Simulating embodied carbon emissions of buildings: comparing concrete with timber buildings

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Abstract

The construction industry is the largest consumer of concrete and steel worldwide, resulting in one-third of global carbon emissions. Achieving low-carbon buildings is a key concept to reducing carbon emissions and mitigating climate change. Wood is a carbon sink that absorbs carbon dioxide from the atmosphere and stores it in building elements until the end-of-life cycle. The reduction of carbon emissions is critical to addressing energy and climate issues. Due to safety and structural property concerns, the use of timber for structures is limited to low-rise structures. Tall buildings constructed with concrete impose high carbon emissions on the environment which has been overlooked on its embodied carbon more than the operational carbon.

In this research, the multi-story concrete residential building is simulated into a Timber-concrete building used as a comparative case study. To ensure the validity of the building, the timber-concrete building is verified on its feasibility. The embodied carbon analysis and comparative analysis are performed between the two buildings in terms of effects on the material quantities, embodied carbon, and global warming potential. It is found that the Timber-concrete building has a significantly lower embodied carbon emissions compared to its existing-concrete building. Furthermore, comparative analysis showed the implications of building materials and components on its embodied carbon emissions. Overall, this study can aid architects, engineers, and construction teams to adapt and implement timber in the construction of tall buildings in the future.

List of Keywords and abbreviations:

GHG: - Greenhouse Gases; GW: - Global warming; GWP: - Global warming potential; LCA: - Life cycle assessment; LCI: - Life cycle inventory; BIM: - Building information modelling; ECF: - Embodied carbon factor

RFEM: - 3d finite element modelling; ECB: - Existing-concrete building; TCB: - Timber-concrete building.

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Carbon dioxide	CO_2
Embodied carbon emissions	CO_2 emissions
Tons of embodied carbon emissions	t CO_2 e
Tons of carbon dioxide emissions per ton	t CO_2 e/t
Carbon dioxide equivalent emissions	CO_2 eq
Kilogram of carbon dioxide equivalent	Kg CO_2 eq
Tons of carbon dioxide equivalent emissions	t CO_2 eq
Giga Pascal	GPa
Tons per meter cube	t/m^3
Meter	M
Meter square	m2
Meter cube	m3

1. Introduction

1.1 Background research

In the construction industry, the buildings are responsible for the consumption up to 40% of global energy consumption and one-third of global greenhouse gas (GHG) emissions in developed and developing countries can be related to the activities in the building and construction sectors of the economy (UNEP, 2009). The world population is rapidly increasing foreseeing that by 2050 population living in cities will reach 70% (Karsch, 2012), and tall buildings will become even more common in the future. However, tall buildings are linked to high negative impacts on the GW (Global warming) raising the need for sustainable solutions. The GWP (Global warming potential) is defined by The Intergovernmental Panel on Climate Change (IPCC) (Delmotte, 2018), as a relative measure of how much a given quantity of GHG is estimated to contribute to the global warming over a time scale of 100 years. The environmental impacts of concrete and timber building, including their role in GWP, is the primary motivation behind this research paper.

Timber is a natural material used throughout the world. With proper management, there is a potential for a continuous and sustainable supply of raw timber material in the future (Kohler, 2006). Especially in Europe, the use of Cross-laminated timber (CLT) and Glulam timber (GLT) for wood construction systems are taking the lead in the construction of low-rise and high-rise buildings. Such timber materials like the CLT and GLT are known to be popular for their beneficial structural properties and efficient construction systems. Timber material can be used in walls, floors, and roofs, where it constitutes the bearing structures through walls, and provides weather protection. As a result, the layered makeup of the building envelope is simplified and reduced. CLT and GLT are lightweight and have easier constructability when compared to concrete. Yet, adaptation of CLT to engineering and architecture practices has been limited. It is also noteworthy that a GLT differs from a CLT member in the way its lamination of layers is formed. Hence, GLT members are mainly used as columns and beams. The one-directional strength of GLT is quite different from that of a CLT member (panel) in which the strength is two-directional (Mohammad, 2012). GLT has two main functions: (1) GLT beams help with transferring wind forces to the stability system and (2) the columns support loads of the floors. Timber panels are multifunctional from both a structural and a constructive point of view. Timber material panels are mainly developed in three stages (Santos, 2008). The first stage involves making sawn timber into fiber panels/boards and laminated boards. The second stage involves converting wood panels strips into multi-layered sheets with high strength. The third stage produces fiberboards by pressing them into thick sheets. Even though timber engineering provides an opportunity for timber material use in construction. However, timber is still not being used to its full potential in the construction sector. Despite the numerous beneficial properties and benefits of timber buildings, wood is still a complex material for tall structures (Santos, 2008).

1.2 Statement of problem

Tall timber buildings are a concept that emerged connected with a sustainable solution, as timber is a sustainable material to reduce the negative environmental impacts of the construction sector (Silva, 2013). But they are still not considered very feasible for taller heights. Tall buildings constructed with concrete and steel produce high carbon emissions during the whole life cycle of the building. Due to safety and structural properties concerns, the use of timber has been limited to low and mid-rise structures. Therefore, concrete and steel are still the main/primary structural material in the construction of tall structures. The carbon emissions produced in construction using concrete and steel material leads to high environmental impact on the GW. Whereas wood has significantly lower embodied carbon compared to concrete/steel materials because its CO_2 emissions are completely offset by the CO_2 absorption of trees (Zabalza, 2011). To construct a tall structure with less carbon emissions, a change in the main/primary material of the structure is required.

While researchers have found a lack of aiding designers, engineers, and construction teams, it is due to fact that lack of FEM (Finite Element Method) implementation for designing and evaluating the embodied carbon of tall timber structures is limited. The finite element method is a numerical method which is used for problems where analytical mathematical solutions are not possible to be obtained due to complicated geometries, loadings, and material properties. Despite the maturity in timber material engineering, limited research has been done on the feasibility, comparative embodied carbon, and environmental impact of embodied carbon emissions on tall buildings. Hence, this research will focus on calculating the embodied carbon and comparative analysis of building materials & components through the feasibility of case study.

1.3 Research objective

The main objective of this research is to calculate the embodied carbon emissions to find a lower global warming potential between a tall ECB (Existing-concrete building) and an TCB (timber-concrete building). For carbon emissions calculations, material quantification will be done through the feasibility of concrete and timber building in this research. ECF (Embodied carbon factor) will be determined from the relevant literature. Eventually, the total embodied carbon will be calculated in two cases: Case 1 – ECB and Case 2 – TCB to find a lower embodied carbon emission. It is expected that the analyzation would not only aid the designers and engineers, but also the construction team by utilizing the digital model outcomes to analyze the structure virtually. Also, the research can help plan, estimate the fabrication of the material components efficiently through its quantities and rehearse the on-site assembly of prefab parts for tall timber buildings.

1.4 Significance of study

The interest in timber is constantly increasing in EU countries and worldwide. Timber material has proven to be sustainable while providing possibilities for a fast assembly at the building site; still the existing research is limited on its embodied carbon of the first and second stages of LCA (Gervasio, 2018). The need for providing housing to on-going densification in different cities requires taller buildings, which should not only be operationally sustainable but also have lower embodied carbon.

By considering the three strong developments in the construction industry: environmentally friendly construction, urban densification, and extended use of FE-modelling. This research paper tries to determine the embodied carbon emissions of both ECB and TCB with detailed carbon analysis and comparative analysis.

1.5 Research questions

The prominent way to achieve the objective is with formulated research questions:

1. How feasible is simulating an existing-concrete building into a timber-concrete building on the maximal allowable lateral displacement?
2. What is the difference between existing-concrete and timber-concrete building in terms of effects on the material quantities, embodied carbon and GWP?
3. What implication does the building materials and components (ECB and TCB) have on its embodied carbon emissions over the 100 years in terms of GWP or carbon-dioxide equivalency?

1.6 Research scope

The research scope explores the data collection and modelling of ECB which is simulated into TCB. The analyzed data of modelling was used to calculate the material quantities and determine ECF from the relevant literature has helped the purpose of embodied carbon analysis and comparative analysis. GWP used as an impact category supports the scope of analysis in this research. The thesis is divided into seven chapters.

2. Literature review

This chapter reviews the relevant literature on CLT/Glulam material use and its efficient composition in tall buildings. This section also reviews the importance of BIM (Revit) and Rfem modelling for computational evaluation of a building, its input data requirements and material quantification extraction. Finally, the importance of embodied carbon and GWP in LCA of concrete and timber buildings are reviewed. Thus, the section elaborates on the existing literature in following three parts:

2.1 CLT and GLT material use in tall structures

The recognition of timber as a main material for tall building construction follows a proposal by (Foster, 2017) presented for consideration in the industry. (Kuzmanovska, 2018) mentioned, the enabling of CLT and GLT material is required to become competitors of steel and concrete in the construction market of medium to high-rise timber structures. Whereas (Harte, 2017) mentioned the number of tall multi-story buildings with a Glulam-CLT frame structure remains negligible compared to those with steel and concrete. Importantly, the UK (Committee on Climate Change, 2018) has indicated that increasing uptake of wood products in construction is the most effective option towards zero-carbon buildings. According to the Council on Tall Buildings and Urban Habitat (Wells, 2011), around 60% of the high-rise buildings (out of one hundred tallest buildings) completed between 2001 and 2015 used concrete core-outrigger structure systems.

The current research on timber high-rise structures adopted steel/concrete core-outriggers system leading to limited research on CLT walls system with Glulam frame. One of the research projects by (Rismanchi, 2018) analyzes a high-rise building with a composition of CLT walls, a concrete-core, and concrete outrigger systems. The study showed a reduction of 50,000 tons of CO_2 emissions but the outriggers made of concrete/steel in the structure added certain high emissions to the GWP and reduced the possibility for more sequestration. Thus, the idea of zero carbon buildings does not fully accomplish with alternatives of concrete/steel core-outriggers. There is also existing study by (Chiniforush, 2018) on the environmental implications of composite steel-CLT building structure at a whole-building scale. These structural systems are proving their practical feasibility but not the most effective option towards zero-carbon buildings due to added CO_2 emissions

from steel/concrete outriggers.
By replacing the steel-concrete outriggers systems in the super-structure, the CLT shear-walls with Glulam frame and concrete-core could be an effective option towards zero-carbon buildings. This study seems yet to be conducted as there is no existing research found. Another study by (Roos, 2010) focuses on architects and structural engineers' perception of timber constructions. And mentioned that CLT has poor form-stability for taller heights. Whereas (Falk, 2005) defined the structural behavior based on CLT timber plates in tall structures, mentioning the significance of orientation of walls and walls as well as warning for stability dependency on both orientation and jointing.

To achieve a lower GWP towards zero-carbon buildings, the CLT walls can be used as the load-bearing structure with Glulam frame support and concrete-core for its practical feasibility and embodied carbon efficiency in the tall timber building.

2.2 BIM (Revit) & RFEM-based material quantification

Building Information Modelling (BIM) has emerged as an advanced methodology to provide the needed common data environment (CDE) and facilitate sharing data among various disciplines in design activities (Kuiper, 2013). The finite element method (FEM) is a mathematical method for the analysis of structural and non-structural problems. It is a numerical method which is used for problems where analytical mathematical solutions are not possible to be obtained due to complicated geometries, loadings, and material properties (Logan, 2012).

A significant challenge still exists to acquire necessary data related to building information in an accurate and efficient manner when conducting LCA in the building and construction sector (Scheur, 2003). Although BIM (Revit) provides an effective platform that consists of essential information for conducting LCA of buildings, which could simplify the procedure for fundamental data collection (Chen, 2015). (Khosakitchalert, 2019) mentioned that the quality of BIM model affects the accuracy of extracted material quantities. The quality of BIM model depends on the definition of detailing. In practice, the detail in a BIM model is developed through design and construction phases. This research used the "BIM-based compound element quantity takeoff improvement"

(BCEQTI) method to extract the accurate material quantities. Another study by (Berg, 2014) mentioned the definition of detail can be used in existing BIM LCA tools such as IMPACT (Impact, 2014) and Tally (KT Innovations, 2014). Fira explored a BIM-based quantity takeoff process in two case studies and concluded that the lack of modelling guidelines obstructs the quantity takeoff process, and the model should be created in a way that is easy and possible for quantity takeoff (Fira, 2018).

These methods and tools could be used for accuracy in extracting material quantities to eliminate the overlapping and unconnected building components. However, they are very time-consuming, require extensive detailing of components and lack of proper guidelines. Importantly, there is no clear validation of extracted material quantities from the BIM models using additional tools and methods. Therefore, it is unclear that the extracted material quantities are completely accurate.

On the other hand, Rfem is powerful 3D FEA (finite element analysis) based on a modular system. It can be used to define structures, materials & loads for planar and spatial structural systems consisting of plates, walls, shells, and members (Rohini, 2017). Rfem model developed by (Connolly, 2018) shows the original geometry and assumptions adopted by structural engineers. Fixed end-node restraints are adopted on the concrete columns, slabs, and cores, whereas timber elements were assumed pinned at their ends. The geometry of the model is defined by nodes that connects lines and, thus members, surfaces, and solids. Rfem can easily model check any overlapping and unconnected nodes, lines & surfaces to avoid discrepancies in the model (Dlubal manual). Thus, Rfem can extract the material quantities faster in terms of the original geometry and assumptions that does not require any additional method or tools. However, the nodes placed centre to centre of the columns to keep limited number of nodes results in a small overlap of wall & floor on the column & beam. This overlap is unavoidable due to centre-to-centre connectivity of nodes. Hence, Rfem extracted material quantities are not completely accurate. Yet, these quantities can be validated easily with a manual calculation.

In this research, material quantification of concrete components in substructure & superstructure for case 1: ECB (Existing-concrete building) and CLT walls system with Glulam frame as the superstructure & concrete as the substructure for case 2: TCB

(Timber-concrete building) needs to be determined. By implementing the Rfem software for material quantification, more accurate quantities can be determined with only a small overlap as explained previously.

2.3 Importance of Embodied Carbon & GWP in LCA

Low-carbon buildings have been considered an important strategy in achieving embodied carbon reduction and sequestration in tall buildings. More use of timber material in comparison to concrete/steel in buildings helps in achieving the low-carbon strategy goal. For its development, several studies have evaluated the GHG emissions over the life cycle of buildings like (Ala-Mantila, 2014).

According to (Sandanayake, 2018), the building sector is one of the major industries for producing a large amount of GHGs. The building sector represents significant potential for reducing emissions and lowering GW. (Hafner, 2014) mentioned that GHG emissions can be significantly influenced by the selection of primary material. Wood buildings are considered low carbon (less fossil fuel intensive) construction than the concrete and steel buildings. Another study by (Borjesson, 2000) revealed that the primary energy input (fossil fuels) in the production of building materials is about 60-80% lower for timber frames compared to concrete frames.

Embodied carbon (t CO_2 e) is the sum of greenhouse gas emission released during the following life-cycle stages: raw material extraction, transportation, manufacturing, construction, maintenance, renovation and end-of-life for a product or system (SE database, 2050). A ratio denoting the effect of a quantity of a greenhouse gas on climate change compared with an equal quantity of carbon dioxide is Global warming potentials (GWP). It is usually expressed over a 100-year period. The GWP value of carbon dioxide is 1 as per (Assessment report 4, IPCC 2007). The results of applying GWP can be expressed as carbon dioxide equivalent (i.e., t CO_2eq). That means, one kilogram of carbon dioxide gas has a GWP of 1 kgCO_2eq, whereas, for example, one kilogram of methane gas is approximately 28 kgCO_2eq. There are seven major categories of GHGs which includes carbon dioxide, methane, nitrous oxides, perfluorinated compounds, hydrofluorocarbons, and nitrogen trifluoride. All these gases contribute at different magnitudes to the global warming. Carbon-dioxide is the main GHG contributing 75% of the overall warming effect when measured on a 100-year time frame. Since carbon dioxide is the prominent greenhouse gas, all other gases are scaled to the impact of carbon dioxide, this is called (CO_2 eq) carbon dioxide equivalency or GWP.

As different greenhouse gases have different capacities for absorbing heat in the atmosphere and therefore, warming the globe. The ability for a greenhouse gas to absorb heat is called radiative forcing. For example, methane has a stronger warming impact or radiative forcing on the atmosphere than carbon dioxide. GWP as a factor is used to scale all the GHGs that is calculated as (CO_2 eq) carbon dioxide equivalency. The GWP or the warming impact of GHGs relative to the carbon dioxide depends not only on the gases ability to absorb heat but also on how long the gas lives in the atmosphere. That’s why, time frame also plays a role in GWP calculations, for instance, methane lives shorter than the carbon dioxide in the atmosphere. However, in building construction, the total carbon emissions emitted results the same amount of carbon dioxide equivalency or GWP due to value 1 of carbon dioxide over the 100 years. Thus, the embodied carbon emissions produce same amount of carbon dioxide as the carbon dioxide equivalency/GWP.

LCA can provide quantitative and comparative values for the environmental impacts of various building materials (Takano, 2015). But the main issue is with ECF available today lacking in standardization and which stages of LCA to include in. An embodied carbon/emission factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant (EPA, 2007). Due to non-standardization of ECF, existing research varies from each other. According to (De Wolf, 2016), the reports which analyzed the environmental impact of concrete (Collins, 2010), steel (ISSF, 2013), and timber (Pullen, 2000) also showed significant variability in the results for both embodied carbon dioxide and ECF. The efforts to summarize the ECF of common construction materials by the University of Bath Inventory of Carbon & Energy (Hammond, 2011) is one of the most complete open-source databases. This inventory has the best available embodied carbon factor. With embodied carbon reduction, carbon sequestration also plays a significant role in the process of storing carbon dioxide from the environment. There is increasing awareness of the potential role that construction materials can play in mitigating climate change by sequestering carbon (Pomponi, 2020). The (Istructure guide, 2020) shows a rational approach for calculation of embodied carbon and carbon sequestration values. Therefore, the embodied carbon and carbon sequestration calculations in this research will be calculated based on this available data.

2.4 Summary

Determining the total structural materials used in the analysis is contingent on meeting the design requirements, which will influence comparative carbon analysis to a lower GWP. So, it is important that before analyzing GWP impact category for TCB, it is necessary to ensure that the structural elements and material meet the relevant design requirements to have practical feasibility. Further, embodied carbon emissions and carbon sequestration will be calculated on the most accurate data available validated.

3. Research Methodology

This chapter describes the methodology that is applied in this research, which is summarized in Figure 1 in this chapter. Detailed elaboration of the methodology is provided in sections 3.1 to 3.4 respectively. Firstly, the data collection and modelling (ECB & TCB) of the research project is described. Secondly, the data modelled in Rfem is used to perform the data analysis for both cases: ECB and TCB on its material properties and specification for the feasibility of building. Thirdly, the validation of data analysis is explained to validate the accurate material quantities for both cases. Lastly the formulation and calculation of embodied carbon data is explained to evaluate the total embodied carbon emissions and make a comparison for the implication of building components & materials on its embodied carbon emissions. This methodology can be used by designers and engineers towards constructing zero carbon buildings to a lower GWP. The four phases of the research methodology are shown in Figure 1:

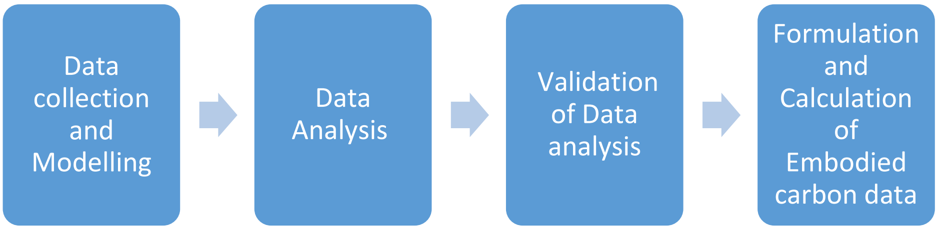

Fig 1: Methodology Phases

3.1 Data collection & modelling

The purpose of data collection is based on quantitative data for the case study. Data is collected by the author referring to an Architectural firm (GA design) in India. The collected data is mainly based on the architectural and structural drawings used in this research. It includes the layout, elevation, and section drawings that is based on multi-story apartment building. This data is applied to model the two cases for this research. The modelling of case study focuses on the feasibility of TCB on its lateral displacement. The data collected and modelled could be extended to other projects having similar characteristics. Figure 2 below shows steps of methodology phase 1:

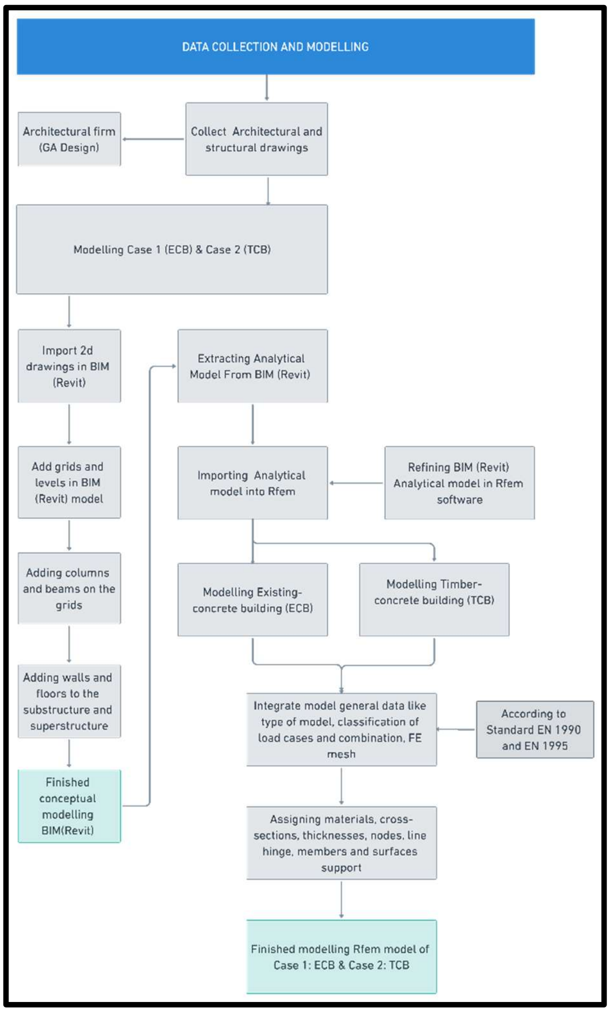

Fig 2: Methodology phase 1

The modelling starts by developing a conceptual building in the BIM(Revit) software. The architectural and structural drawings collected are used for modelling. Firstly, the grids and levels are placed in the BIM (Revit) model. Secondly, the columns and beams are modelled creating a frame structure. Thirdly, the walls and floors are added to all the levels. After finishing the conceptual model, the extraction of analytical model is done from BIM (Revit) in the IFC format. The analytical model is a simplified 3d representation of the structural physical model that consists of components, geometry, material properties and loads. This conceptual analytical model is imported into Rfem software integrating general data like type of model, classification of load cases & combination (according to standard EN 1990 and EN 1995). Lastly, assigned the materials, cross-sections, thicknesses, nodes, line hinges, members, and surface support. Thus, the modelling for both cases is finished (see appendix F).

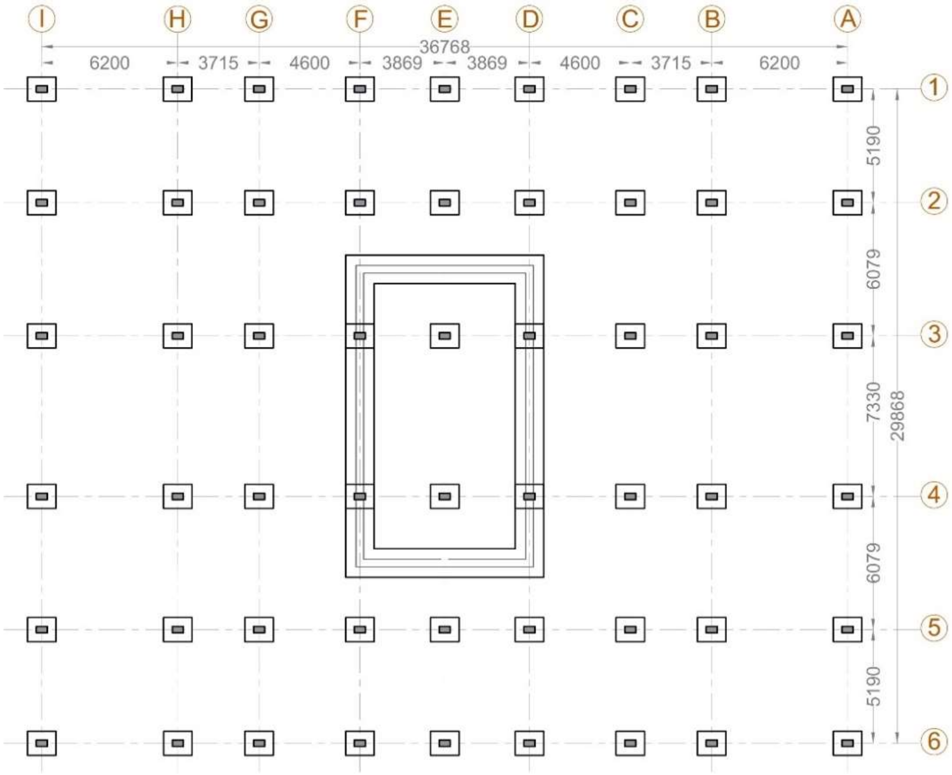

Fig 3: Typical Foundation Plan (Case 1 & 2)

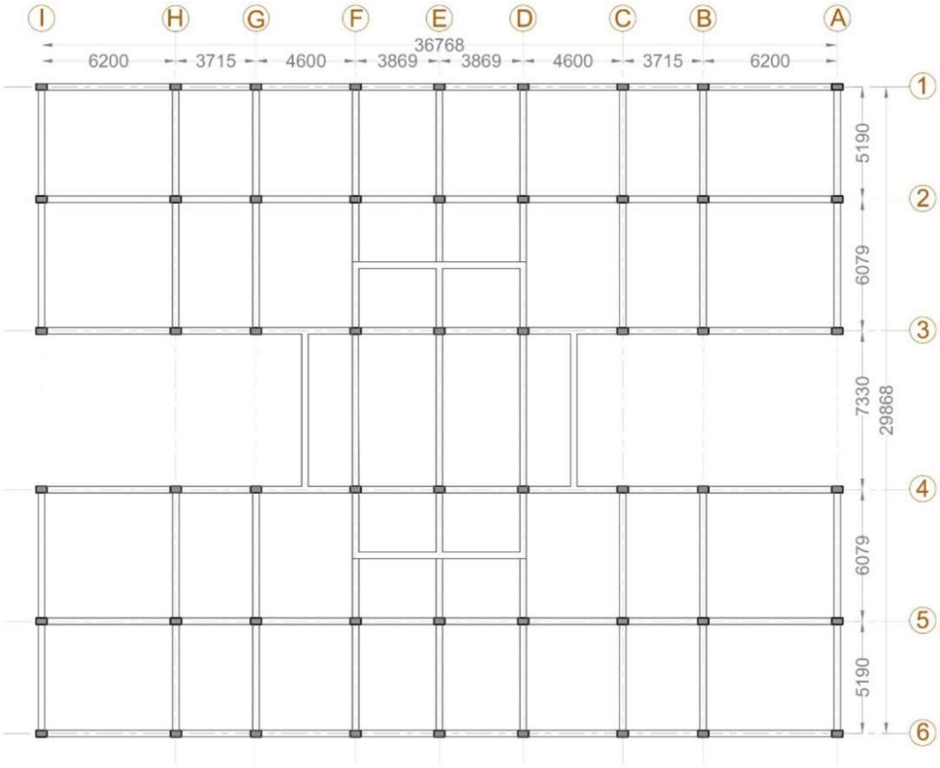

Fig 4: Typical Column-Beam Plan (Case 1 & 2)

Figure 3 & 4 above shows the foundation plan and column-beam plan that is typical in both cases. In both cases, building stands at a height of 84m, a width of 30m and a length of 37m.

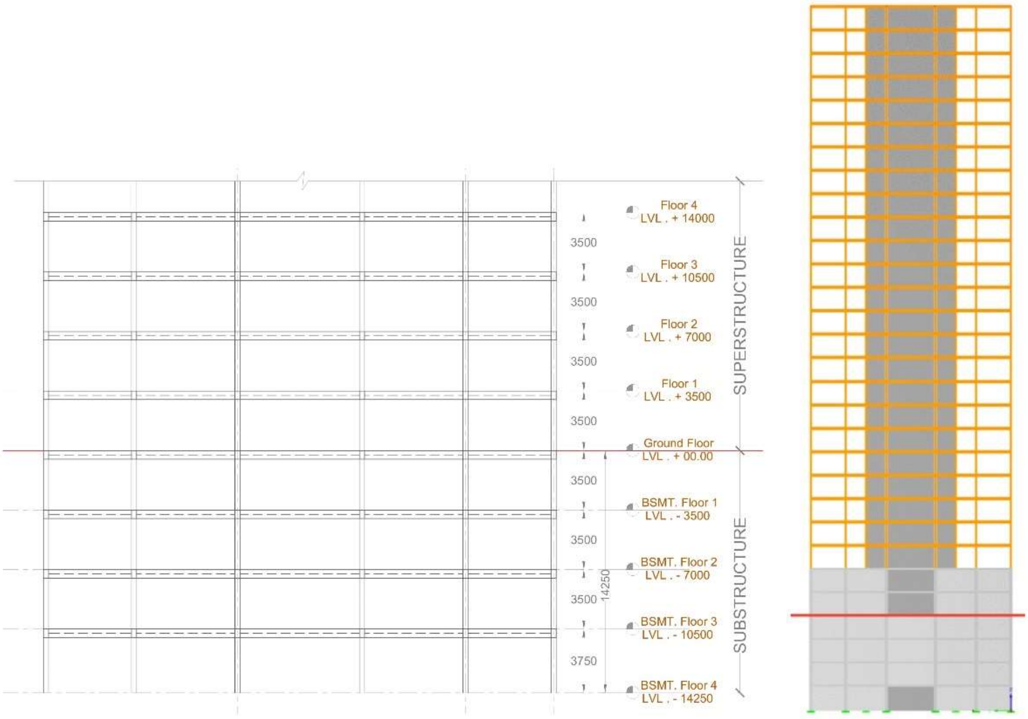

Fig 5: Elevation blow-up (left) and Building elevation (right)

Figure 5 above shows the elevation blow-up (left) and building elevation (right) marked with red line as the ground line. The modelling was divided into two parts: the substructure and superstructure as shown in above (left) image with floor levels and (right) image with red line marked. The substructure is part of the building that is built below ground level whereas superstructure is the part of the structure that is constructed above the ground level (constructor, 2010). For both cases, the substructure has four levels below the ground level that is completely in concrete material. And the superstructure above ground level for case one is in concrete and for case 2 is GLT frame (columns & beams) & CLT in walls and floors.

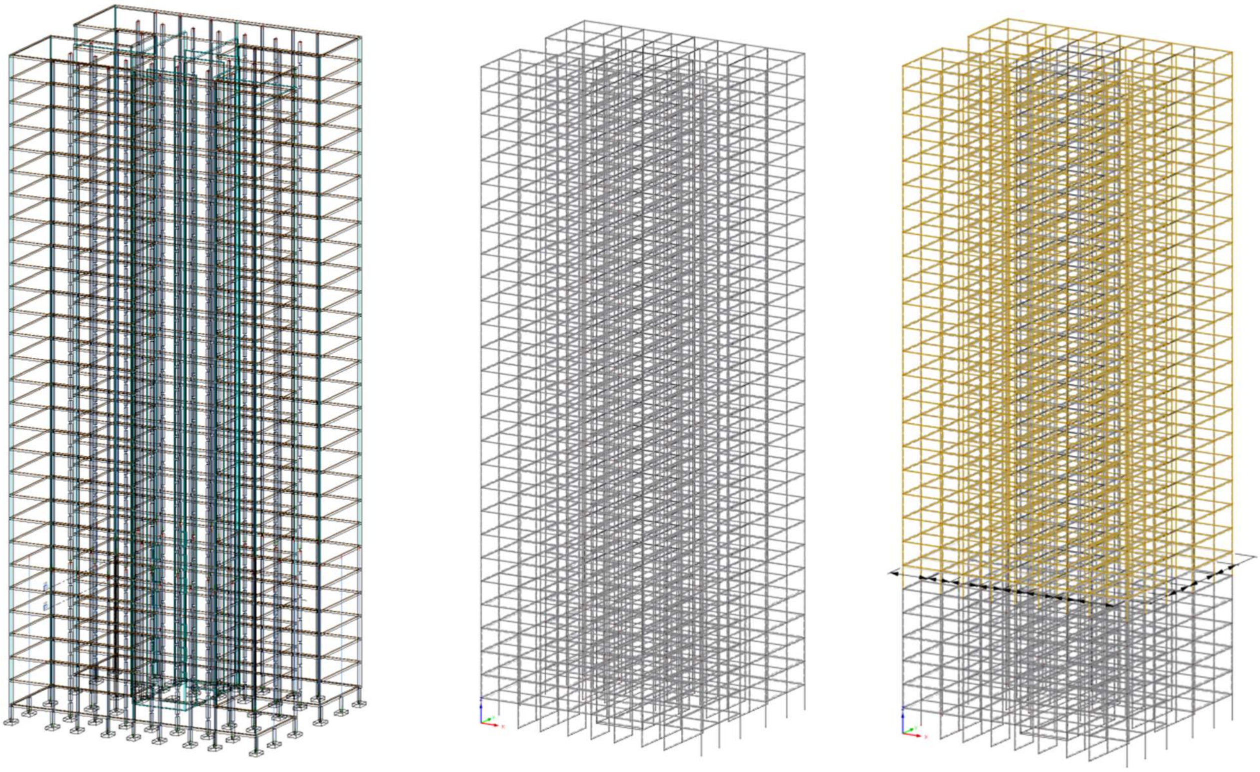

Fig 6: BIM (Revit) conceptual analytical model (left), Rfem ECB analytical model (middle) and Rfem TCB analytical model (right)

Figure 6 (left) shows the BIM(Revit) conceptual analytical model that is generated unfinished from BIM(Revit) software. This conceptual analytical model (left) requires refinement from multiple lines (overlapping/unconnected lines) into a single line analytical model. Therefore, the conceptual analytical model (left) is then imported & refined in Rfem by adding nodes, correcting lines, supports, materials and generating FE-mesh of the structure. The analytical model (middle) shows refined single line analytical model for case 1: ECB (Existing-concrete building). Likewise, the analytical model (right) shows refined single line analytical model for case 2: TCB (Timber-concrete building). Even though BIM(Revit) is a powerful tool, however, in case of modelling and generating efficient analytical model it still lacks. It is very time consuming to refine the conceptual analytical model in BIM(Revit) itself. Thus, it is chosen to import this conceptual model into the Rfem for modelling both cases.

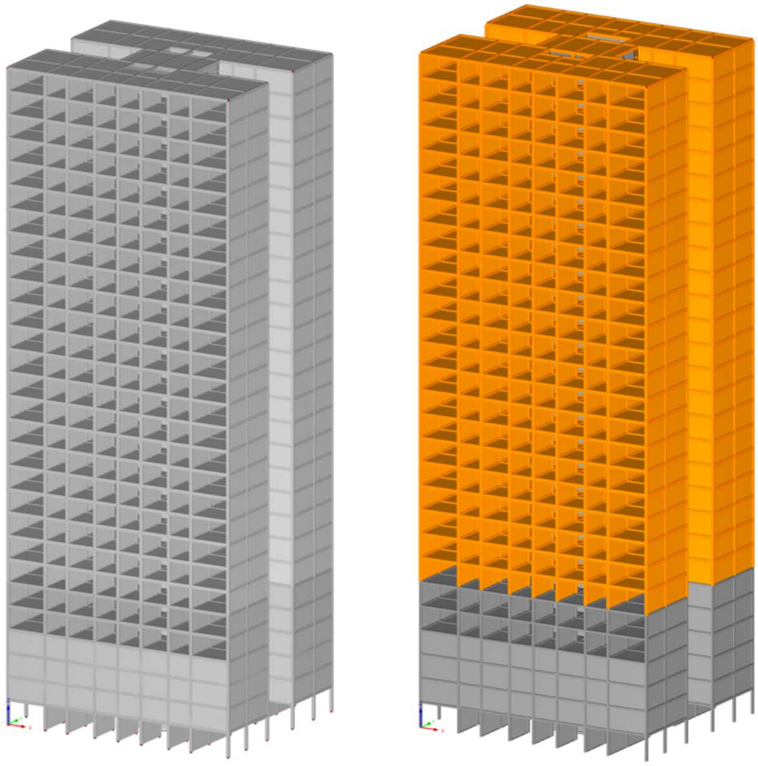

Fig 7: Existing-concrete (left) and Timber-concrete building(right)

Figure 7 (left) shows the finished model for case 1: ECB and figure 3 (right) shows the finished model for case 2: TCB. In both cases, the concrete-core is used as the central stability system for the superstructure and concrete frame, walls, and floors as the substructure for load-bearing support system. The superstructure in case 1 is in concrete material but in case 2, GLT framing and CLT is the key in the superstructure of floors and walls.

The modelling in Rfem has been simplified to what is essential regarding load bearing and stability. The building assembly is modelled with the following steps. It starts with the substructure by setting the concrete columns and beams where the floor merge in-between. The walls are then placed in and merged between columns & beams to give the right continuity. Substructure will consist of four levels in concrete frame, walls, and floors below the ground level. The superstructure is modelled with two levels of concrete frame, walls and floors that connect with substructure below. Concrete-core is continued from the bottom of substructure and connects with the superstructure as the main stability support. Above the two levels of concrete of the superstructure, the GLT frame is placed that extends throughout the total height of the structure. With each level of GLT framing, CLT walls are placed in-between the columns. The CLT floor is also merged between the GLT beams to give higher strength in the superstructure. For the modelling to be successful with simplification, the connection nodes between columns, beams and floor will be assigned with hinge/line connections. The modelled data for Case 1 and 2 is kept consistent in terms of dimension and size but materials are different. These cases are explained below:

Case 1 – ECB

ECB is a load-bearing structural system composed of concrete walls, frame, and floors. Concrete-core is integrated with lift shaft and concrete stairs. Walls are load bearing for lateral support; beams/columns for structural stability and floors are 250mm thick spanning between 3500-6000mm. The lateral forces resisting of 200mm thick walls proved adequate for wind design, based on wind speed of 140 km/hr. The seismic forces are not used in this research. In terms of strength and stiffness of the floor plans and building enclosure, the stability system in Case 1 (ECB) proved satisfactory from both standpoints.

Case 2 – TCB

TCB is a combination of load bearing CLT walls and GLT frame system. CLT and GLT replace the concrete material in walls, floors, and frame of the Superstructure as load bearing. The core remains the same as in Case 1. The lateral load path between floor and wall panels was resolved with a hinge/line connection in Rfem model. CLT wall openings is used at the north and south sides of the structure. Balconies are assumed to be pre-manufactured components of the building frame, and therefore, not included in its load. The 250mm thick CLT shear-wall panels assumed in this study have adequate strength and stiffness to support the gravity and lateral loads. Similarly, CLT floor panels of the same thickness have adequate strength and stiffness for the spans chosen. Floor vibration is assumed to be mitigated with a concrete topping floor on CLT floor panels. For input data, requirements, and results summary (see appendix B).

3.2 Data analysis

The modelled data is analyzed in this phase on its material properties and specifications. Also, assumptions and simplifications are established in this phase to verify the feasibility of TCB model on its lateral displacement and stability. Below figure 8 explains the methodology phase 2 steps.

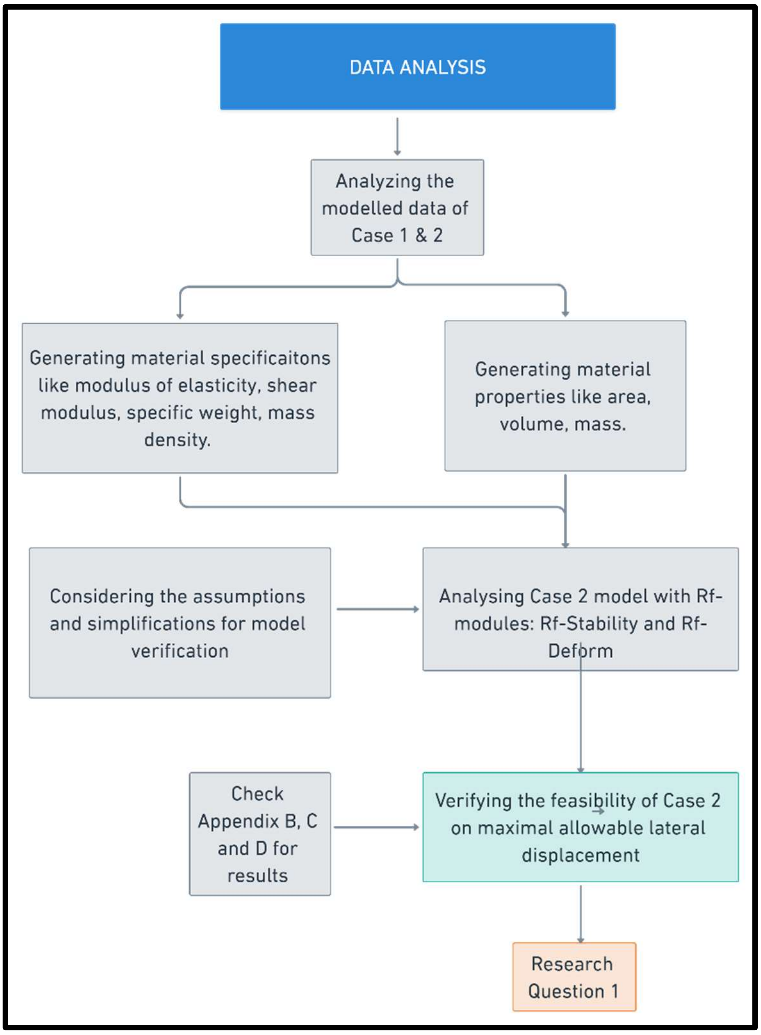

Fig 8: Methodology phase 2

To have higher accuracy in material quantities data of both the cases: ECB & TCB are identical in size and dimension (see appendix F). Internal validity can be ensured with the data analysis through accuracy of modelling in Rfem software. Thus, Rfem modelling is used for material quantity analyzation (see appendix D) for Rfem building models (centre of gravity info). Table 1 below shows material properties for both cases.

Table 1: Material properties

Material Type	**Material Standard**	**Modulus of Elasticity, E [GPa]**	**Shear Modulus, G [GPa]**	**Specific Weight γ [t/m³]**	**Material Model**
Concrete	Concrete C40/50*	35	14.58	2.5	Isotropic linear elastic
CLT	Softwood C45**	15	5.03	0.49	Isotropic linear elastic
CLT	Softwood C50**	16	5.3	0.52	Isotropic linear elastic
Glulam timber	GL 30c***	13	0.65	0.43	Isotropic linear elastic

* EN 1992-1-1:2004/A1:2014

** EN 338:2016-04

*** EN 14080: 2013 – 08

To facilitate the feasibility of TCB, the following assumptions and simplifications will be made in the process:

- Load combination: Live load and Wind load
- The eccentricity of force is neglected to simplify the analysis
- The analysis includes only the main structural elements.
- The detailed design of connections between elements is used as a hinge connection in FEM model.
- The core is constructed in concrete connected to a timber structure as a line/hinge connection.
- The reinforcement in concrete is based on the library material selection properties.

This data analysis is verified against two Rf-modules which are Rf-Deformation and Rf-Stability characterized by the standards (EN 1990, 2002) + (EN 1995, 2004). The Rf-Deform performs the deformation analysis of individual members or entire sets of members. Whereas Rf-stability module analyzes the stability of structures by analyzing the critical load factors and corresponding stability nodes. These two modules chosen are the most effective modules for analyzing timber building data.

For TCB to meet the requirements of the Eurocode in combination of the Dutch National Annex, the lateral displacement at the top of the building is checked with the maximal allowable lateral displacement i.e., H/800 with H being the height of the building. Since the foundation of the building is assumed to be stiff, to still incorporate the effect of foundation on the displacement is a maximal allowable displacement set on H/800 instead of more commonly used H/500 (de Jong, 2017).

Thus, the lateral displacement results of the Rf-modules for Case 2 (TCB) decide what modifications can be done further, aiming for an improvement on stability and deformation (see appendix C). External validity can be ensured with results of lateral displacement of the Rf-modules as the modifications of modules could be applied/compared to other building models.

3.3 Validation of data analysis

In this phase, the validation of data analysis is established for ECB and TCB cases. The validation of data analysis is based on the accuracy of material quantities. In Rfem model of ECB and TCB, the material quantities extracted from both the models are validated with manual calculations. Figure 9 steps of methodology phase 3.

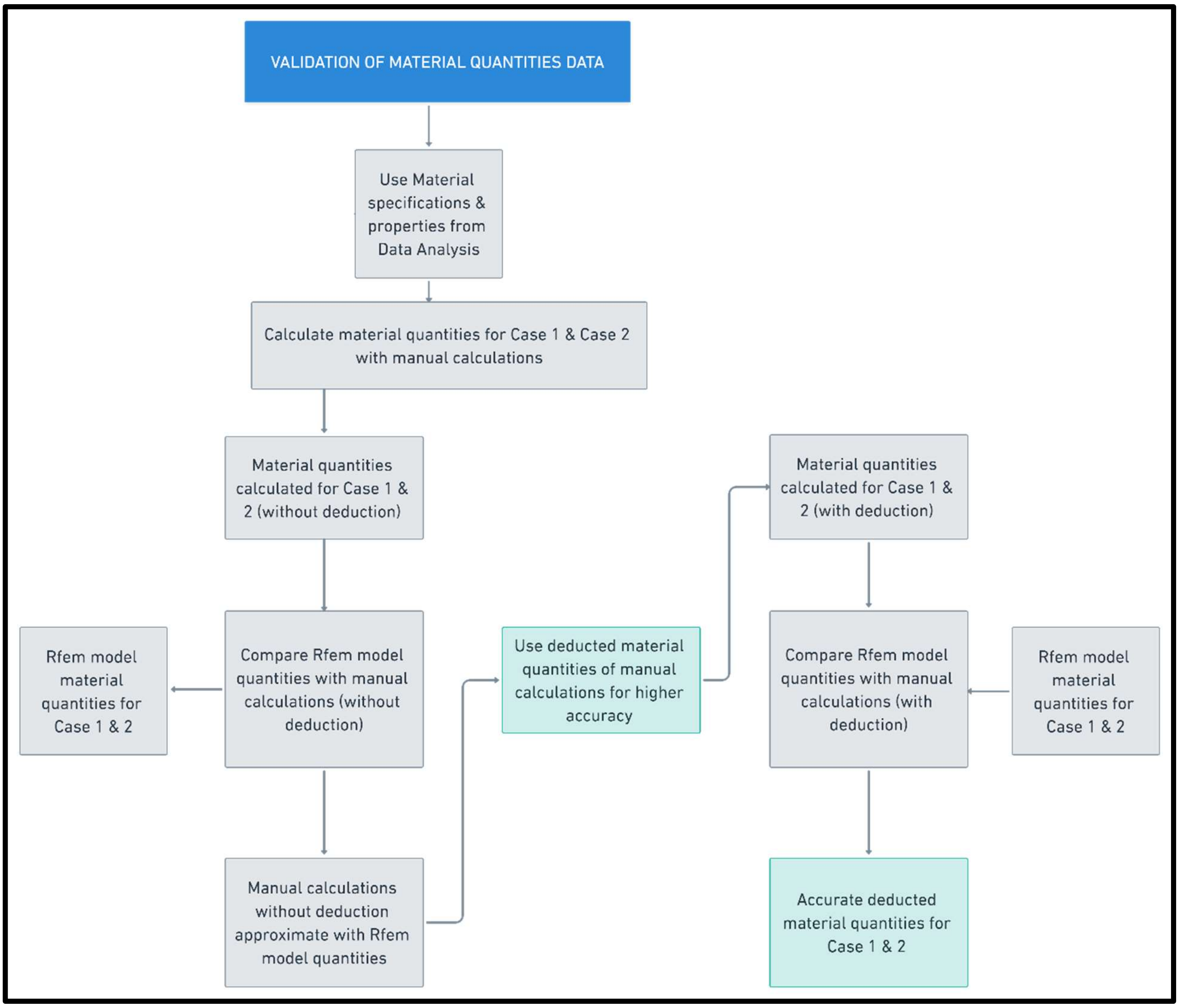

Fig 9: Methodology phase 3

After modelling and analysing the data in previous phases, the material quantities in Rfem model of ECB and TCB are compared with the manual calculations to find accurate material quantities. The approach for manual calculations is performed with two options: non-deducted and deducted quantities (see appendix G). The non-deducted quantities are those in which building components like floor/wall overlap to the centre of column/beam. The deducted quantities are those in which the overlaps to the centre of column/beam are manually deducted. For these overlaps in Rfem models, (see appendix E).

In validation of case 1 (ECB) material quantities, the Rfem ECB model quantities are compared with two options of manual calculations (non-deducted and deducted). The Rfem model is a structural model that is modelled using nodes and lines from centre-to-centre grid. Thus, the model shows overlapping components of columns, walls, floors, and wall as all are connected centre to centre (see appendix E). To validate the material quantities of Rfem model, the manual calculations are compared with non-deducted and deducted calculation.

Similarly in validation of case 2 (TCB) material quantities, the Rfem TCB model quantities are also compared with similar method as Case 1. By utilizing the two options of manual calculations, deducted material quantities option provides the most accurate material quantities for the total volume of the building in both cases. The material quantities comparison of Rfem model, non-deducted and deducted calculations is presented in the results.

3.4 Formulation and calculation of embodied carbon data

In this phase, the deducted material quantities of both ECB and TCB cases are used. As the primary goal of the report is to analyse the comparative LCA of TCB and ECB. To perform LCA, generate emissions factors and analyse contributions in A1-A5 module, the (ICE database) and (IstructE guide) guide will be used for calculations. Figure 10 below shows methodology phase 4 steps.

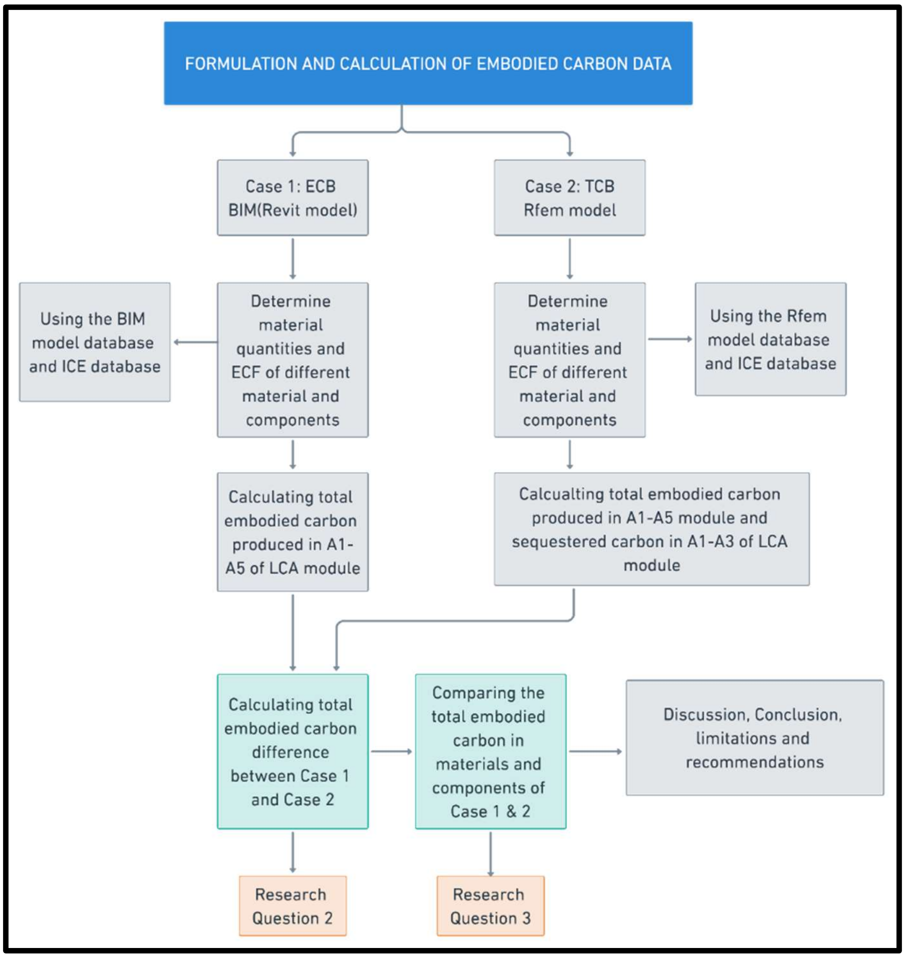

Fig 10: Methodology phase 4

The scope of LCA was cradle to practical completion occurring over the whole life cycle of the 50-year building, excluding the operational carbon during the building use. The product stage (A1-A3) includes raw materials supply (A1, primary resource harvesting and mining), transport (A2, transport up to manufacturing plant gate) and manufacturing (A3, manufacture of raw materials into products). The construction stage includes (A4-5) includes transport (A4, transport of materials to site) and construction installation process (A5, construction equipment energy use). The A4 transport was based on a diesel truck and the estimated transport distances for the building materials are used hypothetically. The A5 equipment energy inputs are also estimated from diesel use in Energy database (LCI). The Life cycle inventory (LCI) of building materials is sourced from Inventory of Carbon and Energy (ICE database) for Embodied carbon. (Gibbons, 2020) mentioned the fundamental principle associated with finding the embodied carbon and carbon sequestration of the structure:

Embodied carbon (t CO_2 e) = material quantity (t) × embodied carbon factor (t CO_2 e/t)

To calculate the material quantity, the volume is multiplied with weight/density of material per cum to find the material quantities (BIPM, 1901). Whereas the Embodied carbon factor (ECF) is obtained through the (ICE database) and (IstructE guide) for A1-A5 modules of LCA.

Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide. It is one method of reducing the amount of carbon dioxide in the atmosphere with the goal of reducing global climate change (U.S. Geological survey). The carbon sequestration for timber material is -1.64 kgCO_2 emissions per kg of timber given in the (IstructE guide). GWP regarded as a major indicator in LCA studies (Knauf, 2015) is used as the unit of measure for the comparison expressed in terms of carbon dioxide equivalents. The GWP values for different GHGs over a 100-year time horizon from (AR4 IPCC, 2007) is shown in (see appendix A.3). GWP value of carbon dioxide is 1 over a 100 to 500-year time horizon. If the calculated embodied carbon emissions (t CO_2 e) are multiplied by GWP value 1 of carbon dioxide, it results in equal tonnes of carbon dioxide equivalents (t CO_2 eq) emitted to the atmosphere as carbon dioxide (t CO_2) emitted from construction. Thus, the implication of building material and components on its embodied carbon emissions results in the same amount of carbon dioxide equivalency or GWP over the 100 years. The results of these calculations ensure the construct validity of the two-analysis performed and concluded in the results & findings.

3.5 Summary

The methodology of this research is established in four phases: (1) data collection and modelling phase summarizes the process of developing two buildings (ECB and TCB) that were required as the basis of this research, (2) data analysis phase establishes the material specifications and material properties in Rfem of building structure to verify the feasibility of timber-concrete building on its lateral displacement at the top of building, (3) validation of material quantities data evaluated the deducted and non-deducted manual calculation for validation with Rfem model, (4) formulation and calculation of embodied carbon data phase calculates the material quantities, total embodied carbon and GWP i.e. carbon dioxide equivalency of the two buildings. Based on the methodology, the results and findings are drawn in the next chapter.

4. Results & Findings

The results and findings focus through the validated material quantities into formulating and calculating the embodied carbon data. This data is processed in three chapters namely: material quantities calculation & validation, embodied carbon analysis and comparative analysis. The first chapter calculate and validate the material quantities for both cases. The second chapter calculates the total carbon emissions emitted from both cases (ECB & TCB) from A1-A5 module. Lastly, the third chapter determines the implications of material and components used in both buildings on its embodied carbon emissions.

4.1 Material quantities calculation & validation

This chapter is based on the material quantities calculation and validation of both cases: ECB and TCB. As per the analytical models, the finished Rfem models are used as the base for determining accurate material quantities calculation and the manual calculations are used for validation. Below are the two sub-chapters for both cases.

4.1.1 Material quantities calculation & validation (Case 1)

The data analysed in research methodology (phase 2) of the research generates material specifications of case 1: ECB (existing-concrete building) as per the original geometry modelled in Rfem. The original geometry is as shown in the Rfem 3d model of case 1. This 3d model is simulated by utilizing the refined analytical model of existing-concrete building. The model check option in Rfem assisted to identify any overlapping lines and unused/identical nodes. Hence, the analytical model is simplified with single line connection to all the nodes located at the centre of columns. These material specifications are shown in table 2 below.

Table 2: Material specifications for Case 1 (ECB)

Component & Material Type	Thickness (m)	Width × depth (m)	Length of Members (m)	Area (m2)	Volume (m3)
Substructure– Columns	-	0.5×0.3	684.0	-	103
Substructure– Beams	-	0.5×0.3	1616.9	-	243

Component & Material Type	**Thickness (m)**	**Width × depth (m)**	**Length of Members (m)**	**Area (m2)**	**Volume (m3)**
Substructure– Slabs	0.250	-	-	3486.3	871
Substructure– Walls	0.250	-	-	3639.4	1090
Core – Columns	-	0.5×0.3	589.5	-	88
Core – Beams	-	0.5×0.3	1992.9	-	298
Core – Walls	0.350	-	-	4155.2	1451
Superstructure– Columns	-	0.5×0.3	4032.0	-	605
Superstructure– Beams	-	0.5×0.3	9702.3	-	1454
Superstructure– Slabs	0.250	-		21780.8	5442
Superstructure– Walls	0.250	-	18073.1		4519
Total					**16164**

Based on the above material specification of case 1, the volume is determined from Rfem model for all the components of substructure, superstructure, and concrete-core. Although, this volume is determined from the refined analytical model. However, due to the nodes connecting from centre of columns to one another overlaps a certain part of geometry between wall, floor, beam, and column. This overlap is unavoidable to keep the model simplified with a single node on each column. Hence, this overlap volume is deducted by performing manual calculation of the volume (see appendix G). Table 3 below shows the calculated material quantities of Rfem model, non-deducted, deducted and their differences with original Rfem model material quantity.

Table 3: Material quantities validation for Case 1 (ECB)

Material & Component Type	**Material Quantity (Rfem model)**	**Material Quantity: Non-deducted (Manual Calculations)**	**Material Quantity Difference b/w Rfem Model and Non-deducted (manual calculations)**	**Material Quantities: Deducted (Manual Calculations)**	**Material Quantity Difference b/w Rfem Model and Deducted (manual calculations)**
Substructure– Columns	262	262	0	229	-32

Material & Component Type	**Material Quantity (Rfem model)**	**Material Quantity: Non-deducted (Manual Calculations)**	**Material Quantity Difference b/w Rfem Model and Non-deducted (manual calculations)**	**Material Quantities: Deducted (Manual Calculations)**	**Material Quantity Difference b/w Rfem Model and Deducted (manual calculations)**
Substructure–Beams	618	619	0.4	619	0.4
Substructure–Slabs	2222	2220	-1.9	1942	-279
Substructure–Walls	2783	2779	-4.16	2250	-533
Core - Columns	225	225	0.06	193	-32
Core - Beams	762	759	-2.9	759	-2.9
Core - Walls	3710	3699	-10.6	3046	-664
Superstructure–Columns	1542	1542	0	1542	0
Superstructure–Beams	3710	3708	-2.3	3708	-2.3
Superstructure–Slabs	13881	13874	-7.4	12209	-1673
Superstructure–Walls	11518	11519	0.8	9842	-1676
Total	**41233**	**41206**	**-28**	**36340**	**-4894**

The non-deducted and Rfem model quantities are approximately the same as Rfem model with only a difference of 28 tons. However, the deducted manual calculations show a difference of 4894 tons of material quantity. This deducted manual calculation of material quantity difference accounts for approximately 12% of Rfem model material quantity i.e., 41233 tons. To validate the deducted material quantities, the deducted volume in substructure floor & wall, core wall and superstructure floor & wall are used from the manual calculations. With this, the volume in Rfem model per floor for the floors and walls in superstructure is extracted. The difference of total volume per floor and deducted volume per floor is calculated. The deducted volume of manual calculations for all the levels of building accounts for approximately 11% of the total Rfem model volume (see appendix G.5.1). The differences of deducted material quantity and deducted volume of the building is approximately the same. Hence, the deducted manual calculations of ECB case 1 are calculated accurately and validated for utilizing in the embodied carbon calculations.

4.1.2 Material quantities calculation & validation (Case 2)

The data analysed in research methodology (phase 2) of the research generates material specifications of case 2: TCB (Timber-concrete building) as per the original geometry modelled in Rfem. The original geometry is as shown in the 3d model of case 1. This 3d model is simulated by utilizing the refined analytical model of existing-concrete building. The model check option in Rfem assisted to identify any overlapping lines and unused/identical nodes. Hence, the analytical model is simplified with single line connection to all the nodes located at the centre of columns. These material specifications are shown in table 4 below.

Table 4: Material specifications for Case 2 (TCB)

Material & Component Type	**Thickness (m)**	**Width × depth (m)**	**Length of members (m)**	**Area (m2)**	**Volume (m3)**
Substructure– Columns	-	0.5×0.3	684.0	-	103
Substructure– Beams	-	0.5×0.3	1616.9	-	242
Substructure– Slabs	0.250	-	-	3486.3	871
Substructure– Walls	0.250	-	-	3639.4	1090
Core - Columns	-	0.5×0.3	589.5	-	88
Core - Beams	-	0.5×0.3	1992.9	-	299
Core - Walls	0.350	-	-	4155.2	1451
Superstructure– Columns	-	0.5×0.3	336.0	-	50
Superstructure– Beams	-	0.5×0.3	808.4	-	121
Superstructure– Slabs	0.250	-		1742.7	435
Superstructure– Walls	0.250	-	1506.0	-	452
Superstructure – GLT Columns	-	0.5×0.3	3696.0	-	554
Superstructure – GLT Beams	-	0.5×0.3	8893.8	-	1335

Material & Component Type	**Thickness (m)**	**Width × depth (m)**	**Length of members (m)**	**Area (m2)**	**Volume (m3)**
Superstructure – CLT Slabs	0.250	-	-	19166.5	4789
Superstructure – CLT Walls	0.250	-	-	16567.1	4143
Total					**16025**

Based on the above material specification of case 2, the volume is determined from Rfem model for all the components of substructure, superstructure, and concrete-core. Although, this volume is determined from the refined analytical model. However, due to the nodes connecting from centre of columns to one another overlaps a certain part of geometry between wall, floor, beam, and column. This overlap is unavoidable to keep the model simplified with a single node on each column. Hence, this overlap volume is deducted by performing manual calculation of the volume (see appendix G). Table 5 below shows the material quantities of Rfem model, non-deducted, deducted and their differences with Rfem model material quantity.

Table 5: Material quantities validation for Case 2 (TCB)

Component & Material Type	**Material Quantity (Rfem model)**	**Material Quantity: Non-deducted (Manual Calculations)**	**Material Quantity Difference b/w Rfem Model and Non-deducted (manual calculations)**	**Material Quantities: Deducted (Manual Calculations)**	**Material Quantity Difference b/w Rfem Model and Non-deducted (manual calculations)**
Substructure– Columns	262	262	0	262	0
Substructure– Beams	618	618	-0.4	618	-0.3
Substructure– Slabs	2222	2220	-2	1942	-279
Substructure– Walls	2783	2779	-4.2	2176	-608
Core - Columns	225	225	0.1	193	-32
Core - Beams	762	763	1.4	759	-3
Core - Walls	3707	3699	-8.0	3082	-625

Component & Material Type	Material Quantity (Rfem model)	Material Quantity: Non-deducted (Manual Calculations)	Material Quantity Difference b/w Rfem Model and Non-deducted (manual calculations)	Material Quantities: Deducted (Manual Calculations)	Material Quantity Difference b/w Rfem Model and Non-deducted (manual calculations)
Superstructure–Columns	128	128	0	110	-18
Superstructure–Beams	309	309	-0.2	309	-1.3
Superstructure–Slabs	1111	1110	-0.8	971	-139
Superstructure–Walls	1152	1152	0.1	925	-226
Superstructure – GLT Columns	238	238	0.2	204	-34
Superstructure – GLT Beams	574	574	0.2	574	0.2
Superstructure – CLT Slabs	2492	2490	-1.2	2179	-313
Superstructure – CLT Walls	2154	2154	0.5	1599	-554
Total	**18737**	**18723**	**-14**	**15904**	**-2834**

The non-deducted and Rfem model quantities are approximately the same as Rfem model with only a difference 14 tons. However, the deducted manual calculations show a difference of 2834 tons of material quantity. This deducted manual calculation of material quantity difference accounts for approximately 15% of Rfem model material quantity i.e., 18737 tons. To validate the deducted material quantities, the deducted volume in substructure floor & wall, core wall and superstructure floor & wall are used from the manual calculations. With this, the volume in Rfem model per level for the floors and walls in superstructure is extracted. The difference of total volume per floor and deducted volume per floor is calculated. The deducted volume of manual calculations for all the levels of building accounts for approximately 14% of the total Rfem model volume (see appendix G.5.2). The differences of deducted material quantity and deducted volume of the building is approximately the same. Hence, the deducted manual calculations of TCB case 2 are calculated accurately and validated for utilizing in the embodied carbon calculations.

4.2 Embodied carbon analysis

This chapter shows the embodied carbon analysis of two cases: Case (1) ECB and Case (2) TCB. As the carbon efficient structure in the near-future is aimed to reach Net-Zero carbon, this analysis contributes to the findings of embodied carbon of the building cases. The module used is A1-A5 of the LCA (see appendix A.1). The analysis also includes carbon sequestration impact on timber material used in building case 2.

4.2.1 Carbon analysis (Case 1)

In Case 1, the material quantity calculated with deduction is utilized for calculating the embodied carbon data of ECB. The carbon sequestration is not determined considering ECB is constructed with traditional concrete material. The embodied carbon contribution for each component is the product of ECF values and the material quantity for each material component. Based on this, the embodied carbon emissions are calculated for this case. The ECF is determined for building materials and components using the (ICE database) and (IstructE guide). Table 6 shows the embodied carbon calculation for case 1.

Table 6: Embodied carbon calculations (A1-A5 module) Case 1

Material & Component Type	**Material Quantity (tons)**	**ECF (tCO_2e/t)**			**Embodied Carbon (t CO_2 emissions)**			**Total EC (t CO_2 emissions)**
		A1-A3	A4	A5	A1-A3	A4	A5	A1-A5
Substructure - Columns	229	0.242	0.16	0.250	55	37	57	149
Substructure - Beams	619	0.242	0.16	0.250	150	99	155	404
Substructure - Slabs	1942	0.242	0.16	0.250	470	311	486	1266
Substructure - Walls	2250	0.242	0.16	0.250	545	360	563	1467

Material & Component Type	**Material Quantity (tons)**	**ECF (tCO_2e/t)**			**Embodied Carbon (t CO_2 emissions)**			**Total EC (t CO_2 emissions)**
Core - Columns	193	0.242	0.16	0.250	47	31	48	126
Core - Beams	759	0.242	0.16	0.250	184	121	190	495
Core - Walls	3046	0.242	0.16	0.250	737	487	762	1986
Superstructure - Columns	1542	0.242	0.16	0.250	373	247	385	1005
Superstructure - Beams	3708	0.242	0.16	0.250	897	593	927	2417
Superstructure - Slabs	12209	0.242	0.16	0.250	2955	1953	3052	7960
Superstructure - Walls	9842	0.242	0.16	0.250	2382	1575	2461	6417
Total	**36340**				**8794**	**5814**	**9085**	**23693**

The highest material quantity is estimated for the superstructure floors with a total material of 12209 tons, while the least amount of material is estimated for the core columns with 193 tons of material. The ECB case with concrete as the primary material utilized the amount of material with a total of 36340 tons. The material quantities are multiplied with ECF for calculating the total embodied carbon of ECB. The lowest embodied carbon emissions are estimated in core columns at 126 tons and the highest embodied carbon calculated in superstructure slabs at 7960 tons. Thus, the total embodied carbon emissions for ECB case are 23693 tons emitted in LCI (product and construction process).

4.1.2 Carbon analysis (Case 2)

For Case 2, the material quantities calculated with deduction of TCB is utilized for calculating embodied carbon and carbon sequestration. The LCI modules for the calculation are like previous carbon analysis of the ECB. Except that carbon sequestration is calculated for only this case. The embodied carbon contribution for each component is the product of ECF values and the total material quantity for each material component using the (ICE database) and (IstructE guide). Table 7 shows the embodied carbon calculations of case 2.

Table 7: Embodied carbon calculations (A1-A5 module) Case 2

Material & Component Type	**Material Quantity (tons)**	**ECF (t CO_2e/t)**			**Embodied Carbon (t CO_2 emissions)**			**Total EC (t CO_2 emissions)**
		A1 –A3	A4	A5	A1-A3	A4	A5	A1-A5
Substructure– Columns	262	0.242	0.16	0.250	63	42	66	171
Substructure– Beams	618	0.242	0.16	0.250	150	99	155	403
Substructure– Slabs	1942	0.242	0.16	0.250	470	311	486	1266
Substructure - Walls	2176	0.242	0.16	0.250	527	348	544	1419
Core - Columns	193	0.242	0.16	0.250	47	31	48	126
Core - Beams	759	0.242	0.16	0.250	184	121	190	495
Core - Walls	3082	0.242	0.16	0.250	746	493	771	2009
Superstructure - Columns	110	0.242	0.16	0.250	27	18	28	72
Superstructure - Beams	309	0.242	0.16	0.250	75	49	77	201
Superstructure - Slabs	971	0.242	0.16	0.250	235	155	243	633
Superstructure - Walls	925	0.242	0.16	0.250	224	148	231	603
Superstructure – GLT Columns	204	0.512	0.16	0.111	105	33	23	160
Superstructure – GLT Beams	574	0.512	0.16	0.111	294	92	64	449
Superstructure – CLT Slabs	2179	0.263	0.16	0.111	573	349	242	1164
Superstructure – CLT Walls	1599	0.263	0.16	0.111	421	256	177	854
Total	**15904**				**4138**	**2544**	**3342**	**10025**
Sequestration	**(A1-A3) × -1.64**							**-6786**

The total quantity of material utilized in TCB was 15904 tons, of which the substructure utilizes 1942 tons of material in slabs, and the superstructure utilized 2179 tons of material in CLT slabs and core utilizes 3082 tons of material in walls. All the quantities are multiplied with A1-A3, A4 and A5 module of LCA to calculate the total embodied carbon. The total embodied carbon emissions produced by TCB case was 10025 tons. The carbon sequestered of -1.64 kg CO_2 emissions per ton of timber is used for sequestration. The sequestered carbon is calculated for A1-A3 module when the raw material is extracted and manufactured. Thus, the total carbon sequestration calculated is -6786 tons of carbon dioxide from A1-A3 module of LCA. Figure 11 shows the percentage of total embodied carbon emissions for Case 1 and Case 2. If Case 1 utilized 100% of embodied carbon from A1-A5, Case 2 percentage is drawn at 42%.

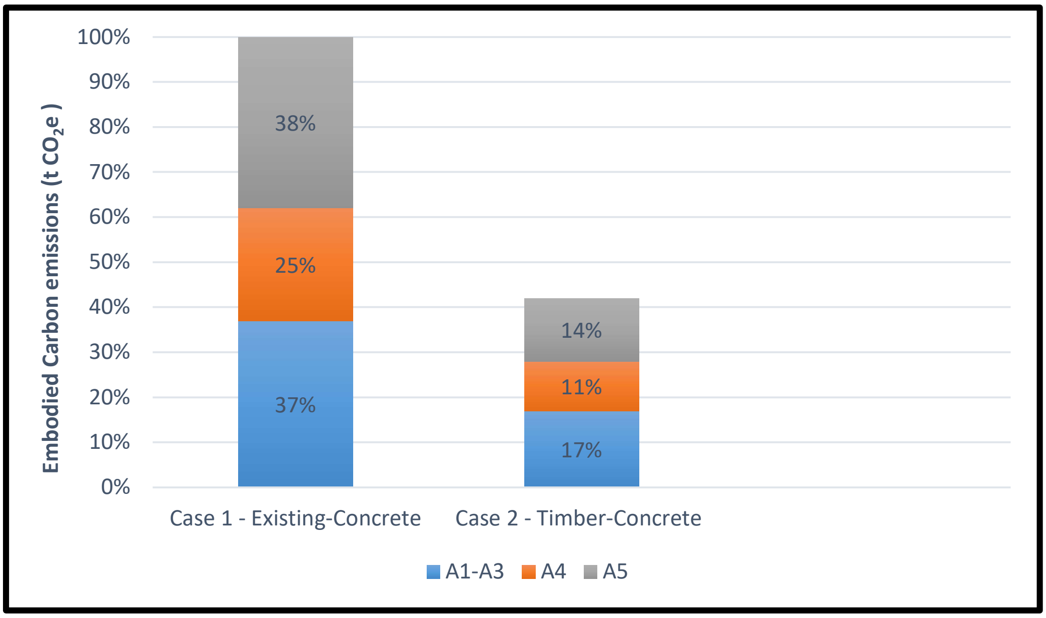

Fig 11: Embodied carbon comparison

The maximum embodied carbon difference is estimated in A5 module of Case 1 with 38% compared to 14% in Case 2. It clearly shows that the construction of Case 2 TCB has less effect in terms of carbon emissions on the environment as compared to Case 1. There is also significant reduction in A1-A3 and A4 modules. Hence, the application of timber as primary material for construction in case 2 showed only 42% of embodied carbon emission compared to case 1 which is used as 100% at 23963 tons of carbon emissions.

4.3 Comparative analysis

A comparative analysis is performed to draw the implications of GWP value of carbon dioxide on building materials and components of ECB and TCB. The difference of CO_2e in building components and material of both cases in A1-A5 module is calculated. Below are the two chapters with comparisons of building components and materials.

4.3.1 Building components comparison

A comparative analysis is performed to calculate the total difference in tons of CO_2e emitted from the building components. Also, the total difference in embodied carbon emissions of components between Case 1 and Case 2 is used as the baseline. The difference in percentage between both the cases is used with the existing concrete building as the maximum baseline, i.e., 100%. The components used for comparison are columns, beams, slabs, and walls.

In module A1-A3, 4648 tons of CO_2e is less emitted to the atmosphere in case 2 than case 1. Similarly, in module A4 and A5, 3262 and 5742 tons of CO_2e are less emitted in case 2 from total of A4 and A5 in case 1. The total reduction in implication of building components in terms of carbon emissions is 13668 tons of CO_2e over the 100-year time frame. Table 8 shows the building component comparison of the two cases.

Table 8: Building components comparison calculation (Case 1 & 2)

Components	**Existing Concrete**	**Timber-Concrete**	**Total tons of CO2e Difference b/w Existing-concrete and Timber-concrete**
A1-A3 (t CO_2 emissions)			
Columns	475	241	
Beams	1231	712	
Slabs	3425	1278	
Walls	3664	1916	
Total	**8795**	**4147**	**4648**
A4 (t CO_2 emissions)			
Columns	315	123	
Beams	813	369	

Components	Existing Concrete	Timber-Concrete	Total tons of CO2e Difference b/w Existing-concrete and Timber-concrete
Slabs	2264	815	
Walls	2422	1245	
Total	**5814**	**2552**	**3262**
A5 (t CO_2 emissions)			
Columns	490	165	
Beams	1272	486	
Slabs	3538	971	
Walls	3786	1723	
Total	**9086**	**3343**	**5742**
Total A1-A5 (t CO_2 emissions)			
Columns	1280	528	
Beams	3316	1577	
Slabs	9227	3063	
Walls	9872	4884	
Total	**23693**	**10025**	**13668**

Figure 12 below shows the total tons of CO_2e of each component emitted in the A1-A5 module. Whistle the walls emitted amount CO_2e in case 1 with 42% compared to 20% in case 2. The floors emitted 39% and 13% in case 1 & 2. The columns and beams emitted 5% & 14% in case 1, comparatively much less than in case 2 with 3% & 7% respectively.

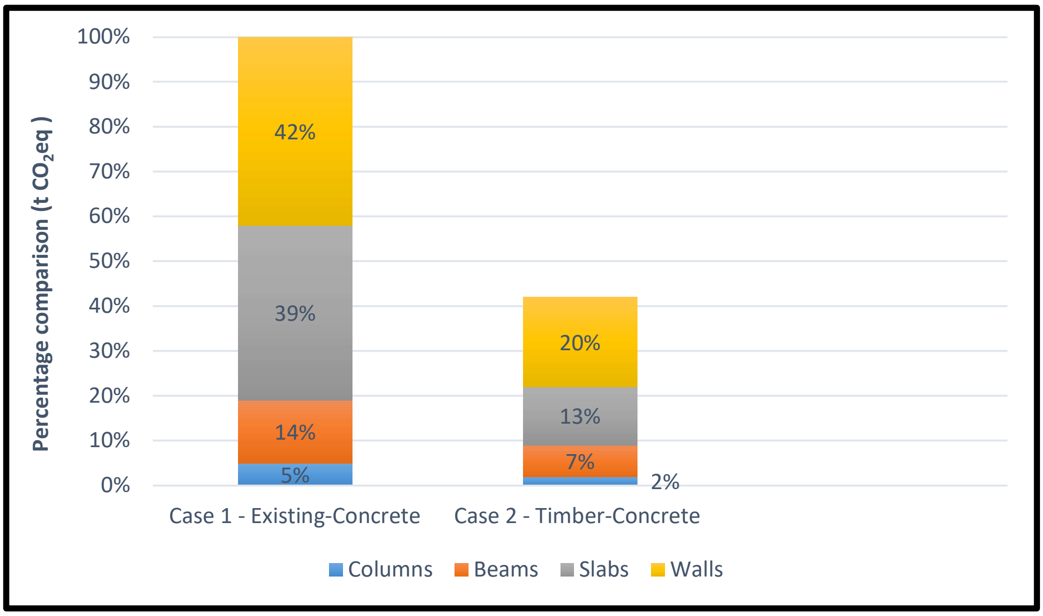

Fig 12: Building components comparison

4.3.2 Building materials comparison

A building material comparison analysis between the two cases is also performed to calculate the total difference in tons of CO_2e emitted from the building materials. Also, the total difference in embodied carbon emissions of materials between Case 1 and Case 2 is used as the baseline. The difference in percentage between both the cases is used with the existing concrete building as the maximum baseline, i.e., 100%.

The concrete material emitted large amount of embodied carbon emissions in each module of Case 1 compared to a small amount in Case 2. This is expected since the timber building replaced most of the concrete in the superstructure. In module A1-A3, 4648 tons of CO_2e is less emitted to the atmosphere in case 2 than case 1. Similarly, in module A4 and A5, 3262 and 5742 tons of CO_2e are less emitted in case 2 from total of A4 and A5 in case 1. The total reduction in implication of building materials is 13668 tons of CO_2e reduced over the 100-year time frame. Table 9 shows the building material comparison calculation of the two cases.

Table 9: Building material comparison calculation (Case 1 & 2)

Material	**Existing Concrete**	**Timber-Concrete**	**Total tons of CO_2e Difference b/w Existing-concrete and Timber-concrete**
A1-A3 (t CO_2 emissions)			
Cross-Laminated Timber	0	994	
Glulam Timber	0	399	
Concrete	7827	1771	
Core	968	977	
Total	**8795**	**4147**	**4648**
A4 (t CO_2 emissions)			
Cross-Laminated Timber	0	604	
Glulam Timber	0	125	
Concrete	5175	1170	
Core	639	639	
Total	**5814**	**2552**	**3262**
A5 (t CO_2 emissions)			
Cross-Laminated Timber	0	419	
Glulam Timber	0	86	
Concrete	8086	1828	

Material	**Existing Concrete**	**Timber-Concrete**	**Total tons of CO_2e Difference b/w Existing-concrete and Timber-concrete**
Core	1000	1009	
Total	**9086**	**3344**	**5742**
Total A1-A5 (t $CO_{2\ \mathrm{emissions}}$)			
Cross-Laminated Timber	0	2017	
Glulam Timber	0	610	
Concrete	21088	4769	
Core	2607	2625	
Total	**23693**	**10025**	**13668**

Figure 13 illustrates the contribution of each building material relative to total emitted tons of CO_2e in percentage. CLT and GLT are the primary materials used in case 2, accounting for 8% and 3% respectively. Whereas in case 1, concrete material accounted for 89% compared to only 20% in case 2. Since the material for core is similar in both the cases, so it accounted 11% contribution to the embodied carbon emissions.

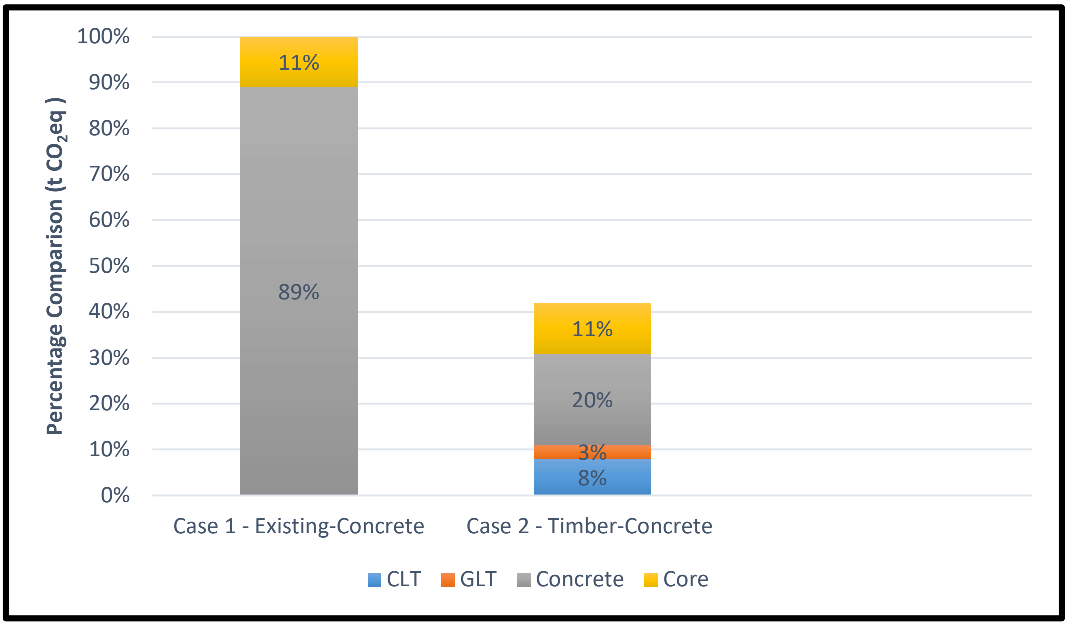

Fig 13: Building material comparison

4.4 Summary

This section accounts for the final outcomes of the results and findings. The TCB case is feasible as it is under the maximal allowable displacement and stable with the lowest eigenvalue. With hinge/line connection in the Rfem model, the combination of wind and live load counter minimal instability in building. Also, the total embodied carbon emissions in TCB are much lower as compared to ECB. Interestingly, the comparative analysis showed the implication of building components and material comparison on its embodied carbon emissions. The statistical analysis showed high construct validity of the research. These results can aid the architects, engineers, and construction teams to compare the results with their upcoming projects to be constructed with timber.

5. Discussion

As stated in the problem statement, despite the maturity in timber material engineering there is limited research on the feasibility, comparative embodied carbon, and implication of building components & materials on its embodied carbon emissions. The proposed methodology is proven to be adaptable and implementable in the development of tall timber buildings. Thus, designers and engineers can see value in it and utilize it to the future projects. It also benefits the construction team with a comprehensive overview on the feasibility and carbon emissions between concrete and timber as the primary material. Distinguishly, it provides a comparative analysis of material and components differently that can be taken into a strategy to lower the impact of embodied carbon emission on global warming. The answer to the research questions is followed with the results defined below. Then, the final conclusions are made with additional limitations and recommendations in the next chapter.

The feasibility of Timber-concrete building on its lateral displacement was tested in Rfem model with Rf-deformation and stability analysis module. Lateral displacement at the top of the building was expected to be the limiting factor for the stability of timber-concrete building. Hence, it is the first focus point of this research. It can be stated that it is feasible to build 24 storey building using timber as the primary material in the superstructure. Due to the lightweight nature of timber structure, the feasibility analysis was focused on a combination of wind load and live load to find the highest impact on the lateral displacement. The results of the deformation analysis were as follows:

- The highest deformation occurred in timber-concrete building is around 64 mm only at the top floors.
- The maximal allowable displacement at H/800, 100mm is the maximal displacement for the building height of 84m.
- The deformation of the building is under maximal allowable displacement with a difference of 20 mm at the wind speed of 140 km/hr.

The stability analysis is calculated with 4 lowest eigenvalues that calculates the total buckling of the building. The critical load factor generated for the 4 lowest eigenvalue numbers are 9.40, 11.95, 13.36 and 14.60. If the lowest eigenvalue value has critical load factor less than 1, then the structure can be unstable and have buckling problems. In this case, the lowest eigenvalue 1 has critical load factor of 9.40. That means, the lowest eigen value 1 will only buckle in case of 9.40 times more than the present load case. This analysis showed that the lateral support of building with CLT and GLT is feasible for 24 floors. Secondly, the total embodied carbon was calculated for both cases: ECB (case 1) and TCB (case 2). Rfem models were utilized for the material specification and properties. ECF were determined from the (ICE database) and (IstructE guide). In A1-A5 module, the total embodied carbon emissions produced by Case 1 was 23693 tons, while Case 2 produced only 10025 tons of CO_2e. When the total embodied carbon of both cases was compared in different modules, A5 module in Case 1 was seen to be 38%, compared to only 14% in Case 2. This results in much higher embodied carbon emissions of case 1 as compared to case 2. Modules A1-A3 and A4 also showed a significant reduction in Case 2 in comparison to Case 1. The sequestered carbon temporarily stored in Case 2 was -6786 tons of CO_2e for module A1-A3.

Thirdly, a comparative analysis of total embodied carbon emission was drawn in terms of building materials and building components. Case 2 was found to exhibit only 42% impact as compared to Case 1 with 100% on the embodied carbon emissions. Therefore, the TCB utilizes much less carbon emissions attaining better sequestration as compared to the ECB. The carbon emissions implication on the carbon dioxide equivalency or GWP is directly connected to the accuracy of the ECF, and material quantities used in the analysis. Therefore, it is necessary to analyze an accurate baseline for calculating embodied carbon so that any carbon reduction attempts can be as effective as possible. In principle, a straightforward process for calculating embodied carbon, based on a comprehensive set of data (the LCI) is needed. And a breakdown of material quantities can be implemented with manual calculations for higher accuracy of the total quantities. At present, there is considerable variation in the data for basic materials, but it is likely to improve in future with consistent methodologies. Therefore, in principle, there are no such obstacles for designers and structural engineers to perform embodied carbon analysis during the design phase. Likewise, the commitment to an 80% reduction in carbon dioxide by 2050 is likely to change soon. This provides an opportunity for the designers, engineers, and construction teams to achieve zero-carbon building strategy by minimizing the embodied carbon.

6. Conclusion

The main aim of this study was the impact of carbon emissions on global warming potential or carbon dioxide equivalency through a comparative case study between ECB and TCB. To achieve zero-carbon buildings strategy, the impact of embodied carbon emissions on GWP i.e., carbon dioxide equivalency is analysed. An existing-concrete building was used to form the basis of this study. The existing concrete building was converted into a timber-concrete building to verify its feasibility on the lateral displacement and find the critical load factor. Literature review and case study building were used as the two primary data sources for this study. Data was collected from the ECB and TCB model, the ICE database and IstructE. Unlike operational carbon, embodied carbon is permanent. The percentage of embodied carbon in the whole building life cycle is becoming significant with increasing operational energy efficiency and shortening building lifespans. Therefore, architects and structural engineers need a transparent way of comparing the life cycle impact of their projects with reference buildings. The contribution of this thesis paves the way to a more simplified method for material quantities, defining ECF, calculating embodied carbon emissions and implication of carbon dioxide equivalency or GWP. The additional conclusion of this research is followed below with three types of results feasibility, embodied carbon, and comparative analysis:

1. The timber-concrete building of 24 storeys timber-concrete building withstands the maximum lateral displacement of 62 mm at the top of building with high wind forces.
2. In stability analysis of wind with live load, the lowest eigenvalue 1 has critical load factor of 9.40 times more the present load. The buckling in this case is only visible on one CLT wall at 4th floor from ground level, rest of the building is stable at 9.40 times more than the present load. Thus, the building is stable with lowest eigenvalue.
3. Embodied carbon analysis shown a 42% of carbon emissions emitted in TCB as compared to ECB i.e., 100% which indicates the impact of carbon dioxide gas is extremely high in ECB to the environment.

4. The carbon emissions by TCB are less than concrete building. Difference in comparison of building component and comparison is 13668 tons of CO_2eq in span of over 100 years. As carbon dioxide has a GWP of 1. Lower the possibility for global warming, the better for the environment.

7. Limitations & recommendations

A few limitations and recommendations could lead in the wider implementation of reducing the embodied carbon and improve the reliability of results. The following limitations are:

- The stiffness of connections was not modelled in detail. Default hinged connection in Rfem was applied limiting the capacity of structural loads.
- Due to simplification in connections stiffness, high instability occurred in wind and live load. In other wind area than wind area 1, better stability might be possible.
- The main structural elements were used for the analysis, to limit the intensive modelling and analysis process.
- The life cycle information module for analysis was “cradle to practical completion” i.e. A1-A5 module instead of “cradle to grave” to keep limited scope of research.

The following recommendations are:

- This research calculated only the embodied carbon data. Future research should combine the embodied carbon and operational carbon to get a complete view of the whole life cycle impact of timber building.
- Future research should explore how embodied carbon correlates with financial cost of the building. To pave the way to cost efficiency strategy for zero-carbon buildings.
- Accuracy of the embodied carbon study could be improved by using full-scale CLT/GLT timber manufacturing input data.

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APPENDICES

Appendix A: Life Cycle Information

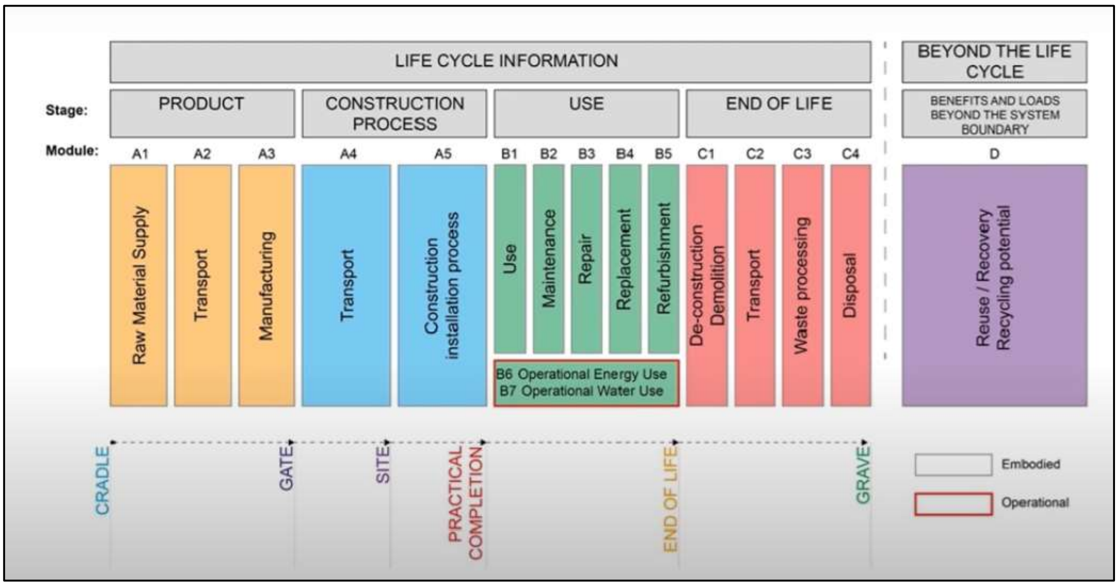


Figure A.1: Life cycle information (from BS EN 15804) defines the various building life cycle stages that can be included within LCA. LCA involves the collection and evaluation of quantitative data on the inputs and outputs of material, energy and waste flows associated with a product over its entire life cycle so that its whole-life environmental impacts can be determined.

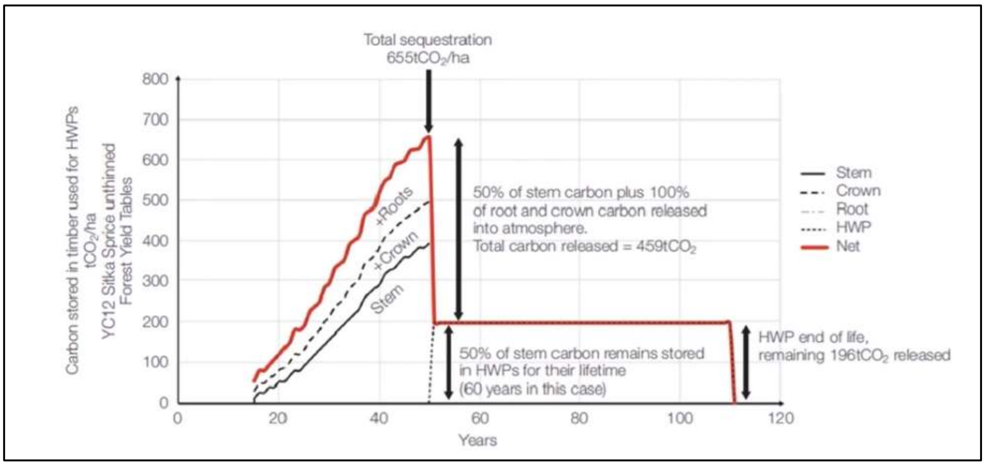
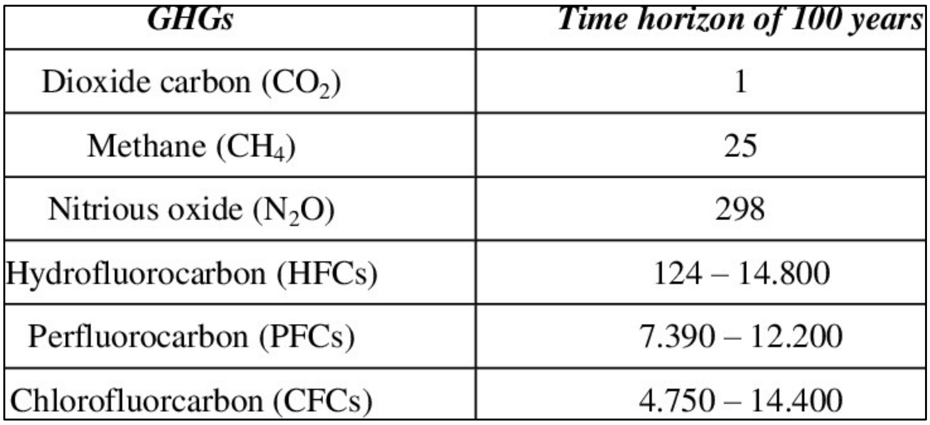


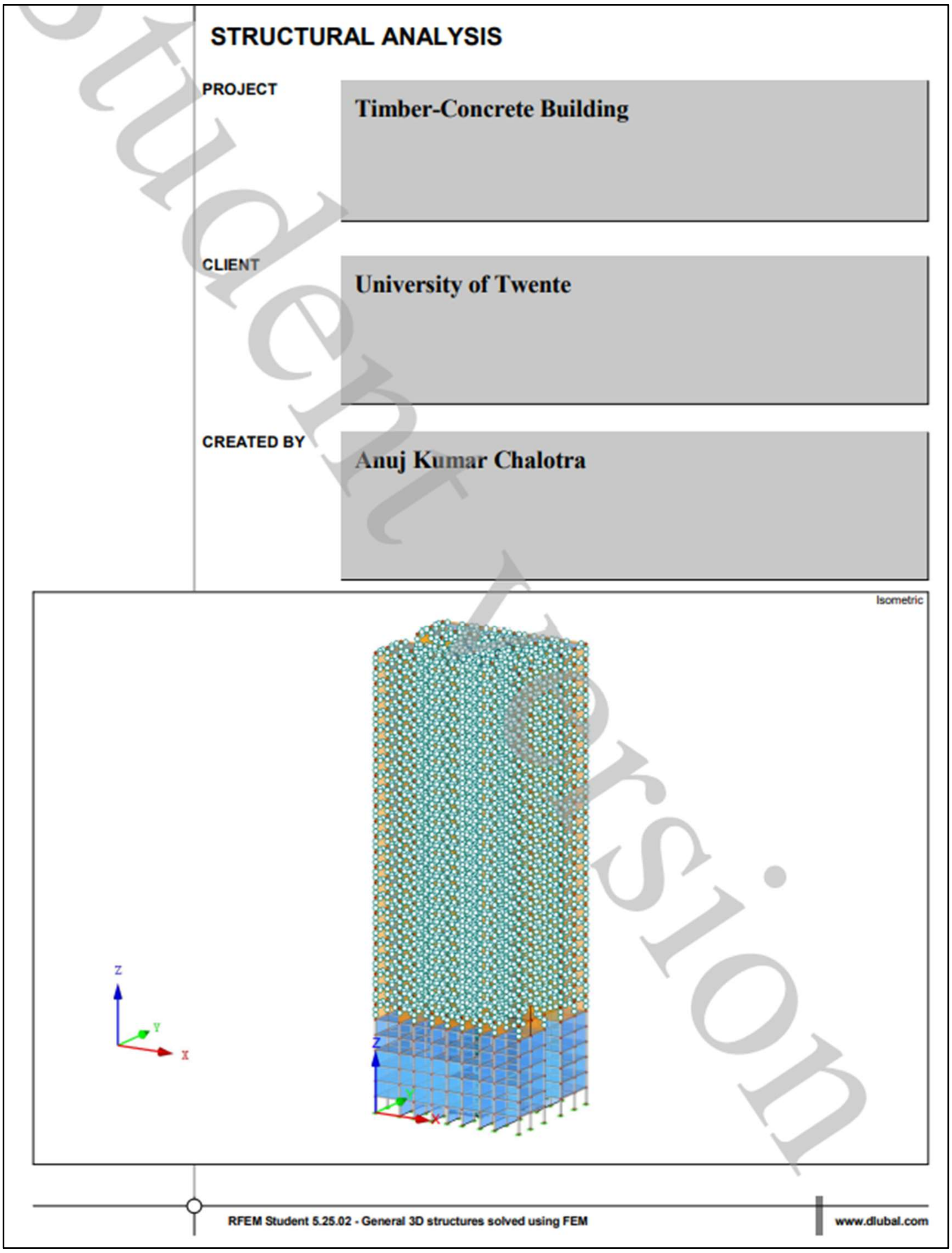
Figure A.2: Carbon sequestration in timber



GHGs	***Time horizon of 100 years***
Dioxide carbon (CO_2)	1
Methane (CH_4)	25
Nitrious oxide (N_2O)	298
Hydrofluorocarbon (HFCs)	124 – 14.800
Perfluorocarbon (PFCs)	7.390 – 12.200
Chlorofluorcarbon (CFCs)	4.750 – 14.400

Figure A.3: Global warming potential values (Assessment report 4, IPCC 2007)

Appendix B: RFEM – Printout Report



STRUCTURAL ANALYSIS

PROJECT
Timber-Concrete Building

CLIENT
University of Twente

CREATED BY
Anuj Kumar Chalotra

RFEM Student 5.25.02 - General 3D structures solved using FEM

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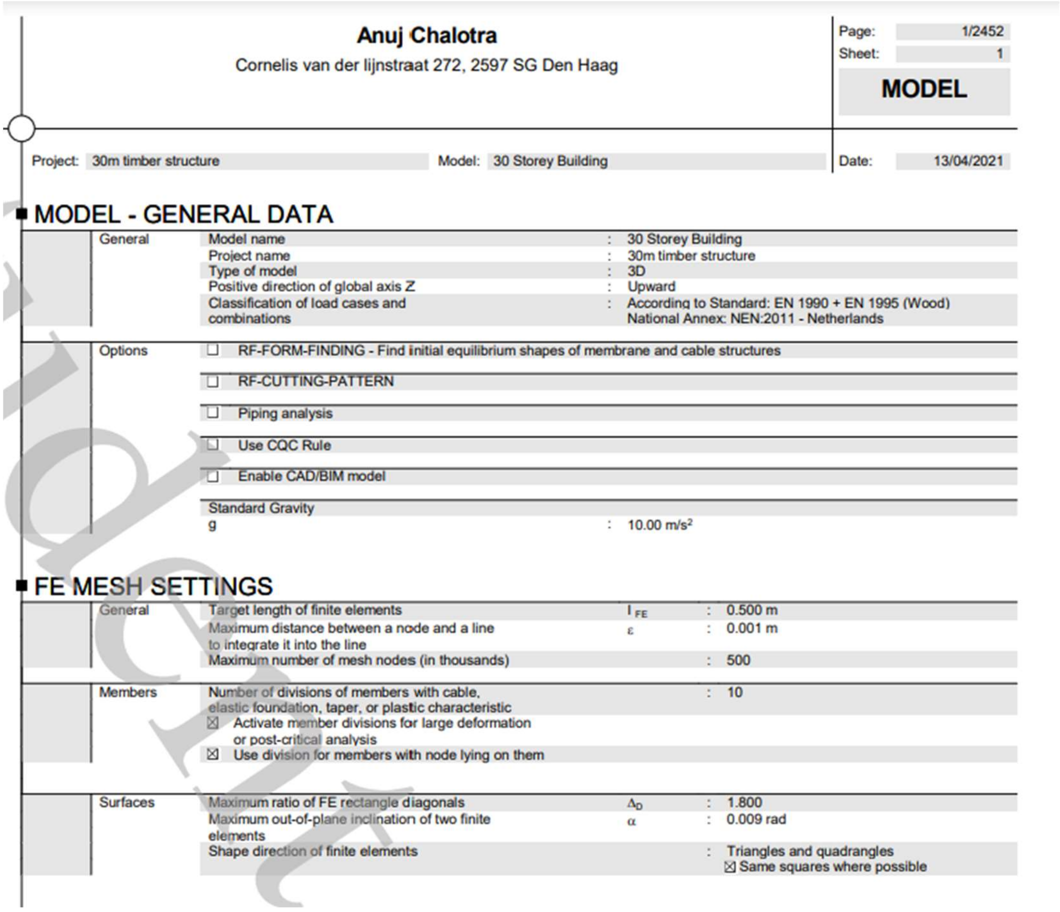

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Sheet: 1

MODEL

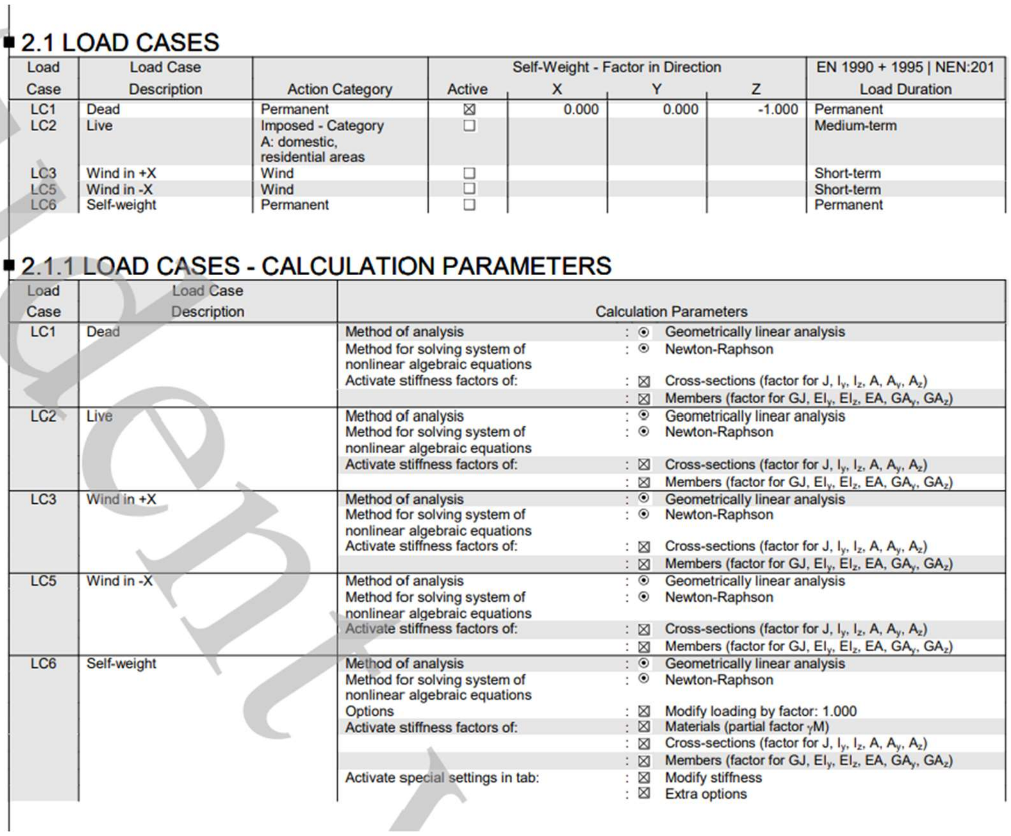
Project: 30m timber structure
Model: 30 Storey Building
Date: 13/04/2021

MODEL - GENERAL DATA

General	Model name	: 30 Storey Building
	Project name	: 30m timber structure
	Type of model	: 3D
	Positive direction of global axis Z	: Upward
	Classification of load cases and combinations	: According to Standard: EN 1990 + EN 1995 (Wood) National Annex: NEN:2011 - Netherlands
Options	☐ RF-FORM-FINDING - Find initial equilibrium shapes of membrane and cable structures	
	☐ RF-CUTTING-PATTERN	
	☐ Piping analysis	
	☐ Use CQC Rule	
	☐ Enable CAD/BIM model	
	Standard Gravity	
	g	: 10.00 m/s²

FE MESH SETTINGS

General	Target length of finite elements	l_{FE}	: 0.500 m
	Maximum distance between a node and a line to integrate it into the line	ε	: 0.001 m
	Maximum number of mesh nodes (in thousands)		: 500
Members	Number of divisions of members with cable, elastic foundation, taper, or plastic characteristic		: 10
	☒ Activate member divisions for large deformation or post-critical analysis		
	☒ Use division for members with node lying on them		
Surfaces	Maximum ratio of FE rectangle diagonals	Δ_D	: 1.800
	Maximum out-of-plane inclination of two finite elements	α	: 0.009 rad
	Shape direction of finite elements		: Triangles and quadrangles ☒ Same squares where possible

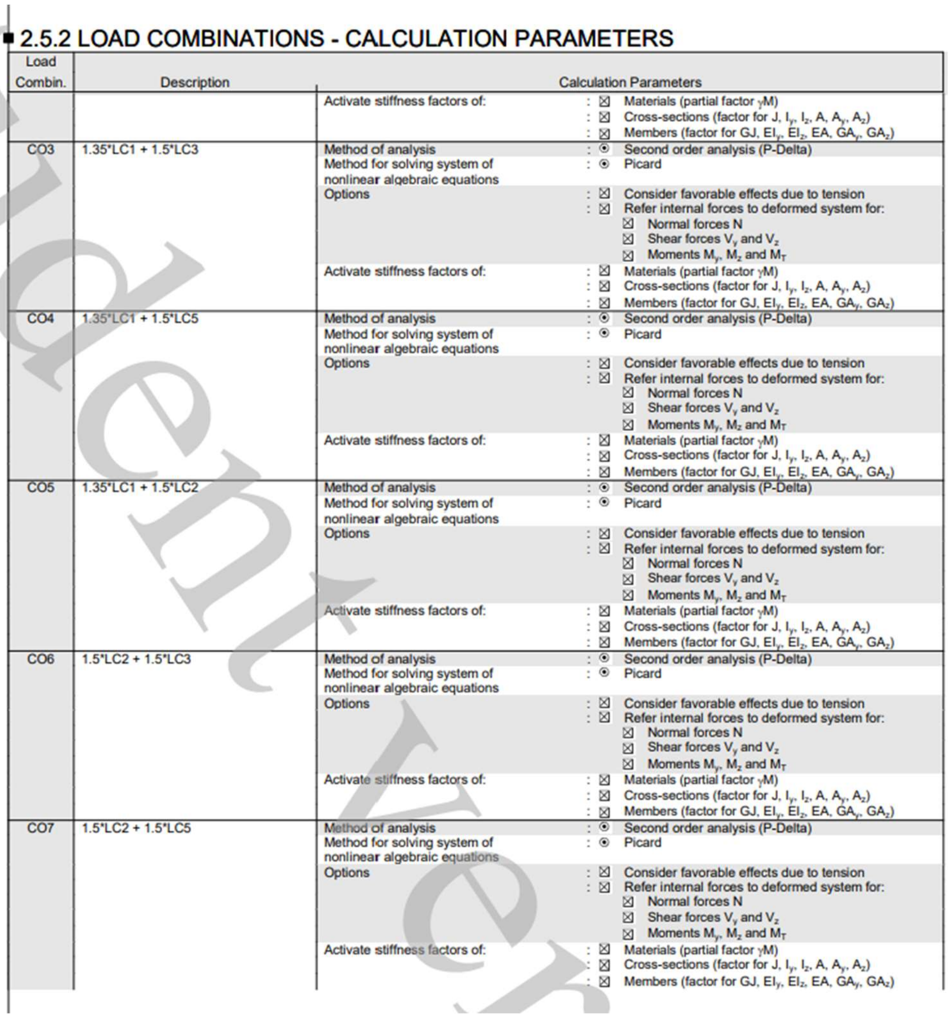


2.1 LOAD CASES

Load Case	Load Case Description	Action Category	Active	Self-Weight - Factor in Direction X	Y	Z	EN 1990 + 1995 | NEN:201 Load Duration
LC1	Dead	Permanent	☒	0.000	0.000	-1.000	Permanent
LC2	Live	Imposed - Category A: domestic, residential areas	☐				Medium-term
LC3	Wind in +X	Wind	☐				Short-term
LC5	Wind in -X	Wind	☐				Short-term
LC6	Self-weight	Permanent	☐				Permanent

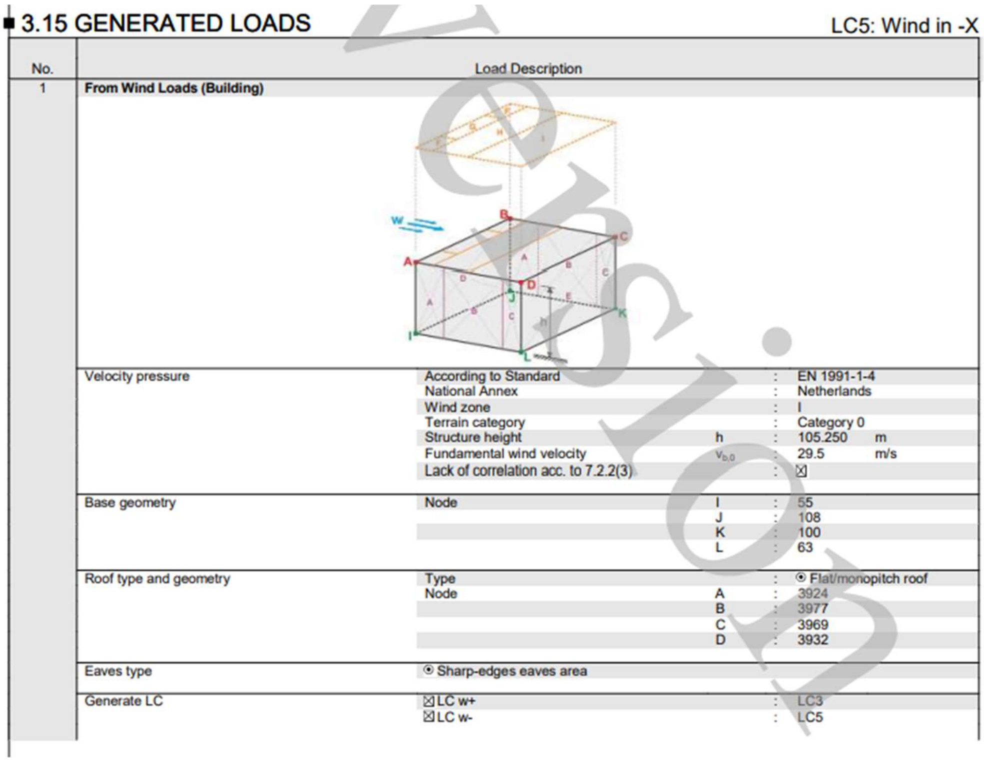
2.1.1 LOAD CASES - CALCULATION PARAMETERS

Load Case	Load Case Description	Calculation Parameters	
LC1	Dead	Method of analysis	: ● Geometrically linear analysis
		Method for solving system of nonlinear algebraic equations	: ● Newton-Raphson
		Activate stiffness factors of:	: ☒ Cross-sections (factor for J, I_y, I_z, A, A_y, A_z)
			: ☒ Members (factor for GJ, EI_y, EI_z, EA, GA_y, GA_z)
LC2	Live	Method of analysis	: ● Geometrically linear analysis
		Method for solving system of nonlinear algebraic equations	: ● Newton-Raphson
		Activate stiffness factors of:	: ☒ Cross-sections (factor for J, I_y, I_z, A, A_y, A_z)
			: ☒ Members (factor for GJ, EI_y, EI_z, EA, GA_y, GA_z)
LC3	Wind in +X	Method of analysis	: ● Geometrically linear analysis
		Method for solving system of nonlinear algebraic equations	: ● Newton-Raphson
		Activate stiffness factors of:	: ☒ Cross-sections (factor for J, I_y, I_z, A, A_y, A_z)
			: ☒ Members (factor for GJ, EI_y, EI_z, EA, GA_y, GA_z)
LC5	Wind in -X	Method of analysis	: ● Geometrically linear analysis
		Method for solving system of nonlinear algebraic equations	: ● Newton-Raphson
		Activate stiffness factors of:	: ☒ Cross-sections (factor for J, I_y, I_z, A, A_y, A_z)
			: ☒ Members (factor for GJ, EI_y, EI_z, EA, GA_y, GA_z)
LC6	Self-weight	Method of analysis	: ● Geometrically linear analysis
		Method for solving system of nonlinear algebraic equations	: ● Newton-Raphson
		Options	: ☒ Modify loading by factor: 1.000
		Activate stiffness factors of:	: ☒ Materials (partial factor γM)
			: ☒ Cross-sections (factor for J, I_y, I_z, A, A_y, A_z)
			: ☒ Members (factor for GJ, EI_y, EI_z, EA, GA_y, GA_z)
		Activate special settings in tab:	: ☒ Modify stiffness
			: ☒ Extra options



2.5.2 LOAD COMBINATIONS - CALCULATION PARAMETERS

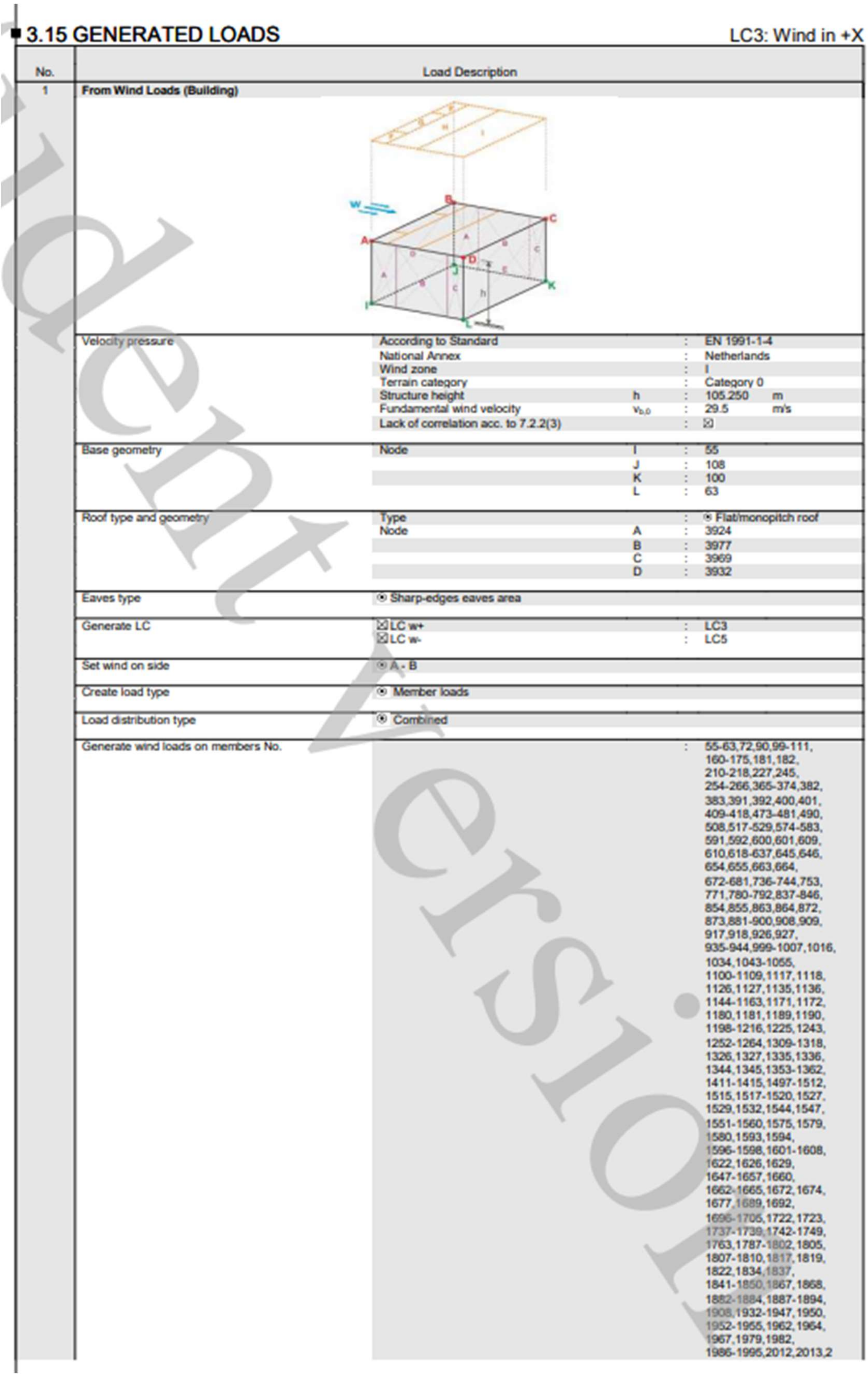
Load Combin.	Description	Calculation Parameters		
		Activate stiffness factors of:	: ☒	Materials (partial factor γM)
			: ☒	Cross-sections (factor for J, I_y, I_z, A, A_y, A_z)
			: ☒	Members (factor for GJ, EI_y, EI_z, EA, GA_y, GA_z)
CO3	1.35*LC1 + 1.5*LC3	Method of analysis	: ●	Second order analysis (P-Delta)
		Method for solving system of nonlinear algebraic equations	: ●	Picard
		Options	: ☒	Consider favorable effects due to tension
			: ☒	Refer internal forces to deformed system for:
				☒ Normal forces N
				☒ Shear forces V_y and V_z
				☒ Moments M_y, M_z and M_T
		Activate stiffness factors of:	: ☒	Materials (partial factor γM)
			: ☒	Cross-sections (factor for J, I_y, I_z, A, A_y, A_z)
			: ☒	Members (factor for GJ, EI_y, EI_z, EA, GA_y, GA_z)
CO4	1.35*LC1 + 1.5*LC5	Method of analysis	: ●	Second order analysis (P-Delta)
		Method for solving system of nonlinear algebraic equations	: ●	Picard
		Options	: ☒	Consider favorable effects due to tension
			: ☒	Refer internal forces to deformed system for:
				☒ Normal forces N
				☒ Shear forces V_y and V_z
				☒ Moments M_y, M_z and M_T
		Activate stiffness factors of:	: ☒	Materials (partial factor γM)
			: ☒	Cross-sections (factor for J, I_y, I_z, A, A_y, A_z)
			: ☒	Members (factor for GJ, EI_y, EI_z, EA, GA_y, GA_z)
CO5	1.35*LC1 + 1.5*LC2	Method of analysis	: ●	Second order analysis (P-Delta)
		Method for solving system of nonlinear algebraic equations	: ●	Picard
		Options	: ☒	Consider favorable effects due to tension
			: ☒	Refer internal forces to deformed system for:
				☒ Normal forces N
				☒ Shear forces V_y and V_z
				☒ Moments M_y, M_z and M_T
		Activate stiffness factors of:	: ☒	Materials (partial factor γM)
			: ☒	Cross-sections (factor for J, I_y, I_z, A, A_y, A_z)
			: ☒	Members (factor for GJ, EI_y, EI_z, EA, GA_y, GA_z)
CO6	1.5*LC2 + 1.5*LC3	Method of analysis	: ●	Second order analysis (P-Delta)
		Method for solving system of nonlinear algebraic equations	: ●	Picard
		Options	: ☒	Consider favorable effects due to tension
			: ☒	Refer internal forces to deformed system for:
				☒ Normal forces N
				☒ Shear forces V_y and V_z
				☒ Moments M_y, M_z and M_T
		Activate stiffness factors of:	: ☒	Materials (partial factor γM)
			: ☒	Cross-sections (factor for J, I_y, I_z, A, A_y, A_z)
			: ☒	Members (factor for GJ, EI_y, EI_z, EA, GA_y, GA_z)
CO7	1.5*LC2 + 1.5*LC5	Method of analysis	: ●	Second order analysis (P-Delta)
		Method for solving system of nonlinear algebraic equations	: ●	Picard
		Options	: ☒	Consider favorable effects due to tension
			: ☒	Refer internal forces to deformed system for:
				☒ Normal forces N
				☒ Shear forces V_y and V_z
				☒ Moments M_y, M_z and M_T
		Activate stiffness factors of:	: ☒	Materials (partial factor γM)
			: ☒	Cross-sections (factor for J, I_y, I_z, A, A_y, A_z)
			: ☒	Members (factor for GJ, EI_y, EI_z, EA, GA_y, GA_z)



3.15 GENERATED LOADS

LC5: Wind in -X

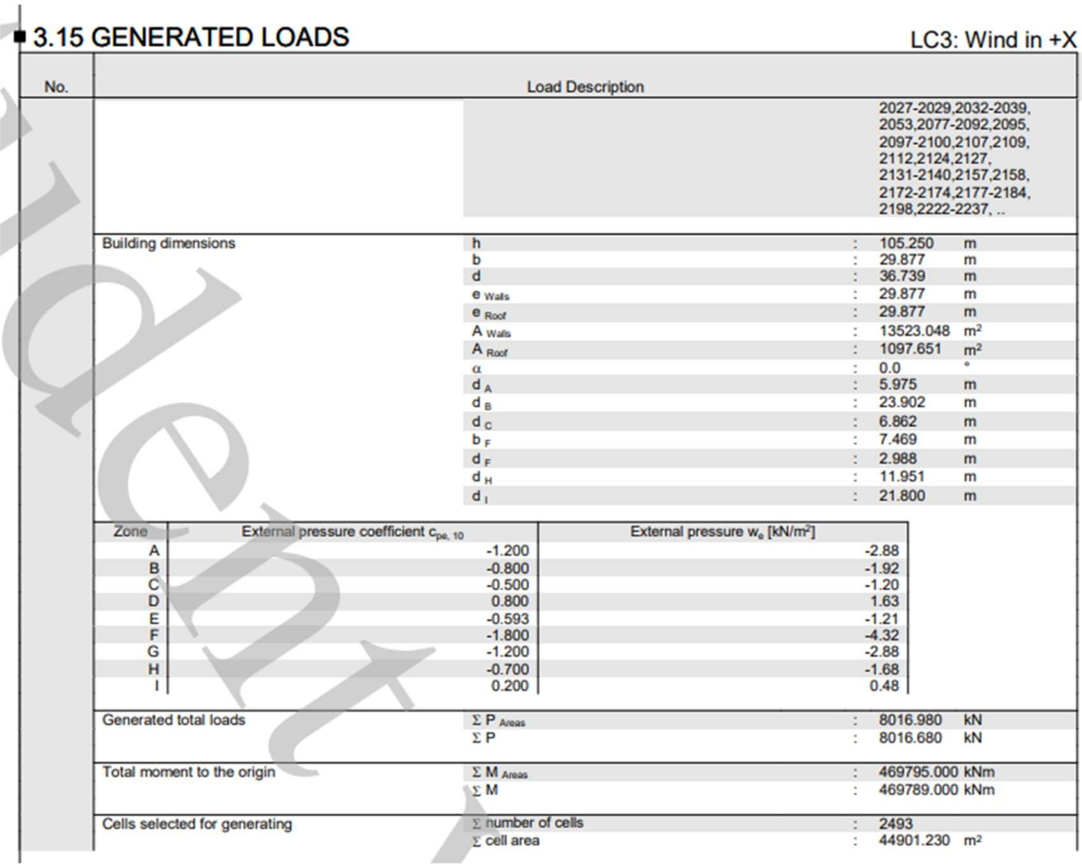
No.	Load Description			
1	**From Wind Loads (Building)**			
	Velocity pressure	According to Standard		: EN 1991-1-4
		National Annex		: Netherlands
		Wind zone		: I
		Terrain category		: Category 0
		Structure height	h	: 105.250 m
		Fundamental wind velocity	$v_{b,0}$	: 29.5 m/s
		Lack of correlation acc. to 7.2.2(3)		: ☒
	Base geometry	Node	I	: 55
			J	: 108
			K	: 100
			L	: 63
	Roof type and geometry	Type		: ● Flat/monopitch roof
		Node	A	: 3924
			B	: 3977
			C	: 3969
			D	: 3932
	Eaves type	● Sharp-edges eaves area		
	Generate LC	☒ LC w+		: LC3
		☒ LC w-		: LC5



3.15 GENERATED LOADS

LC3: Wind in +X

No.	Load Description				
1	**From Wind Loads (Building)**				
	Velocity pressure	According to Standard		:	EN 1991-1-4
		National Annex		:	Netherlands
		Wind zone		:	I
		Terrain category		:	Category 0
		Structure height	h	:	105.250 m
		Fundamental wind velocity	$v_{b,0}$	:	29.5 m/s
		Lack of correlation acc. to 7.2.2(3)		:	☒
	Base geometry	Node	I	:	55
			J	:	108
			K	:	100
			L	:	63
	Roof type and geometry	Type		:	● Flat/monopitch roof
		Node	A	:	3924
			B	:	3977
			C	:	3969
			D	:	3932
	Eaves type	● Sharp-edges eaves area			
	Generate LC	☒ LC w+		:	LC3
		☒ LC w-		:	LC5
	Set wind on side	● A - B			
	Create load type	● Member loads			
	Load distribution type	● Combined			
	Generate wind loads on members No.			:	55-63,72,90,99-111, 160-175,181,182, 210-218,227,245, 254-266,365-374,382, 383,391,392,400,401, 409-418,473-481,490, 508,517-529,574-583, 591,592,600,601,609, 610,618-637,645,646, 654,655,663,664, 672-681,736-744,753, 771,780-792,837-846, 854,855,863,864,872, 873,881-900,908,909, 917,918,926,927, 935-944,999-1007,1016, 1034,1043-1055, 1100-1109,1117,1118, 1126,1127,1135,1136, 1144-1163,1171,1172, 1180,1181,1189,1190, 1198-1216,1225,1243, 1252-1264,1309-1318, 1326,1327,1335,1336, 1344,1345,1353-1362, 1411-1415,1497-1512, 1515,1517-1520,1527, 1529,1532,1544,1547, 1551-1560,1575,1579, 1580,1593,1594, 1596-1598,1601-1608, 1622,1626,1629, 1647-1657,1660, 1662-1665,1672,1674, 1677,1689,1692, 1696-1705,1722,1723, 1737-1739,1742-1749, 1763,1787-1802,1805, 1807-1810,1817,1819, 1822,1834,1837, 1841-1850,1867,1868, 1882-1884,1887-1894, 1908,1932-1947,1950, 1952-1955,1962,1964, 1967,1979,1982, 1986-1995,2012,2013,2



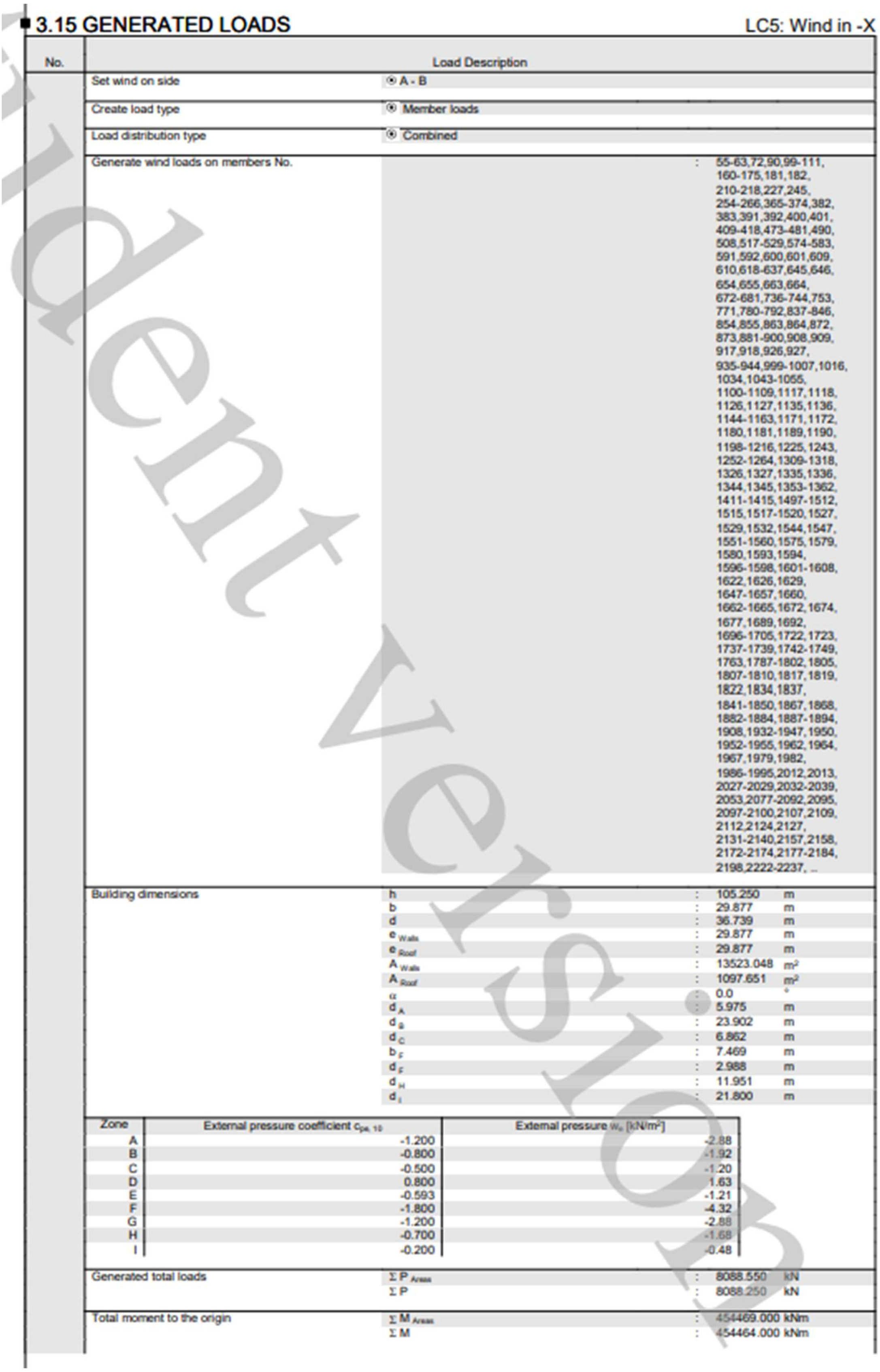
3.15 GENERATED LOADS

LC3: Wind in +X

No.	Load Description			
			2027-2029,2032-2039, 2053,2077-2092,2095, 2097-2100,2107,2109, 2112,2124,2127, 2131-2140,2157,2158, 2172-2174,2177-2184, 2198,2222-2237, ..	
	Building dimensions	h	: 105.250	m
		b	: 29.877	m
		d	: 36.739	m
		e_{Walls}	: 29.877	m
		e_{Roof}	: 29.877	m
		A_{Walls}	: 13523.048	m^2
		A_{Roof}	: 1097.651	m^2
		α	: 0.0	°
		d_A	: 5.975	m
		d_B	: 23.902	m
		d_C	: 6.862	m
		b_F	: 7.469	m
		d_F	: 2.988	m
		d_H	: 11.951	m
		d_I	: 21.800	m

Zone	External pressure coefficient $c_{pe,\,10}$	External pressure w_e [kN/m^2]
A	-1.200	-2.88
B	-0.800	-1.92
C	-0.500	-1.20
D	0.800	1.63
E	-0.593	-1.21
F	-1.800	-4.32
G	-1.200	-2.88
H	-0.700	-1.68
I	0.200	0.48

	Generated total loads	ΣP_{Areas}	: 8016.980	kN
		ΣP	: 8016.680	kN
	Total moment to the origin	ΣM_{Areas}	: 469795.000	kNm
		ΣM	: 469789.000	kNm
	Cells selected for generating	Σ number of cells	: 2493	
		Σ cell area	: 44901.230	m^2



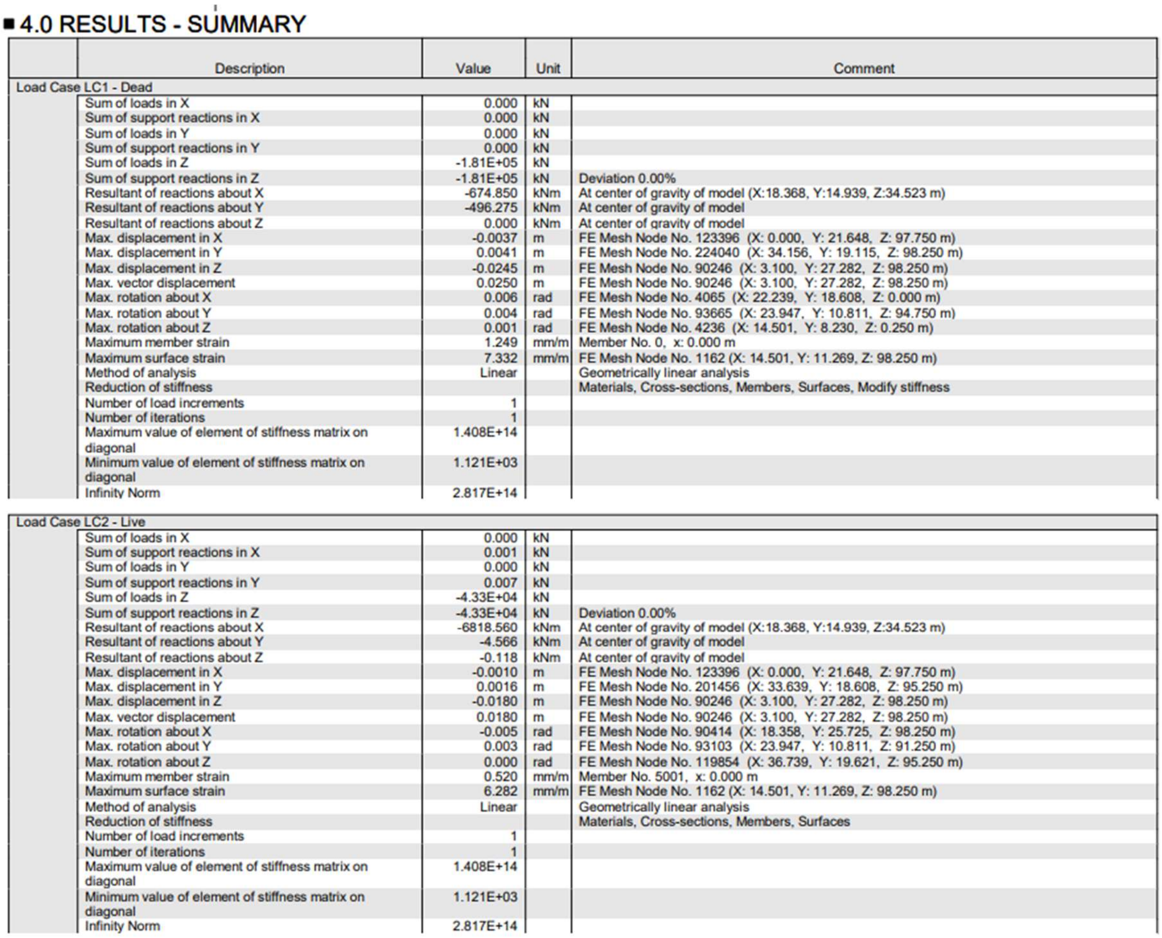
3.15 GENERATED LOADS

LC5: Wind in -X

No.	Load Description				
	Set wind on side	● A - B			
	Create load type	● Member loads			
	Load distribution type	● Combined			
	Generate wind loads on members No.		:	55-63,72,90,99-111,160-175,181,182,210-218,227,245,254-266,365-374,382,383,391,392,400,401,409-418,473-481,490,508,517-529,574-583,591,592,600,601,609,610,618-637,645,646,654,655,663,664,672-681,736-744,753,771,780-792,837-846,854,855,863,864,872,873,881-900,908,909,917,918,926,927,935-944,999-1007,1016,1034,1043-1055,1100-1109,1117,1118,1126,1127,1135,1136,1144-1163,1171,1172,1180,1181,1189,1190,1198-1216,1225,1243,1252-1264,1309-1318,1326,1327,1335,1336,1344,1345,1353-1362,1411-1415,1497-1512,1515,1517-1520,1527,1529,1532,1544,1547,1551-1560,1575,1579,1580,1593,1594,1596-1598,1601-1608,1622,1626,1629,1647-1657,1660,1662-1665,1672,1674,1677,1689,1692,1696-1705,1722,1723,1737-1739,1742-1749,1763,1787-1802,1805,1807-1810,1817,1819,1822,1834,1837,1841-1850,1867,1868,1882-1884,1887-1894,1908,1932-1947,1950,1952-1955,1962,1964,1967,1979,1982,1986-1995,2012,2013,2027-2029,2032-2039,2053,2077-2092,2095,2097-2100,2107,2109,2112,2124,2127,2131-2140,2157,2158,2172-2174,2177-2184,2198,2222-2237, ...	
	Building dimensions	h	:	105.250	m
		b	:	29.877	m
		d	:	36.739	m
		e_{Walls}	:	29.877	m
		e_{Roof}	:	29.877	m
		A_{Walls}	:	13523.048	m^2
		A_{Roof}	:	1097.651	m^2
		α	:	0.0	°
		d_A	:	5.975	m
		d_B	:	23.902	m
		d_C	:	6.862	m
		b_F	:	7.469	m
		d_F	:	2.988	m
		d_H	:	11.951	m
		d_I	:	21.800	m

Zone	External pressure coefficient $c_{pe,10}$	External pressure w_e [kN/m²]
A	-1.200	-2.88
B	-0.800	-1.92
C	-0.500	-1.20
D	0.800	1.63
E	-0.593	-1.21
F	-1.800	-4.32
G	-1.200	-2.88
H	-0.700	-1.68
I	-0.200	-0.48

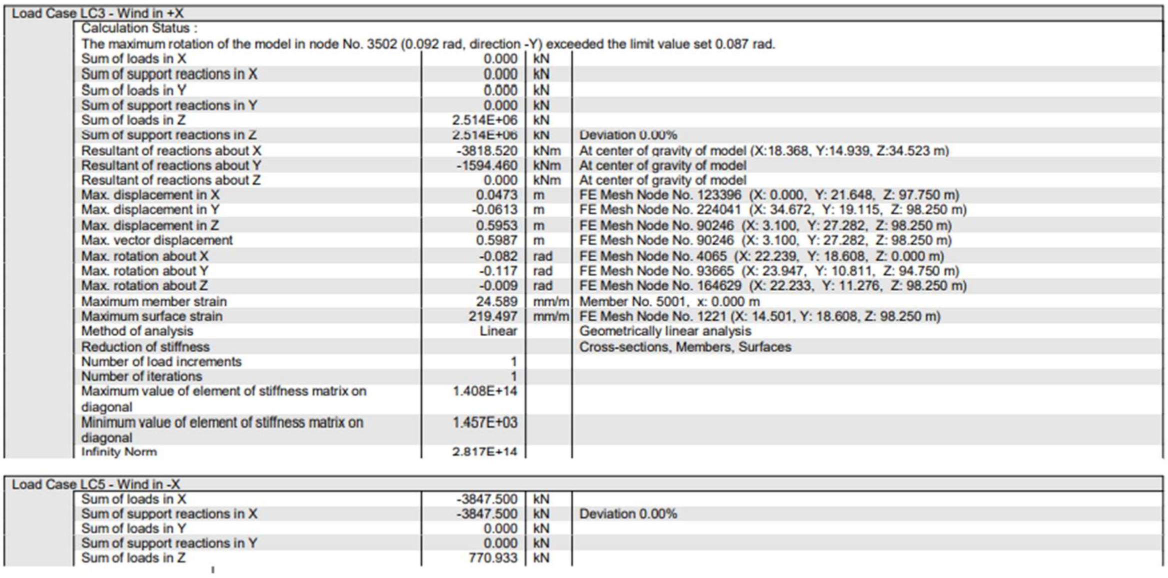
Generated total loads	ΣP_{Areas}	:	8088.550	kN
	ΣP	:	8088.250	kN
Total moment to the origin	ΣM_{Areas}	:	454469.000	kNm
	ΣM	:	454464.000	kNm



■ 4.0 RESULTS - SUMMARY

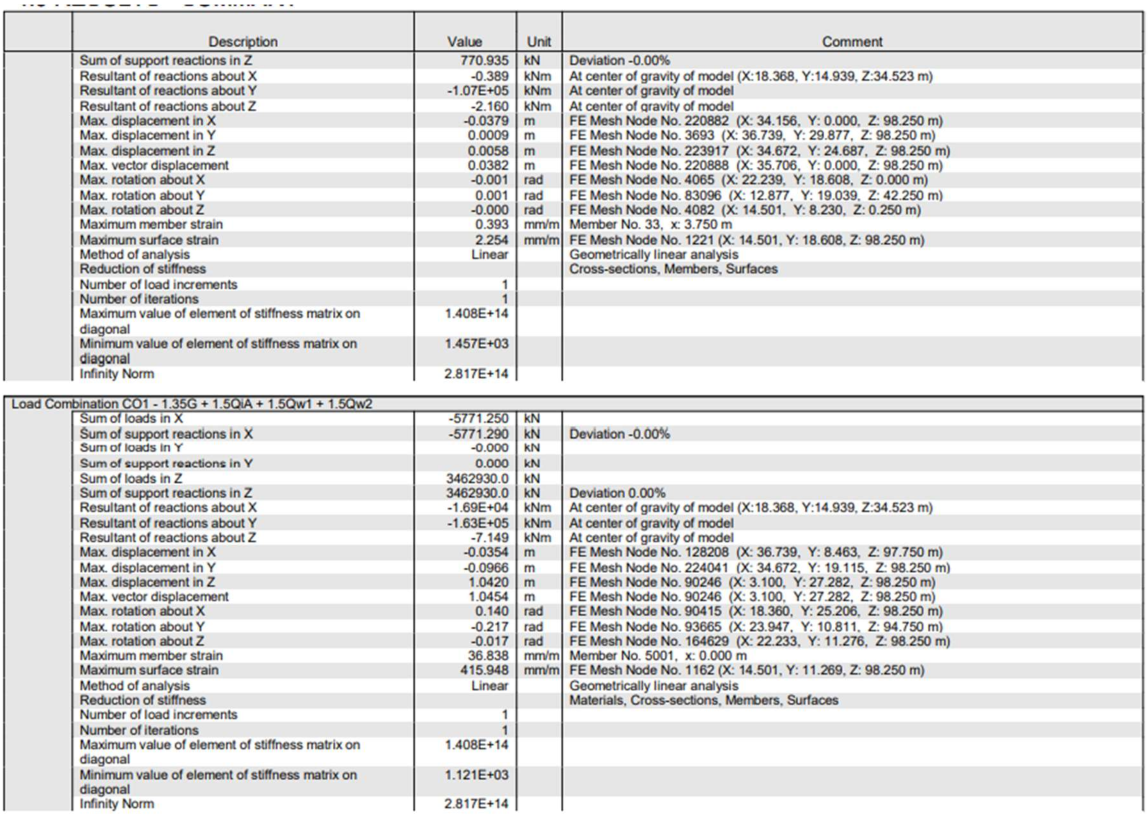
	Description	Value	Unit	Comment
Load Case LC1 - Dead				
	Sum of loads in X	0.000	kN	
	Sum of support reactions in X	0.000	kN	
	Sum of loads in Y	0.000	kN	
	Sum of support reactions in Y	0.000	kN	
	Sum of loads in Z	-1.81E+05	kN	
	Sum of support reactions in Z	-1.81E+05	kN	Deviation 0.00%
	Resultant of reactions about X	-674.850	kNm	At center of gravity of model (X:18.368, Y:14.939, Z:34.523 m)
	Resultant of reactions about Y	-496.275	kNm	At center of gravity of model
	Resultant of reactions about Z	0.000	kNm	At center of gravity of model
	Max. displacement in X	-0.0037	m	FE Mesh Node No. 123396 (X: 0.000, Y: 21.648, Z: 97.750 m)
	Max. displacement in Y	0.0041	m	FE Mesh Node No. 224040 (X: 34.156, Y: 19.115, Z: 98.250 m)
	Max. displacement in Z	-0.0245	m	FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. vector displacement	0.0250	m	FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. rotation about X	0.006	rad	FE Mesh Node No. 4065 (X: 22.239, Y: 18.608, Z: 0.000 m)
	Max. rotation about Y	0.004	rad	FE Mesh Node No. 93665 (X: 23.947, Y: 10.811, Z: 94.750 m)
	Max. rotation about Z	0.001	rad	FE Mesh Node No. 4236 (X: 14.501, Y: 8.230, Z: 0.250 m)
	Maximum member strain	1.249	mm/m	Member No. 0, x: 0.000 m
	Maximum surface strain	7.332	mm/m	FE Mesh Node No. 1162 (X: 14.501, Y: 11.269, Z: 98.250 m)
	Method of analysis	Linear		Geometrically linear analysis
	Reduction of stiffness			Materials, Cross-sections, Members, Surfaces, Modify stiffness
	Number of load increments	1		
	Number of iterations	1		
	Maximum value of element of stiffness matrix on diagonal	1.408E+14		
	Minimum value of element of stiffness matrix on diagonal	1.121E+03		
	Infinity Norm	2.817E+14		

Load Case LC2 - Live				
	Sum of loads in X	0.000	kN	
	Sum of support reactions in X	0.001	kN	
	Sum of loads in Y	0.000	kN	
	Sum of support reactions in Y	0.007	kN	
	Sum of loads in Z	-4.33E+04	kN	
	Sum of support reactions in Z	-4.33E+04	kN	Deviation 0.00%
	Resultant of reactions about X	-6818.560	kNm	At center of gravity of model (X:18.368, Y:14.939, Z:34.523 m)
	Resultant of reactions about Y	-4.566	kNm	At center of gravity of model
	Resultant of reactions about Z	-0.118	kNm	At center of gravity of model
	Max. displacement in X	-0.0010	m	FE Mesh Node No. 123396 (X: 0.000, Y: 21.648, Z: 97.750 m)
	Max. displacement in Y	0.0016	m	FE Mesh Node No. 201456 (X: 33.639, Y: 18.608, Z: 95.250 m)
	Max. displacement in Z	-0.0180	m	FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. vector displacement	0.0180	m	FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. rotation about X	-0.005	rad	FE Mesh Node No. 90414 (X: 18.358, Y: 25.725, Z: 98.250 m)
	Max. rotation about Y	0.003	rad	FE Mesh Node No. 93103 (X: 23.947, Y: 10.811, Z: 91.250 m)
	Max. rotation about Z	0.000	rad	FE Mesh Node No. 119854 (X: 36.739, Y: 19.621, Z: 95.250 m)
	Maximum member strain	0.520	mm/m	Member No. 5001, x: 0.000 m
	Maximum surface strain	6.282	mm/m	FE Mesh Node No. 1162 (X: 14.501, Y: 11.269, Z: 98.250 m)
	Method of analysis	Linear		Geometrically linear analysis
	Reduction of stiffness			Materials, Cross-sections, Members, Surfaces
	Number of load increments	1		
	Number of iterations	1		
	Maximum value of element of stiffness matrix on diagonal	1.408E+14		
	Minimum value of element of stiffness matrix on diagonal	1.121E+03		
	Infinity Norm	2.817E+14		

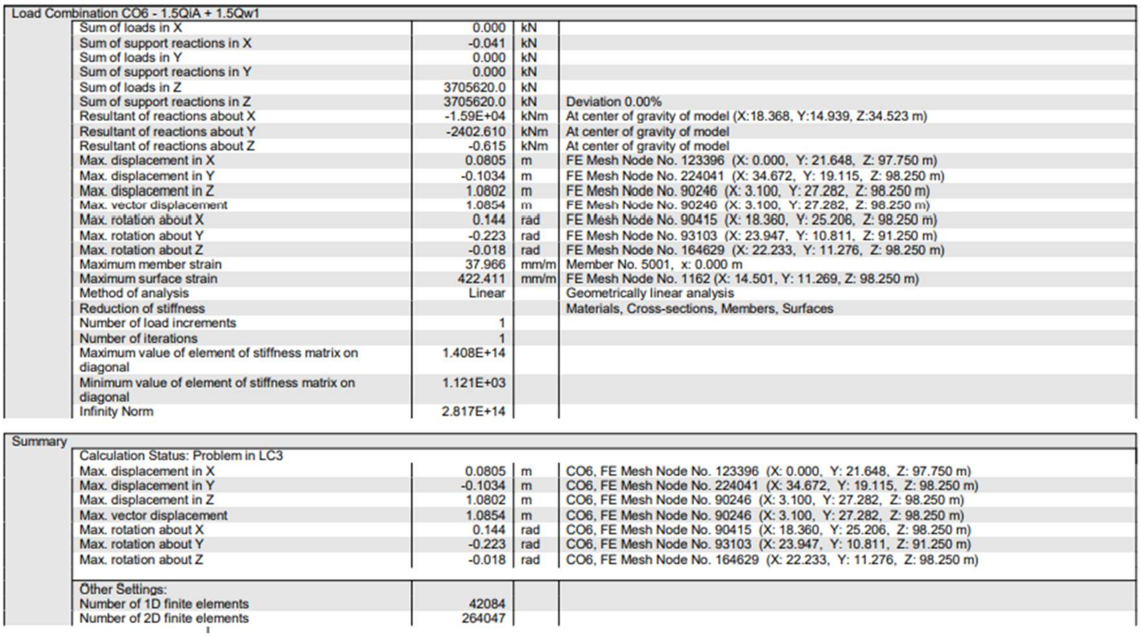


Load Case LC3 - Wind in +X				
	Calculation Status : The maximum rotation of the model in node No. 3502 (0.092 rad, direction -Y) exceeded the limit value set 0.087 rad.			
	Sum of loads in X	0.000	kN	
	Sum of support reactions in X	0.000	kN	
	Sum of loads in Y	0.000	kN	
	Sum of support reactions in Y	0.000	kN	
	Sum of loads in Z	2.514E+06	kN	
	Sum of support reactions in Z	2.514E+06	kN	Deviation 0.00%
	Resultant of reactions about X	-3818.520	kNm	At center of gravity of model (X:18.368, Y:14.939, Z:34.523 m)
	Resultant of reactions about Y	-1594.460	kNm	At center of gravity of model
	Resultant of reactions about Z	0.000	kNm	At center of gravity of model
	Max. displacement in X	0.0473	m	FE Mesh Node No. 123396 (X: 0.000, Y: 21.648, Z: 97.750 m)
	Max. displacement in Y	-0.0613	m	FE Mesh Node No. 224041 (X: 34.672, Y: 19.115, Z: 98.250 m)
	Max. displacement in Z	0.5953	m	FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. vector displacement	0.5987	m	FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. rotation about X	-0.082	rad	FE Mesh Node No. 4065 (X: 22.239, Y: 18.608, Z: 0.000 m)
	Max. rotation about Y	-0.117	rad	FE Mesh Node No. 93665 (X: 23.947, Y: 10.811, Z: 94.750 m)
	Max. rotation about Z	-0.009	rad	FE Mesh Node No. 164629 (X: 22.233, Y: 11.276, Z: 98.250 m)
	Maximum member strain	24.589	mm/m	Member No. 5001, x: 0.000 m
	Maximum surface strain	219.497	mm/m	FE Mesh Node No. 1221 (X: 14.501, Y: 18.608, Z: 98.250 m)
	Method of analysis	Linear		Geometrically linear analysis
	Reduction of stiffness			Cross-sections, Members, Surfaces
	Number of load increments	1		
	Number of iterations	1		
	Maximum value of element of stiffness matrix on diagonal	1.408E+14		
	Minimum value of element of stiffness matrix on diagonal	1.457E+03		
	Infinity Norm	2.817E+14		

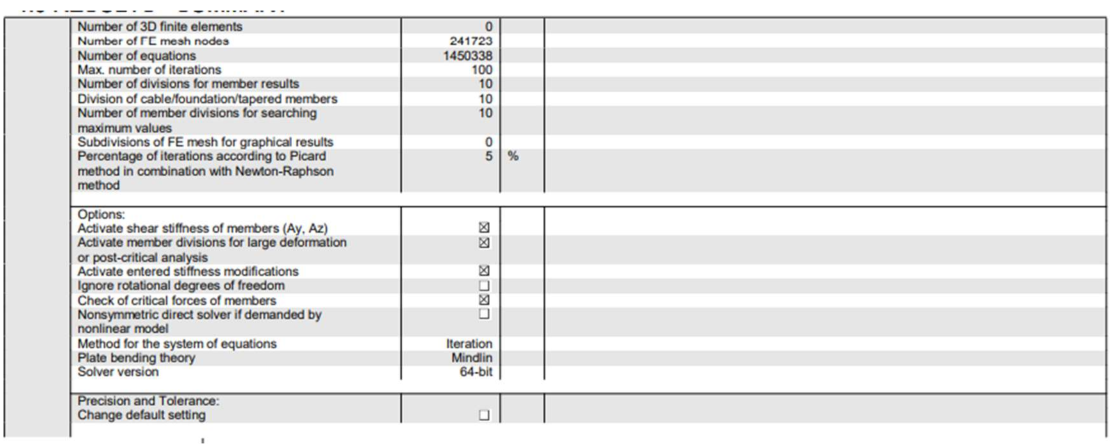
Load Case LC5 - Wind in -X				
	Sum of loads in X	-3847.500	kN	
	Sum of support reactions in X	-3847.500	kN	Deviation 0.00%
	Sum of loads in Y	0.000	kN	
	Sum of support reactions in Y	0.000	kN	
	Sum of loads in Z	770.933	kN	



	Description	Value	Unit	Comment
	Sum of support reactions in Z	770.935	kN	Deviation -0.00%
	Resultant of reactions about X	-0.389	kNm	At center of gravity of model (X:18.368, Y:14.939, Z:34.523 m)
	Resultant of reactions about Y	-1.07E+05	kNm	At center of gravity of model
	Resultant of reactions about Z	-2.160	kNm	At center of gravity of model
	Max. displacement in X	-0.0379	m	FE Mesh Node No. 220882 (X: 34.156, Y: 0.000, Z: 98.250 m)
	Max. displacement in Y	0.0009	m	FE Mesh Node No. 3693 (X: 36.739, Y: 29.877, Z: 98.250 m)
	Max. displacement in Z	0.0058	m	FE Mesh Node No. 223917 (X: 34.672, Y: 24.687, Z: 98.250 m)
	Max. vector displacement	0.0382	m	FE Mesh Node No. 220888 (X: 35.706, Y: 0.000, Z: 98.250 m)
	Max. rotation about X	-0.001	rad	FE Mesh Node No. 4065 (X: 22.239, Y: 18.608, Z: 0.000 m)
	Max. rotation about Y	0.001	rad	FE Mesh Node No. 83096 (X: 12.877, Y: 19.039, Z: 42.250 m)
	Max. rotation about Z	-0.000	rad	FE Mesh Node No. 4082 (X: 14.501, Y: 8.230, Z: 0.250 m)
	Maximum member strain	0.393	mm/m	Member No. 33, x: 3.750 m
	Maximum surface strain	2.254	mm/m	FE Mesh Node No. 1221 (X: 14.501, Y: 18.608, Z: 98.250 m)
	Method of analysis	Linear		Geometrically linear analysis
	Reduction of stiffness			Cross-sections, Members, Surfaces
	Number of load increments	1		
	Number of iterations	1		
	Maximum value of element of stiffness matrix on diagonal	1.408E+14		
	Minimum value of element of stiffness matrix on diagonal	1.457E+03		
	Infinity Norm	2.817E+14		
Load Combination CO1 - 1.35G + 1.5QiA + 1.5Qw1 + 1.5Qw2				
	Sum of loads in X	-5771.250	kN	
	Sum of support reactions in X	-5771.290	kN	Deviation -0.00%
	Sum of loads in Y	-0.000	kN	
	Sum of support reactions in Y	0.000	kN	
	Sum of loads in Z	3462930.0	kN	
	Sum of support reactions in Z	3462930.0	kN	Deviation 0.00%
	Resultant of reactions about X	-1.69E+04	kNm	At center of gravity of model (X:18.368, Y:14.939, Z:34.523 m)
	Resultant of reactions about Y	-1.63E+05	kNm	At center of gravity of model
	Resultant of reactions about Z	-7.149	kNm	At center of gravity of model
	Max. displacement in X	-0.0354	m	FE Mesh Node No. 128208 (X: 36.739, Y: 8.463, Z: 97.750 m)
	Max. displacement in Y	-0.0966	m	FE Mesh Node No. 224041 (X: 34.672, Y: 19.115, Z: 98.250 m)
	Max. displacement in Z	1.0420	m	FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. vector displacement	1.0454	m	FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. rotation about X	0.140	rad	FE Mesh Node No. 90415 (X: 18.360, Y: 25.206, Z: 98.250 m)
	Max. rotation about Y	-0.217	rad	FE Mesh Node No. 93665 (X: 23.947, Y: 10.811, Z: 94.750 m)
	Max. rotation about Z	-0.017	rad	FE Mesh Node No. 164629 (X: 22.233, Y: 11.276, Z: 98.250 m)
	Maximum member strain	36.838	mm/m	Member No. 5001, x: 0.000 m
	Maximum surface strain	415.948	mm/m	FE Mesh Node No. 1162 (X: 14.501, Y: 11.269, Z: 98.250 m)
	Method of analysis	Linear		Geometrically linear analysis
	Reduction of stiffness			Materials, Cross-sections, Members, Surfaces
	Number of load increments	1		
	Number of iterations	1		
	Maximum value of element of stiffness matrix on diagonal	1.408E+14		
	Minimum value of element of stiffness matrix on diagonal	1.121E+03		
	Infinity Norm	2.817E+14		



Load Combination CO6 - 1.5QiA + 1.5Qw1				
	Sum of loads in X	0.000	kN	
	Sum of support reactions in X	-0.041	kN	
	Sum of loads in Y	0.000	kN	
	Sum of support reactions in Y	0.000	kN	
	Sum of loads in Z	3705620.0	kN	
	Sum of support reactions in Z	3705620.0	kN	Deviation 0.00%
	Resultant of reactions about X	-1.59E+04	kNm	At center of gravity of model (X:18.368, Y:14.939, Z:34.523 m)
	Resultant of reactions about Y	-2402.610	kNm	At center of gravity of model
	Resultant of reactions about Z	-0.615	kNm	At center of gravity of model
	Max. displacement in X	0.0805	m	FE Mesh Node No. 123396 (X: 0.000, Y: 21.648, Z: 97.750 m)
	Max. displacement in Y	-0.1034	m	FE Mesh Node No. 224041 (X: 34.672, Y: 19.115, Z: 98.250 m)
	Max. displacement in Z	1.0802	m	FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. vector displacement	1.0854	m	FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. rotation about X	0.144	rad	FE Mesh Node No. 90415 (X: 18.360, Y: 25.206, Z: 98.250 m)
	Max. rotation about Y	-0.223	rad	FE Mesh Node No. 93103 (X: 23.947, Y: 10.811, Z: 91.250 m)
	Max. rotation about Z	-0.018	rad	FE Mesh Node No. 164629 (X: 22.233, Y: 11.276, Z: 98.250 m)
	Maximum member strain	37.966	mm/m	Member No. 5001, x: 0.000 m
	Maximum surface strain	422.411	mm/m	FE Mesh Node No. 1162 (X: 14.501, Y: 11.269, Z: 98.250 m)
	Method of analysis	Linear		Geometrically linear analysis
	Reduction of stiffness			Materials, Cross-sections, Members, Surfaces
	Number of load increments	1		
	Number of iterations	1		
	Maximum value of element of stiffness matrix on diagonal	1.408E+14		
	Minimum value of element of stiffness matrix on diagonal	1.121E+03		
	Infinity Norm	2.817E+14		
Summary				
	Calculation Status: Problem in LC3			
	Max. displacement in X	0.0805	m	CO6, FE Mesh Node No. 123396 (X: 0.000, Y: 21.648, Z: 97.750 m)
	Max. displacement in Y	-0.1034	m	CO6, FE Mesh Node No. 224041 (X: 34.672, Y: 19.115, Z: 98.250 m)
	Max. displacement in Z	1.0802	m	CO6, FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. vector displacement	1.0854	m	CO6, FE Mesh Node No. 90246 (X: 3.100, Y: 27.282, Z: 98.250 m)
	Max. rotation about X	0.144	rad	CO6, FE Mesh Node No. 90415 (X: 18.360, Y: 25.206, Z: 98.250 m)
	Max. rotation about Y	-0.223	rad	CO6, FE Mesh Node No. 93103 (X: 23.947, Y: 10.811, Z: 91.250 m)
	Max. rotation about Z	-0.018	rad	CO6, FE Mesh Node No. 164629 (X: 22.233, Y: 11.276, Z: 98.250 m)
	Other Settings:			
	Number of 1D finite elements	42084		
	Number of 2D finite elements	264047		



Number of 3D finite elements	0	
Number of FE mesh nodes	241723	
Number of equations	1450338	
Max. number of iterations	100	
Number of divisions for member results	10	
Division of cable/foundation/tapered members	10	
Number of member divisions for searching maximum values	10	
Subdivisions of FE mesh for graphical results	0	
Percentage of iterations according to Picard method in combination with Newton-Raphson method	5	%
Options:		
Activate shear stiffness of members (Ay, Az)	☒	
Activate member divisions for large deformation or post-critical analysis	☒	
Activate entered stiffness modifications	☒	
Ignore rotational degrees of freedom	☐	
Check of critical forces of members	☒	
Nonsymmetric direct solver if demanded by nonlinear model	☐	
Method for the system of equations	Iteration	
Plate bending theory	Mindlin	
Solver version	64-bit	
Precision and Tolerance:		
Change default setting	☐	

Appendix C: RFEM – Timber-concrete building

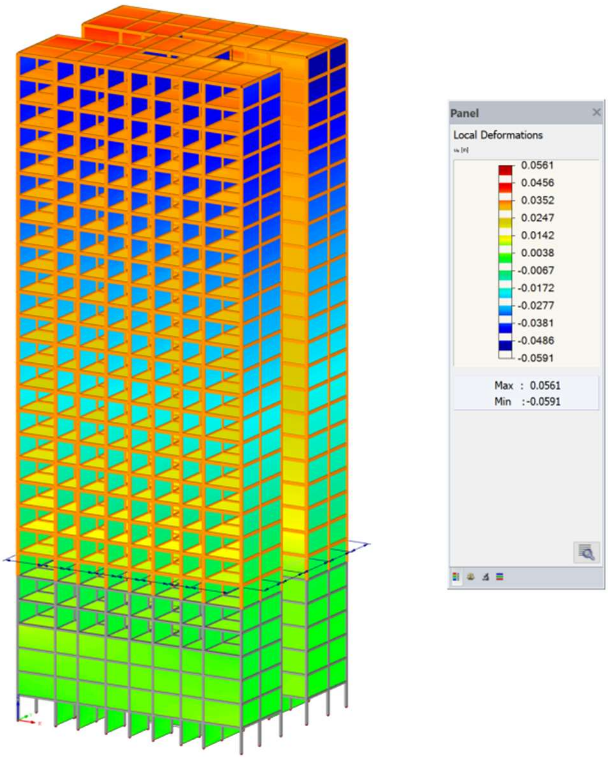
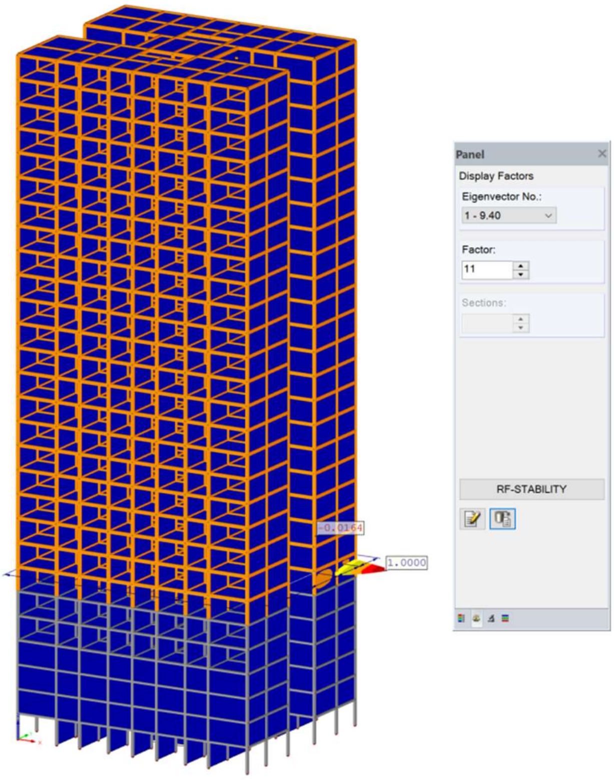


Figure C.1: Deformation analysis (Max. – 0.0937, Min. - -0.09)

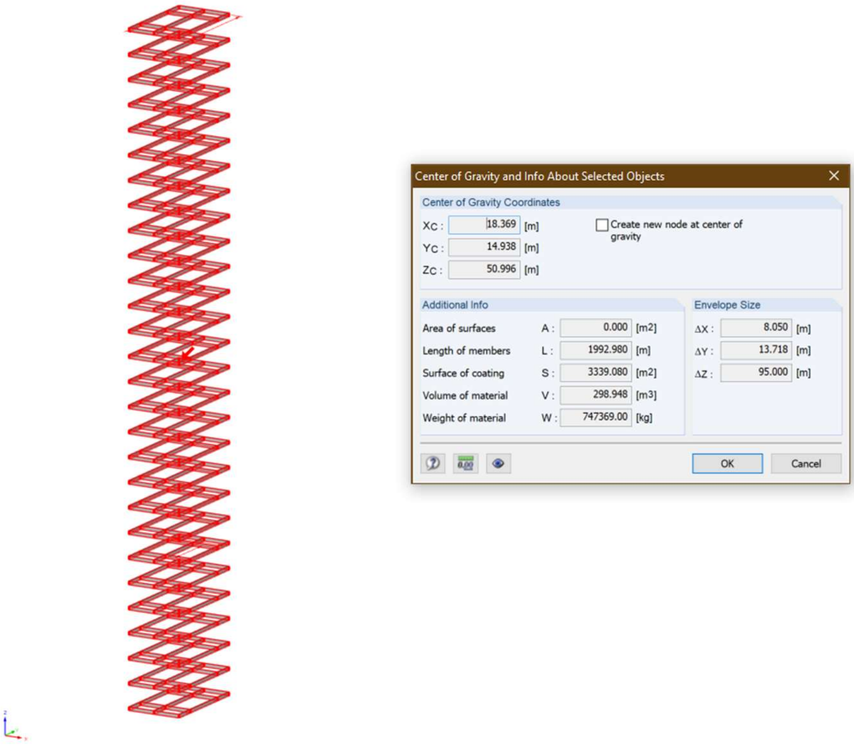


Eigenvector No.: 1 - 9.40

Factor: 11

Figure C.2: Stability analysis (Lowest Eigenvalue 1 – 9.40 times more the present load)

Appendix D: Rfem model– ECB and TCB (material quantity data)



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

XC : 18.369 [m]
YC : 14.938 [m]
ZC : 50.996 [m]

☐ Create new node at center of gravity

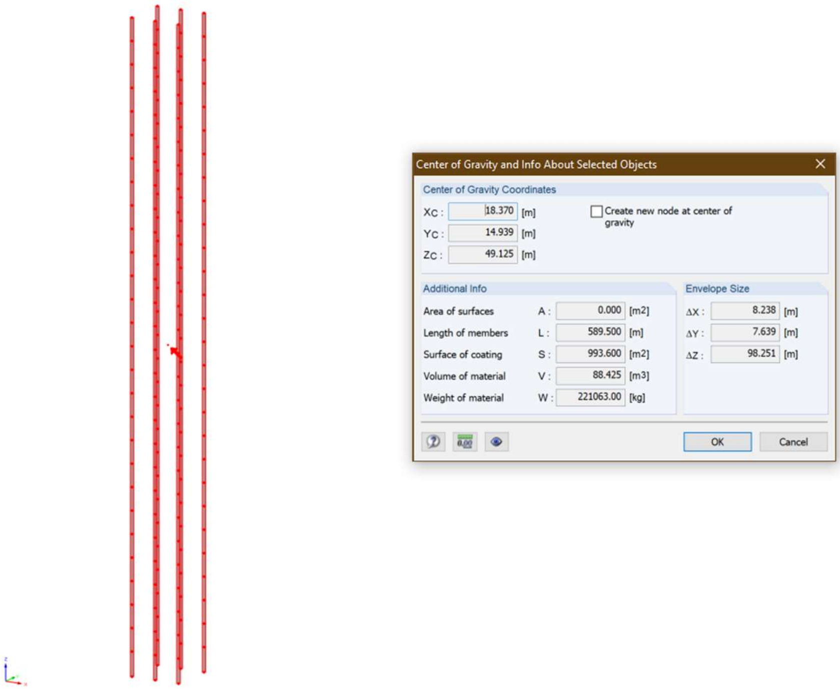
Additional Info

Area of surfaces A : 0.000 [m2]
Length of members L : 1992.980 [m]
Surface of coating S : 3339.080 [m2]
Volume of material V : 298.948 [m3]
Weight of material W : 747369.00 [kg]

Envelope Size

ΔX : 8.050 [m]
ΔY : 13.718 [m]
ΔZ : 95.000 [m]

Figure D.1: Core – Beams (view and centre of gravity information) in ECB & TCB



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

XC : 18.370 [m]
YC : 14.939 [m]
ZC : 49.125 [m]

☐ Create new node at center of gravity

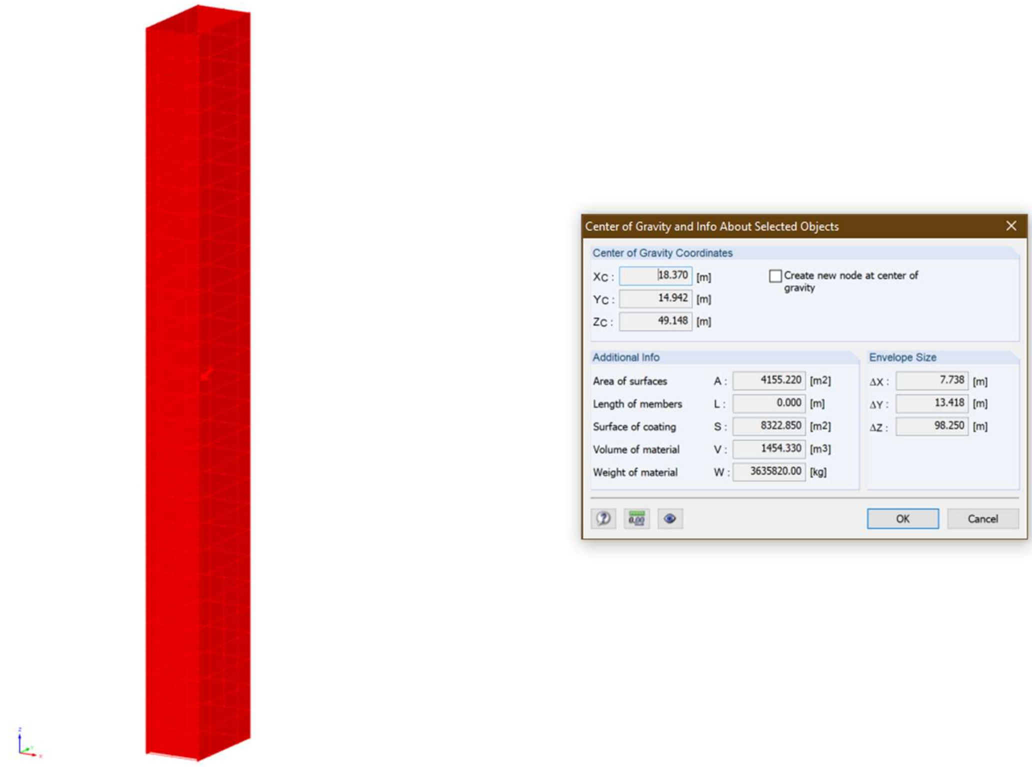
Additional Info

Area of surfaces A : 0.000 [m2]
Length of members L : 589.500 [m]
Surface of coating S : 993.600 [m2]
Volume of material V : 88.425 [m3]
Weight of material W : 221063.00 [kg]

Envelope Size

ΔX : 8.238 [m]
ΔY : 7.639 [m]
ΔZ : 98.251 [m]

Figure D.2: Core – Columns (view and centre of gravity information) in ECB & TCB



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.370 [m]
Yc : 14.942 [m]
Zc : 49.148 [m]

☐ Create new node at center of gravity

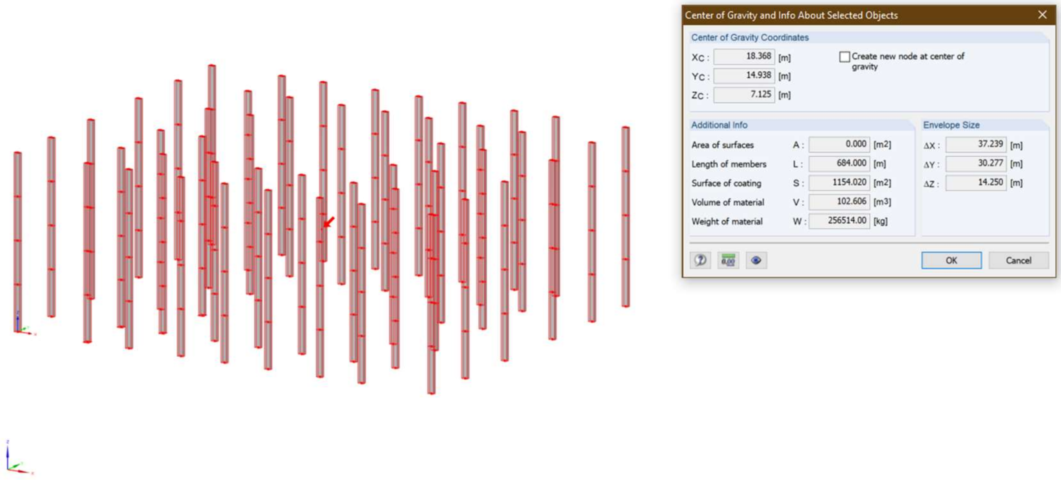
Additional Info

Area of surfaces	A :	4155.220	[m2]
Length of members	L :	0.000	[m]
Surface of coating	S :	8322.850	[m2]
Volume of material	V :	1454.330	[m3]
Weight of material	W :	3635820.00	[kg]

Envelope Size

ΔX : 7.738 [m]
ΔY : 13.418 [m]
ΔZ : 98.250 [m]

Figure D.3: Core – Walls (view and centre of gravity information) in ECB & TCB



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.368 [m]
Yc : 14.938 [m]
Zc : 7.125 [m]

☐ Create new node at center of gravity

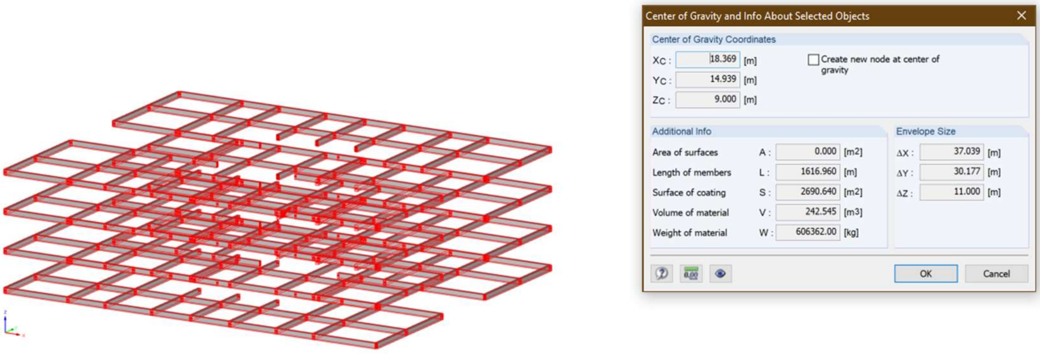
Additional Info

Area of surfaces	A :	0.000	[m2]
Length of members	L :	684.000	[m]
Surface of coating	S :	1154.020	[m2]
Volume of material	V :	102.606	[m3]
Weight of material	W :	256514.00	[kg]

Envelope Size

ΔX : 37.239 [m]
ΔY : 30.277 [m]
ΔZ : 14.250 [m]

Figure D.4: Substructure – Columns (view and centre of gravity information) in ECB & TCB



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.369 [m]
Yc : 14.939 [m]
Zc : 9.000 [m]

☐ Create new node at center of gravity

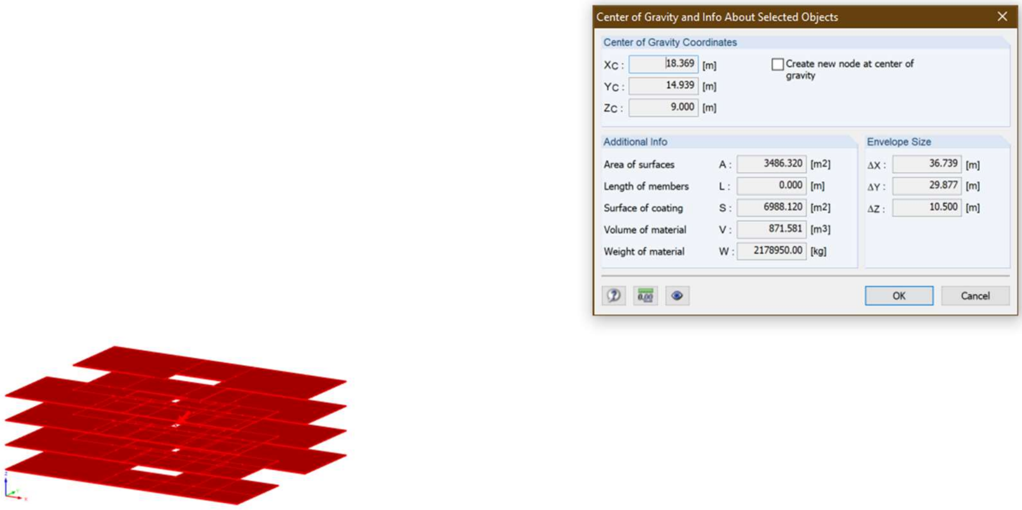
Additional Info

Area of surfaces A : 0.000 [m2]
Length of members L : 1616.960 [m]
Surface of coating S : 2690.640 [m2]
Volume of material V : 242.545 [m3]
Weight of material W : 606362.00 [kg]

Envelope Size

ΔX : 37.039 [m]
ΔY : 30.177 [m]
ΔZ : 11.000 [m]

Figure D.5: Substructure – Beams (view and centre of gravity information) in ECB & TCB



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.369 [m]
Yc : 14.939 [m]
Zc : 9.000 [m]

☐ Create new node at center of gravity

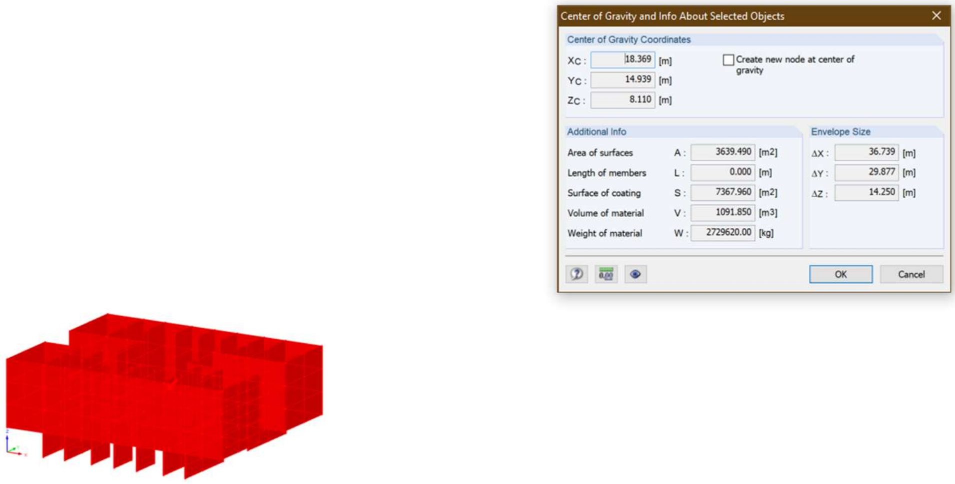
Additional Info

Area of surfaces A : 3486.320 [m2]
Length of members L : 0.000 [m]
Surface of coating S : 6988.120 [m2]
Volume of material V : 871.581 [m3]
Weight of material W : 2178950.00 [kg]

Envelope Size

ΔX : 36.739 [m]
ΔY : 29.877 [m]
ΔZ : 10.500 [m]

Figure D.6: Substructure – floors (view and centre of gravity information) in ECB & TCB

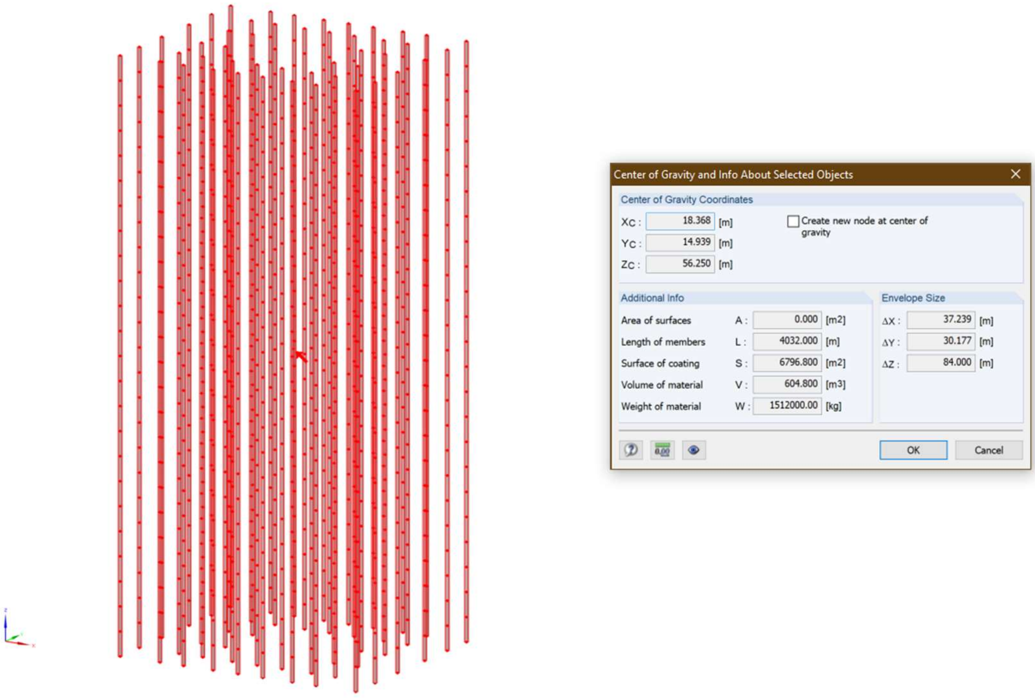


XC : 18.369 [m]
YC : 14.939 [m]
ZC : 8.110 [m]
☐ Create new node at center of gravity

Area of surfaces A : 3639.490 [m2]
Length of members L : 0.000 [m]
Surface of coating S : 7367.960 [m2]
Volume of material V : 1091.850 [m3]
Weight of material W : 2729620.00 [kg]

ΔX : 36.739 [m]
ΔY : 29.877 [m]
ΔZ : 14.250 [m]

Figure D.7: Substructure - walls (view and centre of gravity information) in ECB & TCB

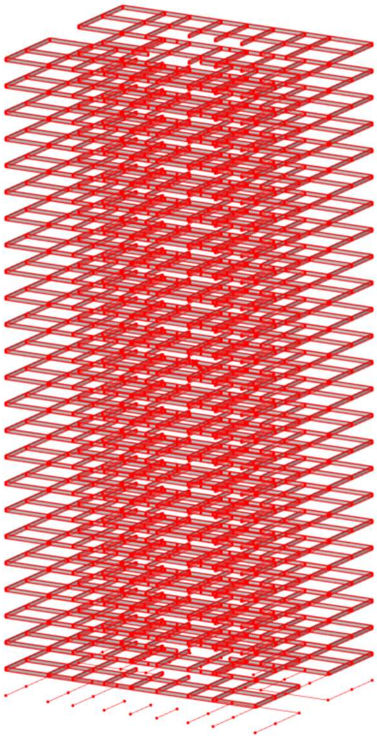


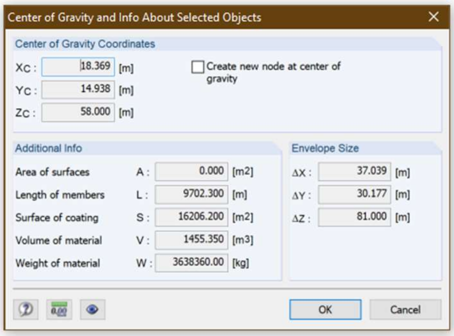
XC : 18.368 [m]
YC : 14.939 [m]
ZC : 56.250 [m]
☐ Create new node at center of gravity

Area of surfaces A : 0.000 [m2]
Length of members L : 4032.000 [m]
Surface of coating S : 6796.800 [m2]
Volume of material V : 604.800 [m3]
Weight of material W : 1512000.00 [kg]

ΔX : 37.239 [m]
ΔY : 30.177 [m]
ΔZ : 84.000 [m]

Figure D.8: Superstructure – Columns (view and centre of gravity information) in ECB





Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.369 [m]

Yc : 14.938 [m]

Zc : 58.000 [m]

☐ Create new node at center of gravity

Additional Info

Area of surfaces	A :	0.000	[m2]
Length of members	L :	9702.300	[m]
Surface of coating	S :	16206.200	[m2]
Volume of material	V :	1455.350	[m3]
Weight of material	W :	3638360.00	[kg]

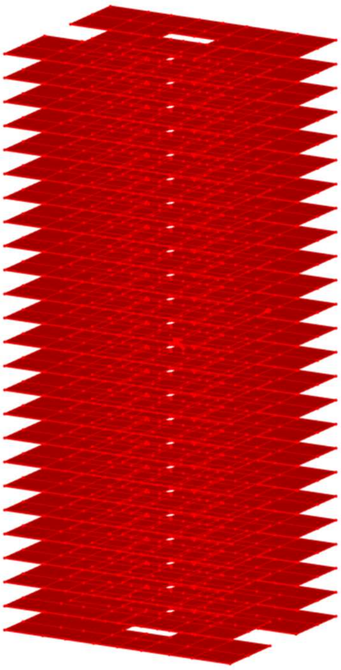
Envelope Size

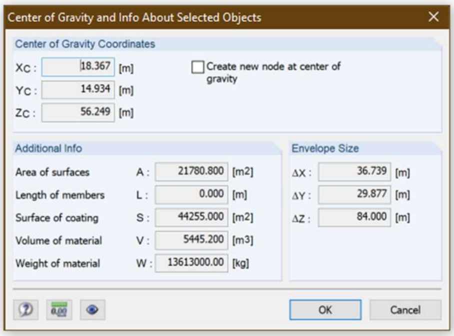
ΔX : 37.039 [m]

ΔY : 30.177 [m]

ΔZ : 81.000 [m]

Figure D.9: Superstructure - Beams (view and centre of gravity information) in ECB





Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.367 [m]

Yc : 14.934 [m]

Zc : 56.249 [m]

☐ Create new node at center of gravity

Additional Info

Area of surfaces	A :	21780.800	[m2]
Length of members	L :	0.000	[m]
Surface of coating	S :	44255.000	[m2]
Volume of material	V :	5445.200	[m3]
Weight of material	W :	13613000.00	[kg]

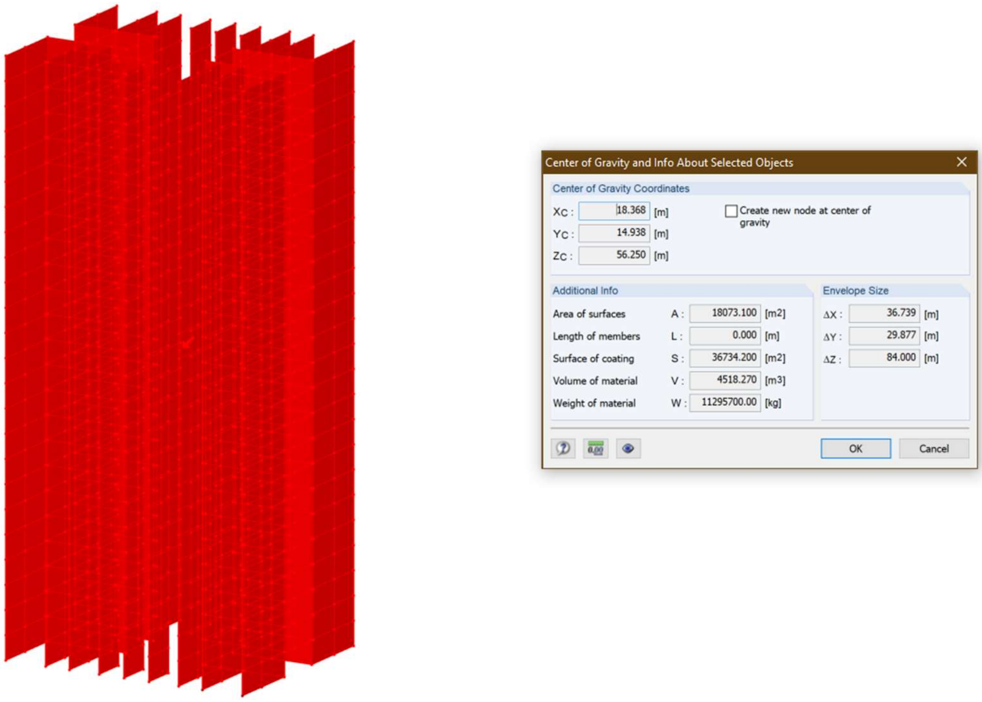
Envelope Size

ΔX : 36.739 [m]

ΔY : 29.877 [m]

ΔZ : 84.000 [m]

Figure D.10: Superstructure - Floors (view and centre of gravity information) in ECB



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.368 [m]
Yc : 14.938 [m]
Zc : 56.250 [m]

☐ Create new node at center of gravity

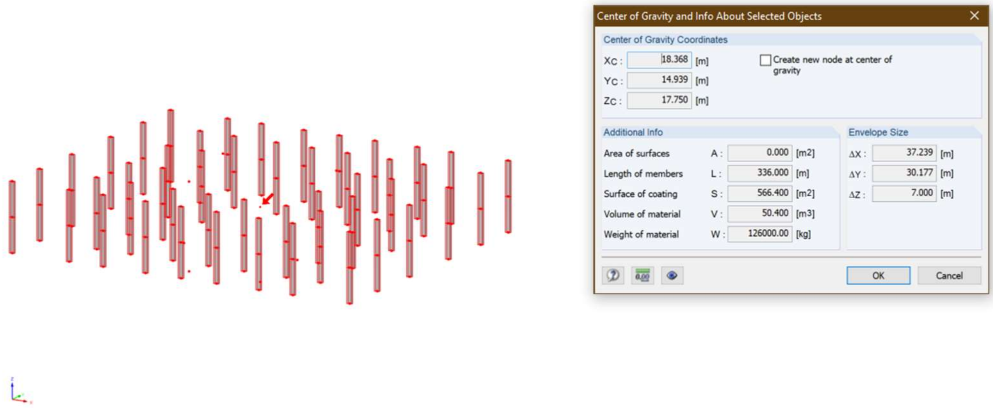
Additional Info

Area of surfaces A : 18073.100 [m2]
Length of members L : 0.000 [m]
Surface of coating S : 36734.200 [m2]
Volume of material V : 4518.270 [m3]
Weight of material W : 11295700.00 [kg]

Envelope Size

ΔX : 36.739 [m]
ΔY : 29.877 [m]
ΔZ : 84.000 [m]

Figure D.11: Superstructure - Walls (view and centre of gravity information) in ECB



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.368 [m]
Yc : 14.939 [m]
Zc : 17.750 [m]

☐ Create new node at center of gravity

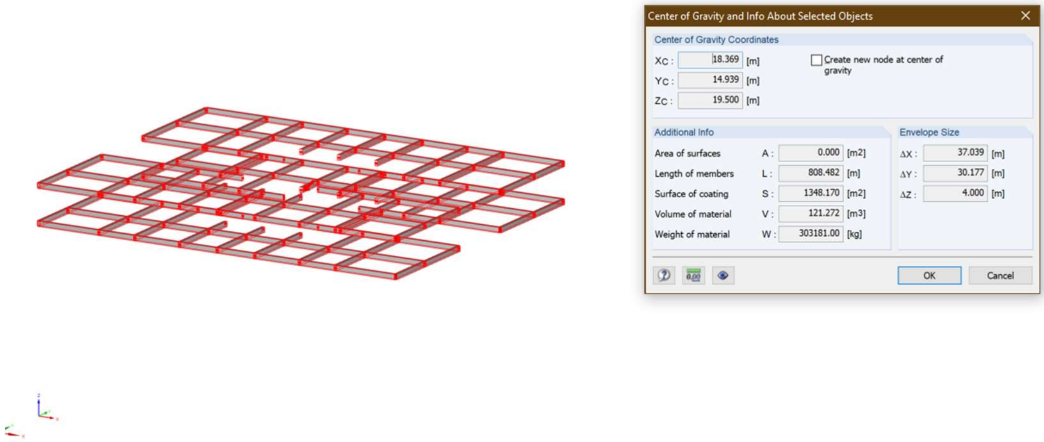
Additional Info

Area of surfaces A : 0.000 [m2]
Length of members L : 336.000 [m]
Surface of coating S : 566.400 [m2]
Volume of material V : 50.400 [m3]
Weight of material W : 126000.00 [kg]

Envelope Size

ΔX : 37.239 [m]
ΔY : 30.177 [m]
ΔZ : 7.000 [m]

Figure D.12: Superstructure - Columns (view and centre of gravity information) in TCB



Center of Gravity Coordinates

Xc : 18.369 [m]
Yc : 14.939 [m]
Zc : 19.500 [m]

☐ Create new node at center of gravity

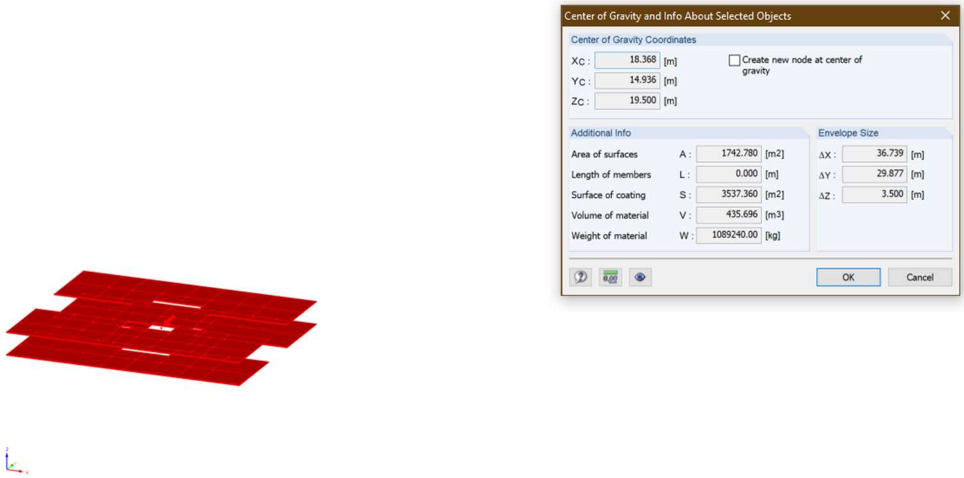
Additional Info

Area of surfaces A : 0.000 [m2]
Length of members L : 808.482 [m]
Surface of coating S : 1348.170 [m2]
Volume of material V : 121.272 [m3]
Weight of material W : 303181.00 [kg]

Envelope Size

ΔX : 37.039 [m]
ΔY : 30.177 [m]
ΔZ : 4.000 [m]

Figure D.13: Superstructure - Beams (view and centre of gravity information) in ECB



Center of Gravity Coordinates

Xc : 18.368 [m]
Yc : 14.936 [m]
Zc : 19.500 [m]

☐ Create new node at center of gravity

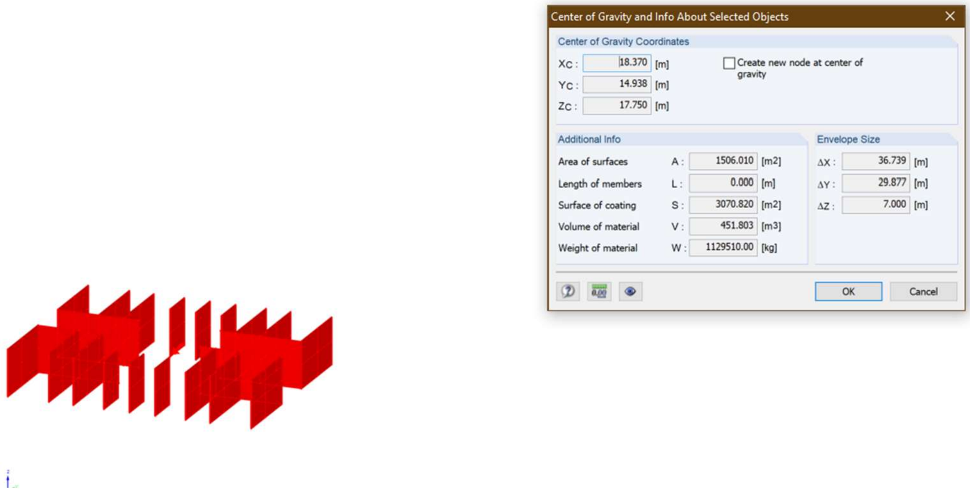
Additional Info

Area of surfaces A : 1742.780 [m2]
Length of members L : 0.000 [m]
Surface of coating S : 3537.360 [m2]
Volume of material V : 435.696 [m3]
Weight of material W : 1089240.00 [kg]

Envelope Size

ΔX : 36.739 [m]
ΔY : 29.877 [m]
ΔZ : 3.500 [m]

Figure D.14: Superstructure - Beams (view and centre of gravity information) in TCB



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

XC : 18.370 [m]
YC : 14.938 [m]
ZC : 17.750 [m]

☐ Create new node at center of gravity

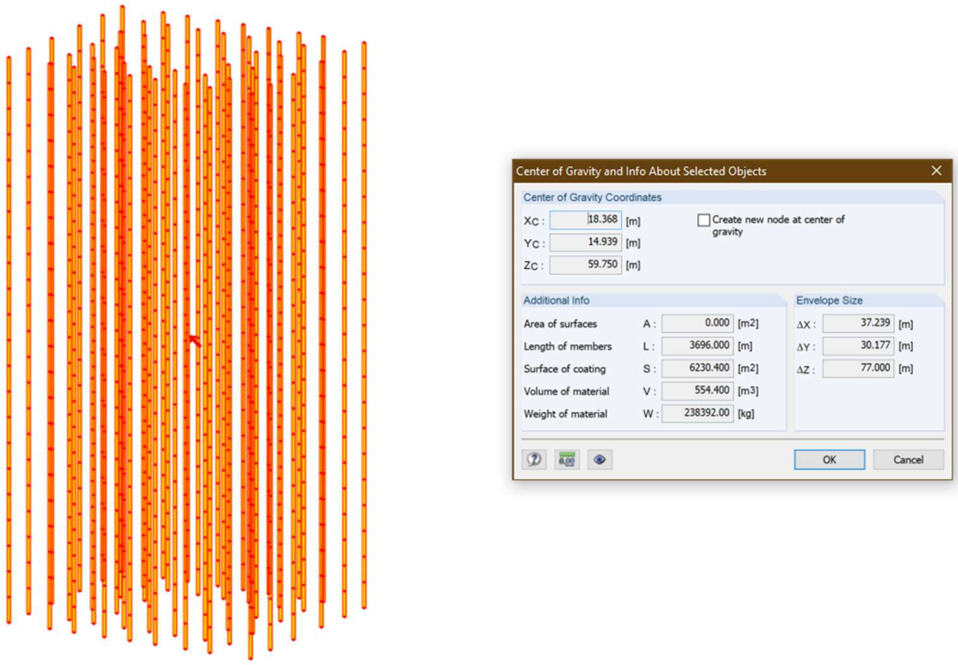
Additional Info

Area of surfaces	A :	1506.010	[m2]
Length of members	L :	0.000	[m]
Surface of coating	S :	3070.820	[m2]
Volume of material	V :	451.803	[m3]
Weight of material	W :	1129510.00	[kg]

Envelope Size

ΔX : 36.739 [m]
ΔY : 29.877 [m]
ΔZ : 7.000 [m]

Figure D.15: Superstructure - Walls (view and centre of gravity information) in TCB



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

XC : 18.368 [m]
YC : 14.939 [m]
ZC : 59.750 [m]

☐ Create new node at center of gravity

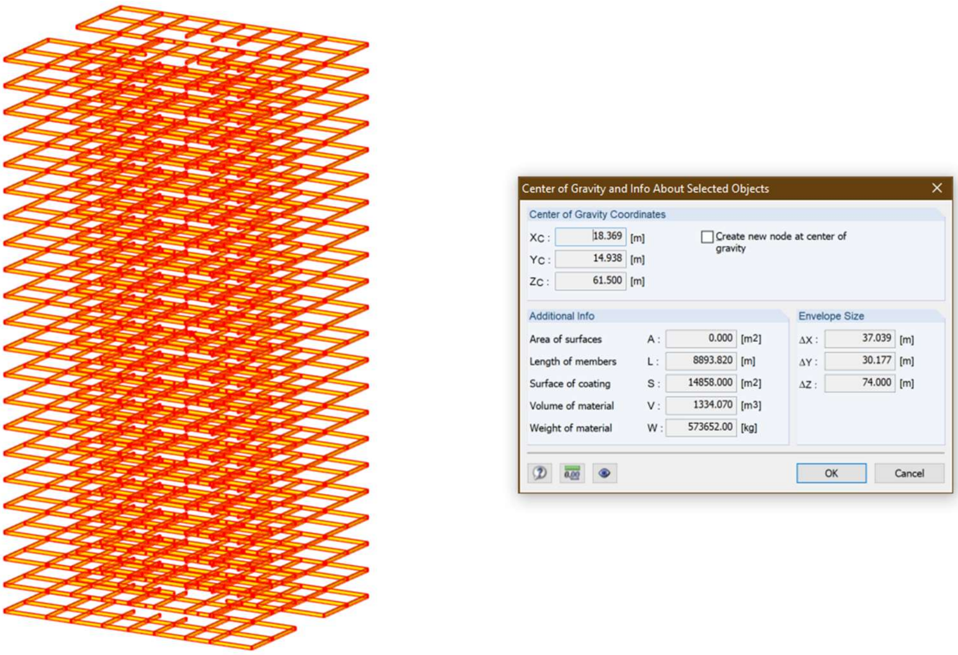
Additional Info

Area of surfaces	A :	0.000	[m2]
Length of members	L :	3696.000	[m]
Surface of coating	S :	6230.400	[m2]
Volume of material	V :	554.400	[m3]
Weight of material	W :	238392.00	[kg]

Envelope Size

ΔX : 37.239 [m]
ΔY : 30.177 [m]
ΔZ : 77.000 [m]

Figure D.16: Superstructure – GLT columns (view and centre of gravity information) in TCB


Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.369 [m]
Yc : 14.938 [m]
Zc : 61.500 [m]

☐ Create new node at center of gravity

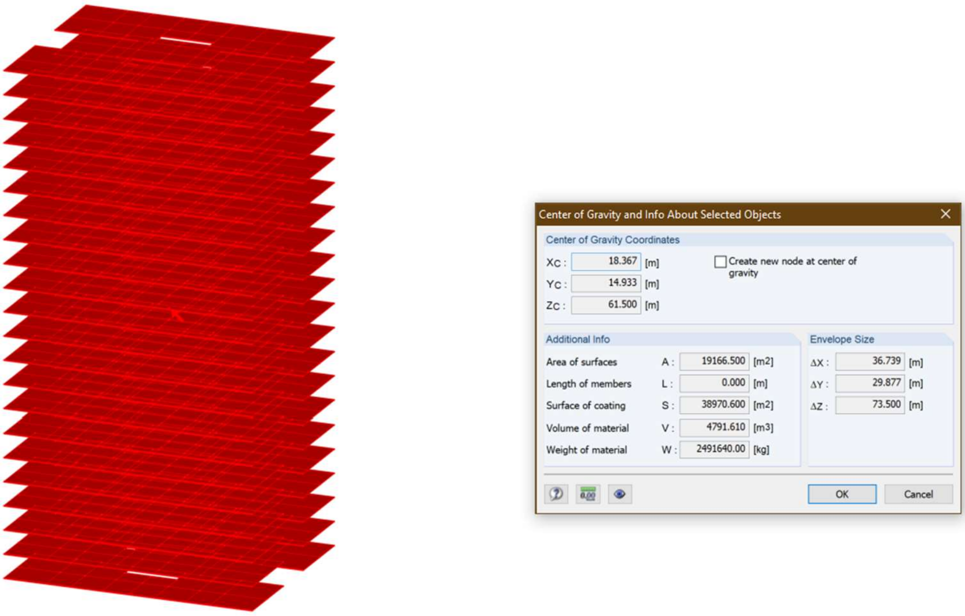
Additional Info

Area of surfaces	A :	0.000	[m2]
Length of members	L :	8893.820	[m]
Surface of coating	S :	14858.000	[m2]
Volume of material	V :	1334.070	[m3]
Weight of material	W :	573652.00	[kg]

Envelope Size

ΔX : 37.039 [m]
ΔY : 30.177 [m]
ΔZ : 74.000 [m]

Figure D.17: Superstructure – GLT Beams (view and centre of gravity information) in TCB


Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.367 [m]
Yc : 14.933 [m]
Zc : 61.500 [m]

☐ Create new node at center of gravity

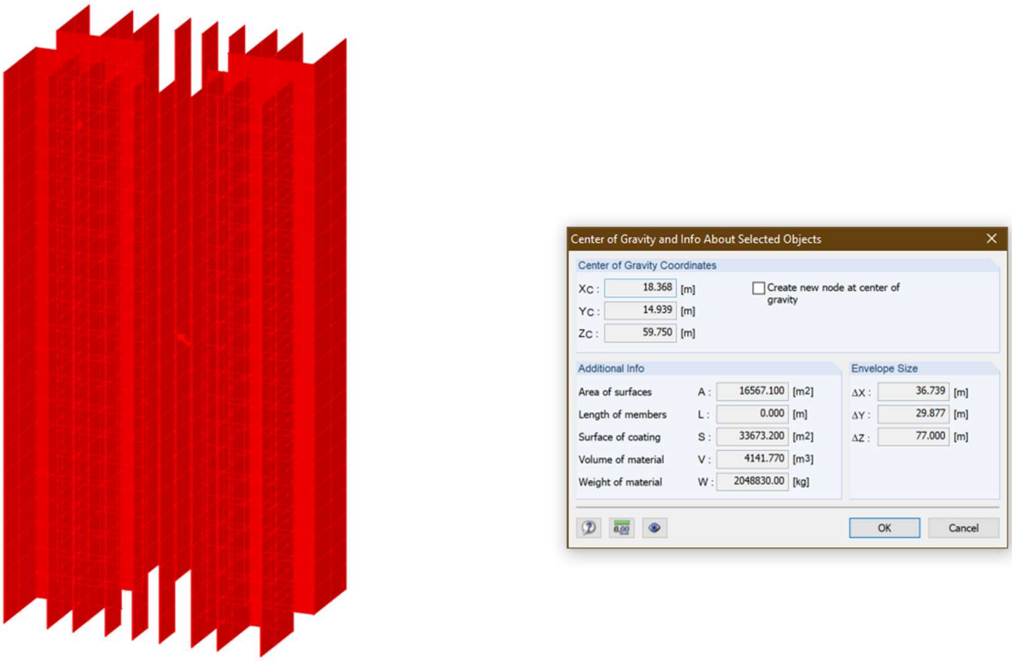
Additional Info

Area of surfaces	A :	19166.500	[m2]
Length of members	L :	0.000	[m]
Surface of coating	S :	38970.600	[m2]
Volume of material	V :	4791.610	[m3]
Weight of material	W :	2491640.00	[kg]

Envelope Size

ΔX : 36.739 [m]
ΔY : 29.877 [m]
ΔZ : 73.500 [m]

Figure D.18: Superstructure – CLT floors (view and centre of gravity information) in TCB



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.368 [m]
Yc : 14.939 [m]
Zc : 59.750 [m]

☐ Create new node at center of gravity

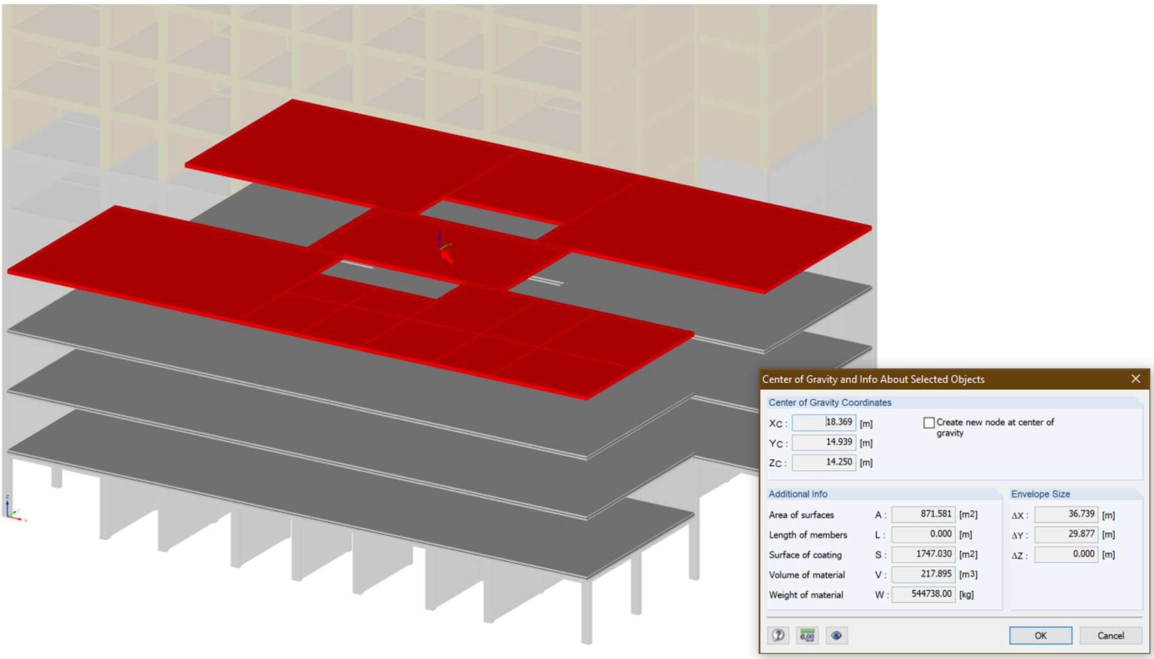
Additional Info

Area of surfaces A : 16567.100 [m2]
Length of members L : 0.000 [m]
Surface of coating S : 33673.200 [m2]
Volume of material V : 4141.770 [m3]
Weight of material W : 2048830.00 [kg]

Envelope Size

ΔX : 36.739 [m]
ΔY : 29.877 [m]
ΔZ : 77.000 [m]

Figure D.19: Superstructure – CLT walls (view and centre of gravity information) in TCB



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

Xc : 18.369 [m]
Yc : 14.939 [m]
Zc : 14.250 [m]

☐ Create new node at center of gravity

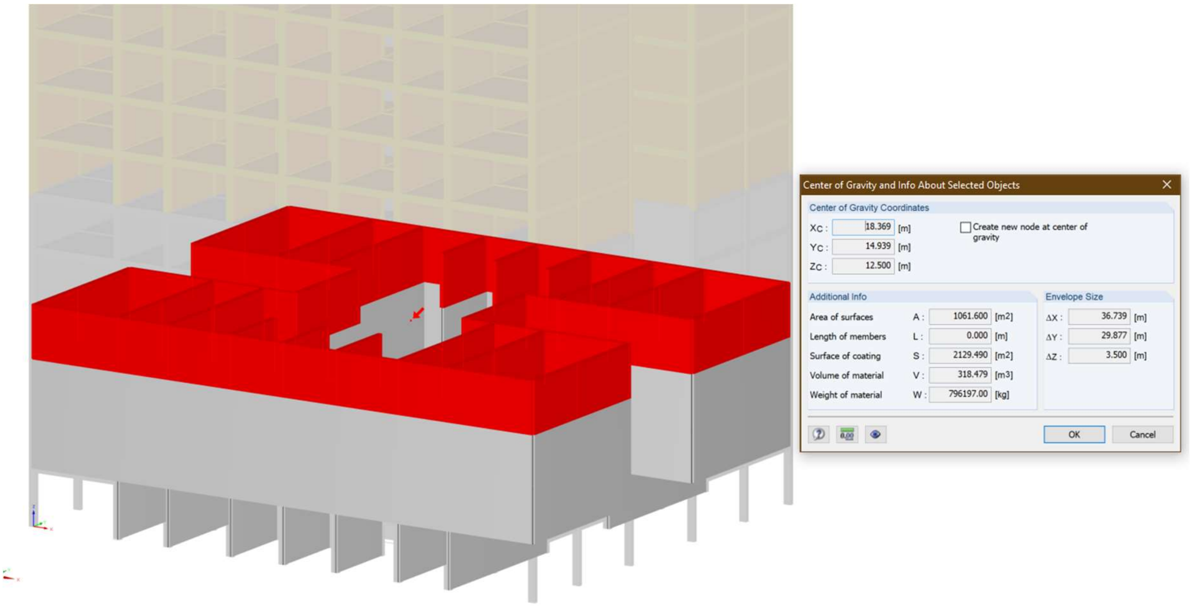
Additional Info

Area of surfaces A : 871.581 [m2]
Length of members L : 0.000 [m]
Surface of coating S : 1747.030 [m2]
Volume of material V : 217.895 [m3]
Weight of material W : 544738.00 [kg]

Envelope Size

ΔX : 36.739 [m]
ΔY : 29.877 [m]
ΔZ : 0.000 [m]

Figure D.20: Substructure floor volume per level (view and centre of gravity information)



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

XC : 18.369 [m]
YC : 14.939 [m]
ZC : 12.500 [m]

☐ Create new node at center of gravity

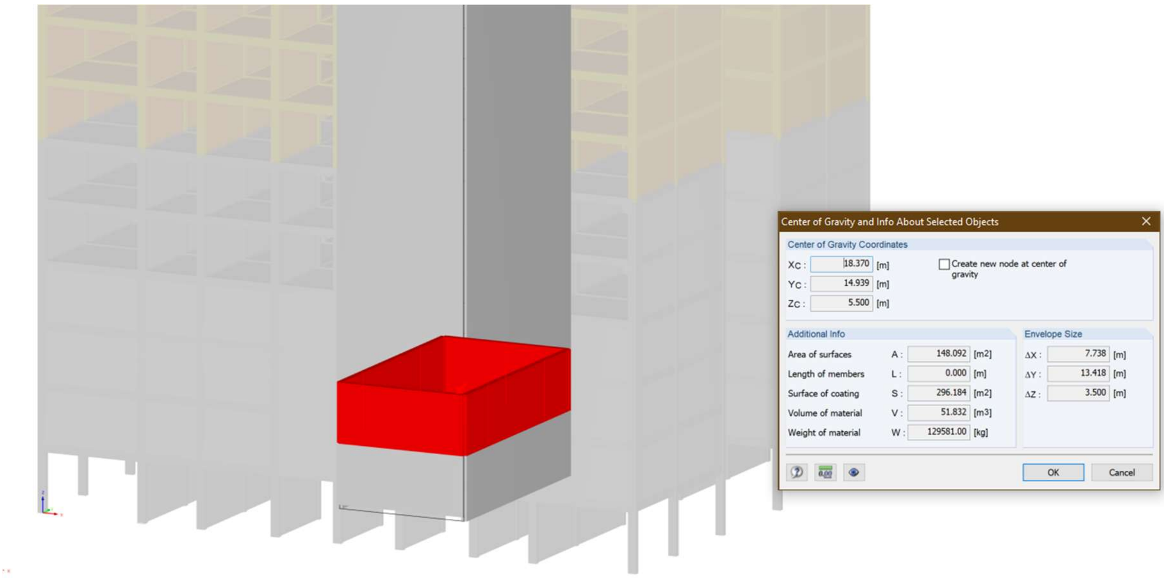
Additional Info

Area of surfaces	A :	1061.600	[m2]
Length of members	L :	0.000	[m]
Surface of coating	S :	2129.490	[m2]
Volume of material	V :	318.479	[m3]
Weight of material	W :	796197.00	[kg]

Envelope Size

ΔX : 36.739 [m]
ΔY : 29.877 [m]
ΔZ : 3.500 [m]

Figure D.21: Substructure walls volume per level (view and centre of gravity information)



Center of Gravity and Info About Selected Objects

Center of Gravity Coordinates

XC : 18.370 [m]
YC : 14.939 [m]
ZC : 5.500 [m]

☐ Create new node at center of gravity

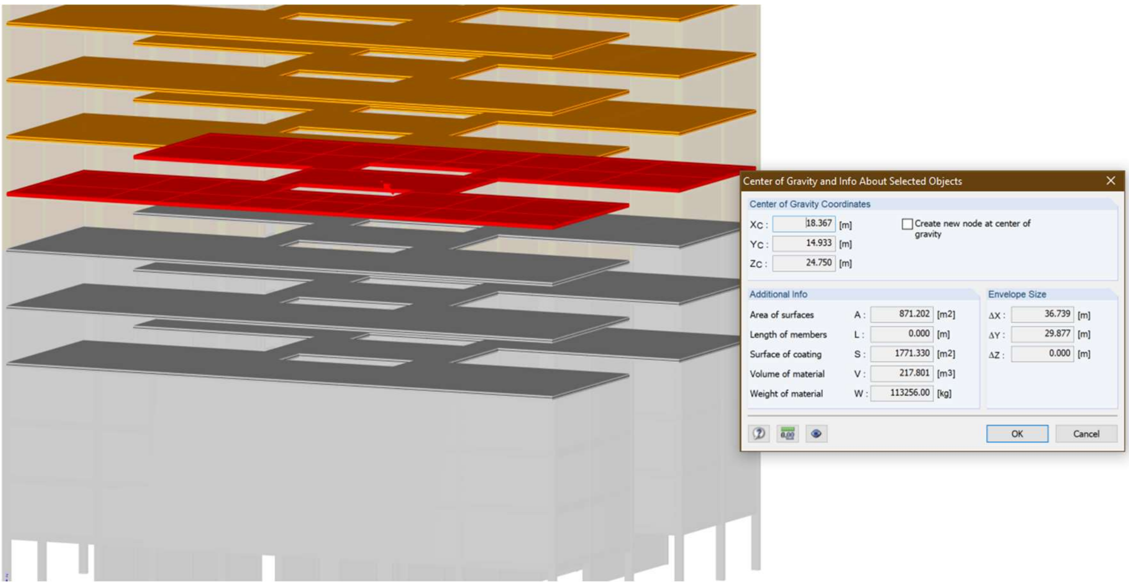
Additional Info

Area of surfaces	A :	148.092	[m2]
Length of members	L :	0.000	[m]
Surface of coating	S :	296.184	[m2]
Volume of material	V :	51.832	[m3]
Weight of material	W :	129581.00	[kg]

Envelope Size

ΔX : 7.738 [m]
ΔY : 13.418 [m]
ΔZ : 3.500 [m]

Figure D.22: Core wall volume per level (view and centre of gravity information)



Center of Gravity Coordinates

XC : 18.367 [m]
YC : 14.933 [m]
ZC : 24.750 [m]

☐ Create new node at center of gravity

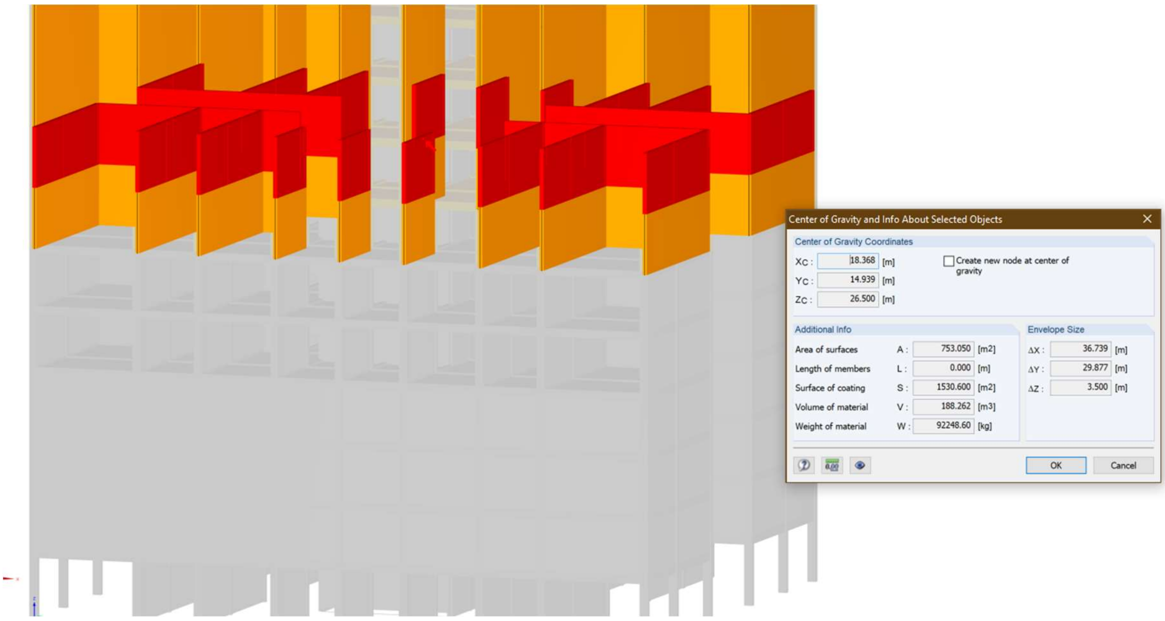
Additional Info

Area of surfaces A : 871.202 [m2]
Length of members L : 0.000 [m]
Surface of coating S : 1771.330 [m2]
Volume of material V : 217.801 [m3]
Weight of material W : 113256.00 [kg]

Envelope Size

ΔX : 36.739 [m]
ΔY : 29.877 [m]
ΔZ : 0.000 [m]

Figure D.23: Superstructure floor volume per level (view and centre of gravity information)



Center of Gravity Coordinates

XC : 18.368 [m]
YC : 14.939 [m]
ZC : 26.500 [m]

☐ Create new node at center of gravity

Additional Info

Area of surfaces A : 753.050 [m2]
Length of members L : 0.000 [m]
Surface of coating S : 1530.600 [m2]
Volume of material V : 188.262 [m3]
Weight of material W : 92248.60 [kg]

Envelope Size

ΔX : 36.739 [m]
ΔY : 29.877 [m]
ΔZ : 3.500 [m]

Figure D.24: Superstructure wall volume per floor (view and centre of gravity information)

Appendix E: Building components (Overlapping views)

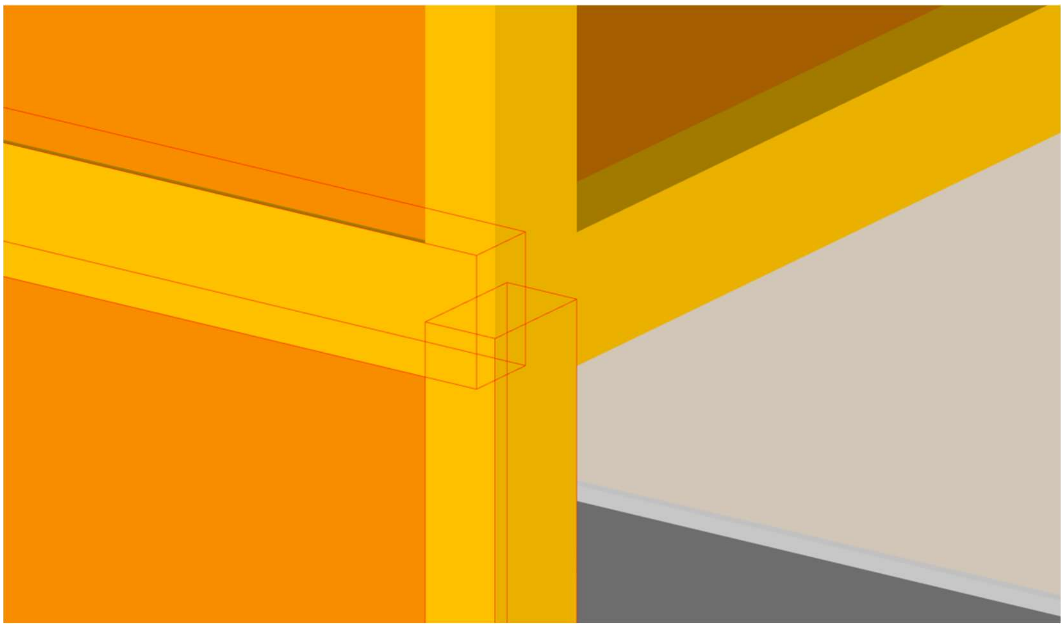


Figure E.1: Beam-column overlap view

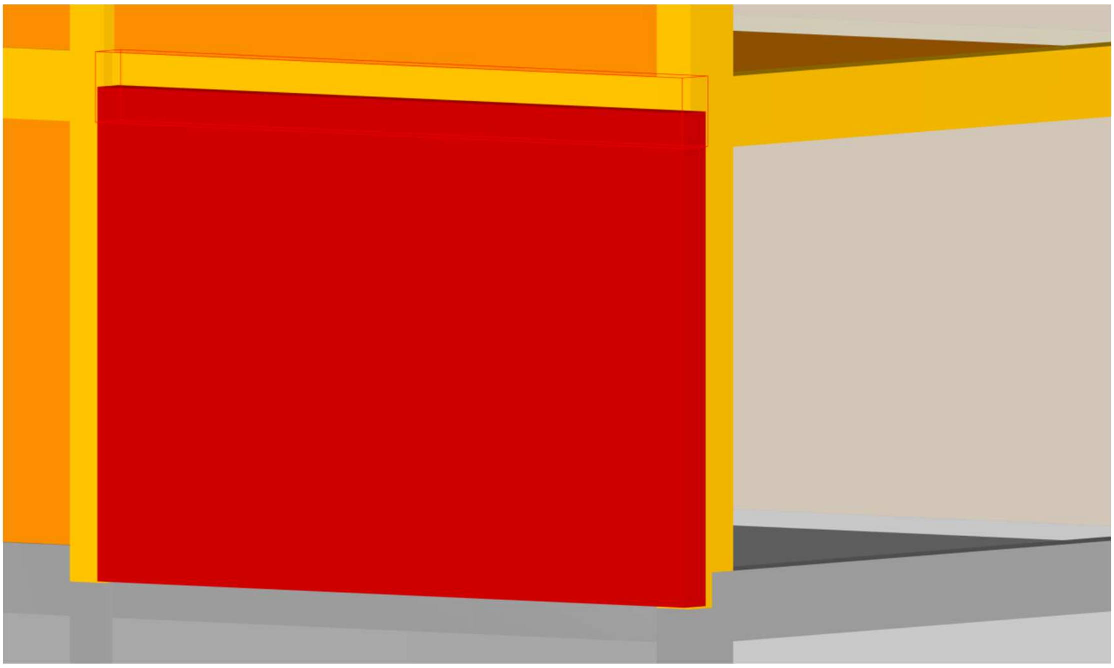


Figure E.2: Beam-wall overlap view

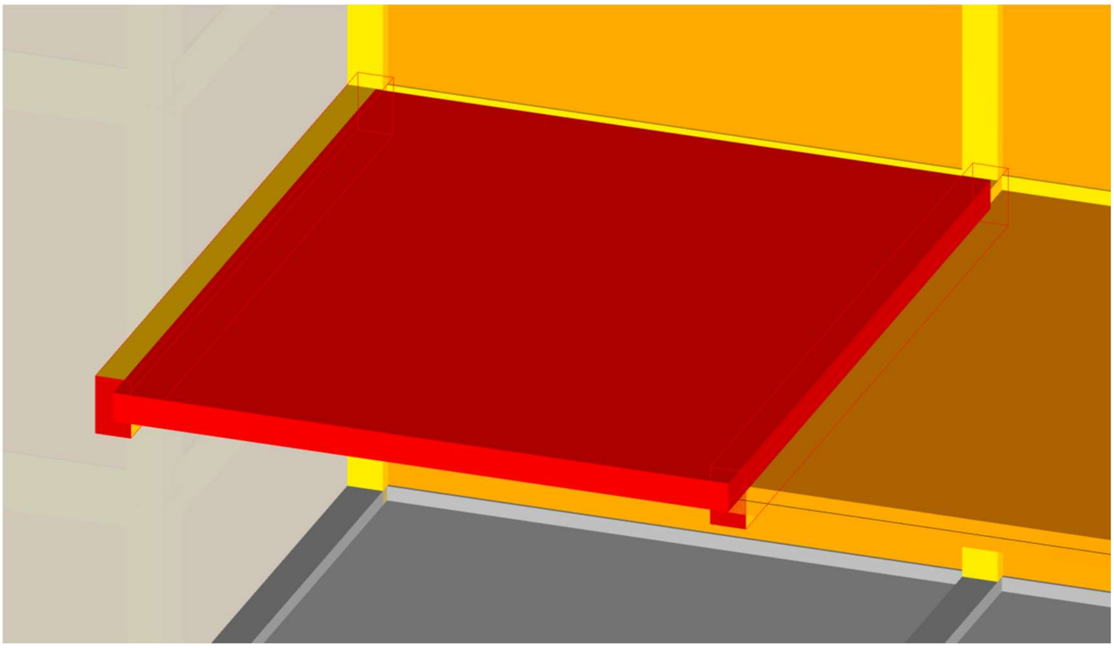


Figure E.3: Beam-Floor overlap view

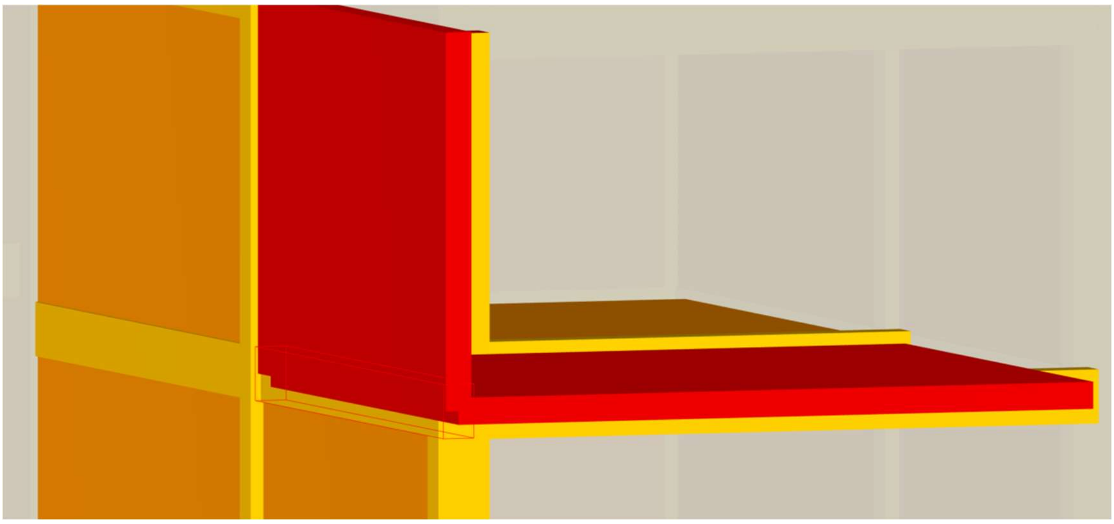


Figure E.4: Floor-wall overlap view

Appendix F: Typical Building Drawings (Color, Tag and Type)

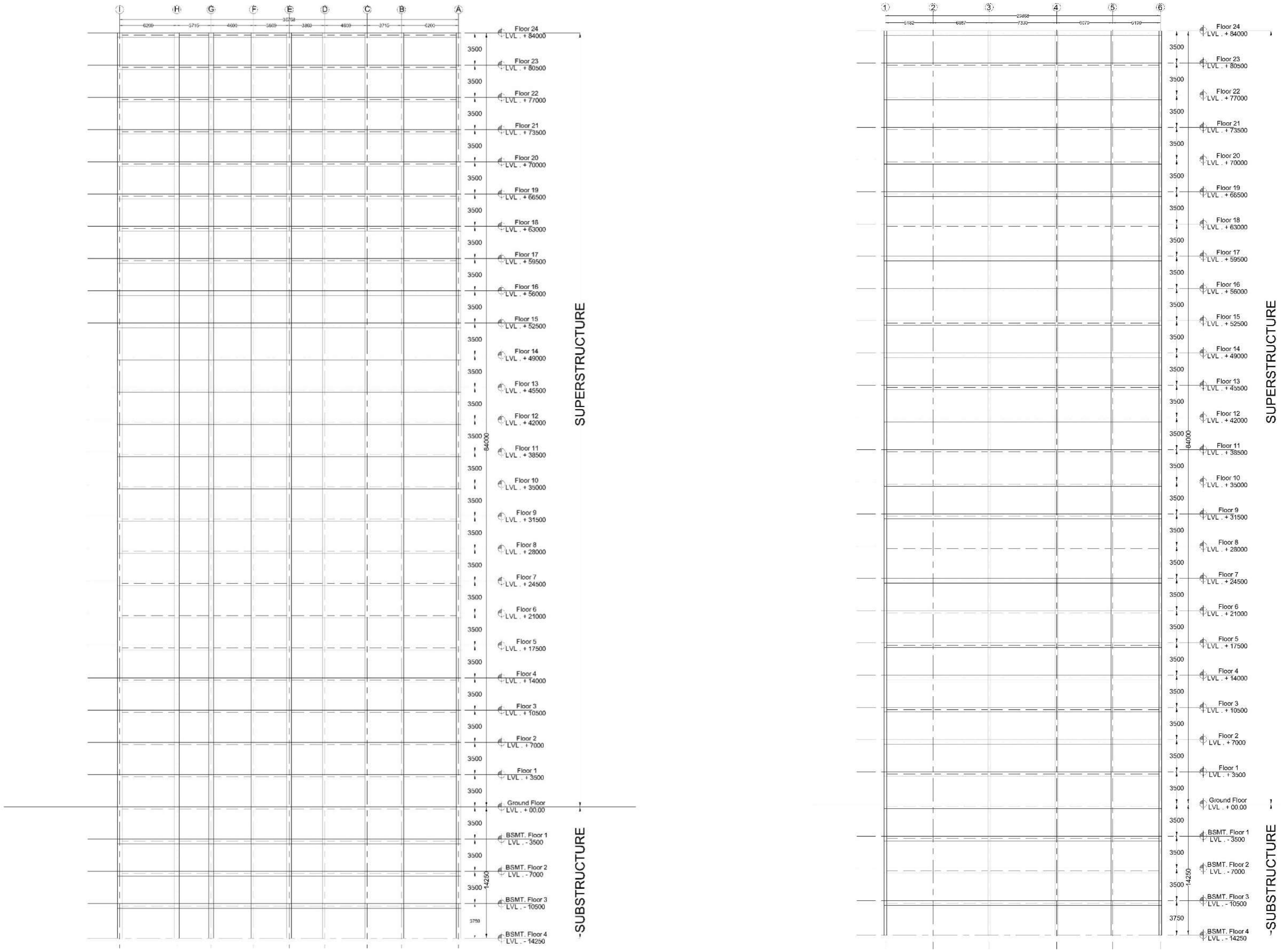
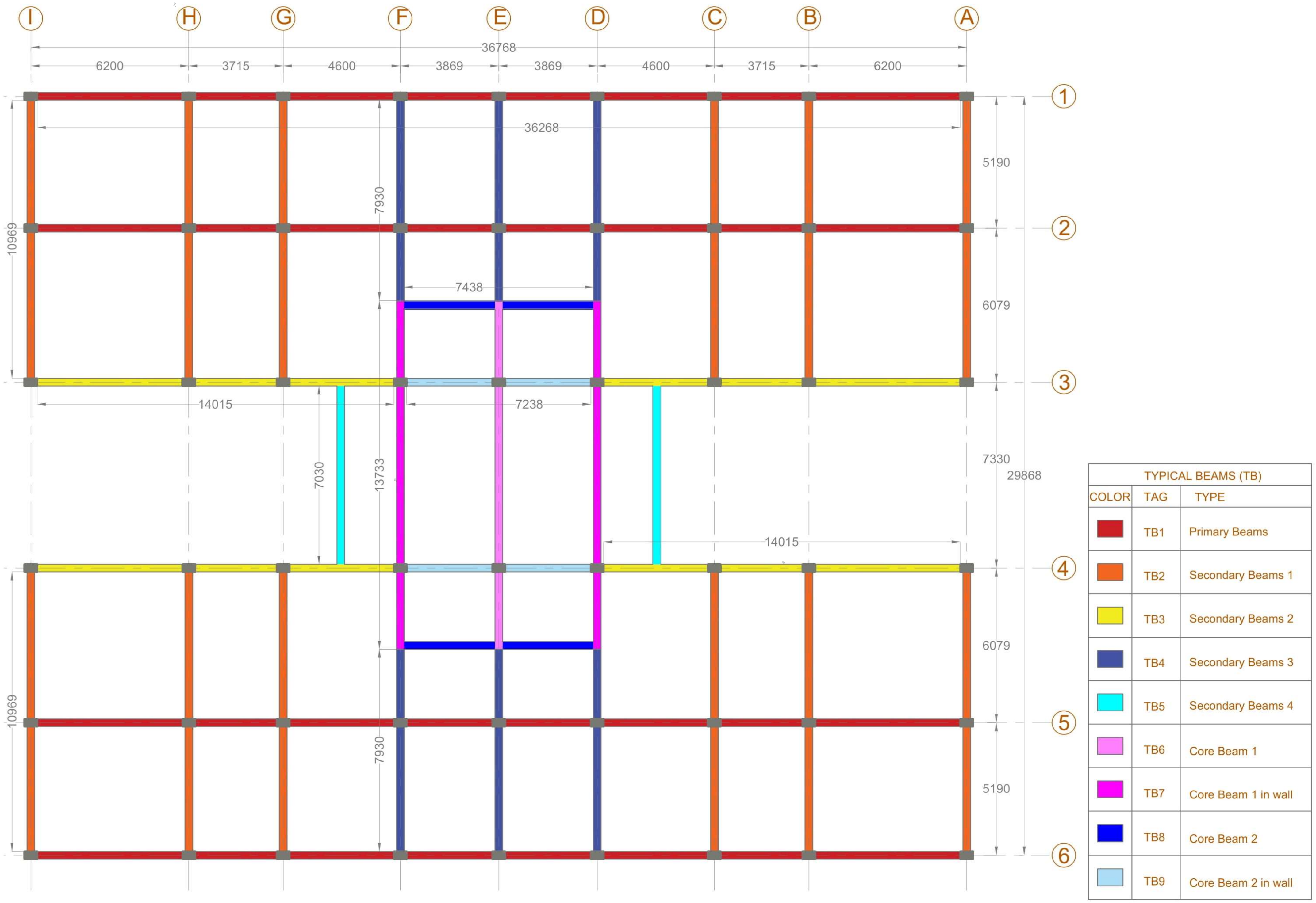


Figure F.1: Building elevation front (left) and side (right)



TYPICAL BEAMS (TB)		
COLOR	TAG	TYPE
🟥	TB1	Primary Beams
🟧	TB2	Secondary Beams 1
🟨	TB3	Secondary Beams 2
🟦	TB4	Secondary Beams 3
■	TB5	Secondary Beams 4
■	TB6	Core Beam 1
🟪	TB7	Core Beam 1 in wall
■	TB8	Core Beam 2
■	TB9	Core Beam 2 in wall

Figure F.2: Typical Beams (Colour, Tag and Type)

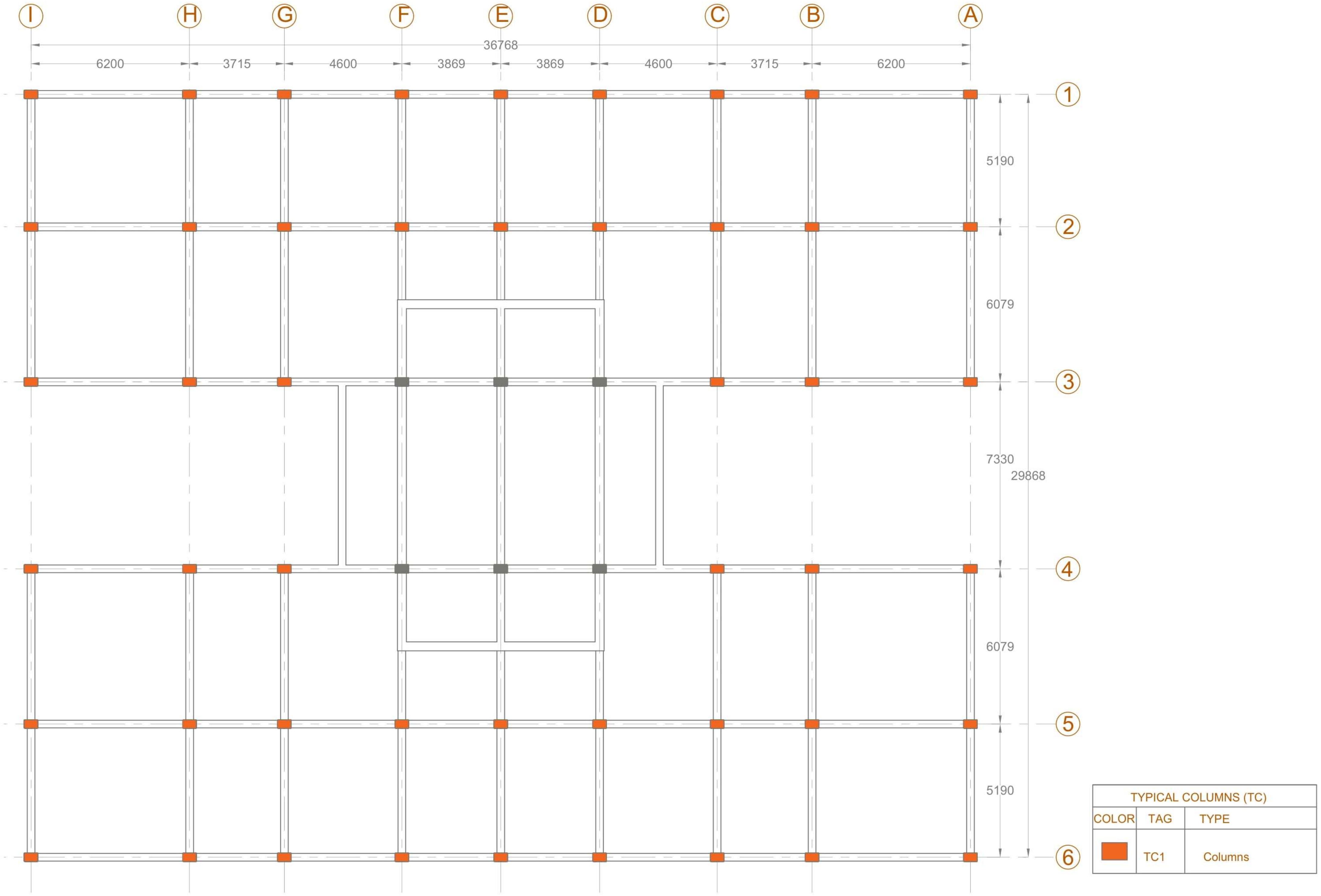


Figure F.3: Typical Columns (Colour, Tag and Type)

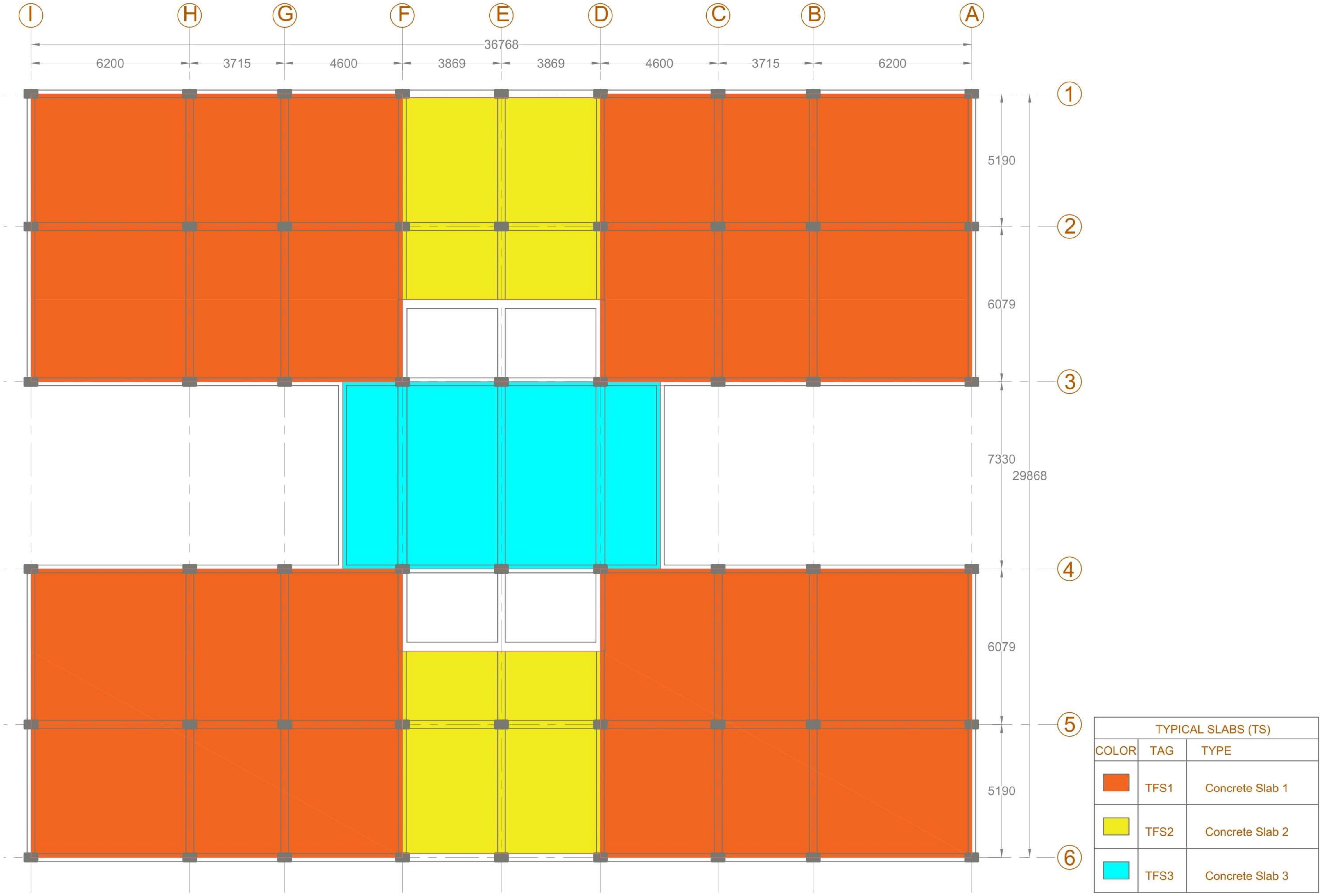


Figure F.4: Typical Slabs (Colour, Tag and Type)

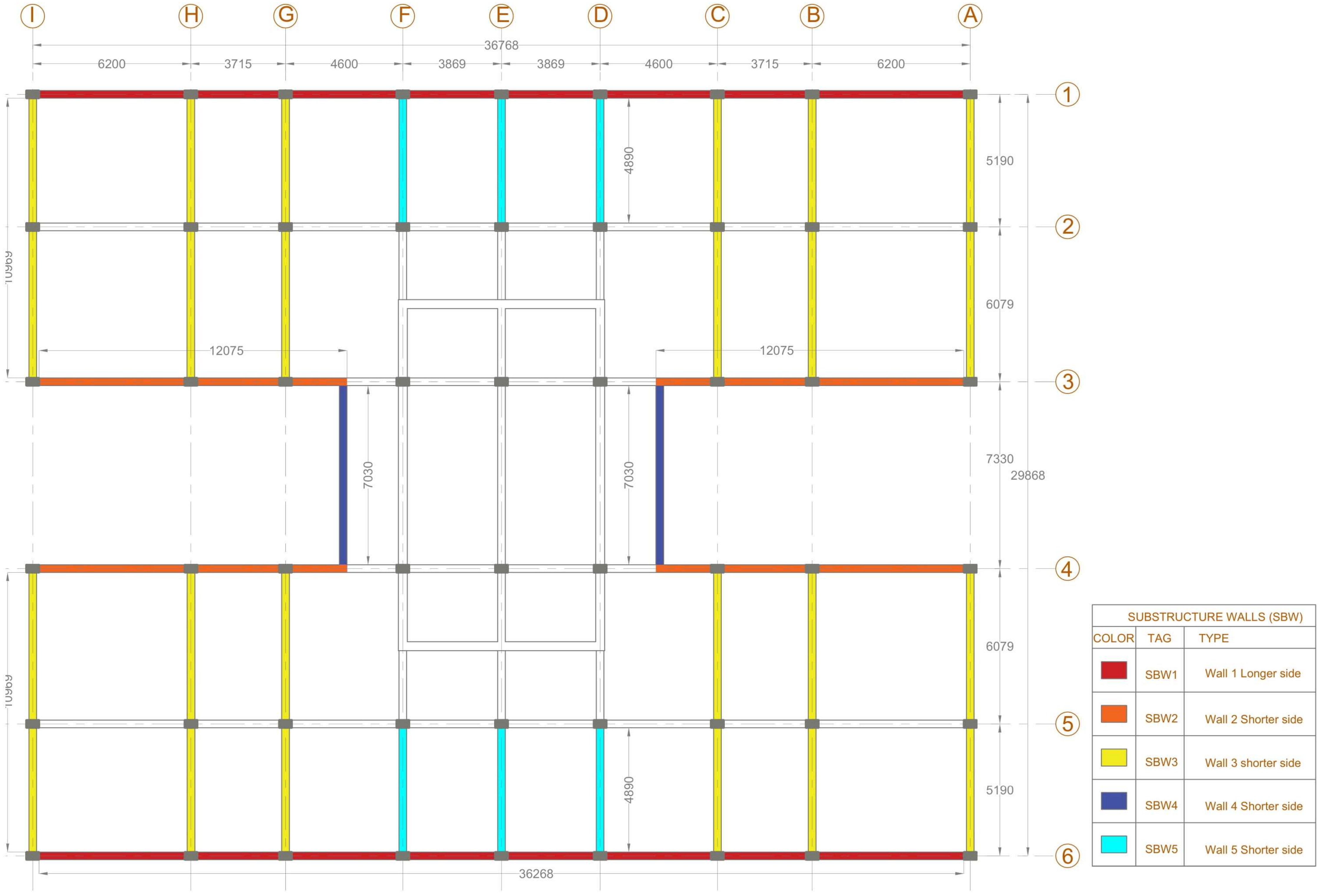
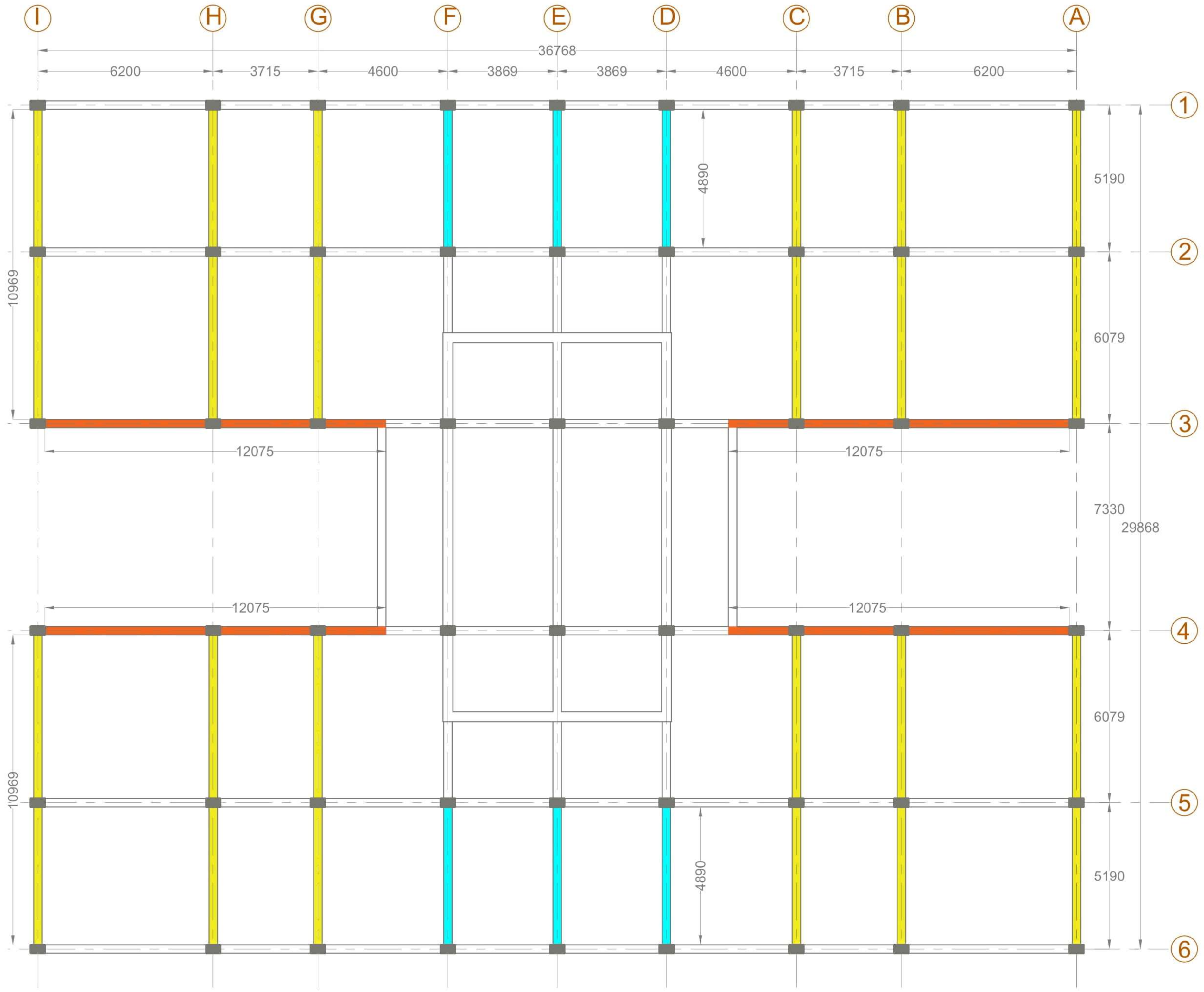


Figure F.5: Substructure walls (Colour, Tag and Type)



SUPERSTRUCTURE WALLS (SPW)		
COLOR	TAG	TYPE
🟨	SPW1	Wall 1
🟦	SPW2	Wall 2
🟧	SPW3	Wall 3

Figure F.6: Substructure walls (Colour, Tag and Type)

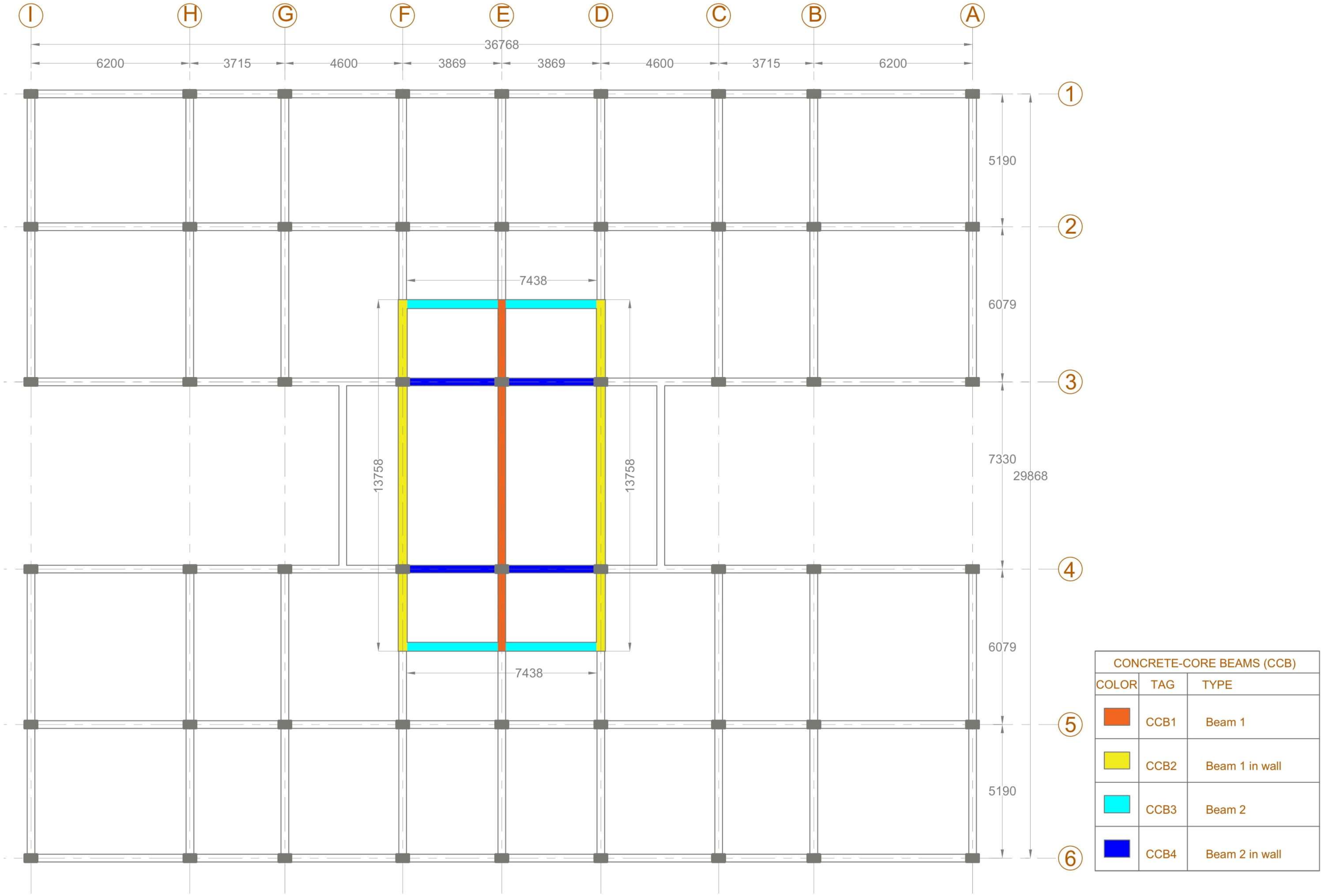


Figure F.7: Concrete-core beams (Colour, Tag and Type)

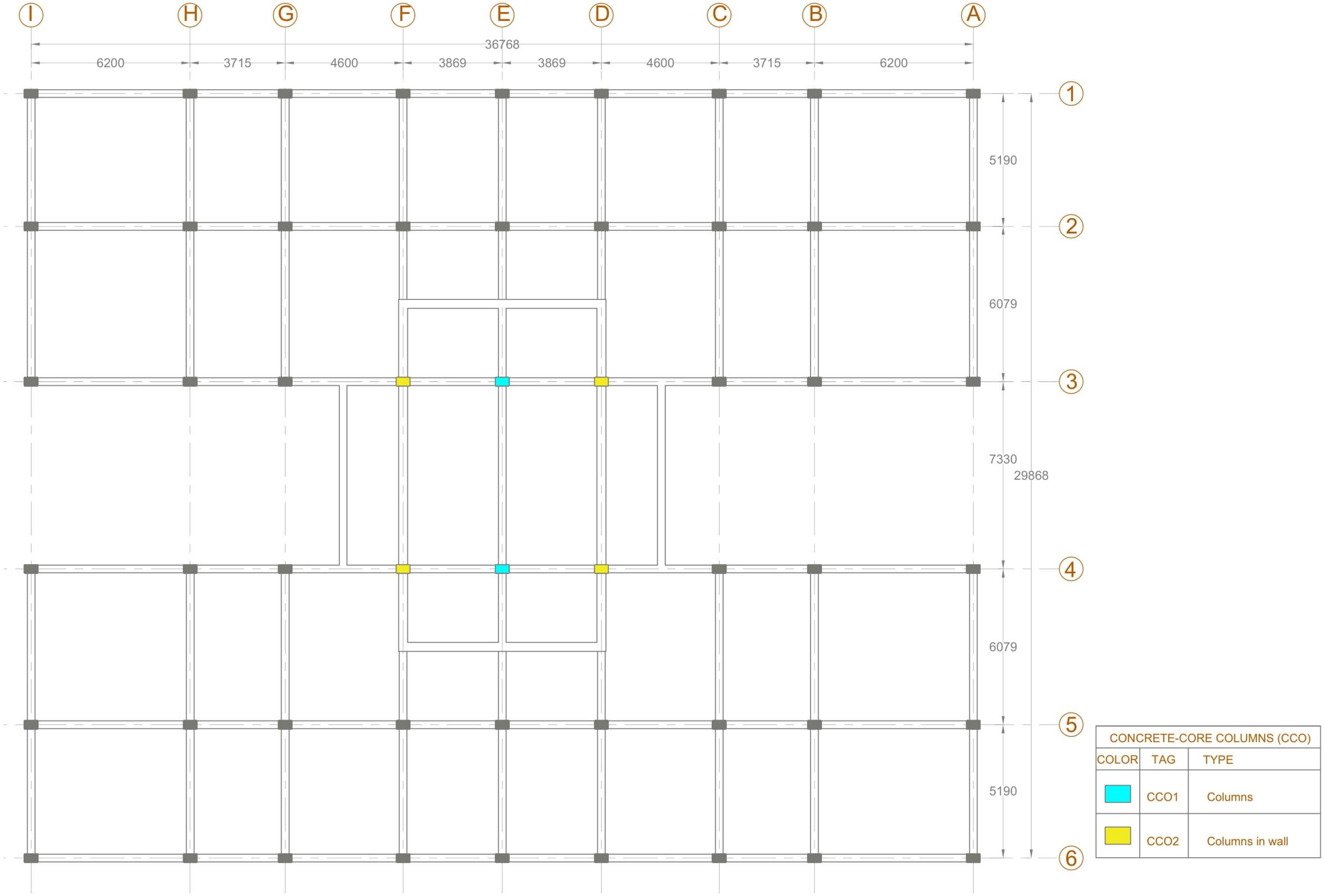


Figure F.8: Concrete-core columns (Colour, Tag and Type)

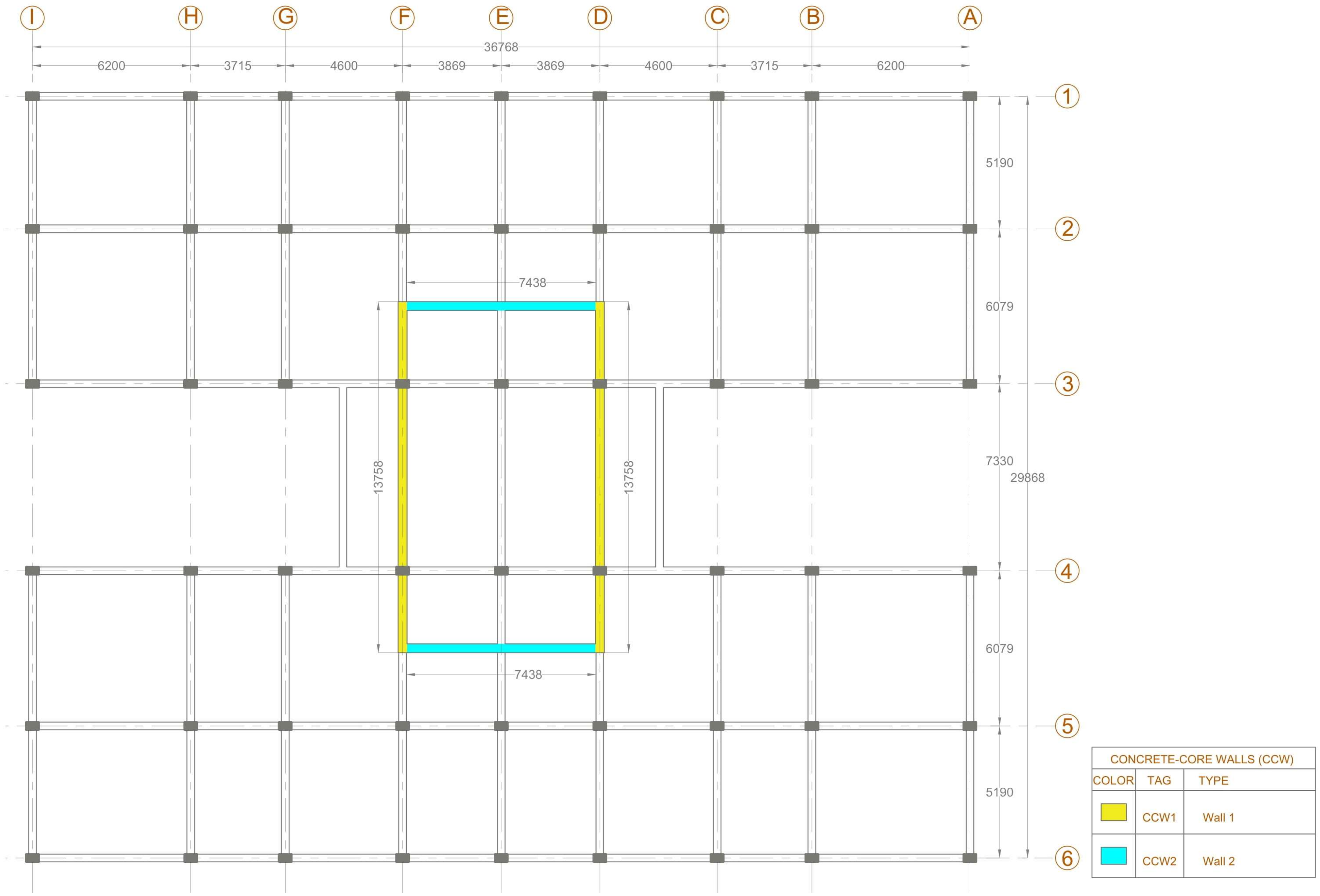
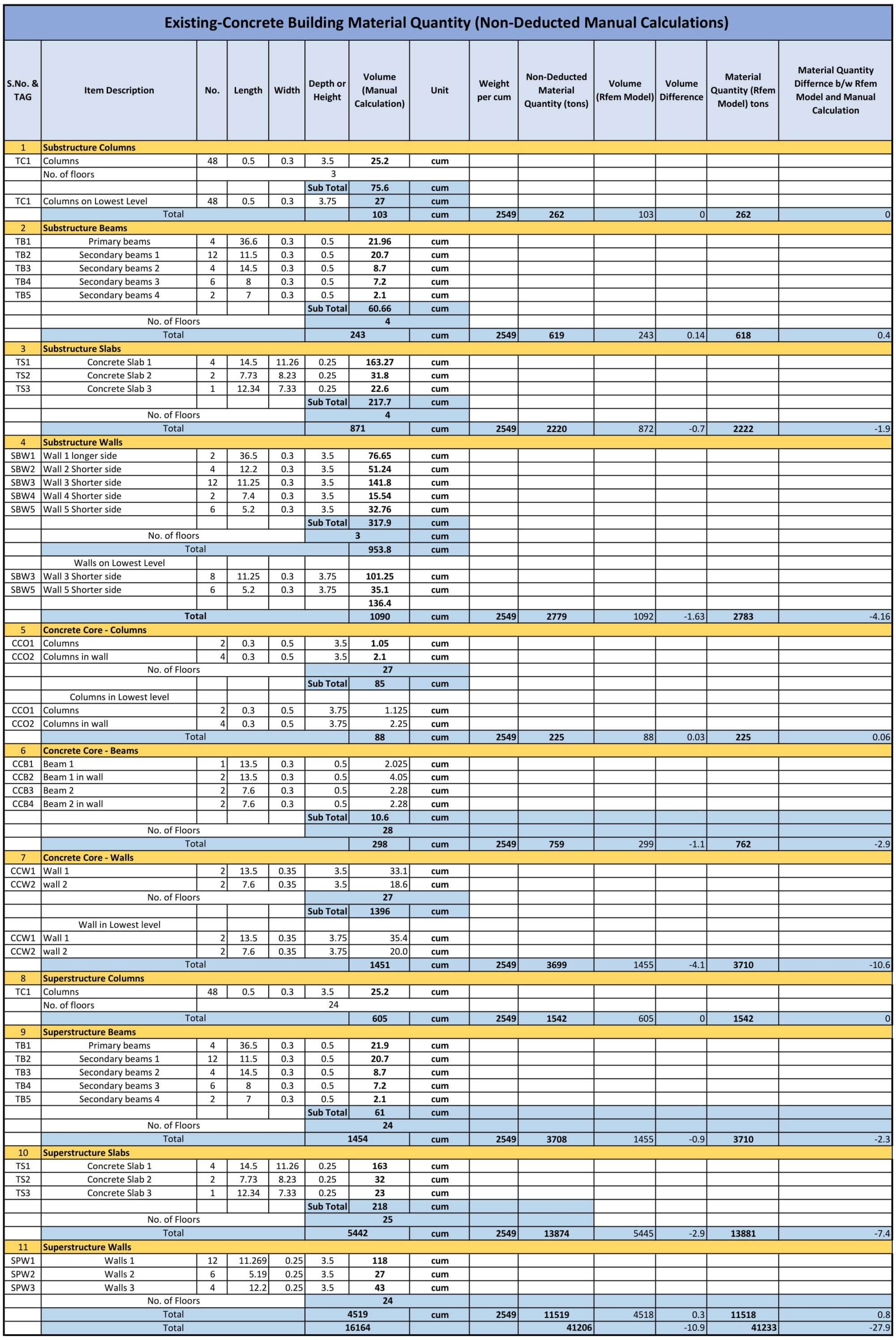


Figure F.9: Concrete-core walls (Colour, Tag and Type)

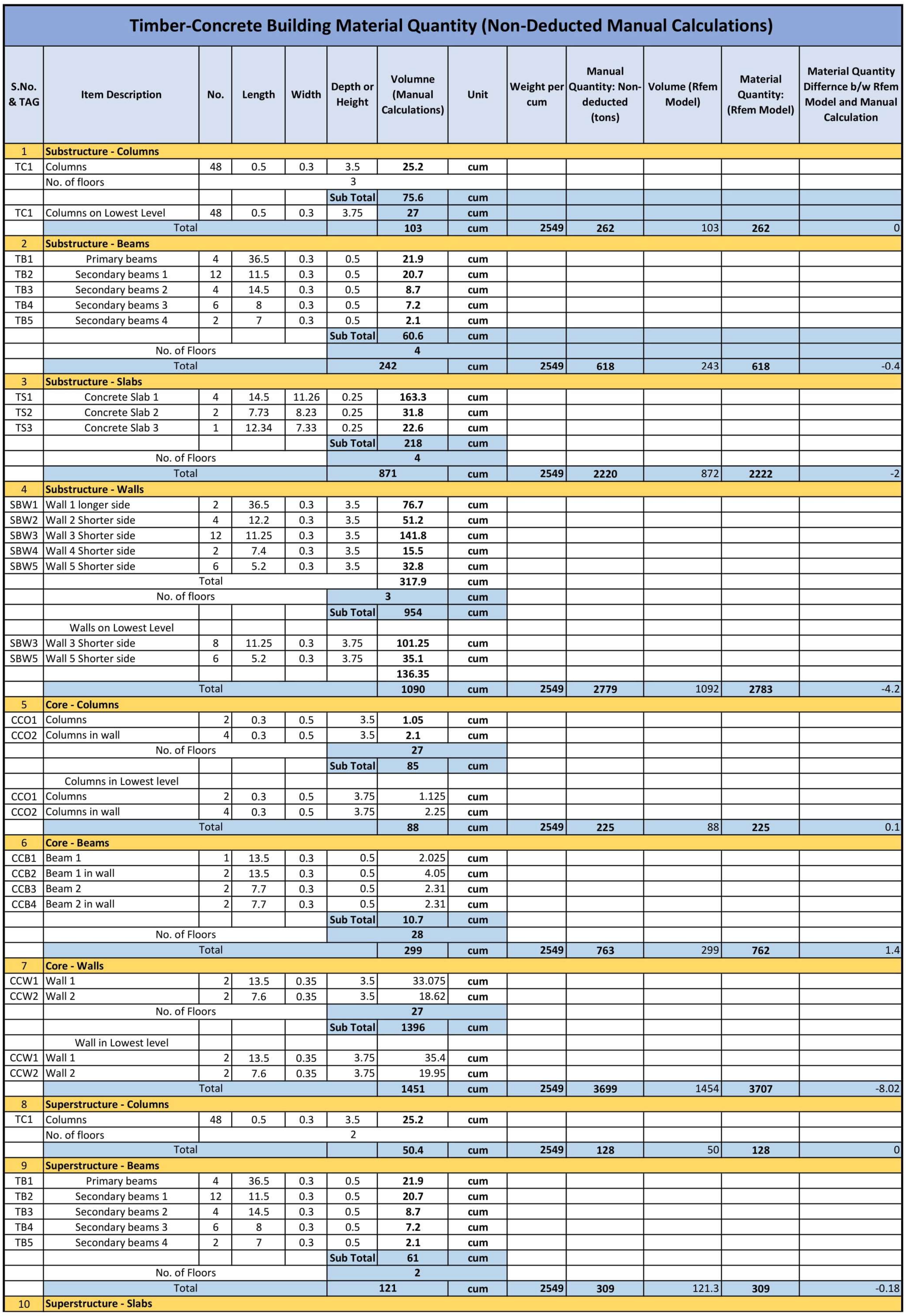
Appendix G: Manual Calculations – ECB and TCB data



Existing-Concrete Building Material Quantity (Non-Deducted Manual Calculations)

S.No. & TAG	Item Description	No.	Length	Width	Depth or Height	Volume (Manual Calculation)	Unit	Weight per cum	Non-Deducted Material Quantity (tons)	Volume (Rfem Model)	Volume Difference	Material Quantity (Rfem Model) tons	Material Quantity Differnce b/w Rfem Model and Manual Calculation
1	**Substructure Columns**												
TC1	Columns	48	0.5	0.3	3.5	**25.2**	cum						
	No. of floors				3								
					Sub Total	**75.6**	cum						
TC1	Columns on Lowest Level	48	0.5	0.3	3.75	**27**	cum						
	Total					**103**	cum	**2549**	**262**	103	0	**262**	0
2	**Substructure Beams**												
TB1	Primary beams	4	36.6	0.3	0.5	**21.96**	cum						
TB2	Secondary beams 1	12	11.5	0.3	0.5	**20.7**	cum						
TB3	Secondary beams 2	4	14.5	0.3	0.5	**8.7**	cum						
TB4	Secondary beams 3	6	8	0.3	0.5	**7.2**	cum						
TB5	Secondary beams 4	2	7	0.3	0.5	**2.1**	cum						
					Sub Total	**60.66**	cum						
	No. of Floors					**4**							
	Total					**243**	cum	**2549**	**619**	243	0.14	**618**	0.4
3	**Substructure Slabs**												
TS1	Concrete Slab 1	4	14.5	11.26	0.25	**163.27**	cum						
TS2	Concrete Slab 2	2	7.73	8.23	0.25	**31.8**	cum						
TS3	Concrete Slab 3	1	12.34	7.33	0.25	**22.6**	cum						
					Sub Total	**217.7**	cum						
	No. of Floors					**4**							
	Total					**871**	cum	**2549**	**2220**	872	-0.7	**2222**	-1.9
4	**Substructure Walls**												
SBW1	Wall 1 longer side	2	36.5	0.3	3.5	**76.65**	cum						
SBW2	Wall 2 Shorter side	4	12.2	0.3	3.5	**51.24**	cum						
SBW3	Wall 3 Shorter side	12	11.25	0.3	3.5	**141.8**	cum						
SBW4	Wall 4 Shorter side	2	7.4	0.3	3.5	**15.54**	cum						
SBW5	Wall 5 Shorter side	6	5.2	0.3	3.5	**32.76**	cum						
					Sub Total	**317.9**	cum						
	No. of floors					**3**	cum						
	Total					**953.8**	cum						
	Walls on Lowest Level												
SBW3	Wall 3 Shorter side	8	11.25	0.3	3.75	**101.25**	cum						
SBW5	Wall 5 Shorter side	6	5.2	0.3	3.75	**35.1**	cum						
						136.4							
	Total					**1090**	cum	**2549**	**2779**	1092	-1.63	**2783**	-4.16
5	**Concrete Core - Columns**												
CCO1	Columns	2	0.3	0.5	3.5	**1.05**	cum						
CCO2	Columns in wall	4	0.3	0.5	3.5	**2.1**	cum						
	No. of Floors					**27**							
					Sub Total	**85**	cum						
	Columns in Lowest level												
CCO1	Columns	2	0.3	0.5	3.75	1.125	cum						
CCO2	Columns in wall	4	0.3	0.5	3.75	2.25	cum						
	Total					**88**	cum	**2549**	**225**	88	0.03	**225**	0.06
6	**Concrete Core - Beams**												
CCB1	Beam 1	1	13.5	0.3	0.5	2.025	cum						
CCB2	Beam 1 in wall	2	13.5	0.3	0.5	4.05	cum						
CCB3	Beam 2	2	7.6	0.3	0.5	2.28	cum						
CCB4	Beam 2 in wall	2	7.6	0.3	0.5	2.28	cum						
					Sub Total	**10.6**	cum						
	No. of Floors					**28**							
	Total					**298**	cum	**2549**	**759**	299	-1.1	**762**	-2.9
7	**Concrete Core - Walls**												
CCW1	Wall 1	2	13.5	0.35	3.5	33.1	cum						
CCW2	wall 2	2	7.6	0.35	3.5	18.6	cum						
	No. of Floors					**27**							
					Sub Total	**1396**	cum						
	Wall in Lowest level												
CCW1	Wall 1	2	13.5	0.35	3.75	35.4	cum						
CCW2	wall 2	2	7.6	0.35	3.75	20.0	cum						
	Total					**1451**	cum	**2549**	**3699**	1455	-4.1	**3710**	-10.6
8	**Superstructure Columns**												
TC1	Columns	48	0.5	0.3	3.5	**25.2**	cum						
	No. of floors				24								
	Total					**605**	cum	**2549**	**1542**	605	0	**1542**	0
9	**Superstructure Beams**												
TB1	Primary beams	4	36.5	0.3	0.5	**21.9**	cum						
TB2	Secondary beams 1	12	11.5	0.3	0.5	**20.7**	cum						
TB3	Secondary beams 2	4	14.5	0.3	0.5	**8.7**	cum						
TB4	Secondary beams 3	6	8	0.3	0.5	**7.2**	cum						
TB5	Secondary beams 4	2	7	0.3	0.5	**2.1**	cum						
					Sub Total	**61**	cum						
	No. of Floors					**24**							
	Total					**1454**	cum	**2549**	**3708**	1455	-0.9	**3710**	-2.3
10	**Superstructure Slabs**												
TS1	Concrete Slab 1	4	14.5	11.26	0.25	**163**	cum						
TS2	Concrete Slab 2	2	7.73	8.23	0.25	**32**	cum						
TS3	Concrete Slab 3	1	12.34	7.33	0.25	**23**	cum						
					Sub Total	**218**	cum						
	No. of Floors					**25**							
	Total					**5442**	cum	**2549**	**13874**	5445	-2.9	**13881**	-7.4
11	**Superstructure Walls**												
SPW1	Walls 1	12	11.269	0.25	3.5	**118**	cum						
SPW2	Walls 2	6	5.19	0.25	3.5	**27**	cum						
SPW3	Walls 3	4	12.2	0.25	3.5	**43**	cum						
	No. of Floors					**24**							
	Total					**4519**	cum	**2549**	**11519**	4518	0.3	**11518**	0.8
	Total					**16164**			**41206**		-10.9	**41233**	-27.9

Figure G.1: Existing-concrete building material quantities (non-deducted manual calculations)



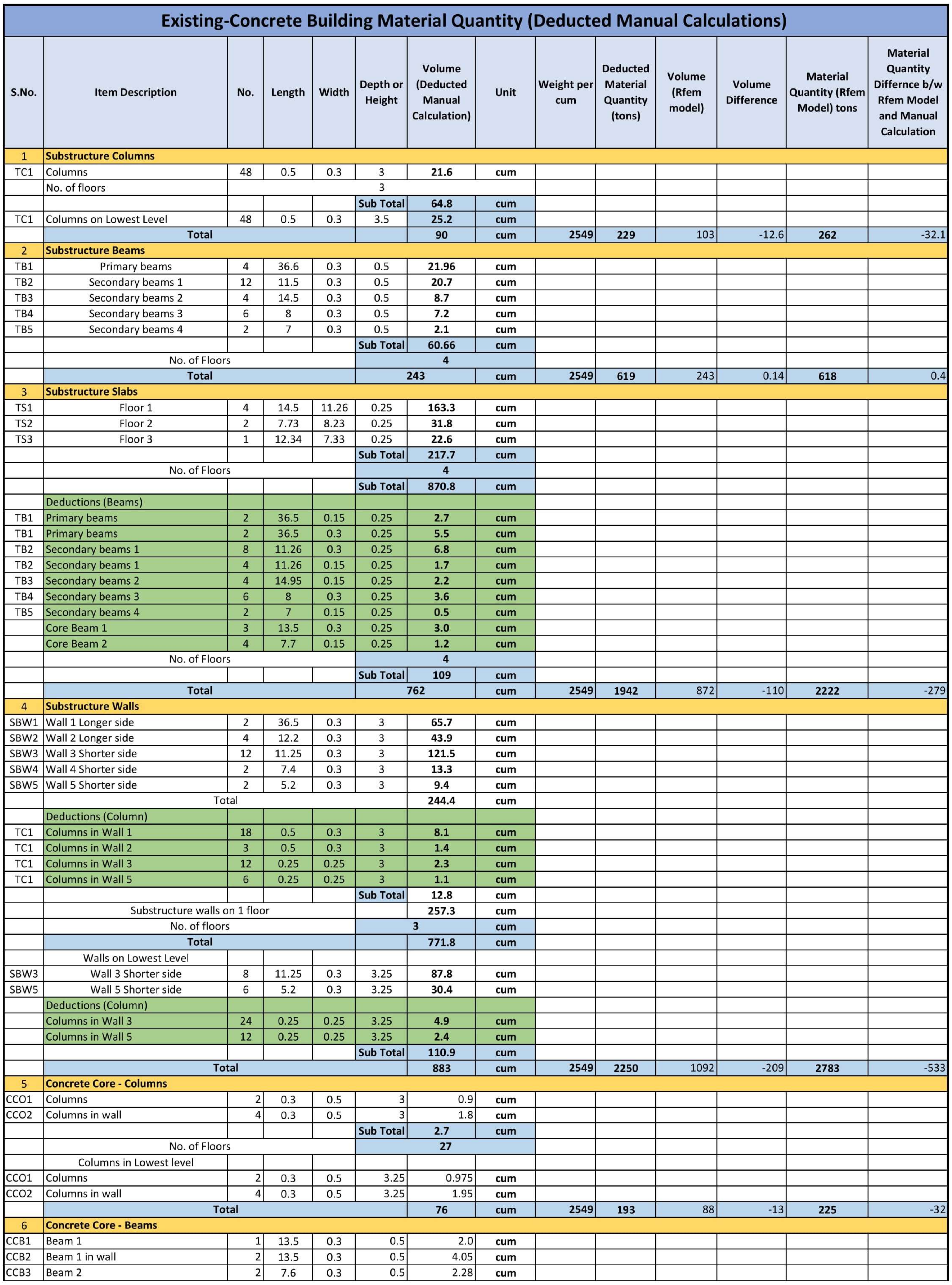
Timber-Concrete Building Material Quantity (Non-Deducted Manual Calculations)

S.No. & TAG	Item Description	No.	Length	Width	Depth or Height	Volumne (Manual Calculations)	Unit	Weight per cum	Manual Quantity: Non-deducted (tons)	Volume (Rfem Model)	Material Quantity: (Rfem Model)	Material Quantity Differnce b/w Rfem Model and Manual Calculation
1	**Substructure - Columns**											
TC1	Columns	48	0.5	0.3	3.5	25.2	cum					
	No. of floors				3							
					Sub Total	75.6	cum					
TC1	Columns on Lowest Level	48	0.5	0.3	3.75	27	cum					
	Total					103	cum	2549	262	103	262	0
2	**Substructure - Beams**											
TB1	Primary beams	4	36.5	0.3	0.5	21.9	cum					
TB2	Secondary beams 1	12	11.5	0.3	0.5	20.7	cum					
TB3	Secondary beams 2	4	14.5	0.3	0.5	8.7	cum					
TB4	Secondary beams 3	6	8	0.3	0.5	7.2	cum					
TB5	Secondary beams 4	2	7	0.3	0.5	2.1	cum					
					Sub Total	60.6	cum					
	No. of Floors					4						
	Total					242	cum	2549	618	243	618	-0.4
3	**Substructure - Slabs**											
TS1	Concrete Slab 1	4	14.5	11.26	0.25	163.3	cum					
TS2	Concrete Slab 2	2	7.73	8.23	0.25	31.8	cum					
TS3	Concrete Slab 3	1	12.34	7.33	0.25	22.6	cum					
					Sub Total	218	cum					
	No. of Floors					4						
	Total					871	cum	2549	2220	872	2222	-2
4	**Substructure - Walls**											
SBW1	Wall 1 longer side	2	36.5	0.3	3.5	76.7	cum					
SBW2	Wall 2 Shorter side	4	12.2	0.3	3.5	51.2	cum					
SBW3	Wall 3 Shorter side	12	11.25	0.3	3.5	141.8	cum					
SBW4	Wall 4 Shorter side	2	7.4	0.3	3.5	15.5	cum					
SBW5	Wall 5 Shorter side	6	5.2	0.3	3.5	32.8	cum					
	Total					317.9	cum					
	No. of floors					3	cum					
					Sub Total	954	cum					
	Walls on Lowest Level											
SBW3	Wall 3 Shorter side	8	11.25	0.3	3.75	101.25	cum					
SBW5	Wall 5 Shorter side	6	5.2	0.3	3.75	35.1	cum					
						136.35						
	Total					1090	cum	2549	2779	1092	2783	-4.2
5	**Core - Columns**											
CCO1	Columns	2	0.3	0.5	3.5	1.05	cum					
CCO2	Columns in wall	4	0.3	0.5	3.5	2.1	cum					
	No. of Floors					27						
					Sub Total	85	cum					
	Columns in Lowest level											
CCO1	Columns	2	0.3	0.5	3.75	1.125	cum					
CCO2	Columns in wall	4	0.3	0.5	3.75	2.25	cum					
	Total					88	cum	2549	225	88	225	0.1
6	**Core - Beams**											
CCB1	Beam 1	1	13.5	0.3	0.5	2.025	cum					
CCB2	Beam 1 in wall	2	13.5	0.3	0.5	4.05	cum					
CCB3	Beam 2	2	7.7	0.3	0.5	2.31	cum					
CCB4	Beam 2 in wall	2	7.7	0.3	0.5	2.31	cum					
					Sub Total	10.7	cum					
	No. of Floors					28						
	Total					299	cum	2549	763	299	762	1.4
7	**Core - Walls**											
CCW1	Wall 1	2	13.5	0.35	3.5	33.075	cum					
CCW2	Wall 2	2	7.6	0.35	3.5	18.62	cum					
	No. of Floors					27						
					Sub Total	1396	cum					
	Wall in Lowest level											
CCW1	Wall 1	2	13.5	0.35	3.75	35.4	cum					
CCW2	Wall 2	2	7.6	0.35	3.75	19.95	cum					
	Total					1451	cum	2549	3699	1454	3707	-8.02
8	**Superstructure - Columns**											
TC1	Columns	48	0.5	0.3	3.5	25.2	cum					
	No. of floors				2							
	Total					50.4	cum	2549	128	50	128	0
9	**Superstructure - Beams**											
TB1	Primary beams	4	36.5	0.3	0.5	21.9	cum					
TB2	Secondary beams 1	12	11.5	0.3	0.5	20.7	cum					
TB3	Secondary beams 2	4	14.5	0.3	0.5	8.7	cum					
TB4	Secondary beams 3	6	8	0.3	0.5	7.2	cum					
TB5	Secondary beams 4	2	7	0.3	0.5	2.1	cum					
					Sub Total	61	cum					
	No. of Floors					2						
	Total					121	cum	2549	309	121.3	309	-0.18
10	**Superstructure - Slabs**											

Figure G.2.1: Timber-concrete building material quantities (non-deducted manual calculations)

TS1	Floor 1	4	14.5	11.26	0.25	**163.3**	**cum**					
TS2	Floor 2	2	7.73	8.23	0.25	**31.8**	**cum**					
TS3	Floor 3	1	12.34	7.33	0.25	**22.6**	**cum**					
					Sub Total	**217.7**	**cum**					
	No. of Floors				**2**							
	Total					**435**	**cum**	**2549**	**1110**	436	**1111**	-0.8
11	**Superstructure - Walls**											
SPW1	Walls 1	12	11.269	0.3	3.5	**142.0**	**cum**					
SPW2	Walls 2	6	5.19	0.3	3.5	**32.7**	**cum**					
SPW3	Walls 3	4	12.2	0.3	3.5	**51.2**	**cum**					
	Total quantity in 1 floor				**225.9**							
	No. of Floors				**2**							
	Total				**452**		**cum**	**2549**	**1152**	452	**1152**	0.1
	Timber Structure											
	Glulam Components											
12	**Superstructure - Columns**											
TC1	Columns	48	0.5	0.3	3.5	**25.2**	**cum**					
	No. of floors	22										
	Total					**554**	**cum**	**430**	**238**	554	**238**	0.17
13	**Superstructure - Beams**											
TB1	Primary beams	4	36.6	0.3	0.5	**21.96**	**cum**					
TB2	Secondary beams 1	12	11.5	0.3	0.5	**20.7**	**cum**					
TB3	Secondary beams 2	4	14.5	0.3	0.5	**8.7**	**cum**					
TB4	Secondary beams 3	6	8	0.3	0.5	**7.2**	**cum**					
TB5	Secondary beams 4	2	7	0.3	0.5	**2.1**	**cum**					
					Sub Total	**60.7**	**cum**					
	No. of Floors				**22**							
	Total				**1335**		**cum**	**430**	**574**	1334	**574**	0.19
	CLT Components											
14	**Superstructure - Slabs**											
TS1	Floor 1	4	14.5	11.26	0.25	**163.3**	**cum**					
TS2	Floor 2	2	7.73	8.23	0.25	**31.8**	**cum**					
TS3	Floor 3	1	12.34	7.33	0.25	**22.6**	**cum**					
					Sub Total	**217.7**	**cum**					
	No. of Floors				**22**							
	Total				**4789**		**cum**	**520**	**2490**	4792	**2492**	-1.2
15	**Superstructure - Walls**											
SPW1	Walls 1	12	11.2	0.25	3.5	**117.6**	**cum**					
SPW2	Walls 2	6	5.3	0.25	3.5	**27.8**	**cum**					
SPW3	Walls 3	4	12.25	0.25	3.5	**42.9**	**cum**					
					Sub Total	**188.3**	**cum**					
	No. of Floors				**22**							
	Total				**4143**			**520**	**2154**	4142	**2154**	0.5
	Total					**16025**			**18723**	16031	**18737**	-14

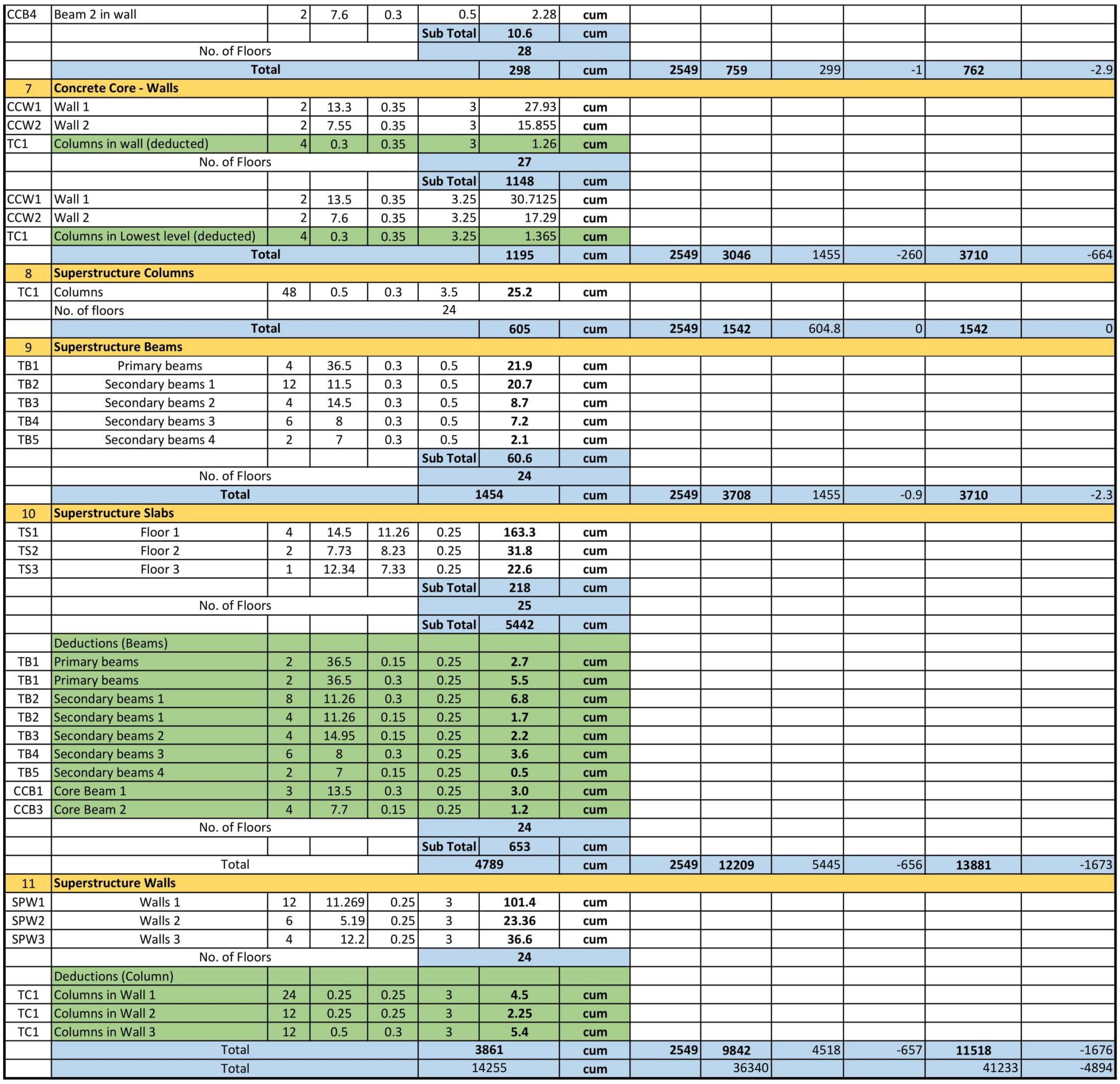
Figure G.2.2: Timber-concrete building material quantities (non-deducted manual calculations)



Existing-Concrete Building Material Quantity (Deducted Manual Calculations)

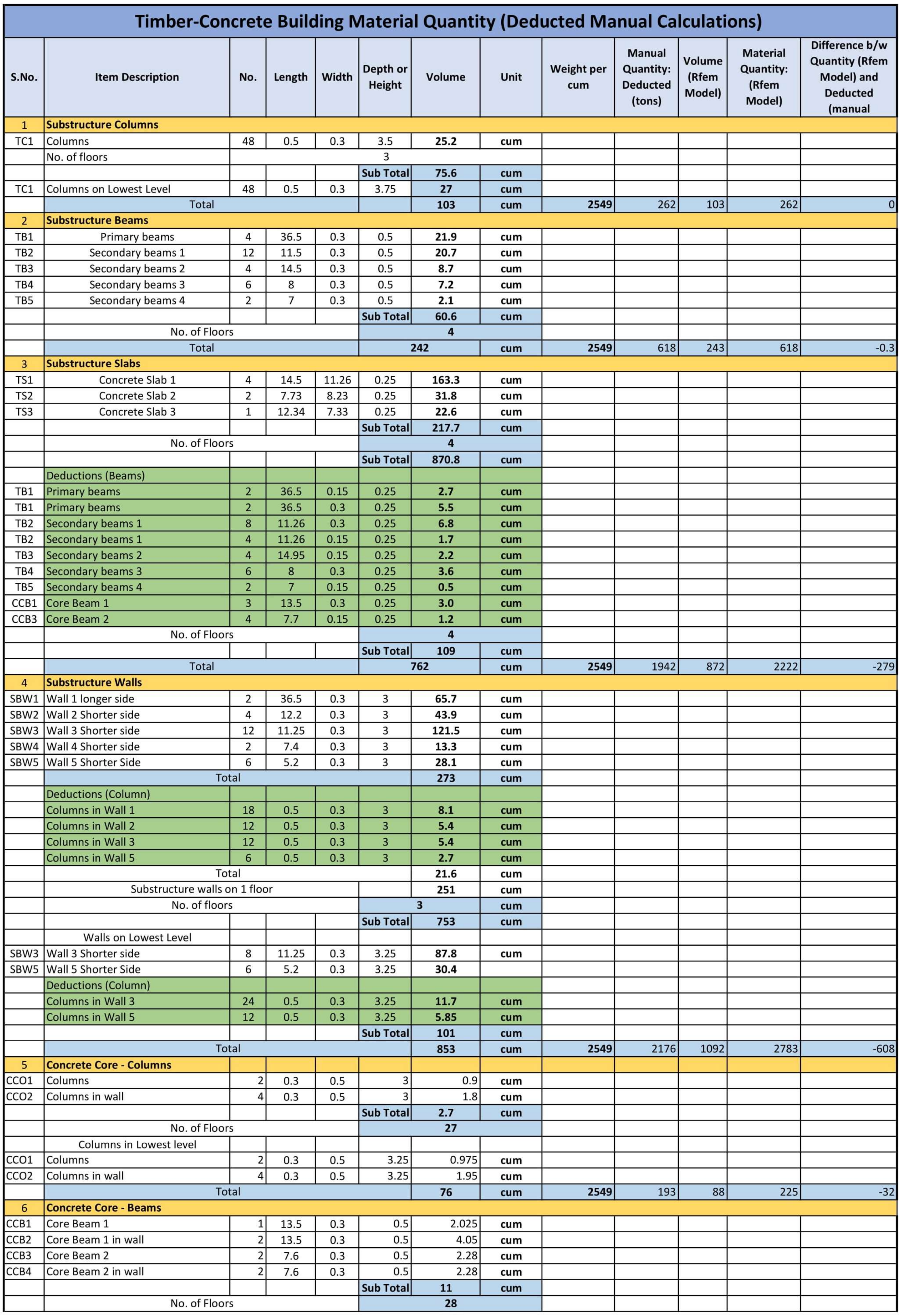
S.No.	Item Description	No.	Length	Width	Depth or Height	Volume (Deducted Manual Calculation)	Unit	Weight per cum	Deducted Material Quantity (tons)	Volume (Rfem model)	Volume Difference	Material Quantity (Rfem Model) tons	Material Quantity Differnce b/w Rfem Model and Manual Calculation
1	**Substructure Columns**												
TC1	Columns	48	0.5	0.3	3	**21.6**	**cum**						
	No. of floors	3											
					Sub Total	**64.8**	**cum**						
TC1	Columns on Lowest Level	48	0.5	0.3	3.5	**25.2**	**cum**						
	Total					**90**	**cum**	**2549**	**229**	103	-12.6	**262**	-32.1
2	**Substructure Beams**												
TB1	Primary beams	4	36.6	0.3	0.5	**21.96**	**cum**						
TB2	Secondary beams 1	12	11.5	0.3	0.5	**20.7**	**cum**						
TB3	Secondary beams 2	4	14.5	0.3	0.5	**8.7**	**cum**						
TB4	Secondary beams 3	6	8	0.3	0.5	**7.2**	**cum**						
TB5	Secondary beams 4	2	7	0.3	0.5	**2.1**	**cum**						
					Sub Total	**60.66**	**cum**						
	No. of Floors				**4**								
	Total				**243**		**cum**	**2549**	**619**	243	0.14	**618**	0.4
3	**Substructure Slabs**												
TS1	Floor 1	4	14.5	11.26	0.25	**163.3**	**cum**						
TS2	Floor 2	2	7.73	8.23	0.25	**31.8**	**cum**						
TS3	Floor 3	1	12.34	7.33	0.25	**22.6**	**cum**						
					Sub Total	**217.7**	**cum**						
	No. of Floors				**4**								
					Sub Total	**870.8**	**cum**						
	Deductions (Beams)												
TB1	Primary beams	2	36.5	0.15	0.25	**2.7**	**cum**						
TB1	Primary beams	2	36.5	0.3	0.25	**5.5**	**cum**						
TB2	Secondary beams 1	8	11.26	0.3	0.25	**6.8**	**cum**						
TB2	Secondary beams 1	4	11.26	0.15	0.25	**1.7**	**cum**						
TB3	Secondary beams 2	4	14.95	0.15	0.25	**2.2**	**cum**						
TB4	Secondary beams 3	6	8	0.3	0.25	**3.6**	**cum**						
TB5	Secondary beams 4	2	7	0.15	0.25	**0.5**	**cum**						
	Core Beam 1	3	13.5	0.3	0.25	**3.0**	**cum**						
	Core Beam 2	4	7.7	0.15	0.25	**1.2**	**cum**						
	No. of Floors				**4**								
					Sub Total	**109**	**cum**						
	Total				**762**		**cum**	**2549**	**1942**	872	-110	**2222**	-279
4	**Substructure Walls**												
SBW1	Wall 1 Longer side	2	36.5	0.3	3	**65.7**	**cum**						
SBW2	Wall 2 Longer side	4	12.2	0.3	3	**43.9**	**cum**						
SBW3	Wall 3 Shorter side	12	11.25	0.3	3	**121.5**	**cum**						
SBW4	Wall 4 Shorter side	2	7.4	0.3	3	**13.3**	**cum**						
SBW5	Wall 5 Shorter side	2	5.2	0.3	3	**9.4**	**cum**						
	Total					**244.4**	**cum**						
	Deductions (Column)												
TC1	Columns in Wall 1	18	0.5	0.3	3	**8.1**	**cum**						
TC1	Columns in Wall 2	3	0.5	0.3	3	**1.4**	**cum**						
TC1	Columns in Wall 3	12	0.25	0.25	3	**2.3**	**cum**						
TC1	Columns in Wall 5	6	0.25	0.25	3	**1.1**	**cum**						
					Sub Total	**12.8**	**cum**						
	Substructure walls on 1 floor					**257.3**	**cum**						
	No. of floors				**3**		**cum**						
	Total					**771.8**	**cum**						
	Walls on Lowest Level												
SBW3	Wall 3 Shorter side	8	11.25	0.3	3.25	**87.8**	**cum**						
SBW5	Wall 5 Shorter side	6	5.2	0.3	3.25	**30.4**	**cum**						
	Deductions (Column)												
	Columns in Wall 3	24	0.25	0.25	3.25	**4.9**	**cum**						
	Columns in Wall 5	12	0.25	0.25	3.25	**2.4**	**cum**						
					Sub Total	**110.9**	**cum**						
	Total					**883**	**cum**	**2549**	**2250**	1092	-209	**2783**	-533
5	**Concrete Core - Columns**												
CCO1	Columns	2	0.3	0.5	3	0.9	**cum**						
CCO2	Columns in wall	4	0.3	0.5	3	1.8	**cum**						
					Sub Total	**2.7**	**cum**						
	No. of Floors				**27**								
	Columns in Lowest level												
CCO1	Columns	2	0.3	0.5	3.25	0.975	**cum**						
CCO2	Columns in wall	4	0.3	0.5	3.25	1.95	**cum**						
	Total					**76**	**cum**	**2549**	**193**	88	-13	**225**	-32
6	**Concrete Core - Beams**												
CCB1	Beam 1	1	13.5	0.3	0.5	2.0	**cum**						
CCB2	Beam 1 in wall	2	13.5	0.3	0.5	4.05	**cum**						
CCB3	Beam 2	2	7.6	0.3	0.5	2.28	**cum**						

Figure G.3.1: Existing-concrete building material quantities (deducted manual calculations)



CCB4	Beam 2 in wall	2	7.6	0.3	0.5	2.28	**cum**						
					Sub Total	**10.6**	**cum**						
	No. of Floors				**28**								
	Total					**298**	**cum**	**2549**	**759**	299	-1	**762**	-2.9
7	**Concrete Core - Walls**												
CCW1	Wall 1	2	13.3	0.35	3	27.93	**cum**						
CCW2	Wall 2	2	7.55	0.35	3	15.855	**cum**						
TC1	Columns in wall (deducted)	4	0.3	0.35	3	1.26	**cum**						
	No. of Floors				**27**								
					Sub Total	**1148**	**cum**						
CCW1	Wall 1	2	13.5	0.35	3.25	30.7125	**cum**						
CCW2	Wall 2	2	7.6	0.35	3.25	17.29	**cum**						
TC1	Columns in Lowest level (deducted)	4	0.3	0.35	3.25	1.365	**cum**						
	Total					**1195**	**cum**	**2549**	**3046**	1455	-260	**3710**	-664
8	**Superstructure Columns**												
TC1	Columns	48	0.5	0.3	3.5	**25.2**	**cum**						
	No. of floors	24											
	Total					**605**	**cum**	**2549**	**1542**	604.8	0	**1542**	0
9	**Superstructure Beams**												
TB1	Primary beams	4	36.5	0.3	0.5	**21.9**	**cum**						
TB2	Secondary beams 1	12	11.5	0.3	0.5	**20.7**	**cum**						
TB3	Secondary beams 2	4	14.5	0.3	0.5	**8.7**	**cum**						
TB4	Secondary beams 3	6	8	0.3	0.5	**7.2**	**cum**						
TB5	Secondary beams 4	2	7	0.3	0.5	**2.1**	**cum**						
					Sub Total	**60.6**	**cum**						
	No. of Floors				**24**								
	Total				**1454**		**cum**	**2549**	**3708**	1455	-0.9	**3710**	-2.3
10	**Superstructure Slabs**												
TS1	Floor 1	4	14.5	11.26	0.25	**163.3**	**cum**						
TS2	Floor 2	2	7.73	8.23	0.25	**31.8**	**cum**						
TS3	Floor 3	1	12.34	7.33	0.25	**22.6**	**cum**						
					Sub Total	**218**	**cum**						
	No. of Floors				**25**								
					Sub Total	**5442**	**cum**						
	Deductions (Beams)												
TB1	Primary beams	2	36.5	0.15	0.25	**2.7**	**cum**						
TB1	Primary beams	2	36.5	0.3	0.25	**5.5**	**cum**						
TB2	Secondary beams 1	8	11.26	0.3	0.25	**6.8**	**cum**						
TB2	Secondary beams 1	4	11.26	0.15	0.25	**1.7**	**cum**						
TB3	Secondary beams 2	4	14.95	0.15	0.25	**2.2**	**cum**						
TB4	Secondary beams 3	6	8	0.3	0.25	**3.6**	**cum**						
TB5	Secondary beams 4	2	7	0.15	0.25	**0.5**	**cum**						
CCB1	Core Beam 1	3	13.5	0.3	0.25	**3.0**	**cum**						
CCB3	Core Beam 2	4	7.7	0.15	0.25	**1.2**	**cum**						
	No. of Floors				**24**								
					Sub Total	**653**	**cum**						
	Total				**4789**		**cum**	**2549**	**12209**	5445	-656	**13881**	-1673
11	**Superstructure Walls**												
SPW1	Walls 1	12	11.269	0.25	3	**101.4**	**cum**						
SPW2	Walls 2	6	5.19	0.25	3	**23.36**	**cum**						
SPW3	Walls 3	4	12.2	0.25	3	**36.6**	**cum**						
	No. of Floors				**24**								
	Deductions (Column)												
TC1	Columns in Wall 1	24	0.25	0.25	3	**4.5**	**cum**						
TC1	Columns in Wall 2	12	0.25	0.25	3	**2.25**	**cum**						
TC1	Columns in Wall 3	12	0.5	0.3	3	**5.4**	**cum**						
	Total				**3861**		**cum**	**2549**	**9842**	4518	-657	**11518**	-1676
	Total				14255		**cum**		36340			41233	-4894

Figure G.3.2: Existing-concrete building material quantities (Deducted manual calculations)

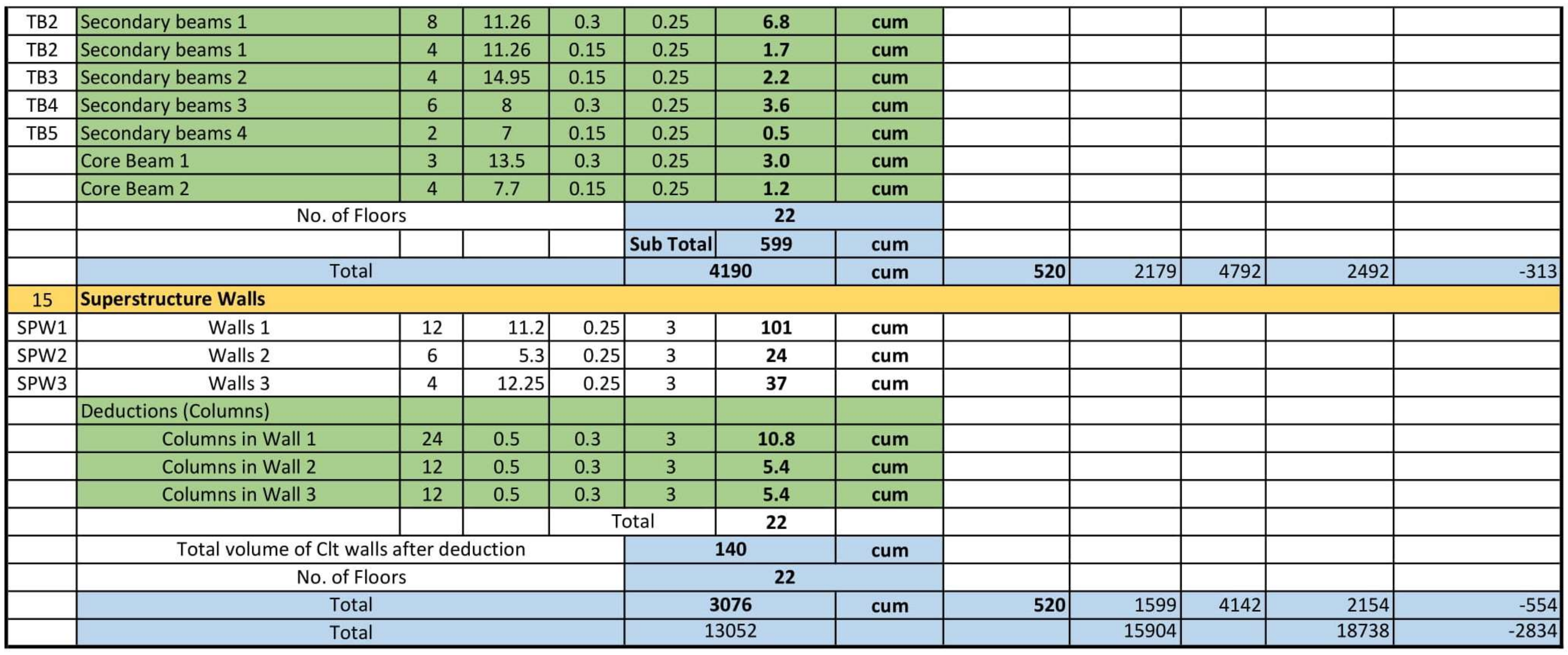


Timber-Concrete Building Material Quantity (Deducted Manual Calculations)												
S.No.	**Item Description**	**No.**	**Length**	**Width**	**Depth or Height**	**Volume**	**Unit**	**Weight per cum**	**Manual Quantity: Deducted (tons)**	**Volume (Rfem Model)**	**Material Quantity: (Rfem Model)**	**Difference b/w Quantity (Rfem Model) and Deducted (manual**
1	**Substructure Columns**											
TC1	Columns	48	0.5	0.3	3.5	**25.2**	**cum**					
	No. of floors	3										
					Sub Total	**75.6**	**cum**					
TC1	Columns on Lowest Level	48	0.5	0.3	3.75	**27**	**cum**					
	Total					**103**	**cum**	**2549**	262	103	262	0
2	**Substructure Beams**											
TB1	Primary beams	4	36.5	0.3	0.5	**21.9**	**cum**					
TB2	Secondary beams 1	12	11.5	0.3	0.5	**20.7**	**cum**					
TB3	Secondary beams 2	4	14.5	0.3	0.5	**8.7**	**cum**					
TB4	Secondary beams 3	6	8	0.3	0.5	**7.2**	**cum**					
TB5	Secondary beams 4	2	7	0.3	0.5	**2.1**	**cum**					
					Sub Total	**60.6**	**cum**					
	No. of Floors				**4**							
	Total				**242**		**cum**	**2549**	618	243	618	-0.3
3	**Substructure Slabs**											
TS1	Concrete Slab 1	4	14.5	11.26	0.25	**163.3**	**cum**					
TS2	Concrete Slab 2	2	7.73	8.23	0.25	**31.8**	**cum**					
TS3	Concrete Slab 3	1	12.34	7.33	0.25	**22.6**	**cum**					
					Sub Total	**217.7**	**cum**					
	No. of Floors				**4**							
					Sub Total	**870.8**	**cum**					
	Deductions (Beams)											
TB1	Primary beams	2	36.5	0.15	0.25	**2.7**	**cum**					
TB1	Primary beams	2	36.5	0.3	0.25	**5.5**	**cum**					
TB2	Secondary beams 1	8	11.26	0.3	0.25	**6.8**	**cum**					
TB2	Secondary beams 1	4	11.26	0.15	0.25	**1.7**	**cum**					
TB3	Secondary beams 2	4	14.95	0.15	0.25	**2.2**	**cum**					
TB4	Secondary beams 3	6	8	0.3	0.25	**3.6**	**cum**					
TB5	Secondary beams 4	2	7	0.15	0.25	**0.5**	**cum**					
CCB1	Core Beam 1	3	13.5	0.3	0.25	**3.0**	**cum**					
CCB3	Core Beam 2	4	7.7	0.15	0.25	**1.2**	**cum**					
	No. of Floors				**4**							
					Sub Total	**109**	**cum**					
	Total				**762**		**cum**	**2549**	1942	872	2222	-279
4	**Substructure Walls**											
SBW1	Wall 1 longer side	2	36.5	0.3	3	**65.7**	**cum**					
SBW2	Wall 2 Shorter side	4	12.2	0.3	3	**43.9**	**cum**					
SBW3	Wall 3 Shorter side	12	11.25	0.3	3	**121.5**	**cum**					
SBW4	Wall 4 Shorter side	2	7.4	0.3	3	**13.3**	**cum**					
SBW5	Wall 5 Shorter Side	6	5.2	0.3	3	**28.1**	**cum**					
	Total					**273**	**cum**					
	Deductions (Column)											
	Columns in Wall 1	18	0.5	0.3	3	**8.1**	**cum**					
	Columns in Wall 2	12	0.5	0.3	3	**5.4**	**cum**					
	Columns in Wall 3	12	0.5	0.3	3	**5.4**	**cum**					
	Columns in Wall 5	6	0.5	0.3	3	**2.7**	**cum**					
	Total					**21.6**	**cum**					
	Substructure walls on 1 floor					**251**	**cum**					
	No. of floors				**3**		**cum**					
					Sub Total	**753**	**cum**					
	Walls on Lowest Level											
SBW3	Wall 3 Shorter side	8	11.25	0.3	3.25	**87.8**	**cum**					
SBW5	Wall 5 Shorter Side	6	5.2	0.3	3.25	**30.4**						
	Deductions (Column)											
	Columns in Wall 3	24	0.5	0.3	3.25	**11.7**	**cum**					
	Columns in Wall 5	12	0.5	0.3	3.25	**5.85**	**cum**					
					Sub Total	**101**	**cum**					
	Total					**853**	**cum**	**2549**	2176	1092	2783	-608
5	**Concrete Core - Columns**											
CCO1	Columns	2	0.3	0.5	3	0.9	**cum**					
CCO2	Columns in wall	4	0.3	0.5	3	1.8	**cum**					
					Sub Total	**2.7**	**cum**					
	No. of Floors				**27**							
	Columns in Lowest level											
CCO1	Columns	2	0.3	0.5	3.25	0.975	**cum**					
CCO2	Columns in wall	4	0.3	0.5	3.25	1.95	**cum**					
	Total					**76**	**cum**	**2549**	193	88	225	-32
6	**Concrete Core - Beams**											
CCB1	Core Beam 1	1	13.5	0.3	0.5	2.025	**cum**					
CCB2	Core Beam 1 in wall	2	13.5	0.3	0.5	4.05	**cum**					
CCB3	Core Beam 2	2	7.6	0.3	0.5	2.28	**cum**					
CCB4	Core Beam 2 in wall	2	7.6	0.3	0.5	2.28	**cum**					
					Sub Total	**11**	**cum**					
	No. of Floors				**28**							

Figure G.4.1: Timber-concrete building material quantities (Deducted manual calculations)

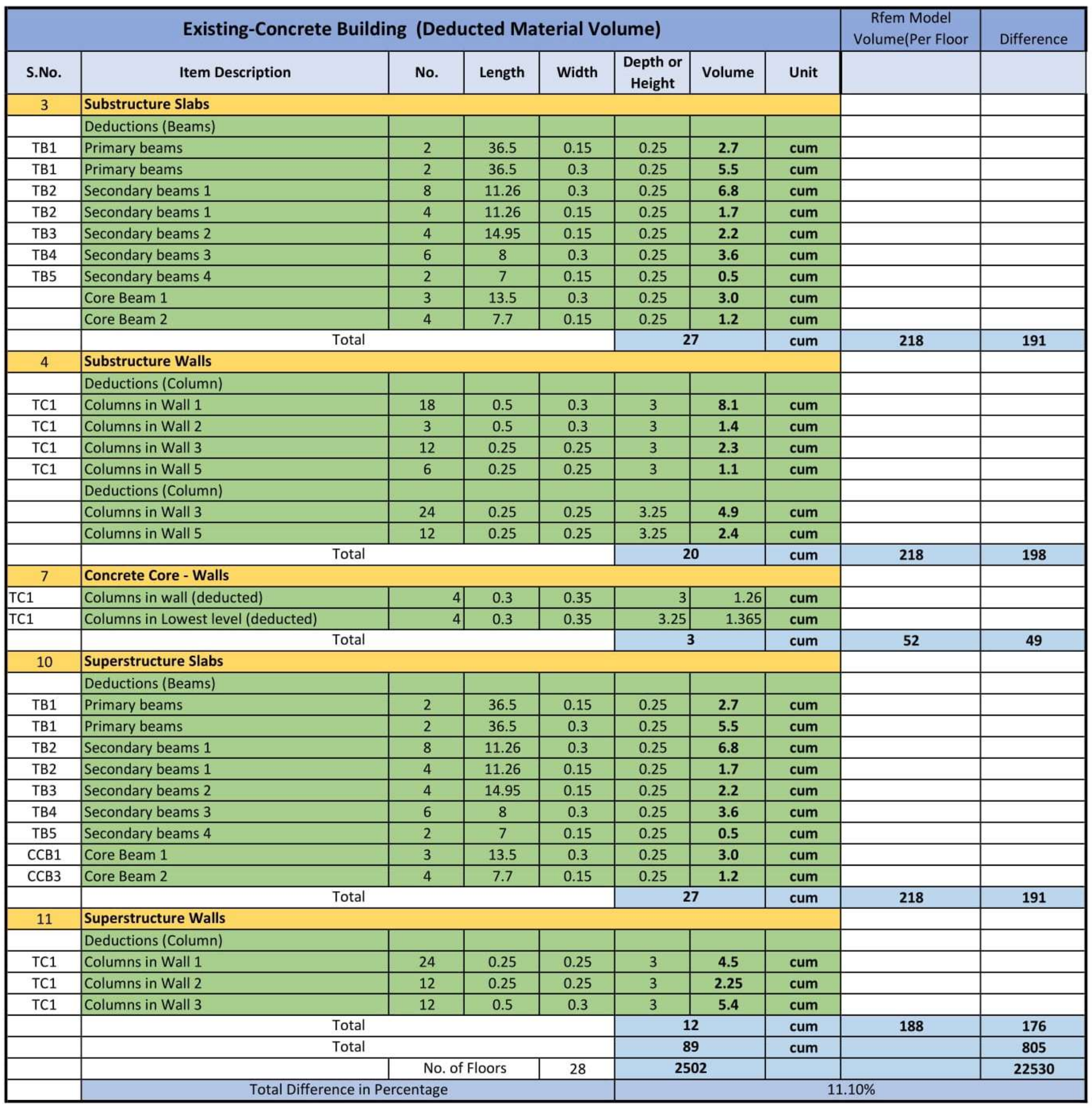
	Total					**298**	**cum**	**2549**	759	299	762	-2.9
7	**Concrete Core - Walls**											
CCW1	Wall 1	2	13.5	0.35	3	28.35	**cum**					
CCW2	Wall 2	2	7.6	0.35	3	15.96	**cum**					
	Columns in wall (deducted)	4	0.3	0.35	3	1.26	**cum**					
	No. of Floors				**27**							
					Sub Total	**1162**	**cum**					
CCW1	Wall 1	2	13.5	0.35	3.25	30.7	**cum**					
CCW2	Wall 2	2	7.6	0.35	3.25	17.3	**cum**					
	Columns in Lowest level (deducted)	4	0.3	0.35	3.25	1.4	**cum**					
	Total					**1209**	**cum**	**2549**	3082	1454	3707	-625
8	**Superstructure Columns**											
TC1	Columns	48	0.5	0.3	3	**21.6**	**cum**					
	No. of floors	2										
	Total					**43**	**cum**	**2549**	110	50	128	-18
9	**Superstructure Beams**											
TB1	Primary beams	4	36.5	0.3	0.5	**21.9**	**cum**					
TB2	Secondary beams 1	12	11.5	0.3	0.5	**20.7**	**cum**					
TB3	Secondary beams 2	4	14.5	0.3	0.5	**8.7**	**cum**					
TB4	Secondary beams 3	6	8	0.3	0.5	**7.2**	**cum**					
TB5	Secondary beams 4	2	7	0.3	0.5	**2.1**	**cum**					
					Sub Total	**60.6**	**cum**					
	No. of Floors				**2**							
	Total				**121**		**cum**	**2549**	309	122	310	-1.3
10	**Superstructure Slabs**											
TS1	Concrete Slab 1	4	14.5	11.26	0.25	**163**	**cum**					
TS2	Concrete Slab 2	2	7.73	8.23	0.25	**32**	**cum**					
TS3	Concrete Slab 3	1	12.34	7.33	0.25	**23**	**cum**					
					Sub Total	**218**	**cum**					
	No. of Floors				**2**							
					Sub Total	**435**	**cum**					
	Deductions (Beams)											
TB1	Primary beams	2	36.5	0.15	0.25	**2.7**	**cum**					
TB1	Primary beams	2	36.5	0.3	0.25	**5.5**	**cum**					
TB2	Secondary beams 1	8	11.26	0.3	0.25	**6.8**	**cum**					
TB2	Secondary beams 1	4	11.26	0.15	0.25	**1.7**	**cum**					
TB3	Secondary beams 2	4	14.95	0.15	0.25	**2.2**	**cum**					
TB4	Secondary beams 3	6	8	0.3	0.25	**3.6**	**cum**					
TB5	Secondary beams 4	2	7	0.15	0.25	**0.5**	**cum**					
	Core Beam 1	3	13.5	0.3	0.25	**3.0**	**cum**					
	Core Beam 2	4	7.6	0.15	0.25	**1.1**	**cum**					
	No. of Floors				**2**							
					Sub Total	**54**	**cum**					
	Total				**381**		**cum**	**2549**	971	436	1110	-139
11	**Superstructure Walls**											
SPW1	Walls 1	12	11.269	0.3	3	**122**	**cum**					
SPW2	Walls 2	6	5.19	0.3	3	**28**	**cum**					
SPW3	Walls 3	4	12.2	0.3	3	**44**	**cum**					
	Deductions (Column)											
	Columns in Wall 1	24	0.25	0.25	3	**4.5**	**cum**					
	Columns in Wall 2	12	0.25	0.25	3	**2.25**	**cum**					
	Columns in Wall 3	12	0.5	0.3	3	**5.4**	**cum**					
	Total					**182**	**cum**					
	No. of Floors				**2**							
	Total				**363**		**cum**	**2549**	925	452	1152	-226
Timber Structure												
Glulam Components												
12	**Superstructure Columns**											
TC1	Columns	48	0.5	0.3	3	**21.6**	**cum**					
	No. of floors	22										
					Total	**475**	**cum**	**430**	204	554	238	-34
13	**Superstructure Beams**											
TB1	Primary beams	4	36.6	0.3	0.5	**21.96**	**cum**					
TB2	Secondary beams 1	12	11.5	0.3	0.5	**20.7**	**cum**					
TB3	Secondary beams 2	4	14.5	0.3	0.5	**8.7**	**cum**					
TB4	Secondary beams 3	6	8	0.3	0.5	**7.2**	**cum**					
TB5	Secondary beams 4	2	7	0.3	0.5	**2.1**	**cum**					
					Sub Total	**61**	**cum**					
	No. of Floors				**22**							
	Total				**1335**		**cum**	**430**	574	1334	574	0.2
CLT Components												
14	**Superstructure Slabs**											
TS1	Concrete Slab 1	4	14.5	11.26	0.25	**163.27**	**cum**					
TS2	Concrete Slab 2	2	7.73	8.23	0.25	**31.81**	**cum**					
TS3	Concrete Slab 3	1	12.34	7.33	0.25	**22.61**	**cum**					
					Sub Total	**217.7**	**cum**					
	No. of Floors				**22**							
					Sub Total	**4789**	**cum**					
	Deductions (Beams)											
TB1	Primary beams	2	36.5	0.15	0.25	**2.7**	**cum**					
TB1	Primary beams	2	36.5	0.3	0.25	**5.5**	**cum**					

Figure G.4.2: Timber-concrete building material quantities (Deducted manual calculations)



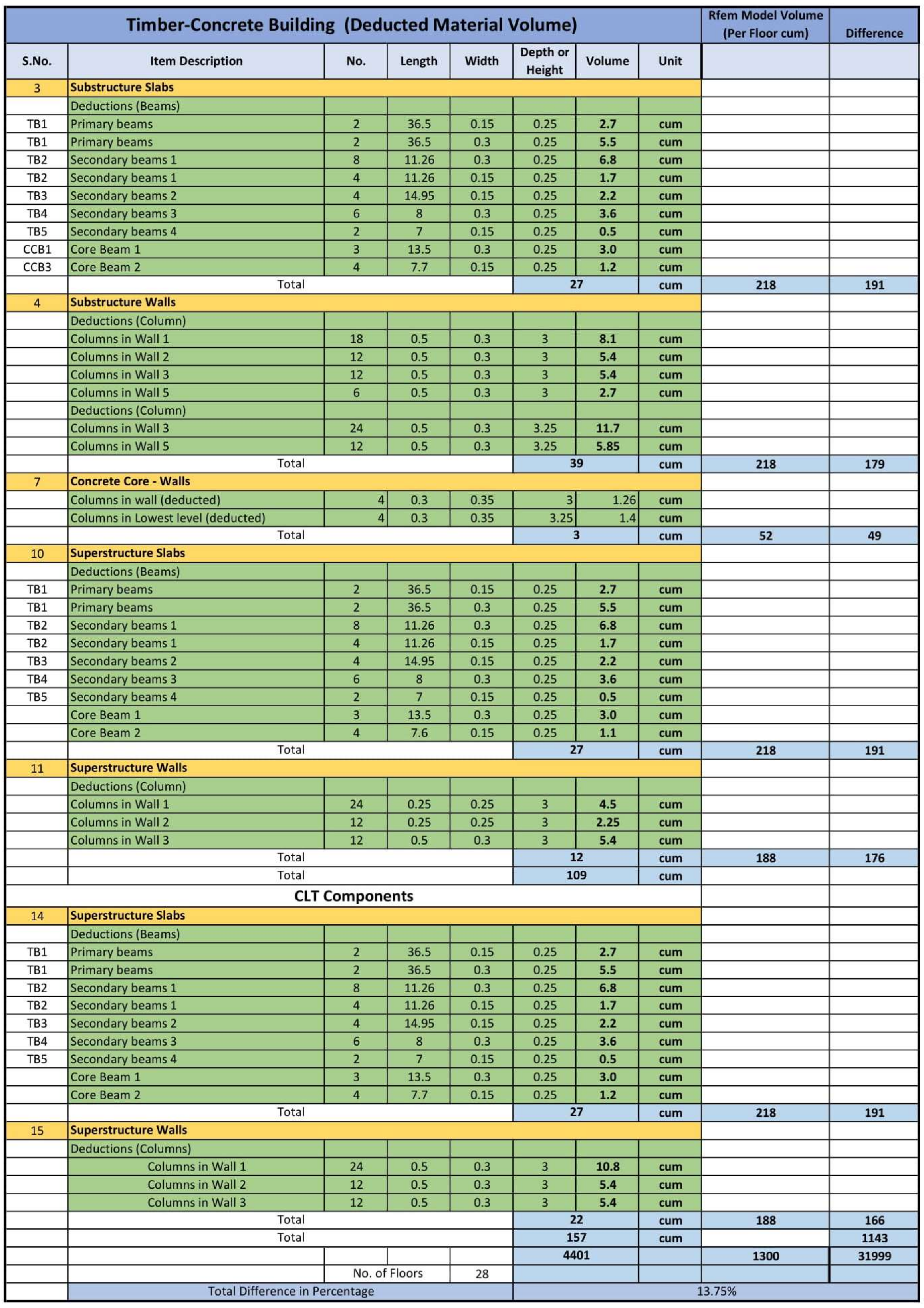
TB2	Secondary beams 1	8	11.26	0.3	0.25	**6.8**	**cum**					
TB2	Secondary beams 1	4	11.26	0.15	0.25	**1.7**	**cum**					
TB3	Secondary beams 2	4	14.95	0.15	0.25	**2.2**	**cum**					
TB4	Secondary beams 3	6	8	0.3	0.25	**3.6**	**cum**					
TB5	Secondary beams 4	2	7	0.15	0.25	**0.5**	**cum**					
	Core Beam 1	3	13.5	0.3	0.25	**3.0**	**cum**					
	Core Beam 2	4	7.7	0.15	0.25	**1.2**	**cum**					
	No. of Floors				**22**							
					Sub Total	**599**	**cum**					
	Total				**4190**		**cum**	**520**	2179	4792	2492	-313
15	**Superstructure Walls**											
SPW1	Walls 1	12	11.2	0.25	3	**101**	**cum**					
SPW2	Walls 2	6	5.3	0.25	3	**24**	**cum**					
SPW3	Walls 3	4	12.25	0.25	3	**37**	**cum**					
	Deductions (Columns)											
	Columns in Wall 1	24	0.5	0.3	3	**10.8**	**cum**					
	Columns in Wall 2	12	0.5	0.3	3	**5.4**	**cum**					
	Columns in Wall 3	12	0.5	0.3	3	**5.4**	**cum**					
				Total		**22**						
	Total volume of Clt walls after deduction				**140**		**cum**					
	No. of Floors				**22**							
	Total				**3076**		**cum**	**520**	1599	4142	2154	-554
	Total				13052				15904		18738	-2834

Figure G.4.3: Timber-concrete building material quantities (Deducted manual calculations)



Existing-Concrete Building (Deducted Material Volume)								Rfem Model Volume(Per Floor	Difference
S.No.	**Item Description**	**No.**	**Length**	**Width**	**Depth or Height**	**Volume**	**Unit**		
3	**Substructure Slabs**								
	Deductions (Beams)								
TB1	Primary beams	2	36.5	0.15	0.25	**2.7**	**cum**		
TB1	Primary beams	2	36.5	0.3	0.25	**5.5**	**cum**		
TB2	Secondary beams 1	8	11.26	0.3	0.25	**6.8**	**cum**		
TB2	Secondary beams 1	4	11.26	0.15	0.25	**1.7**	**cum**		
TB3	Secondary beams 2	4	14.95	0.15	0.25	**2.2**	**cum**		
TB4	Secondary beams 3	6	8	0.3	0.25	**3.6**	**cum**		
TB5	Secondary beams 4	2	7	0.15	0.25	**0.5**	**cum**		
	Core Beam 1	3	13.5	0.3	0.25	**3.0**	**cum**		
	Core Beam 2	4	7.7	0.15	0.25	**1.2**	**cum**		
	Total				**27**		**cum**	**218**	**191**
4	**Substructure Walls**								
	Deductions (Column)								
TC1	Columns in Wall 1	18	0.5	0.3	3	**8.1**	**cum**		
TC1	Columns in Wall 2	3	0.5	0.3	3	**1.4**	**cum**		
TC1	Columns in Wall 3	12	0.25	0.25	3	**2.3**	**cum**		
TC1	Columns in Wall 5	6	0.25	0.25	3	**1.1**	**cum**		
	Deductions (Column)								
	Columns in Wall 3	24	0.25	0.25	3.25	**4.9**	**cum**		
	Columns in Wall 5	12	0.25	0.25	3.25	**2.4**	**cum**		
	Total				**20**		**cum**	**218**	**198**
7	**Concrete Core - Walls**								
TC1	Columns in wall (deducted)	4	0.3	0.35	3	1.26	**cum**		
TC1	Columns in Lowest level (deducted)	4	0.3	0.35	3.25	1.365	**cum**		
	Total				**3**		**cum**	**52**	**49**
10	**Superstructure Slabs**								
	Deductions (Beams)								
TB1	Primary beams	2	36.5	0.15	0.25	**2.7**	**cum**		
TB1	Primary beams	2	36.5	0.3	0.25	**5.5**	**cum**		
TB2	Secondary beams 1	8	11.26	0.3	0.25	**6.8**	**cum**		
TB2	Secondary beams 1	4	11.26	0.15	0.25	**1.7**	**cum**		
TB3	Secondary beams 2	4	14.95	0.15	0.25	**2.2**	**cum**		
TB4	Secondary beams 3	6	8	0.3	0.25	**3.6**	**cum**		
TB5	Secondary beams 4	2	7	0.15	0.25	**0.5**	**cum**		
CCB1	Core Beam 1	3	13.5	0.3	0.25	**3.0**	**cum**		
CCB3	Core Beam 2	4	7.7	0.15	0.25	**1.2**	**cum**		
	Total				**27**		**cum**	**218**	**191**
11	**Superstructure Walls**								
	Deductions (Column)								
TC1	Columns in Wall 1	24	0.25	0.25	3	**4.5**	**cum**		
TC1	Columns in Wall 2	12	0.25	0.25	3	**2.25**	**cum**		
TC1	Columns in Wall 3	12	0.5	0.3	3	**5.4**	**cum**		
	Total				**12**		**cum**	**188**	**176**
	Total				**89**		**cum**		**805**
		No. of Floors		28	**2502**				**22530**
	Total Difference in Percentage				11.10%				

Figure G.5.1: Existing-concrete building (Deducted material volume)



Timber-Concrete Building (Deducted Material Volume)								Rfem Model Volume (Per Floor cum)	Difference
S.No.	Item Description	No.	Length	Width	Depth or Height	Volume	Unit		
3	**Substructure Slabs**								
	Deductions (Beams)								
TB1	Primary beams	2	36.5	0.15	0.25	**2.7**	**cum**		
TB1	Primary beams	2	36.5	0.3	0.25	**5.5**	**cum**		
TB2	Secondary beams 1	8	11.26	0.3	0.25	**6.8**	**cum**		
TB2	Secondary beams 1	4	11.26	0.15	0.25	**1.7**	**cum**		
TB3	Secondary beams 2	4	14.95	0.15	0.25	**2.2**	**cum**		
TB4	Secondary beams 3	6	8	0.3	0.25	**3.6**	**cum**		
TB5	Secondary beams 4	2	7	0.15	0.25	**0.5**	**cum**		
CCB1	Core Beam 1	3	13.5	0.3	0.25	**3.0**	**cum**		
CCB3	Core Beam 2	4	7.7	0.15	0.25	**1.2**	**cum**		
	Total				**27**		**cum**	**218**	**191**
4	**Substructure Walls**								
	Deductions (Column)								
	Columns in Wall 1	18	0.5	0.3	3	**8.1**	**cum**		
	Columns in Wall 2	12	0.5	0.3	3	**5.4**	**cum**		
	Columns in Wall 3	12	0.5	0.3	3	**5.4**	**cum**		
	Columns in Wall 5	6	0.5	0.3	3	**2.7**	**cum**		
	Deductions (Column)								
	Columns in Wall 3	24	0.5	0.3	3.25	**11.7**	**cum**		
	Columns in Wall 5	12	0.5	0.3	3.25	**5.85**	**cum**		
	Total				**39**		**cum**	**218**	**179**
7	**Concrete Core - Walls**								
	Columns in wall (deducted)	4	0.3	0.35	3	1.26	**cum**		
	Columns in Lowest level (deducted)	4	0.3	0.35	3.25	1.4	**cum**		
	Total				**3**		**cum**	**52**	**49**
10	**Superstructure Slabs**								
	Deductions (Beams)								
TB1	Primary beams	2	36.5	0.15	0.25	**2.7**	**cum**		
TB1	Primary beams	2	36.5	0.3	0.25	**5.5**	**cum**		
TB2	Secondary beams 1	8	11.26	0.3	0.25	**6.8**	**cum**		
TB2	Secondary beams 1	4	11.26	0.15	0.25	**1.7**	**cum**		
TB3	Secondary beams 2	4	14.95	0.15	0.25	**2.2**	**cum**		
TB4	Secondary beams 3	6	8	0.3	0.25	**3.6**	**cum**		
TB5	Secondary beams 4	2	7	0.15	0.25	**0.5**	**cum**		
	Core Beam 1	3	13.5	0.3	0.25	**3.0**	**cum**		
	Core Beam 2	4	7.6	0.15	0.25	**1.1**	**cum**		
	Total				**27**		**cum**	**218**	**191**
11	**Superstructure Walls**								
	Deductions (Column)								
	Columns in Wall 1	24	0.25	0.25	3	**4.5**	**cum**		
	Columns in Wall 2	12	0.25	0.25	3	**2.25**	**cum**		
	Columns in Wall 3	12	0.5	0.3	3	**5.4**	**cum**		
	Total				**12**		**cum**	**188**	**176**
	Total				**109**		**cum**		
CLT Components									
14	**Superstructure Slabs**								
	Deductions (Beams)								
TB1	Primary beams	2	36.5	0.15	0.25	**2.7**	**cum**		
TB1	Primary beams	2	36.5	0.3	0.25	**5.5**	**cum**		
TB2	Secondary beams 1	8	11.26	0.3	0.25	**6.8**	**cum**		
TB2	Secondary beams 1	4	11.26	0.15	0.25	**1.7**	**cum**		
TB3	Secondary beams 2	4	14.95	0.15	0.25	**2.2**	**cum**		
TB4	Secondary beams 3	6	8	0.3	0.25	**3.6**	**cum**		
TB5	Secondary beams 4	2	7	0.15	0.25	**0.5**	**cum**		
	Core Beam 1	3	13.5	0.3	0.25	**3.0**	**cum**		
	Core Beam 2	4	7.7	0.15	0.25	**1.2**	**cum**		
	Total				**27**		**cum**	**218**	**191**
15	**Superstructure Walls**								
	Deductions (Columns)								
	Columns in Wall 1	24	0.5	0.3	3	**10.8**	**cum**		
	Columns in Wall 2	12	0.5	0.3	3	**5.4**	**cum**		
	Columns in Wall 3	12	0.5	0.3	3	**5.4**	**cum**		
	Total				**22**		**cum**	**188**	**166**
	Total				**157**		**cum**		**1143**
					4401			**1300**	**31999**
		No. of Floors		28					
	Total Difference in Percentage				13.75%				

Figure G.5.2: Timber-concrete building (Deducted material volume)