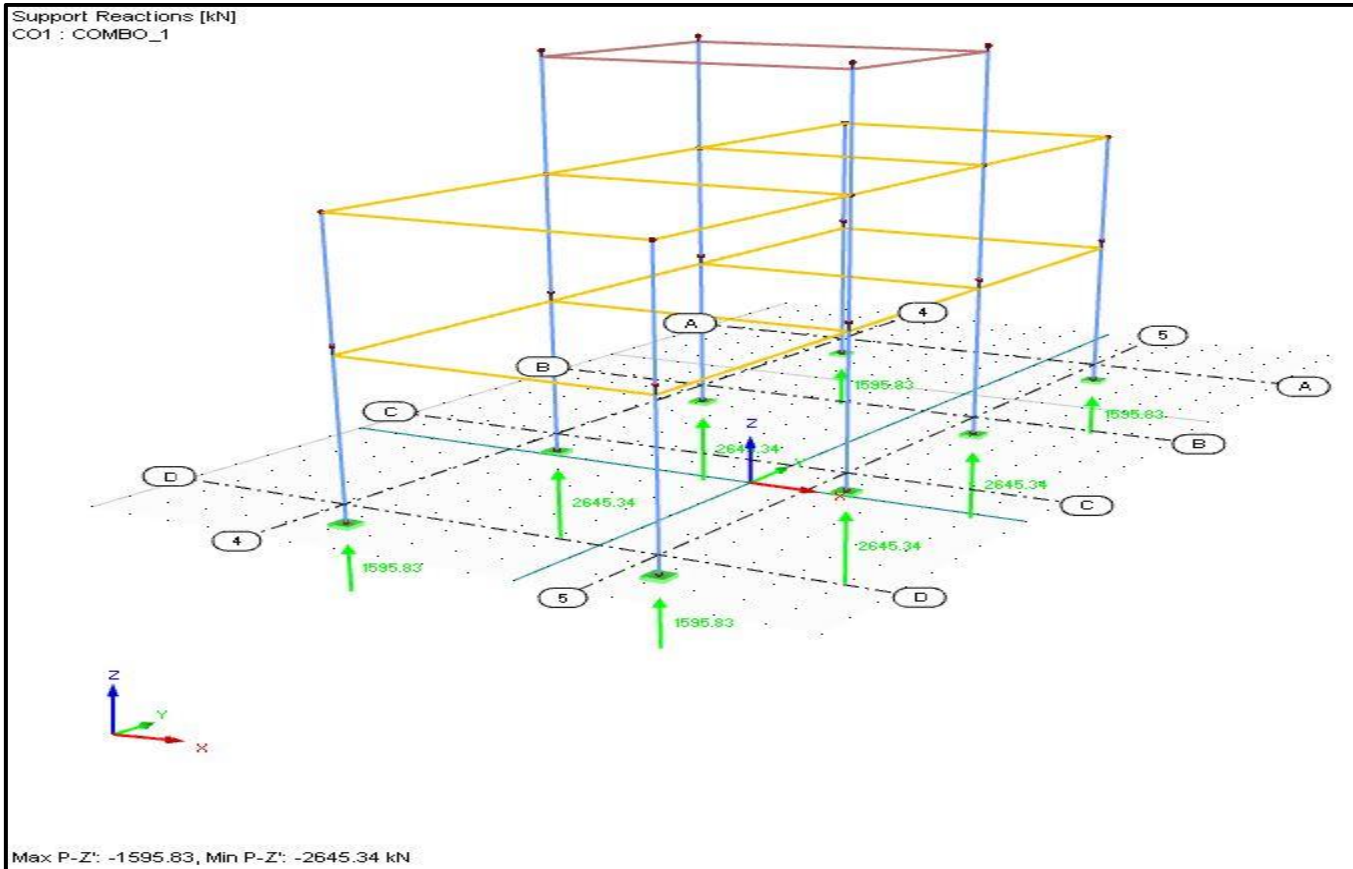
Appendix 1. I: Maximum support reaction obtained from FREM
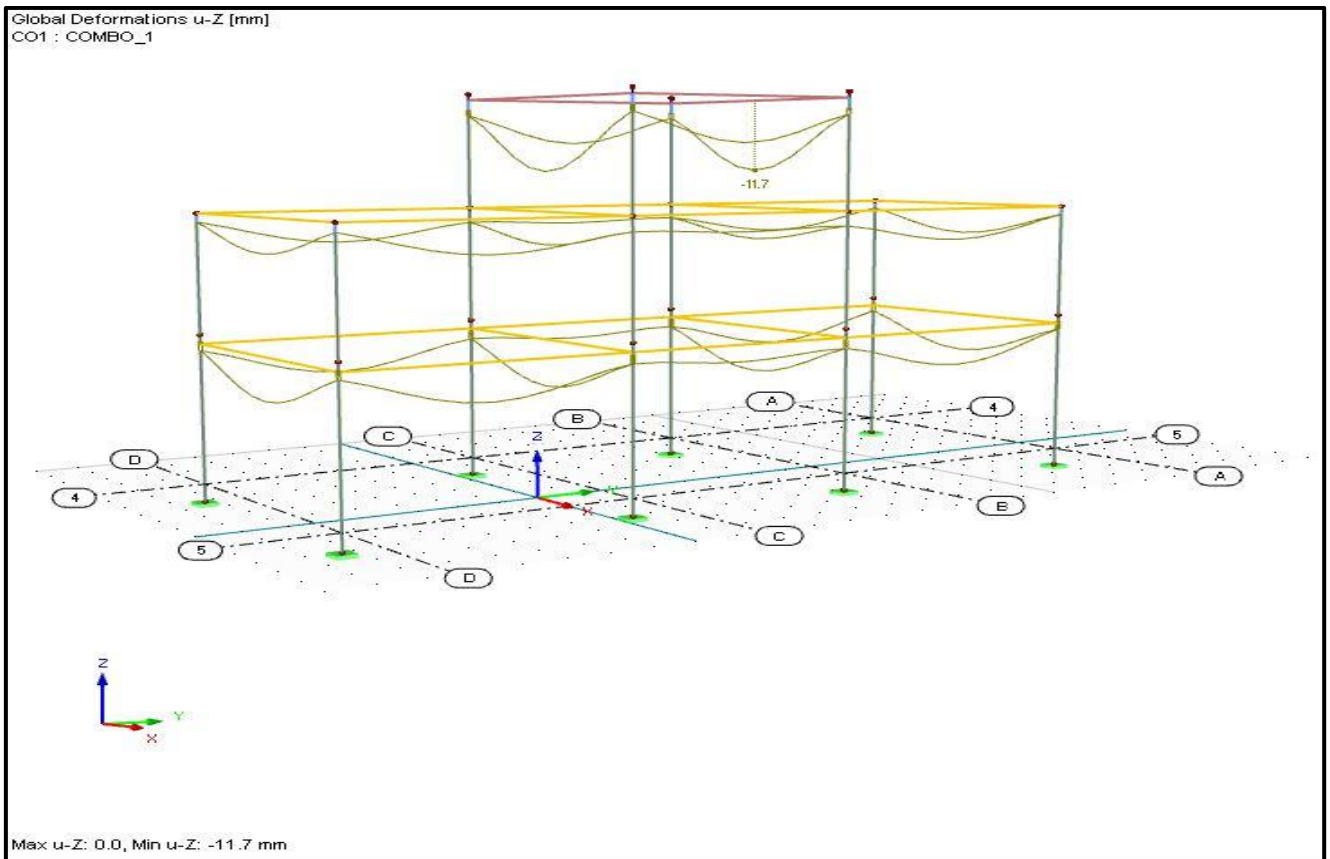
Appendix 1. J: Maximum displacement or global deformation obtained from RFEM

SCIA Engineer
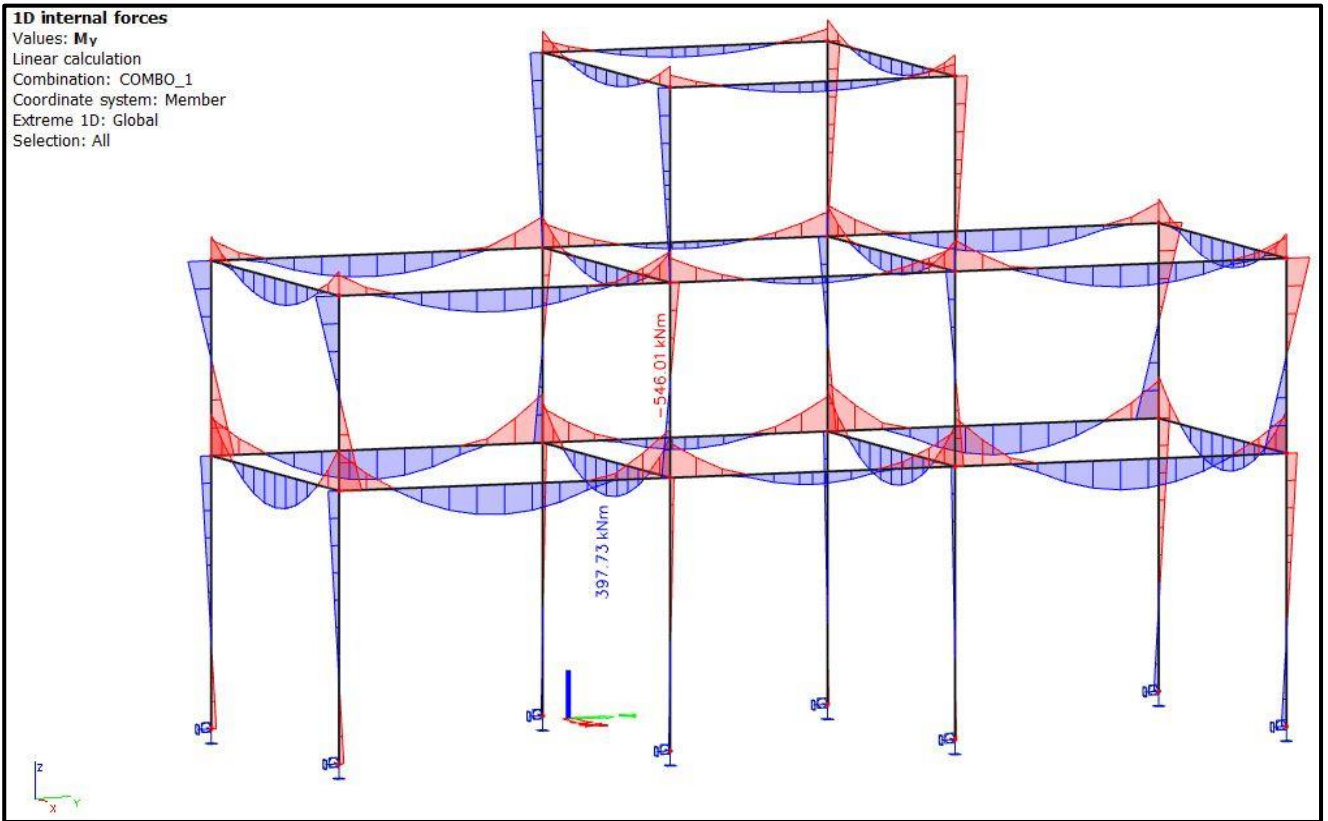
Appendix 1. K: Maximum bending moment obtained from SCIA Engineer
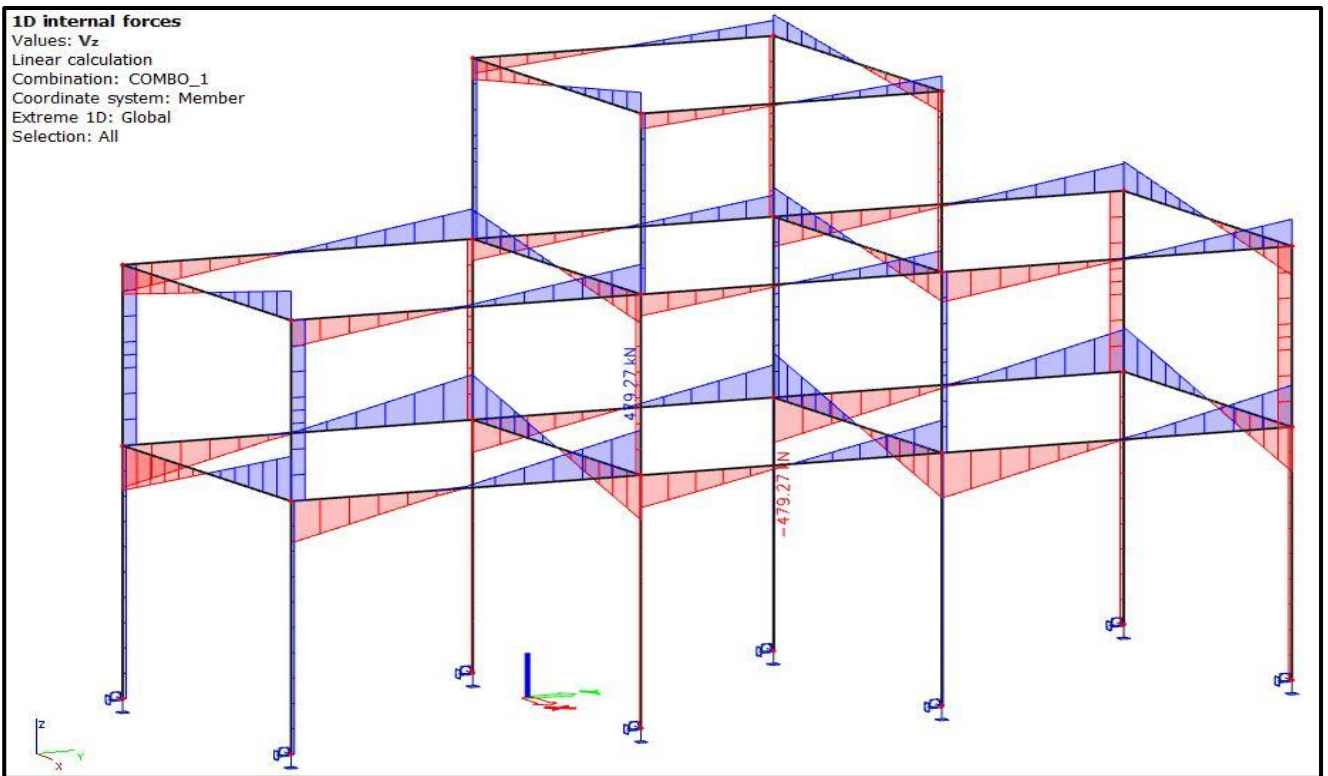
Appendix 1. L: Maximum shear force obtained from SCIA Engineer
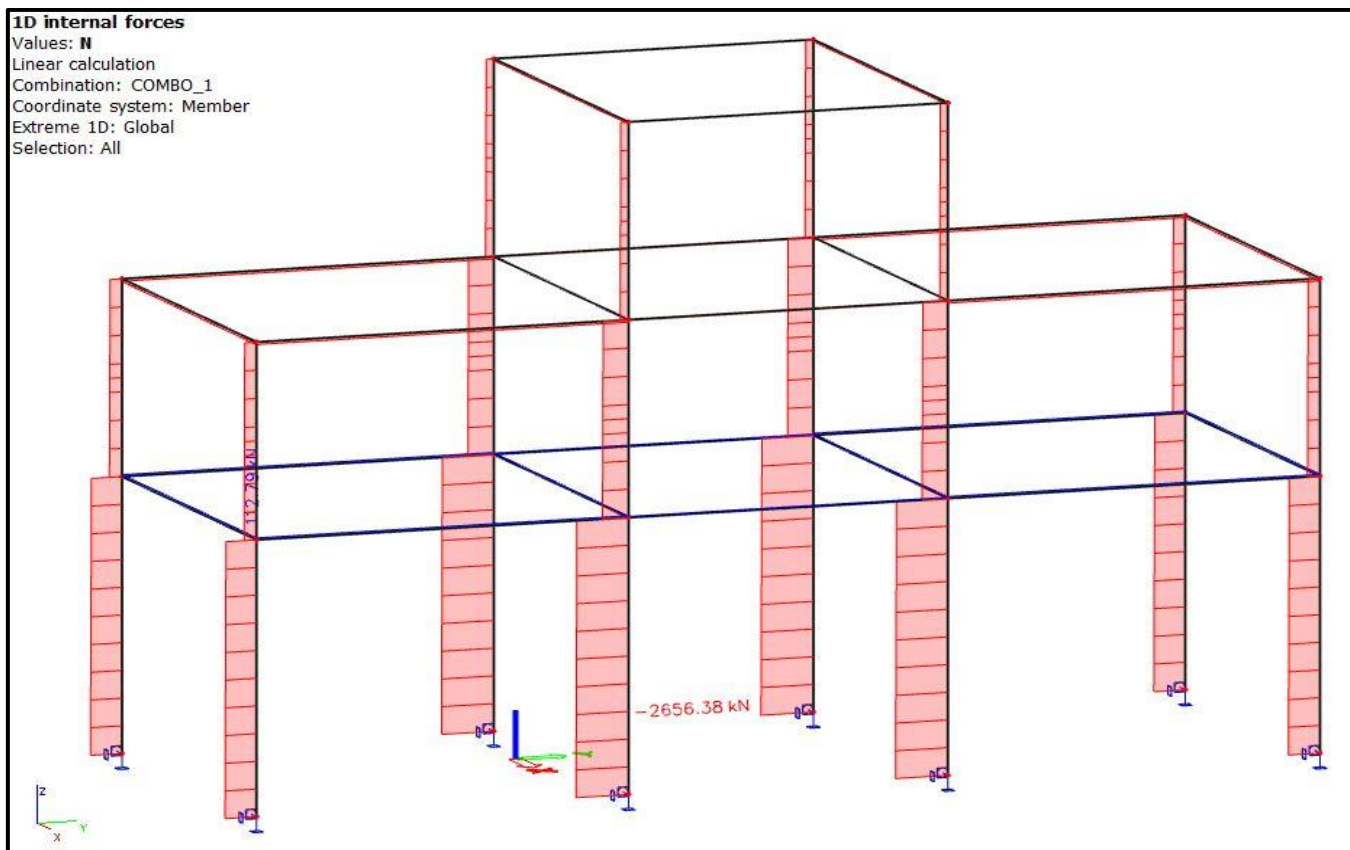
Appendix 1. M: Maximum axial force obtained from SCIA Engineer
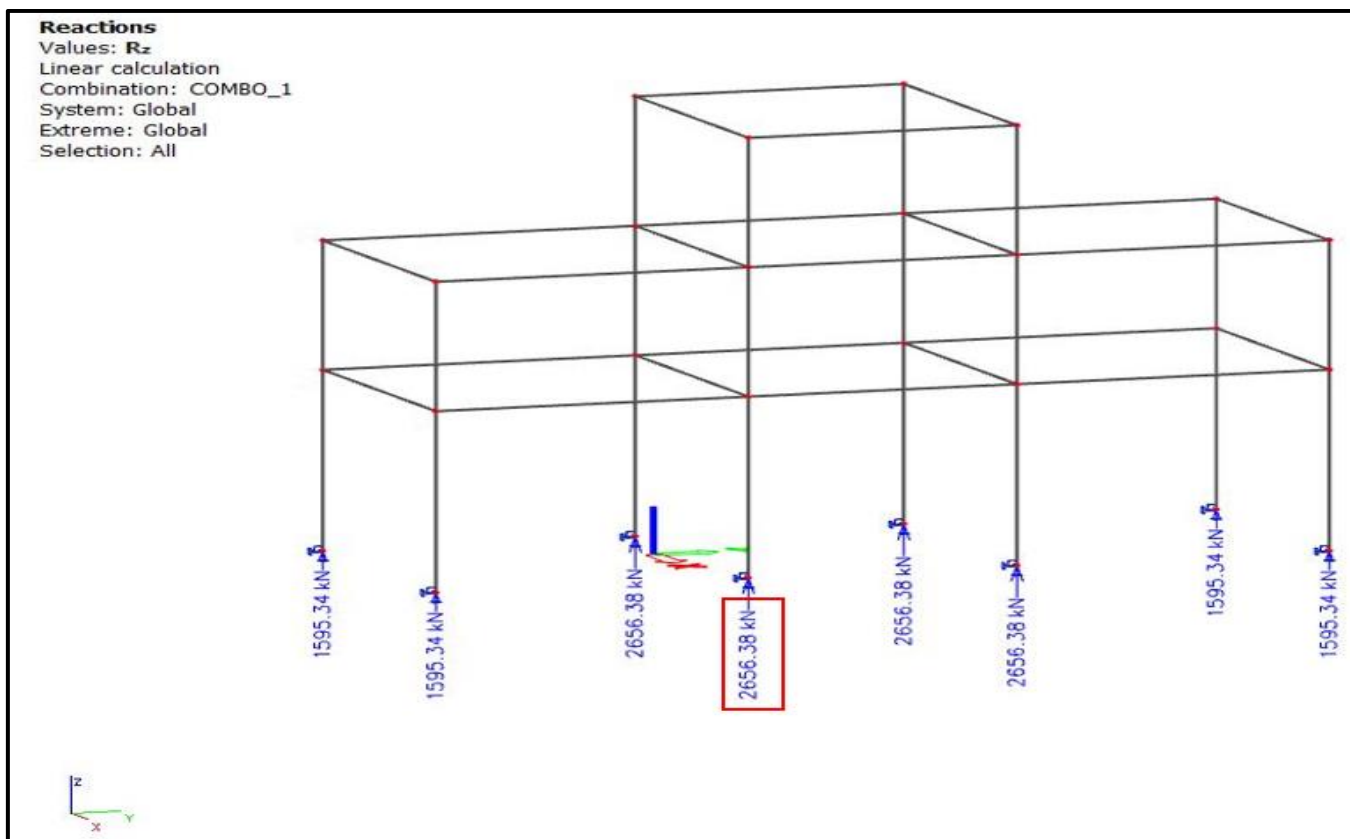
Appendix 1. N: Maximum support reaction obtained from SCIA Engineer

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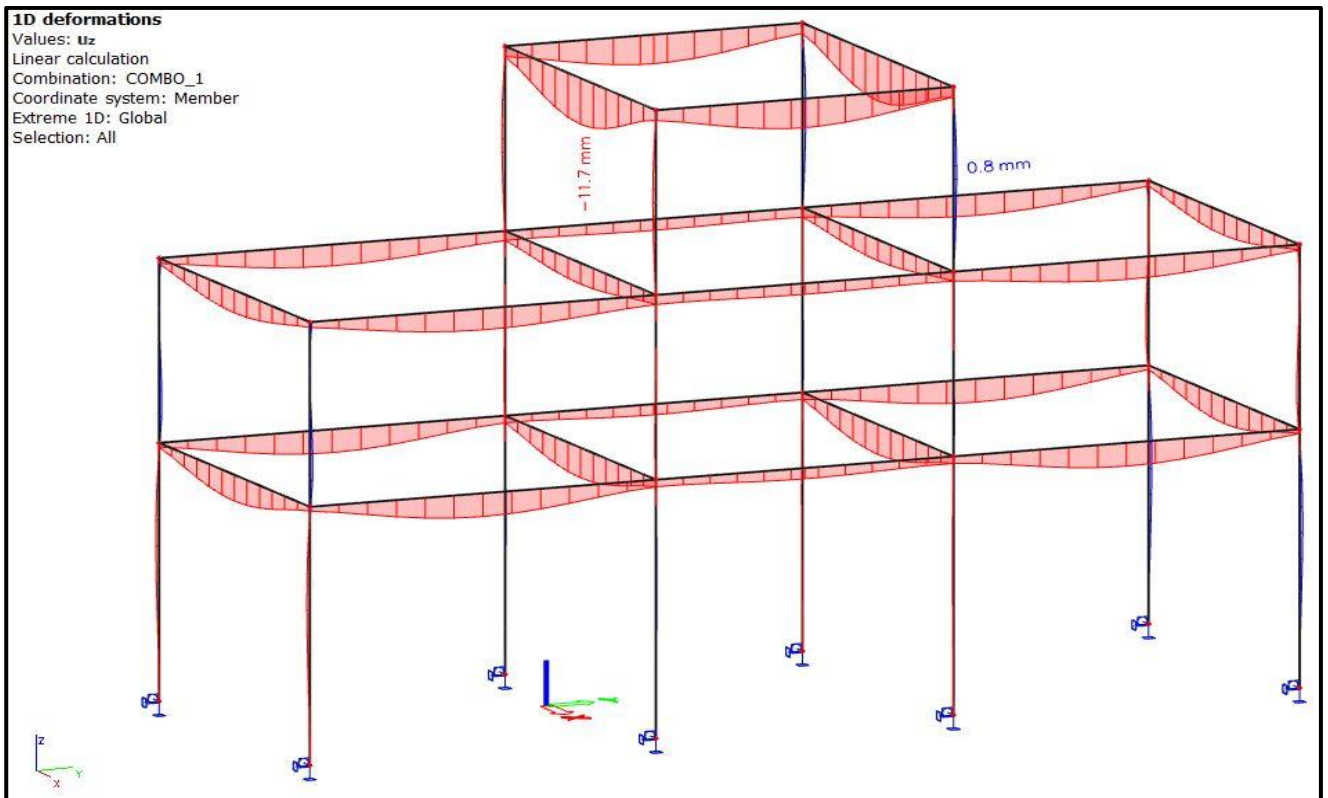
Appendix 1. O: Maximum displacement or global deformation obtained from SCIA Engineer

APPENDIX 2:   HAND CALCULAION

This appendix presents detailed manual calculation performed. This manual calculation is a verification procedure, intended to verify whether the software is giving realistic results, the following checks are performed based on the tables of Nilson and Winter (Design of Concrete Structures, 10th edition) [46].
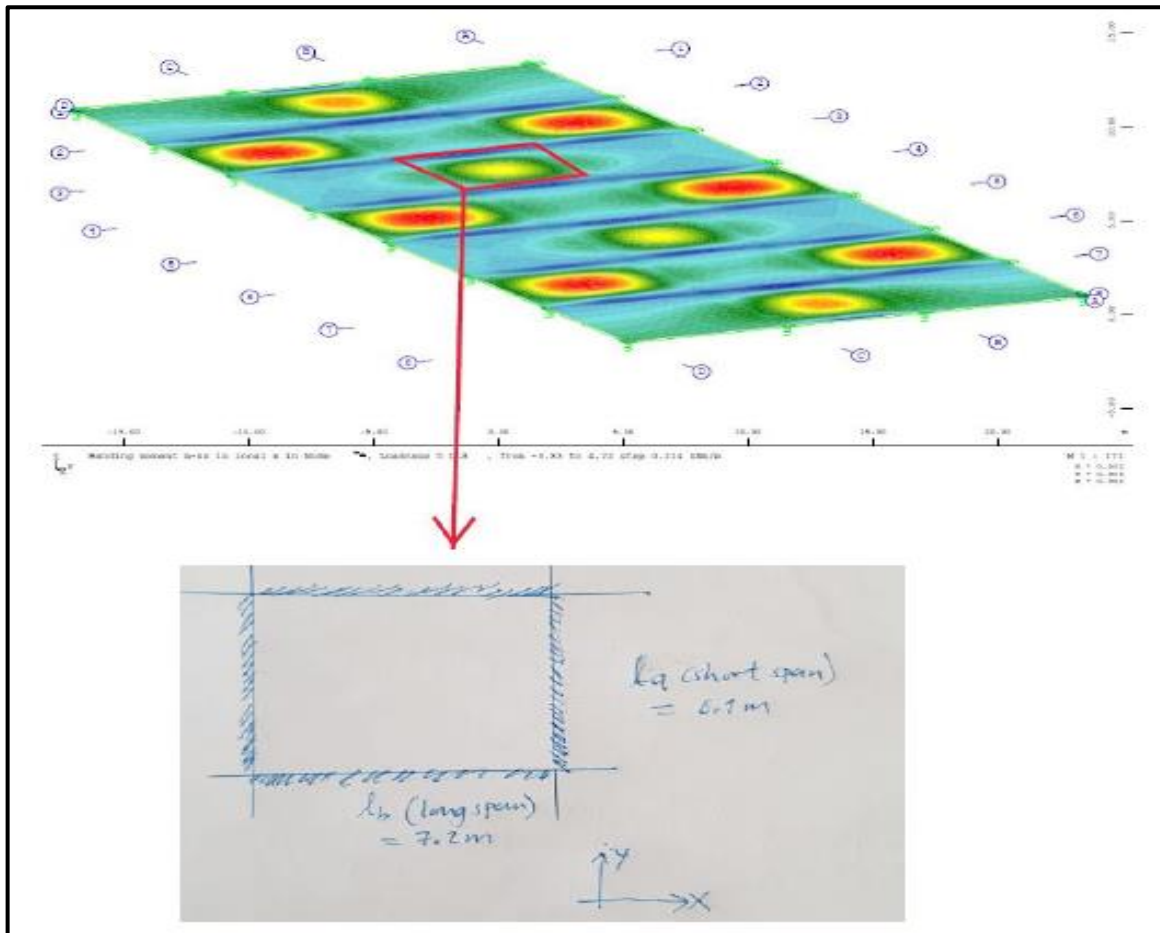
Appendix 2. A: The slab in the middle—all side fixed. Case 2 in Nilson and Winter

Material

Adopted concrete parameters

According to EC2, the following material parameters are valid for C30/37:

- Compressive strength f_{ck} = 30 N/mm²
- Tensile strength f_{ctm} = 2.9 N/mm²
- Modulus of Elasticity E_{c0m} = 32,837 N/mm²
- Weight (reinforced concrete)   = 25 kN/m³
- Partial safety factor γ_c = 1.50
- Design strength f_{cd} = 20 N/mm² = 2.0 kN/cm²

Reinforcing steel

Steel grade B 450 C in accordance with EC2 is chosen for all reinforcing steel.

- Yield strength f_{yk} = 450 N/mm²

- Partial safety factor γ_S = 1.15

- Design strength f_{yd} = 391 N/mm² = 39.1 kN/cm²

Characteristic Load and Design load

The below two load cases considered for both the computer analysis and manual calculation for the slab:

Characteristic loads

Dead load: $g_k = 7.2 \frac{kN}{m^2}$

Live load: $q_k = 3.0 \frac{kN}{m^2}$

Design loads

$g_d = 1.35\,(7.2) = 9.72 \frac{kN}{m^2}$

$q_d = 1.5\,(3) = 4.5 \frac{kN}{m^2}$

Slab thickness assumed: h = 180 mm = 18 cm

Considering that the slab in the middle of neighbouring grids bounded by grids B-C and 3-4; it is supported on all four edges by stiff beams. Applying the "moment coefficient method" proposed in Nilson and Winter's Design of Concrete Structures, 10th edition, the following assumptions are valid:

- Based on the support condition of the chosen grid of slab (fixed at all four edges), case 2 tables 8.3,8.4,8.5, respectively is chosen;

- The moment is represented by the equation $M = c \times w \times l^2$;

- The coefficient "c" is found in the relevant table and considered "case", which represents two parameters including the ratio between the short and long span $\frac{la}{lb}$, and type of support at the edge of slab.

- w is relevant uniformly distributed load on the slab and l is relevant span;

- the positive moment in the slab determines bottom reinforcement, while negative moment over intermediate support determines top reinforcement

- Tables 8.3, 8.4, 8.5 are used to calculate negative moments due to load ($w = g_d + q_d$), positive moments due to dead load ($w = g_d$), and positive moments due to variable load ($w = q_d$), respectively.

Coefficients

If $m = \frac{la}{lb} = 0.847$; considering case 2;

Table 8.3 (negative moments due to load, $w = g_d + q_d$)

$C_{a,negative} = 0.060$

$C_{b,negative} = 0.031$

Negative Moment

$$M_a^- = C_a^- \times (g_d + q_d) \times l_a^2 = 0.060 \times 14.88 \times 6.1^2 = 33.22 \frac{kNm}{m}$$

$$M_b^- = C_b^- \times (g_d + q_d) \times l_b^2 = 0.031 \times 14.88 \times 7.2^2 = 23.91 \frac{kNm}{m}$$

Table 8.4 (positive moments due to dead load, $w = g_d$)

$$C_{a,dl} = 0.024$$

$$C_{b,dl} = 0.012$$

Positive Moments

$$M_a^{+dl} = C_{a,dl}^+ \times gd \times l_a^2 = 0.024 \times 9.72 \times 6.1^2 = 8.68 \frac{kNm}{m}$$

$$M_b^{+dl} = C_{b,dl}^+ \times gd \times l_b^2 = 0.012 \times 9.72 \times 7.2^2 = 6.04 \frac{kNm}{m}$$

Table 8.5 (positive moments due to variable load, $w = q_d$)

$$C_{a,ll} = 0.037$$

$$C_{b,ll} = 0.019$$

Positive Moments

$$M_a^{+ll} = C_{a,ll}^+ \times qd \times l_a^2 = 0.037 \times 4.5 \times 6.1^2 = 6.2 \frac{kNm}{m}$$

$$M_b^{+ll} = C_{b,ll}^+ \times qd \times l_b^2 = 0.019 \times 4.5 \times 7.2^2 = 4.43 \frac{kNm}{m}$$

Reinforcement

For the calculation of reinforcement area, the following parameters are considered:

- k_d and k_s are design coefficients for design of concrete cross sections related to effective depth of cross section

- M_{ds} is design moment computed above

- d is effective height of slab cross section, 16.5 cm

- b is the 1 m strip width of slab

- A_S is calculated steel reinforcement area

- Slab thickness is 18 cm

Positive reinforcement

For reinforcement in short span direction;

$$k_d = \frac{Mds}{f_{cd} \times b \times d^2} = \frac{1488}{2.0 \times 100 \times 16.5^2} = 0.03 \; ; k_s = 1.033$$

$$A_S = k_s \times \frac{Mds}{d \times fyd} = 1.033 \times \frac{1488}{16.5 \times 39.1} = 2.38 \frac{cm^2}{m}$$

For reinforcement in long span direction;

$$k_d = \frac{Mds}{f_{cd} \times b \times d^2} = \frac{1047}{2.0 \times 100 \times 15^2} = 0.02 \approx 0.03;$$

$$A_S = k_s \times \frac{Mds}{d \times fyd} = 1.033 \times \frac{1047}{15 \times 39.1} = 1.84 \frac{cm^2}{m}$$

Negative reinforcement

For reinforcement in short span direction;

$$k_d = \frac{Mds}{f_{cd} \times b \times d^2} = \frac{3322}{2.0 \times 100 \times 16.5^2} = 0.058 \; ; k_s = 1.045;$$

$$A_S = k_s \times \frac{Mds}{d \times fyd} = 1.045 \times \frac{3322}{16.5 \times 39.1} = 5.38 \frac{cm^2}{m}$$

For reinforcement in long span direction;

$$k_d = \frac{Mds}{f_{cd} \times b \times d^2} = \frac{2285}{2.0 \times 100 \times 16.5^2} = 0.04 \; ; k_s = 1.036 \; ;$$

$$A_S = k_s \times \frac{Mds}{d \times fyd} = 1.033 \times \frac{2285}{16.5 \times 39.1} = 3.66 \frac{cm^2}{m}$$

APPENDIX 3:   CASE STUDY 2

BIM Workflow in Structural Engineering

In this appendix, relevant results and figures about case study 2 in section 5. 4 are presented. The case study seeks to demonstrate the applicability of BIM workflow in structural engineering design, utilizing Revit-SOFiSTiK direct link interface. The slab on the first floor of the model was selected for this analysis.
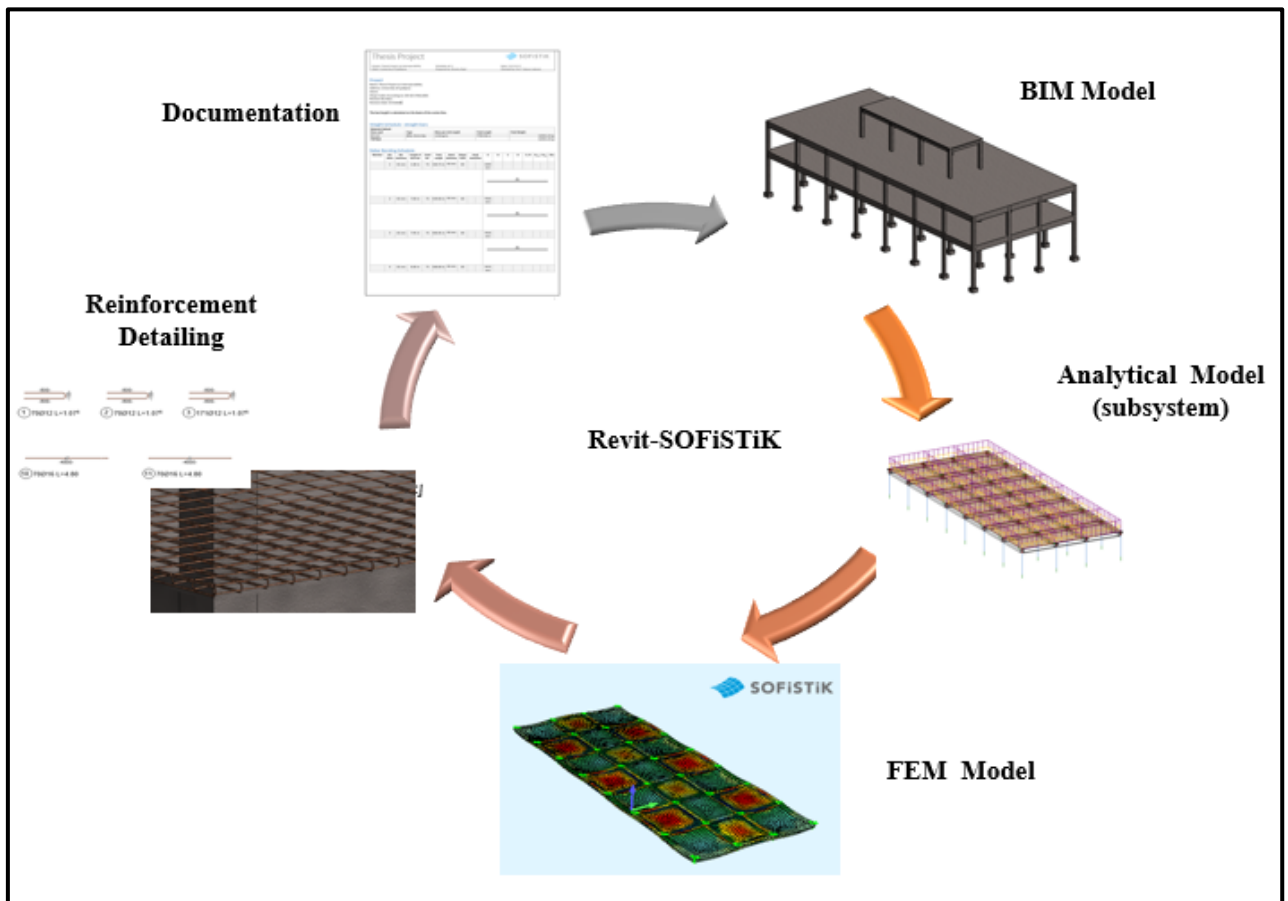
Appendix 3. A: Case study 2 workflow
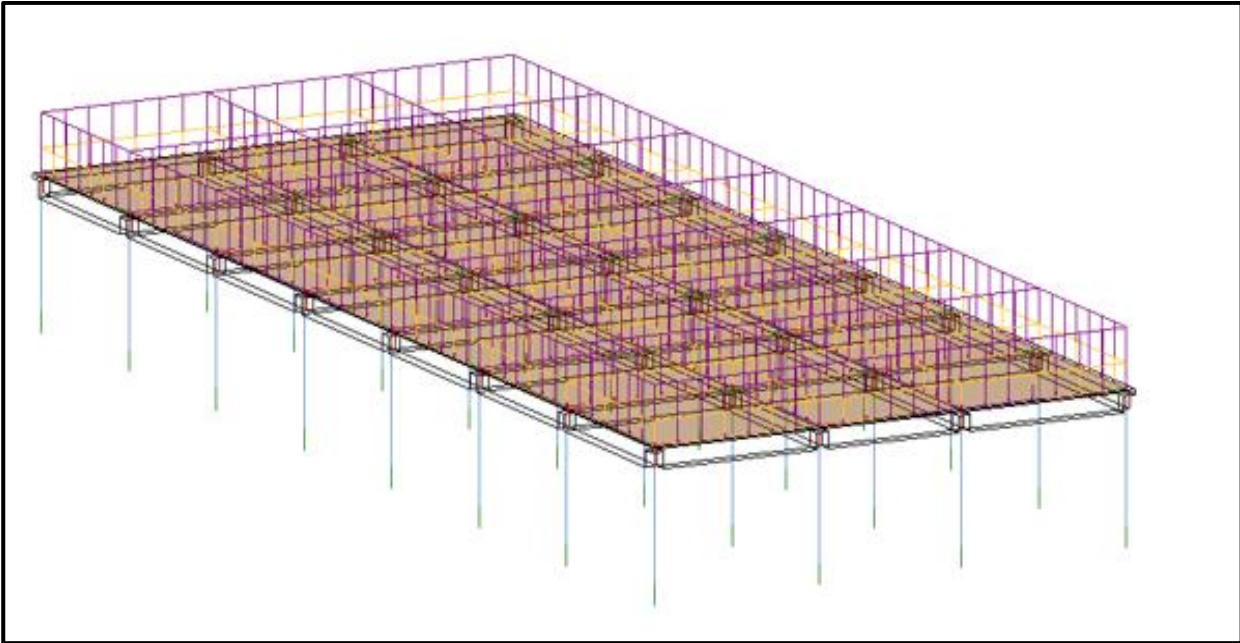
Appendix 3. B: Slab extracted as a subsystem for analysis
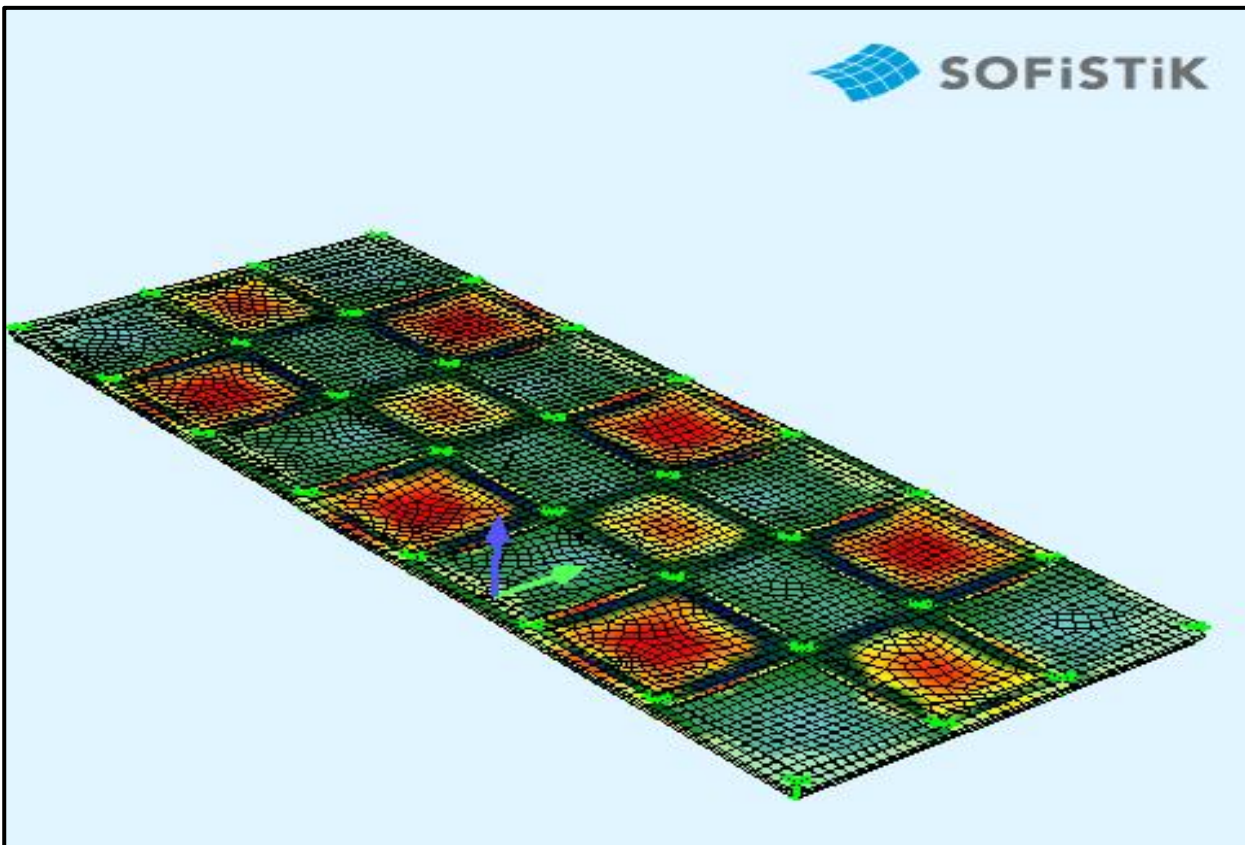
Appendix 3. C: Slab subsystem in SOFiSTiK environment ready for design

Reinforcement area

The Appendices below show the maximum design reinforcement area generated at both bottom and top of the slab. Based on these values, a reinforcement bar diameter of **16mm** and a spacing of **300mm,** were chosen for both the bottom and top reinforcement. Appendix 3.F shows the SOFiSTiK reinforcement setting dialog box.

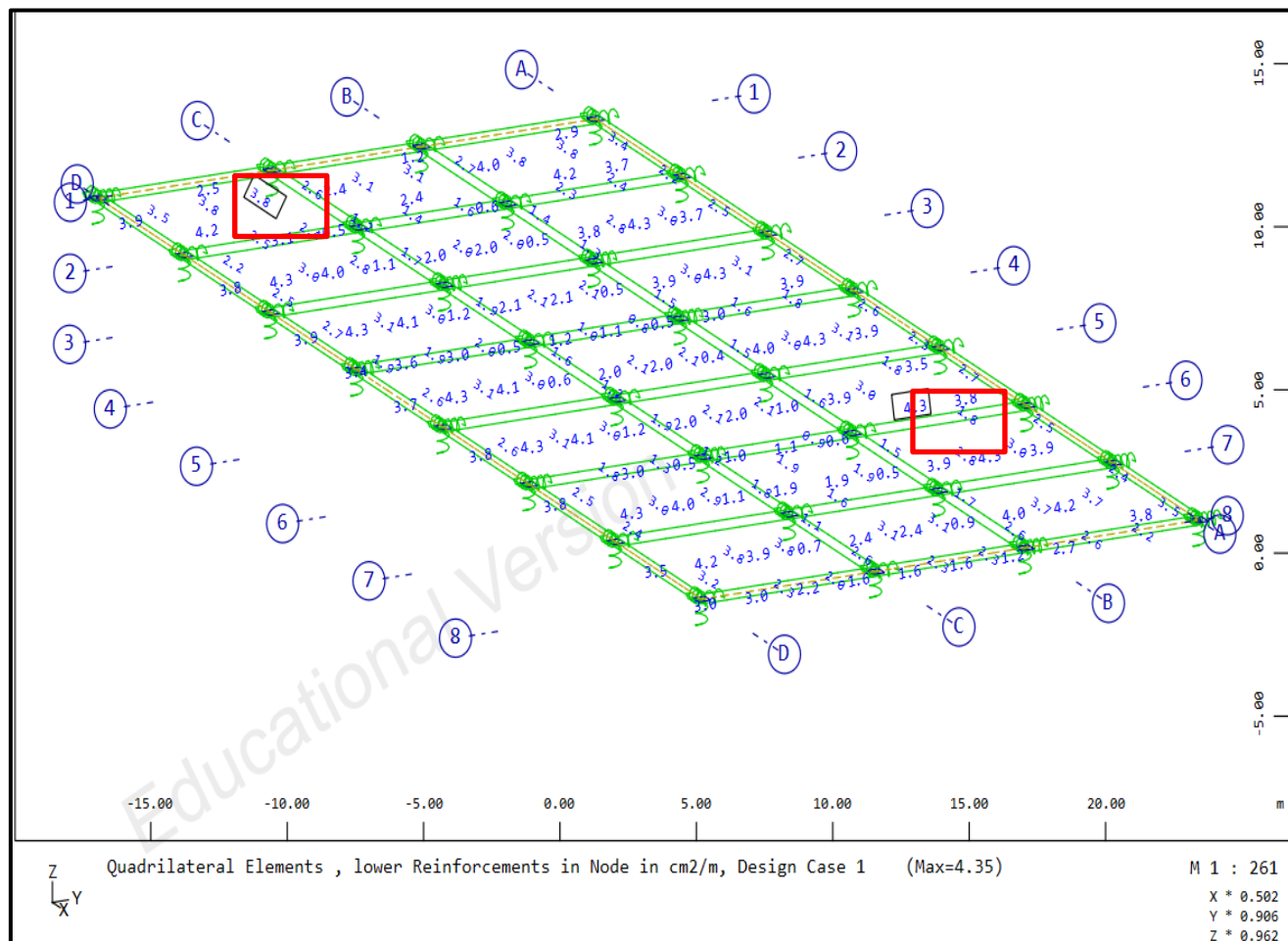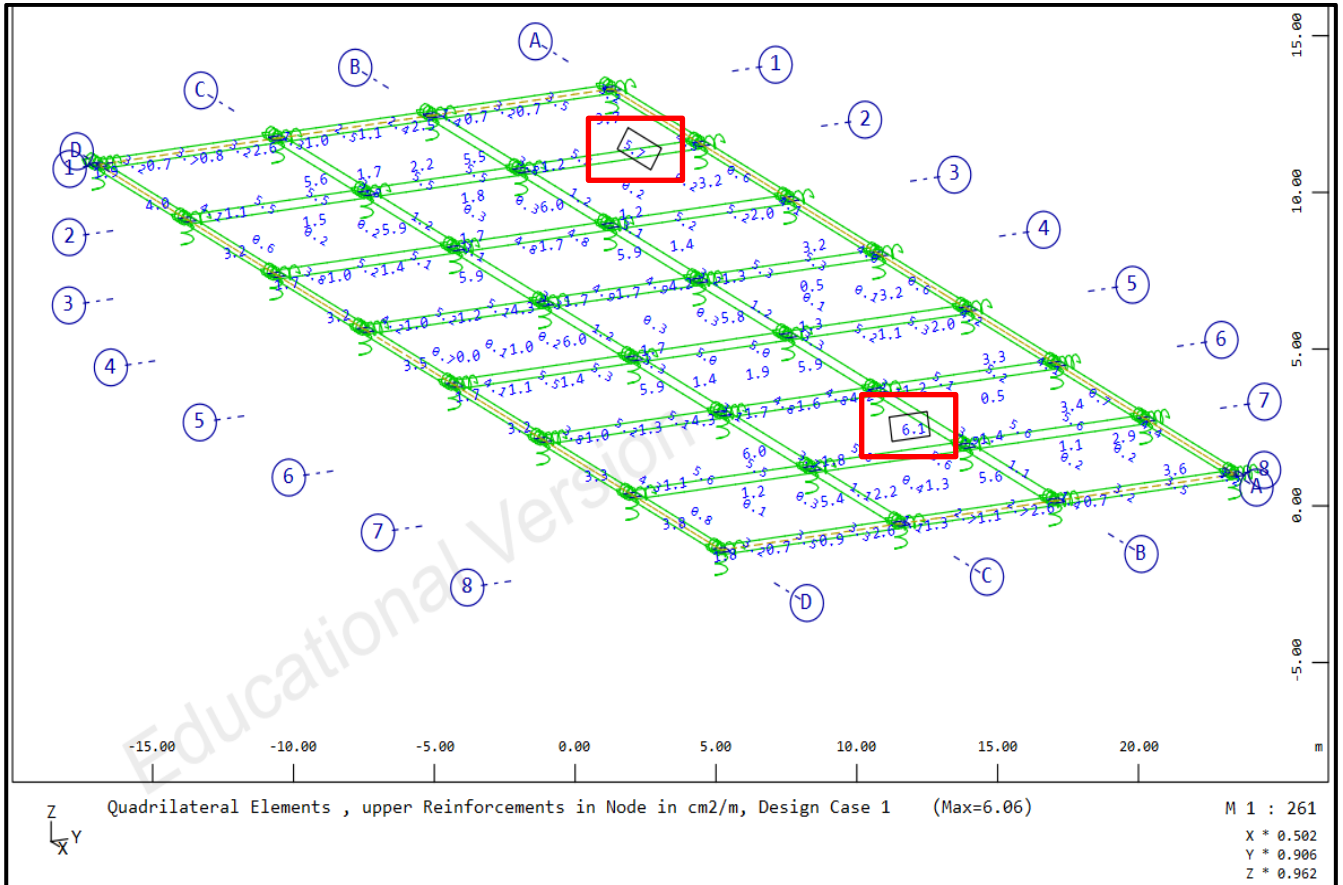Appendix 3.D and 3.E show the results of the bottom and upper reinforcement obtained from SOFISTIK design. The bottom reinforcement comprises of reinforcement in the short direction (*4.3 cm^2 /m*) and in the long direction (*3.8 cm^2 /m*), and the upper reinforcement is provided for the boundaries of the beam or slab extremities. These design results are based on load combination 1, which happened to be the most critical design combination. As engineers, based on these reinforcement areas, it was possible to determine the bar diameter and spacing of the slab, which is done through SOFISTIK reinforcement settings dialogue box (see Appendix 3.F). A uniform bar diameter of *16mm* with a spacing of *300mm,* is provided for the bottom and top reinforcement in all directions. Appendix 3.G shows the 3D generated reinforcement.

Appendix 3. D: Bottom reinforcement in short and long span direction for design combination 1

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Appendix 3. E: Top reinforcement in short and long span direction for design combination 1
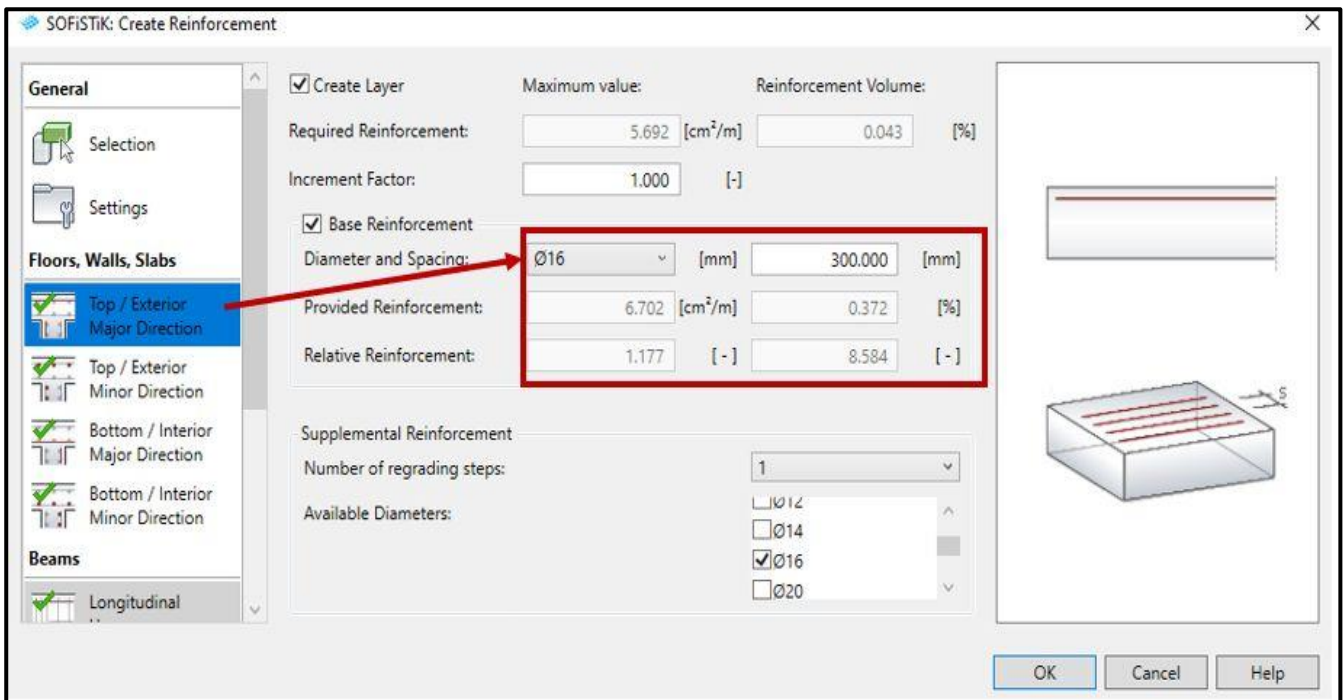
Appendix 3. F: SOFiSTiK reinforcement setting
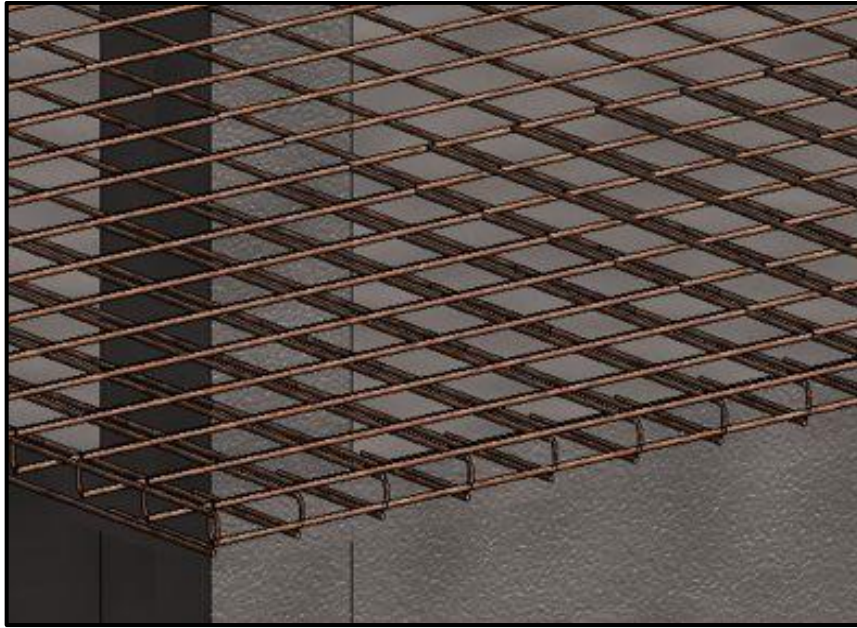
Appendix 3. G: 3D reinforcement of Slab

Please find below the reinforcement plan and rebar schedules for the slab. The total weights of the rebars (top and bottom reinforcement) were calculated separately with SOFiSTiK (documentation sheet) and also Autodesk Revit (Rebar Schedule). The results are the same for both programs. Thus, further confirmation of the correctness of the Revit-SOFiSTiK interface.

Mark	Shape Code	Sheet Number	Diameter (mm)	Image	Bar Length (m)	Qty.	Mass / Length	Total Weight (Kg)
1	00	1	Ø16		6000	70	1.58 kg/m	663.60
2	00	1	Ø16		4025	70	1.58 kg/m	445.17
3	00	1	Ø16		5100	70	1.58 kg/m	564.06
4	00	1	Ø16		2450	70	1.58 kg/m	270.97
5	00	1	Ø16		6025	70	1.58 kg/m	666.37
6	00	1	Ø16		2275	70	1.58 kg/m	251.62
7	00	1	Ø16		6000	70	1.58 kg/m	663.60
8	00	1	Ø16		4625	70	1.58 kg/m	511.53
9	00	1	Ø16		6000		1.58 kg/m	2284.68
10	00	1	Ø16		5000	70	1.58 kg/m	553.00
11	00	1	Ø16		4000	70	1.58 kg/m	442.40
12	00	1	Ø16		6025	70	1.58 kg/m	666.37
14	00	1	Ø16		3050	171	1.58 kg/m	824.05
15	00	1	Ø16		4600	171	1.58 kg/m	1242.83
16	00	1	Ø16		3500	171	1.58 kg/m	945.63
18	00	1	Ø16		6000	171	1.58 kg/m	1621.08

Grand total: 17 — 12616.93
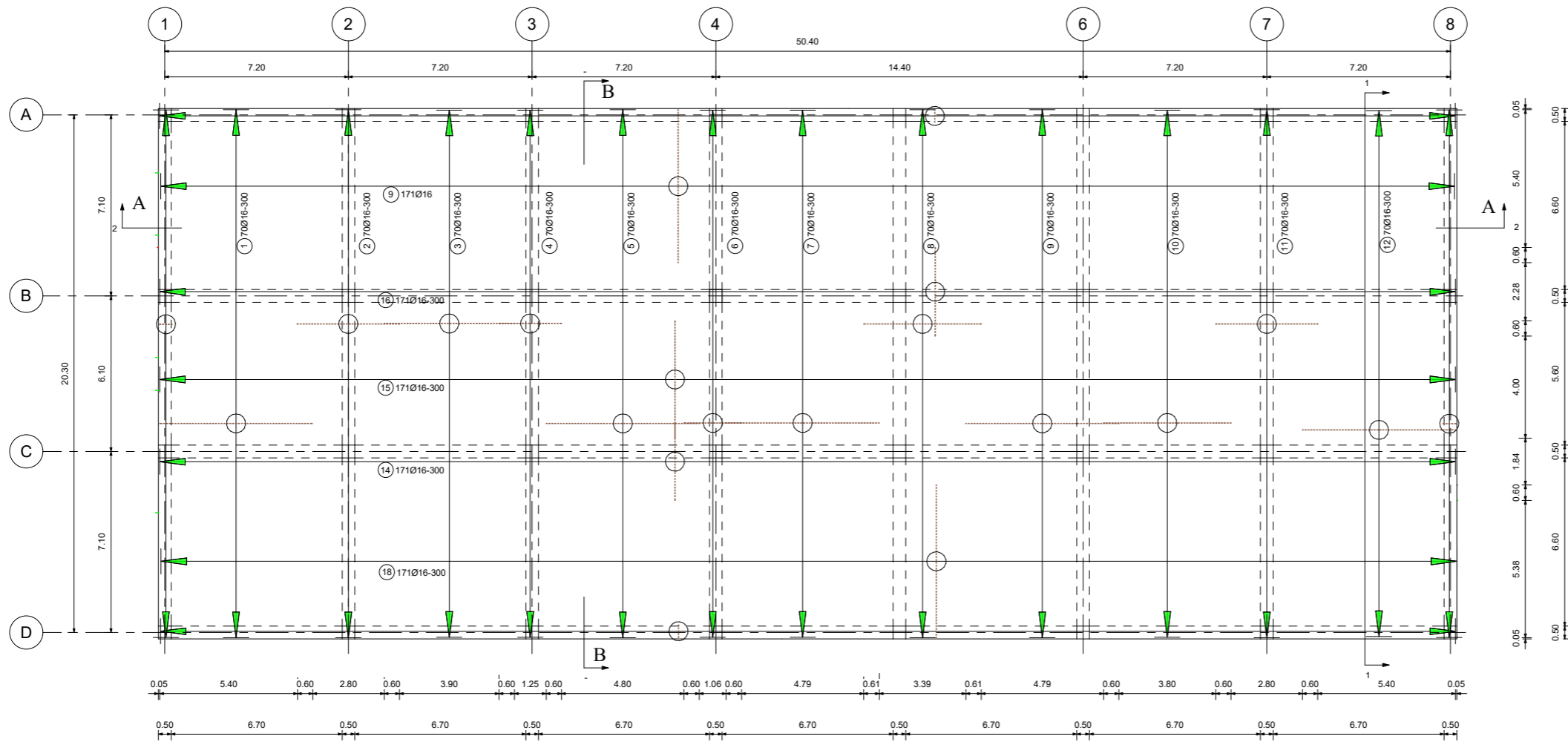
Bottom Reinforcement Plan
1 : 100

Rev	Description	Date

CODE — SUITABILITY DESCRIPTION
STATUS — PURPOSE OF ISSUE

PROJECT
Master Thesis Case Study 2

TITLE
Bottom Reinforcement

CLIENT
FGG

DRAWN BY Muniru Nyei	Prof. Tatjana Isaković	DATE 10/7/20
SCALE (@ A1) 1 : 100	PROJECT NUMBER 1	
DRAWING NUMBER 1		REV

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Mark	Shape Code	Sheet Number	Diameter (mm)	Image	Bar Length (mm)	Qty.	Mass / Length	Total Weight (kg)
1	21	2	Ø12		1075	70	0.89 kg/m	66.82
2	00	2	Ø16	2338	2350	70	1.58 kg/m	259.91
3	00	2	Ø16	4800	4800	70	1.58 kg/m	530.88
4	00	2	Ø16	4800	4800	70	1.58 kg/m	530.88
5	00	2	Ø16	4800	4800	70	1.58 kg/m	530.88
6	00	2	Ø16	4800	4800	70	1.58 kg/m	530.88
7	00	2	Ø16	4800	4800	70	1.58 kg/m	530.88
8	00	2	Ø16	4800	4800	70	1.58 kg/m	530.88
9	00	2	Ø16	2346	2350	70	1.58 kg/m	259.91
10	21	2	Ø12		1075	70	0.89 kg/m	66.82
12	00	2	Ø16	2590	2600	171	1.58 kg/m	702.47
13	00	2	Ø16	4800	4800	171	1.58 kg/m	1296.86
14	00	2	Ø16	4800	4800	171	1.58 kg/m	1296.86
15	00	2	Ø16	2475	2500	171	1.58 kg/m	675.45
16	21	2	Ø12		1075	171	0.89 kg/m	163.24
16	21	2	Ø12		1075	171	0.89 kg/m	163.24
Grand total								8136.86
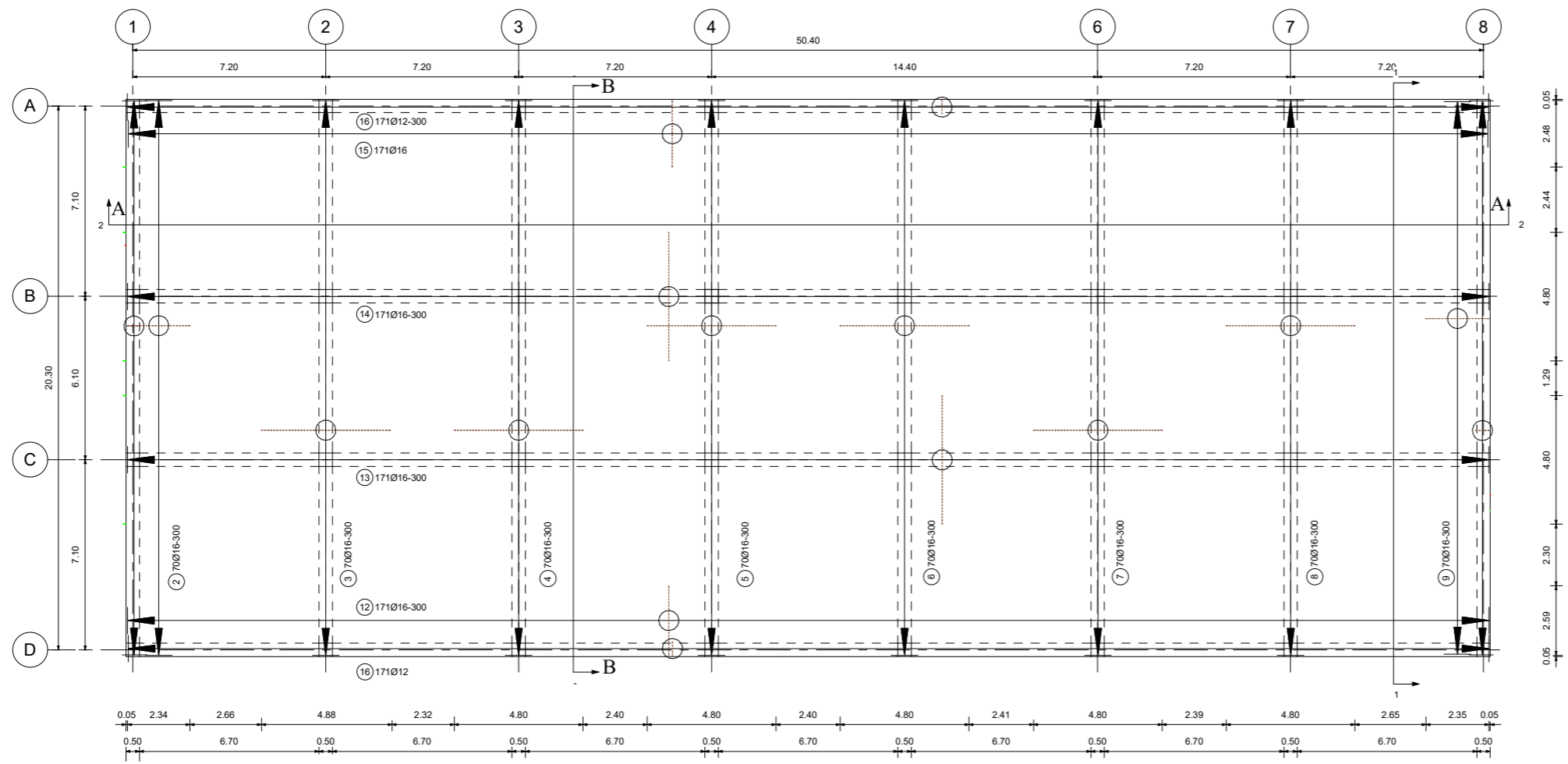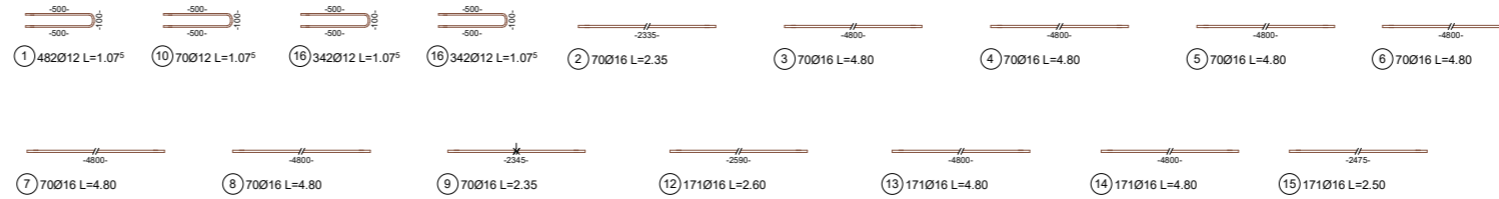
2 SOFiSTiK_ShapeDetails_2_1/25
1 : 25

(1) 482Ø12 L=1.075 (10) 70Ø12 L=1.075 (16) 342Ø12 L=1.075 (16) 342Ø12 L=1.075 (2) 70Ø16 L=2.35 (3) 70Ø16 L=4.80 (4) 70Ø16 L=4.80 (5) 70Ø16 L=4.80 (6) 70Ø16 L=4.80

(7) 70Ø16 L=4.80 (8) 70Ø16 L=4.80 (9) 70Ø16 L=2.35 (12) 171Ø16 L=2.60 (13) 171Ø16 L=4.80 (14) 171Ø16 L=4.80 (15) 171Ø16 L=2.50

1 Top Reinforcement Plan
1 : 100

Rev	Description	Date

CODE — SUITABILITY DESCRIPTION

STATUS — PURPOSE OF ISSUE

PROJECT
Master Thesis Case Study 2

TITLE
Top Reinforcement

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DRAWN BY Muniru Nyei	Prof. Tatjana Isaković	DATE 10/7/20

SCALE (@ A1): As indicated
PROJECT NUMBER: 1
DRAWING NUMBER: 2
REV

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Section A

Section A
1 : 100

Section B

Section B
1 : 100

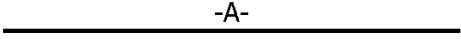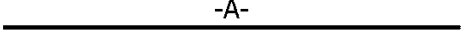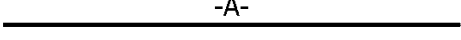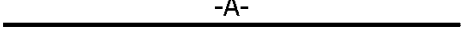| **Project:** Master Thesis Project	**Schedule ref:** 1	**Date:** 2020-10-07
Client: FGG	**Prepared by:** Muniru Nyei	**Checked by:** Prof. Tatjana Isaković
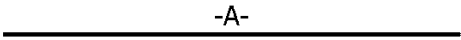
Project

Name: Master Thesis Project
Address: Ljubljana, Slovenia
Client: FGG
Shape Codes According to: EN ISO 3766:2003
Revision Number:
Revision Date:

The bar length is calculated on the basis of the center line.

Weight Schedule - straight bars

Material: Default				
Sizes used	Type	Mass per Unit Length	Total Length	Total Weight
16 mm	Ø16	1.58 kg/m	7985.40	12616.93
TOTALS				12616.93

Rebar Bending Schedule

Member	Bar Mark	Bar Diameter	Length of each bar	Total No.	Total Length	Bend Diameter	Shape Code	Hook Start/End	A	B	C	D	E / R	H$_{Start}$ / H$_{End}$	Rev
	1	16 mm	6.00	70	420.00	64 mm	00		5980						
	2	16 mm	4.03	70	281.75	64 mm	00		4010						
	3	16 mm	5.10	70	357.00	64 mm	00		5095						
	4	16 mm	2.45	70	171.50	64 mm	00		2445						
	5	16 mm	6.03	70	421.75	64 mm	00		6005						

SOFiSTiK

Project: Master Thesis Project					**Schedule ref: 1**						**Date:** 2020-10-07					
Client: FGG					**Prepared by: Muniru Nyei**						**Checked by: Prof. Tatjana Isaković**					

Member	Bar Mark	Bar Diameter	Length of each bar	Total No.	Total Length	Bend Diameter	Shape Code	Hook Start/End	A	B	C	D	E / R	H$_{Start}$ / H$_{End}$	Rev
									-A-						
	6	16 mm	2.27	70	159.25	64 mm	00		2255						
									-A-						
	7	16 mm	6.00	70	420.00	64 mm	00		5995						
									-A-						
	8	16 mm	4.62	70	323.75	64 mm	00		4605						
									-A-						
	9	16 mm	6.00	70	420.00	64 mm	00		5995						
									-A-						
	10	16 mm	5.00	70	350.00	64 mm	00		4995						
									-A-						
	11	16 mm	4.00	70	280.00	64 mm	00		3995						
									-A-						

2

SOFiSTiK

Project: Master Thesis Project					**Schedule ref: 1**						**Date:** 2020-10-07				
Client: FGG					**Prepared by: Muniru Nyei**						**Checked by: Prof. Tatjana Isaković**				

Member	Bar Mark	Bar Diameter	Length of each bar	Total No.	Total Length	Bend Diameter	Shape Code	Hook Start/End	A	B	C	D	E / R	H_{Start} / H_{End}	Rev
	12	16 mm	6.03	70	421.75	64 mm	00		6000						
											-A-				
	13	16 mm	5.98	171	1021.73	64 mm	00		5970						
											-A-				
	14	16 mm	3.05	171	521.55	64 mm	00		3040						
											-A-				
	15	16 mm	4.60	171	786.60	64 mm	00		4595						
											-A-				
	16	16 mm	3.50	171	598.50	64 mm	00		3475						
											-A-				
	17	16 mm	6.03	171	1030.28	64 mm	00		6000						
											-A-				

Project: Master Thesis Porject	**Schedule ref: 2**	**Date:** 2020-10-07
Client: FGG	**Prepared by:** Muniru Nyei	**Checked by:** Prof. Tatjana Isaković

Project

Name: Master Thesis Project
Address: Ljubljana; Slovenia
Client: FGG
Shape Codes According to: EN ISO 3766:2003
Revision Number:
Revision Date:

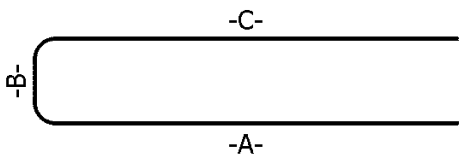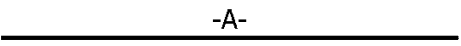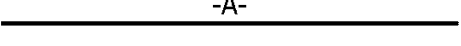**The bar length is calculated on the basis of the center line.**

Weight Schedule - straight bars

Material: Default

Sizes used	Type	Mass per Unit Length	Total Length	Total Weight
16 mm	Ø16	1.58 kg/m	4858.70	7676.75
TOTALS				7676.75

Weight Schedule – bent bars

Material: Default

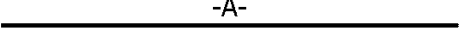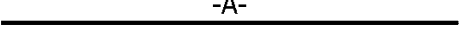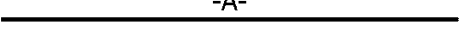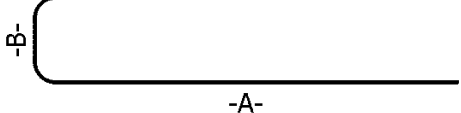| Sizes used	Mass per Unit Length	Total Length	Total Weight
12 mm	0.89 kg/m	518.15	461.15
TOTALS			461.15
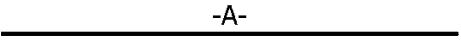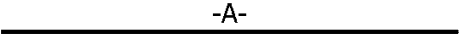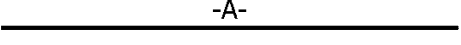
Rebar Bending Schedule
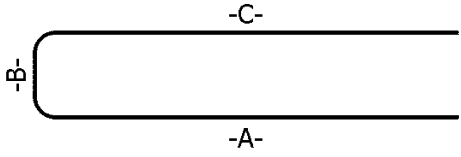
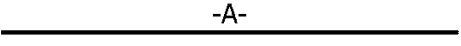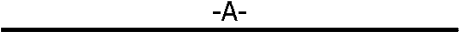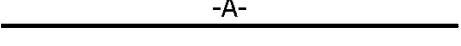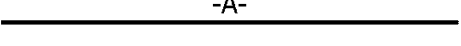| Member	Bar Mark	Bar Diameter	Length of each bar	Total No.	Total Length	Bend Diameter	Shape Code	Hook Start/End	A	B	C	D	E / R	H_Start / H_End	Rev
	1	12 mm	1.07	70	75.25	48 mm	21		500	100	500				
	2	16 mm	2.35	70	164.50	64 mm	00		2335						
	3	16 mm	4.80	70	336.00	64 mm	00		4800						
	4	16 mm	4.80	70	336.00	64 mm	00		4800						

Member	Bar Mark	Bar Diameter	Length of each bar	Total No.	Total Length	Bend Diameter	Shape Code	Hook Start/End	A	B	C	D	E / R	H_{Start} / H_{End}	Rev
	5	16 mm	4.80	70	336.00	64 mm	00		4800						
	6	16 mm	4.80	70	336.00	64 mm	00		4800						
	7	16 mm	4.80	70	336.00	64 mm	00		4800						
	8	16 mm	4.80	70	336.00	64 mm	00		4800						
	9	16 mm	2.35	70	164.50	64 mm	00		2345						
	10	12 mm	1.07	70	75.25	48 mm	21		500	100	500				

SOFiSTiK

Project: Master Thesis Porject	Schedule ref: 2	Date: 2020-10-07
Client: FGG	Prepared by: Muniru Nyei	Checked by: Prof. Tatjana Isaković

Member	Bar Mark	Bar Diameter	Length of each bar	Total No.	Total Length	Bend Diameter	Shape Code	Hook Start/End	A	B	C	D	E / R	H$_{Start}$ / H$_{End}$	Rev
	11	12 mm	1.07	171	183.82	48 mm	21		500	100	500				
	12	16 mm	2.60	171	444.60	64 mm	00		2590						
	13	16 mm	4.80	171	820.80	64 mm	00		4800						
	14	16 mm	4.80	171	820.80	64 mm	00		4800						
	15	16 mm	2.50	171	427.50	64 mm	00		2475						
	16	12 mm	1.07	171	183.82	48 mm	21		500	100	500				