

**T.C.
İSTANBUL KÜLTÜR UNIVERSITY
INSTITUTE OF GRADUATE STUDIES**

**THE LIFE CYCLE ENVIRONMENTAL ASSESSMENT OF
RETROFITTING AND RECONSTRUCTION OF AN ACTUAL
SUBSTANDARD RC BUILDING**

MASTER OF APPLIED SCIENCE THESIS

**Thamer Jumah Mohammed ALKSASBEH
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Department: Civil Engineering

Program: Structural Engineering

Supervisor: Assist. Prof Dr. Pınar İNCİ KOÇAK

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Thamer Jumah Mohammed ALKSASBEH

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ABBREVIATIONS

CFRP	: Carbon Fiber Reinforced Polymer
FL	: Finishing Loads
LL	: Live Loads
SL	: Snow Load
DL	: Dead Load
Eqx	: Earthquake effect in the X-direction
Eqy	: Earthquake effect in the Y-direction
Eqz	: Earthquake effect in the vertical direction
SS	: Spectral Acceleration for Short Periods
S1	: Spectral Acceleration for a period of 1 Second
PGA	: Peak Ground Acceleration
SDS	: Design Spectral Acceleration
SD1	: Design Spectral Acceleration at 1 Second
TBEC	: Turkish Building Earthquake Code
BKS	: Building Usage Class
DTS	: Earthquake Design Classes
LCA	: Life Cycle Assessment
LCI	: Life Cycle Inventory
FEA	: Finite Element Analysis
FBG	: Fiber Bragg Grating
GWP	: Global Warming Potential
HH PM	: Human Health Particulate Matter
ODP	: Ozone Depletion Potential
EUP	: Eutrophication Potential
SP	: Smog Potential
GML	: Ground Motion Levels
TDTH	: Türkiye Deprem Tehlike Haritası (Türkiye Earthquake Hazard Map)
TL	: Transition period for the constant displacement zone (TL= 6 sec)
FS	: Soil Affect Coefficients
BKS	: Building Usage Class
Eq	: Earthquake Loads

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LIST OF SYMBOLS

$\lambda(\delta/h)$	: Relative story drift
θ_{ki}	: Displaced axis rotation at the ii end of the element
Δ	: Inter-storey drift
lc	: Element net span
θ_i	: Nodal rotation
H_N	: Building height
S_S	: Spectral acceleration for short periods
S_1	: Spectral acceleration for a period of 1 second
FS	: Short period local soil affect coefficients
$F1$	: 1 second period local soil affect coefficients
SDS	: Design spectral acceleration
$SD1$	: Design spectral acceleration at 1 second
TA	: Spectrum corner period
TB	: Spectrum corner period
tf	: Thickness of CFRP
wf	: Width of CFRP
Sf	: Spacing of CFRP
rc	: Radius of CFRP
θ_{yi}	: Yield rotation at the ii end of the element
θ_{pi}	: Plastic rotation at the ii end of the element
SO_2	.: Acidification Potential
NO_2	: Eutrophication Potential
$CFC.$	: Ozone Depletion Potential
$O3$	: Smog Potential
MJ	: Total Primary Energy
$MJNR$	: Non-Renewable Energy
MJF	: Fossil Fuel Consumption
CO_2	: Carbon Dioxide

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ABSTRACT

This thesis focuses on the life cycle environmental assessment of retrofitting and reconstruction of an actual substandard reinforced concrete (RC) building. For this purpose, seismic structural performance assessment of an actual 6-storey RC frame building located in Istanbul, Türkiye was carried out with respect to Turkish Building Earthquake Code TBEC (2018). Two different retrofitting approaches as RC jacketing of columns, and RC shear wall addition and Carbon Fiber Reinforced Polymer (CFRP) wrapping of columns were then proposed in order to satisfy the requirements of TBEC (2018). Furthermore, structural design and calculations for reconstructing of the new building for replacement of the existing substandard building was conducted by taking into consideration of Turkish Standard for the Design and Construction of Reinforced Concrete Structures Code TS500 (2000) and TBEC (2018). The Finite Element Model (FEM) of the building and required structural analyses and assessments were carried out using ProtaStructure2022. Accordingly, the life cycle assessment was figured out by comparing the structural, environmental and economical parameters obtained for each retrofitting projects and newly designed building project. For this purpose, the Athena Impact Estimator was employed for providing insights into Life Cycle Assessment (LCA) measures for each retrofitting scenario, focusing on metrics such as Global Warming Potential (GWP), Acidification Potential, and Smog Potential. The results demonstrated that the performance target is achieved with the recommended retrofitting methods. In addition, the environmental impact assessment highlighted significant contributions from the manufacturing and operational phases, emphasizing the roles of material production and energy use. These findings underscore the importance of integrating sustainable practices and materials in construction to mitigate negative environmental impacts and ensure compliance with Turkish standards.

Keywords: Linear Analysis, Seismic Performance, Retrofitting Strategies, Life Cycle Assessment, Building Rehabilitation, Environmental Sustainability, Athena Impact Estimator For Building.

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ÖZET

Bu tez, mevcut standartlı betonarme bir binanın güçlendirme ve yeniden inşa edilmesinin yaşam döngüsü çevresel değerlendirmesine odaklanmaktadır. Bu amaçla, İstanbul'da bulunan altı katlı betonarme bir binanın deprem performansının değerlendirilmesi, Türkiye Bina Deprem Yönetmeliği 2018 TBDY (2018)'e göre yapılmıştır. TBDY (2018) gereksinimlerini karşılamak amacıyla, kolonların betonarme mantolanması ile betonarme perde eklenmesi ve kolonların Karbon Fiber Takviyeli Polimer (CFRP) ile sargılanması şeklinde iki farklı güçlendirme yaklaşımı benimsenmiştir. Ayrıca, mevcut standartlı binanın yeniden inşa edilmesi için yapısal tasarım, Betonarme Yapıların Tasarım ve Yapımına Dair Türk Standardı TS500 (2000) ve TBDY 2018'e göre gerçekleştirilmiştir. Binanın sonlu eleman modelleri ile gerekli yapısal analizler ve değerlendirmeler, ProtaStructure 2022 yazılımı kullanılarak gerçekleştirilmiştir. Yaşam döngüsü değerlendirilmesi, benimsenen farklı güçlendirme projeleri ve yeniden inşaat projesinden elde edilen yapısal, çevresel ve ekonomik parametrelerin karşılaştırılmasıyla gerçekleştirilmiştir. Her güçlendirme durumu için yaşam döngüsü değerlendirme (LCA) ölçütlerinin anlaşılmasını sağlamak için Athena Impact Estimator yazılımı kullanılmıştır. Bu ölçütler arasında küresel ısınma potansiyeli (GWP), asitlenme potansiyeli ve hava kirliliği potansiyeli gibi ölçümler yer almaktadır. Sonuçlar, önerilen güçlendirme yöntemleriyle performans hedefinin gerçekleştirilebildiğini göstermektedir. Ayrıca, çevresel etki değerlendirilmesi, malzeme üretimi ve enerji kullanımının rollerini vurgulayarak, inşaat ve işletme aşamalarının önemli katkılarını öne çıkarmaktadır. Bu bulgular, olumsuz çevresel etkileri azaltmak ve Türk standartlarına uyumu sağlamak için inşaat sektöründe sürdürülebilir uygulamalar ve malzemelerin entegre edilmenin önemini göstermektedir.

Anahtar kelimeler: Doğrusal Analiz, Deprem Performansı, Güçlendirme Yaklaşımları, Yaşam Döngüsü Değerlendirilmesi, Kentsel Dönüşüm, Çevresel Sürdürülebilirlik, Athena Impact Estimator.

1. INTRODUCTION

1.1. Overview

Generally, natural disasters are seen as distinct events like hurricanes, floods, and earthquakes that can occur during a building's lifetime, leading to significant direct and indirect economic losses (McDonald, 2007). To manage these risks, it is essential to evaluate the possible risks to individuals and property (Borghesi and Gaudenzi, 2013). In addition to the structural safety aspect, sustainable construction practices have become increasingly important in recent years due to growing awareness of the environmental impacts related with building activities (Ding, 2008; Ortiz et al., 2009). The construction industry is a significant contributor to environmental degradation, primarily through the retrieval and processing of raw resources, coupled with energy utilization, and emissions throughout a building's life cycle (Chau et al., 2015).

Seismic events are intrinsic to the Earth's existence and a sorrowful aspect of human history. Countless individuals have tragically lost their homes and lives as a result of earthquake occurrences. For instance, a seismic event Mw 7.7 on the Richter scale struck Kocaeli, Türkiye in 1999, resulting in over 17,000 fatalities and approximately 44,000 injuries. The disaster necessitated emergency housing for more than 250,000 individuals (Ortiz et al., 2009). Further more, on 6 February 2023, a Mw 7.8 earthquake struck southern and central Türkiye. The epicentre was 37 km west-northwest of Gaziantep. 107213 injured, 53537 deaths and 140 missing. A damage assessment by the Turkish government revealed at least 61722 buildings has to be demolished.

Türkiye, situated in a region prone to frequent seismic activity, mandates adherence to seismic safety guidelines outlined in codes. However, many RC structures were constructed without following the requirements of seismic design codes enforced their construction times. This deficiency increases the risk of catastrophic collapse. Therefore, buildings constructed taking into account the current regulations are expected to provide adequate earthquake safety (Ng et al. 2013). However, the last earthquakes showed that the existing building stock comprises of many substandard buildings which have not sufficient seismic structural capacity.

Recently, retrofitting has been a practical alternative for enhancing the lateral load bearing capacity of existing buildings.

The seismic performance of the structures could be enhanced using the retrofitting approach determined in the Federal Emergency Management Agency FEMA 356, Applied Technology Council ATC-40 and TBEC (2018) standards and codes (Haghpanah et al., 2017; Zhao et al., 2021, Di Ludovico et al., 2017; Woodson, 2009)

With the global push towards reducing carbon footprints and promoting sustainable development, the need for environmentally conscious construction practices has never been more critical. As a result, a range of tools and methodologies has been developed and aimed for assessing and mitigating the environmental impacts of construction activities (Imran et al., 2014). One such tool is the Athena Impact Estimator for Buildings, developed by the Athena Sustainable Materials Institute. This software enables comprehensive environmental impact assessments for a wide range of construction projects, including new constructions, renovations, and retrofits. The Athena Impact Estimator uses a detailed database of materials and construction activities to model and evaluate the environmental impacts from the raw material extraction phase through to the end-of-life stage of a building. This life cycle approach ensures that all stages of the building's existence are considered, providing a holistic view of its environmental footprint (Kaan et al., 2012).

In the context this thesis, the structural integrity and environmental sustainability of existing substandard reinforced concrete (RC) buildings present significant challenges. Many buildings, especially those constructed before the implementation of modern seismic codes like the TBEC (2018), lack the necessary detailing and reinforcement to withstand seismic events, leading to potential catastrophic collapses. Additionally, the construction industry contributes significantly to environmental degradation through material extraction, energy consumption, and emissions over the building's life cycle. This thesis addresses such dual challenges by evaluating the life cycle environmental impact and structural performance of retrofitting versus reconstruction of a substandard RC building in Istanbul. The specific problem lies in determining the most effective retrofit strategy that not only meets the structural performance requirements as per TBEC (2018) but also minimizes environmental impacts.

The study investigates two retrofit methods: RC shear wall addition and CFRP wrapping of columns and RC jacketing of columns, alongside a complete reconstruction scenario. The goal is to identify a sustainable approach that enhances the seismic resilience of building while reducing its environmental footprint. For this purpose, seismic structural performance assessment of an actual 6-storey RC frame building located in Istanbul, Türkiye was carried out with respect to TBEC (2018). Two different retrofitting approaches as RC jacketing of columns, and RC shear wall addition and CFRP wrapping of columns were then proposed in order to satisfy the requirements of TBEC (2018). Furthermore, structural design and calculations for reconstructing of the new building for replacement of the existing substandard building was conducted by taking into consideration of requirements of TBEC (2018). The FEM of the building and required structural analyses and assessments were carried out using ProtaStructure 2022.

Accordingly, the life cycle assessment was figured out by comparing the structural, environmental and economical parameters obtained for each retrofitting projects and newly designed building project. For this purpose, the Athena Impact Estimator was employed for providing insights into Life Cycle Assessment (LCA) measures for each retrofitting scenario, focusing on metrics such as GWP, Acidification Potential, and Smog Potential. By comparing the retrofitting strategies with the reconstruction scenario, the study aims to provide a comprehensive understanding of the trade-offs involved in choosing between retrofitting and rebuilding. The reconstruction case involves demolishing the current structure and erecting a new building that meets all modern seismic and environmental standards. This comparison is crucial for determining the most sustainable approach to improving the building's performance. The environmental analysis conducted in this thesis aims to provide a detailed comparison of the impacts of the two retrofitting scenarios. Employing Life Cycle Assessment (LCA) methodologies, the research evaluates crucial environmental impact indicators. By leveraging the capabilities of the Athena Impact Estimator, this study not only highlights the environmental performance of the retrofitting methods but also emphasizes the broader implications for sustainable construction practices. The results of this research highlight the importance of integrating sustainable materials and practices into construction and retrofitting activities. They also highlight

the necessity for informed decision-making that balances structural performance and environmental stewardship.

1.2. Objectives

In the above literature, there are a lot of researchs on the performance of the single structural element reinforced with CFRP, but most are FEA, experimental work, and for one specific structural member.

In addition, this thesis aims to make a contribution to the field of sustainable construction by providing a detailed environmental assessment of retrofitting scenarios and reconstruction for an existing building in Istanbul. Through the use of advanced tools and methodologies, the study seeks to promote a deeper understanding of the environmental impacts associated with different construction practices and to advocate for more sustainable approaches in the industry. The ultimate goal is to support the development of buildings that are not only structurally sound and resilient but also environmentally responsible and sustainable in the long term.

1.3. Organization of the Thesis

This thesis is organised into five chapters with the following contents:

Chapter 1 is the introduction of the thesis. Chapter 2 provides an overview of seismic retrofitting systems and also different types of retrofitting systems are summarised and discussed. Chapter 3 introduces the seismic performance assessment procedure in TBEC (2018). Design process based on Performance based seismic design approach of existing building which have been assessed are presented in detail. Chapter 4 introduces the retrofitting strategies of exsiting building. Design process and performance based seismic design approach of CFRP with shear wall and RC jacketing of columns are presented in detail. Chapter 5 introduces the design assumptions, design process and performance based seismic design assessed for redesigned building. Chapter 6 introduces the lif cycle evaluatation of existing, retroffiting and redesigned building. To conclude, Chapter 7 shows a summary and a conclusion of this study.

2. LITERATURE REVIEW

2.1. Studies Related to CFRP Retrofitting Method

The ease of application makes CFRP a preferred material for retrofitting existing structures with minimal disruption. Studies, such as those by ACI Committee 440 (2008) and Seible et al. (1997), highlight the effectiveness of CFRP jackets in improving the seismic resilience of RC columns by enhancing confinement and energy dissipation. Further research, including that by Fardis (2009) and Ghosh (2009), underscores FRP's vital role in retrofitting RC buildings to meet modern seismic standards.

CFRP application can increase the flexural capacity of RC beams, for instance, Eljufout et al., 2021 investigated the impact of the number of CFRP layers on the behavior of RC beams strengthened with CFRP. The results showed that the load-carrying capacity increased with increasing the number of carbon fiber sheet layers. Shomali et al., 2020 conducted a study investigating the effect of the internal reinforcement ratio on the behavior of CFRP-strengthened beams. The authors observed that the flexural strength and stiffness of the strengthened beams improved compared to the control specimens. Additionally, they noted that with a higher reinforcing ratio, the failure of the strengthened beams occurred either due to interfacial debonding caused by a flexural shear crack or interfacial debonding induced by a flexural crack. Wang and Han, 2013 concentrated on investigating the flexural performance of pre-stressed concrete hollow slabs after being reinforced with CFRP following various forms of damage. Using experimental methods, twelve residential pre-stressed concrete hollow slabs were subjected to a concentrated load at two symmetrical points to examine both the flexural behavior and the effects of different bonding techniques. The study concluded that the flexural performance of pre-stressed concrete hollow slabs reinforced with CFRP showed significant improvement and proved to be highly reliable (Wang and Han, 2013).

Banjara and Ramanjaneyulu (2017) carried out an experimental program focusing on beams retrofitted to address shear deficiencies. Their findings emphasized the significant enhancement of shear capacity in continuous RC beams due to the application of externally bonded CFRP.

Imran et al. (2014) performed a study on the impacts of eccentric loading on both unstrengthened and CFRP-strengthened RC beams. The experiments indicated a shift in behavior from flexural failure to local failure due to variations in eccentricity. Thus, the effects of eccentricity cannot be overlooked and require careful consideration before applying a strengthening strategy to RC beams. The RC beams strengthened with CFRP exhibited significantly enhanced load-carrying capacity, but the influence of eccentric loading on the ductility and failure mode of RC beams must be taken into account.

Kaan et al. (2012) evaluated the effectiveness of different methods for preventing and repairing fatigue damage in welded connections, a frequent problem in many steel bridges. They conducted both experimental tests and analytical simulations to investigate the fatigue performance of cover plate specimens with welded connections reinforced with CFRP overlays. The specimens underwent three-point bending under cyclic loads to measure the changes in fatigue-crack initiation life of the welded connections due to the application of CFRP overlays. The results showed that preserving the bond between the CFRP overlays and the steel was critical, as it significantly reduced stress demands and extended the fatigue life of the welded connections from AASHTO fatigue-design Category E' in the unreinforced state to the infinite fatigue life range. Furthermore, the introduction of breather-cloth material within the bond layer greatly enhanced the fatigue strength of the bond layer.

2.2. Studies Related to RC Jacketing of Columns Retrofitting Method

RC jacketing of columns is a technique that nowadays has become very popular in the strengthening and retrofitting of existing structures. The method involves the addition of a new layer of concrete with additional steel reinforcement around an existing structural member in an attempt to enhance its strength, ductility, and stiffness. The beginning of research studies related to jacketing with reinforced concrete started in the mid-last century.

Sezen and Whittaker (2006) studied RC jacketing of columns with regard to buildings damaged in earthquakes. Much of the emphasis in this research has been on how this technique can regain strength and enhance ductility. The aforementioned application has been realized after major seismic events in many cases, such as after

the 1999 Kocaeli Earthquake in Türkiye and the 2003 Boumerdes Earthquake in Algeria.

Campione and Miraglia (2003) showed that RC jacketing of columns significantly increased axial and shear strength, thus increasing the strength of the structure in resisting seismic forces. Moreover, it provided further confinement to core concrete, minimizing the chances of brittle failure under cyclic loads.

Alcocer et al. (2014) investigated the suitability of high-performance concrete for use in RC jackets; this increased the resistance and durability of the RC jackets. The high-performance concrete used would be highly resistant to environmental degradation that would be dominant in aggressive environments such as in coastal or industrial areas.

Sakino et al. (2012) investigated hybrid approaches where RC jacketing was combined with CFRP wrapping and showed better performance compared to seismic retrofitting. The proposed hybrid technique had taken advantage of the two techniques' benefits with increased confinement and strength with limited increase in dead load.

2.3. Studies Related to Life Cycle Assessment

The current literature highlights the crucial requirement of sustainable practices in the construction industry, specifically focusing on retrofitting and using bio-based materials. By reusing and recycling existing structures and using bio-based materials, Besana and Tirelli (2022) show that embodied carbon (EC) can be significantly reduced. They conducted a thorough case study of a Milanese abandoned building and used one-click LCA software to conduct a building information modeling (BIM)-based LCA to examine different retrofit solutions. The results showed 91% decrease in EC compared to new buildings, proving that the "build less, build clever" attitude is effective. According to this idea, reusing old structures has many benefits, including EC and a smaller environmental impact. Nevertheless, the present "-1/+1 approach" to determining the negative carbon contributions of bio-based materials has its limitations, as Besana and Tirelli point out, and they also mention the continuing discussion in the scientific community regarding the biogenic materials' long-term carbon neutrality. Because of this, studies into more accurate ways of accounting for biogenic carbon sequestration are urgently needed.

The study by Dong et al. (2005) addresses the environmental and economic impacts of retrofitting versus rebuilding through a comprehensive life cycle assessment (LCA) and costing analysis of a typical four-bedroom house in Toronto. The LCs considered in their study align with the general stages. These stages include procurement of raw materials, manufacturing of construction components, construction processes, operation, and maintenance over the building's service life, and end-of-life processes such as recycling, reuse, demolition, and disposal. Each stage involves inputs like energy, water, and raw resources, resulting in outputs such as atmospheric emissions, solid wastes, and liquid wastes. During the raw materials acquisition stage, the study considers the environmental impacts of extracting and processing raw materials required for retrofitting and new construction. In the fabrication of construction materials stage, the analysis includes the emissions and energy consumption related to producing the materials used in retrofit and rebuild scenarios. The construction activities stage examines the environmental impacts of on-site construction processes, transportation of materials, and the installation of structural components. In the operation and maintenance stage, the study evaluates the building's energy consumption, emissions, and maintenance requirements over its service life. Finally, the end-of-life stage analyzes the impacts associated with the demolition, disposal, and potential recycling of building materials. Dong et al.'s study underscores the importance of considering all these stages to assess the environmental and economic trade-offs between retrofitting and rebuilding.

Additionally, Fnais et al. (2022) provide a comprehensive review of current LCA applications in buildings, focusing on the limitations of conventional static LCA and advocating for a dynamic, data-driven approach. They identify several critical gaps in current LCA research, including the lack of alignment with domain models like BIM, limited support for temporal information, insufficient consideration of health and well-being impacts, and difficulties in scaling up LCA from individual buildings to larger districts. Fnais et al. (2022) champion "semantic-based dynamic (real-time) LCA," arguing for a more comprehensive framework that leverages real-time data from connected devices, semantic models like BIM and GIS, and intelligent decision support systems powered by machine learning. This approach aims to address the inherent dynamic nature of buildings and their surrounding environment, providing more accurate, timely, and actionable insights for optimizing environmental

performance throughout the building's lifecycle. While this call for a dynamic LCA framework presents a promising direction, the paper leaves several practical implementation details unanswered. Future research should focus on developing standardized methodologies and databases for collecting, integrating, and analyzing dynamic data in the context of LCA while addressing the technical and semantic interoperability challenges associated with connecting various data sources and domain models.

Finally, Vitiello et al. (2016) focus specifically on the environmental impact of seismic retrofitting strategies for existing RC buildings. Using SimaPro software and the IMPACT2002+ methodology, they conduct a comparative LCA of four different strengthening solutions for a building in Naples, Italy. Their findings highlight the importance of incorporating sustainability criteria alongside structural performance in the decision-making process. The study demonstrates that base isolation, a strategy focused on reducing seismic demand rather than increasing structural capacity, achieved the lowest overall environmental impact across various damage categories. This suggests that choosing less material-intensive solutions, when feasible, can offer significant environmental benefits. However, the authors acknowledge that the environmental impact assessment is specific to their case study and might vary depending on the building's vulnerability, seismic hazard, and the databases used. This underscores the need for further research to develop comprehensive and geographically specific databases for LCA applications in seismic retrofitting, enabling more informed decision-making for a wider range of building types and contexts.

Ezer (2012) the environmental impact of buildings primarily addresses the construction of new structures. However, these models often fail to consider variations in productivity, efficiency, and the short- and long-term effects associated with rehabilitation efforts related to rehabilitation projects. Therefore, there is a pressing need to develop a methodology for quantifying resources and calculating environmental impact specifically tailored to rehabilitation projects.

Itard and Klunder (2007) investigated the environmental impacts throughout the life cycle of buildings over time. Their research concluded that in a scenario where a building endures for 100 years, the overall energy consumption during its lifespan is

greater if the building remains in its original state or is demolished and replaced with new construction, and lower if it undergoes refurbishment. While reconstruction presents notable environmental consequences, it also provides an opportunity to enhance the energy efficiency of the building.

Verbeeck and Cornelis (2011) conducted an analysis comparing renovation with demolition and new construction for a portion of the housing stock in Belgium across various scenarios, considering factors such as energy consumption, economic impacts, and environmental effects. They determined that the annual energy savings from demolishing and constructing new buildings did not justify such actions, except in instances where the building was in extremely poor condition or if renovation costs were prohibitively high. From an environmental perspective, they concluded that demolition and new construction might not always be a worse option than renovation. The potential for energy savings is higher when replacing the building with new construction that maximizes waste reuse and recycling during the demolition process.

Dobbelsteen et al. (2004) created a methodology for the simplified mathematical evaluation of the environmental impact of renovation versus demolition and new construction. This method includes assigning specific environmental costs and annual environmental costs, where the former pertain to construction, demolition, and possible renovation, and the latter to the yearly consumption of energy and other resources. Their model assumes that renovation or new construction should result in lower annual costs since the renovated or new building is expected to be more energy-efficient.

Ng et al. (2013) examined the carbon emission determination methods of six prominent Building Environmental Assessment (BEA) tools and conducted a detailed study on an office building. They discovered that these tools mainly evaluated carbon emissions during the operational stage, often qualitatively, rather than considering all LCS. Additionally, they observed that differences in baseline, benchmarking, and auditing methods across various tools led to inconsistencies in the assessed carbon reduction levels of buildings.

Dall'O et al. (2012) investigated the energy-saving potential of retrofitting residential buildings in five municipalities of Milan, Italy. They concentrated on retrofit options for the building envelope, such as window replacement, adding facade

insulation, enhancing roof insulation, and implementing new sealing to reduce ventilation losses. They introduced a retrofitting factor 'i,' assumed to be defined by local authorities, to calculate potential energy savings for each retrofit option. Additionally, they assessed the economic payback period for each retrofit option under various tax deduction scenarios. Notably, their study did not include the energy needed for material production in the calculations, and they analyzed energy and economic savings separately.

Cellura et al. (2013) conducted a study on the environmental advantages of retrofitting buildings in Italy and developed an assessment model. They focused on retrofit measures such as wall insulation, window replacement, installation of solar thermal collectors for hot water, and the installation of condensing boilers, chosen based on government-defined actions eligible for tax deductions. Importantly, they integrated potential changes in consumer behavior into their model by assuming that consumers might spend additional income from energy savings on other goods. As a result, they included the environmental impacts of consumer spending behavior in their analysis.

Asadi et al. (2012) proposed a multi-objective optimization model to assess building retrofits based on environmental and economic performance. They investigated retrofit strategies such as external wall insulation, roof insulation, window replacement, and the installation of solar collectors, considering different materials and technologies for each approach. Energy savings resulting from retrofits were estimated using a simplified model adapted from the Portuguese building code. For the optimization process, they employed the Tchebycheff method and allowed for variable weights for energy and cost reductions. Their findings revealed that the optimal retrofit strategies varied depending on the weights assigned.

In their study, Milaj, Sinha, Miller, and Tokarczyk (2017), evaluated the environmental benefits of replacing steel and concrete with wood in commercial buildings in Oregon using the Athena Impact Estimator for Buildings. By modeling six buildings and analyzing their life-cycle impacts, they found that the use of wood considerably decreased GWP and fossil fuel consumption. (FFC), with an average GWP reduction of about 60%. These findings align with other studies that demonstrate wood's lower environmental footprint compared to traditional construction materials,

emphasizing wood's potential in sustainable commercial construction. The research highlights wood's viability in reducing the construction sector's overall environmental impacts, supporting its increased use in commercial applications.

The study by Abouhamad and Abu-Hamd (2020) assesses the environmental impacts of light steel-framed buildings with cement-based walls and floors using the Athena Impact Estimator for Buildings. It employs a life cycle assessment approach (LCA) methodology to analyze the environmental effects from production to end-of-life stages. The results indicate that cold-formed steel (CFS) systems have lower embodied GWP and primary energy consumption (PE) compared to traditional construction materials, primarily due to the high recycled content and efficient production processes. The study emphasizes the importance of including both embodied and operational impacts in building assessments to inform sustainable construction practices.

Chen et al. (2020) performed a comparative life-cycle assessment of a 12-story mass timber (MT) building and an equivalent RC building using the Athena Impact Estimator for Buildings (IE4B). The analysis demonstrated that the MT building had a 20.6% reduction in embodied carbon compared to the RC building for modules A to C, and a 70% reduction when including module D (beyond the building's lifespan). Additionally, the MT building stored significant amounts of CO₂, resulting in a lower GWP. These findings underscore the environmental benefits of utilizing cross-laminated timber (CLT) in high-rise construction, advocating for its adoption in more sustainable building practices.

3. SEISMIC PERFORMANCE ASSESSMENT OF ACTUAL RC BUILDING

3.1. Seismic Performance Assessment Procedure in TBEC (2018)

In this study, the building was evaluated for seismic performance according to TBEC (2018). The assessment indicated that the structure is expected to achieve the "Controlled Damage" Life Safety performance level during a DD2 earthquake, which has a 10% probability of exceedance within 50 years and corresponds to a return period of 475 years. The total height of the building, from the basement to the top of the fourth floor, is 17.40 meters, placing it in Building Height Class BYS 6. According to the TBEC (2018), a building must satisfy the following criteria to provide "Controlled Damage" performance.-

- At any floor, based on calculations made for each earthquake direction applied, excluding secondary beams, a maximum of 35% of the beams and columns as defined in the following paragraph (b) may transition into the Collapse Prevention Zone.
- The combined shear force the contribution of columns in the Collapse Prevention Zone must not exceed 20% of the total shear force borne by all columns on any given floor. Moreover, the ratio of the cumulative shear forces of columns in the Advanced Damage Zone on the top floor to the total shear forces of all columns on that floor must be limited to a maximum of 40%.
- The proportion of shear forces borne by vertical elements surpassing the Life Safety limit, both in the lower and upper sections of any floor, must not exceed 30% of the total shear force borne by all vertical elements on that floor.
- All elements must have sufficient capacity for shear effects.

3.1.1. Short and 1-Second Periods Factors

From The earthquake map of republic of Türkiye the S_s and S_1 factors are found to be

$$S_s = 0.998 \text{ g} ; S_1 = 0.272 \text{ g}$$

Further more, the local Soil Affect Coefficients (F_s and F_1), for soil type: ZB Short period and 1-second period local soil affect coefficients will be determined as per (TBEC 2018-2.3.3) as shown in Tables 3-1 and 3-2.

Table 3-1 Short-period local soil affect coefficients (TBEC 2018-Table 2.1)

Yerel Zemin Sınıfı	Kısa periyot bölgesi için Yerel Zemin Etki Katsayısı F_s					
	$S_s \leq 0.25$	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s = 1.25$	$S_s \geq 1.50$
ZA	0.8	0.8	0.8	0.8	0.8	0.8
ZB	0.9	0.9	0.9	0.9	0.9	0.9
ZC	1.3	1.3	1.2	1.2	1.2	1.2
ZD	1.6	1.4	1.2	1.1	1.0	1.0
ZE	2.4	1.7	1.3	1.1	0.9	0.8
ZF	Sahaya özel zemin davranış analizi yapılacaktır (Bkz.16.5).					

Table 3-2 Local soil affects coefficients for a period of 1 sec (TBEC 2018-Table 2.2)

Yerel Zemin Sınıfı	1.0 saniye periyot için Yerel Zemin Etki Katsayısı F_1					
	$S_1 \leq 0.10$	$S_1 = 0.20$	$S_1 = 0.30$	$S_1 = 0.40$	$S_1 = 0.50$	$S_1 \geq 0.60$
ZA	0.8	0.8	0.8	0.8	0.8	0.8
ZB	0.8	0.8	0.8	0.8	0.8	0.8
ZC	1.5	1.5	1.5	1.5	1.5	1.4
ZD	2.4	2.2	2.0	1.9	1.8	1.7
ZE	4.2	3.3	2.8	2.4	2.2	2.0
ZF	Sahaya özel zemin davranış analizi yapılacaktır (Bkz.16.5).					

Then, Spectral Acceleration values for Design were calculated as per (TBEC 2018-2.3.2)

$$S_{DS} = S_s \times F_s = 0.998g \times 0.9 = 0.898 \text{ g}$$

$$S_{D1} = S_1 \times F_1 = 0.272g \times 0.8 = 0.218 \text{ g}$$

Hence, Spectrum Corner periods (T_A ve T_B): (TBEC 2018-2.3.4.1)

$$T_A = 0.2 \frac{S_{D1}}{S_{DS}} = 0.2 \times \frac{0.218g}{0.898g} \cong 0.048 \text{ sec}$$

$$T_B = \frac{S_{D1}}{S_{DS}} = \frac{0.218g}{0.898g} \cong 0.242 \text{ sec}$$

3.1.2. Building Usage Class (BKS) and Building Importance Coefficients

The BKS were found for Konut Bina (BKS=3) as per (TBEC 2018-Table 3.1), and Building importance coefficient : $I=1$ as per (TBEC 2018-Table 3.1)

Table 3-3 Building usage class and building importance coefficient (TBEC 2018-Table 3.1)

Bina Kullanım Sınıfı	Binanın Kullanım Amacı	Bina Önem Katsayısı (I)
BKS = 1	Deprem sonrası kullanımı gereken binalar, insanların uzun süreli ve yoğun olarak bulunduğu binalar, değerli eşyanın saklandığı binalar ve tehlikeli madde içeren binalar a) Deprem sonrasında hemen kullanılması gerekli binalar (Hastaneler, dispanserler, sağlık ocakları, itfaiye bina ve tesisleri, PTT ve diğer haberleşme tesisleri, ulaşım istasyonları ve terminalleri, enerji üretim ve dağıtım tesisleri, vilayet, kaymakamlık ve belediye yönetim binaları, ilk yardım ve afet planlama istasyonları) b) Okullar, diğer eğitim bina ve tesisleri, yurt ve yatakhaneler, askeri kışlalar, cezaevleri, vb. c) Müzeler d) Toksik, patlayıcı, parlayıcı, vb. özellikleri olan maddelerin bulunduğu veya depolandığı binalar	1.5
BKS = 2	İnsanların kısa süreli ve yoğun olarak bulunduğu binalar Alışveriş merkezleri, spor tesisleri, sinema, tiyatro, konser salonları, ibadethaneler, vb.	1.2
BKS = 3	Diğer binalar BKS=1 ve BKS=2 için verilen tanımlara girmeyen diğer binalar (Konutlar, işyerleri, oteller, bina türü endüstri yapıları, vb.)	1.0

3.1.3. Earthquake Design Classes and Building Height Classes

Derived from the Building Use Classes outlined in TBEC 2018-3.1.1 and the short period design spectral acceleration coefficient specified in TBEC 2018-2.3.2.2 for the DD-2 earthquake ground motion level, the Earthquake Design Classes (DTS) that govern the earthquake design criteria in this regulation will be determined per TBEC 2018-Table 3.2.

Table 3-4 Earthquake Design Classes (DTS) (TBEC 2018-Table 3.2)

DD-2 Deprem Yer Hareketi Düzeyinde Kısa Periyot Tasarım Spektral İvme Katsayısı (S_{DS})	Bina Kullanım Sınıfı	
	BKS = 1	BKS = 2, 3
$S_{DS} < 0.33$	DTS = 4a	DTS = 4
$0.33 \leq S_{DS} < 0.50$	DTS = 3a	DTS = 3
$0.50 \leq S_{DS} < 0.75$	DTS = 2a	DTS = 2
$0.75 \leq S_{DS}$	DTS = 1a	DTS = 1

The Building Height Classes for $H_N = 17.4$ m, Hence

Table 3-5 Building height classes (TBEC 2018-Table 3.3)

Bina Yükseklik Sınıfı	Bina Yükseklik Sınıfları ve Deprem Tasarım Sınıflarına Göre Tanımlanan Bina Yükseklik Aralıkları [m]		
	DTS = 1, 1a, 2, 2a	DTS = 3, 3a	DTS = 4, 4a
BYS = 1	$H_N > 70$	$H_N > 91$	$H_N > 105$
BYS = 2	$56 < H_N \leq 70$	$70 < H_N \leq 91$	$91 < H_N \leq 105$
BYS = 3	$42 < H_N \leq 56$	$56 < H_N \leq 70$	$56 < H_N \leq 91$
BYS = 4	$28 < H_N \leq 42$	$42 < H_N \leq 56$	
BYS = 5	$17.5 < H_N \leq 28$	$28 < H_N \leq 42$	
BYS = 6	$10.5 < H_N \leq 17.5$	$17.5 < H_N \leq 28$	
BYS = 7	$7 < H_N \leq 10.5$	$10.5 < H_N \leq 17.5$	
BYS = 8	$H_N \leq 7$	$H_N \leq 10.5$	

3.1.4. Building Target Performance Level

The building target performance level were calculated as per (TBEC 2018-Table 3.4-c) and shown in Table 3-6.

Table 3-6 Building target performance level (TBEC 2018-Table 3.4-c)

Deprem Yer H. Düzei	DTS = 1, 2, 3, 3a, 4, 4a		DTS = 1a, 2a	
	Normal Performans Hedefi	Değerlendirme/Tasarım Yaklaşımı	İleri Performans Hedefi	Değerlendirme/Tasarım Yaklaşımı
DD-3	—	—	SH	ŞGDT
DD-2	KH	ŞGDT	—	—
DD-1	—	—	KH	ŞGDT

3.1.5. Damage levels of the members Evaluation

TBEC 2018 considers the elements that are inadequate under shear effects directly as brittle elements. If there is an unsafe element in the building under shear effects, the earthquake performance of the building is directly determined as "Collapse".

With the Linear Calculation Methods given in Chapter 15 of the TBEC (2018), the displaced axis rotation demanded by the earthquake from the element under the bending effect is found for the Earthquake Calculation.

When the bending element undergoes linear elastic deformation, the relationship between the displaced axis, the nodal rotations at the I end, and the inter-story drift is established by Equation (3.1.).

$$\theta_{ki} = \frac{\Delta}{l_c} - \theta_i \quad (3.1)$$

In this equation, θ_{ki} is the displaced axis rotation at the I end of the element, Δ is the inter-story drift, l_c is the element net span, and θ_i is the nodal rotation figure 3.1.

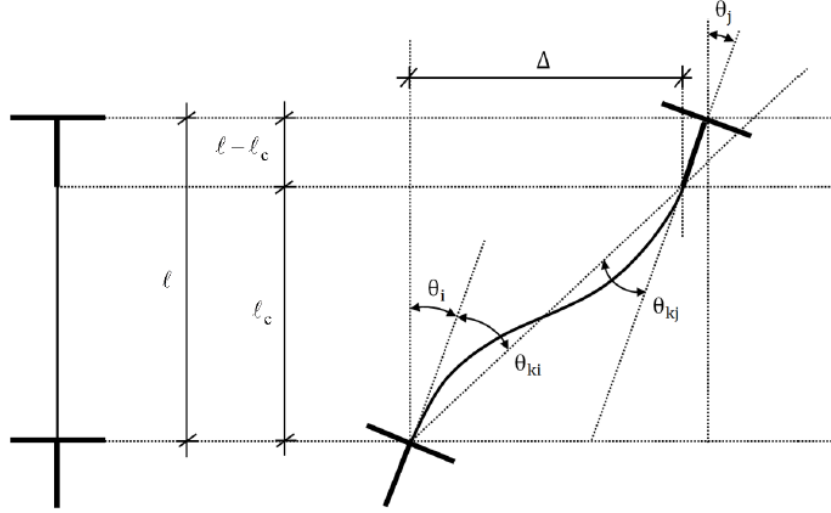


Figure 3.1 Bending member strain properties

After yielding at the I end of the element, the overall rotation of the displaced axis is the sum of the yield rotation and the plastic rotation at that point (Equ. 3.2)

$$\theta_{ki} = \theta_{yi} + \theta_{pi} \quad (3.2)$$

Where, θ_{yi} : yield rotation and θ_{pi} : plastic rotation

The displaced axis rotation calculated as a result of earthquake loadings made in the three-dimensional computer model is compared with the rotation capacities corresponding to the concrete and reinforcement unit strains Table 3.7 determined by the damage limits defined by the TBEC (2018), and the expected element damages in terms of bending effects are determined .

Table 3-7 Strain limits for damage classes of elements

	LD	CD	CP
Concrete	0.0025	$0.75\varepsilon_c^{CP}$	$\varepsilon_c^{CP} = 0.0035 + 0.04\sqrt{\omega_{we}} \leq 0.018$
Reinforcement	0.0075	$0.75\varepsilon_s^{CP}$	$\varepsilon_s^{CP} = 0.4\varepsilon_{su}$

The terms in Table 3-7. are explained below:

LD: Limited Damage

CD: Controlled Damage

CP: Collapse Prevention

ε_c^{CP} : Allowable concrete strain limit for the collapse prevention performance level.

ε_s^{CP} : Allowable reinforcing steel strain limit for the collapse prevention performance level.

ε_{su} : Reinforcement strain corresponding to maximum strength.

ω_{we} : Mechanical reinforcement ratio of effective winding reinforcement.

In this study, the moment and curvature properties of the sections were calculated using the concrete material model (unconfined concrete model) and the reinforcing steel material model recommended in the TBEC (2018). The calculated curvature values were multiplied by the length of the plastic hinge (50% of the section depth in the bending direction was assumed) and the rotation values were obtained.

Yield rotation (θ_{yi}) and plastic rotation (θ_{pi}) values at the ends of bending elements were calculated for all three damage limits (LD, CD, and CP) according to the concrete and reinforcement deformation limits determined in the TBEC (2018) and listed in table 3.7. The damaged regions of the elements were determined by comparing them with the displaced axis rotations at the element ends figure 3.2.

The following notes were considered in the building assessment:

- The bending moment capacity of the vertical structural members is determined by using axial force which is determined under vertical loads according to Part 5.2.2 in TBEC (2018).
- Basement Shear Walls are modeled as linear elements according to Part 5.4.4 in TBEC 2018.

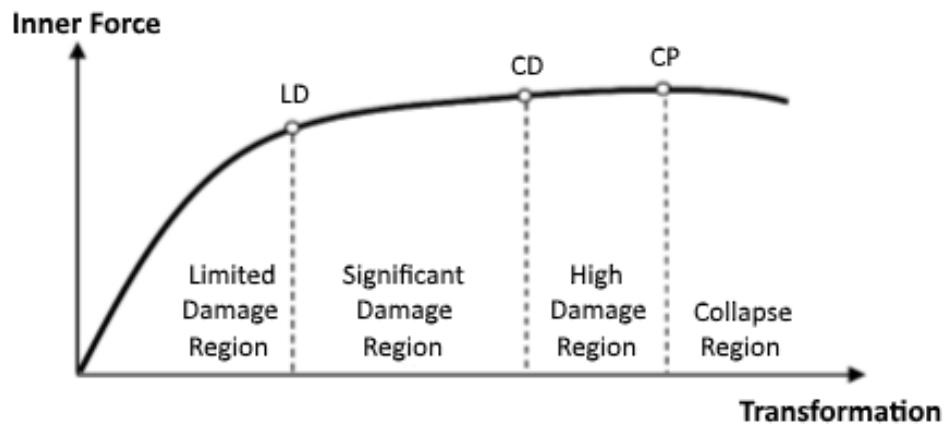


Figure 3.2 Damage regions curve

3.2. Seismic Performannce Assessment

3.2.1.Procedure and Methodology

In this thesis, the current performance-based seismic design of a building located at of Istanbul Province - Kadıköy District. The building whose location is given in figure 3.3 is used as a residence.

The general view of the building given in figure 3.4 consists of a total of 6 floors, including a basement, ground floor, and 4 normal floors. The building has a carrier system formed with a reinforced concrete frame.

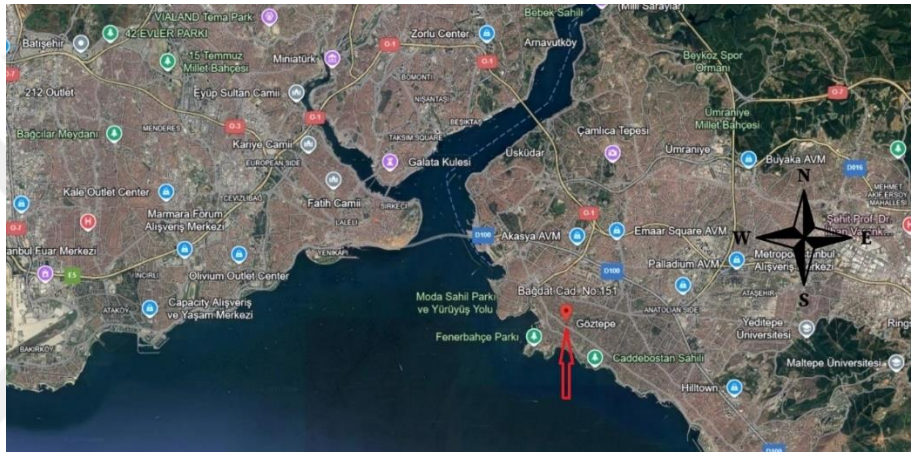


Figure 3.3 Building Location map



Figure 3.4 Building General view

The plan dimensions of the building, which has a rectangular geometry in plan, are measured as 17.50 m x 17.50 m on the basement floor and 20.50 m x 20.50 m on the ground and normal floors. The floor heights of the building were measured as 2.40m in the basement, 3.60m on the ground floor, 2.90m on the 1st-3rd floors, and 2.70m on the 4th floor. The building floor system is a solid slab in the basement and a mixed system (one-way ribbed slab and solid slab) on the other floors. On floors where ribbed slabs are used, the cross-section of ribs is 10x32 cm² and the plate thickness is 7 cm.

a) Loads

The loads and abbreviations taken into account in the analysis and investigations to determine the current performance level of the building are given in Table 3.8.

Table 3-8 Loads taken into account in the study

Abbreviation	Load Description
DL	Self-loads created by the structure's weight
FL	Finishing loads (coating, installation dead loads)
LL	Live loads
SL	snow load
E_{qx}	Earthquake effect in the X-direction
E_{qy}	Earthquake effect in the Y-direction
E_{qz}	Earthquake effect in the vertical direction

Dead Loads

The weights of the elements such as columns, beams, and slabs that make up the carrier system were calculated with the FE program used. In the calculations, the unit volume weights of the reinforced concrete elements are taken as 25 kN/m^3 .

Finishing Loads

Finishing load was taken into account as follows

Floor Finishing Loads (Coating + Plaster + Leveling
Concrete) 1.0 kN/m^2

Partition Wall Loads 1.0 kN/m^2

Live Loads

Live loads are taken into account following the TS498 standard as follows:

Rooms 2.0 kN/m^2

Corridor and Stairs 3.5 kN/m^2

Snow Loads

Snow load is taken into account as 0.75 kN/m^2 following the TS498 standard.

Earthquake Loads (Eqx, Epy, Eqz)

The building was evaluated for seismic performance according to TBEC (2018). According to that, the building is expected to satisfy the requirements of Life Safety performance level (Controlled Damage) under DD2 earthquake (10% probability of exceedance within 50 years and corresponds to a return period of 475 years). For the area where the structure is situated, the spectral acceleration coefficients for short periods (S_S) and for 1 second (S_1), the peak ground acceleration (PGA), and the corner periods of the horizontal elastic acceleration spectrum (T_A and T_B) were sourced from the 2018 Türkiye Earthquake Hazard Maps. The design values were obtained by multiplying these values with the local soil effect coefficients specified in the TBEC (2018) for the ZB class soil. Accordingly, PGA: 0.408, S_{DS} : 0.898 ve S_{D1} : 0.218 T_A :0.048 sec, and T_B :0.242 sec were calculated for the DD2 earthquake level. The location of the building on the Türkiye Earthquake Hazard Map is given in figure 3.5 and the horizontal elastic acceleration spectra obtained for the DD2 earthquake level are given in Figure 3.6.

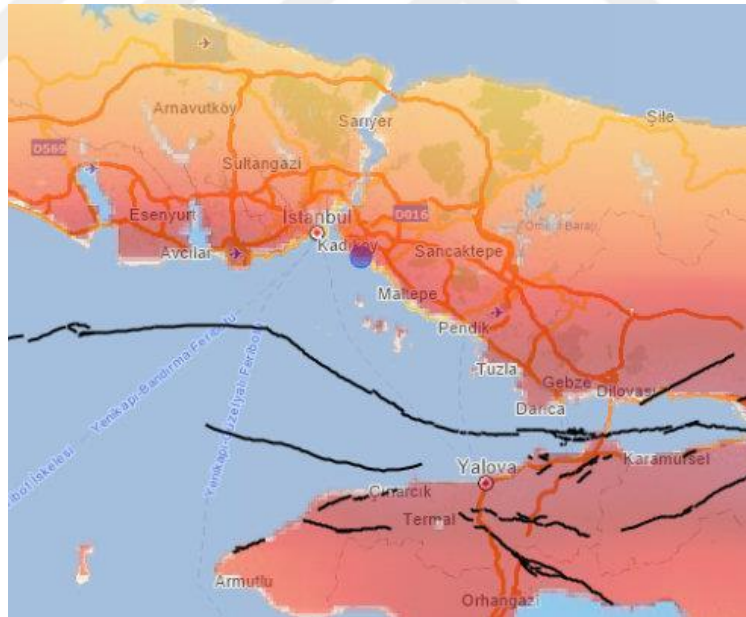
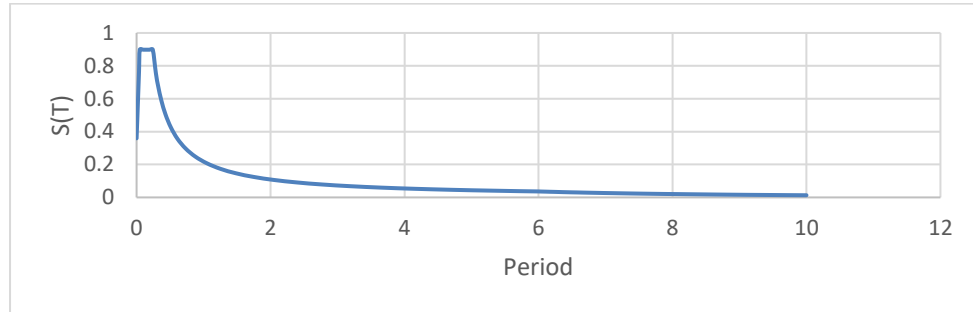


Figure 3.5 Location of the Structure According to Active Faults on the
Türkiye Earthquake

The vertical earthquake effect (E_{qz}) has been added to the relevant combinations as $(2/3 \times S_{DS} \times G)$ following the article 4.4.3.2 of the TBEC (2018) (G : building self-weights and finishing loads DL+FL).

Table 3-9. Spectral Acceleration and Soil Type Factors for Earthquake Classes

Seismic	S _s	S ₁	F _s	F ₁	S _{Ds}	S _{D1}	T _a	T _b	T _L
DD2	0.998	0.272	0.900	0.800	0.898	0.218	0.05	0.24	6.00

**Figure 3.6** Horizontal elastic acceleration spectrum of the DD2 earthquake**b) Load Combinations:**

In this thesis, the load combinations considered during the current examination of the structure and after the strengthening are given in Table 3-10.

Table 3-10. Load combinations

Load Combination	Dead Load		Live Load			Earthquake Load		
	DL	FL	LL	QL	SL	E _{qx}	E _{qy}	E _{qz}
1.4G+1.6Q	1.4	1.4	1.6	1.6	1.6	-	-	-
G+Q±E _x ±0.3E _{qz}	1	1	1	1	1	±1.0	-	±0.3
G+Q±E _y ±0.3E _{qz}	1	1	1	1	1	-	±1.0	±0.3
0.9G±E _x ±0.3E _{qz}	0.9	0.9	-	-	-	±1.0	-	±0.3
0.9G±E _y ±0.3E _{qz}	0.9	0.9	-	-	-	-	±1.0	±0.3

c) Soil Parameters :

According to the geotechnical parameters of the ground of the region where the building is located, the local soil class was determined as ZB according to the TBEC (2018) - Table 16.1. The basic bearing capacity is 9.00 kg/cm² and the bearing coefficient is 3000 tons/m³.

d) Material Mechanical Properties :

The concrete compressive strength obtained from the core test results and the uncoated concrete stress-strain relationship specified in the TBEC (2018) were obtained. On the other hand, in the retrofitting and rebuilding systems, C30 Class concrete and S420 grade structural reinforcement were used. The mechanical properties of C14 and C30 Class concrete are listed in Table 3-11.

Table 3-11. The properties of concrete

Member	Concrete grade	F_{ck} (N/mm ²)	F_{cd} (N/mm ²)	F_{ctd} (N/mm ²)	E (N/mm ²)
Existed Building	C14	14.00	9.33	0.87	26150
Retrofit and new Building	30	30.00	20.00	1.35	32837

The mechanical properties of the reinforcement considered in the calculations are given in Table 3-12.

Table 3-12. Properties of longitudinal and transverse reinforcements

Member	Rebar grade	F_{yk} (N/mm ²)	E (N/mm ²)
Existed Building	S220	220	200000
Retrofit and new Building	S420	420	200000

e) FE Modeling

The FEM of the structure was established using the ProtaStructure software (Figure 3.7). The linear calculation method specified in the TBEC (2018) was used while determining the earthquake performance of the building for the current situation, retrofit, and new situations. The mode combining (superposition) method was used in the analysis of earthquake effects. While calculating the earthquake forces, 95% mass participation was achieved in both main directions. In the FEM, the existing columns and beams are modeled as bar elements and walls and slabs are modeled as shell elements. The assumptions made during modeling are presented below:

- The damping ratio was taken as 5% for DD2 earthquake effects.
- During the determination of earthquake effects, the live load participation coefficient was taken as $n=0.3$.

- Effective section stiffnesses are included in the calculations according to TBEC (2018), and listed in Table 3.12.

Building Target Performance Level in ProtaStructure are shown in Figure 3.8.

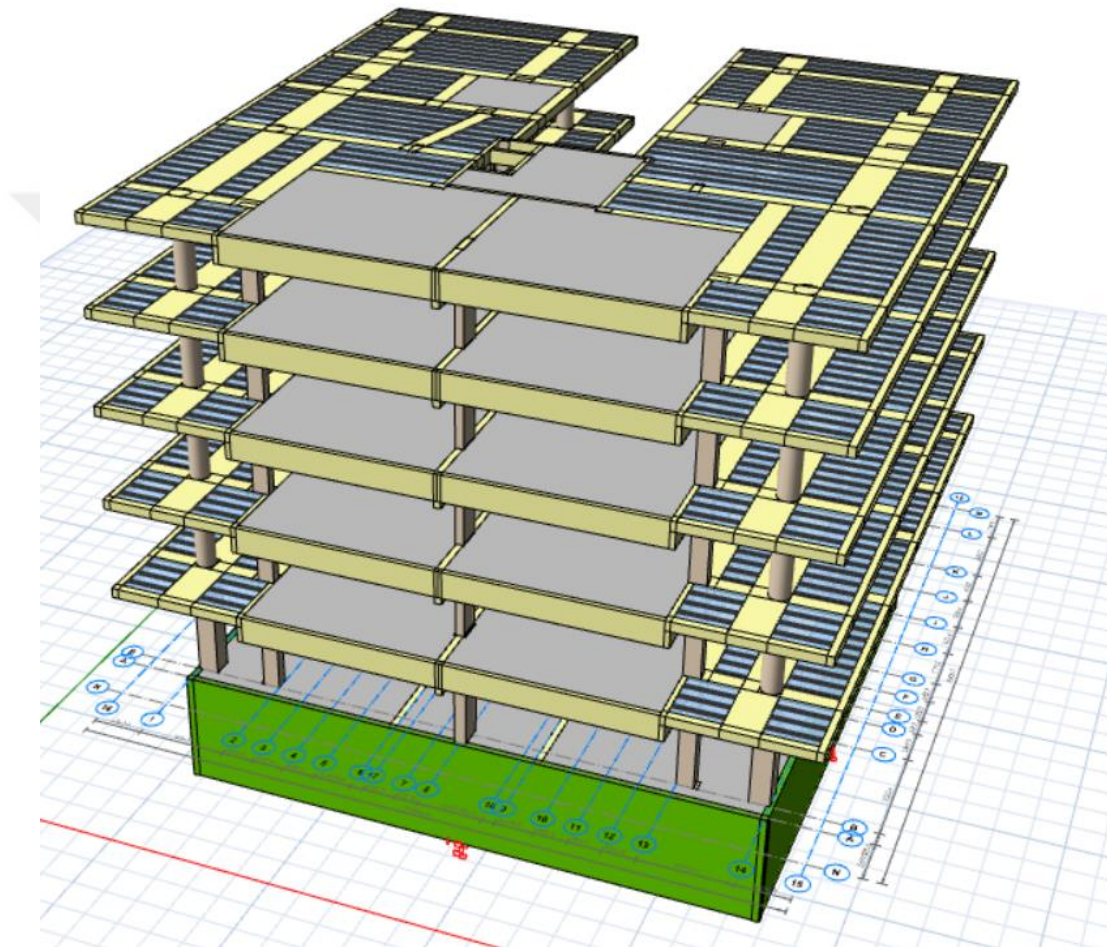


Figure 3.7 FEM of an existing building in ProtaStructure Software

For further structural plans of the existing building modeled using ProtaStructure, please refer to **Appendix B**.

Table 3-13. Effective section stiffnesses are taken into account in the calculations

	Effective Section Stiffness Multiplier	
Shear wall– slab (In-Plane)	Axial	Shear
Shear Wall	0.50	0.50
Basement Wall	0.80	0.50
Slab	0.25	0.25
Shear wall– slab (Out of Plane)	Bending	Shear
Shear Wall	0.25	1.0
Basement Wall	0.50	1.0
Slab	0.25	1.0

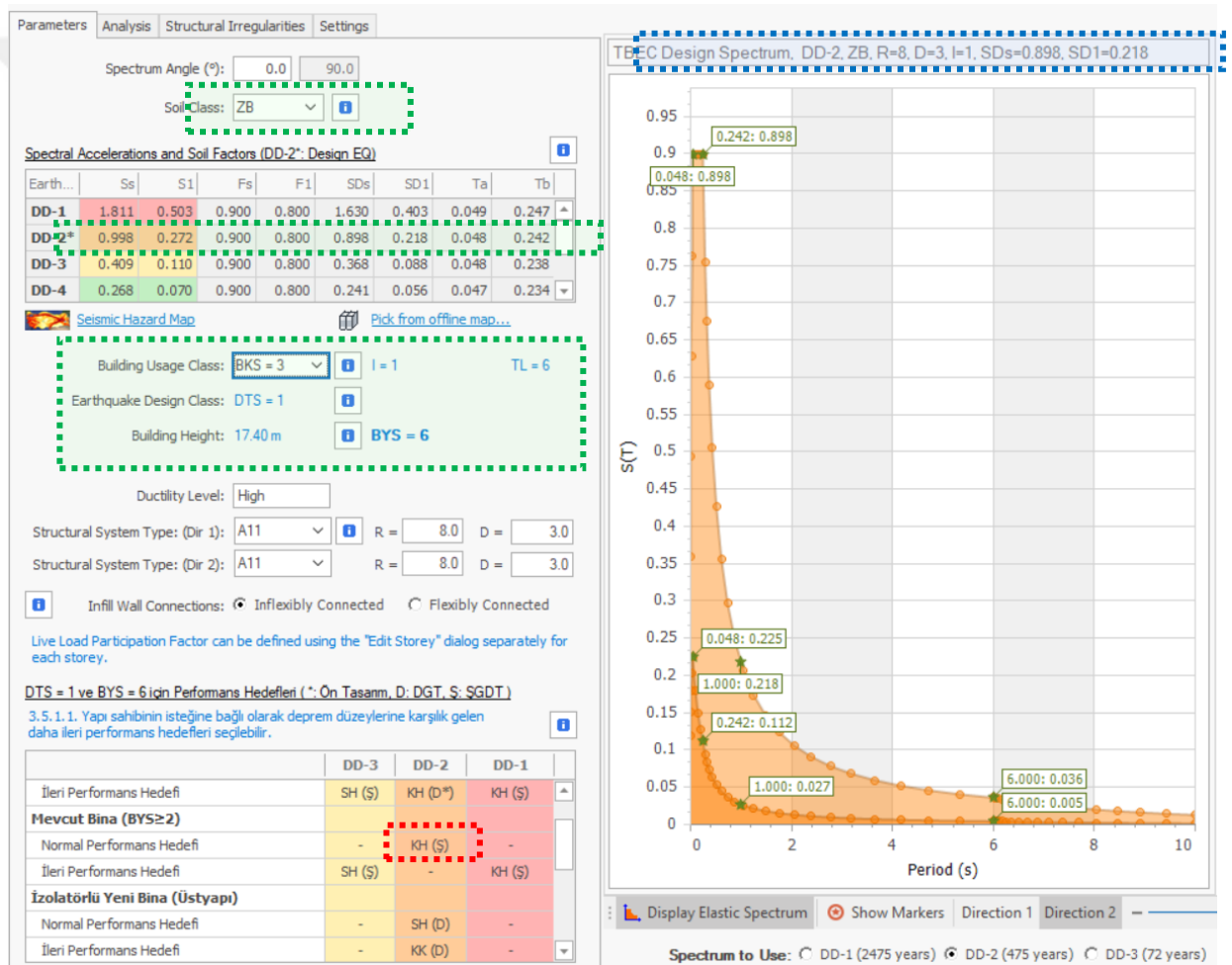


Figure 3.8 Earthquake parameters and building performance level in Protostructure software.

3.2.2. Existing Building Performance Evaluation Procedure and Results

In this study, existed building performance level evaluation procedure was shown in Figure 3.9. Building performance level is a function of stiffness which directly affects story drift and lateral displacement of the building and member's shear strength which affects the damage levels of the members (LD, CD, CP).

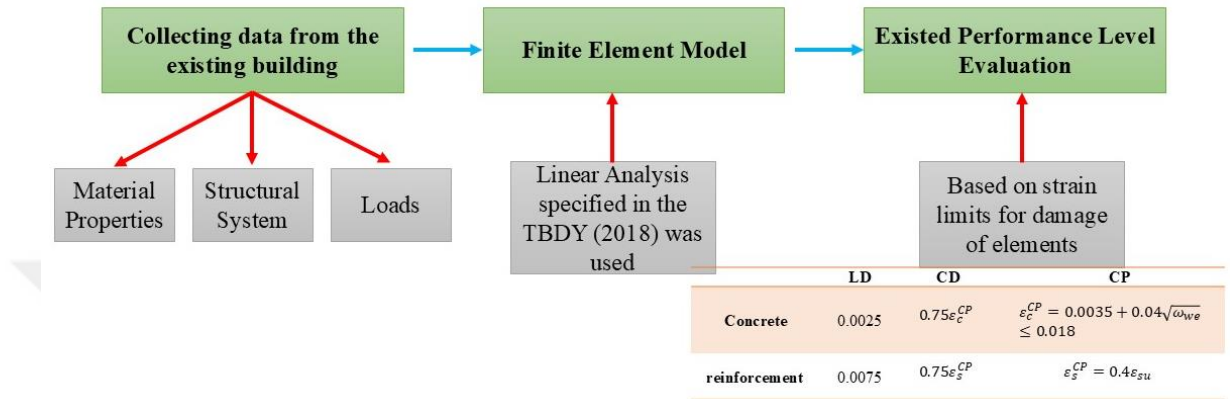


Figure 3.9 Existed building performance level evaluation

According to linear analysis results calculated using Protastuctre software, the damage levels of the members that occurred in beams and columns are summarized in Table 3-14 for existed building. Based on the results, for the existing building, the 2nd story was the most critical. Three columns reached collapse pervention damage and one column reached collapse performance level. In addition, one column reached collapse pervention and one column reached collapse performance level in the 3rd story, while only one column reached collapse performance level in the 4th story. Hence, as shown in Table 3-14, the number of vertical members in the failure region and the shear contribution of the vertical members exceed the controlled damage region at both ends. The actual performance level was determined to be 'collapse', whereas the required performance goal is controlled damage according to (TBEC 2018 - 15.8.4). Therefore, building performance goals are not satisfied.

The results showed that, in the the existing building, the strengths of steel and concrete are around 220 and 14 MPa respectively, which is contrary to modern earthquake codes. This problem caused an excessive rotation of the vertical structural members.

Therefore, the results showed that rotation failure was considered in the beams. This failure typically more gradual and associated with excessive bending or lateral displacement, which can lead to ductile failures, but may also result in progressive collapse if plastic hinges form. As a result, the increase in the shear strength of collapsed columns and the decrease in the rotation of beams should be considered.

Table 3-14. Damage levels of the members for existing building

Storey	Member	Member Quantity					Member Shear Forces Ratio			
		Total	LD	CD	CP	C	LD	CD	CP	C
1	Columns:	32	14	18	0	0	0.7051	0.2905	0.0000	0.0000
	Beams:	14	0	14	0	0				
2	Columns:	26	0	22	3	1	0.0000	0.8196	0.1374	0.0429
	Beams:	17	0	17	0	0				
3	Columns:	26	1	23	1	1	0.0033	0.7613	0.1237	0.1117
	Beams:	17	0	17	0	0				
4	Columns:	26	1	24	0	1	0.0044	0.8772	0.0000	0.1184
	Beams:	17	0	17	0	0				
5	Columns:	26	0	26	0	0	0.0000	1.0000	0.0000	0.0000
	Beams:	17	0	17	0	0				
6	Columns:	26	0	26	0	0	0.0000	1.0000	0.0000	0.0000
	Beams:	17	0	17	0	0				

No. of Beams in Limited Damage Region: $0/99 = 0$ (0 %)

No. of Beams in Controlled Damage Region: $99/99 = 1$ (100 %)

No. of Beams in Collapse Prevention Region: $0/99 = 0$ (0 %)

No. of Beams in Collapse Region: $0/99 = 0$ (0 %)

No. of Vertical Members in Limited Damage Region: $16/162 = 0.098$ (9.8 %)

No. of Vertical Members in Controlled Damage Region: $139/162 = 0.858$ (85.8 %)

No. of Vertical Members in Collapse Prevention Region: $32/162 = 0.025$ (2.5 %)

No. of Vertical Members in Collapse Region: $3/162 = 0.019$ (1.9 %)

Determined Building Performance Level: Controlled Damage (TBEC 2018- 15.8.4)

From ProtaStructure software the maximum lateral, X, and Y-displacements are considered for both Ex+ and Ey+ load combinations and the results are listed in Table 3-15. This result showed that at the top of the building the displacements were 1.9657 mm and from 95.081 mm in X- and Y- directions, respectively.

For further details on the structural analysis tables of the building generated using ProtaStructure software , please refer to **Appendix A**.

Table 3-15. Story displacements results

Load Case	Storey	Existed Building	
		Displacement-X (m)	Displacement-Y (m)
Ex+	1	2.9644 E-04	-3.9205 E-07
Ey+		1.2571 E-05	1.2739 E-04
Ex+	2	1.9997 E-02	-1.9124 E-04
Ey+		-1.8684 E-04	1.9952 E-02
Ex+	3	4.5220 E-02	-5.4595 E-04
Ey+		-5.8077 E-04	4.3810 E-02
Ex+	4	7.0144 E-02	-9.7260 E-04
Ey+		-1.0541 E-03	6.6142 E-02
Ex+	5	9.0694 E-02	-1.4102 E-03
Ey+		-1.5372 E-03	8.3893 E-02
Ex+	6	1.0468 E-01	-1.8033 E-03
Ey+		-1.9657 E-03	9.5081 E-02

4. RETROFITTING OF THE ACTUAL RC BUILDING

4.1. RC Shear Wall Addition and CFRP Wrapping of Columns Retrofitting Alternative

4.1.1. Procedure and Methodology

CFRP wrapping was applied to the ground story columns with three layers, as well as selected columns in the first story. Additionally, three shear walls were incorporated into the structural retrofit. RC shear wall addition and CFRP wrapping of columns were applied to limit the excessive rotation of the vertical structural members.

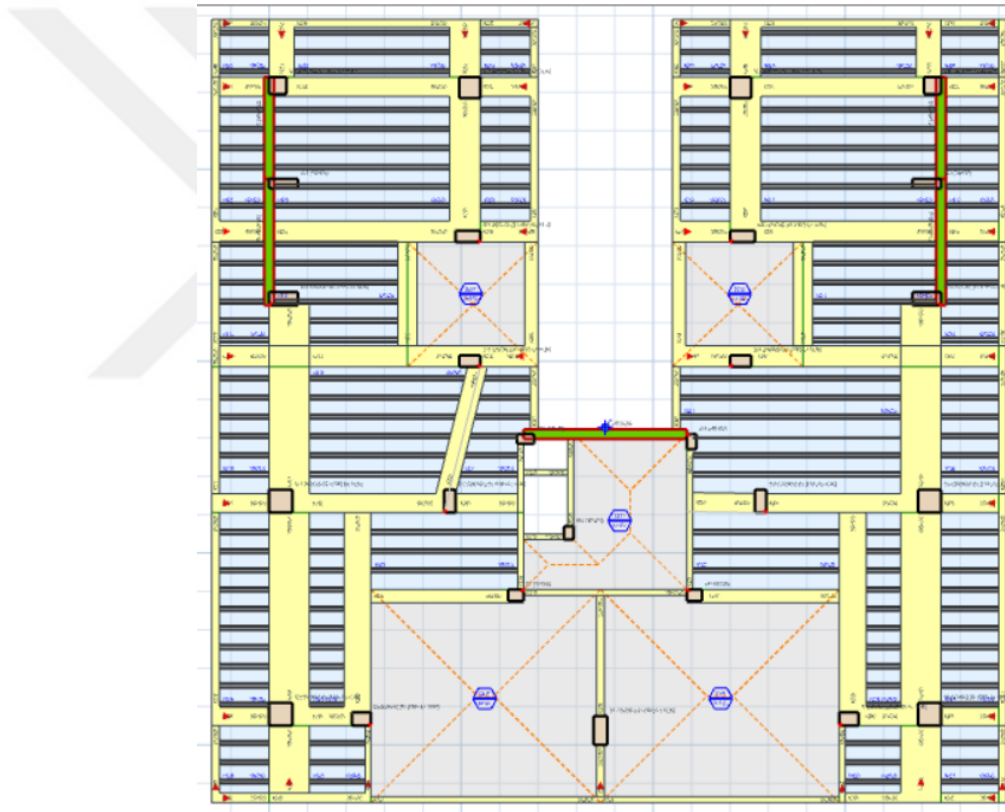


Figure 4.1 RC shear wall addition and CFRP wrapping of columns retrofit's FEM.

a) CFRP Application

In this study a 3 layers CFRP for the ground floor columns and only one column in the 1st story has been used. The characteristics of the CFRP sheets were selected according to Inci et al. 2021 and summarized in Table 4-1. Then shear contribution and compressive strength were calculated as per TBEC 2018 Eqs (15B.1 -15B.7). As an example shear contribution and compressive strength calculations are summarized in Table 4-2 and Table 4-3.

Table 4-1. The characteristics of the CFRP sheets

Structural Parameters	Symbol	Unit	Value
Number Of Layers	n_f		3.0
Effective Thickness	t_f	mm	0.165
Strip Width	w_f	mm	100.0
Fillet Radius	r_c	mm	30.0
Modulus of Elasticity	E_f	N/mm ²	240000.0
Ultimate Strain	ε_{fu}		0.02
Strain Limit	ε_f		0.004

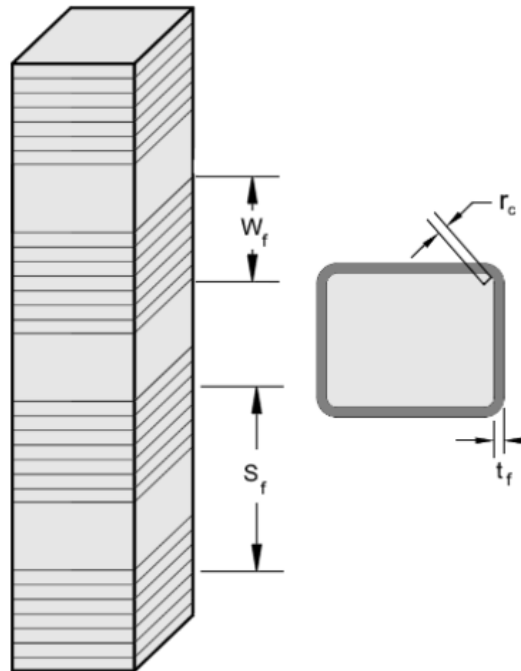


Figure 4.2 CFRP Confinement of Rectangular Columns

$$V_r = V_c + V_w + V_f \leq V_{max} \quad \text{TBEC 2018 (15B.1)}$$

$$V_f = \frac{2n_f t_f w_f E_f \varepsilon_f d}{S_f} \quad \text{TBEC 2018 (15B.2)}$$

The maximum effective strain was calculated using TBEC 2018 Eqs. (15B.3 and 15B.4)

$$\varepsilon_f \leq 0.004 \quad \text{TBEC 2018 (15B.3)}$$

$$\varepsilon_f = 0.50 \varepsilon_{fu} \quad \text{TBEC 2018 (15B.4)}$$

The compressive strength was calculated using TBEC 2018 Eq. (15B.5)

$$f_{cc} = f_{cm} \left[1 + 2.4 \left(\frac{f_1}{f_{cm}} \right) \right] \geq 1.2 f_{cm} \quad \text{TBEC (15B.5)}$$

The lateral pressure by CFRP was calculated using TBEC 2018 Eq. (15B.6)

$$f_1 = \frac{1}{2} K_a \rho_f E_f \varepsilon_f \quad \text{TBEC (15B.6)}$$

The shape factor was calculated using TBEC 2018 Eq. (15B.7)

$$K_a = \begin{cases} 1 \\ b/h \\ 1 - \frac{(b-2r_c)^2 + (h-2r_c)^2}{3bh} \end{cases} \quad \text{TBEC 2018 (15B.7)}$$

Example C1-in story No. 1

Table 4-2. Shear Contribution Calculations

Structural Parameters	Symbol	Unit	X	Y
Effective Depth of Member	d	mm	413.0	413.0
Shear Contribution	V _f	kN	193.12	193.12

Table 4-3. Compressive Strength Calculations

Structural Parameters	Symbol	Unit	Value
Unwrapped Concrete Compressive Strength	cm	N/mm ²	14.00
Shape Effect Factor	K _a		0.50
Volumetric Ratio Of LP	ρ _f		0.002
Lateral Pressure By LP	f _l	N/mm ²	0.57
Calculated Compressive Strength	f _{cc}	N/mm ²	16.80

b) Sizing and Locating Shear Walls

In this study, RC shear wall addition and CFRP wrapping of columns were applied to limit the excessive rotation of the vertical structural members, the dimensions and location of shear walls were selected based on the following points:

1. Achieve the performance goal,
2. Provide symmetry in X and Y direction,
3. Keep the distance of the centre of gravity and resistance near to each other.

Hence trial-error method was used until the final dimension and positions achieved the performance goal. In this study, the RC shear wall addition and CFRP wrapping of columns retrofit building performance evaluation procedure was shown in Figure 4.3.

For illustrative examples of reinforcement detailing of shear walls, please refer to **Appendix C**.

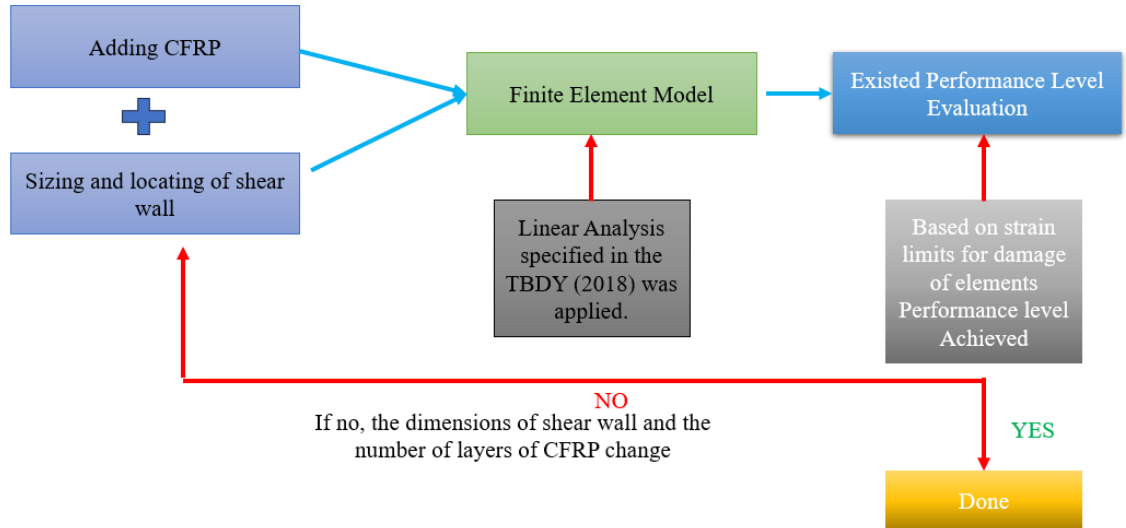


Figure 4.3 RC shear wall addition and CFRP wrapping of columns retrofit building performance level evaluation

4.1.2. Seismic Performance Level Evaluation Results

According to linear analysis results calculated using Protastrucutre software, the number of plastic rotation occurred in beams and columns are summarized in Table 4-4 for RC shear wall addition and CFRP wrapping of columns retrofit building.

As shown in Table 4-4, the using of RC shear wall addition and CFRP wrapping of columns retrofit significantly decreased the shear capacity of the members, and all damage levels of the members are located in the limited and controlled damage level. Table 4-4 shows that there are no vertical members in the collapse pervention damage region nor failure region and the shear contribution of the vertical members which exceeded the controlled damage region at both ends was less than 30%. Hence the overall building performance satisfies the requirements of controlled damage performance level according to (TBEC 2018 -15.8.4).

Table 4-4. Damage levels of the members for RC shear wall addition and CFRP wrapping of columns retrofit building

Storey	Member	Member Quantity					Member Shear Forces Ratio			
		Total	LD	CD	CP	C	LD	CD	CP	C
1	Columns:	32	32	0	0	0	1.0000	0.0	0.000	0.0
	Beams:	14	4	10	0	0				
2	Columns:	27	9	18	0	0	0.6695	0.3305	0.000	0.000
	Beams:	16	5	11	0	0				
3	Columns:	27	24	3	0	0	0.9545	0.0455	0.000	0.0000
	Beams:	16	7	9	0	0				
4	Columns:	27	25	2	0	0	0.9809	0.0191	0.000	0.0000
	Beams:	16	4	12	0	0				
5	Columns:	27	26	1	0	0	0.9867	0.0133	0.000	0.0000
	Beams:	16	5	11	0	0				
6	Columns:	27	19	8	0	0	0.7965	0.2035	0.000	0.0000
	Beams:	16	8	8	0	0				

No. of Beams in Limited Damage Region: $33/94 = 0.351$ (35.1 %)

No. of Beams in Controlled Damage Region: $61/94 = 0.649$ (64.9 %)

No. of Vertical Members in Limited Damage Region: $135/167 = 0.808$ (80.8 %)

No. of Vertical Members in Controlled Damage Region: $32/167 = 0.192$ (19.2 %)

Determined Building Performance Level: Controlled Damage (TBEC 2018- 15.8.4)

From ProtaStructure software the maximum lateral, X, and Y-displacements are considered for both Ex+ and Ey+ load combinations and the results are listed in Table 4-5. This result proved that CRFP with shear wall retrofits significantly decreased building lateral displacements in the upper stories. At the top of the building the displacement were decreased from 1.9657 mm to 1.5453 mm and from 95.081 mm to 35.586 mm in X- and Y- directions, respectively. In other words, building the displacement was decreased by 21.4% and 62.6% in X- and Y- directions, respectively. This significant decrease was mainly due to the addition of shear walls increasing the building stiffness and reducing the eccentricity between the center of gravity and the center of rigidity. For further details on the structural

analysis tables of the building generated using ProtaStructure software , please refer to Appendix A.

Table 4-5. Story displacements results

Load Case	Storey	RC shear wall addition and CFRP wrapping of columns	
		Displacement-X (m)	Displacement-Y (m)
Ex+	1	6.7900 E-04	4.7867 E-06
Ey+		5.4415 E-06	5.0989 E-04
Ex+	2	1.2303 E-02	6.7839 E-05
Ey+		1.6506 E-04	6.4438 E-03
Ex+	3	2.6106 E-02	2.0268 E-04
Ey+		4.1684 E-04	1.3246 E-02
Ex+	4	4.1526 E-02	3.8082 E-04
Ey+		7.5817 E-04	2.0924 E-02
Ex+	5	5.7205 E-02	5.8486 E-04
Ey+		1.1580 E-03	2.8765 E-02
Ex+	6	7.1027 E-02	7.9040 E-04
Ey+		1.5453 E-03	3.5586 E-02

4.2. RC jacketing of columns Retrofitting Alternative

4.2.1. Procedure and Methodology

The column's jacketing increased both the building's lateral stiffness and increased the column's shear strength capacity. The following points were considered in modeling column's jacketing:

- RC jacketing was applied on columns only.
- RC jacketing was applied to all columns on the underground floor, ground floor, and first floor, as well as to one column on the second floor.
- The thickness of the jacketing was selected to be 150 mm in each dimension correspondingly the reinforcement was determined.
- The interaction diagram method was used to calculate the final column capacity after jacketing.

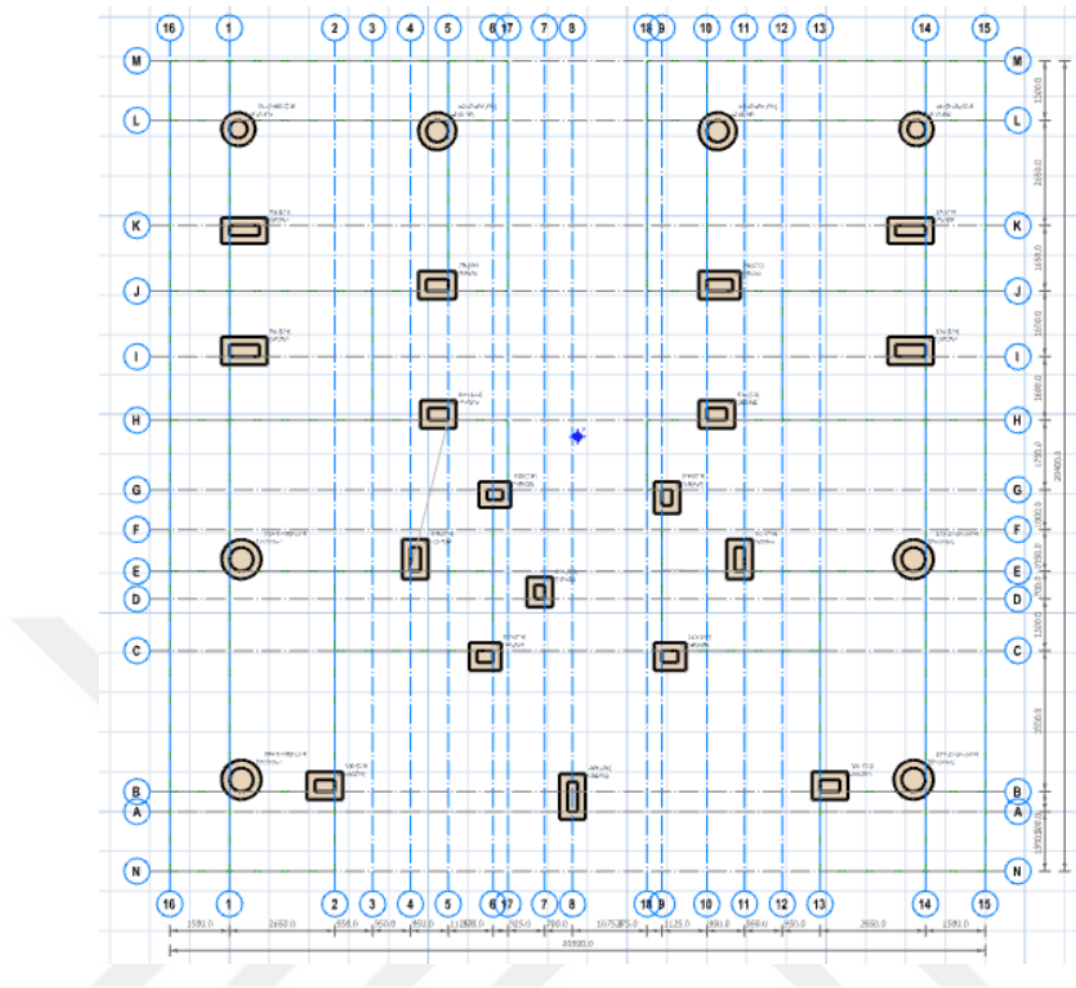


Figure 4.4 Jacketing retrofit's FEM of the building in ProtaStructure Software

Figures 4.5 and 4.6 show the columns's jacketing and used interaction diagram.

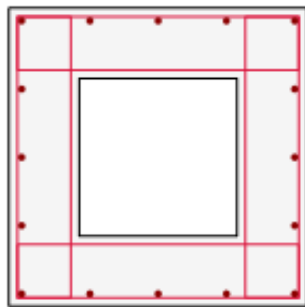


Figure 4.5 column's jacketing

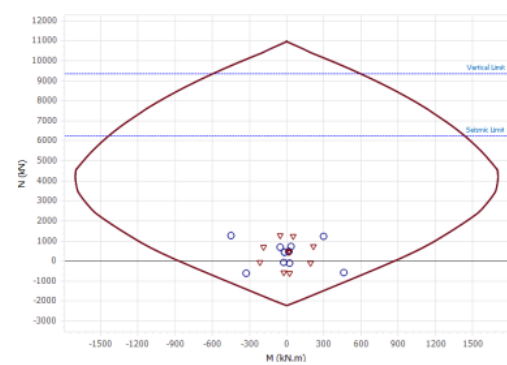


Figure 4.6 used interaction diagram

For illustrative examples of reinforcement detailing, please refer to **Appendix C**.

In this study, the procedure used for determining the performance level for the jacketing retrofit building is shown in figure 4.7.

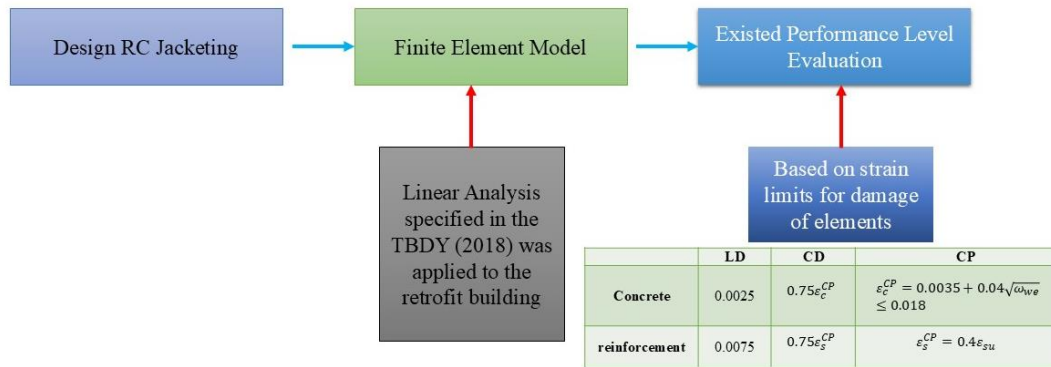


Figure 4.7 Column's jacketing retrofit building performance level evaluation

4.2.2. Seismic Performance Level Evaluation Results

According to linear analysis results calculated using Protastrucutre software, the damage levels of the members that occurred in beams and columns are summarized in table 4.6 for RC jacketing of columns retrofit building. RC jacketing of columns was applied for columns in the ground story and one column only in the first story, quite enhanced the shear capacity of the members and most of the damage levels of the members occurred are located in the limited damage level, and a small amount are located in the controlled damage level as it is shown in Table 4-6 , the results show that there are no vertical members in the collapse pervention region or failure region, and the shear contribution of the vertical members that exceeded the controlled damage region was less than 30%, the total building performance goals was life safety and satisfied according to (TBEC 2018 -15.8.4) requirements.

Similar to RC shear wall addition and CFRP wrapping of columns retrofitting method, the addition of RC jacketing of columns method significantly improved the resistance to collapse of columns and indirectly reduced the rotational deformation of beams, and which successfully increased the overall building performance level.

Table 4-6. Damage levels of the members for RC jacketing of columns retrofit building

Storey	Member	Member Quantity					Member Shear Forces Ratio			
		Total	LD	CD	CP	C	LD	CD	CP	C
1	Columns:	60	60	0	0	0	1.0000	0.0000	0.0	0.0
	Beams:	14	5	9	0	0				
2	Columns:	52	50	2	0	0	0.8993	0.1007	0.0	0.0
	Beams:	17	12	5	0	0				
3	Columns:	27	14	13	0	0	0.4796	0.5204	0.0	0.0
	Beams:	17	15	2	0	0				
4	Columns:	26	20	6	0	0	0.6953	0.3047	0.0	0.0
	Beams:	17	10	7	0	0				
5	Columns:	26	26	0	0	0	1.0000	0.0000	0.0	0.0
	Beams:	17	13	4	0	0				
6	Columns:	26	26	0	0	0	1.0000	0.0000	0.0	0.0
	Beams:	17	9	8	0	0				

No. of Beams in Limited Damage Region: $64/99 = 0.646$ (64.6 %)

No. of Beams in Controlled Damage Region: $35/99 = 0.354$ (35.4 %)

No. of Vertical Members in Limited Damage Region: $196/217 = 0.903$ (90.3 %)

No. of Vertical Members in Controlled Damage Region: $21/217 = 0.097$ (9.7 %)

Determined Building Performance Level: Controlled Damage (TBDY 2018 - 15.8.4)

From ProtaStructure software the maximum lateral, X, and Y-displacements are considered for both Ex+ and Ey+ load combinations and the results are listed in Table 4.7. For RC jacketing of columns retrofit system, the building displacement at the top slightly decreased from 1.9657 mm to 1.9652 mm and from 95.081 mm to 85.704 mm in X- and Y- directions, respectively. This small decrease in the lateral displacement was because RC jacketing of columns was applied to the second story columns. For further details on the structural analysis tables of the building generated using ProtaStructure software, please refer to **Appendix A**.

Table 4-7. Story displacements results

Load Case	Storey	Jacketing Retrofit Building	
		Displacement-X (m)	Displacement-Y (m)
Ex+	1	6.2079 E-04	1.6649 E-06
Ey+		1.3089 E-05	2.7000 E-04
Ex+	2	8.5559 E-03	-8.5206 E-07
Ey+		-3.1082 E-05	6.9148 E-03
Ex+	3	2.8618 E-02	-1.3644 E-04
Ey+		-6.9121 E-05	2.6486 E-02
Ex+	4	5.6647 E-02	-3.8238 E-04
Ey+		-5.6109 E-04	5.1551 E-02
Ex+	5	8.2660 E-02	-6.0000 E-04
Ey+		-1.2827 E-03	7.2540 E-02
Ex+	6	1.0137 E-01	-8.1726 E-04
Ey+		-1.9652 E-03	8.5704 E-02

5. RECONSTRUCTION ACTUAL RC BUILDING

5.1. Procedure and Methodology

One of the suggested alternatives is re-designing the building since the existing building has some deficiencies in the structural system Figure 3.16. The following mistakes are listed below:

1. The lacking of the proper reinforcement and lack of the confinement.
2. The strengths of steel and concrete are around 220 and 14 MPa respectively, which is contrary to modern earthquake codes.
3. The continuity of frames does not exist, most of the columns were offset.
4. Some of the columns are in the middle of slabs, connecting columns by beams increases the lateral stiffness.
5. The sections of the second story are not efficient for the large height of the story, hence soft story irregularity has been considered.
6. The distribution of columns was random, so the rigidity center of the building was far away from the building center causing additional torsional force in the building due to the earthquake story forces.

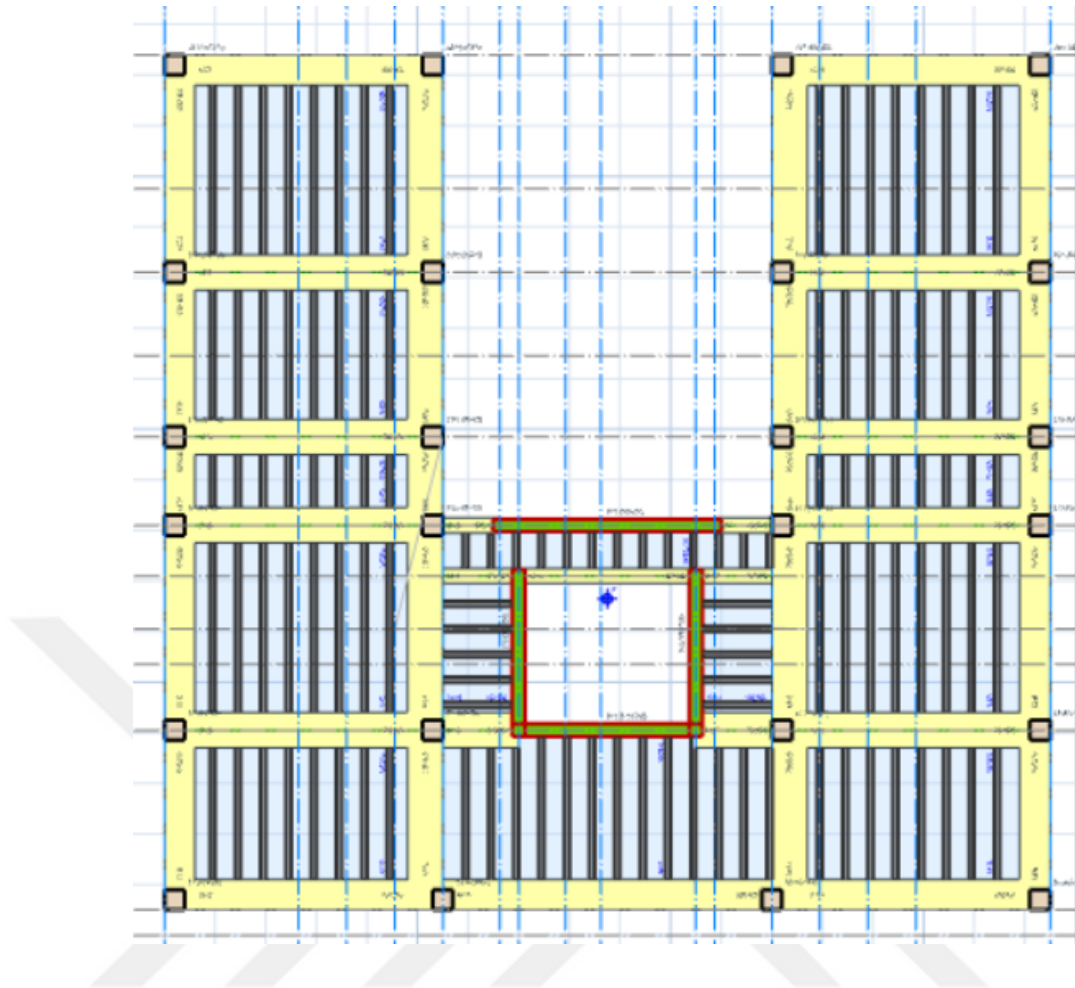


Figure 5.1 Rebuilt building's FEM of the building in ProtaStructure Software

During the design of the new building, the following criteria for the RC frame-wall system are followed:

1. The continuity of frames is taken into consideration to provide an efficient lateral diaphragm.
2. Columns are uniformly distributed to get continuous frames.
3. Beam sizes are kept constant to help in rebar distribution.
4. Core shear wall around stairs zone and normal shear wall were added to, maintain the rigidity (Stiffness) of the building and to keep the centre of mass in the middle of the building.

The structural design and calculations for the reconstruction of the new building, intended to replace the existing substandard structure, were conducted in accordance with TS500 (2000) and TBEC (2018).

The procedure used for determining the performance level of the new building is shown in figure 5.2.

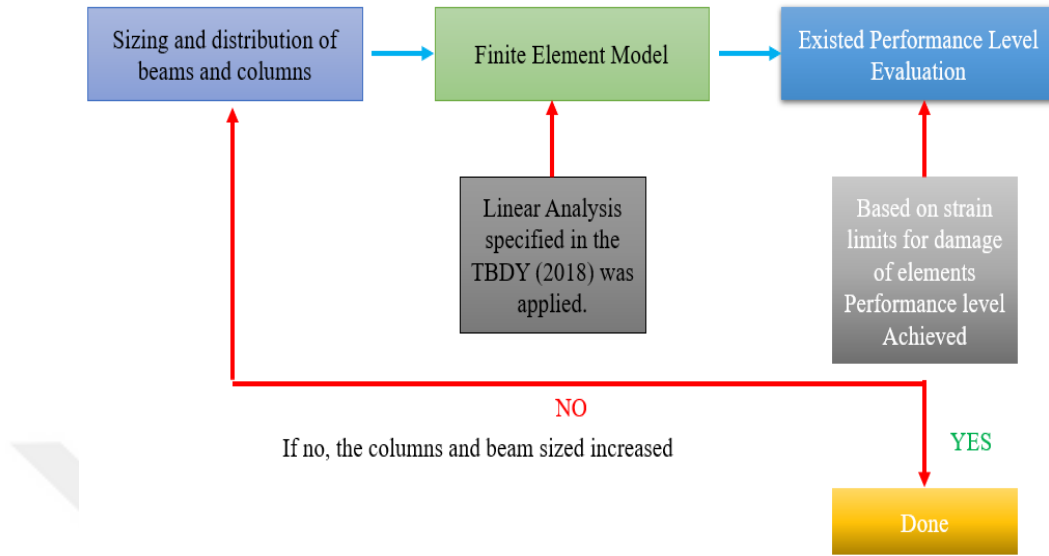


Figure 5.2 Re-designed building performance level evaluation

5.2. Seismic Performance Level Evaluation Results

According to linear analysis results calculated using Protastrucutre software, the damage levels of the members that occurred in beams and columns are summarized in Table 5-1 for the re-designed building. Table 5-1 shows that most of the damage levels of the members are located in the limited damage level and a small amount are located in the controlled damage level. In addition, Table 5-1 shows that there are no vertical members in the controlled damage region or failure region and the shear contribution of the vertical members that exceed the controlled damage region was less than 30%, the total building performance goals were life safety and satisfied according to (TBEC 2018 -15.8.4) requirements.

Table 5-1. Damage levels of the members for re-designed building

Storey	Member	Member Quantity					Member Shear Forces Ratio			
		Total	LD	CD	CP	C	LD	CD	CP	C
1	Columns:	29	29	0	0	0	1.0000	0.0000	0.0	0.0
	Beams:	18	5	13	0	0				
2	Columns:	26	6	20	0	0	0.8085	0.1915	0.0	0.0
	Beams:	20	5	15	0	0				
3	Columns:	26	26	0	0	0	1.0000	0.0000	0.0	0.0
	Beams:	20	9	11	0	0				
4	Columns:	26	26	0	0	0	1.0000	0.0000	0.0	0.0
	Beams:	20	14	6	0	0				
5	Columns:	26	26	0	0	0	1.0000	0.0000	0.0	0.0
	Beams:	20	14	6	0	0				
6	Columns:	26	26	0	0	0	1.0000	0.0000	0.0	0.0
	Beams:	20	14	6	0	0				

No. of Beams in Limited Damage Region: $61/118 = 0.517$ (51.7 %)

No. of Beams in Controlled Damage Region: $57/118 = 0.483$ (48.3 %)

No. of Vertical Members in Limited Damage Region: $139/159 = 0.874$ (87.4 %)

No. of Vertical Members in Controlled Damage Region: $20/159 = 0.126$ (12.6 %)

Determined Building Performance Level: Controlled Damage (TBDY 2018 - 15.8.4)

From ProtaStructure software the maximum lateral, X, and Y-displacements are considered for both Ex+ and Ey+ load combinations and the results are listed in Table 5-2. At the top of the building the displacement were decreased with comparing to the existed building. For further details on the structural analysis tables of the building generated using ProtaStructure software , please refer to Appendix A.

Table 5-2. Story displacements results

Load Case	Storey	Re-designed Building	
		Displacement-X (m)	Displacement-Y (m)
Ex+	1	5.2385 E-04	-1.7427 E-07
Ey+		-8.4525 E-07	2.6542 E-04
Ex+	2	8.4878 E-03	9.3159 E-06
Ey+		-8.4720 E-06	7.6052 E-03
Ex+	3	1.7721 E-02	1.7480 E-05
Ey+		-1.2184 E-05	1.5856 E-02
Ex+	4	2.7811 E-02	-3.1246 E-05
Ey+		-1.3303 E-05	2.4944 E-02
Ex+	5	3.7506 E-02	-2.6420 E-05
Ey+		-1.3696 E-05	3.4045 E-02
Ex+	6	4.5724 E-02	-3.0097 E-05
Ey+		-1.3670 E-05	4.1988 E-02

6. LIFE CYCLE ENVIROMENTAL ASSESSMENT OF ALL ALTERNATIVES

6.1. Life Cycle Enviromental Assessment Methodology

The section concludes the findings, and the effectiveness of the Athena Impact Estimator in facilitating data-driven decisions for sustainable construction practices. Recommendations are provided based on the comparative analysis, suggesting the most environmentally friendly retrofitting options among the assessed scenarios. The Athena Impact Estimator for Buildings is a robust software tool designed to provide environmental impact assessments for various construction projects, including new constructions, renovations, and retrofits. Developed by the Athena Sustainable Materials Institute, this tool offers a comprehensive database that spans multiple materials and construction activities, providing a platform for users to model and analyze environmental impacts across a project's lifecycle. For a visual reference of the user interface in the Athena Impact Estimator for Buildings software utilized in the environmental analysis, please refer to Appendix D. It allows users to assess the environmental ramifications of different construction materials and methods, thereby facilitating informed decision-making aimed at sustainability.(Alauddin Ahammed et al., 2016). the following figure shows the stages of whole-building life cycle assessment.

Whole-Building LCA quantitatively measures the environmental ramifications associated with each phase of a building's existence. This method spans from the extraction of raw materials to the building's end-of-life, including demolition and material recycling or disposal. The primary areas of environmental impact assessed include embodied energy, GWP, and various pollution and resource depletion forms. Following are the key stages in the Whole-Building LCA

- a. Raw Materials: This initial stage involves extracting and processing raw materials used in building construction.
- b. Manufacturing: After the extraction, the raw materials experience different manufacturing processes to convert them into construction products. This stage assesses the energy used and emissions released while manufacturing building components like windows, doors, roofing materials, and insulation.
- c. Construction/Installation: This phase evaluates the on-site processes of constructing the building, which includes the energy consumption and emissions associated with construction activities, transportation of materials to the site, and the installation of structural components.

- d. **Use & Maintenance:** The longest phase of a building's life involves its operational life. This includes the use of energy for heating, cooling, lighting, and running appliances and systems. Maintenance, repair, and renovation activities are also considered, which contribute to the building's overall environmental footprint over time.
- e. **Demolition & End-of-Life:** The final phase of the life cycle involves the demolition of the building and the subsequent handling of the waste materials. This includes assessing the impacts of dismantling the building, transporting waste, and the potential for recycling or landfilling materials.

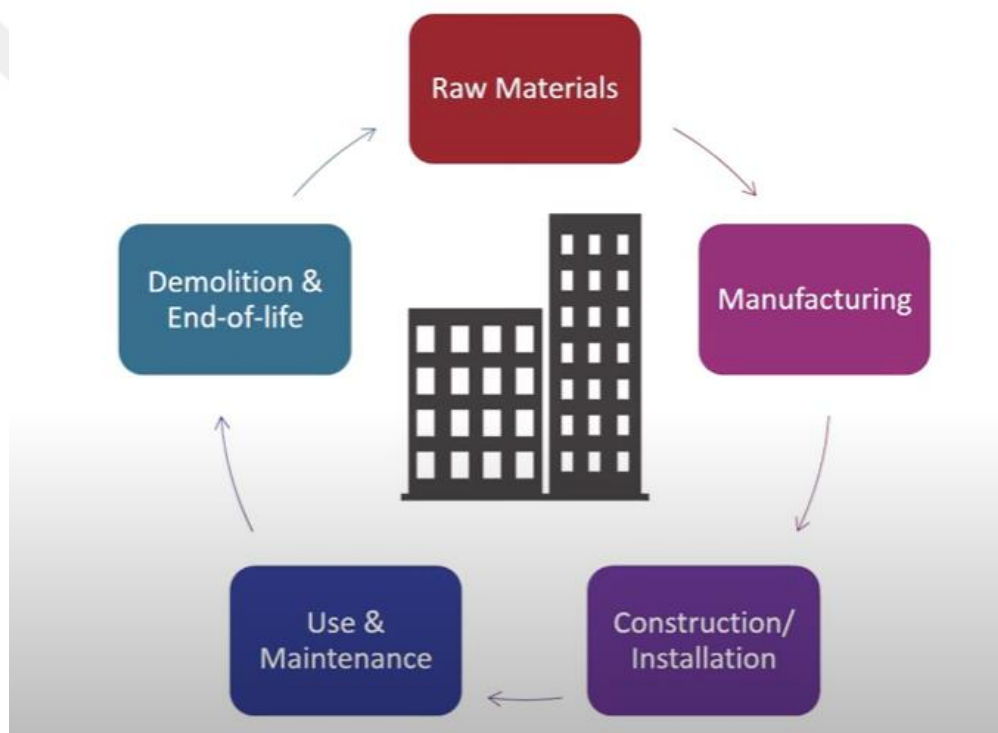


Figure 6. 1 Whole-Building LCA (Bowick et al., 2014)

The importance of LCA in evaluating the environmental sustainability of construction projects has been well documented in recent literature. The Athena Impact Estimator facilitates such assessments by incorporating lifecycle inventories that measure inputs like material usage and waste alongside outputs such as emissions and energy consumption. For instance, studies like those presented by Ahammed et al. 2016 highlighted the tool's capability to compare different pavement strategies, focusing on how modifications in materials or processes can lead to significant environmental benefits (Alauddin Ahammed et al., 2016).

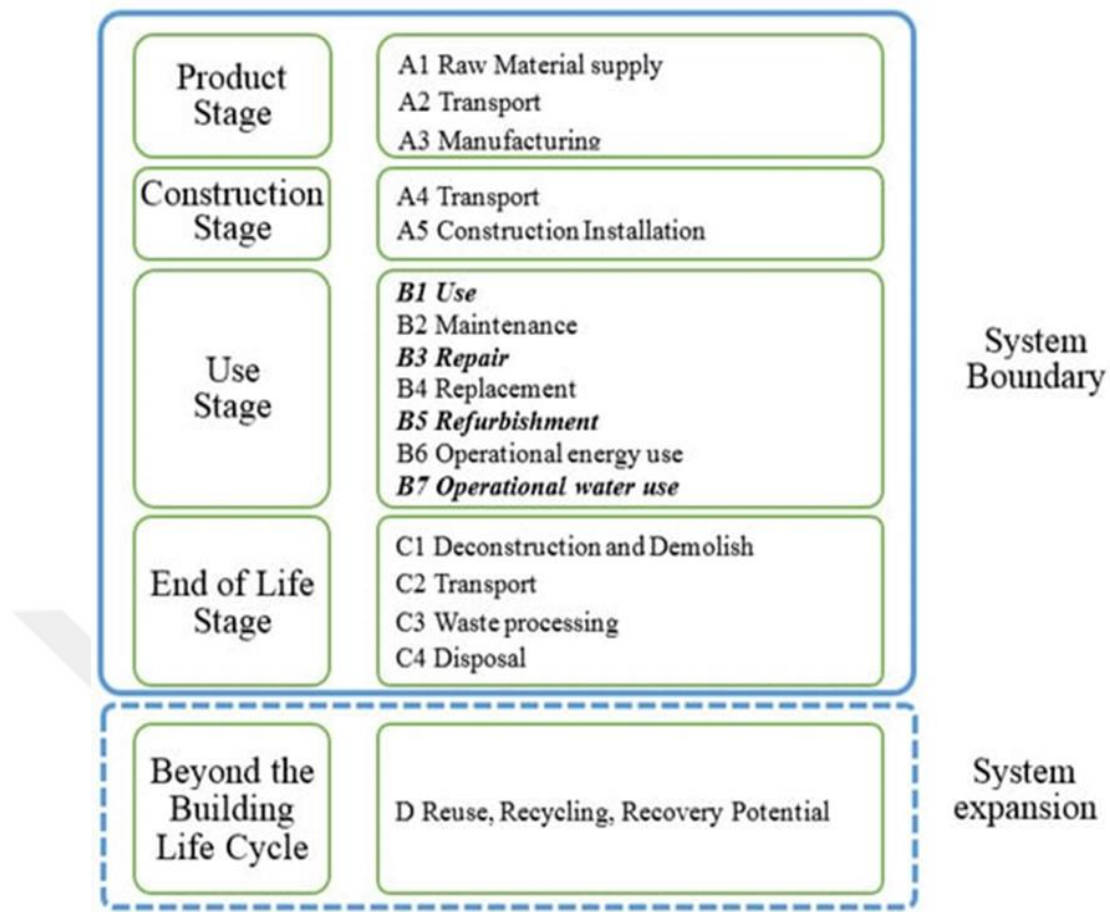


Figure 6.2 Assessment system boundary based on EN15978 (Chen et al., 2020)

The system life stages according to the European norm -EN15978 framework- are depicted in the attached diagram. This framework defines the life cycle of a building into several stages, starting with the Product Stage (A1-A3), which includes raw material supply (A1), transport (A2), and manufacturing (A3). Following this is the Construction Stage (A4-A5), which encompasses the transportation of materials to the site (A4) and the construction installation (A5). The Use Stage (B1-B7) involves various phases such as use (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), operational energy use (B6), and operational water use (B7). Finally, the End-of-Life Stage (C1-C4) covers the processes of deconstruction and demolition (C1), transport of waste (C2), waste processing (C3), and disposal (C4). Beyond these stages, the framework also considers the potential for reuse, recycling, and recovery (D) which lies beyond the building's life cycle. This holistic approach ensures that every phase of the building's life, from the extraction of raw materials to the end of its life, is assessed for environmental impact. (Chen et al., 2020).

The assessment involves the following steps:

1. **Data Input:** Input the detailed materials and construction processes for each retrofit scenario into the Athena software.
2. **Scenario Analysis:** Run simulations for each scenario to capture data on material consumption, energy use, and emissions throughout the lifecycle phases from material production through to construction, maintenance, and end-of-life stages.
3. **Impact Comparison:** by using Athena's comparison feature to juxtapose the environmental impacts of each retrofit scenario, thereby identifying which modifications yield the most significant environmental advantages.

The assessment considers four specific retrofitting scenarios: Existed Building, Re-designed Building, RC jacketing of columns, and RC shear wall addition and CFRP wrapping of columns. Each scenario is strategically developed to address specific deficiencies and improve the building's resilience, particularly against seismic activities, while also considering the environmental impacts.

a) Existed Building:

This scenario serves as the control or baseline, evaluating the building's current state without modifications. It assesses inherent structural weaknesses, such as inadequate concrete strength and suboptimal reinforcement detailing, which may affect the building's performance during seismic events.

b) Re-designed Building:

A comprehensive renovation of the building's structural system addresses and rectifies the identified deficiencies. This scenario involves reconfiguring the building's layout to improve load distribution, enhancing column and beam connections, and optimizing the structural frame to withstand seismic forces better.

c) RC jacketing of columns:

This technique focuses on reinforcing existing columns with additional layers of construction material, enhancing their load-bearing capacity and stiffness. It is a targeted approach meant to improve the overall structural integrity and ductility of the building, contributing to its seismic resilience.

d) RC shear wall addition and CFRP wrapping of columns:

The RC shear wall addition and CFRP wrapping of columns represents a dual approach to retrofitting. In addition to Athena's impact, a manual calculation for the CFRP combination environmental impact was conducted based on (Prenzel et al., 2023). This approach was needed because the Athena Impact Estimator software's CFRP approximation differed from the project's carbon fiber-reinforced polymer. The table shows how the manual calculations used Comprehensive quantitative life cycle inventory (LCI) data to produce one kilogram of carbon fibers from polyacrylonitrile (PAN). Table 6-1. outlines the inputs required for the production of carbon fibers, including raw materials like PAN fiber, air, nitrogen, and various chemicals, as well as the energy consumed during the manufacturing process. Outputs from this process include not only the carbon fiber but also by-products such as gaseous emissions, wastewater, and waste heat. This data forms the basis for calculating the environmental footprint of the CFRP used in the retrofit, allowing for more accurate integration of these impacts into the overall environmental assessment of the retrofit project.

Table 6-1 Quantitative Life Cycle Inventory for Carbon Fiber Manufacturing (Prenzel et al., 2023)

Flow	Amount	Unit
Input		
Polyacrylonitrile (PAN) fiber	1.95	kg/kg CF
Air	9.6	kg/kg CF
Nitrogen [N ₂]	10.0	kg/kg CF
Electrolyte [Ammonium bicarbonate]	0.03	kg/kg CF
Sizing agent [Epoxy resin]	0.02	kg/kg CF
Water [H ₂ O]	5.5	kg/kg CF
Process energy (electric and thermal)	170	MJ/kg CF
Output		
Carbon fiber	1.0	kg
Gaseous carbon emissions [HCN, C ₂ H ₆ , CO ₂ , CO]	0.6	kg/kg CF
Gaseous non-carbon emissions [exhaust air, N ₂ , NH ₃ , H ₂ O (g)]	20.0	kg/kg CF
Wastewater	5.5	kg/kg CF
Recovered thermal energy	11.2	MJ/kg CF
Waste heat	8.32	MJ/kg CF

Following the method of (Sadhukhan et al., 2021), who presented the Mathematics of life cycle sustainability assessment, the following calculation was conducted:

$$\text{Mass per } m^2 \text{ (kg/m}^2\text{)} = \text{Density (kg/m}^3\text{)} \times \text{Thickness (m)}$$

$$\text{Total Mass (kg)} = \text{Mass per } m^2 \text{ (kg/m}^2\text{)} \times \text{Area (m}^2\text{)}$$

$$\text{kgTotal PAN Fiber (kg)} = \text{PAN Fiber per kg CF (kg/kg CF)} \times \text{Total Mass of CFRP (kg)}$$

$$\text{kgTotal Water (kg)} = \text{Water per kg CF (kg/kg CF)} \times \text{Total Mass of CFRP (kg)}$$

$$\text{Total Process Energy (MJ)} = \text{Energy per kg CF (MJ/kg CF)} \times \text{Total Mass of CFRP (kg)}$$

$$\begin{aligned} \text{Total Gaseous Carbon Emissions (kg)} \\ &= \text{Gaseous Carbon Emissions per kg CF (kg/kg CF)} \\ &\times \text{Total Mass of CFRP (kg)} \end{aligned}$$

$$\text{Total Gaseous Non – Carbon Emissions (kg)} =$$

$$\text{Gaseous Non – Carbon Emissions per kg CF (kg/kg CF)} \times \text{Total Mass of CFRP (kg)}$$

$$\text{Total Wastewater (kg)} = \text{Wastewater per kg CF (kg/kg CF)} \times \text{Total Mass of CFRP (kg)}$$

The LCA measures used in the ATHENA impact estimator are the same as in the US LCI database and standard EN15978, the following is the definition of the key LCA measures used in the results from (Alauddin Ahammed et al., 2016; Bowick et al., 2014; Mančík et al., 2013):

GWP : quantifies the amount of heat that a greenhouse gas retains in the atmosphere compared to carbon dioxide within a specified timeframe. This metric is denoted in kilograms of CO₂ equivalents (kg CO₂ eq).

GWP - Calcination: measures the carbon dioxide emissions specifically from the calcination process, which is the thermal decomposition of materials such as limestone to produce lime, a key component in cement manufacturing.

Acidification Potential: quantifies the capacity of emissions to induce acid rain, posing risks to ecosystems, infrastructure, and human well-being. This is usually denoted in kilograms of sulfur dioxide equivalents (kg SO₂ eq).

HH Particulate: measures the potential impact of particulate matter (PM_{2.5}) emissions on human health. Particulate matter can cause respiratory and cardiovascular illnesses. This impact is measured in kilograms of PM_{2.5} equivalents (kg PM_{2.5} eq).

Eutrophication Potential: measures the potential for nutrient enrichment in water bodies, causing an overgrowth of algae and other aquatic plants. This can result in oxygen depletion and negatively impact aquatic life. It is expressed in kilograms of nitrogen equivalents (kg N eq).

Ozone Depletion Potential: evaluates the possible influence of emissions on the depletion of the stratospheric ozone layer, vital for shielding the Earth from harmful ultraviolet radiation. This impact is generally quantified in kilograms of CFC-11 equivalents. (kg CFC-11 eq).

Smog Potential: measures The potential of emissions to generate ground-level ozone, a significant element of smog, leading to respiratory complications and various health concerns. This is typically quantified in kilograms of ozone equivalents (kg O₃ eq).

Total Primary Energy: quantifies the total amount of energy required from all sources, both renewable and non-renewable, to produce, use, and dispose of a product. It is expressed in megajoules (MJ).

Non-Renewable Energy: measures the amount of energy derived from non-renewable sources, such as fossil fuels (coal, oil, natural gas), utilized throughout the life cycle of a product. It is expressed in megajoules. (MJ).

Fossil Fuel Consumption: measures the total amount of energy consumed from fossil fuels throughout the life cycle of a product. It is a subset of non-renewable energy and is also expressed in megajoules (MJ).

The quantities of all alternatives and re-designed buildings to use them in building environmental evaluation were investigated and summarized in Table 6.2.

Table 6.2. Quantities required for retrofit and re-design

Quantity	Price/Unit (27.12.2023)	Retrofitting systems		Re- designed Building	Existed Building
		RC shear wall addition and CFRP wrapping of columns	RC jacketing of column		
Concrete (m ³)	1920	34.27	50.35	565.88	712.909
Steel (ton)	21550	7.5	3.5	129.586	114.812
CFRP (m ²)	4565	614.82	---	---	---

6.2. Life Cycle Enviromental Assessment Results

The environmental impact assessment for the building using the Athena Impact Estimator software provided detailed insights into the LCA measures for each retrofitting scenario. The scenarios examined include the existed building, re-designed building, RC jacketing of columns, and RC shear wall addition and CFRP wrapping of columns. Each scenario was assessed based on different environmental impact metrics across different assembly groups and LCS.

6.2.1. Existed Building Life Cycle Environmental Assessment

GWP has been calculated across various building components, with the total impact measured at approximately 449,000 kg CO₂ eq. The largest contributions are noted from the floors, contributing around 303,000 kg CO₂ eq., followed by columns and beams with 112,000 kg CO₂ eq., and foundations at 33,600 kg CO₂ eq. This indicates a significant use of materials with high carbon footprints, primarily concrete and steel, throughout the structure.

The Acidification Potential of the building totals 1,920 kg SO₂ eq., with the floors being the primary contributors, accounting for approximately 1,350 kg SO₂ eq. In terms of Eutrophication Potential, a similar trend is observed where the floors contribute the majority, with a total impact of 291 kg N eq. These impacts are largely driven by the emissions associated with the production and processing of the building materials used.

The Smog Potential for the entire building has been estimated at approximately 51,900 kg O₃ eq. The minimal Ozone Depletion Potential, measured at 0.0105 kg CFC-11 eq., suggests limited contributions to stratospheric ozone layer depletion from the current building materials.

The assessment reveals that the Total Primary Energy consumption of the building is approximately 4.14 million MJ. A significant portion of this energy is derived from non-renewable sources, highlighting the need for integrating renewable energy sources in future construction practices to mitigate environmental impacts. Table 6 2 shows the LCA Measure Table By Assembly results in the existing building.

Table 6-2 LCA Measure Table by Assembly results in the existing building

LCA Measures	Unit	Foundations	Columns and Beams	Floors	Total
GWP	kg CO ₂ eq	3.36E+04	1.12E+05	3.03E+05	4.49E+05
GWP - Biogenic	kg CO ₂ eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP - Calcination	kg CO ₂ eq	9.62E+03	2.00E+04	8.67E+04	1.16E+05
Acidification Potential	kg SO ₂ eq	1.35E+02	4.37E+02	1.35E+03	1.92E+03
HH Particulate	kg PM _{2.5} eq	3.48E+01	7.55E+01	3.14E+02	4.25E+02
Eutrophication Potential	kg N eq	3.14E+01	9.73E+01	2.91E+02	4.19E+02

Ozone Depletion Potential	kg CFC-11 eq	7.99E-04	2.61E-03	7.05E-03	1.05E-02
Smog Potential	kg O3 eq	3.54E+03	1.11E+04	3.73E+04	5.19E+04
Total Primary Energy	MJ	3.01E+05	1.25E+06	2.58E+06	4.14E+06
Non-Renewable Energy	MJ	2.87E+05	1.18E+06	2.48E+06	3.95E+06
Fossil Fuel Consumption	MJ	2.75E+05	1.13E+06	2.37E+06	3.78E+06

Table 6-3 shows that the manufacturing phase contributes significantly to GWP, with approximately 334,000 kg CO₂ eq. produced, and an additional 8,140 kg CO₂ eq. from the transportation of materials, resulting in a total of 342,000 kg CO₂ eq. for the product stage. The construction process adds another 64,000 kg CO₂ eq., driven by onsite activities and additional transport of materials. This highlights the considerable impact of material production and construction practices on the building's carbon emissions.

Acidification Potential is also notable, with manufacturing and transportation contributing a combined 835 kg SO₂ eq., and the construction process adding another 581 kg SO₂ eq. Similarly, Smog Potential is significantly impacted by these stages, tallying a total of 18,200 kg O₃ eq. from both product creation and construction activities. These metrics underscore the environmental challenges associated with the early stages of the building's life, particularly in terms of air quality impacts.

Table 6-3 LCA measures table results by LCS (A : product and construction process)
for existing building

		PRODUCT			CONSTRUCTION PROCESS		
		(A1 to A3)			(A4 & A5)		
LCA Measures	Unit	Manufacturing	Transport	Total	Construction- Installation Process	Transport	Total
GWP	kg CO2 eq	3.34E+05	8.14E+03	3.42E+05	4.28E+04	2.12E+04	6.40E+04
GWP - Biogenic	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP - Calcination	kg CO2 eq	1.11E+05	0.00E+00	1.11E+05	5.54E+03	0.00E+00	5.54E+03
Acidification Potential	kg SO2 eq	7.41E+02	9.42E+01	8.35E+02	3.69E+02	2.12E+02	5.81E+02
HH Particulate	kg PM2.5 eq	1.26E+02	4.11E+00	1.30E+02	2.48E+01	1.14E+01	3.62E+01
Eutrophication Potential	kg N eq	3.21E+02	5.84E+00	3.27E+02	3.55E+01	1.31E+01	4.87E+01
Ozone Depletion Potential	kg CFC- 11 eq	8.04E-03	2.98E-07	8.04E-03	4.52E-04	7.64E-07	4.52E-04
Smog Potential	kg O3 eq	1.47E+04	3.03E+03	1.78E+04	1.15E+04	6.69E+03	1.82E+04
Total Primary Energy	MJ	2.74E+06	1.16E+05	2.86E+06	3.25E+05	3.08E+05	6.33E+05
Non- Renewable Energy	MJ	2.57E+06	1.16E+05	2.68E+06	3.21E+05	3.08E+05	6.29E+05
Fossil Fuel Consumption	MJ	2.42E+06	1.16E+05	2.53E+06	3.13E+05	3.08E+05	6.20E+05

Table 6-4 shows the operational phase, particularly energy use, is a major contributor to GWP, adding 298,000 kg CO2 eq. This phase's impact is critical as it underscores the ongoing energy demands of the building, emphasizing the importance of energy efficiency measures in reducing overall greenhouse gas emissions. The end-of-life stage, including deconstruction and waste processing, contributes an additional 43,400 kg CO2 eq. to the GWP, highlighting opportunities for improving waste management and recycling practices to minimize environmental impacts.

Table 6-4 LCA measures table results by LCS (B: use and end of life) for existing building

		USE				END OF LIFE		
		(B2, B4 & B6)				(C1 to C4)		
LCA Measures	Unit	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	Total	Deconstruction, Demolition, Disposal & Waste Processing	Transport	Total
GWP	kg CO2 eq	0.00E+00	0.00E+00	2.98E+05	2.98E+05	3.54E+04	8.03E+03	4.34E+04
GWP - Biogenic	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP - Calcination	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Acidification Potential	kg SO2 eq	0.00E+00	0.00E+00	7.71E+02	7.71E+02	4.32E+02	7.73E+01	5.09E+02
HH Particulate	kg PM2.5 eq	0.00E+00	0.00E+00	6.21E+02	6.21E+02	2.54E+02	4.28E+00	2.59E+02
Eutrophication Potential	kg N eq	0.00E+00	0.00E+00	1.71E+03	1.71E+03	3.88E+01	4.81E+00	4.36E+01
Ozone Depletion Potential	kg CFC-11 eq	0.00E+00	0.00E+00	1.95E-02	1.95E-02	1.96E-03	2.81E-07	1.96E-03
Smog Potential	kg O3 eq	0.00E+00	0.00E+00	7.68E+03	7.68E+03	1.35E+04	2.44E+03	1.60E+04
Total Primary Energy	MJ	0.00E+00	0.00E+00	5.64E+06	5.64E+06	5.27E+05	1.17E+05	6.44E+05
Non-Renewable Energy	MJ	0.00E+00	0.00E+00	5.09E+06	5.09E+06	5.24E+05	1.17E+05	6.41E+05
Fossil Fuel Consumption	MJ	0.00E+00	0.00E+00	3.39E+06	3.39E+06	5.08E+05	1.17E+05	6.25E+05

Table 6-5 shows the impacts beyond the building's operational life, adding 357,000 kg CO2 eq. to the GWP, which brings the total from stages A to C up to 747,000 kg CO2 eq., and the comprehensive total including beyond life impacts to approximately 1.10 million kg CO2 eq. This table also shows significant figures for Total Primary Energy and Non-Renewable Energy usage, which are indicative of the energy demands associated with the building's materials and construction, totaling up to approximately 13.4 million MJ when considering the full life cycle.

Table 6-5 LCA measures table results by LCS (C : beyond building life and total effects) for existing building

		BEYOND BUILDING LIFE			TOTAL EFFECTS	
		(D)				
LCA Measures	Unit	BBL Material	BBL Transport	Total	A to C	A to D
GWP	kg CO2 eq	3.57E+05	0.00E+00	3.57E+05	7.47E+05	1.10E+06
GWP - Biogenic	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP - Calcination	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	1.16E+05	1.16E+05
Acidification Potential	kg SO2 eq	7.09E+02	0.00E+00	7.09E+02	2.70E+03	3.40E+03
HH Particulate	kg PM2.5 eq	-2.13E-03	0.00E+00	-2.13E-03	1.05E+03	1.05E+03
Eutrophication Potential	kg N eq	4.23E+01	0.00E+00	4.23E+01	2.13E+03	2.18E+03
Ozone Depletion Potential	kg CFC-11 eq	-9.73E-09	0.00E+00	-9.73E-09	2.99E-02	2.99E-02
Smog Potential	kg O3 eq	7.65E+03	0.00E+00	7.65E+03	5.96E+04	6.72E+04
Total Primary Energy	MJ	3.59E+06	0.00E+00	3.59E+06	9.78E+06	1.34E+07
Non-Renewable Energy	MJ	3.73E+06	0.00E+00	3.73E+06	9.04E+06	1.28E+07
Fossil Fuel Consumption	MJ	3.76E+06	0.00E+00	3.76E+06	7.17E+06	1.09E+07

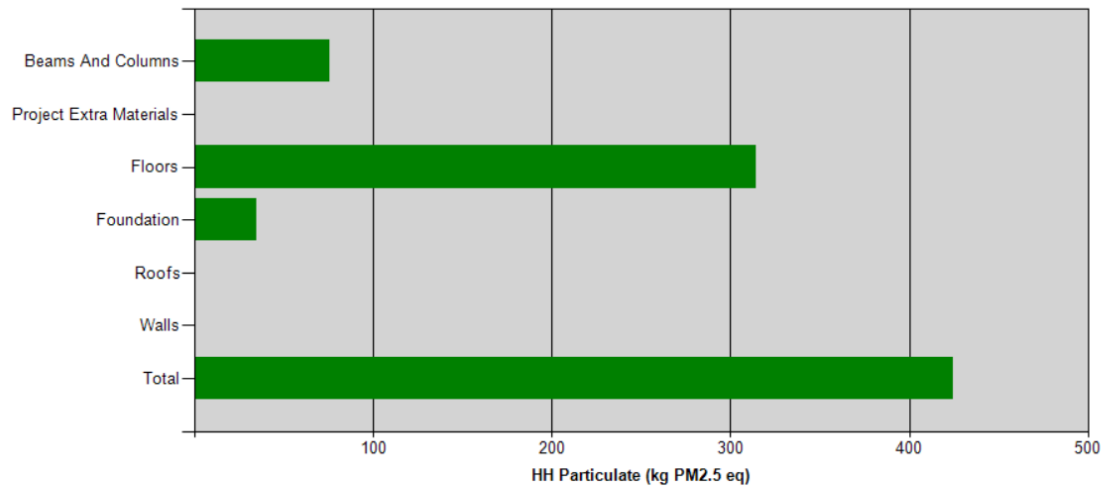


Figure 6.3 HH Particulate LCA Measure Chart By Assembly Groups existing building

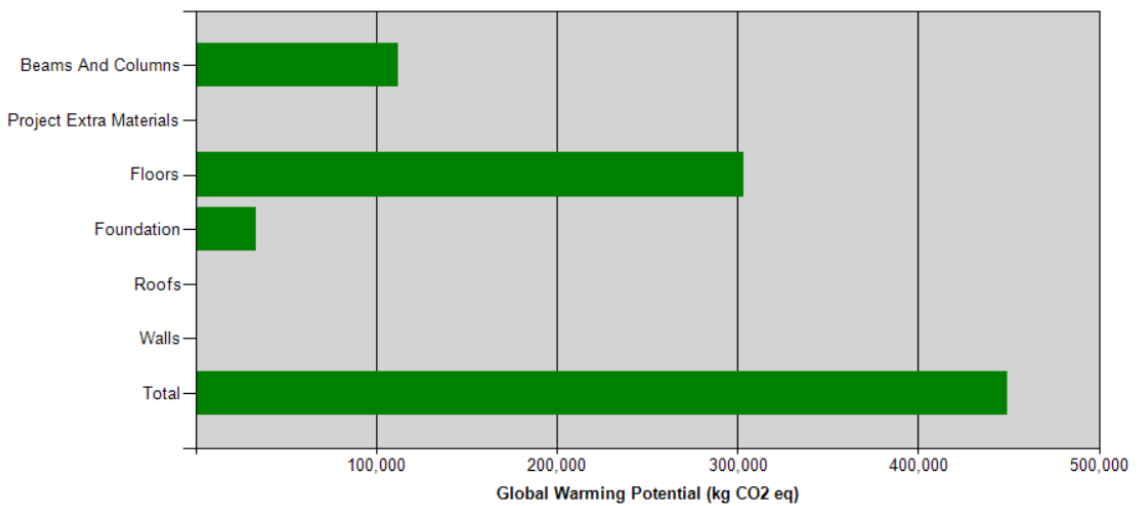


Figure 6. 4 GWP LCA Measure Chart By Assembly Groups existing building

6.2.2. RC jacketing of columns Retrofitting Life Cycle Environmental Assessment

The LCA results for the Retrofitting by RC jacketing of columns scenario, detailed in Table 6-6, show the environmental impacts associated with the additional materials used specifically for this retrofit. This scenario involves the addition of concrete and steel to enhance the structural integrity of existing columns.

Table 6-6 LCA Measure Table By Assembly Groups RC jacketing of columns

LCA Measures	Unit	Project Extra Materials Concrete C30 and steel S420	Total
GWP	kg CO2 eq	2.83E+04	2.83E+04
GWP - Biogenic	kg CO2 eq	0.00E+00	0.00E+00
GWP - Calcination	kg CO2 eq	7.72E+03	7.72E+03
Acidification Potential	kg SO2 eq	1.03E+02	1.03E+02
HH Particulate	kg PM2.5 eq	2.15E+01	2.15E+01
Eutrophication Potential	kg N eq	2.38E+01	2.38E+01
Ozone Depletion Potential	kg CFC-11 eq	5.65E-04	5.65E-04
Smog Potential	kg O3 eq	2.61E+03	2.61E+03
Total Primary Energy	MJ	2.50E+05	2.50E+05
Non-Renewable Energy	MJ	2.41E+05	2.41E+05
Fossil Fuel Consumption	MJ	2.31E+05	2.31E+05

As shown in Table 6-6, the LCA results for the RC jacketing of columns scenario show that the GWP reached 28,300 kg CO2 eq. This value highlights the significant environmental impact, largely driven by the use of concrete and steel, materials known for their high carbon emissions. One major contributor is the calcination process during cement production, responsible for 7,720 kg CO2 eq. It's clear that this stage, which is integral to producing concrete, heavily influences the overall carbon footprint of the project.

The Acidification Potential stands at 103 kg SO2 eq, a reflection of sulfur dioxide and similar emissions released during the production and installation of materials. These emissions have the potential to cause acid rain, which can severely damage natural ecosystems and man-made structures alike. Similarly, particulate

matter is a growing concern, with a measure of 21.5 kg PM_{2.5} eq. This points to the dust and small particles generated in the production and construction phases that can harm air quality and lead to respiratory issues. Quite an interesting result is the Eutrophication Potential of 23.8 kg N eq., showing that not only construction activities or energy use, but also some materials when used in excess here -concrete and steel- lead to nutrient runoff. If this runoff was to run off into water bodies nearby, it would be over-fertilized and algal blooms along with oxygen depletion would severely disrupt aquatic life. These impacts demonstrate the need to properly manage runoff in an environmentally responsible manner during and post construction. And finally, the larger concern is smog formation, with a smog potential of 2,610 kg O₃ eq., though the Ozone Depletion Potential is low at 0.000565 kg CFC-11 eq. This value shows the effect of VOCs and nitrogen oxides in smog, i.e., photochemical oxidants. That aspect of these emissions underscores the balance needed between material production and air in cities.

Error! Reference source not found. outlines the environmental impacts during the RC jacketing of columns scenario's product and construction process stages. The GWP for the manufacturing phase alone is recorded at 23,300 kg CO₂ eq., while the total GWP from all stages, including transportation and installation, amounts to 29,800 kg CO₂ eq. This significant contribution reflects the emissions associated with producing and transporting materials like concrete and steel, which are both resource-intensive and high in carbon emissions. Notably, the calcination process during cement production accounts for 7,350 kg CO₂ eq., marking it as a critical factor in the overall carbon footprint of the project. acidification potential, the data reveals a combined total of 51.5 kg SO₂ eq. during manufacturing and transport stages, with an additional 26.7 kg SO₂ eq. resulting from the construction process. These values highlight the environmental threat posed by emissions of sulfur dioxide and other acidic compounds, which contribute to acid rain, leading to soil degradation and building material corrosion. The smog potential also presents significant concerns, with the total across the product and construction processes reaching 1,832 kg O₃ eq. This value is largely driven by the release of volatile organic compounds (VOCs) and nitrogen oxides, which are known precursors to ground-level ozone formation. In Human Health Particulate measure, recorded at 7.44 kg PM_{2.5} eq. during the manufacturing stage and an additional 1.92 kg PM_{2.5} eq. during construction, draws attention to the

direct impact of particulate emissions on public health. Particulate matter is known for its detrimental effects on respiratory and cardiovascular health, and the figures provided in the table suggest that dust control and air filtration measures will be crucial during construction to protect both workers and nearby communities. Eutrophication potential, although lower in comparison to other impacts, is still noteworthy at a combined total of 24.7 kg N eq. from all stages. This environmental measure points to the likelihood of nitrogen runoff entering nearby water bodies, potentially leading to harmful algal blooms and oxygen depletion in aquatic ecosystems. These results highlight the real environmental issues associated with this RC jacketing of columns process. From carbon to energy and particulate emissions, all stages of the life cycle have varying impacts on the environment. Consequently, these results indicate that although the jacketing of columns has increased the constructive characteristics of buildings structures especially in earthquake-prone regions much more potential is still available to realize sustainability by the utilization of energy reduction, controlling emissions and monitoring responsible procurement implementations.

Table 6-7 LCA measures table results by LCS (A : product and construction process)
RC jacketing of columns

LCA Measures	Unit	PRODUCT			CONSTRUCTION PROCESS		
		Manufacturing	Transport	Total	Construction-Installation Process	Transport	Total
GWP	kg CO2 eq	2.29E+04	3.88E+02	2.33E+04	1.73E+03	1.25E+03	2.98E+03
GWP - Biogenic	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP - Calcination	kg CO2 eq	7.35E+03	0.00E+00	7.35E+03	3.68E+02	0.00E+00	3.68E+02
Acidification Potential	kg SO2 eq	4.70E+01	4.50E+00	5.15E+01	1.40E+01	1.27E+01	2.67E+01
HH Particulate	kg PM2.5 eq	7.24E+00	1.96E-01	7.44E+00	1.24E+00	6.78E-01	1.92E+00
Eutrophication Potential	kg N eq	1.91E+01	2.79E-01	1.93E+01	1.68E+00	7.87E-01	2.47E+00
Ozone Depletion Potential	kg CFC-11 eq	4.50E-04	1.42E-08	4.50E-04	2.55E-05	4.58E-08	2.55E-05
Smog Potential	kg O3 eq	8.67E+02	1.45E+02	1.01E+03	4.30E+02	4.02E+02	8.32E+02
Total Primary Energy	MJ	1.78E+05	5.54E+03	1.83E+05	1.75E+04	1.82E+04	3.57E+04
Non-Renewable Energy	MJ	1.70E+05	5.54E+03	1.75E+05	1.73E+04	1.81E+04	3.54E+04

Fossil Fuel Consumption	MJ	1.61E+05	5.53E+03	1.66E+05	1.69E+04	1.81E+04	3.50E+04
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Table 6-8 highlights the environmental impacts during the use and end-of-life stages of the RC jacketing of columns scenario. The operational energy use is responsible for a substantial GWP of 298,000 kg CO₂ eq., underscoring the energy intensity of maintaining the building after retrofitting. End-of-life processes, including demolition and waste handling, contribute an additional 2,060 kg CO₂ eq., emphasizing the importance of sustainable material disposal. Smog potential is also notable, with 7,680 kg O₃ eq. generated during the building's use phase, while 765 kg O₃ eq. arises during deconstruction. These figures reflect ongoing air quality impacts, especially in urban settings. Additionally, acidification (771 kg SO₂ eq.), human health particulates (621 kg PM_{2.5} eq.), and eutrophication potential (1,710 kg N eq.) during the operational phase highlight the ongoing environmental burdens of energy consumption, contributing to air pollution and water quality issues.

Table 6-8 LCA measures table results by LCS (B : use and end of life) RC jacketing of columns

LCA Measures	Unit	USE				END OF LIFE		
		Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	Total	Deconstruction, Demolition, Disposal & Waste Processing	Transport	Total
GWP	kg CO ₂ eq	0.00E+00	0.00E+00	2.98E+05	2.98E+05	1.68E+03	3.79E+02	2.06E+03
GWP - Biogenic	kg CO ₂ eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP - Calcination	kg CO ₂ eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Acidification Potential	kg SO ₂ eq	0.00E+00	0.00E+00	7.71E+02	7.71E+02	2.07E+01	3.65E+00	2.43E+01
HH Particulate	kg PM _{2.5} eq	0.00E+00	0.00E+00	6.21E+02	6.21E+02	1.20E+01	2.02E-01	1.22E+01
Eutrophication Potential	kg N eq	0.00E+00	0.00E+00	1.71E+03	1.71E+03	1.81E+00	2.27E-01	2.04E+00
Ozone Depletion Potential	kg CFC-11 eq	0.00E+00	0.00E+00	1.95E-02	1.95E-02	8.96E-05	1.32E-08	8.96E-05
Smog Potential	kg O ₃ eq	0.00E+00	0.00E+00	7.68E+03	7.68E+03	6.50E+02	1.15E+02	7.65E+02
Total Primary Energy	MJ	0.00E+00	0.00E+00	5.64E+06	5.64E+06	2.50E+04	5.53E+03	3.05E+04
Non-Renewable Energy	MJ	0.00E+00	0.00E+00	5.09E+06	5.09E+06	2.48E+04	5.53E+03	3.04E+04
Fossil Fuel Consumption	MJ	0.00E+00	0.00E+00	3.39E+06	3.39E+06	2.41E+04	5.52E+03	2.97E+04

Table 6-9 extends the analysis to the environmental impacts beyond the building's life (BBL) and aggregates the total effects of the RC jacketing of columns retrofit across all LCS. The BBL section shows a decrease of 7,530 kg CO₂ eq. in GWP, suggesting some carbon offset or material recovery after deconstruction. However, when considering the entire life cycle from production to disposal, the total GWP is 319,000 kg CO₂ eq., reflecting the comprehensive environmental impact of the retrofit. Acidification potential across all stages totals 858 kg SO₂ eq., indicating the cumulative contribution to acid rain over the project's life span. This is a significant rise from earlier phases, pointing to long-term emissions from material decomposition and processing. Smog potential, another key concern, reaches 10,100 kg O₃ eq., further emphasizing the ongoing air quality impacts even after the building's operational life. The overall results from Table 9 demonstrate that while there are reductions in some emissions post-use, the cumulative environmental footprint of the RC jacketing of columns retrofit remains substantial across multiple measures, especially in terms of energy consumption, GWP, and air pollution.

Table 6-9 LCA measures table results by LCS (C : beyond building life and total effect) RC jacketing of columns

LCA Measures	Unit	BEYOND BUILDING LIFE			TOTAL EFFECTS	
		BBL Material	BBL Transport	Total	A to C	A to D
GWP	kg CO ₂ eq	-7.53E+03	0.00E+00	-7.53E+03	3.26E+05	3.19E+05
GWP - Biogenic	kg CO ₂ eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP - Calcination	kg CO ₂ eq	0.00E+00	0.00E+00	0.00E+00	7.72E+03	7.72E+03
Acidification Potential	kg SO ₂ eq	-1.50E+01	0.00E+00	-1.50E+01	8.73E+02	8.58E+02
HH Particulate	kg PM _{2.5} eq	4.49E-05	0.00E+00	4.49E-05	6.42E+02	6.42E+02
Eutrophication Potential	kg N eq	-8.93E-01	0.00E+00	-8.93E-01	1.74E+03	1.74E+03
Ozone Depletion Potential	kg CFC-11 eq	2.05E-10	0.00E+00	2.05E-10	2.00E-02	2.00E-02
Smog Potential	kg O ₃ eq	-1.62E+02	0.00E+00	-1.62E+02	1.03E+04	1.01E+04
Total Primary Energy	MJ	-7.58E+04	0.00E+00	-7.58E+04	5.89E+06	5.82E+06
Non-Renewable Energy	MJ	-7.88E+04	0.00E+00	-7.88E+04	5.33E+06	5.25E+06
Fossil Fuel Consumption	MJ	-7.94E+04	0.00E+00	-7.94E+04	3.62E+06	3.54E+06

RC shear wall addition and CFRP wrapping of columns Retrofitting Life Cycle Environmental Assessment:

For this scenario the retrofitting LCA simulated in ATHENA environmental impact software along with manual calculations following the guidelines and data for the CFRP specifically in (Prenzel et al., 2023; Sadhukhan et al., 2021).

Table 6-10 highlights the environmental impacts of the RC shear wall addition and CFRP wrapping of columns retrofitting scenario, where advanced materials such as concrete, steel, and CFRP are used. The overall GWP amounts to 34,700 kg CO₂ eq., while the GWP of 5,250 kg CO₂ eq. connected to the calcination practice in cement making. This further reinforces the large carbon footprints from the materials, primarily concrete. And even in this case, the acidification potential of 156 kg SO₂ eq. shows that acid-rain emission could be significantly higher because different materials were used together; Particulates (HH Particulate): 38.7 kg PM_{2.5}. Raising concerns with and about air quality, mainly during the process of material production and installation. The moderate eutrophication potential 24.1 kg N eq indicates a possibility for nutrient runoff to water bodies due to construction material production. It still has large influence of smog potential (e.g. 3,160 kg O₃ eq.), which is also a noticeable category contributing to urban ground level ozone formation relevant for local air quality considerations.

Table 6-10 LCA Measure Table by Assembly Groups (RC shear wall addition and CFRP wrapping of columns)

LCA Measures	Unit	Project Extra Materials The concrete steel and CFRP	Total
GWP	kg CO ₂ eq	3.47E+04	3.47E+04
GWP - Biogenic	kg CO ₂ eq	0.00E+00	0.00E+00
GWP - Calcination	kg CO ₂ eq	5.25E+03	5.25E+03
Acidification Potential	kg SO ₂ eq	1.56E+02	1.56E+02
HH Particulate	kg PM _{2.5} eq	3.87E+01	3.87E+01
Eutrophication Potential	kg N eq	2.41E+01	2.41E+01
Ozone Depletion Potential	kg CFC-11 eq	5.39E-04	5.39E-04
Smog Potential	kg O ₃ eq	3.16E+03	3.16E+03
Total Primary Energy	MJ	3.10E+05	3.10E+05
Non-Renewable Energy	MJ	3.01E+05	3.01E+05
Fossil Fuel Consumption	MJ	2.89E+05	2.89E+05

Table 6-11 highlights the environmental impacts during the production and construction phases of the RC shear wall addition and CFRP wrapping of columns scenario. The GWP is measured at 27,500 kg CO₂ eq. for material manufacturing and transport, with an additional 3,600 kg CO₂ eq. from construction activities. A significant portion of this comes from the cement calcination process, contributing 5,000 kg CO₂ eq. to the total emissions. Acidification potential, which affects air quality and can lead to acid rain, reaches 87.7 kg SO₂ eq., while smog potential totals 1,300 kg O₃ eq., with most emissions generated during transport and construction activities. The particulate matter (PM_{2.5}) released into the air during this phase is 20.3 kg, posing health risks related to respiratory issues. The eutrophication potential, which reflects the possibility of nutrient runoff affecting water bodies, is 17.8 kg N eq. for manufacturing and 2.76 kg N eq. for the construction process. Energy consumption during these stages is high, with a total of 228,000 MJ, mostly derived from non-renewable energy sources (219,000 MJ), highlighting the reliance on fossil fuels.

Table 6-11 LCA measures table results by LCS (A : product and construction process) for RC shear wall addition and CFRP wrapping of columns

LCA Measures	Unit	PRODUCT			CONSTRUCTION PROCESS		
		Manufacturing	Transport	Total	Construction-Installation Process	Transport	Total
GWP	kg CO ₂ eq	2.71E+04	3.72E+02	2.75E+04	1.89E+03	1.72E+03	3.60E+03
GWP - Biogenic	kg CO ₂ eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP - Calcination	kg CO ₂ eq	5.00E+03	0.00E+00	5.00E+03	2.50E+02	0.00E+00	2.50E+02
Acidification Potential	kg SO ₂ eq	8.35E+01	4.19E+00	8.77E+01	1.49E+01	1.82E+01	3.31E+01
HH Particulate	kg PM _{2.5} eq	2.01E+01	1.89E-01	2.03E+01	2.60E+00	9.50E-01	3.55E+00
Eutrophication Potential	kg N eq	1.75E+01	2.60E-01	1.78E+01	1.64E+00	1.13E+00	2.76E+00
Ozone Depletion Potential	kg CFC-11 eq	3.71E-04	1.35E-08	3.71E-04	2.53E-05	6.56E-08	2.54E-05
Smog Potential	kg O ₃ eq	1.17E+03	1.34E+02	1.30E+03	3.78E+02	5.77E+02	9.56E+02
Total Primary Energy	MJ	2.23E+05	5.33E+03	2.28E+05	1.64E+04	2.50E+04	4.14E+04
Non-Renewable Energy	MJ	2.14E+05	5.33E+03	2.19E+05	1.61E+04	2.50E+04	4.11E+04
Fossil Fuel Consumption	MJ	2.05E+05	5.32E+03	2.10E+05	1.56E+04	2.49E+04	4.05E+04

Table 6-12 evaluates the environmental impacts during the use and end-of-life stages of the RC shear wall addition and CFRP wrapping of columns retrofit. GWP during the operational phase stands at 299,000 kg CO₂ eq., indicating the high energy requirements for maintaining the building over its lifetime. Deconstruction and waste disposal at the end-of-life phase add another 2,300 kg CO₂ eq., emphasizing the environmental burden even after the building ceases operation. Acidification potential over the entire life cycle totals 780 kg SO₂ eq., with 25.9 kg SO₂ eq. from end-of-life activities, showing ongoing risks for acid rain formation. Human health particulate emissions (PM_{2.5}) are also a concern, with 625 kg during operation and 11.1 kg from deconstruction, affecting air quality and respiratory health. The smog potential reaches 7,800 kg O₃ eq. during the operational phase, and an additional 786 kg O₃ eq. is generated during demolition, reflecting continued air quality challenges.

Table 6-12 LCA measures table results by LCS (B: use and end of life) RC shear wall addition and CFRP wrapping of columns

LCA Measures	Unit	USE				END OF LIFE		
		Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	Total	Deconstruction, Demolition, Disposal & Waste Processing	Transport	Total
GWP	kg CO ₂ eq	1.20E+03	9.57E+01	2.98E+05	2.99E+05	1.98E+03	3.28E+02	2.30E+03
GWP - Biogenic	kg CO ₂ eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP - Calcination	kg CO ₂ eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Acidification Potential	kg SO ₂ eq	8.50E+00	1.02E+00	7.71E+02	7.80E+02	2.28E+01	3.16E+00	2.59E+01
HH Particulate	kg PM _{2.5} eq	3.75E+00	5.25E-02	6.21E+02	6.25E+02	1.09E+01	1.75E-01	1.11E+01
Eutrophication Potential	kg N eq	8.71E-01	6.33E-02	1.71E+03	1.72E+03	2.46E+00	1.96E-01	2.66E+00
Ozone Depletion Potential	kg CFC-11 eq	1.61E-05	3.64E-09	1.95E-02	1.95E-02	1.26E-04	1.15E-08	1.26E-04
Smog Potential	kg O ₃ eq	8.51E+01	3.24E+01	7.68E+03	7.80E+03	6.86E+02	9.98E+01	7.86E+02
Total Primary Energy	MJ	4.92E+03	1.39E+03	5.64E+06	5.65E+06	2.94E+04	4.79E+03	3.42E+04
Non-Renewable Energy	MJ	4.76E+03	1.39E+03	5.09E+06	5.10E+06	2.92E+04	4.79E+03	3.40E+04
Fossil Fuel Consumption	MJ	4.26E+03	1.39E+03	3.39E+06	3.40E+06	2.80E+04	4.78E+03	3.27E+04

Table 6-13 summarizes the overall environmental impacts of the RC shear wall addition and CFRP wrapping of columns retrofit, including the "Beyond Building Life" (BBL) phase. The total GWP reaches 319,000 kg CO₂ eq., with the BBL phase reducing GWP by 13,300 kg CO₂ eq., likely due to material recovery or recycling. Despite this reduction, the cumulative acidification potential still rises to 901 kg SO₂ eq., illustrating the long-term risk of acid rain over the building's lifecycle. Smog potential remains significant, totaling 10,600 kg O₃ eq., indicating ongoing air quality concerns. The project consumes a total of 5.82 million MJ of primary energy, most of which comes from non-renewable sources (5.25 million MJ), with fossil fuels alone contributing 3.54 million MJ.

Table 6-13 LCA measures table results by LCS (C : beyond building life and total effects) RC shear wall addition and CFRP wrapping of columns

LCA Measures	Unit	BEYOND BUILDING LIFE			TOTAL EFFECTS	
		BBL Material	BBL Transport	Total	A to C	A to D
GWP	kg CO ₂ eq	-1.33E+04	0.00E+00	-1.33E+04	3.33E+05	3.19E+05
GWP - Biogenic	kg CO ₂ eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP - Calcination	kg CO ₂ eq	0.00E+00	0.00E+00	0.00E+00	5.25E+03	5.25E+03
Acidification Potential	kg SO ₂ eq	-2.64E+01	0.00E+00	-2.64E+01	9.27E+02	9.01E+02
HH Particulate	kg PM _{2.5} eq	7.92E-05	0.00E+00	7.92E-05	6.60E+02	6.60E+02
Eutrophication Potential	kg N eq	-1.58E+00	0.00E+00	-1.58E+00	1.74E+03	1.74E+03
Ozone Depletion Potential	kg CFC-11 eq	3.62E-10	0.00E+00	3.62E-10	2.00E-02	2.00E-02
Smog Potential	kg O ₃ eq	-2.85E+02	0.00E+00	-2.85E+02	1.08E+04	1.06E+04
Total Primary Energy	MJ	-1.34E+05	0.00E+00	-1.34E+05	5.95E+06	5.82E+06
Non-Renewable Energy	MJ	-1.39E+05	0.00E+00	-1.39E+05	5.39E+06	5.25E+06
Fossil Fuel Consumption	MJ	-1.40E+05	0.00E+00	-1.40E+05	3.68E+06	3.54E+06

Calculations for RC shear wall addition and CFRP wrapping of columns Scenario

Mass Calculation per m²:

$$\text{Thickness} = 0.165 \text{ mm} = 0.000165 \text{ m}$$

$$\text{Density} = 1.8 \text{ g/cm}^3 = 1.8 \text{ kg/L} = 1.8 \text{ kg/m}^3/\text{cm}$$

$$\text{Mass per m}^2 = \text{Density} \times \text{Thickness}$$

$$\text{Mass per m}^2 = 1.8 \text{ kg/m}^3 \times 0.000165 \text{ m} = 0.297 \text{ kg/m}^2$$

Total Mass for 2830 m²:

$$\text{Total Mass} = \text{Mass per m}^2 \times \text{Area}$$

$$\text{Total Mass} = 0.297 \text{ kg/m}^2 \times 2830 \text{ m}^2 = 840.81 \text{ kg}$$

Total Inputs and Outputs for 840.81 kg of CFRP:**Total PAN Fiber:**

$$\text{Total PAN Fiber} = 1.95 \text{ kg/kg CF} \times 840.81 \text{ kg} = \mathbf{1640.58 \text{ kg}}$$

Total Water:

$$\text{Total Water} = 5.5 \text{ kg/kg CF} \times 840.81 \text{ kg} = \mathbf{4624.46 \text{ kg}}$$

Total Process Energy:

$$\text{Total Process Energy} = 170 \text{ MJ/kg CF} \times 840.81 \text{ kg} = \mathbf{142937.7 \text{ MJ}}$$

Total Gaseous Carbon Emissions:

$$\text{Total Gaseous Carbon Emissions} = 0.6 \text{ kg/kg CF} \times 840.81 \text{ kg} = \mathbf{504.49 \text{ kg}}$$

Total Gaseous Non-Carbon Emissions:

$$\text{Total Gaseous Non-Carbon Emissions} = 20 \text{ kg/kg CF} \times 840.81 \text{ kg} = \mathbf{16816.2 \text{ kg}}$$

$$\text{Total Wastewater} = 5.5 \text{ kg/kg CF} \times 840.81 \text{ kg} = \mathbf{4624.46 \text{ kg}}$$

The results for the RC shear wall addition and CFRP wrapping of columns retrofit compared to manual calculations to verify that trends and orders of magnitude were consistent with Athena Impact Estimator calculations. References to manual calculations suggest the GWP from the simulation (88,500 kg CO₂ eq.), are in reasonable agreement with carbon emissions associated with the cement calcination process component (5,250 kg CO₂ eq.). With the simulation also acidification potential at 464 kg SO₂ eq., it confirmed manual estimates which warn against sulfur emissions that lead to acid rain. Smog potential are also close to each other, giving 8,470 kg O₃ eq the simulation which confirm the doubt from manual calculations namely with high contribution of volatile organic compounds (VOCs) and nitrogen oxides (NO_x) In general, both methods allow validating the high cut-off point of the improvement with respect to energy utilization, GWP and air quality weights which

affirms the outcomes and stresses the importance of sustainable behavioral trek Canlis-
A framework for normalizing source emissions using Canadian urban discharges.

6.2.3. Re-designed Scenario

In the rebuild and redesign scenario, the structural components of the building were significantly upgraded. The columns and beams were reconstructed with concrete of grade C30, replacing the previous grade C14, and the steel reinforcement was upgraded to S420. Additionally, the beam type was modified to Laminated Veneer Lumber (LVL) / Parallel Strand Lumber (PSL). This scenario aimed to enhance the building's structural reliability and performance using higher-grade materials.

shows the LCA findings for this scenario, revealing a significant increase in GWP reaches 890,000 kg CO₂ eq., primarily due to the materials used in the foundations, columns, and beams, which alone account for 491,000 kg CO₂ eq. A significant part of this comes from the cement calcination process, contributing 148,000 kg CO₂ eq. Also, Acidification potential stands at 3,550 kg SO₂ eq., reflecting the high emissions of sulfur dioxide, while the smog potential is considerable at 82,500 kg O₃ eq., indicating a strong contribution to urban air pollution. Human Health Particulate (PM_{2.5}) emissions total 493 kg, highlighting the release of fine particles that impact air quality during construction. Finally, Eutrophication potential, at 735 kg N eq., points to the risk of nutrient runoff affecting water ecosystems. Energy use is substantial, with total primary energy demand hitting 10.9 million MJ, of which 10.2 million MJ are from non-renewable sources, primarily fossil fuels (9.98 million MJ).

Table 6-14 shows the LCA findings for this scenario, revealing a significant increase in GWP reaches 890,000 kg CO₂ eq., primarily due to the materials used in the foundations, columns, and beams, which alone account for 491,000 kg CO₂ eq. A significant part of this comes from the cement calcination process, contributing 148,000 kg CO₂ eq. Also, Acidification potential stands at 3,550 kg SO₂ eq., reflecting the high emissions of sulfur dioxide, while the smog potential is considerable at 82,500 kg O₃ eq., indicating a strong contribution to urban air pollution. Human Health Particulate (PM_{2.5}) emissions total 493 kg, highlighting the release of fine particles that impact air quality during construction. Finally, Eutrophication potential, at 735 kg N eq., points to the risk of nutrient runoff affecting water ecosystems. Energy use is

substantial, with total primary energy demand hitting 10.9 million MJ, of which 10.2 million MJ are from non-renewable sources, primarily fossil fuels (9.98 million MJ).

Table 6-14 LCA Measure Table by Assembly Groups redesign scenario

LCA Measures	Unit	Foundations	Columns and Beams	Floors	Project Extra Materials	Total
GWP	kg CO2 eq	3.50E+04	0.00E+00	2.13E+05	0.00E+00	2.93E+05
GWP - Biogenic	kg CO2 eq	0.00E+00	0.00E+00	-1.45E+05	0.00E+00	0.00E+00
GWP - Calcination	kg CO2 eq	9.60E+03	0.00E+00	2.15E+04	0.00E+00	8.54E+04
Acidification Potential	kg SO2 eq	1.40E+02	0.00E+00	1.51E+03	0.00E+00	1.31E+03
HH Particulate	kg PM2.5 eq	3.50E+01	0.00E+00	1.53E+02	0.00E+00	3.08E+02
Eutrophication Potential	kg N eq	3.18E+01	0.00E+00	5.29E+02	0.00E+00	2.84E+02
Ozone Depletion Potential	kg CFC-11 eq	8.09E-04	0.00E+00	7.69E-03	0.00E+00	6.89E-03
Smog Potential	kg O3 eq	3.66E+03	0.00E+00	3.59E+04	0.00E+00	3.63E+04
Total Primary Energy	MJ	3.20E+05	0.00E+00	5.69E+06	0.00E+00	2.46E+06
Non-Renewable Energy	MJ	3.05E+05	0.00E+00	4.64E+06	0.00E+00	2.36E+06
Fossil Fuel Consumption	MJ	2.92E+05	0.00E+00	4.52E+06	0.00E+00	2.26E+06

The redesign scenario's environmental impacts during the product and construction process stages, as shown in -15 highlights key concerns. Manufacturing alone contributes 309,000 kg CO2 eq. to the GWP, largely due to the energy-intensive production of concrete C30 and steel S420. While biogenic carbon offsets 235,000 kg CO2 eq., the overall impact remains high, with calcination adding 111,000 kg CO2 eq. Acidification potential reaches 1,490 kg SO2 eq., primarily from material production, contributing to acid rain risks. Smog potential is significant at 30,300 kg O3 eq., driven by VOC and NOx emissions, which degrade air quality. Eutrophication potential of 716 kg N eq. underscores the risk of nutrient runoff affecting aquatic ecosystems.

Table 6-15 highlights key concerns. Manufacturing alone contributes 309,000 kg CO2 eq. to the GWP, largely due to the energy-intensive production of concrete C30 and steel S420. While biogenic carbon offsets 235,000 kg CO2 eq., the overall impact remains high, with calcination adding 111,000 kg CO2 eq. Acidification potential reaches 1,490 kg SO2 eq., primarily from material production, contributing to acid rain risks. Smog potential is significant at 30,300 kg O3 eq., driven by VOC and NOx emissions, which degrade air quality. Eutrophication potential of 716 kg N eq. underscores the risk of nutrient runoff affecting aquatic ecosystems.

Table 6-15 LCA measures table results by LCS (A: product and construction process) redesign scenario

LCA Measures	Unit	PRODUCT			CONSTRUCTION PROCESS		
		Manufacturing	Transport	Total	Construction- Installation Process	Transport	Total
GWP	kg CO2 eq	3.01E+05	8.03E+03	3.09E+05	4.53E+04	3.58E+04	8.11E+04
GWP - Biogenic	kg CO2 eq	-2.35E+05	0.00E+00	-2.35E+05	-8.84E+02	0.00E+00	-8.84E+02
GWP - Calcination	kg CO2 eq	1.11E+05	0.00E+00	1.11E+05	5.47E+03	0.00E+00	5.47E+03
Acidification Potential	kg SO2 eq	1.40E+03	9.29E+01	1.49E+03	3.96E+02	3.67E+02	7.63E+02
HH Particulate	kg PM2.5 eq	1.57E+02	4.05E+00	1.61E+02	2.54E+01	1.95E+01	4.50E+01
Eutrophication Potential	kg N eq	7.11E+02	5.76E+00	7.16E+02	4.00E+01	2.28E+01	6.28E+01
Ozone Depletion Potential	kg CFC-11 eq	1.20E-02	2.94E-07	1.20E-02	4.71E-04	1.33E-06	4.72E-04
Smog Potential	kg O3 eq	2.74E+04	2.99E+03	3.03E+04	1.22E+04	1.16E+04	2.38E+04
Total Primary Energy	MJ	6.56E+06	1.15E+05	6.67E+06	3.78E+05	5.20E+05	8.99E+05
Non-Renewable Energy	MJ	5.42E+06	1.15E+05	5.54E+06	3.65E+05	5.20E+05	8.85E+05
Fossil Fuel Consumption	MJ	5.21E+06	1.14E+05	5.32E+06	3.57E+05	5.19E+05	8.76E+05

The use and end-of-life stages of the redesign scenario also present significant environmental impacts, as outlined in Table 6-16. During the operational phase, energy use contributes a substantial 298,000 kg CO2 eq. to the GWP. The end-of-life stage adds 151,000 kg CO2 eq., primarily from deconstruction and waste processing. While biogenic carbon sequestration offsets 90,900 kg CO2 eq., the overall emissions remain high. Acidification potential reaches 1,471 kg SO2 eq., reflecting emissions during both use and waste disposal. The smog potential is also notable, rising to 29,800 kg O3 eq., indicating a continued impact on air quality. Total primary energy consumption during these stages is 9.83 million MJ, with 9.75 million MJ of this from non-renewable energy, showing a heavy reliance on fossil fuels (9.42 million MJ).

Table 6-16 LCA measures table results by LCS (B: use and end of life stages) redesign scenario

LCA Measures	Unit	USE				END OF LIFE		
		Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	Total	De-construction, Demolition, Disposal & Waste Processing	Transport	Total
GWP	kg CO2 eq	0.00E+00	0.00E+00	2.98E+05	2.98E+05	1.43E+05	8.73E+03	1.51E+05
GWP - Biogenic	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.09E+04	0.00E+00	9.09E+04
GWP - Calcination	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Acidification Potential	kg SO2 eq	0.00E+00	0.00E+00	7.71E+02	7.71E+02	6.18E+02	8.40E+01	7.02E+02
HH Particulate	kg PM2.5 eq	0.00E+00	0.00E+00	6.21E+02	6.21E+02	2.86E+02	4.65E+00	2.91E+02
Eutrophication Potential	kg N eq	0.00E+00	0.00E+00	1.71E+03	1.71E+03	6.10E+01	5.23E+00	6.62E+01
Ozone Depletion Potential	kg CFC-11 eq	0.00E+00	0.00E+00	1.95E-02	1.95E-02	2.92E-03	3.05E-07	2.92E-03
Smog Potential	kg O3 eq	0.00E+00	0.00E+00	7.68E+03	7.68E+03	1.90E+04	2.65E+03	2.17E+04
Total Primary Energy	MJ	0.00E+00	0.00E+00	5.64E+06	5.64E+06	7.71E+05	1.27E+05	8.98E+05
Non-Renewable Energy	MJ	0.00E+00	0.00E+00	5.09E+06	5.09E+06	7.65E+05	1.27E+05	8.92E+05
Fossil Fuel Consumption	MJ	0.00E+00	0.00E+00	3.39E+06	3.39E+06	7.38E+05	1.27E+05	8.65E+05

The impacts beyond the building's operational life and the total effects of the redesign scenario, presented in Table 6-17, emphasize the long-term environmental footprint of the upgraded materials. The GWP for the beyond building life stage reaches 146,000 kg CO2 eq., adding to a cumulative total of nearly 1 million kg CO2 eq. across the entire lifecycle. Acidification potential continues to grow, reaching 4,020 kg SO2 eq., due to ongoing emissions from material degradation and waste processing. The smog potential is also high, totaling 86,600 kg O3 eq., indicating a sustained contribution to air pollution throughout the building's lifecycle and beyond.

Table 6-17 LCA measures table results by LCS (C: beyond building life and total effects stages) redesign scenario

LCA Measures	Unit	BEYOND BUILDING LIFE (D)			TOTAL EFFECTS	
		BBL Material	BBL Transport	Total	A to C	A to D
GWP	kg CO2 eq	1.46E+05	0.00E+00	1.46E+05	8.39E+05	9.85E+05
GWP - Biogenic	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	-1.45E+05	-1.45E+05
GWP - Calcination	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	1.16E+05	1.16E+05
Acidification Potential	kg SO2 eq	2.90E+02	0.00E+00	2.90E+02	3.73E+03	4.02E+03
HH Particulate	kg PM2.5 eq	-8.70E-04	0.00E+00	-8.70E-04	1.12E+03	1.12E+03
Eutrophication Potential	kg N eq	1.73E+01	0.00E+00	1.73E+01	2.56E+03	2.58E+03
Ozone Depletion Potential	kg CFC- 11 eq	-3.98E-09	0.00E+00	-3.98E-09	3.48E-02	3.48E-02
Smog Potential	kg O3 eq	3.13E+03	0.00E+00	3.13E+03	8.35E+04	8.66E+04
Total Primary Energy	MJ	1.47E+06	0.00E+00	1.47E+06	1.41E+07	1.56E+07
Non-Renewable Energy	MJ	1.53E+06	0.00E+00	1.53E+06	1.24E+07	1.39E+07
Fossil Fuel Consumption	MJ	1.54E+06	0.00E+00	1.54E+06	1.05E+07	1.20E+07

The chart in Figure 6.5 shows the distribution of human health particulate (HH Particulate) emissions across different assembly groups in the redesign scenario. The floors are the largest contributor, with emissions of 308 kg PM2.5 eq, making up the bulk of the total particulate matter. Beams and columns follow, emitting 153 kg PM2.5 eq, indicating that a significant portion of particulate matter comes from the manufacturing and construction of these structural elements. The foundation contributes a smaller but still notable 35 kg PM2.5 eq. Interestingly, there are no particulate emissions from project extra materials, roofs, or walls, suggesting that these components either do not involve processes that release PM2.5 or are managed in a way that minimizes particulate emissions. On the whole, the total particulate emissions for the redesign scenario amount to 497 kg PM2.5 eq, indicating an impact on air quality and human health.

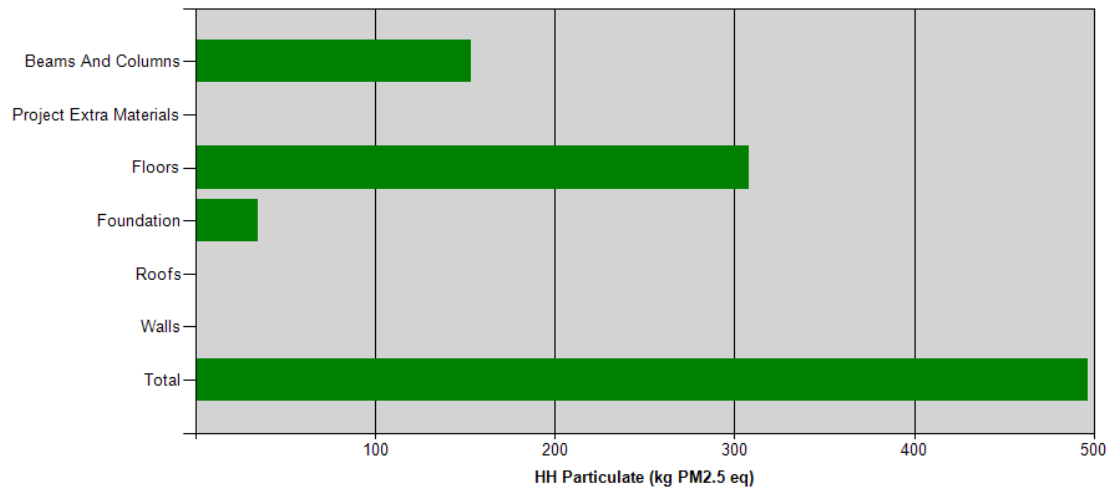


Figure 6.5 HH Particulate LCA Measure Chart by Assembly Groups

The chart in Figure 6.6 displays the GWP across various assembly groups in the redesign scenario. Floors exhibit the highest GWP, contributing 293,000 kg CO₂ eq, making them the largest source of emissions in this scenario. Beams and columns are the second-highest contributors, with 213,000 kg CO₂ eq, reflecting the high carbon footprint of these structural elements. The foundation adds 35,000 kg CO₂ eq, while no emissions are recorded for project extra materials, roofs, or walls in this context. Overall, the total GWP for the redesign scenario is 541,000 kg CO₂ eq, with most emissions coming from the production and installation of floors and beams/columns.

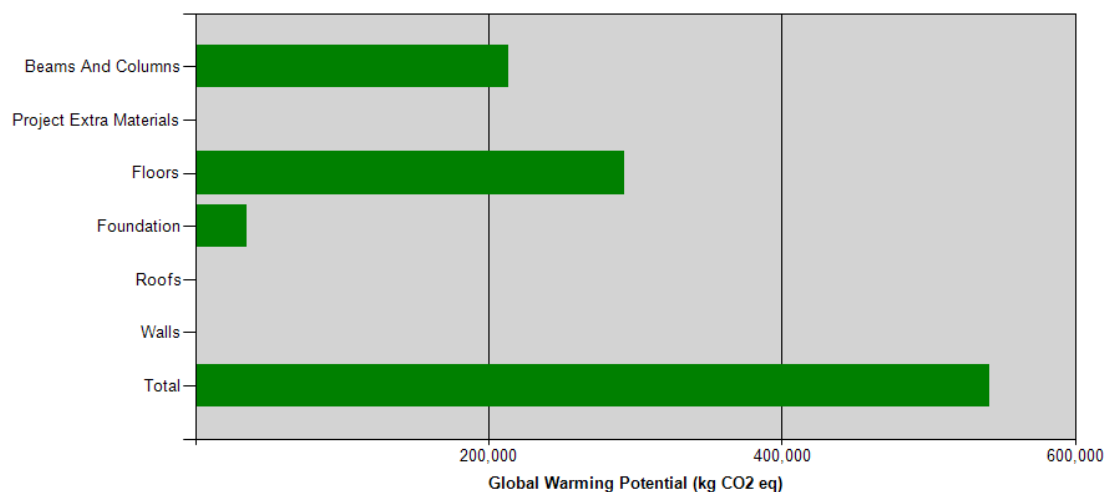


Figure 6.6 GWP LCA Measure Chart By Assembly Groups

6.2.4. All scenarios comparison

The comparison of the different retrofitting scenarios against the redesigned buildings provides insights into the environmental impacts associated with each approach. Table 6-18 summarizes the GWP across the LCS for all scenarios, which serves as a foundational reference for analyzing and comparing the impacts.

Table 6-18 Comparison of GWP By LCS

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Total
CFRP +Shear Wall	kg CO2 eq	2.75E+04	3.60E+03	1.30E+03	2.98E+05	2.30E+03	3.33E+05
Column Jacketing	kg CO2 eq	2.33E+04	2.98E+03	0.00E+00	2.98E+05	2.06E+03	3.26E+05
Re-designed Building	kg CO2 eq	3.09E+05	8.11E+04	0.00E+00	2.98E+05	1.51E+05	8.39E+05

Table 6-18 presents a comparison of the GWP across different LCS for the RC shear wall addition and CFRP wrapping of columns, RC jacketing of columns, and redesigned building scenarios. The most noticeable difference occurs in the product stage (A1 to A3), where the redesigned building shows an exceptionally high GWP of 309,000 kg CO2 eq., a result of the energy-intensive production of materials like concrete and steel. This contrasts sharply with the RC shear wall addition and CFRP wrapping of columns and RC jacketing of columns scenarios, which exhibit significantly lower GWPs of 27,500 kg CO2 eq. and 23,300 kg CO2 eq., respectively. In the construction process (A4 & A5), the redesigned building again has a much higher GWP (81,100 kg CO2 eq.) compared to RC shear wall addition and CFRP wrapping of columns (3,600 kg CO2 eq.) and RC jacketing of columns (2,980 kg CO2 eq.), reflecting the larger scale and complexity of the construction work in this scenario. During the use stage (B2 & B4), both the redesigned building and RC jacketing of columns scenarios have no recorded emissions, while RC shear wall addition and CFRP wrapping of columns has a minor contribution of 1,300 kg CO2 eq. In total, the redesigned building shows the highest GWP, reaching 839,000 kg CO2 eq., while the RC shear wall addition and CFRP wrapping of columns and RC jacketing of columns scenarios are far lower, at 333,000 kg CO2 eq. and 326,000 kg CO2 eq.,

respectively, indicating the substantial environmental benefits of retrofitting compared to full-scale rebuilding.

The chart in Figure 6.7 illustrates the GWP across various LCS for all scenarios. The redesigned building stands out during the product stage (A1 to A3) with a GWP of 363,000 kg CO₂ eq, a clear reflection of the heavy environmental toll from producing new materials like concrete and steel. In comparison, the RC jacketing of columns and RC shear wall addition and CFRP wrapping of columns retrofitting scenarios demonstrate much lower GWP values during this stage, showcasing their eco-friendlier nature by significantly reducing the carbon footprint linked to material production. During the construction process (A4 & A5), both the redesigned building and the existing building scenarios maintain higher GWP values compared to the retrofitting approaches, further underscoring the environmental costs of more extensive construction activities. Interestingly, the total operational energy (B6) remains consistent across all scenarios, demonstrating that the energy consumption for running the buildings over their lifespan is similar regardless of the structural changes or upgrades. But the end-of-life stage (C1 to C4) tells a different point of view, with the redesigned building once again showing a higher GWP. This increase points to the environmental burden associated with deconstruction, demolition, and waste management.

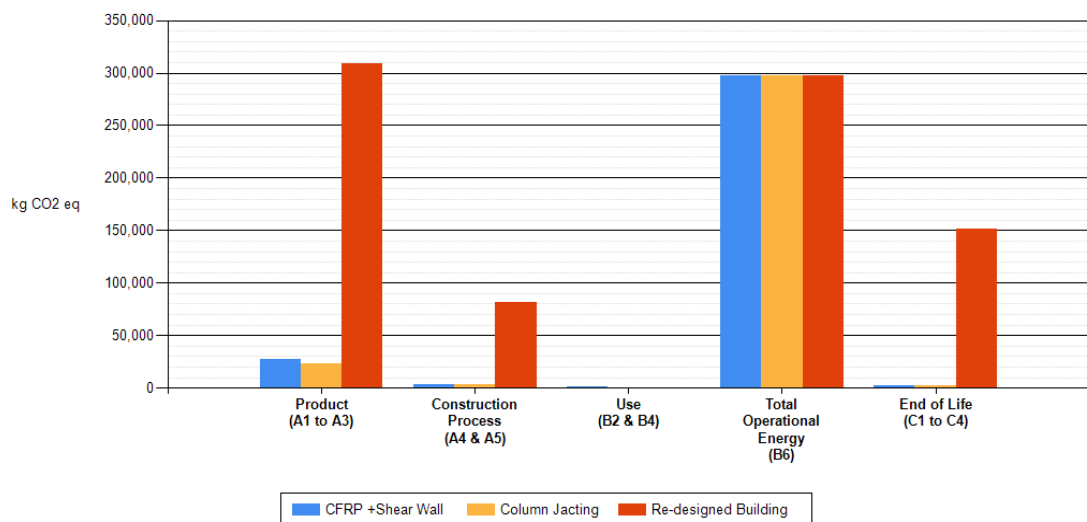


Figure 6.7 Comparison of GWP By LCS

The chart in Figure 6.8 breaks down the eutrophication potential across different stages for each scenario, highlighting the environmental impacts. In the

product stage (A1 to A3), the redesigned building stands out with the highest potential for water pollution, mainly due to the use of materials like concrete C30 and steel S420. On the other hand, the retrofitting scenarios, especially RC jacketing of columns, show much lower numbers. Moving into the construction process (A4 & A5), the redesigned building continues to have a bigger impact compared to the other options. During the use stage (B2 & B4), the pollution potential is small for all scenarios, as it's mainly tied to operational energy use, which is steady across the board. When it comes to total operational energy (B6), all scenarios show similar levels, meaning building operation has a consistent impact no matter which option is chosen. At the end-of-life stage (C1 to C4), the redesigned building once again has the highest pollution potential, reflecting the environmental cost of material breakdown and waste handling. Overall, the data shows that while the redesigned building uses more advanced materials, it comes with a heavier environmental burden compared to the retrofitting options like RC jacketing of columns, which prove to be more eco-friendly throughout the building's life.

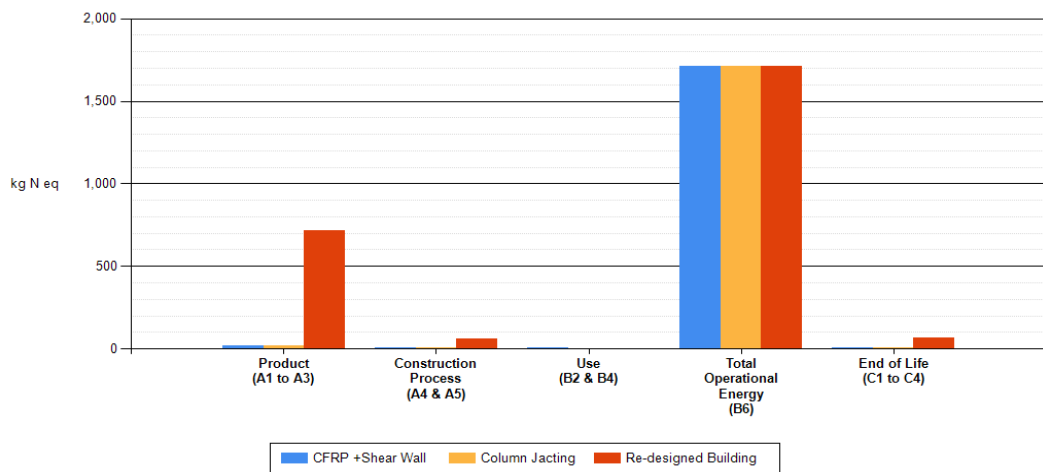


Figure 6. 8 Comparison of Eutrophication Potential By LCS

The smog potential comparison shown in Figure 6.9 shows a clear distinction between the different scenarios in terms of their contribution to air pollution, specifically ground-level ozone formation. The redesigned building exhibits the highest smog potential during the product stage (A1 to A3), with emissions reaching 30,300 kg O₃ eq. This is significantly higher than the RC shear wall addition and CFRP wrapping of columns scenario (1,300 kg O₃ eq.) and the RC jacketing of columns scenario (1,010 kg O₃ eq.), largely due to the high emissions from material production,

particularly concrete and steel. Similarly, in the construction stage (A4 & A5), the redesigned building records 23,800 kg O₃ eq., which is again much higher compared to the retrofitting scenarios (956 kg O₃ eq. for RC shear wall addition and CFRP wrapping of columns and 832 kg O₃ eq. for RC jacketing of columns).

During the use stage (B2 & B4), the smog potential remains low across all scenarios, with consistent figures around 7,680 kg O₃ eq., reflecting the energy consumption in building operation. The end-of-life stage (C1 to C4) follows a similar pattern to earlier stages, with the redesigned building showing a smog potential of 21,700 kg O₃ eq., significantly higher than 786 kg O₃ eq. for the RC shear wall addition and CFRP wrapping of columns and 765 kg O₃ eq. for RC jacketing of columns. Overall, the redesigned building generates a total smog potential of 83,500 kg O₃ eq., dwarfing the contributions from the retrofitting scenarios (10,800 kg O₃ eq. for RC shear wall addition and CFRP wrapping of columns and 10,300 kg O₃ eq. for RC jacketing of columns).

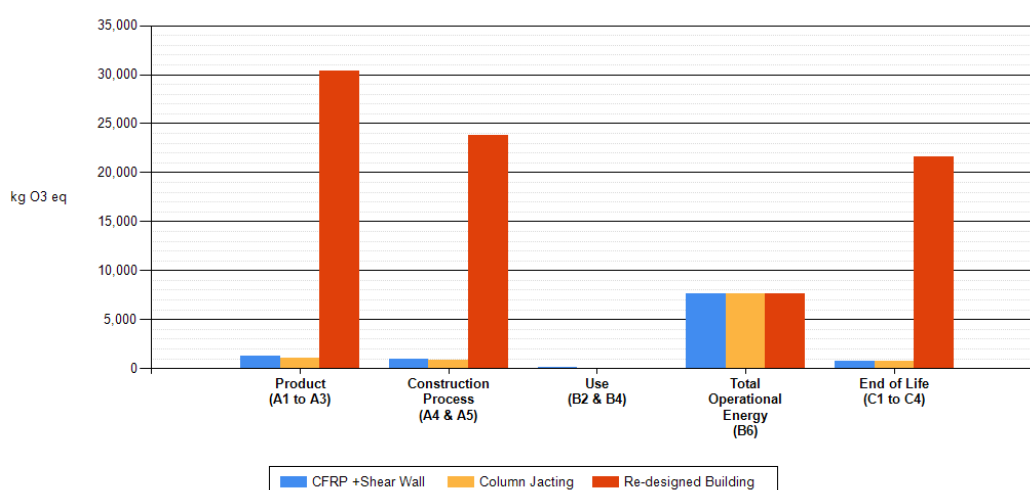


Figure 6.9 Comparison of Smog Potential By LCS

Figure 6.10 compares the acidification potential across the LCS, providing a clear comparison of the impacts associated with each scenario. As seen, the redesigned building scenario stands out with the highest acidification potential, especially in the product stage (A1 to A3), with emissions reaching 1,490 kg SO₂ eq. This is significantly higher compared to RC shear wall addition and CFRP wrapping of columns at 87.7 kg SO₂ eq., and RC jacketing of columns at 51.5 kg SO₂ eq. The construction process (A4 & A5) follows a similar trend, where the redesigned building continues to exhibit a high acidification potential (763 kg SO₂ eq.), while RC shear wall addition and

CFRP wrapping of columns and RC jacketing of columns display much lower impacts at 33.1 kg SO₂ eq. and 26.7 kg SO₂ eq., respectively. Throughout the use stage (B2 & B4), the acidification potential remains steady across all scenarios, primarily influenced by energy consumption. The end-of-life stage (C1 to C4) once again sees the redesigned building as the highest contributor, with 702 kg SO₂ eq., far exceeding the contributions from RC shear wall addition and CFRP wrapping of columns (25.9 kg SO₂ eq.) and RC jacketing of columns (24.3 kg SO₂ eq.). Overall, the redesigned building records a total acidification potential of 3,730 kg SO₂ eq., nearly quadrupling the impacts of the retrofitting alternatives, which hover around 927 kg SO₂ eq. for RC shear wall addition and CFRP wrapping of columns and 873 kg SO₂ eq. for RC jacketing of columns.

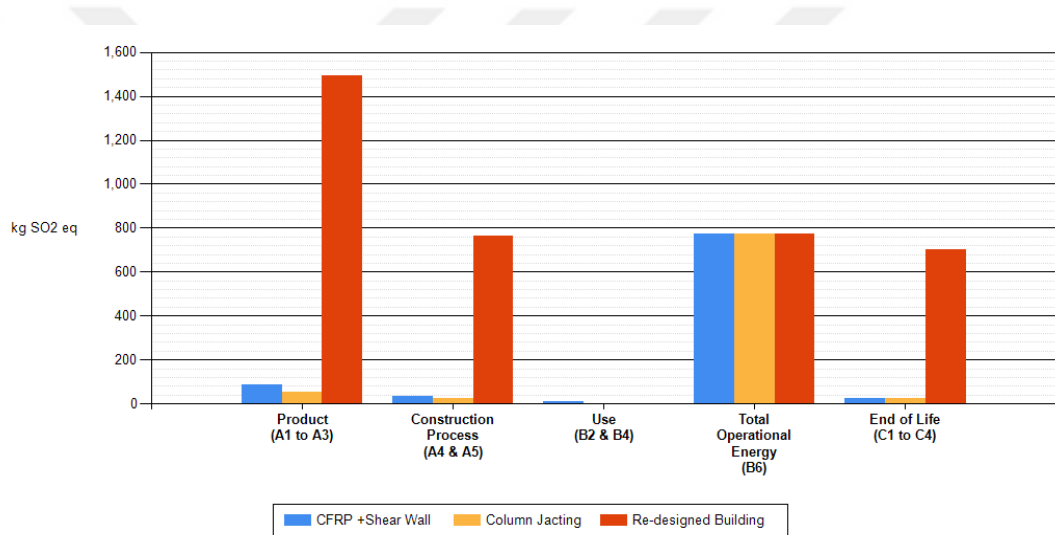


Figure 6.10 Comparison of Acidification Potential By LCS

Figure 6.11 shows the big differences in total energy use across the life cycle stages between the retrofitting scenarios and the redesigned building. The product stage (A1 to A3) stands out the most, with the redesigned building using 6.67 million MJ, compared to just 228,000 MJ for the RC shear wall addition and CFRP wrapping of columns scenario and 183,000 MJ for RC jacketing of columns. This reflects how much more material is needed for the redesign. During the construction phase (A4 & A5), the redesigned building again uses much more energy—899,000 MJ, while RC shear wall addition and CFRP wrapping of columns and RC jacketing of columns only use 41,400 MJ and 35,700 MJ. The energy use during the operational stage (B6) stays the same across all scenarios at 5.64 million MJ. However, the end-of-life stage (C1 to C4) shows the redesigned building requires 898,000 MJ for deconstruction and waste

handling, compared to just 34,200 MJ for RC shear wall addition and CFRP wrapping of columns and 30,500 MJ for RC jacketing of columns. This highlights how much more energy the redesigned building needs over time.

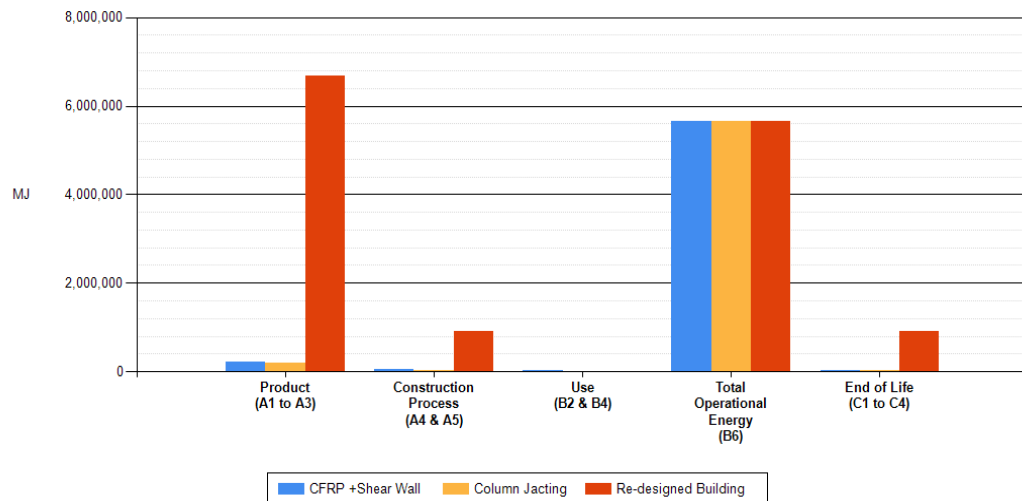


Figure 6.11 Comparison of Total Primary Energy By LCS

Figure 6.12 presents a comparison of Human Health Particulate (HH PM_{2.5}) emissions across different LCS, focusing on particulate matter emissions in various building scenarios. The redesigned building has the highest emissions in the product stage, reaching 161 kg PM_{2.5} eq, due to the use of high-impact materials like concrete C30 and steel S420. Similarly, the existing building shows notable emissions in this stage, but less than the redesigned building. In contrast, the RC shear wall addition and CFRP wrapping of columns and RC jacketing of columns scenarios emit significantly less particulate matter, with 20.3 kg PM_{2.5} eq and 7.44 kg PM_{2.5} eq, respectively, highlighting their lower environmental burden. The construction process also reflects higher emissions for the redesigned building (45 kg PM_{2.5} eq), compared to the lower-impact retrofitting scenarios. At the end-of-life stage, the redesigned building shows another spike in emissions (291 kg PM_{2.5} eq), driven by the energy demands of deconstruction and waste processing.

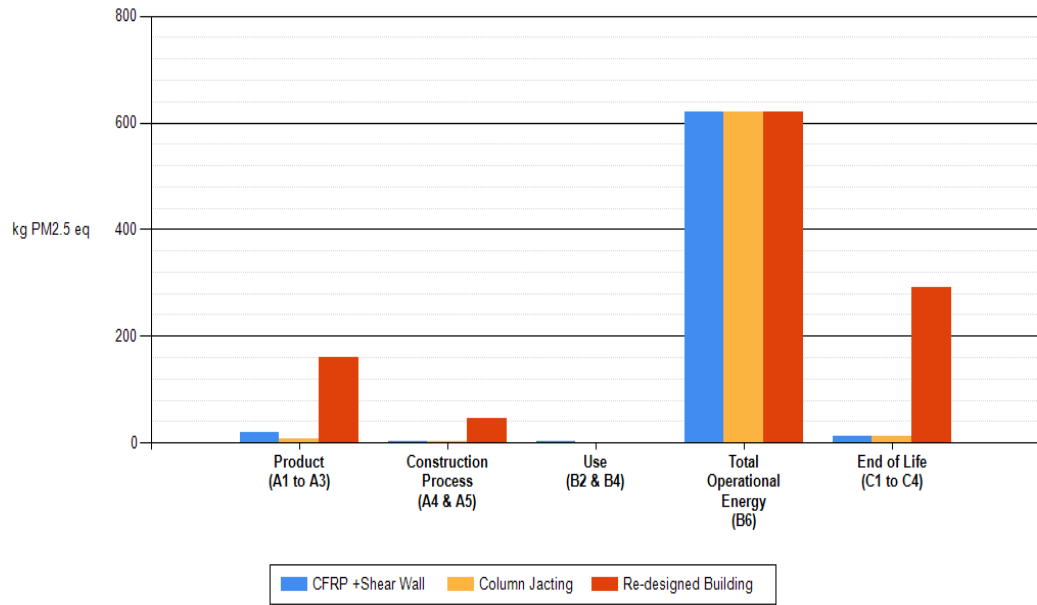


Figure 6.12 Comparison of HH Particulate by LCS (Embodied Effects)

7. CONCLUSION

In this thesis, an existing six-story concrete building was investigated in terms of structural performance under seismic effect, and economic and environmental aspects. Structural performance was studied using linear analysis in Protastucture Software. Environmental aspects were investigated using a whole-building life cycle assessment (LCA) by Athena Impact Estimator Robust Software for all alternatives.

Two different retrofit methodology (RC shear wall addition and CFRP wrapping of columns, and Concrete jacketing) were implemented to enhance the building's overall performance. In addition to that, the building was re-designed. The life-cycle environmental effect of different retrofitting strategies and re-construction of the building were investigated. The results can be summarized in the following points:

1. Retrofitting methods successfully helped to enhance the building performance goal as per TBEC 2018.
2. Two different approach as RC shear wall addition and CFRP wrapping of columns and RC jacketing of columns significantly increased the building shear strength capacity and limited the excessive plastic rotations of the members.
3. Utilizing RC jacketing of columns for column retrofitting represents the most cost-effective solution for renovating and strengthening such a building based on lower consumption and use of building materials compared to other alternatives.
4. The study identified that manufacturing and operational phases significantly contribute to the overall environmental footprint, with retrofitting methods presenting lower environmental impacts compared to a complete reconstruction.
5. Complete reconstruction ensures compliance with modern standards and offers the highest structural integrity, it also results in the highest environmental impact due to extensive resource use and emissions.
6. The retrofitting scenarios, particularly involving RC shear wall addition and CFRP wrapping of columns and RC jacketing of columns, provide a balanced approach by enhancing structural resilience and reducing environmental impacts associated with material production and energy use.

7. The importance of integrating sustainable practices in construction and retrofitting is emphasized. Utilizing advanced materials and methodologies, alongside tools like the Athena Impact Estimator, can achieve high structural performance and minimize environmental impacts, supporting the goal of sustainable development in the construction industry.
8. The redesigned building, which incorporated big amounts of upgraded materials like concrete C30 and steel S420, exhibited a substantial increase in GWP, acidification potential, and smog potential during the product and construction stages. This scenario also demonstrated higher total primary energy consumption, reflecting the energy-intensive nature of producing and implementing these materials.
9. The RC jacketing of columns and RC shear wall addition and CFRP wrapping of columns scenarios, while showing lower impacts compared to the existing and redesigned buildings, still contributed notably to the environmental burdens, particularly regarding human health particulate emissions and total primary energy use.
10. The comparison of LCS across all scenarios highlighted the importance of considering both embodied and operational impacts. The product and construction stages were identified as the most critical phases for GWP, acidification potential, smog potential, and energy consumption.
11. The use stage, primarily driven by operational energy demands, remained consistent across scenarios, underscoring the need for energy efficiency measures. Due to the deconstruction and waste processing activities, the end-of-life stage also presented significant impacts, particularly for the redesigned building.
12. Embodied effects like biogenic GWP were prominent in the redesigned building scenario, illustrating the carbon sequestration and release associated with biogenic materials. These findings highlight the need to integrate sustainable materials and practices in retrofitting projects to minimize environmental impacts and enhance building resilience.

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APPENDICES

APPENDIX A

Table A.1 Storey seismic weight calculations

		Existed Building	RC shear wall addition and CFRP wrapping of columns	RC jacketing of columns	Re-designed Building
Storey	h (m)	W (kN)	W (kN)	W (kN)	W (kN)
6	2.700	3284.66	3499.32	3284.66	2234.61
5	2.900	3308.28	3543.13	3308.28	2272.37
4	2.900	3308.28	3543.13	3306.37	2265.38
3	2.900	3282.51	3520.40	3256.38	2307.43
2	3.600	3410.66	3720.76	4229.71	2426.33
1	2.400	2952.30	3005.10	3571.46	3063.01
Total		19546.71	20831.84	20956.86	14569.12

Table A.2. Story centre of gravity coordinates

Storey	Existed Building		RC shear wall addition and CFRP wrapping of columns		RC jacketing of columns		Re-designed Building	
	X _g (m)	Y _g (m)	X _g (m)	Y _g (m)	X _g (m)	Y _g (m)	X _g (m)	Y _g (m)
6	10.299741	9.715829	10.296680	9.988123	10.299741	9.715829	8.750000	7.964947
5	10.299389	9.718962	10.296106	10.013576	10.299389	9.718962	8.750000	7.955866
4	10.299389	9.718962	10.296106	10.013576	10.304478	9.715480	8.752781	7.960908
3	10.300530	9.708335	10.297120	10.011545	10.225845	9.751759	8.730736	7.914427
2	10.291758	9.731517	10.288321	10.103726	10.277818	9.811110	8.726811	7.887111
1	10.255630	9.720244	10.255635	9.578423	10.249363	9.757440	8.752330	7.961352

Table A.3. Story centre of rigidity coordinates

	Existed Building		RC shear wall addition and CFRP wrapping of columns		RC jacketing of columns		Re-designed Building	
Storey	X _R (m)	Y _R (m)	X _R (m)	Y _R (m)	X _R (m)	Y _R (m)	X _R (m)	Y _R (m)
Storey: 6	8.76143	9.82874	8.750356	8.265898	8.761434	9.828740	8.750000	6.149620
Storey: 5	8.76143	9.82874	8.750356	8.265898	8.761434	9.828740	8.750000	6.149620
Storey: 4	8.76143	9.82874	8.750356	8.265898	8.761434	9.828740	8.750000	6.149620
Storey: 3	8.76143	9.82874	8.750356	8.265898	7.450784	11.216746	8.744375	6.150461
Storey: 2	8.74448	9.43290	8.749748	8.267683	8.741853	9.338433	8.744375	6.150461
Storey: 1	8.75001	1.22932	8.750010	0.999372	8.750047	1.294747	8.750104	1.285589

Table A.4. Eigenvalues and Frequencies

	Existed Building			RC shear wall addition and CFRP wrapping of columns		
Mode	Period (sec)	Circular Frequency (rad/sec)	Eigenvalue (rad/sec) ²	Period (sec)	Circular Frequency (rad/sec)	Eigenvalue (rad/sec) ²
1	1.095736	5.734214	5.734214	0.684249	9.182603	9.182603
2	1.046868	6.001888	6.001888	0.353455	17.776483	17.776483
3	0.971716	6.466073	6.466073	0.344571	18.234796	18.234796
4	0.318025	19.756901	19.756901	0.155153	40.496733	40.496733
5	0.302961	20.739251	20.739251	0.095358	65.890523	65.890523
6	0.290506	21.628383	21.628383	0.093476	67.216899	67.216899

Table A.5. Eigenvalues and Frequencies

RC jacketing of columns			Re-designed Building		
Period (sec)	Circular Frequency (rad/sec)	Eigenvalue (rad/sec) ²	Period (sec)	Circular Frequency (rad/sec)	Eigenvalue (rad/sec) ²
1.083045	6.80497	6.80497	0.556404	11.292482	11.292482
1.13959	7.160255	7.160255	0.379149	16.571797	16.571797
1.252955	7.872546	7.872546	0.266663	23.562312	23.562312
3.78855	23.80416	23.80416	0.152097	41.310392	41.310392
3.879535	24.375834	24.375834	0.086269	72.832355	72.832355
4.208867	26.445091	26.445091	0.076062	82.60571	82.60571

Table A.6. Modal Participating Factors

Mode	Existed Building			RC shear wall addition and CFRP wrapping of columns		
	Period (sec)	X-dir	Y-dir	Period (sec)	X-dir	Y-dir
1	1.095736	19.153434	4.009972	0.684249	36.314517	0.483258
2	1.046868	29.237758	-9.452819	0.353455	1.075642	-1.310523
3	0.971716	5.907865	34.241725	0.344571	-0.542493	36.424489
4	0.318025	-0.41117	-2.817408	0.155153	17.568999	0.301869
5	0.302961	13.789291	-1.97011	0.095358	0.411785	0.765136
6	0.290506	1.837769	12.893089	0.093476	-0.153961	18.207448

Table A.7. Modal Participating Factors

RC jacketing of columns			Re-designed Building		
Period (sec)	X-dir	Y-dir	Period (sec)	X-dir	Y-dir
1.083045	23.312627	1.095668	0.556404	11.816216	-0.01362
1.13959	23.831352	-4.531419	0.379149	-0.00178104	28.81692
1.252955	2.558263	33.271962	0.266663	26.367527	0.003095
3.78855	4.067425	2.453518	0.152097	-5.77084	-0.038947
3.879535	16.462356	-1.51395	0.086269	-0.016859	13.705915
4.208867	0.841332	15.265314	0.076062	-0.74066	0.000581918

Table A.8 Modal Participating Mass (%)

Mode	Existed Building			RC shear wall addition and CFRP wrapping of columns		
	Period (sec)	X-dir	Y-dir	Period (sec)	X-dir	Y-dir
1	1.095736	20.156815	0.883509	0.684249	67.348943	0.011927
2	1.046868	46.969588	4.909659	0.353455	0.059089	0.087712
3	0.971716	1.91774	64.422841	0.344571	0.01503	67.757467
4	0.318025	0.009289	0.436142	0.155153	15.763922	0.004654
5	0.302961	10.447502	0.21326	0.095358	0.00866	0.029898
6	0.290506	0.185571	9.133613	0.093476	0.001211	16.930446

Table A.9 Modal Participating Mass (%)

RC jacketing of columns			Re-designed Building		
Period (sec)	X-dir	Y-dir	Period (sec)	X-dir	Y-dir
1.083045	27.710699	0.06121	0.556404	10.419531	1.38432E-05
1.13959	28.957589	1.046968	0.379149	2.36721E-07	61.970704
1.252955	0.3337	56.444531	0.266663	51.8836	7.15028E-07
3.78855	0.843537	0.306933	0.152097	2.485246	0.0001132
3.879535	13.818122	0.116866	0.086269	2.12119E-05	14.018688
4.208867	0.036091	11.881645	0.076062	0.040938	2.52706E-08

Table A.10 Cumulative Modal Participating Mass (%)

Mode	Existed Building			RC shear wall addition and CFRP wrapping of columns		
	Period (sec)	X-dir	Y-dir	Period (sec)	X-dir	Y-dir
1	1.095736	20.156815	0.883509	0.684249	67.348943	0.011927
2	1.046868	67.126403	5.793168	0.353455	67.408032	0.099639
3	0.971716	69.044143	70.216009	0.344571	67.423062	67.857106
4	0.318025	69.053432	70.652151	0.155153	83.186984	67.86176
5	0.302961	79.500934	70.865411	0.095358	83.195644	67.891658
6	0.290506	79.686505	79.999024	0.093476	83.196855	84.822104

Table A.11 Cumulative Modal Participating Mass (%)

RC jacketing of columns			Re-designed Building		
Period (sec)	X-dir	Y-dir	Period (sec)	X-dir	Y-dir
1.083045	27.710699	0.06121	0.556404	10.419531	1.38432E-05
1.13959	56.668288	1.108178	0.379149	10.419531	61.970718
1.252955	57.001988	57.552709	0.266663	62.303131	61.970719
3.78855	57.845525	57.859642	0.152097	64.788376	61.970832
3.879535	71.663646	57.976508	0.086269	64.788398	75.98952
4.208867	71.699737	69.858153	0.076062	64.829336	75.98952

Table A.12 Weak Storey Irregularity (B1) Check for X-Direction

	Existed Building	RC shear wall addition and CFRP wrapping of columns	RC jacketing of columns	Re-designed Building
Storey No	η_c	η_c	η_c	η_c
Storey: 6	-	-	-	-
Storey: 5	$1.000 > 0.80$	$1.000 > 0.80$	$1.000 > 0.80$	$1.000 > 0.80$
Storey: 4	$1.000 > 0.80$	$1.000 > 0.80$	$1.000 > 0.80$	$1.000 > 0.80$
Storey: 3	$1.000 > 0.80$	$1.000 > 0.80$	$1.083 > 0.80$	$1.098 > 0.80$
Storey: 2	$1.182 > 0.80$	$1.148 > 0.80$	$2.989 > 0.80$	$1.000 > 0.80$
Storey: 1	$2.308 > 0.80$	$2.073 > 0.80$	$1.530 > 0.80$	$2.315 > 0.80$

Table A.13 Weak Storey Irregularity (B1) Check for Y-Direction

Storey No	Existed Building	RC shear wall addition and CFRP wrapping of columns	RC jacketing of columns	Re-designed Building
	η_c	η_c	η_c	η_c
Storey: 6	-	-	-	-
Storey: 5	$1.000 > 0.80$	$1.000 > 0.80$	$1.000 > 0.80$	$1.000 > 0.80$
Storey: 4	$1.000 > 0.80$	$1.000 > 0.80$	$1.000 > 0.80$	$1.000 > 0.80$
Storey: 3	$1.000 > 0.80$	$1.000 > 0.80$	$1.083 > 0.80$	$1.106 > 0.80$
Storey: 2	$1.182 > 0.80$	$1.111 > 0.80$	$2.989 > 0.80$	$1.000 > 0.80$
Storey: 1	$3.048 > 0.80$	$1.988 > 0.80$	$1.800 > 0.80$	$3.233 > 0.80$

Table A.14 Torsion irregularity (A1) check for X-direction

Storey	Existed Building	RC shear wall addition and CFRP wrapping of columns	RC jacketing of columns	Re-designed Building
	η_b	η_b	η_b	η_b
Storey: 6	$1.102 \leq 1.20$	$1.021 \leq 1.20$	$1.244 > 1.20$	$1.697 > 1.40$
Storey: 5	$1.078 \leq 1.20$	$1.019 \leq 1.20$	$1.200 > 1.20$	$1.773 > 1.40$
Storey: 4	$1.066 \leq 1.20$	$1.018 \leq 1.20$	$1.149 \leq 1.20$	$1.822 > 1.40$
Storey: 3	$1.047 \leq 1.20$	$1.016 \leq 1.20$	$1.074 \leq 1.20$	$1.859 > 1.40$
Storey: 2	$1.010 \leq 1.20$	$1.006 \leq 1.20$	$1.066 \leq 1.20$	$1.818 > 1.40$
Storey: 1	$1.073 \leq 1.20$	$1.147 \leq 1.20$	$1.029 \leq 1.20$	$1.097 \leq 1.20$

Table A.15 Torsion irregularity (A1) check for Y-direction

	Existed Building	RC shear wall addition and CFRP wrapping of columns	RC jacketing of columns	Re-designed Building
Storey	η_b	η_b	η_b	η_b
Storey: 6	$1.058 \leq 1.20$	$1.007 \leq 1.20$	$1.070 \leq 1.20$	$1.001 \leq 1.20$
Storey: 5	$1.056 \leq 1.20$	$1.005 \leq 1.20$	$1.073 \leq 1.20$	$1.001 \leq 1.20$
Storey: 4	$1.056 \leq 1.20$	$1.004 \leq 1.20$	$1.089 \leq 1.20$	$1.000 \leq 1.20$
Storey: 3	$1.047 \leq 1.20$	$1.002 \leq 1.20$	$1.123 \leq 1.20$	$1.001 \leq 1.20$
Storey: 2	$1.025 \leq 1.20$	$1.001 \leq 1.20$	$1.080 \leq 1.20$	$1.003 \leq 1.20$
Storey: 1	$1.001 \leq 1.20$	$1.004 \leq 1.20$	$1.083 \leq 1.20$	$1.001 \leq 1.20$

Table A.16 Relative storey drift check for X-direction

	Existed Building	RC shear wall addition And CFRP wrapping of columns	RC jacketing of columns	Re-designed Building
Storey	$\lambda(\delta / h)$ effective	$\lambda(\delta / h)$ effective	$\lambda(\delta / h)$ effective	$\lambda(\delta / h)$ effective
Storey: 6	$0.002315 \leq 0.008$ ✓	$0.002109 \leq 0.008$ ✓	$0.003527 \leq 0.008$ ✓	$0.002257 \leq 0.008$ ✓
Storey: 5	$0.003092 \leq 0.008$ ✓	$0.002223 \leq 0.008$ ✓	$0.004389 \leq 0.008$ ✓	$0.002633 \leq 0.008$ ✓
Storey: 4	$0.003704 \leq 0.008$ ✓	$0.002184 \leq 0.008$ ✓	$0.004516 \leq 0.008$ ✓	$0.002804 \leq 0.008$ ✓
Storey: 3	$0.003682 \leq 0.008$ ✓	$0.001950 \leq 0.008$ ✓	$0.003008 \leq 0.008$ ✓	$0.002660 \leq 0.008$ ✓
Storey: 2	$0.002227 \leq 0.008$ ✓	$0.001309 \leq 0.008$ ✓	$0.000950 \leq 0.008$ ✓	$0.001807 \leq 0.008$ ✓
Storey: 1	$0.000054 \leq 0.008$ ✓	$0.000132 \leq 0.008$ ✓	$0.000108 \leq 0.008$ ✓	$0.000097 \leq 0.008$ ✓

Table A.17 Relative storey drift check for Y-direction

	Existed Building	RC shear wall addition And CFRP wrapping of columns	RC jacketing of columns	Re-designed Building
Storey	$\lambda(\delta / h)$ effective	$\lambda(\delta / h)$ effective	$\lambda(\delta / h)$ effective	$\lambda(\delta / h)$ effective
Storey: 6	$0.001768 \leq 0.008$ ✓	$0.001026 \leq 0.008$ ✓	$0.002103 \leq 0.008$ ✓	$0.001188 \leq 0.008$ ✓
Storey: 5	$0.002608 \leq 0.008$ ✓	$0.001096 \leq 0.008$ ✓	$0.003132 \leq 0.008$ ✓	$0.001267 \leq 0.008$ ✓
Storey: 4	$0.003279 \leq 0.008$ ✓	$0.001072 \leq 0.008$ ✓	$0.003789 \leq 0.008$ ✓	$0.001265 \leq 0.008$ ✓
Storey: 3	$0.003474 \leq 0.008$ ✓	$0.000948 \leq 0.008$ ✓	$0.003057 \leq 0.008$ ✓	$0.001149 \leq 0.008$ ✓
Storey: 2	$0.002276 \leq 0.008$ ✓	$0.000665 \leq 0.008$ ✓	$0.000804 \leq 0.008$ ✓	$0.000825 \leq 0.008$ ✓
Storey: 1	$0.000021 \leq 0.008$ ✓	$0.000086 \leq 0.008$ ✓	$0.000049 \leq 0.008$ ✓	$0.000045 \leq 0.008$ ✓

Table A.18 Earthquake parameters and base shear for Load Case (Ex+)

Model	Period (sec)	Limit Period (sec)	Effective PGA (g)	Total Base Shear (kN)	Min. Base Shear (kN)	Added Roof Load (kN)
Existed building	1.047	1.193	0.208	3785.75	653.89	170.36
RC shear wall addition And CFRP wrapping of columns	0.684	1.193	0.321	6276.29	703.50	282.43
RC jacketing of columns	0.878	1.193	0.248	4864.27	704.64	218.89
Re-designed Building	0.267	1.193	0.822	11017.19	481.44	495.77

Table A.19 Earthquake parameters and base shear for Load Case (Ey+)

Dir	Period (sec)	Limit Period (sec)	Effective PGA (g)	Total Base Shear (kN)	Min. Base Shear (kN)	Added Roof Load (kN)
Existed building	0.972	1.193	0.226	4108.24	653.89	184.87
RC shear wall addition And CFRP wrapping of columns	0.345	1.193	0.634	12422.33	703.50	559.00
RC jacketing of columns	0.798	1.193	0.275	5391.24	704.64	242.61
Re-designed Building	0.379	1.193	0.576	7717.17	481.44	347.27

Table A.20 The distribution of forces to stories for load case (Ex+)

	Existed Building	RC shear wall addition And CFRP wrapping of columns	RC jacketing of columns	Re-designed Building
Storey	F _x (kN)	F _x (kN)	F _x (kN)	F _x (kN)
6	1192.35	1968.25	1489.92	3365.33
5	870.15	1443.40	1082.19	2469.85
4	698.48	1158.64	868.69	1982.65
3	522.37	873.89	644.05	1520.96
2	367.09	620.85	575.21	1083.94
1	135.32	211.26	204.20	594.45
Total	3785.75	6276.29	4864.27	11017.19

Table A.21 The distribution of forces to stories for load case (Ey+)

Storey	Existed Building	RC shear wall addition And CFRP wrapping of columns	RC jacketing of columns	Re-designed Building
	F _y (kN)	F _y (kN)	F _y (kN)	F _y (kN)
6	1293.92	3895.65	1651.33	2357.30
5	944.27	2856.84	1199.43	1730.05
4	757.98	2293.24	962.80	1388.78
3	566.87	1729.65	713.82	1065.38
2	398.36	1228.82	637.53	759.26
1	146.84	418.13	226.33	416.39
Total	4108.24	12422.32	5391.24	7717.17

The architectural floor plan is a detailed layout of a building, organized by a grid system. The grid lines are labeled with letters (B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, R) along the top and bottom, and numbers (2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13) along the left and right sides. The plan includes various rooms, corridors, and structural elements. Rooms are labeled with codes like SB01, SB02, etc., and dimensions. Corridors are labeled with codes like KB01, KB02, etc., and dimensions. The plan includes a north arrow and a scale bar.

Figure B.1 Basement floor plan view

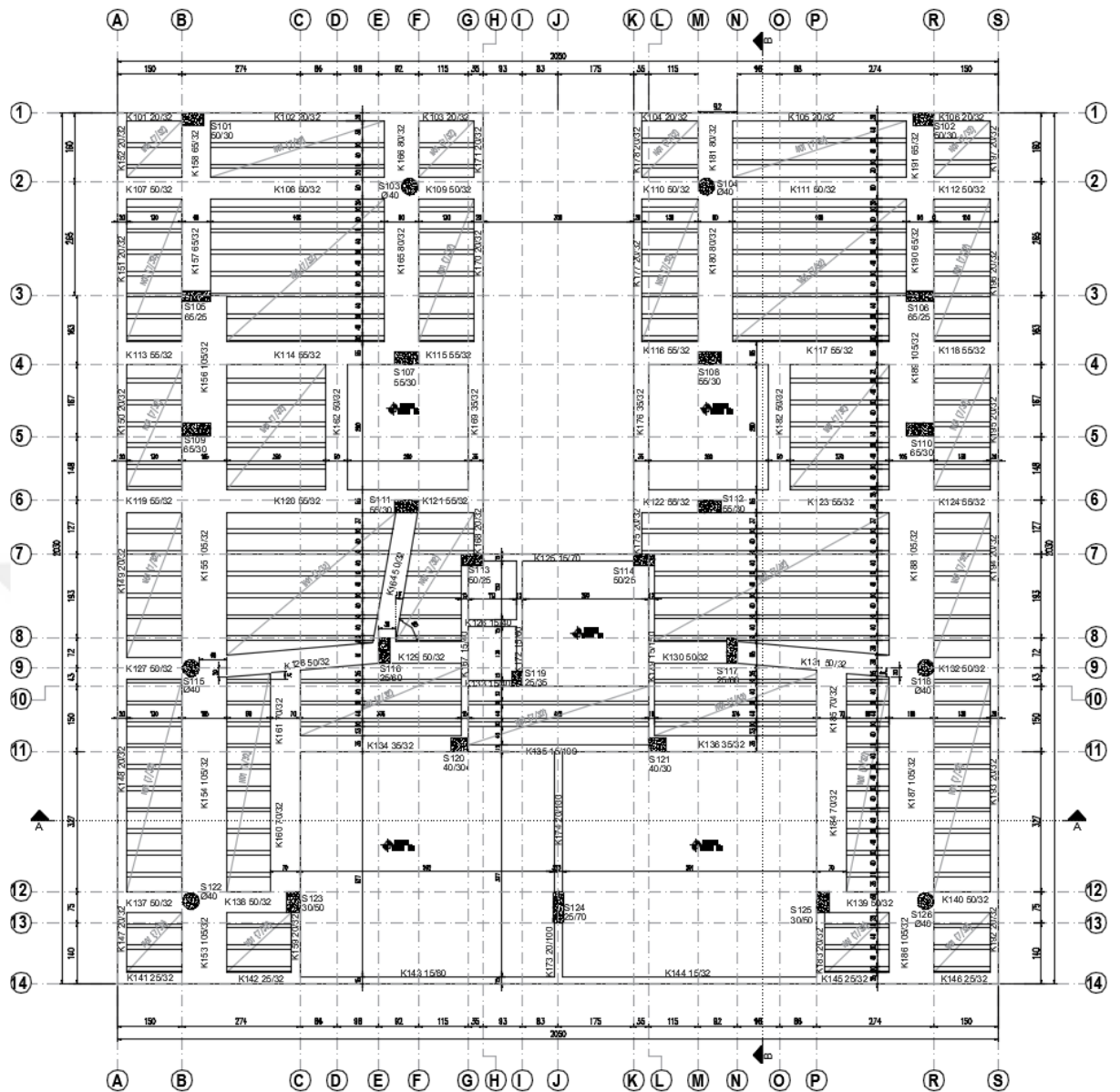


Figure B.3 Repeated floor plan view for first, second, third and fourth floors

APPENDIX C

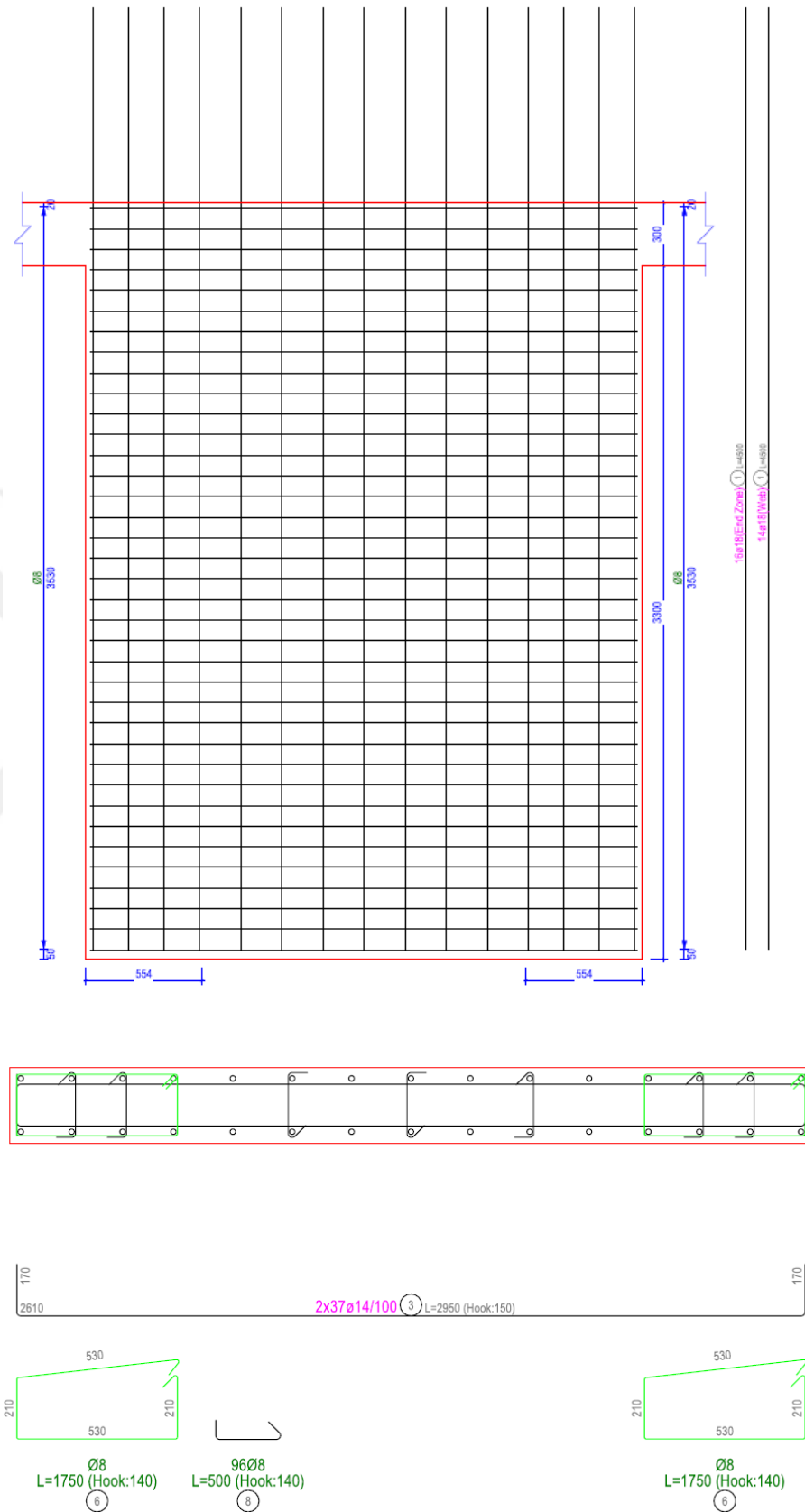


Figure C.1 Reinforcement detailing for shear walls 1 and 2

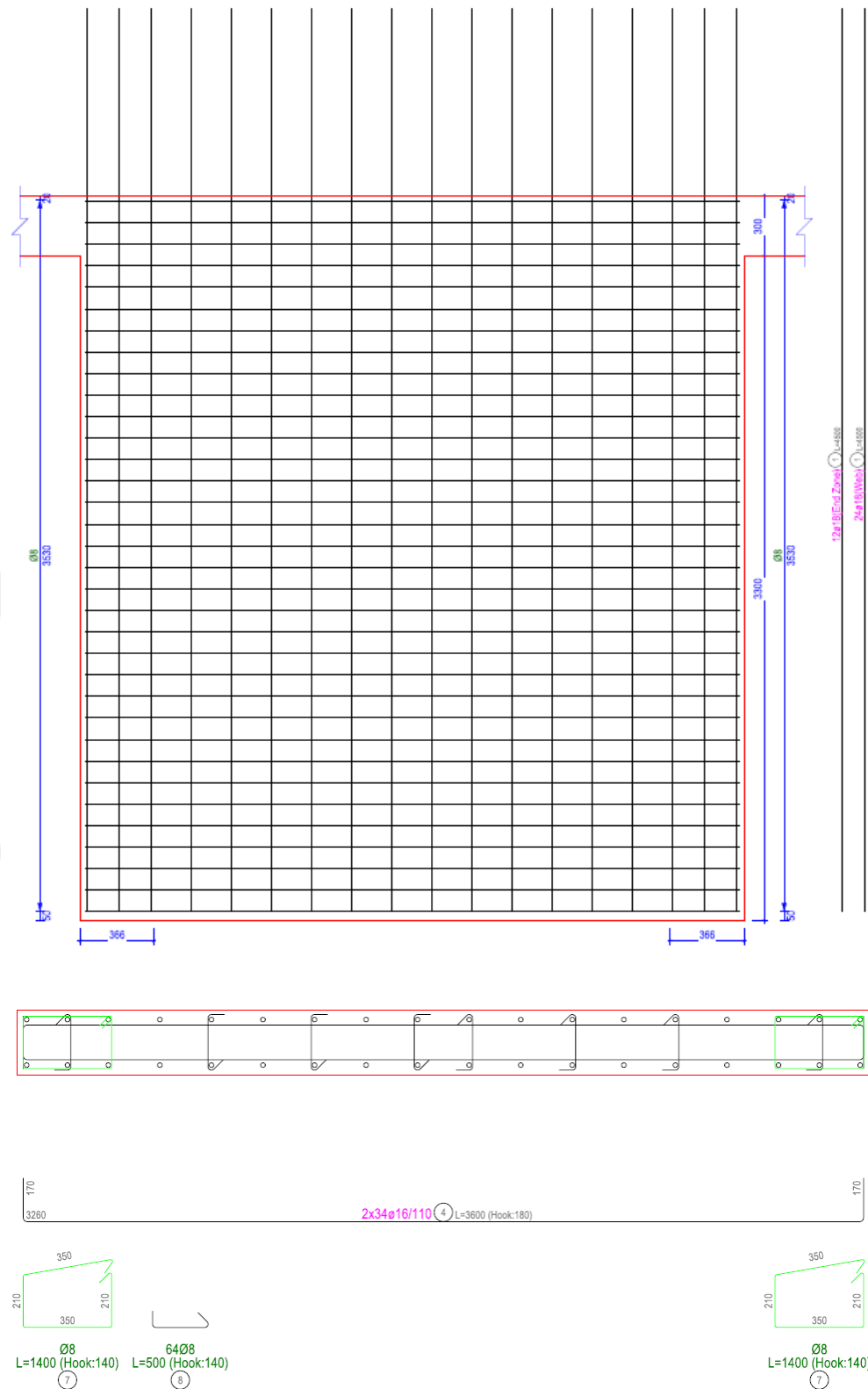


Figure C.2 Reinforcement detailing for shear walls 3 and 4

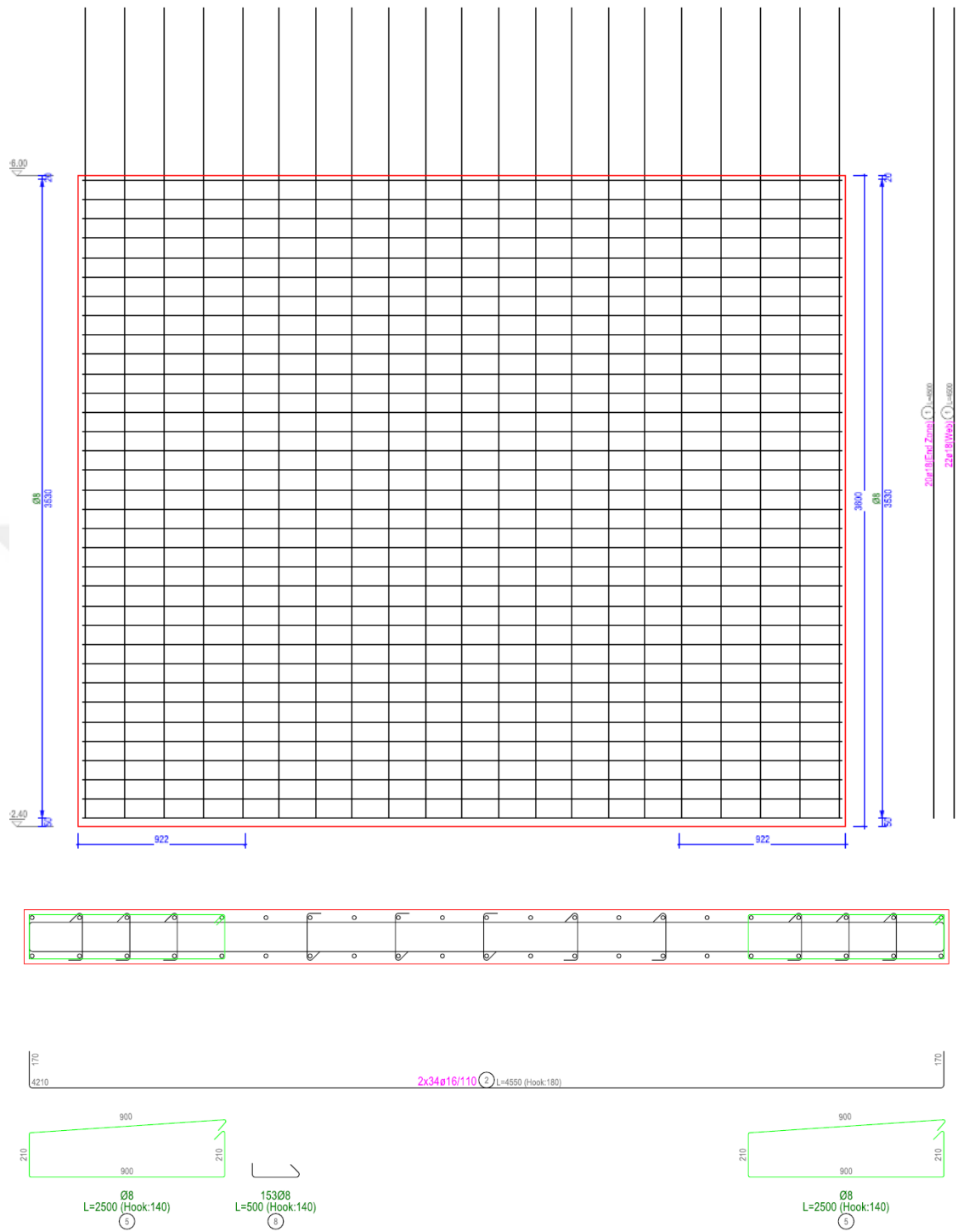


Figure C.3 Reinforcement detailing for shear walls 5 and 6

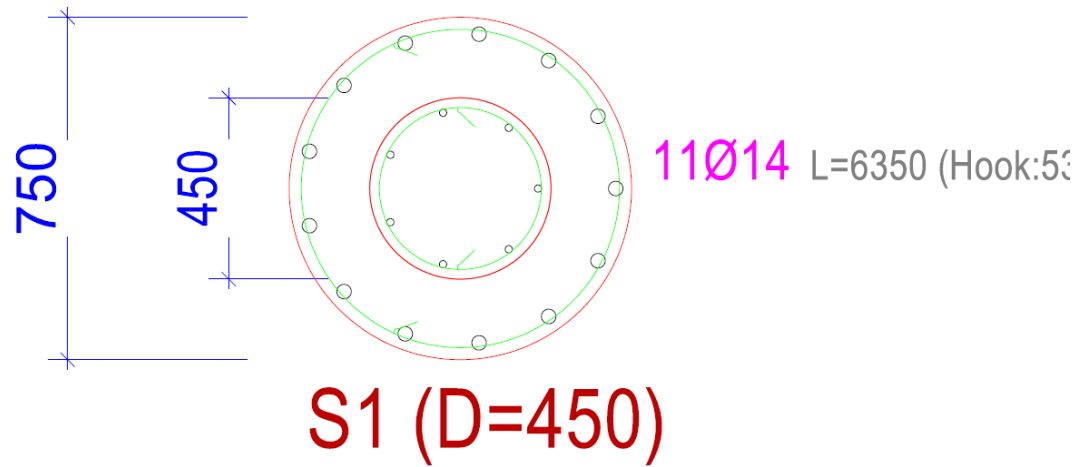


Figure C.4 Reinforcement detailing for RC jacketing of columns 1

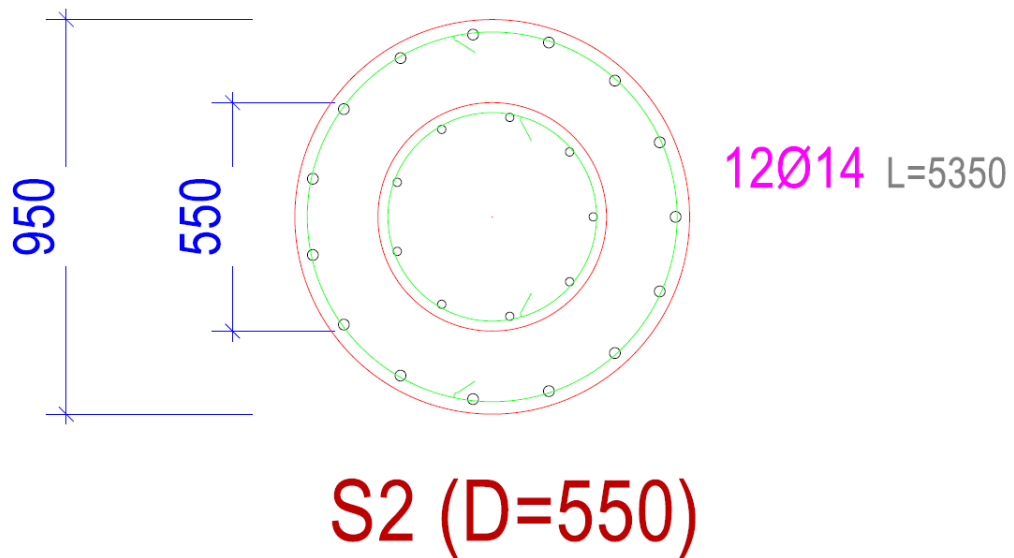


Figure C.5 Reinforcement detailing for RC jacketing of columns 2

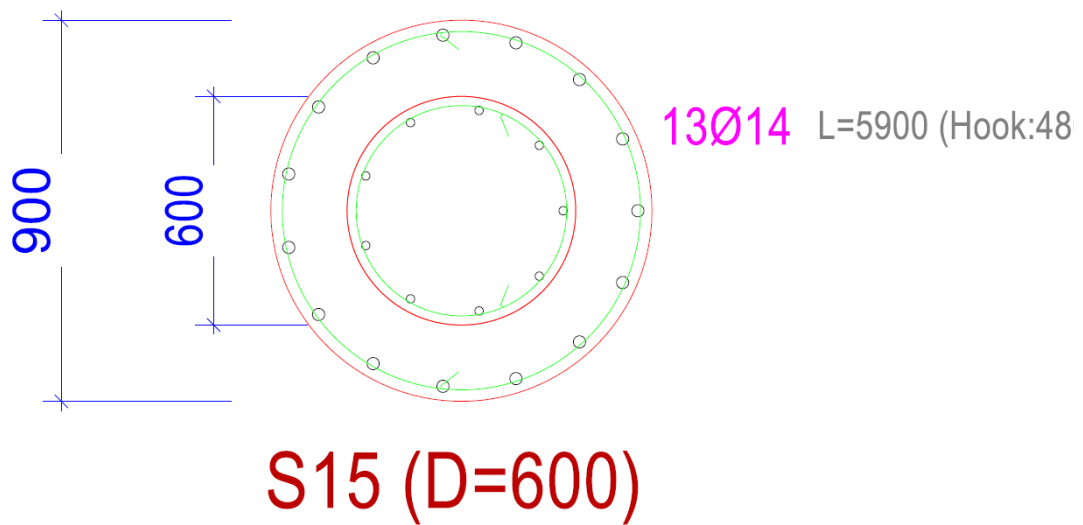


Figure C.6 Reinforcement detailing for RC jacketing of columns 3

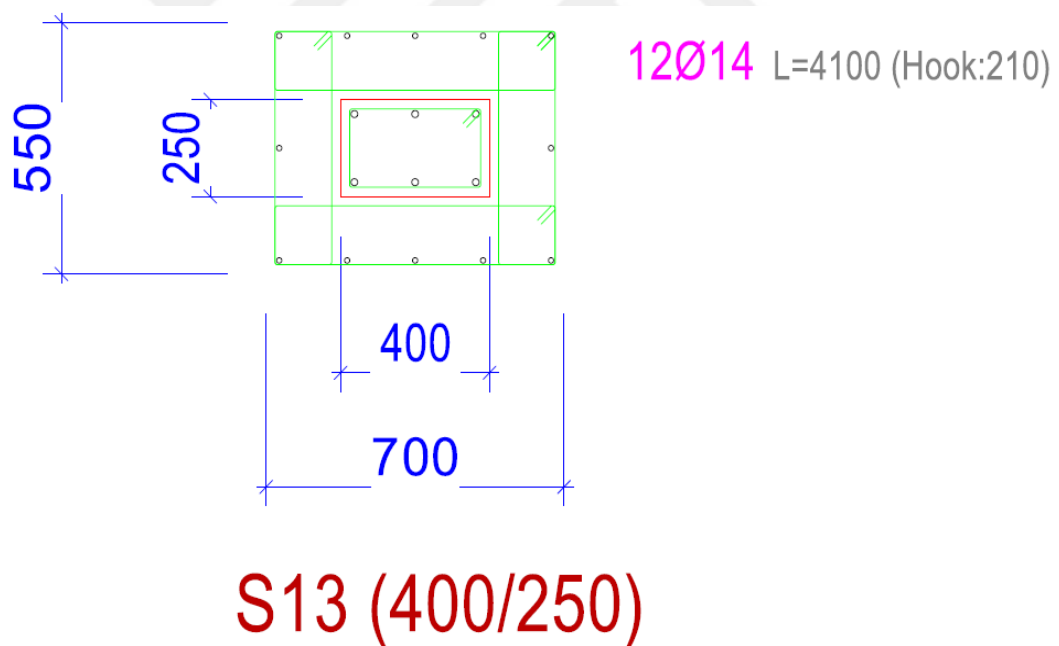
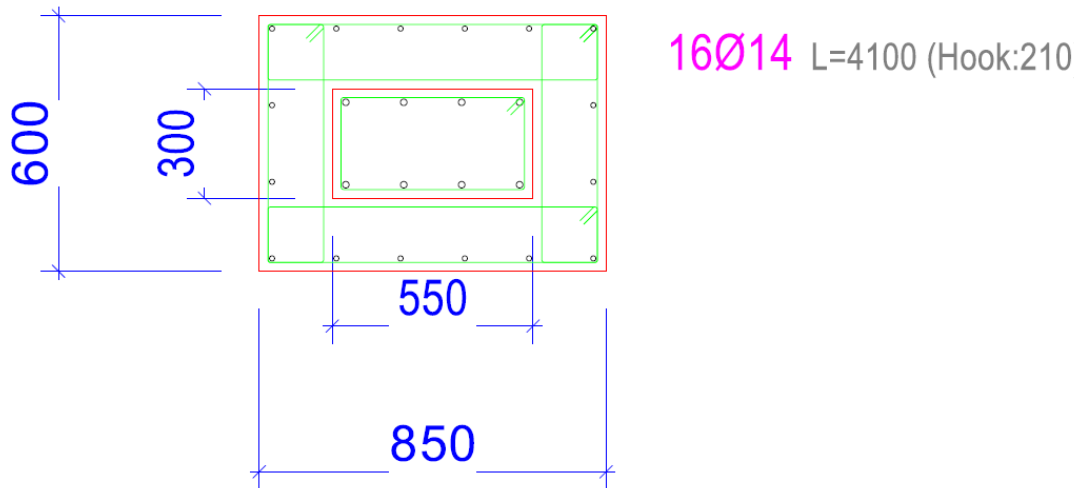
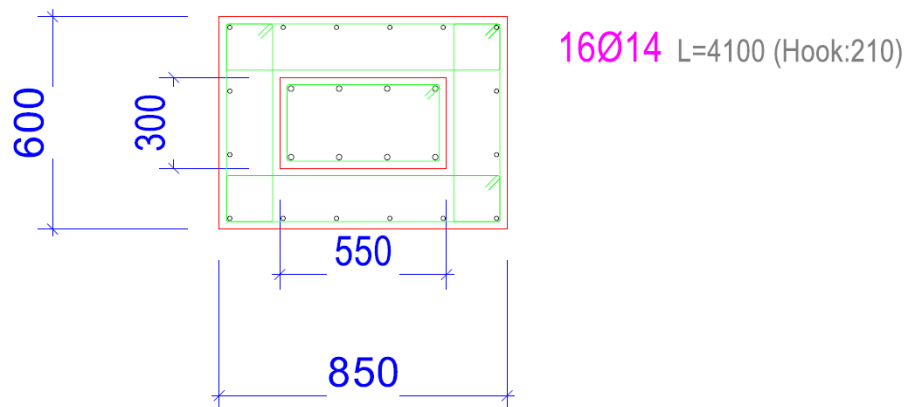


Figure C.7 Reinforcement detailing for RC jacketing of columns 4



S7 (550/300)

Figure C.8 Reinforcement detailing for RC jacketing of columns 5



S7 (550/300)

Figure C.9 Reinforcement detailing for RC jacketing of columns 6

APPENDIX D

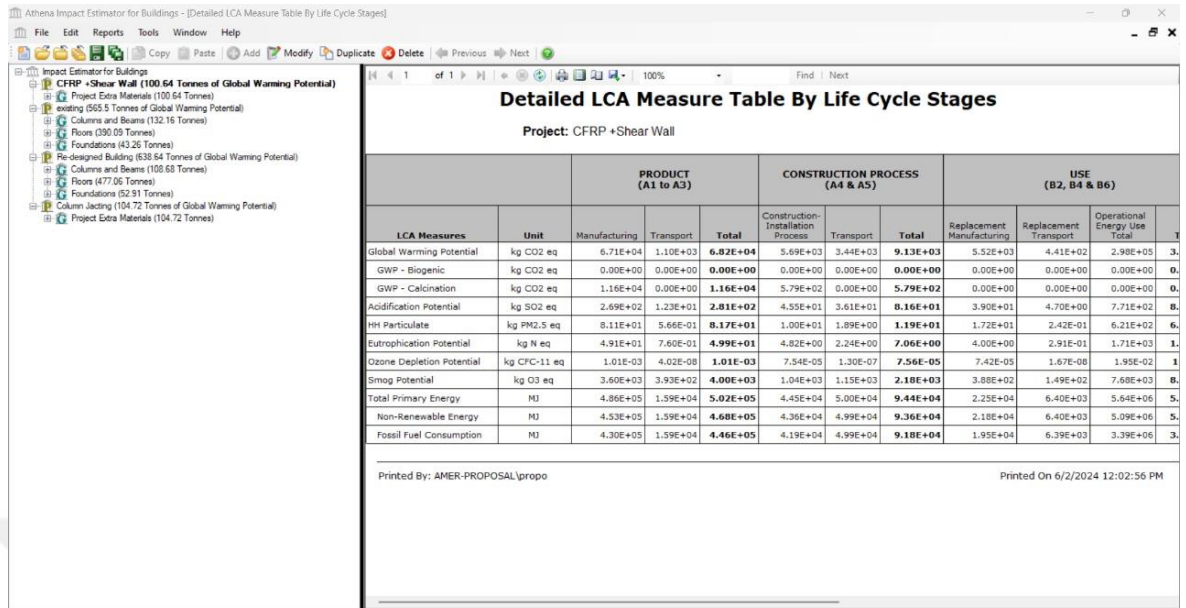


Figure D.1 ATHENA impact estimator for building during the LCA stages analyzing

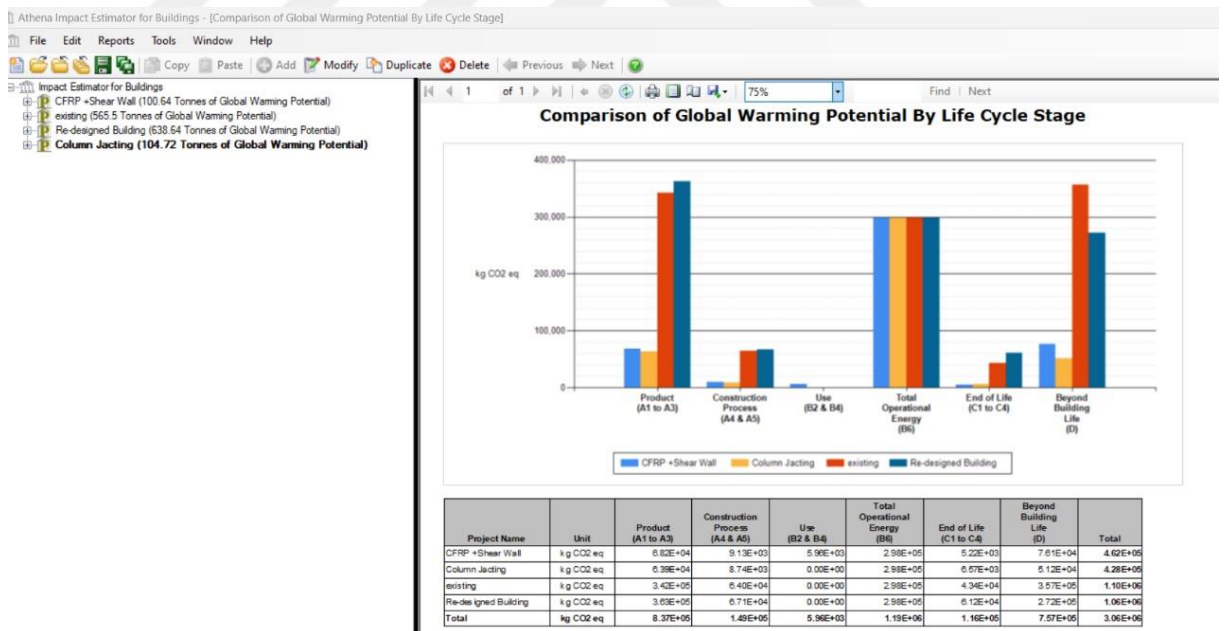


Figure D.2 ATHENA impact estimator for building during the LCA stages comparing