# SUSTAINABILITYAND RESILIENCY COMPARISON OF SOFT-STORY WOOD-FRAME BUILDING RETROFITS

By

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# ABSTRACT

Soft-story wood-frame buildings have been identified as a major issue of disaster preparedness. Both the City of San Francisco and the City of Los Angeles have mandated retrofit of these building types. Thus an abundance of research is being conducted on soft-story retrofits. Two popular design approaches being investigated include the FEMA P-807 guidelines and various performance based seismic design methodologies. Despite the large amount of effort being invested in understanding the behavior of soft-story buildings, the anticipated losses if these buildings go un-retrofitted, the improved performance achieved via retrofit, and the optimal way to retrofit the large quantity of soft-story wood-frame buildings (on the order of 14,000 buildings) in a timely and cost-efficient manner, no such research is being conducted on the sustainability of the various retrofit options. Resilience and sustainability are both important research themes, and thus both need to be investigated. This paper performs a sustainability and cost analysis on several soft-story wood-frame building retrofits found in the research literature that have been previously tested for their seismic performance. These include two retrofit designs following the FEMA P-807 guidelines, with cross-laminated timber (CLT) rocking walls and special steel moment frames (SMF). Additionally, a performance-based seismic retrofit is analyzed which uses special steel moment frames on the soft-story and wood shear walls on the upper stories. The sustainability analysis measures the weighted resource use (e.g., iron ore, wood fiber), the $CO_2$ emissions and the primary energy consumption from the life cycle of each retrofit being considered. The raw material cost and sustainability analysis are performed for the life cycle of the raw materials making up the soft-story retrofits. The life cycle includes the product phase (manufacturing and construction), construction phase (construction installation process and transport) a 50-year use phase (operation), and the end-use phase (demolition, and disposal including recycling and

landfill). Recommendations are made based on cost, sustainability, and resilience tradeoffs for better informed decision making.

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# CHAPTER 1: INTRODUCTION

Multistory wood-frame buildings with large openings at their first floor (typically used for garage parking) and high-density partition walls on the upper stories possess a stiffness and strength deficiency at the first story compared to the stories above. This building type is known as soft-story wood-frame building. Significant in-plane torsion could occur because of the structural and architectural asymmetry of the first story (Bahmani et al., 2014). These deficiencies make the first story much weaker than the story above and lead to premature failure under moderate to high earthquakes. Thus, soft-story wood-frame buildings have been identified as a major issue of disaster preparedness.

The damage of multistory wood-frame buildings was extensive in 1989 Loma Prieta earthquake and 1994 Northridge earthquake in California (Bahmani et al., 2014). This earthquake was considered as the costliest natural disaster in U.S. history, reaching $49 billion of damages (Sutley et al. 2016). The loss in wood-frame structures reached above $16.7 billion (Sutley et al., 2016). After this earthquake, extra effective and complex design provisions were considered in seismic design.

For soft-story wood-frame building retrofit, two design philosophies have been investigated extensively in the literature: FEMA P-807 guideline and performance-based seismic retrofit (PBSR) design. FEMA P-807 guideline design the retrofit for the soft-story only, but not for the upper stories. Whereas, in PBSR design philosophy the retrofit is designed to distribute its design strength and stiffness throughout the height of the building while keeping the inter-story drift (ISD) below the design drift (Bahmani et al., 2015).

Several studies have already been done on seismic performance of different types of soft-story wood-frame building retrofits following PBRS and FEMA P-807 guideline, but no such research is being done on the sustainability of various retrofit options. Sustainability and resiliency are both important research themes and should be investigated with high importance. In this research, a sustainability and cost analysis has been done for three different types of wood-frame soft-story building retrofits and recommendations are made based on cost, sustainability, and resiliency tradeoff.

## 1.1 Research approaches

First of all, a suitable building was selected to investigate for this research. A multi-story, multi-family, residential wood-frame building with a soft first story was decided to analyze. The NEES-Soft building was a four story apartment building, investigated with three different types of retrofits. All the building data were taken from NEES-Soft project experiments (Bahmani et al., 2014 and van de Lindt et al., 2014).

There are several types of retrofit design options available for soft-story wood-frame buildings. In NEES-Soft project experiments, cross-laminated timber (CLT) rocking wall retrofit (FEMA P-807), steel special-moment frame (SMF) (FEMA P-807), steel special-moment frame (SMF)  (PBSR) and fluid damper frame assembly (PBSR) were investigated at UCSD outdoor shake table (Bahmani et al., 2014) For this research, first three of these mentioned retrofits were selected to be investigated. This selection was made based on their design methodology, retrofit materials and practice in general.

For the cost analysis, raw materials of these retrofits were identified using different reliable dealer sources (see Chapter 3 for more details). A total cost was not investigated, thus the cost of the raw materials is used as the only cost measure.

For sustainability analysis, life cycle inventory analysis (LCIA) was done for the NEES-Soft project soft-story building with and without retrofits. Athena impact estimator for buildings software was used to perform LCIA analysis. Normally, the life cycle analysis has three phases: the pre-use phase (manufacturing and construction), use phase (operation), and the end-use phase (demolition, and disposal including recycling and landfill). In Athena, the pre-use phase divides into two other phases: product phase (manufacturing and transportation of construction material) and construction process phase (construction installation process and transportation). The use phase is considered as a 50-year period.

There are seven different environmental impact results provided in Athena from life cycle inventory analysis. Only the global warming potential (GWP) and total primary energy (TPE) were considered here since they are more applicable to the research topic. GWP is the calculation of the influence of greenhouse gases relative to $CO_2$ and TPE is the energy directly obtained from sources like natural gas, oil, coal, biomass, or hydropower energy. These aspects have a powerful impact on the environment.

The resiliency of the retrofits is presented based on their inter-story drift limits. The drift limit results are collected from previous NEES-Soft projects (Bahmani et al.., 2014).

Finally, recommendations are made between these three types of retrofits based on sustainability, cost and resiliency tradeoff.

## 1.2 Three E's of sustainability

Sustainability is commonly measured using environmental performance, or a reduction in environmental impacts (State sustainability index, 2016). Sustainability is best known, however, by its definition from the Report of the World Commission on Environment and Development, "Our Common Good", which indicated that development, or decisions, are sustainable if they meet the needs of today without compromising the ability of future generations to meet their own needs

(USEPA 2012). Thus, sustainability is generally discussed as being composed of three pillars: environmental protection, social equity, and economic prosperity.

The environmental pillar is the most well studied aspect of sustainability. It deals with the maintenance of natural resources and reduction of the negative impact on the environment. This section ensures the protection of natural habitats, production of environment friendly products, confirming water and air quality, waste management and reducing pollutants. From the sustainability of a building point of view, it relates to the appropriate selection of building site, reduction of energy usage, use of local material sources, and consumption of sustainable building materials. It is a whole system approach to minimize its impact on environment, usage of electricity and natural gas. The LCA results of this research are directly related with providing a better environmental performance by the retrofits. Chapter 4 compares the $CO_2$ emission and total energy used for each retrofit being considered in this study.

The social equity pillar basically deals with maintaining community and personal wellbeing. This part is not investigated in this research but it is related. If soft-story wood-frame buildings is selected to be retrofitted, it would cause benefit to the residents and community by decreasing the probability of being killed during an earthquake. They would have less probability of being placed from a damaged building. The owners of the buildings would benefit by not losing rent and having less repair costs. It also benefits businesses by avoiding loss of equipment and employees.

For the economic pillar, life cycle cost assessments can be performed. In this research, however, only the cost of the raw materials is provided.

### 1.3 Thesis presentation

Chapter 1 includes introduction. In introduction, a small description on the background study of this research is given, as well as a short discussion on the thesis layout.

Chapter 2 reviews the relevant literature. A detailed review on soft-story wood-frame buildings, the NEES-Soft project, various types of retrofits, FEMA P-807, performance-based seismic design, life cycle analysis, and environmental impacts are provided.

Chapter 3 presents the methodology. This includes the building selection, retrofit selections, cost estimation, and modeling in Athena.

Chapter 4 presents the results and discussion, including cost analysis, inter-story drift limits of the retrofits, and LCIA results.

Chapter 5 includes the conclusion with the findings, limitations and makes a final recommendation.

All the LCIA results from Athena and NEES-Soft project building design data are documented in the Appendices at the end.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Resilience

Resilience has been used in many different extents holding a different meaning and investigated or correlated with a certain definition for any specific research area like engineering, social science, ecology and so on. Thus, resilience has several definitions rather than having a broadly established single one (Klein et al., 2003; Manyena, 2006; Cutter et al., 2008). The term was first used by Holling in 1973 as defining the capacity of a system to overcome or absorb shock and changes through maintaining the same relationship with the people (Cutter et al., 2008). In environmental perspective, it was defined by the capacity of a system to absorb disturbance and transform into an advanced and flexible one through the learning process of adaptation (Adger et al., 2005; Klein et al., 2003; Folke, 2006; Cutter et al., 2008). From structural engineering point of view, resilience was defined by the structural capacity to resist damage without suffering complete failure ("Resilience," n.d.). In this research, it was adapted as the capacity of a retrofit to withstand seismic load and avoid collapse or failure. Resilience was confirmed by the investigation of the inter-story drift (ISD) of three different types of retrofits collected from previous NEES-Soft experiments (Bahmani et al., 2014 and Jennings et al., 2015). Permissible ISD of a structure confirmed its resiliency to seismic load. Thus, the ISD limits of three types of retrofit were decided to be investigated as a measure of comparing resiliency of the retrofits.

### 2.1.1 Seismic resilience

The work of Bruneau and colleagues (Bruneau et al., 2003 and Bruneau et al., 2006) has led the way in defining how structural engineers view seismic resilience. It can be defined as the ability of a system to reduce the chances of a shock, absorb shock if occurs and recover quickly after a shock. It includes the following steps: (1) decrease failure probabilities, (2) reduce consequence from failures in terms of loss of lives, economic and social loss and damage and finally (3) reduce the time of recovery after shock. These measures of seismic resilience can be illustrated by the concepts explained in Figure 2.1. The quality of a infrastructure in a community Q(t), can vary from 0% to 100%, where 100% means no reduction in quality and 0% means total loss. If an earthquake occurs at time $t_o$, it could cause significant damage to the infrastructure and reduce its quality Q(t) from 100% to 50% as shown in Figure 2.1. The recovery time is $t_1$. After this time ($t_1$), the system is fully recovered and Q(t) reaches 100% again. The community earthquake loss of resilience for a specific earthquake, R, can be measured by the size of the expected loss in quality over time and expressed as follows:

$$R = \int_{to}^{t1} [(100 - Q(t)]dt \quad \ldots\ldots \quad (1)$$

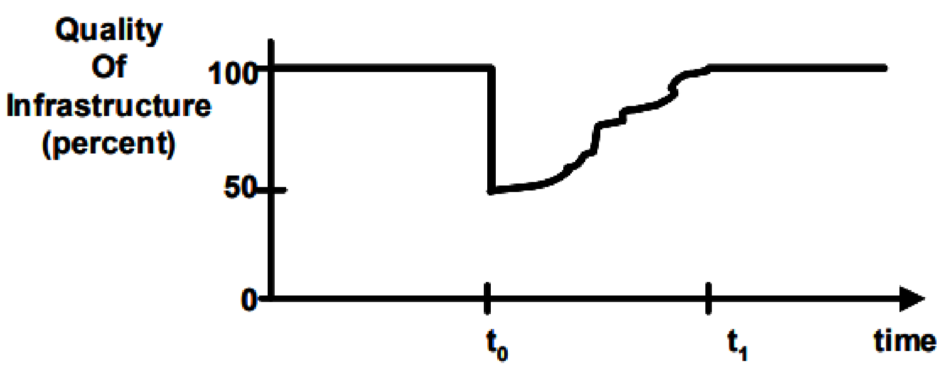


**Figure 2. 1: Conceptual definition of seismic resilience (Bruneau et al., 2006)**

### 2.1.2 Dimensions of resilience

For both physical and social system, resilience can be defined as a combination of the following properties: (1) Robustness, (2) Redundancy, (3) Resourcefulness, and (4) Rapidity (Bruneau et al., 2006; Bruneau et al., 2006). These are often referred to as the 4R's.

These properties can be explained from of the work of Bruneau and colleagues (Bruneau et al. 2003 and Bruneau et al. 2006). Robustness is the strength or the capacity of a system, elements or community to cope with a certain level of stress or demand without suffering loss of function. Redundancy is the limit to which a system is capable of satisfying functional requirements during disturbance, degradation, or loss of functionality. Resourcefulness is the capability to recognize problems, set priorities and use resources when adverse conditions exist. Rapidity ensures priorities to accomplish goals in a timely manner in order to cover losses, regain functionality and avoid future disturbance.

In this research, seismic resilience of soft-story wood-frame building retrofits was decided to be compared based on their ISD limit. In next section, brief descriptions on soft-story wood-frame buildings, their various retrofit options and why they were chosen to be investigated are presented.

## 2.2 Soft-story wood frame buildings

Multistory wood-frame buildings suffered intensive damage due to major earthquakes like 1989 Loma Prieta earthquake and 1994 Northridge earthquake in California (Bahmani et al 2014). Northridge earthquake occurred in San Fernando Valley region of Los Angeles, California on January 17, 1994. Its magnitude was 6.7 and lasting 10-20 seconds ("1994 Northridge earthquake,"n.d.). Over 8,700 people were injured during this earthquake and the death toll was 57 ("1994 Northridge earthquake,"n.d.). The property loss in wood-frame structures was more than $16.7 billion from Northridge earthquake (Schierle, 2003). After 1971 San Fernando Valley earthquake, major changes occurred in seismic hazard plannings, law and building codes standard regarding seismic design (Sutley and van de Lindt 2016). Thus, most of the structures constructed after San Fernando Valley earthquake followed some sort of seismic design. Even though around

20,000 structures were emptied and 12,500 structures were damaged during Northridge earthquake (Sutley and van de Lindt 2016). This earthquake is considered as the costliest earthquake in U.S. history so far, reaching $49 billion of damage (Sutley and van de Lindt 2016). After this earthquake, more effective and complex design provisions were considered in seismic design. As a result, performance based design (PBD) philosophy was born (Sutley and van de Lindt 2016).

The multistory wood-frame buildings can be described from the work of Bahmani and colleagues (Bahmani et al., 2014). The building types with large openings in the first story (typically use for garage parking) and high density partition walls on above floors often experience stiffness deficiency in the first story compared to the story above. This building type is classified as soft-story building. In soft-story buildings, first floor has strength deficiency also compared to the other floors because of the building layout. First story is structurally and architecturally asymmetric in these buildings. This causes significant torsional in-plane moment. These deficiencies make the first story significantly weaker under seismic load, resulting in a premature failure under moderate to high intensity earthquake.

The benefits of retrofitting can be described from CAPSS report (2009). The cost of retrofitting is readily, but most of the benefits of retrofitting are not visible until after an earthquake strikes. As the predicted losses can be avoided during an earthquake of a retrofitted building, the benefits of it are understandable.

Retrofitting of multi-unit, soft-story, wood-frame buildings generally saves the money of building owner by reducing damage, decreasing the post-earthquake repairs cost and avoiding business disruption such as losing rent. This benefits of retrofitting vary with the intensity of earthquake and the retrofit design of the building. According to the report by the CAPSS project, building owners save between $400 million to $5.1 billion depending on retrofit used in the buildings. The total cost of retrofits would about $260 million citywide.

The following benefits would ensue for the residents and neighborhood: (1) the residents would have less possibility of being killed or injured during an earthquake, (2) their properties are more likely safe from damage, (3) they would not need to leave their house due to the disaster damage. Thus, they could avoid the trauma and expense of the displacement, (4) they could remain close to their job place.

The following benefits would ensure for business: (1) the employers and customers would have a lower probability of being killed or injured during an earthquake, (2) the business could remain in the same place as before, (3) inventories and apparatus of the business are less likely to be damaged.

FEMA funded ATC for creating a new set of guidelines for “Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings with Weak First Story” [FEMA P-807 (FEMA 2012)]. FEMA P-807 guidelines is focused on design of retrofit for the first (weak) story only but not for the upper story. It reduces the probability of transferring building occupants during construction as it is designed for first story only. This design methodology considers the strength of non-structural walls also to count their contribution on building performance. FEMA P-807 assumes that the floor diaphragm of upper stories and foundation below are sufficient. The building has adequate load transfer elements to get the desired performance. If the existing condition of the building doesn’t meet these requirements then it needs to be fixed before designing retrofit (FEMA P-807).

Thus soft-story wood-frame buildings have been identified as a major issue of disaster preparedness and needed to be investigated. An abundance of research has been conducted on soft-story wood frame building to investigate the behavior of soft-story buildings, the anticipated losses if these buildings go un-retrofitted, the improved performance achieved via retrofit, and the optimal way to retrofit the large quantity of soft-story wood-frame buildings (on the order of 14,000 buildings) in a timely and cost-efficient manner (CAPSS report, 2009; Jennings et al., 2014; Jennings et al., 2015; Van de lindt et al., 2012; Bahmani et al., 2014; FEMA P-807, 2012; Sutley and Van de lindt 2016). Some of this work includes the NEES-Soft project. NEES-Soft project was a five-university, multi-industry, NSF-funded project (Van de lindt et al., 2012). The main objectives of NEES-Soft project were to enable PBSR retrofit design for soft-story wood-frame buildings and to experimentally validate FEMA P-807 retrofit guideline. NEES-Soft project conducted the following researches:

A 3-story soft-story wood-frame building with an overretrofitted first story was investigated by Jennings and colleagues (Jennings et al.,2015). This study was performed to measure the collapse shift limit into upper story with overretrofitted first story and the collapse mechanism of the building. Another study was done by Jennings and colleagues to present a seismic retrofit methodology using shape memory alloy (SMA) devices for a three-story soft-story woodframe building (Jennings et al., 2014). In 2014, a full scale hybrid testing was done on two different types of different types of retrofits following FEMA P-807 guidelines by Jennings and colleagues. These retrofits were investigated at several different seismic intensity levels.

A 4-story soft-story, wood-frame building was investigated by NEES-Soft project research (Bahmani et al., 2014). Four different types of retrofits were developed and tested full scaled on shake table ranging from 0.2-g to 1.8-g spectral acceleration. This study was based on building and retrofit design methodologies. From the Bahmani and colleagues work (Bahmani et al., 2014), PBSR design philosophy can be described. It is articulated to meet or exceed a minimum performance criteria identified by the owner. The biggest challenge of an engineer following PBSR design philosophy is to deal with the existing building design and condition and the buildings that were not built in accordance with the current building codes. In addition, the architectural contains of the building such as openings, load bearing walls, room positions make the retrofit design more complicated. In PBSR the retrofit is designed in such a manner that stiffness and strength of retrofit will be distributed over the height of the building while keeping the inter-story drift (ISD) below the design drift. This design philosophy allows to meet the overall desirable performance of the building, but to obtain this almost every floor needs to be retrofitted. PBSR methodology is normally used for extreme seismic condition and to confirm excellent performance.

For this research, a multi-story, multi-family, residential wood-frame building with a soft first story was decided to be analyzed with three different types of retrofits. This building was selected from NEES-Soft project. Several buildings architecture had been investigated from San Francisco bay area to decide the test building architype for NEES-Soft project (Bahmani et al. 2014). A multi-story, multi-family, residential soft-story wood-frame building was designed for shake table test at University of California at San Diego (UCSD). It was a four story residential apartment building. The exterior architecture of the building was important to fix the aspect ratio and determine the number of opening and its location in first and other floors. Some other factors such as interior wall densities in each floor, typical room sizes, floor and wall assemblies and nailing schedules were designed (Bahmani et al. 2014). In Figure 2.2, a photo of typical bay area soft-story wood-frame building and a photo the test building of NEES-Soft project in San Diego (prior to start testing) are shown.

**Figure 2. 2: Typical bay area soft-story wood-frame building & NEES-Soft four-story soft-story wood-frame test building (Bahmani et al., 2014)**

The NEES-Soft building (24ft x 38ft) was investigated at full scale with four different types of retrofits on the shaking table at NEES-UCSD laboratory. Prior to the retrofit, the first story of this building was a soft story with a garage with four doors on south side, a large laundry room, a storage and a light well. The light well was provided because the building was surrounded by other buildings on its north and west side (Bahmani et al., 2014). The upper stories were designed as two-bedroom units with bay windows on south and east sides. The floor plan of first and upper stories are shown in Figure 2.3. Because of the opening positions on first story the building was soft and weak on south and east sides, resulting in significant torsion (Bahmani et al., 2014).

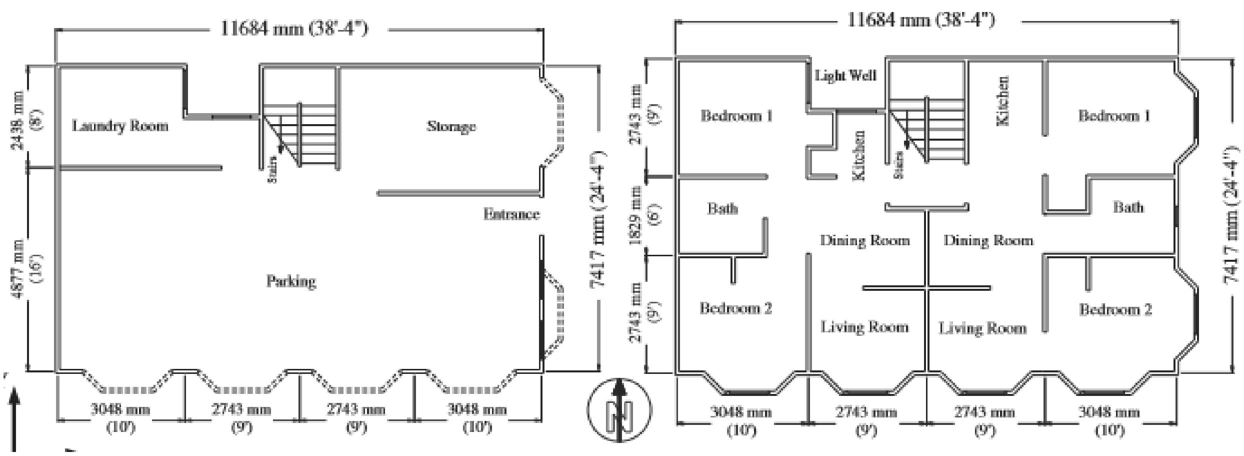


**Figure 2. 3: First floor (Soft-story) and upper floors plans for the NEES-Soft test building (Bahmani et al., 2014)**

The details design chart of exterior-interior wall assemblies, roof and floor framing, foundation details are attached in Appendix A.

In NEES-Soft projects several types of retrofits were investigated: (1) cross-laminated timber rocking wall retrofit (FEMA P-807), (2) steel special-moment frame (FEMA P-807), (3) steel special-moment frame (PBSR), (4) cantilever column soft-story (CLT) rocking wall retrofit (FEMA P-807), (5) fluid damper frame assembly (PBSR) and (6) SMA-(shape memory alloy) device retrofit (PBSR) (Bahmani et al. 2014; Jennings et al. 2014; van de Lindt et al., 2014). Among these first three retrofits were selected to be investigated in this research. They were selected based on their design methodology, retrofit materials and practice in general.

Cross-laminated timber (CLT) rocking wall retrofit was designed for the first story only following FEMA P-807 guidelines. CLT is an engineering wood made with cross-oriented layers of dimension lumber glued together. CLT rocking wall retrofit was designed such a way that the panel could shake freely though the vertical slotted holes at the top shear connection. To resist the overturning moment, 16mm threaded rods were used on each side of the CLT panel. Shear connector were attached to transfer shear from CLT panel to foundation. This whole CLT retrofit design was taken from NEES-Soft project test experiment (Bahmani et al, 2014). In Figure 2.4, the CLT retrofit is shown in elevation and cross section.

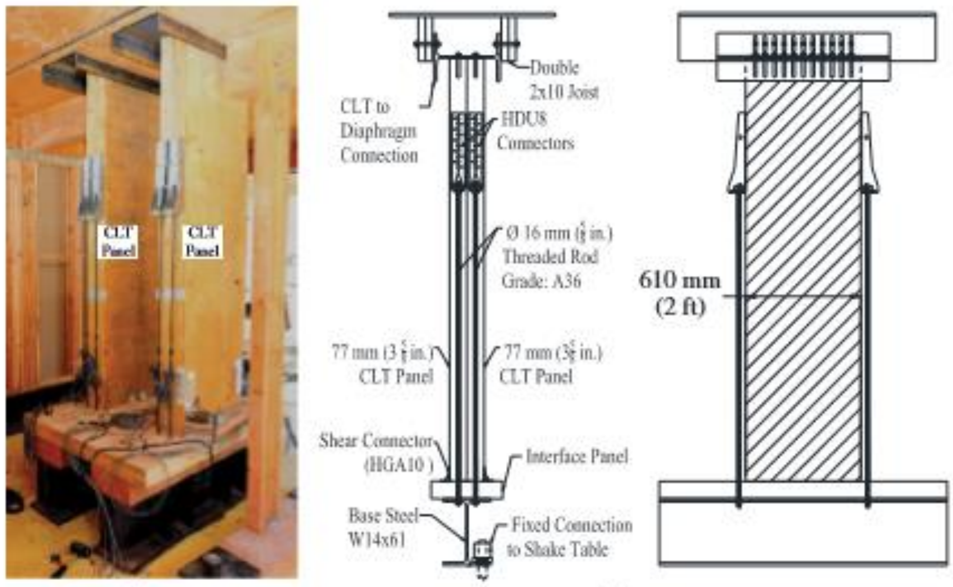


**Figure 2. 4: CLT retrofit for the first soft story with elevation and cross section (Bahmani et al., 2014)**

This Steel special-moment (SMF) frame was designed combined with wood structural panel according to FEMA P-807 guidelines. The columns of the SMF and foundation were pin connected which made the installation much easier. This SMF retrofit had snug-tight field bolted connections, which were very easy to install (Bahmani et al. 2015). In Table 2.1, the beam-column schedule for SMF retrofit (FEMA P-807) is presented.

**Table 2. 1. Beam-Column schedule for SMF retrofit (FEMA P-807) (Bahmani, 2014)**

| Retrofit name | Retrofit Methodology | Column sections | Beam sections |
|---|---|---|---|
| Steel special-moment frame retrofit (SMF) | FEMA P-807 | W 10X30<br>W 10X26 | W 12X35<br>W 12X26 |

In figure 2.5, the installation of SMF (FEMA P-807) in ground story and its elevation are shown.

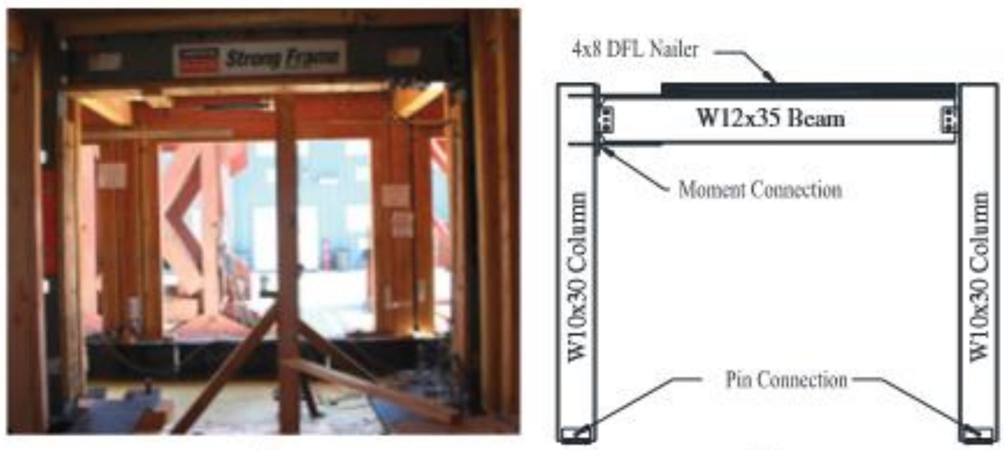


**Figure 2. 5: SMF (FEMA P-807) retrofit installation and its elevation (Bahmani et al., 2014)**

The special steel moment frame (PBSR) retrofit was designed following PBSR design philosophy. To achieve the desire design goal 2 SMF frame were installed in each direction with 12 mm thick sheathing-rated plywood shear panels with different nail schedules and tie down on several wall of the upper stories (Bahmani et al, 2014). The interstory drift was maintained at 2%. In Table 2.2, the beam-column schedule for SMF retrofit (PBSR) is tabulated.

**Table 2. 2. Beam-Column schedule for SMF retrofit (PBSR) (Bahmani et al., 2014)**

| Retrofit name | Retrofit Methodology | Column sections | Beam sections |
|---|---|---|---|
| Steel special-moment frame retrofit (SMF) | PBSR | W 14X38/W 16x57<br>W 10X30 | W 12X50<br>W 12X30 |

In figure 2.6, the installation SMF (PBSR) in ground story and its elevation are shown.

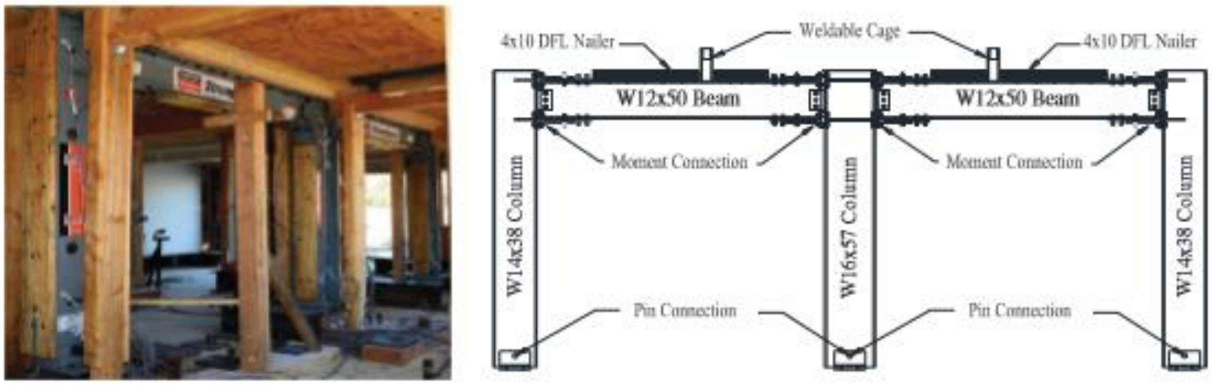


**Figure 2. 6: SMF (PBSR) retrofit installation and elevation (Bahmani et al., 2014)**

## 2.3 Sustainability

USEPA 2012 provided a definition of sustainability as general concept. According to the theory, sustainability can be defined as generating and upholding situations under which humans and nature can exist in dynamic harmony and fulfill the social, economic and other requirements of present and future generation. It also provided a definition describing construction perspective. According to the definition, it is the method of increasing the productivity of buildings and its use of energy, water, and materials, then protecting the environment throughout the building life-cycle. In this research, sustainability is being measured as environmental context also. It is investigated based on the environmental impact results from LCA analysis of different types of retrofit. A system is more sustainable if it has less environmental impacts. By doing sustainability comparison of these three types of retrofit, a better retrofit option can be established in a greener sense. That means choosing the retrofit which has less environmental impact throughout its lifetime.

The three pillars of sustainability are as follows: (1) economy, (2) environmental and (3) equity or society. These are represented by three circles as Venn diagram in Figure 2.7 (Webb et al., 2016). Four intersection region are created by these three circles (Figure 2.7). In these overlap areas, any valid definition of sustainability should fit (Webb et al., 2016).

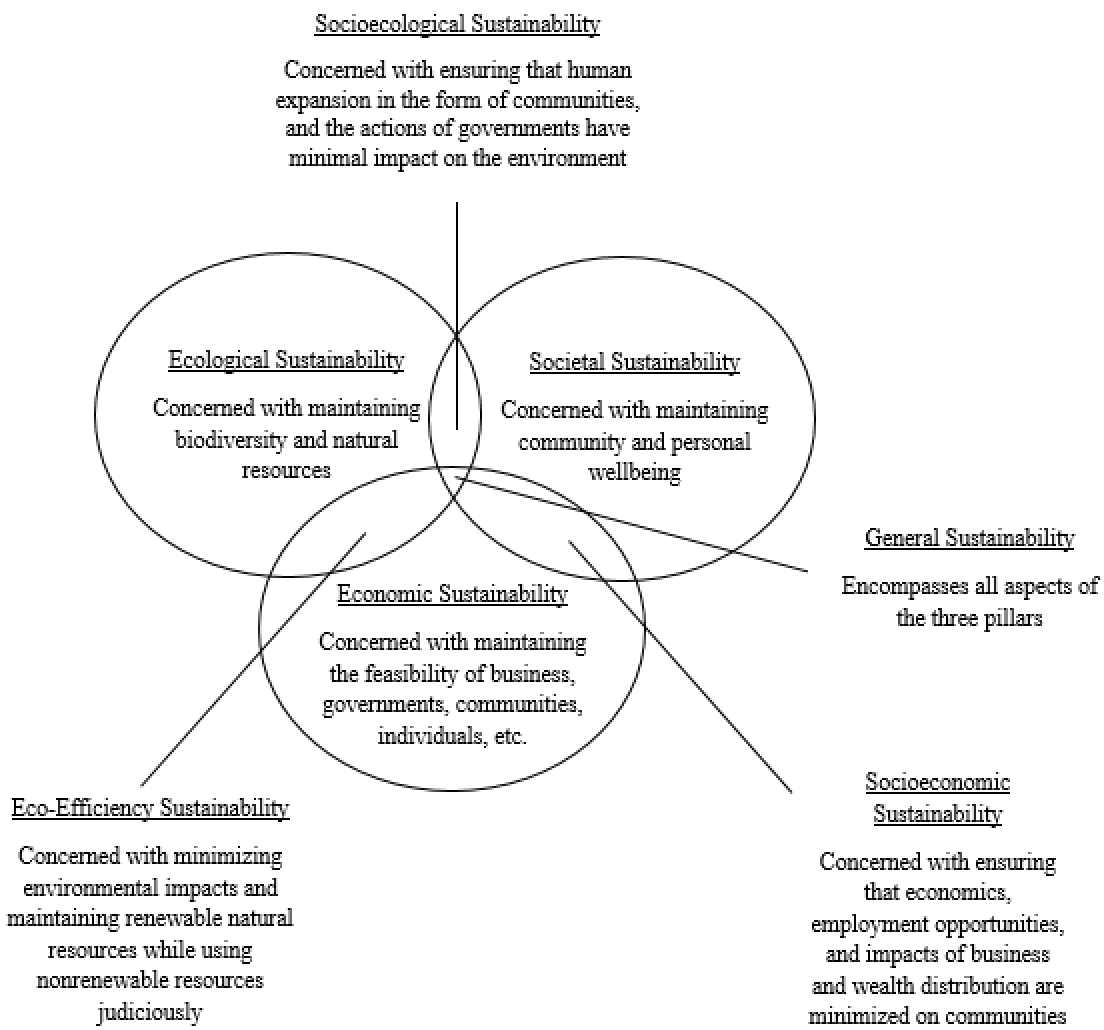


**Figure 2. 7: Venn diagram of three pillars of sustainability (Webb et al., 2016)**

The aim of sustainable development is to improve the quality of living for present and future generation by means of equity (social), economic and environment measures (Wei et al., 2015). An equilibrium between social, economic and environmental performance must be gained over its entire life cycle to improve the sustainability of a building for long-term basis (Wei et al., 2015). Though, most of the previous researches on buildings' sustainability focused on only social or economic issues mainly but did not include the environmental part due to lack of well-established standards and methods of measuring (Wei et al., 2015). Although environmental impact of natural hazard on buildings are getting more priority recently as a research theme due to the increasing energy demand needed for post disaster recovery (Padgett et al., 2013; Feese et al., 2014; Hossain et al., 2014; Wei et al., 2015). Though, only a few recent studies had been evaluated all three dimensions of sustainability together to examine the sustainability of infrastructure (Dong et al., 2013; Wei et al., 2015). And there is no such study which evaluated all three aspects of sustainability for a building open to a natural hazard risk (Wei et al., 2015). This research is done to choose a seismic retrofit option for soft-story wood-frame buildings which is sustainable to environment, resilience to earthquake and moreover less costly. For establishing the sustainability goal of this research, LCA analysis of three different types of retrofits was performed.

### 2.4 Life Cycle assessment (LCA)

Several types of techniques are available to evaluate the environmental impacts of a building for its lifetime, among these life cycle assessment (LCA) is an appropriate tool to measure lifetime environmental impacts of a building as it is able to determine both direct and indirect energy consumption related with the processes (Wei et al., 2015). LCA is an analytical process to construe the material and energy flow of a product or process to or from environment for its entire life cycle. It provides a comprehensive vision of a product about its environmental aspects like energy consumption, material and provides more clear view of the environmental trade-offs of the product selection. LCA complies the supply of raw materials needed for the production of a product, manufacturing of intermediates, transportation of raw materials, production of the product, use and disposal after use (Resource Guide: Conducting a Life Cycle Assessment (LCA), 2008). The product life usually follows three phases in a LCA analysis: (1) the pre-use phase (manufacturing and construction), (2) use phase (operation), and (3) the end-use phase (demolition, and disposal including recycling and landfill).

The philosophies and outline of LCA analysis include the goal and scope of LCA, the life cycle inventory analysis phase, the life cycle impact assessment phase, the life cycle interpretation phase, reporting and critical review of LCA, relationship between LCA phases and conditions for use of value choices and optional elements (ISO 14040:2006). LCA helps in identifying opportunities to improve the environmental performance of a product during its lifespan and notifying decision makers in industries, government and non-government organizations (ISO 14040:2006).

### 2.4.1 Importance of life cycle assessment in buildings (LCA)

According to the study of Khasreen and colleagues (Khasreen et al., 2009), LCA has been a well-adopted for buildings since 1990. Governments, engineers, designers and researchers all are influenced by the eco-green strategies. Thus, the importance of environmental analysis by LCA is widely accepted. The important factors of LCA are discussed as follows: first, building has a lifespan often more than 50 years. Thus, it is complex to forecast the whole life cycle from cradle-to-grave. Second, the building may experience many significant changes during its lifetime. Thus, LCA is like a part of the design to minimize environmental impacts. Third, many environmental changes could occur during building lifetime, so proper design and material selection are critical without LCA analysis.

Life cycle assessment analysis is often recommended to make green decisions, whether in product manufacturing or in building design. It is an inventory analysis of a product based on the raw materials involved to manufacture it, its transportation procedures, the amount of waste implies with the usage of the product during its life time and what will happen after its use phase.

Without these measured data, we never can make a better and appropriate choice in the larger picture. LCA is being practiced at a national level now to construct environmental sound buildings but still much possibility remains for broader participation and co-operation (Khasreen et al., 2009).

LCA is not a comparison between good or bad products. It's about a concerned decision-making. Everything has some level on environmental impact. LCA deals with those impacts and helps to make a better decision in choosing any product.

### 2.4.2 Stages of LCA analysis

According to international standard ISO 14040, there are 4 stages of a complete LCA analysis as shown in Fig 2.5: (1) Goal and scope definition, (2) Inventory analysis, (3) Impact assessment, and (4) Interpretation.

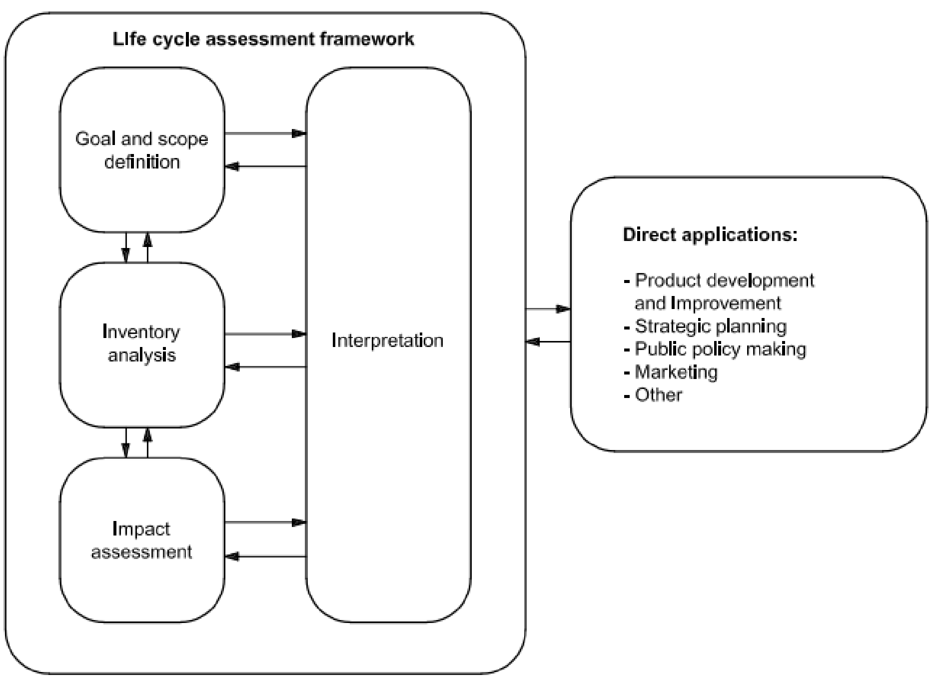


**Figure 2. 8: Stages of LCA as per ISO 14040:2006**

Goal and scope of a LCA analysis should be stated very clearly and consistent with the intended application. This analysis starts with a specific goal and scope of the study, the functional unit, system boundary of the unit, assumptions and limitations, step by step methodology and selected impact categories ("LCA of cross-laminated timber product in Canada", Athena Sustainable Materials Institute, 2013). The functional unit specifies what is being studied. It is important to measure the service delivered by the product system and relate input and output results ("LCA of cross-laminated timber product in Canada", Athena Sustainable Materials Institute, 2013). To set the system boundaries these are the important factors: attainment of raw materials, inputs and outputs in main manufacturing sequence, transportation, production of fuel, electricity and heat, use and maintenance products, disposal of waste and products and recycling (ISO 14044:2006) Goals of LCA analysis is to explain the intended application and reasons for performing the study, to whom and how the results of the study are envisioned to be communicated (ISO 14040:2006). Scope of LCA includes objects like the product system to be studied, the functional unit and system boundary of the product, data requirements, assumptions, limitations, critical views of the product (if any) (ISO 14040:2006).

Inventory analysis involves with data collection and calculation procedure to get specific inputs and outputs of a product (ISO 14040:2006). It's a continuous process as new data is collected or added time to time, new requirements and limitations of the analysis are set. Data is collected to closely meet the goal and scope of the study (ISO 14040:2006).

Data collection involves energy, raw material, supplementary and other physical inputs, emission to air, discharges of water and soil and other environmental aspects (ISO 14040:2006). Data calculation deals with the validation of data collected, the relating data unit process and reference flow of the functional unit. The energy flow calculation should also be taken into account from different energy sources (ISO 14044:2006).

The purpose of life cycle impact assessment is to evaluate significant of potential environmental impacts using LCA results. This phase relates the life cycle inventory data with specific environmental impacts and categories them, thus trying to investigate them. Impact assessment continues an iterative process to observe whether the scope and goal of the study have been achieved or not. In some cases, it could modify the scope and goal if it can't be met (ISO 14040: 2006).

LCIA incorporates two types of elements: (1) mandatory elements and (2) optional element. In Figure 2.6 these elements are illustrated in flow chart.

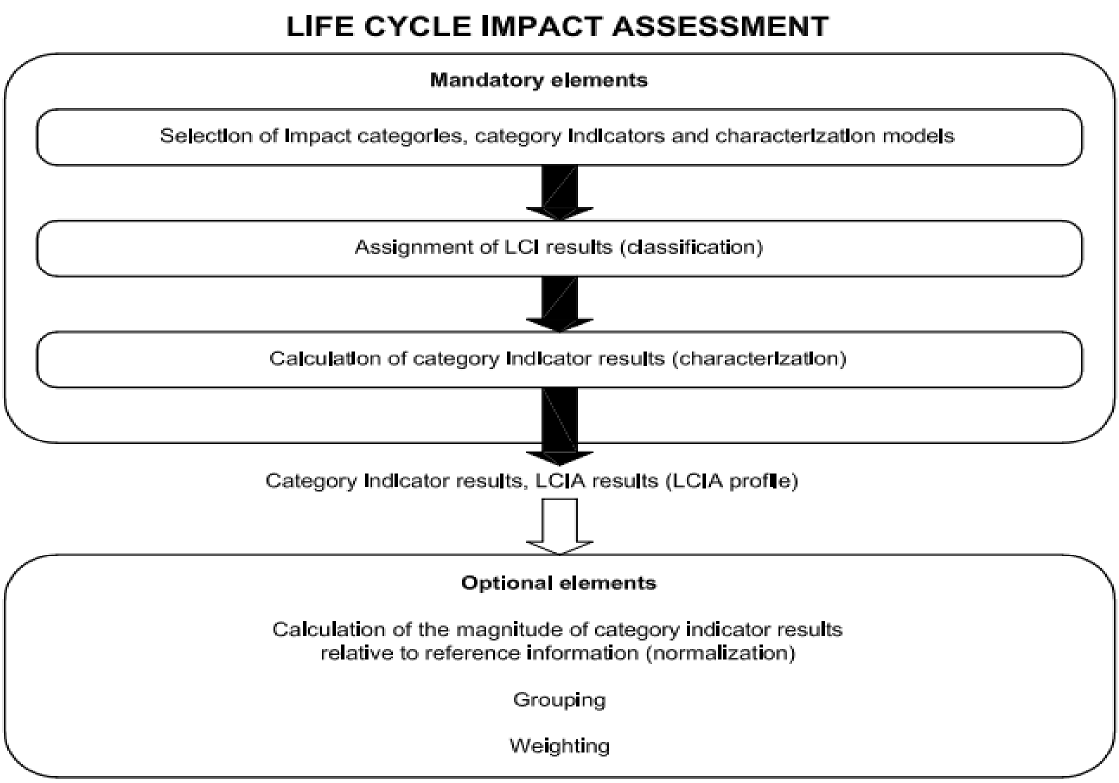


**Figure 2. 9: Elements of LCIA (ISO 14040:2006)**

LCIA discusses only the environmental issues that are stated in goal and scope. So, it isn't a complete valuation of all environmental issues associated with the product system (ISO 14040: 2006). The environmental impacts incorporates in this research are: (1) global warming potential (GWP) and (2) total primary energy (TPE). These are selected to investigate as they are more applicable to the research topic.

Global warming potential, a mid-point metric developed by the US environmental protection agency (EPA), for the calculation of the influence of greenhouse gases relative to $CO_2$. The methodology and calculation behind global warming potential is considered as one of the most accepted LCIA categories ("LCA of cross-laminated timber product in Canada", Athena Sustainable Materials Institute, 2013). In other word, it's the measurement of heat trapped by greenhouse gases ($CO_2$) in environment.

Generally, there are two types of carbon emission from a building: (1) operational carbon and (2) embodied carbon. The operational carbon refers to the $CO_2$ emission during the life time of a building. Alone with the regulated and unregulated load system of the building heating, cooling and lighting systems are also considered as the sources of this operational carbon (Danielle, 2012).The embodied carbon refers to the $CO_2$ emission that is produced during the manufacturing period of materials, transport, maintenance and replacement (Rawlinson, 2007). Total primary energy is the energy directly obtained from sources like natural gas, oil, coal, biomass or hydropower energy. There are two types: renewable and non-renewable energy. Renewable energy includes the power obtained from oil, natural gas or coal, whereas the energy obtained from biomass or hydropower is non-renewable energy.

In the interpretation phase of LCA, the findings from LCI and LCIA are incorporated together. The interpretation results should be consistent with defined scope and goal of the study.

This phase should confirm that LCIA results are based on a relative approach, follow potential environmental effects and do not predict actual impacts (ISO 14040:2006). The findings from this phase may present as a form of conclusions and recommendations of the LCA results. It is also proposed to present an understandable, completely and consistent report on the LCA results according to the goal of the study (ISO 14040:2006).

### 2.5 Athena Sustainable Materials Institute and LCA software tools

LCA is the most reliable way to measure environmental impacts of a product. The Athena Sustainable Materials Institute applies LCA for construction products, building assemblies, whole structures, building portfolios and highways. Athena provides two LCA software tools for buildings: (1) the Athena impact estimator and (2) EcoCalculator. These two software tools provide LCA results as a whole building and reports on different assemblies of the building. For this research Athena impact estimator for building software tools was used for LCA analysis. This software is applicable for new construction, renovations and additions in all North American Building types. It provides Cradle-to-grave life cycle inventory analysis of a whole building.

#### 2.5.1 Athena impact estimator for buildings (IEB)

The software allows to add all buildings materials need to be investigated through its dialogue boxes. The LCA results are reported based on several environmental impacts consistent with the latest US EPA TRACI methodology. TRACI is an impact assessment methodology developed by U.S. environmental protection agency (EPA). It stands for “Tool for the Reduction and Assessment of the Chemical and Other Environmental Impacts”. Ozone depletion, climate change, acidification, eutrophication, smog formation, human health impacts and ecotoxicity are the impact categories for TRACI methodology (EPA, 2012). For this research, only global warming potential and total primary energy are discussed as they are more relevant. Location of the building can be customized in IEB. Appropriate electricity grids, transportation and manufacturing of product are depending on the location of building selected during modeling. Additionally, the building service life and types of building also can affect the results. The annual electricity and natural gas consumption of a building per year can be included through operating energy dialogue bar. The environmental impact results are computed in four stages of LCA analysis: Product, construction process, use and end of life.

## 2.6 LCA analysis of buildings

In 2001, load bearing masonry buildings were investigated to measure embodied carbon. This research was done in India. The findings of the research indicated that, total amount of embodied carbon can be reduced by 50% if energy efficient building materials are used (Khasreen et al., 2009). Timber material has been compared with other building materials in many researches. $CO_2$ emission of a multi-story buildings constructed with timber or concrete material. This research showed that, the primary energy input in production was 60-80% higher when the material was concrete (Borjesson et al.,2002). A building constructed with timber and concrete material to evaluate $CO_2$ emission following input-output based hybrid framework. The finding showed that the GWP emission was doubled (Lenzen et al. 2002). Gustavsson and colleagues investigated the change in energy and $CO_2$ emission in manufacturing materials in a timber and concrete frame building. The timber frame building had lower energy and $CO_2$ emission than concrete frame building in all cases but one (Gustavsson et al., 2006). Asif and colleagues investigated $CO_2$ emission of a dwelling in Scotland with nine different construction materials like timber, concrete, glass, aluminum, slate, ceramic tiles, plasterboard, damp course and mortar. The findings showed that, 61% of the embodied energy was generated by concrete in the house. Timber and ceramic tiles contributed around 14% and 15% respectively. 99% of the $CO_2$ emission occurred because of concrete construction procedure (Asif et al., 2007).

LCA is well established tool but still there are many sectors to improve for using it for buildings analysis. The main problem is the lifespan of a building is long with critical future assumptions. There is a clear gap in data implication about it in LCA (Khasreen et al., 2009). Researchers are trying hard to overcome this problem (Khasreen et al., 2009). There should be an internationally adopted framework for LCA. Current available database is not transparent (Khasreen et al., 2009). There need to produce an accurate database for any analysis (Khasreen et al., 2009).

Like any other energy simulation, LCA has some uncertainties in calculation that involves with assumptions and future conditions. Other variables that affect LCA results are quality of underlying LCA data, applied method and selection of impact indicator framework ("About LCA," Athena sustainability materials institute). Now LCA has become more matured as a method from earlier days when two different LCA results of a same product were completely different. It is now a standardized practice with third-party evaluation and centralized data sources which are assisting to minimize inequalities. Considering these limitations, LCA is best applied for relative comparison between products, choosing one over another.

## 2.7 Life cycle cost analysis

Life cycle cost analysis is a method of estimating the economic condition of a building over its entire lifetime. It can be expressed as the whole cost counting or the total cost of ownership. It balances initial investment of money with the long-term expense of maintaining and functioning the building (Guideline for life cycle cost analysis, 2005).

By comparing the life cycle cost of various design options, an evaluation can be made between initial cost and long-term cost savings and estimate the most cost effective option. (Guideline for life cycle cost analysis, 2005). Generally, the following costs are included in life cycle cost analysis: Initial cost; energy and water cost; operation, maintenance and repair costs; replacement costs; residual values and other costs (Sieglinde, 2016).

## 2.8 Sustainability and resiliency analysis

The aim of sustainable development is to improve the quality of living for present and future generation by means of equity (social), economic and environment measures (Menna et al., 2013). Now a days, a big challenge for the structural engineer is to establish a sustainable design with sufficient structural reliability for safety.

Natural resources are consumed by buildings in a significant amount and it (building) produces major portion of $CO_2$ emission and causes climate change (DOE 1993). According to DOE 2013, in U.S. the primary energy consumed by the buildings is about 41% in 2010 which is 44% than the transportation sector and 36% more than the industrial sector. According to Horvath (2004), 54% of energy consumption is caused by buildings and its construction procedure in U.S. Though few studies have conducted to correlate between natural disasters overcome and environmental impacts initiated by the buildings (Feese et al., 2014).

From Feese and colleagues study (Feese et al., 2014), LCA studies have been done to establish sustainable design for buildings by considering its construction, use and end of life phase. On the other hand, only limited studies have combined structural integrity and their resistance to earthquake disaster and environmental impacts by the repair and damage cost together, though they are closely related to sustainable design.

Sustainability development has been a major research theme for long period of time, but recently it has been incorporated for the building infrastructure. LCA sustainability analysis of a building emphasizes on evaluating the environmental effects produced by the building in its lifetime. The buildings with advanced design techniques and inventive material technologies, have less impacts on environment. LCA calculates environmental impacts based on initial construction, maintenance and energy usage of a building for its lifetime but limited research has considered the effects of natural disaster event. So, this gap can be filled by the investigation of seismic performance of a building, then collaborate it with the life-cycle effect and minimize the environmental impacts of the building. Although including post-disaster damage and repair was outside of the present scope, seismic performance was incorporated as a comparison to environmental performance. The main goal of this research is to choose a better retrofit option based on seismic performance (ISD limits) and environmental impacts in a cost effective manner.

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# CHAPTER 3: METHODOLOGY

## 3.1 Stages of LCA

Life cycle assessment (LCA) is an analytical process to construe the material and energy flow of a product or process to or from environment for its entire life cycle. It provides a comprehensive vision of a product about its environmental aspects like energy consumption, material and more clear view of the environmental trade-offs of the product selection. According to international standard ISO 14040, there are 4 phases of a complete LCA as shown in Fig 3.1: (1) Goal and scope definition, (2) Inventory analysis, (3) Impact assessment, and (4) Interpretation.

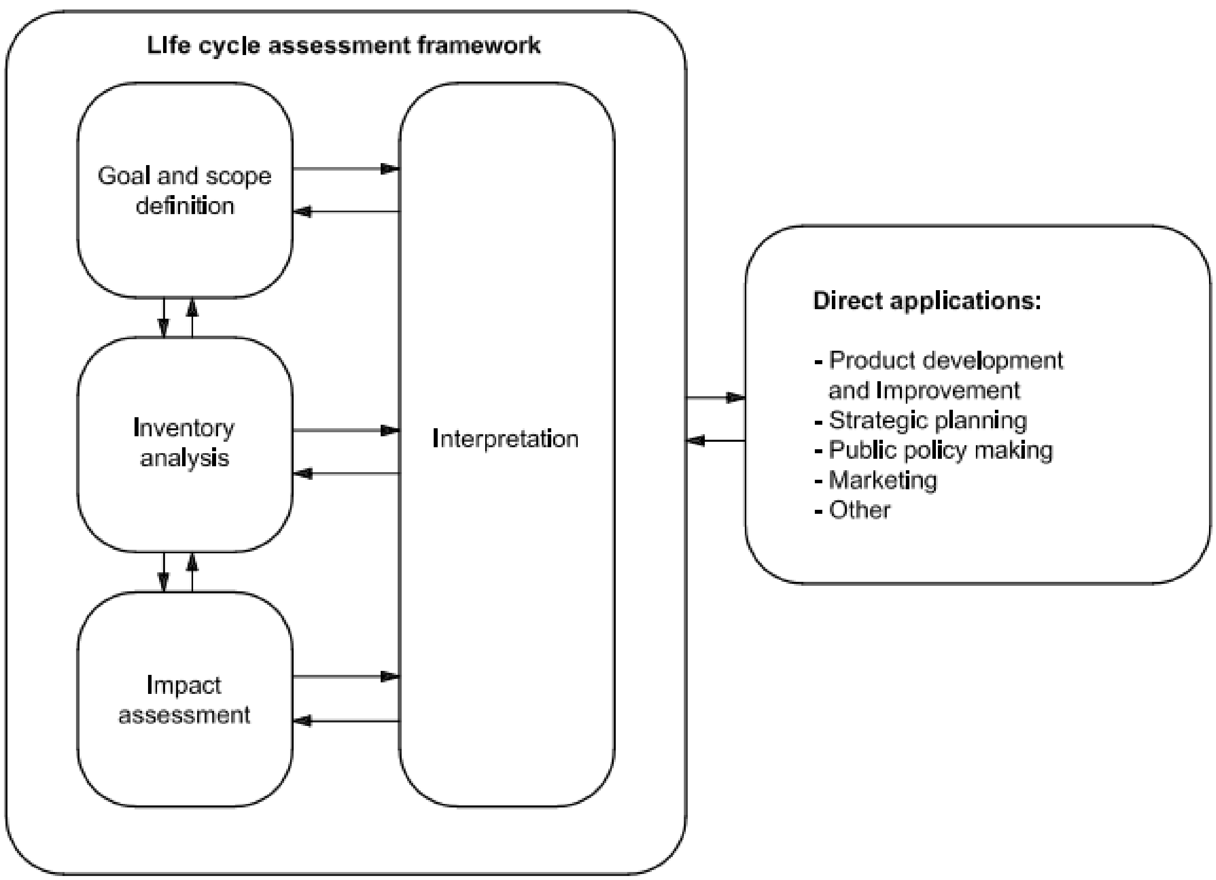



**Figure 3.1. Phases of LCA as per ISO 14040**

### 3.1.2 Goals and Scope Definition

One of the goal of this research is to perform a LCA on a multi-story residential wood-frame building with a soft first story with three different types of retrofits and compare them based on their sustainability. In addition, a raw material cost analysis of the three retrofits is provided. Finally, by using existing seismic performance data of the retrofits, an ultimate comparison is made based on sustainability and resilience.

### 3.1.3 Life cycle inventory analysis (LCI)

The life cycle inventory analysis includes data collection and data calculations procedures of the product. As data is collected gradually, so the required data can be found out to meet the goal of the study. Data collection involves raw material inputs, energy inputs, emission to air, discharge to water and soil and other environmental aspects. Data calculation deals with mainly the validation of data collected.

In this research, all building data was taken from the NEES-Soft project of a four story wood-frame apartment building investigated at full scale with four retrofits on a shaking table at NEES-UCSD laboratory (van de Lindt et al., 2014). The location of the building was assumed to be Los Angeles, California for determination of the seismic hazard spectral parameters. Therefore, the electricity and natural gas consumption of the residential building per year was calculated from the California energy commission website.

### 3.1.4 Life cycle impact assessment (LCIA)

LCIA involves in evaluating the potential environmental impacts using LCA results. It also offers the information about the interpretation phase. This phase ensures that all goals and scope have been met, or makes any changes in goals of the study if needed.

The main environmental impacts that are included in this research are:

(1) Global warming potential

(2) Total primary energy

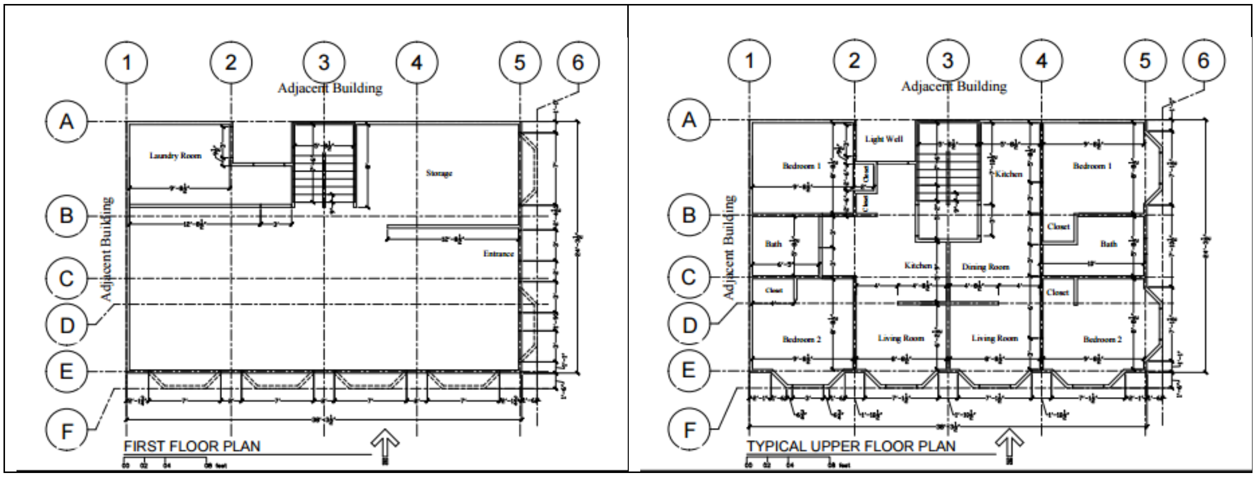
Global warming potential, a mid-point metric developed by the US environmental protection agency (EPA), for the calculation of the influence of greenhouse gases relative to $CO_2$. The methodology and calculation behind global warming potential is considered as one of the most accepted LCIA categories. Total primary energy is the energy directly obtained from sources like natural gas, oil, coal, biomass or hydropower energy. There are two types: renewable and non-renewable energy. Renewable energy includes the power obtained from oil, natural gas or coal, whereas the energy obtained from biomass or hydropower is non-renewable energy.

### 3.1.5 Life cycle interpretation (LCI)

Life cycle interpretation includes the results from LCI and LCIA. This section provides conclusion and recommendations. The environmental impacts will be discussed practically in this phase. The findings from this phase may be presented as the form of recommendation or conclusion.

## 3.2 Selection of building

For this research a multi-story, multi-family, residential wood-frame building with a soft first story was analyzed. For the building, all design data was taken from the NEES-Soft project (Bahmani et al., 2014; van de Lindt et al., 2014). The NEES-Soft building was a four story apartment building (38.4ft x 28.4ft) investigated at full scale with four different types of retrofits on a shaking table at NEES-UCSD laboratory. Prior to the retrofit, the first story of this building was a soft story with four garage doors on its south side, two windows, storage and an entrance on its east side. The upper stories were designed as two-bedroom units with bay windows on the south and east sides.




(a) (b)

**Figure 3.2. NEES-Soft Four-Story Building Plan: (a) First story; (b) Upper stories (Bahmani et al., 2014 and Van de Lindt et al., 2014)**

### 3.3 Selection of retrofits

Soft-story retrofits were designed for the first floor to prevent the pancake-like collapse prone to soft-story buildings when subjected to earthquake ground motions. Two different methodologies were followed to design the retrofits: the FEMA P807 retrofit guidelines, and a performance based seismic retrofit (PBSR) methodology. Three different types of retrofit elements were selected to be analyzed and compared for this study. The three retrofits using different retrofit elements and following one of two retrofit methodologies included:

1. Cross-laminated timber (CC) rocking wall retrofit (FEMA P-807)
2. Steel special-moment frame (SMF) retrofit (FEMA P-807)
3. Steel special-moment frame (SMF) (PBSR)

The FEMA P807 guidelines restrict the retrofit to the soft-story only, and do not allow for upper story retrofits thereby not bringing the structurally deficient building up to a current code level. Performance-based design allows for upper story retrofits, and therefore only the steel special-moment frame (PBSR) included retrofit up the upper floors. In this case, wood shear walls were designed for the second, third, and fourth floors with the moment frame installed on the first floor. The NEES-Soft building was analyzed with these three different types of retrofit to perform a sustainability and resilience analysis in this study.

In Figure 3.3, the positions of these three retrofits in first floor of the NEES-Soft building were shown:

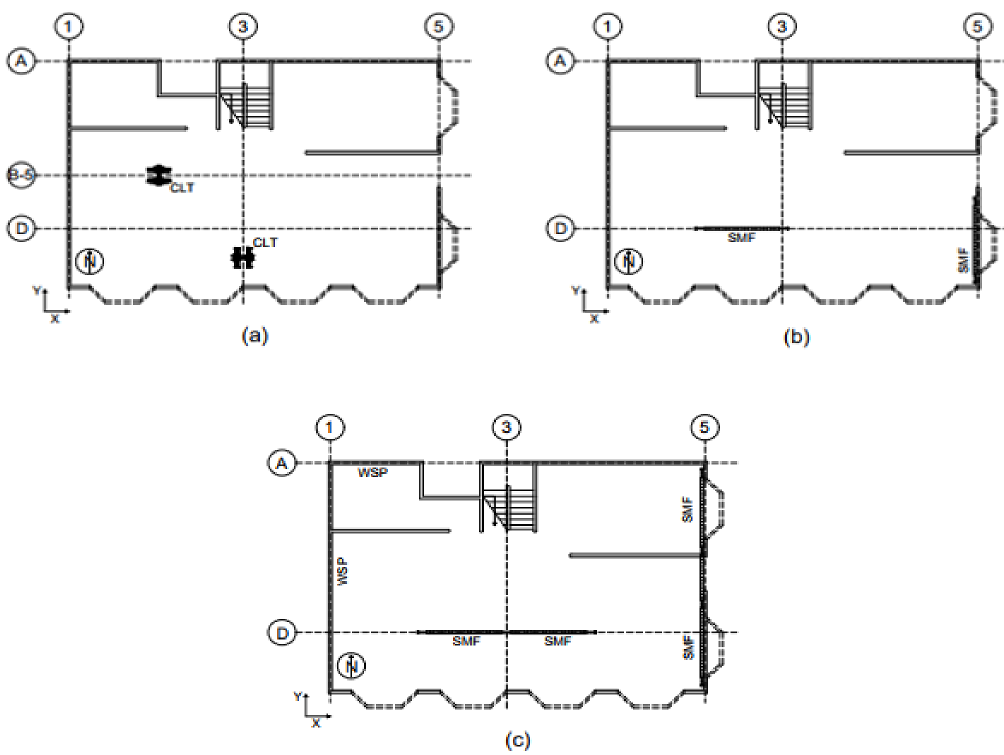



**Figure 3.3**. **Retrofits position on first story of NEES-Soft building: (a) CLT (FEMA P-807); (b) SMF (FEMA P-807) and (c) SMF (PBSR) (Bahmani et at., 2014)**

### 3.4 Cost estimation of different types of retrofit

A detailed cost estimation of the three retrofits was conducted based on the raw materials required for the construction. The detailed element, raw materials and costs are tabulated in Table

3.1 for each of the three retrofits. The element list and raw materials were determined from the NEES-Soft publications (Bahmani et al., 2014).

**Table 3. 1. Cost estimation of retrofits**

| Retrofit names | Element List | Raw materials | Cost |
|---|---|---|---|
| 1. Cross-Laminated Timber Rocking wall (FEMA P807) | HDU8 Connectors | HDU8 Connectors | $40.04/each (Simpson strong tie) |
| | (2) 16mm dia threaded rod G-A36 | 16mm dia threaded rod G-A36 | $29.78/each (Fastenal) |
| | (2) 77mm CLT panel | | $20/ft$^3$ (FPInnocations) |
| | Shear Connector (HGA10) | HGA10 | $53.63/each (Simpson strong tie) |
| | Base steel for connection W14X61 | Hot rolled steel | $791.0/10' (discount steel.com) |
| | Fixed Connection to foundation used 6.5 mm self-tapping wood screws. | 6.5 mm self-tapping wood screws | $12.09/box (Walmart) |
| 2. Steel Special Moment Frame (FEMA P807) | Column W10X30 | Hot rolled steel | $322.4/10'(discount steel.com) |
| | W10X26 | Hot rolled steel | $265.7/10' (discount steel.com) |
| | Beam W12X50 | Hot rolled steel | $650.0/10' (discount steel.com) |
| | W12X30 | Hot rolled steel | $303.5/10' (discount steel.com) |
| | 12mm thick sheathing-rated plywood shear panel | Plywood | $15.65/4'X8'(Home depot) |
| | 10d common nail | 10d common nail | $15.27/box (Home depot) |
| 3. Steel Special moment Frame Panel (PBSR) | Column W14X38 | Hot rolled steel | $380.00/10' (discount steel.com) |
| | W10X30 | Hot rolled steel | $322.00/10' (discount steel.com) |
| | Beam W12X50 | Hot rolled steel | $650.00/10' (discount steel.com) |
| | W12X30 | Hot rolled steel | $303.50/10' (discount steel.com) |

| | | | |
|---|---|---|---|
| | 12mm thick sheathing-rated plywood shear panel | Plywood | \$15.65/4'X8'(Home depot) |
| | 10d common nail | 10d common nail | \$15.27/box (Home depot) |

### 3.5 Athena-impact estimator for buildings (IE4B)

For this research the LCA software Athena-impact estimator for buildings (IE4B) was used to perform the life cycle analysis on the four-story retrofitted apartment building. The life cycle analysis complies with ISO 14040 and North American standards. Based on geographic location, building types, life-span, energy uses and other factors Athena provides cradle-to-grave implications as a form of global warming potential (GWP) ($CO_2$ equivalent mass), human health respiratory effects potential (PM 2.5 equivalent mass), acidification potential ($SO_2$ equivalent mass), ozone depletion potential, photochemical smog potential, eutrophication potential, fossil fuel consumption and total potential energy (TPE). Results of GWP and TPE from the Athena analysis are provided in Chapter 4.

#### 3.5.1 Scope and system boundary of Athena

The impact building estimator can accommodate buildings of any scale, any usage type (e.g., residential, commercial, industrial), and any construction type (e.g., new, renovation, or refurbishment). Athena Sustainable Materials Institute has developed some data on their software for building material, energy uses, constructions, and transportations. Every life cycle analysis, regardless of what software is being used, is based on some assumptions and uncertainties. Accordingly, the margin error in LCA results should be approximately 15% or less (Athena Sustainable Materials Institute, website). However, determining the margin of error is difficult.

### 3.5.2 Modeling the building

For this research, whole building from NEES-Soft project has been modeled in IE4B with and without retrofits. Imperial unit is followed throughout the modeling. The whole modeling steps followed in IE4B are described below:

#### 3.5.2.1 Project description

Project name: Residential building-NEES-Soft project

Project Location: Los Angeles, California

Building Type: Multi Unit Residential- Rental

Building Life Expectancy: 50 years

Building Height: 35.7 ft

Gross Floor Area: 930.7 $ft^2$

Unit: Imperial

#### 3.5.2.3 Floor assembly

Three floor assemblies were modeled. The detailed input measures included:

(1) From the add assembly option of the project tree, floor assembly was selected. After that from various options of floors "wood joist floor" was chosen as per design data.

(2) Under the floor assembly, floor width was entered as 116.25 ft with a span length of 8 ft. Note: Athena limits the span length for floor assemblies, and therefore the equivalent number of 8-ft span floor assemblies must be determined and entered.

(3) Live load was selected as 50 psf.

(4) Decking type was plywood with a thickness of ½ in.

#### 3.5.2.4 Roof assembly

The detailed inputs for modeling the roof assembly included:

(1) From the add assembly option of the project tree, roof assembly was selected. After that from various options of roof "wood joist roof" was chosen as per design data.

(2) Under the floor assembly, roof width was entered as 116.25 ft with a span length of 8 ft.

(3) Live load was selected as 50 psf.

(4) Decking type was plywood with a thickness of ½ in.

(5) In envelope option, glass felt shingles 30 years was added as roof envelope.

#### 3.5.2.5 Foundation assembly

Three types of data has been entered for foundation assembly: (1) Concrete strip footing-underneath all the exterior wall, (2) Garage slab on grade- in garage area only as slab on grade foundation and (3) Stoop slab on grade-at the entrance of the building.

**(1) Concrete strip footing**

a) From the add assembly option of the project tree, foundation assembly was selected. Under this assembly concrete footing option was designated.

b) The length of concrete strip footing was entered as 170 ft and width 2 ft with a thickness of 8.006 in.

c) #5 rebar was selected.

d) The design strength of concrete was chosen as 4000 psi.

e) In envelope option, polyethylene 6 mil was added as concrete strip footing envelope.

**(2) Garage slab on grade**

a) From the add assembly option of the project tree, foundation assembly was selected. Under this assembly concrete slab on grade option was chosen.

b) The length of garage slab on grade was entered as 38.3 ft and width 16.3 ft with a thickness of 4 in.

c) The design strength of concrete was chosen as 4000 psi.

d) In envelope option, polyethylene 6 mil was added as garage slab on grade envelope as well.

**(3) Stoop slab on grade**

(a) From the add assembly option of the project tree, foundation assembly was selected. Under this assembly concrete slab on grade option was chosen.

(b) The length of stoop slab on grade was entered as 4 ft and width 6 ft with a thickness of 4 in.

(c) The design strength of concrete was chosen as 4000 psi.

(d) In envelope option, polyethylene 6 mil was added as stoop slab on grade envelope.

#### 3.5.2.6 Wall assembly

External and internal wall assemblies were modeled. The detailed input data are described as follows.

##### 3.5.2.6.1 Exterior wall

4X and 2X4 stud wall have been used for this design, so the model was done according to this. The details for modeling the external walls on level 1 with 4X4 studs include:

(a) From the wall assembly options of the project tree, custom wall was chosen.

(b) Wood stud was selected as external wall assembly.

(c) The length of the 4X4 external stud wall was entered as 130.6 ft and height 8.9 ft.

(d) The wall was selected as load bearing with kiln-dried stud type and plywood sheathing.

(e) Stud spacing was entered as 16 o.c.

(f) Wood bevel siding- spruce, air barrier, gypsum regular ½", latex water based, blown cellulose (139.7 mm) were chosen as wall envelope.

(g) 2 windows and 8 doors were used as the opening area on the wall.

The details for modeling the external walls on level 1 with 2X4 studs included:

(a) From the wall assembly options of the project tree, custom wall was chosen.

(b) Wood stud was selected as external wall assembly.

(c) The length of the 2X4 external stud wall was entered as 24.15 ft and height 8.9 ft.

(d) The wall was selected as load bearing with kiln-dried stud type and plywood sheathing.

(e) Stud spacing was entered as 16 o.c.

(f) Wood bevel siding- spruce, air barrier, gypsum regular ½", latex water based, blown cellulose (5.5 in.) were chosen as wall envelope.

(g) 1 window and 3 doors were used as the opening area on the wall.

The steps for external wall level 2 with 4X4 studs are given below:

(a) From the wall assembly options of the project tree, custom wall was chosen.

(b) Wood stud was selected as external wall assembly.

(c) The length of the 4X4 external stud wall was entered as 90 ft and height 8.95 ft.

(d) The wall was selected as load bearing with kiln-dried stud type and plywood sheathing.

(e) Stud spacing was entered as 16 o.c.

(f) Wood bevel siding- spruce, air barrier, gypsum regular ½", latex water based, blown cellulose (139.7 mm) were chosen as wall envelope.

(g) 4 windows and no door were used as the opening area on the wall.

The steps for external wall level 2 with 2X4 studs are given below:

(a) From the wall assembly options of the project tree, custom wall was chosen.

(b) Wood stud was selected as external wall assembly.

(c) The length of the 2X4 external stud wall was entered as 45.24 ft and height 8.9 ft.

(d) The wall was selected as load bearing with kiln-dried stud type and plywood sheathing.

(e) Stud spacing was entered as 16 o.c.

(f) Wood bevel siding- spruce, air barrier, gypsum regular ½", latex water based, blown cellulose (139.7 mm) were chosen as wall envelope.

(g) 3 windows and no door were used as the opening area on the wall.

The same steps as level 2 were followed to model external wall of level 3 and 4.

#### 3.5.2.6.2 Interior wall

The steps for interior wall level 1 with 4X4 studs are given below:

(a) From the wall assembly options of the project tree, custom wall was chosen.

(b) Wood stud was selected as external wall assembly.

(c) The length of the 4X4 interior stud wall was entered as 35 ft and height 8.9 ft.

(d) The wall was selected as load bearing with kiln-dried stud type and plywood sheathing.

(e) Stud spacing was entered as 16 o.c.

(f) (2) Gypsum regular ½"and (2) latex water based were chosen as wall envelope.

(g) 1 door was used as the opening area on the wall.

The steps for interior wall level 2 with 4X4 studs are given below:

(a) From the wall assembly options of the project tree, custom wall was chosen.

(b) Wood stud was selected as external wall assembly.

(c) The length of the 4X4 interior stud wall was entered as 100 ft and height 8.95 ft.

(d) The wall was selected as load bearing with kiln-dried stud type and plywood sheathing.

(e) Stud spacing was entered as 16 o.c.

(f) (2) Gypsum regular ½"and (2) latex water based were chosen as wall envelope.

(g) 6 doors were used as the opening area on the wall.

The steps for interior wall level 2 with 2X4 studs are given below:

(a) From the wall assembly options of the project tree, custom wall was chosen.

(b) Wood stud was selected as external wall assembly.

(c) The length of the 2X4 interior stud wall was entered as 28.8 ft and height 8.95 ft.

(d) The wall was selected as load bearing with kiln-dried stud type and plywood sheathing.

(e) Stud spacing was entered as 16 o.c.

(f) (2) Gypsum regular ½"and (2) latex water based were chosen as wall envelope.

(g) 2 doors were used as the opening area on the wall.

The same steps as level 2 were followed to model interior wall of level 3 and 4.

#### 3.5.2.7 Extra basic material

In this section, the materials were inserted which didn't have the option to enter as floor, wall, roof or foundation assembly. 4X10 dimension lumber beam were inserted. The whole volume of all lumber used in the building were calculated as cubic feet. Then converted into Mbfm, this was the unit of dimension lumber in Athena (conversion 1 Mbfm= 1 thousand board feet measure= 88.33 cubic feet). Dimension lumber was inserted as 1.60 Mbfm large dimension softwood lumber in extra basic material category. Another material inserted in this assembly was asphalt roofing. 40 lbs of roofing asphalt were entered.

#### 3.5.2.8 Operation energy consumption

Consumption of electricity and natural gas per year residential buildings in Los Angeles were determined using the California energy commission website. The electricity usage was estimated as 20233.46 million kWh and the natural gas usage was estimated as 1084.35 million of therms in 2015.

### 3.5.3 Modeling of cross laminated timber (CLT) rocking wall (FEMA P-807) retrofit

CLT retrofit had 3 basic materials: CLT panels, anchor rods and steel wide flange beam for connections. CLT panel was inserted in extra basic material as $ft^3$. As CLT retrofits was not a part of wall, roof or floor assembly, it was inserted as extra basic material. Anchor rods inserted in tons. Volume was calculated of rods in $m^3$ then converted into tonnes (1 tonnes=1.1 tons), (density of the rod 7.851 tonnes/$m^3$). Wide flange steel beam was calculated following the same steps as rods. The amount of each material inserted in extra basic material were as follows:

(1) 0.033 tons of steel plates.

(2) 0.023 tons of rebar, rod, light sections.

(3) 0.17 tons of wide flange sections

### 3.5.4 Modeling of special moment frame (SMF) (FEMA P807) retrofit

Special moment frame (SMF) (P807) retrofit had 4 basic materials: wide flange beam, structural wood panel, steel connection plates for moment frame and connection bolts. The amount of each material inserted in extra basic material were as follows:

(1) 0.95 tons of steel wide flange.

(2) 0.35 tons of steel plates.

(3) 0.62 msf of wood structural panel.

(4) 0.009 tons of bolts.

### 3.5.5 Modeling of Special moment frame (SMF) (PBSR) retrofit

Special moment frame (SMF) (P807) retrofit had 4 basic materials: wide flange beam, structural wood panel, steel connection plates for moment frame and connection bolts. The amount of each material inserted in extra basic material were as follows:

(1) 5.18 tons of steel wide flange.

(2) 0.07 tons of steel plate.

(3) 1.1 msf of wood structural panel.

(4) 0.035 tons of bolts.

# CHAPTER 4: RESULTS AND DISCUSSION

## 4.1 Inter story drift (ISD)

The inter-story drift (ISD) limits data for three types of retrofits had been collected from previous NEES-Soft project (Bahmani et al., 2014) experiments. Collected data are tabulated in Table 4.1. 4% ISD limit was defined as the onset of collapse by FEMA P-807. SMF (PBSR) was designed by the performance based seismic retrofit (PBSR) design philosophy. SMF (FEMA P-807), SMF (PBSR) and CLT (FEMA P-807) were tested on NEES outdoor shake table, ranging from 0.2-1.8g spectral acceleration (Bahmani et al., 2014). Based on these collected data, ISD limit was 3.8% for SMF (FEMA P-807) and CLT (FEMA P-807) both under 1.1g spectral acceleration and 3.4% for SMF (PBSR) for 1.8g spectral acceleration. As the ISD limits for these retrofits were under permissible limit so, all of them were resilience to earthquake.

**Table 4.1. Peak Inter-story drift (ISD) limits of different types of retrofits**

| Retrofit Descriptions | Retrofit Design Philosophy | Peak ISD (%) |
|---|---|---|
| Steel Special Moment Frame (SMF) | FEMA P-807 | 3.8 |
| Steel Special Moment Frame (SMF) | PBSR | 3.4 |
| Cross-Laminated Timber Rocking Wall (CLT) | FEMA P-807 | 3.8 |

In Figure 4.1, the ISD limits for the retrofits had been plotted. The comparison was clearly observed in this plot. Vertical axis represented the different ISD limit in percentage and horizontal axis signified the three types of retrofits. The comparison was observed in this plot.

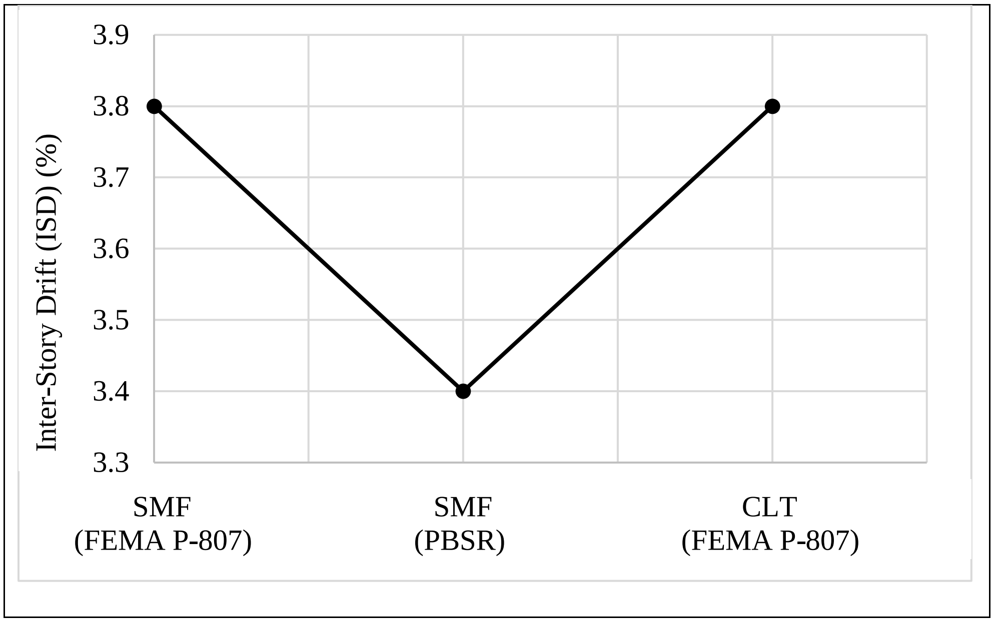



**Figure 4.1. Inter-story drift (ISD) of retrofits @ 80% probability of nonexceedance (Bahmani et al., 2014)**

### 4.2 Raw material costs

In this cost analysis, raw material cost of the retrofits was considered only. Construction, transportation, manufacturing and other related costs were not included. Each types of retrofits were investigated to find out their raw elements. Based on the raw material cost, total cost of each retrofits was finalized. The raw material cost was confirmed from different reliable dealer sources (for details see Chapter 3, Table 3.1). In Table 4.2, total cost of retrofits based on raw material cost are presented. According to this cost results, SMF (PBSR) was the costliest one among these three retrofits. Because it was designed to strengthen the structure over its entire height. Wood structural panels were placed in every single story along with special steel moment frame in the first story. As a results, cost became higher around $8500 (material cost only) for SMF (PBSR). SMF (FEMA P-807) was second costly one, around $3100. The least expensive retrofit was CLT (FEMA P-807), whose total material cost was calculated around $2100.

**Table 4.2. Raw material cost of different types of retrofits**

| Retrofit Descriptions | Retrofit Design Philosophy | Raw material cost ($) |
|---|---|---|
| Steel Special Moment Frame (SMF) | FEMA P-807 | 3100 |
| Steel Special Moment Frame (SMF) | PBSR | 8850 |
| Cross-Laminated Timber Rocking Wall (CLT ) | FEMA P-807 | 2100 |

In Figure 4.2, total cost of the retrofits was plotted. Vertical axis represented the raw material cost in dollar and horizontal axis specified the three types of retrofits accordingly. Steel special moment frame SMF (PBSR) was most expensive ($8850) and CLT (FEMA P-807) was the least ($2100).

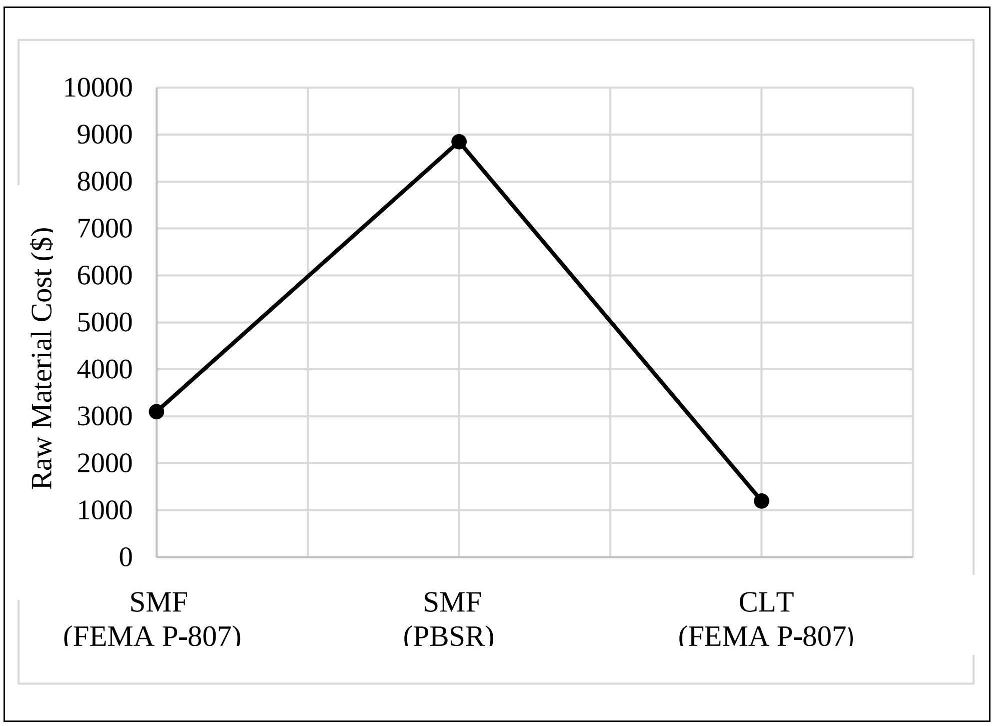



**Figure 4.2. Raw material cost of three different types of retrofit**

## 4.3 Life cycle environmental assessment LCEA results

In this section, LCEA results of whole building with and without retrofits were provided. LCA results were presented based on two environmental measures: global warming potential (GWP) and total primary energy (TPE).

### 4.3.1 LCEA results of unretrofitted building in different phases

In Table 4.3, the GWP and TPE results of unretrofitted NEES-Soft project building for 50 years of life span were tabulated. The Athena analysis results were articulated with four LCA phases: product, construction process, use and end of life. In product phase, manufacturing and transportation of construction material were considered for analyzing. In construction process phase, construction installation process and transportation were included. For use phase, manufacturing and operational energy use of the whole building were considered. End of life included de-construction, demolition and disposal of building materials. Two environmental measures were decided to describe in this LCA analysis: GWP and TPE. GWP was the measure of $CO_2$ emission by the building through its entire life cycle. The use phase produced the highest portion of $CO_2$ emission, around 7.81E+10 Kg $CO_2$ eq which was almost 99.3% total $CO_2$ emission by the whole building. During use phase, the major cause for this huge amount of $CO_2$ emission was the use of operational energy by the building. Product phase, construction process phase and end of life phase produced $CO_2$ emission around 2.81E+04 Kg $CO_2$ eq, 1.48 E+04 Kg $CO_2$ eq and 1.78 E+03 Kg $CO_2$ eq respectively. The TPE results explained the sum of all energies directly retained from natural sources like natural gas, coal, or oil. From the results shown in Table 4.3, use phase of the building consumed the highest amount of TPE, around 1.42 E+12 MJ, during its lifetime which was about 99.4% of the total TPE drawn by the building. In this case, operational energy usage was also the key factor for TPE consumption in use phase. The amount of TPE drawn by product, construction process and end of life phases were calculated around 4.17E+05 MJ, 2.16E+05 MJ and 2.65E+04 MJ respectively. The GWP and TPE results were completely depending on the building materials, construction and manufacturing process of building materials, construction process of the building, life span, energy usage by the building though its entire lifetime, building location and building type (like residential or industrial). From the results, it can be concluded that, operational energy is the main cause of GWP emission and TPE consumption. So, by saving operational energy use, the life cycle environmental impacts of the building could be improved. As an example, using better insulation could be one of the solutions for better environmental performance by the building.

**Table 4.3. LCEA results of unretrofitted building in different phases (LCA Measures: Global Warming Potential and Total Primary Energy)_Life span 50 years**

| Phases of LCA | | Global Warming Potential, Kg $CO_2$ eq | Total Primary Energy, MJ |
|---|---|---|---|
| Product | Manufacturing | 2.71E+04 | 4.03E+05 |
| | Transport | 9.90E+02 | 1.44E+04 |
| | Total | 2.81E+04 | 4.17E+05 |
| Construction Process | Construction-Installation Process | 2.17E+03 | 3.40E+04 |
| | Transport | 1.26E+04 | 1.82E+05 |
| | Total | 1.48E+04 | 2.16E+05 |
| Use | Replacement Manufacturing | 5.74E+03 | 1.19E+05 |
| | Replacement Transport | 1.99E+03 | 2.89E+04 |
| | Operational Energy Use Total | 7.81E+10 | 1.42E+12 |
| | Total | 7.81E+10 | 1.42E+12 |

| | | | |
|---|---|---|---|
| End of life | De-construction, Demolition, Disposal & Waste Processing | 1.28E+03 | 1.91E+04 |
| | Transport | 5.06E+02 | 7.38E+03 |
| | Total | 1.78E+03 | 2.65E+04 |

In Figure 4.3, GWP results of unretrofitted building were provided. GWP exhibited in significant amount in use phase (about 99.3%) The amount of $CO_2$ produced in three other phases were very less in volume compared to the use phase.

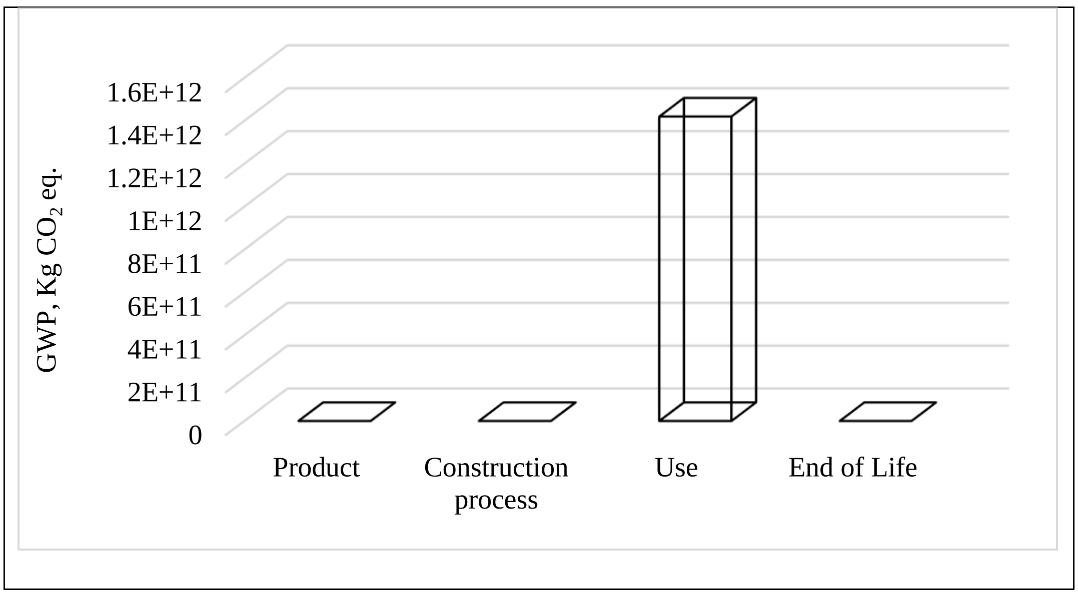



**Figure 4.3. Global warming potential (GWP) distribution of unretrofitted building**

In Figure 4.4, TPE results of unretrofitted building for different phases were plotted. Like GWP, TPE also exhibited in significant amount in use phase (about 99.4%). The amount of TPE in three other phases was significantly less compared to the use phase.

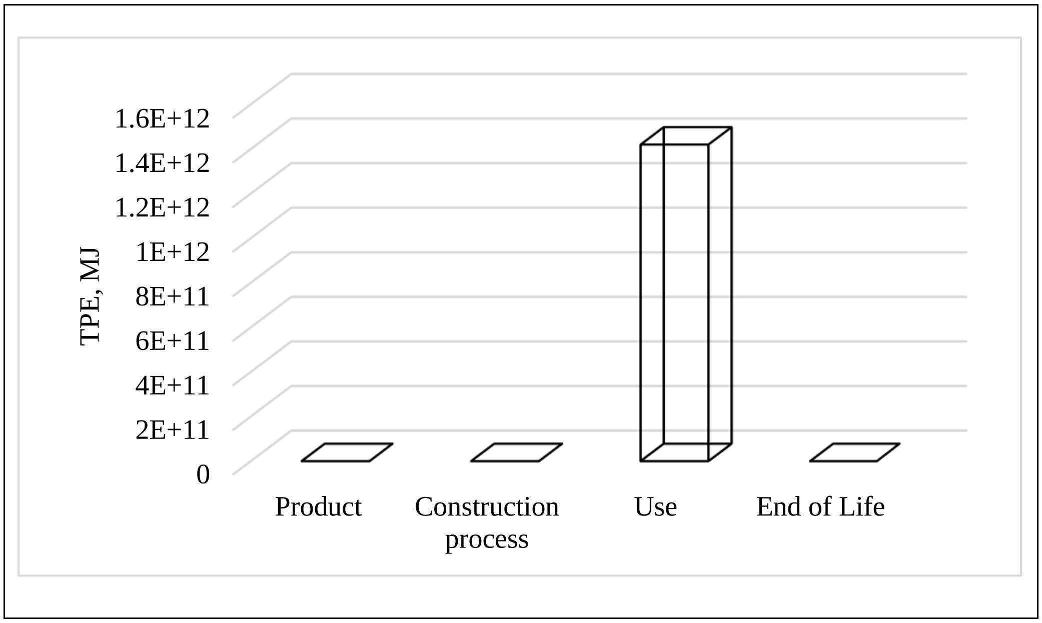



**Figure 4.4. Total primary energy (TPE) distribution of unretrofitted building**

**4.3.2 LCEA results of different assemblies of the unretrofitted building**

In table 4.4, the embodied carbon and TPE results of different assemblies of the unretrofitted building were tabulated. The considered assemblies were foundation, wall, roof, floor, and extra basic material (large dimension lumber beams and roofing asphalt). From the LCEA results, wall assembly produced the higher amount of $CO_2$ emission and primary energy use, 3.06E+04 Kg $CO_2$ eq and 5.19E+05 MJ respectively. This embodied carbon and TPE results were estimated during the manufacturing, transport, replacement and maintenance period of the building materials. As the wall assembly contributed most in $CO_2$ emission and TPE consumption so, using better or advanced or greener materials for walls could decrease the environmental impacts and improve the life cycle of the building. The amount of embodied carbon produced by the foundation, roof, floor and extra basic material assemblies were 1.73E+04 Kg $CO_2$ eq, 1.87E+03 Kg $CO_2$ eq, 2.15E+03 Kg $CO_2$ eq and 5.45E+02 Kg $CO_2$ eq respectively. The TPE consumption results for foundation, roof, floor and extra basic material assemblies were 1.65E+05 MJ, 5.77E+04 MJ, 5.03E+04 MJ and 1.47E+04 MJ respectively.

**Table 4.4. LCEA results of different assemblies of the unretrofitted building (LCA Measures: Embodied Carbon and Total Primary Energy), Life span 50 years**

| Assembly | Embodied Carbon, Kg $CO_2$ eq | Total Primary Energy, MJ |
|---|---|---|
| Foundation | 1.73E+04 | 1.65E+05 |
| Wall | 3.06E+04 | 5.19E+05 |
| Roof | 1.87E+03 | 5.77E+04 |
| Floor | 2.15E+03 | 5.03E+04 |
| Extra Basic Material | 5.45E+02 | 1.47E+04 |

In Figure 4.5, embodied carbon of whole building without retrofits were provided. Wall assembly produced the highest amount of $CO_2$. It was about 58.3% of total production of $CO_2$ of the building material in their manufacturing, transport, replacement and maintenance period. Foundation, roof, floor and extra basic material assemblies produced $CO_2$ about 32.9%, 3.6%, 4.1% and 1% accordingly of total calculated result.

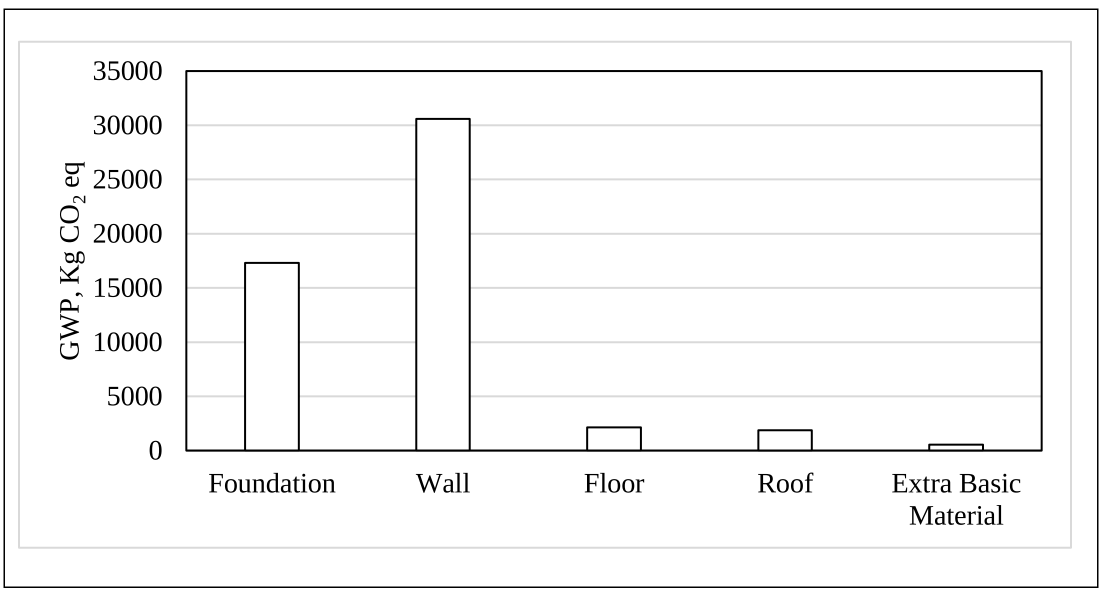



**Figure 4.5. Embodied carbon distribution of different assemblies of unretrofitted building**

In figure 4.6, TEP results of unretrofitted building assemblies were provided. Wall assembly produced the highest amount of TPE consumption. It was about 64.3% of total production of TPE consumption of the building material in their manufacturing, transport, replacement and maintenance period. Foundation, roof, floor and extra basic material assemblies produced about 20.46%, 3.6%, 7.1% and 1.8% accordingly.

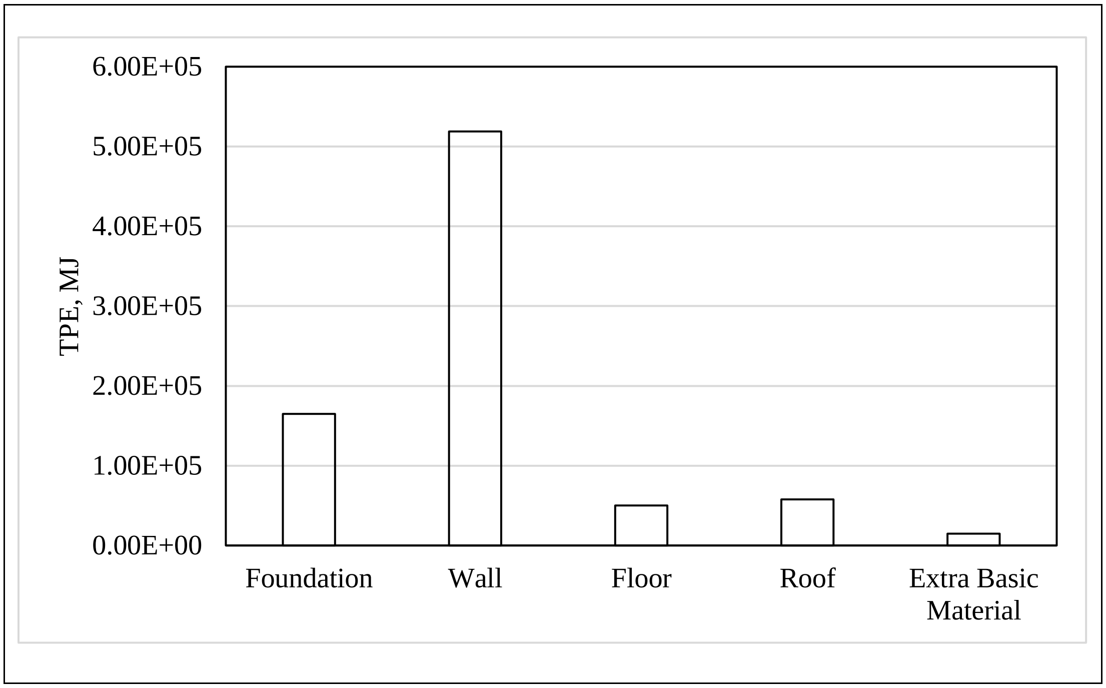



**Figure 4.6. Total primary energy (TPE) distribution of different assemblies of unretrofitted building**

### 4.3.3 LCEA results of different types of retrofits

In table 4.5, GWP and TPE results of different types of retrofits were tabulated for different phases of LCA. LCA results from different LCA phases are calculated here. For SMF (FEMA P-807) retrofit, the highest amount of $CO_2$ was produced in its product phase around 895 Kg $CO_2$ eq, which was 77.1% of total $CO_2$ emission by this retrofit. For SMF (PBSR) retrofit, product phase also contributed for the highest amount of $CO_2$ emission, around 4650 Kg $CO_2$ eq, which was 78.7% of total $CO_2$ emission by this retrofit. GWP was highest for SMF (PBSR) among these three retrofits. The materials (steel moment frame and wood structural panel) used for SMF (PBSR) retrofit highly contributes in GWP emission. For CLT (FEMA P-807) retrofit, the highest amount of $CO_2$ was produced by its product phase around 442 Kg $CO_2$ eq, which was around 64.3% of total $CO_2$ emission by this retrofit.

For SMF (FEMA P-807) retrofit, the maximum TPE consumption was caused in its product phase around 18100 MJ, which was 81.5% of total TPE by this retrofit. For SMF (PBSR) retrofit, product phase also contributed for the highest TPE intake, around 90400 MJ, which was 82.9% of total TPE by this retrofit. Like GWP, TPE was highest for SMF (PBSR) among these three retrofits. For CLT (FEMA P-807) retrofit, the highest amount of TPE intake was caused by its product phase around 12300 MJ, which was around 76.8% of total TPE by this retrofit. From the results presented in Table 4.5, the highest amount of $CO_2$ emission and TPE consumption was found in product phase for all three types of retrofits. So, manufacturing process and transportation of retrofit materials contributed most in $CO_2$ emission and TPE consumption.

**Table 4.5. LCEA results of different types of the retrofits (LCA Measures: Global warming potential (GWP) and Total Primary Energy (TPE))_Life span 50 years**

| Types of Retrofits | Global Warming Potential (GWP), Kg CO2 eq | | | | | Total Primary Energy, MJ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Phases of LCA | | | | | Phases of LCA | | | | |
| | Product | Construction Process | Use | End of Life | Total | Product | Construction Process | Use | End of life | Total |
| Steel Special Moment Frame (SMF) (FEMA P-807) | 895 | 207 | 0 | 62.3 | 1160 | 18100 | 3020 | 0 | 998 | 22200 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Steel Special Moment Frame (SMF) (PBSR) | 4650 | 953 | 0 | 301 | 5910 | 90400 | 13700 | 0 | 4870 | 109000 |
| Cross-Laminated Timber Rocking Wall (CLT) (FEMA P-807) | 442 | 202 | 0 | 43 | 687 | 12300 | 2950 | 0 | 665 | 16000 |

In Figure 4.7, GWP of different types of retrofits was plotted. The vertical axis represented the amount of GWP in Kg $CO_2$ eq produced by the retrofits and horizontal axis indicated the phases of LCA. An insignificant difference was observed for the environmental impact across these retrofits expect SMF (PBSR).

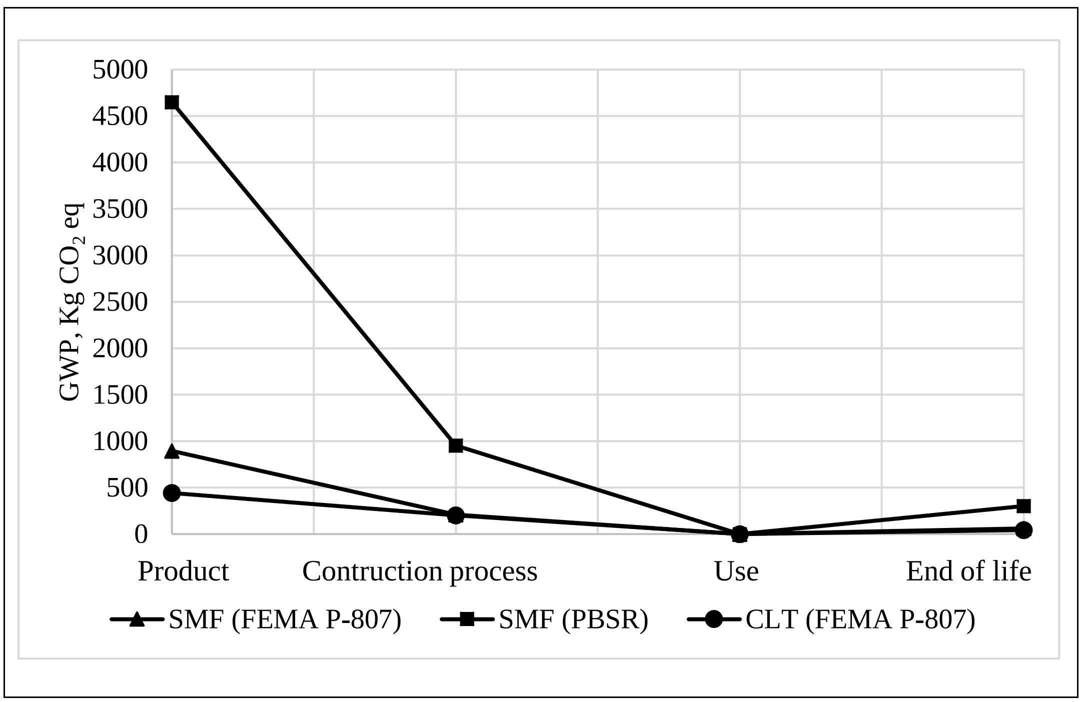



**Figure 4.7. Global warming potential (GWP) comparison of three different types of retrofits**

In Figure 4.8, TPE intake for different types of retrofits was plotted. The vertical axis represented the TPE consumption in MJ produced by the retrofits and horizontal axis indicated the phases of LCA.

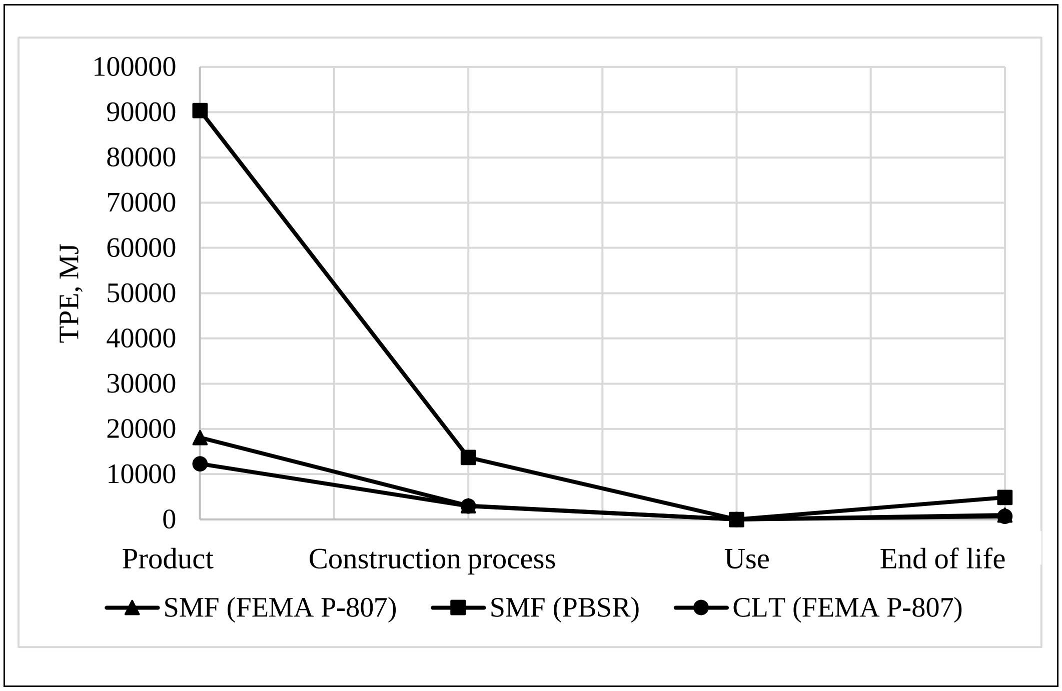



**Figure 4.8. TPE comparison of three different types of retrofits**

In Figure 4.9, GWP production of the building with three different types of retrofits options was plotted. SMF (PBSR) contributed for highest amount of $CO_2$ emission between these three retrofits.

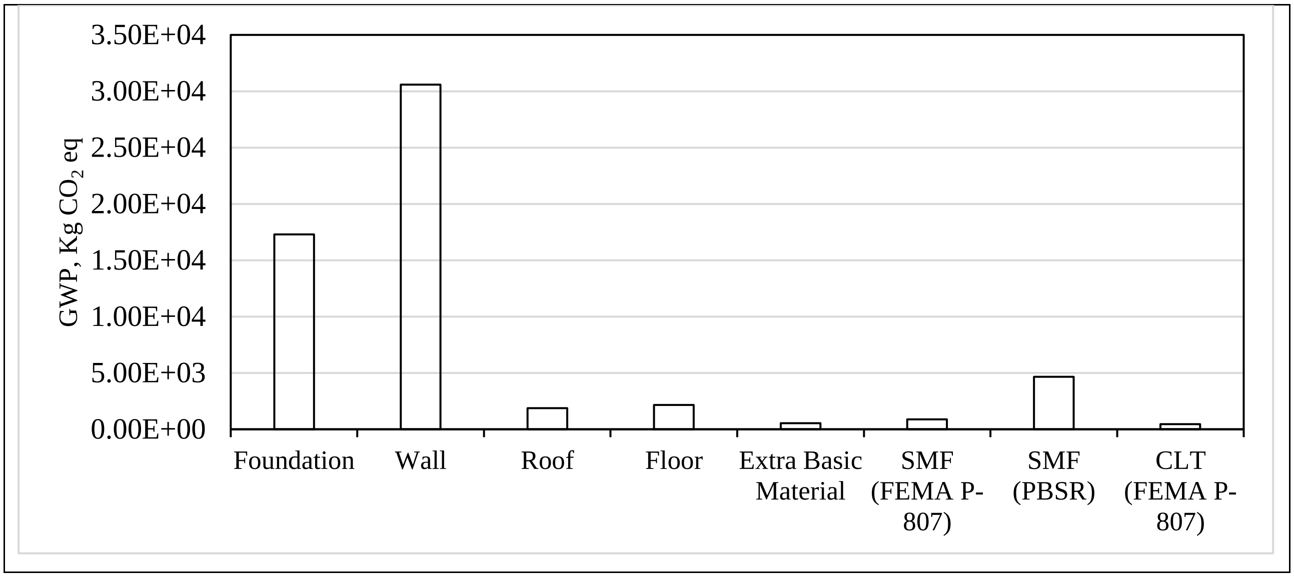



**Figure 4. 9. GWP distribution of the building with different retrofits options**

In Figure 4.10, TPE consumption of the building with three different types of retrofits options was plotted. SMF (PBSR) contributed for highest amount of TPE consumption between these three retrofits.

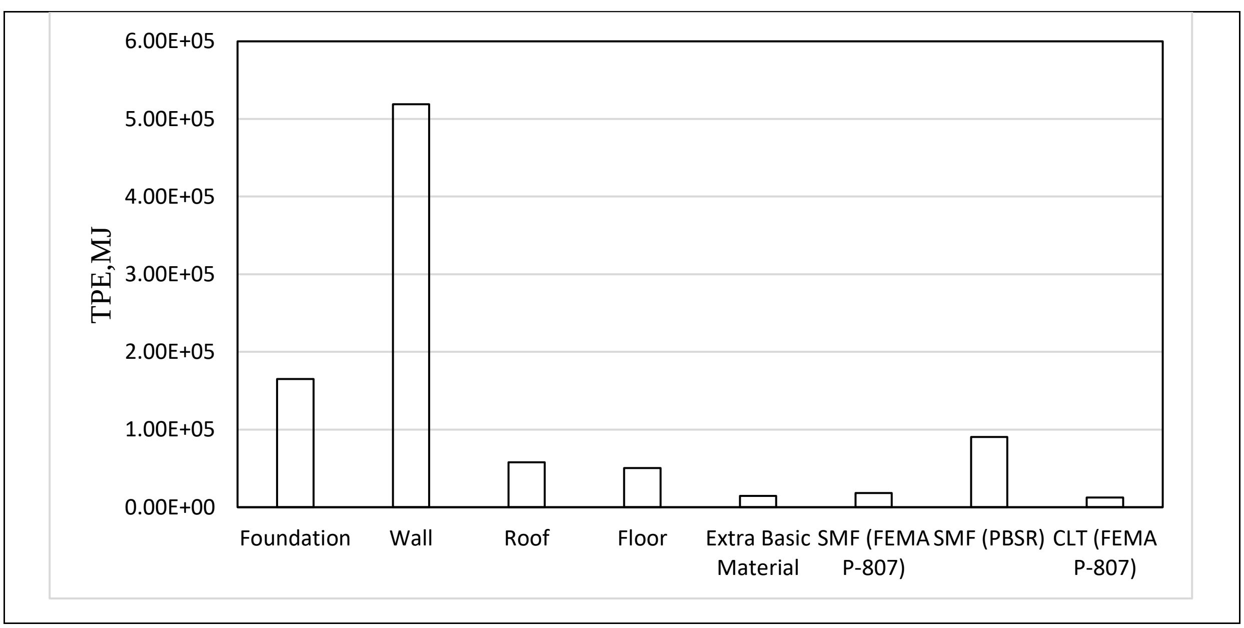



**Figure 4. 10. TPE distribution of the building with different retrofits options**

### 4.4 Resiliency and Sustainability trade off

In Figure 4.9, sustainability and resiliency of the retrofits were compared by presenting ISD, raw material cost, GWP and TPE results from analysis. Resiliency was presented by ISD values. Thus, GWP and TEP represented sustainability environmental indexes. For plotting this trade off, ISD, raw material cost, GWP and TPE results for SMF (FEMA P-807) were taken as 1 and results for other retrofits were recalculated as a fraction of it. So, the results of SMF (PBSR) and CLT (FEMA P-807) were compared with SMF (FEMA P-807) in this plot. There wasn't any significant comparison of resiliency between these three types of retrofits in terms of ISD values as those ISD were under permissible limit. So, these three retrofits were established as resilience to earthquake. Though SMF (PBSR) had the lowest ISD, as it was design by performance based retrofit design philosophy but highest GWP, TPE and raw material cost. CLT (FEMA P-807) retrofit had lower GWP, TPE and lowest raw material cost compared with SMF (FEMA P-807) retrofit and had the same ISD. By comparing all these three retrofits based on sustainability, resilience and raw material cost, CLT (FEMA P-807) could be a good retrofit option for Soft-story wood-frame building.

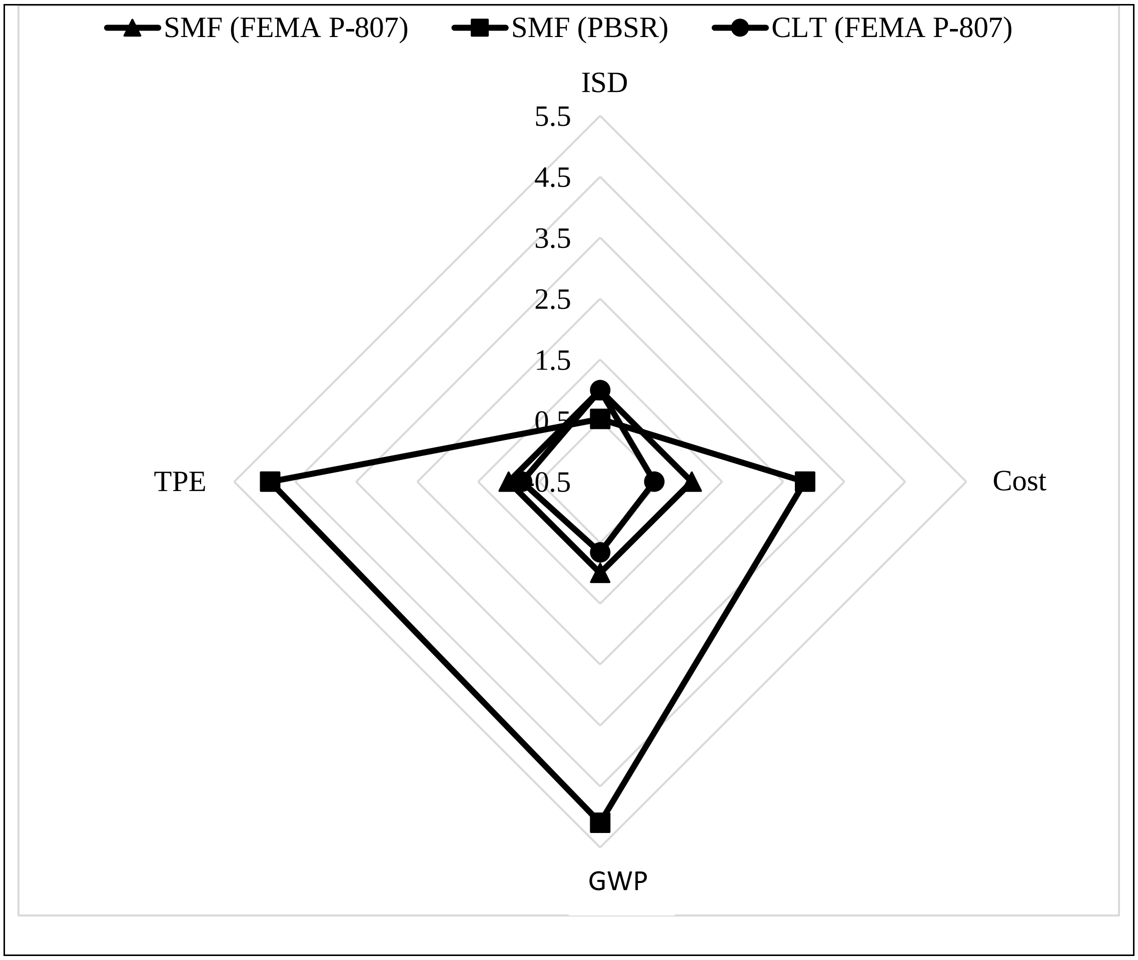



**Figure 4. 11. Resiliency-sustainability trade off**

# CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusion and recommendations

The main goal of this study was to investigate soft-story wood-frame building retrofits based on sustainability, resiliency and cost trade off. To achieve this goal NEES-Soft project multiunit 4-story soft-story building was selected to analyze with three different types of retrofits. These three retrofits were the following: SMF (FEMA P-807), SMF (PBSR) and CLT (FEMA P-807). ISD limits of these SMF (FEMA P-807), SMF (PBSR) and CLT (FEMA P-807) retrofits under specific acceleration (1.1g and 1.8g) were 3.8%, 3.4% and 3.8% respectively at 80% of probability of nonexceedance. According to FEMA P-807, the permissible ISD limit for any seismic retrofit design is 4%. As the collected ISD results were under permissible limit for all the retrofits so these were resilience to seismic load. For performing a sustainable analysis, a LCA assessment analysis of the building (Life span 50 year) with and without retrofit was performed by Athena impact estimator for building LCA software. The LCA results were described with respect to two environmental impacts: GWP and TPE. GWP was the measure of total $CO_2$ emission for the entire lifetime of the building and TPE was the energy drawn by the building from natural sources. LCA results were calculated based on 4 phases: product phase, construction phase, use phase and end of life. The unretrofitted building, the highest amount of GWP emission and TPE consumption were found in use phase because of the operational energy use of the building, 7.81E+10 Kg $CO_2$ eq and 1.42E+12 MJ accordingly. Thus, for a better environmental performance by the building, operational energy use should be decreased. Using better insulation could be one of the solutions for this problem. By the LCA results of these three retrofits, it was clear that SMF (PBSR) produced highest amount of GWP and TPE and the raw material cost was also very high among these three retrofits, 4650 Kg $CO_2$ eq, 90400 MJ and $8850 respectively. Thus, SMF

(PBSR) retrofit was not a better solution. Based on sustainably, cost and resiliency CLT (FEMA P-807) could be a better solution. Note that, LCA analysis doesn't indicate a good or bad product, but it's a comparison between choices of products to make a better decision in a greener way.

### 5.2 limitations of these research

- One resilience measure, peak inter-story drift, was considered for this research whereas there are many measures that could be used for resilience like floor acceleration, plastic hinge rotation or base shear. Peak inter-story drift was taken here because it was well accepted as a resilience measure in research area, easy to measure, and accurate data was available.
- Raw material cost was measured as opposed to life cycle cost of these three types of retrofits. This limitation may be considered acceptable because the total life cycle cost trend would be similar as the trend shown in Figure 4.2. Raw material cost could consider as initial cost but it did not have construction or transportation cost included and in addition there were maintenance or repair cost also. But based on the material types and amount of material used for the three types of retrofits, it would consider that the total life cycle cost would exhibit more or less same trend as raw material cost.
- Athena impact estimator for building software has a number of built-in limitations, including electricity usage, transportation modes and distances or product manufacturing techniques. These results were depending on building location. The location was specified as Los Angeles, even though there were some uncertainties. Like for CLT panel, the manufacturing place was Canada and so there would be some effects on results for CLT because of the transportation modes and distances.

### 5.3 Contribution of this research

This thesis offers the following contributions to the literature:

- This thesis incorporated and compared structural resiliency, cost and environmental impacts of lifecycle of different soft-story retrofit options together as a measure of sustainability.
- It performed a details LCA analysis of different soft-story retrofit options and recommendations are made based on the results.
- A better soft-story retrofit option was provided based seismic performance (ISD limits) and LCA results with environmental impacts in a cost effective manner.

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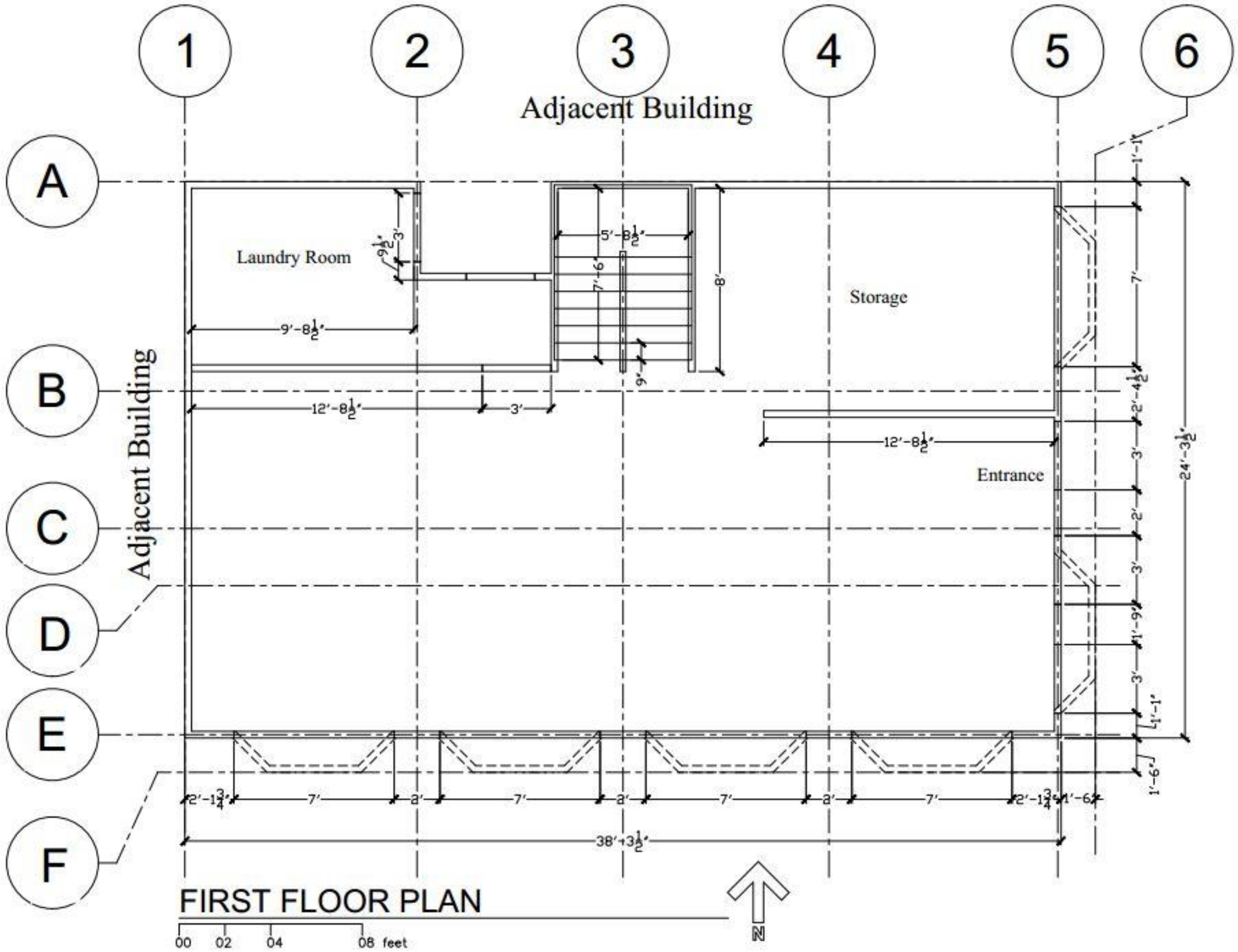
## Appendix A

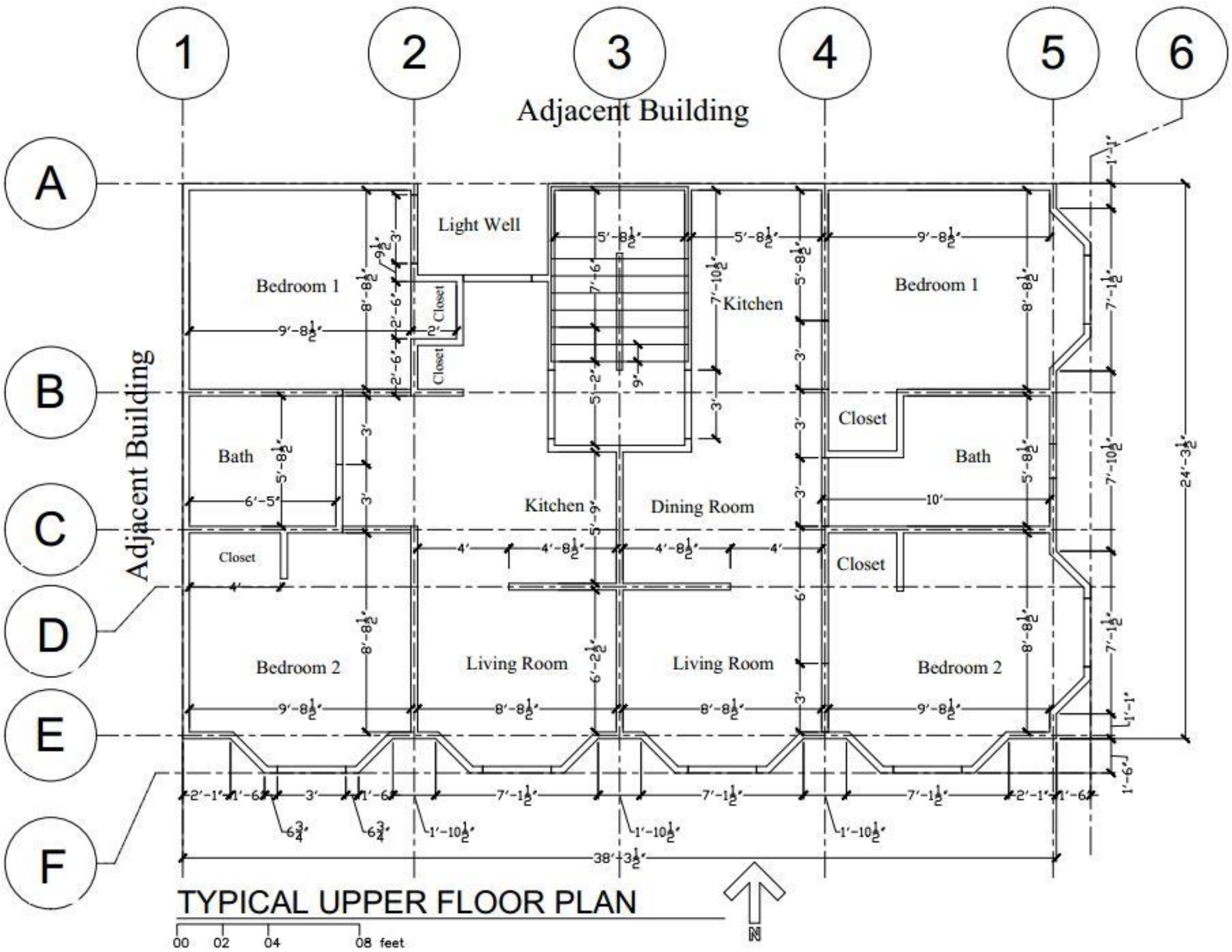
Reference: NEES-Soft project building design data

Table of Contents

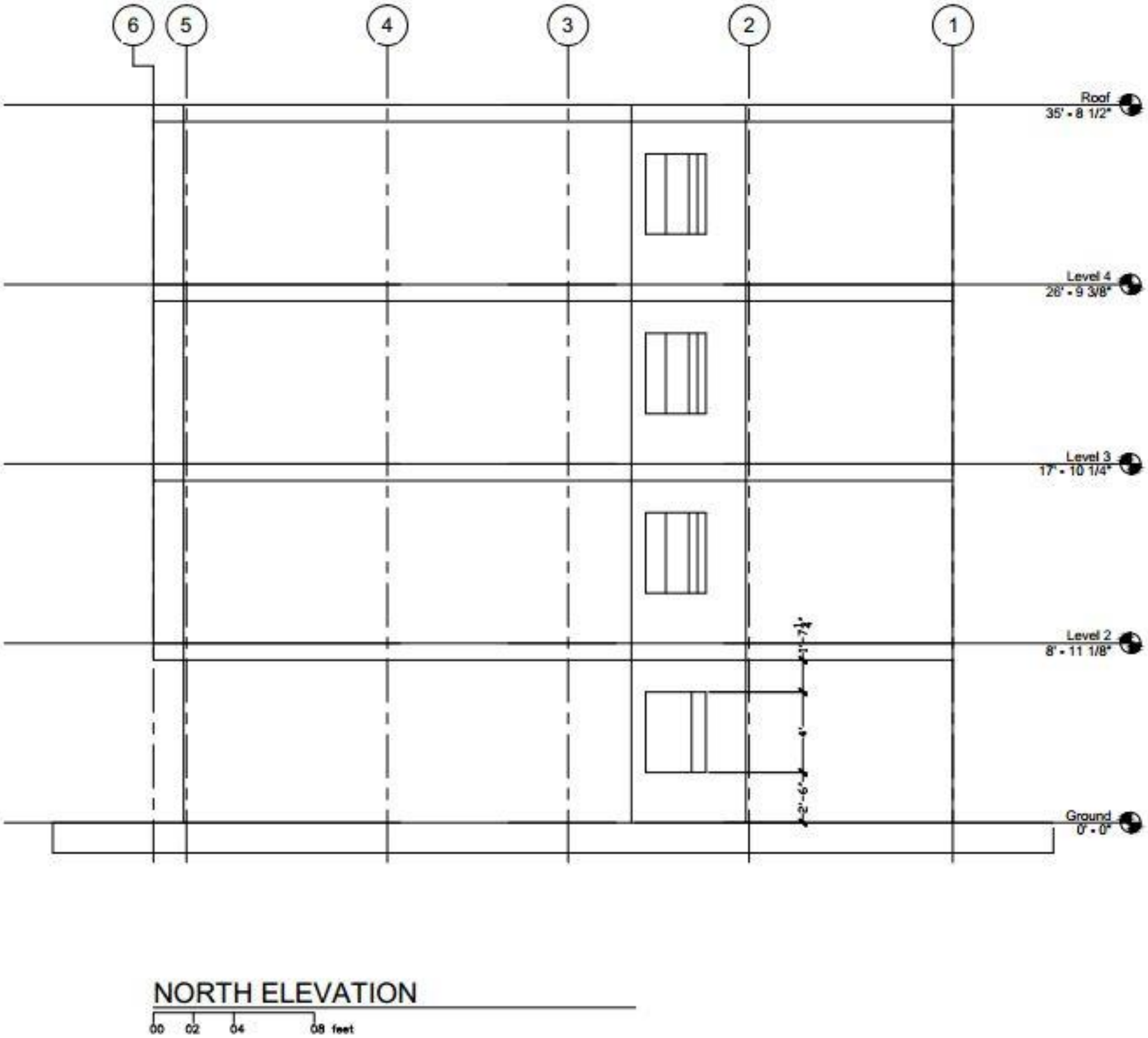
## A2.1: First floor plan



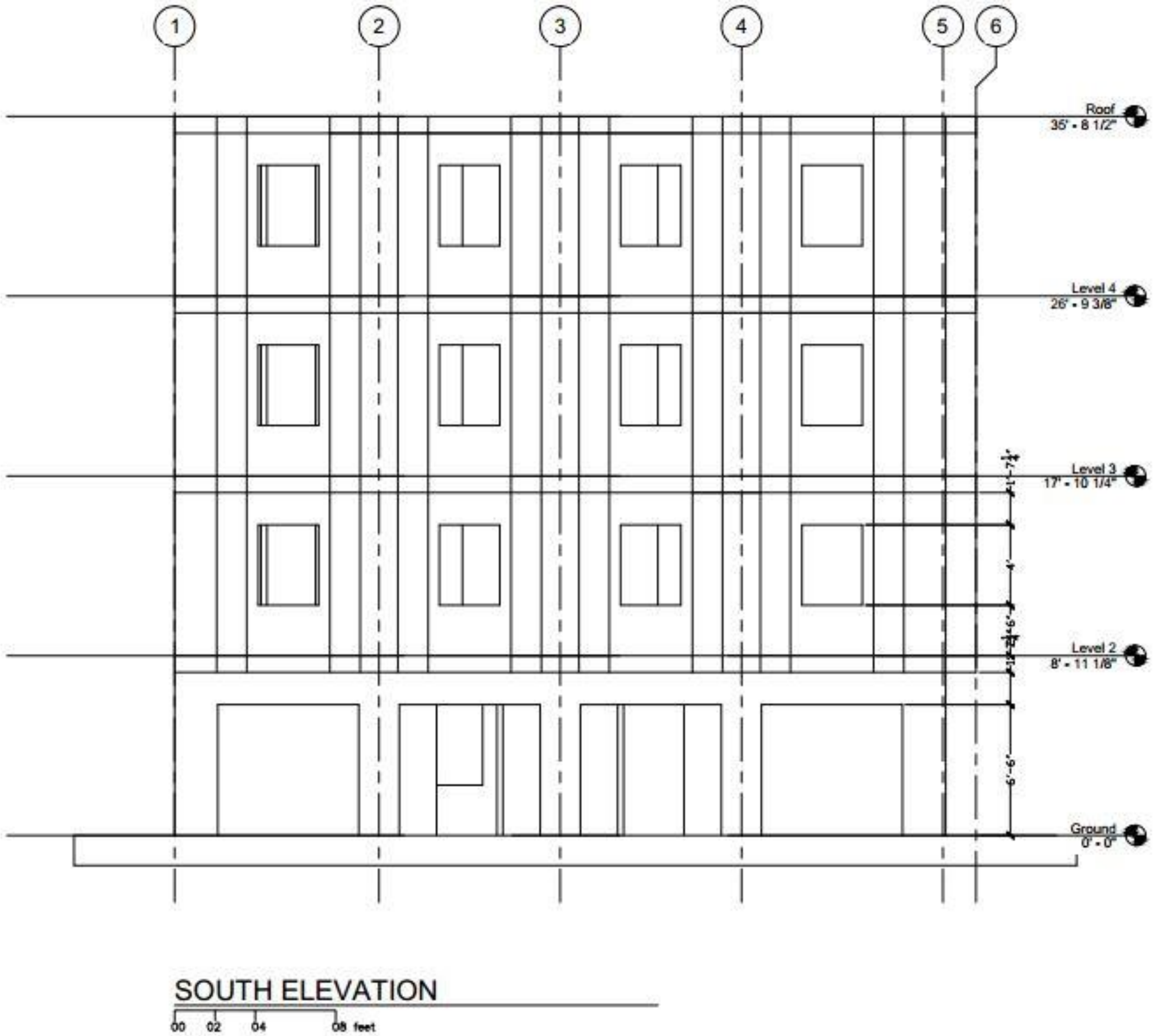
## A2.2: Typical upper floor plan



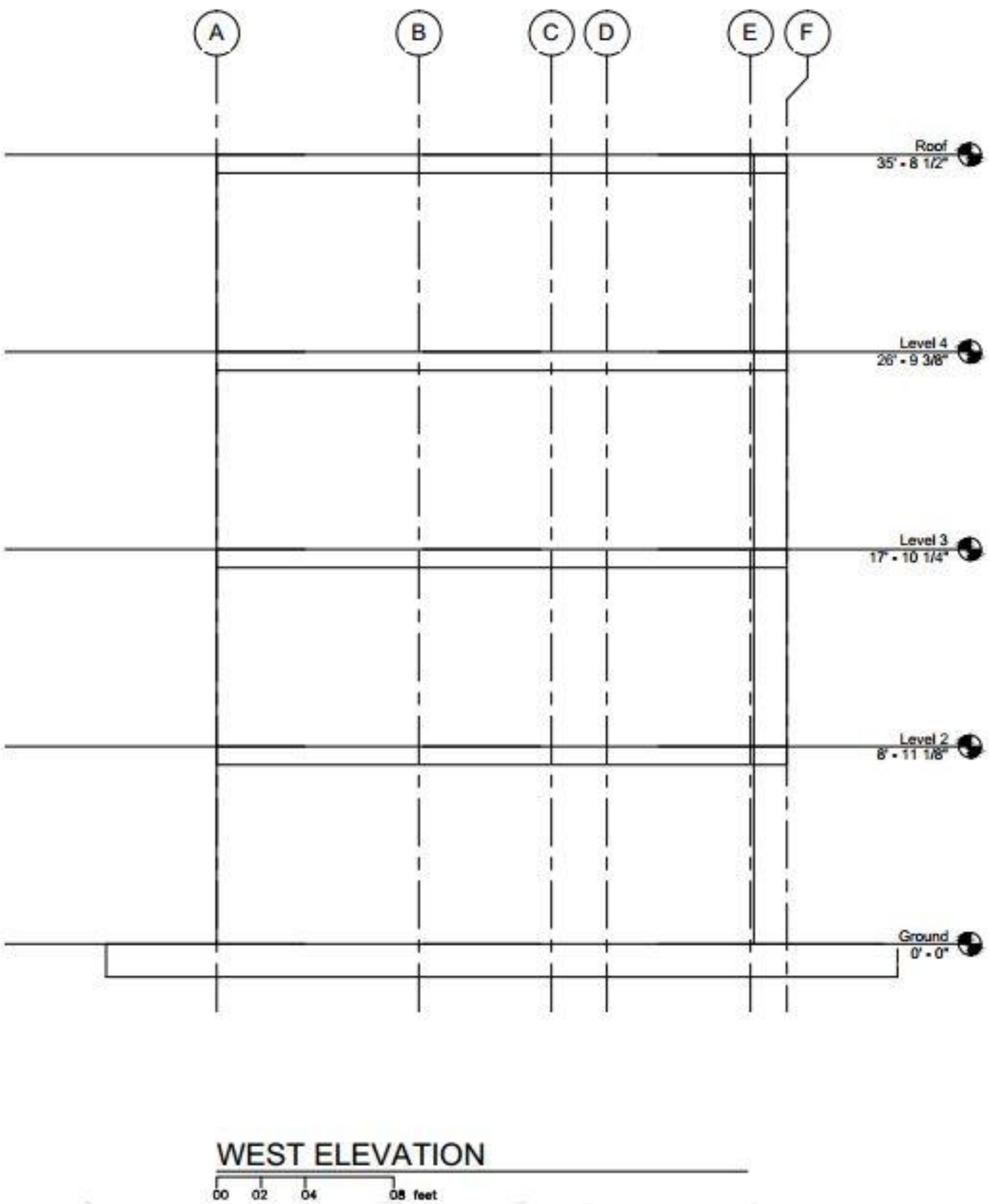
## A3.1: North elevation



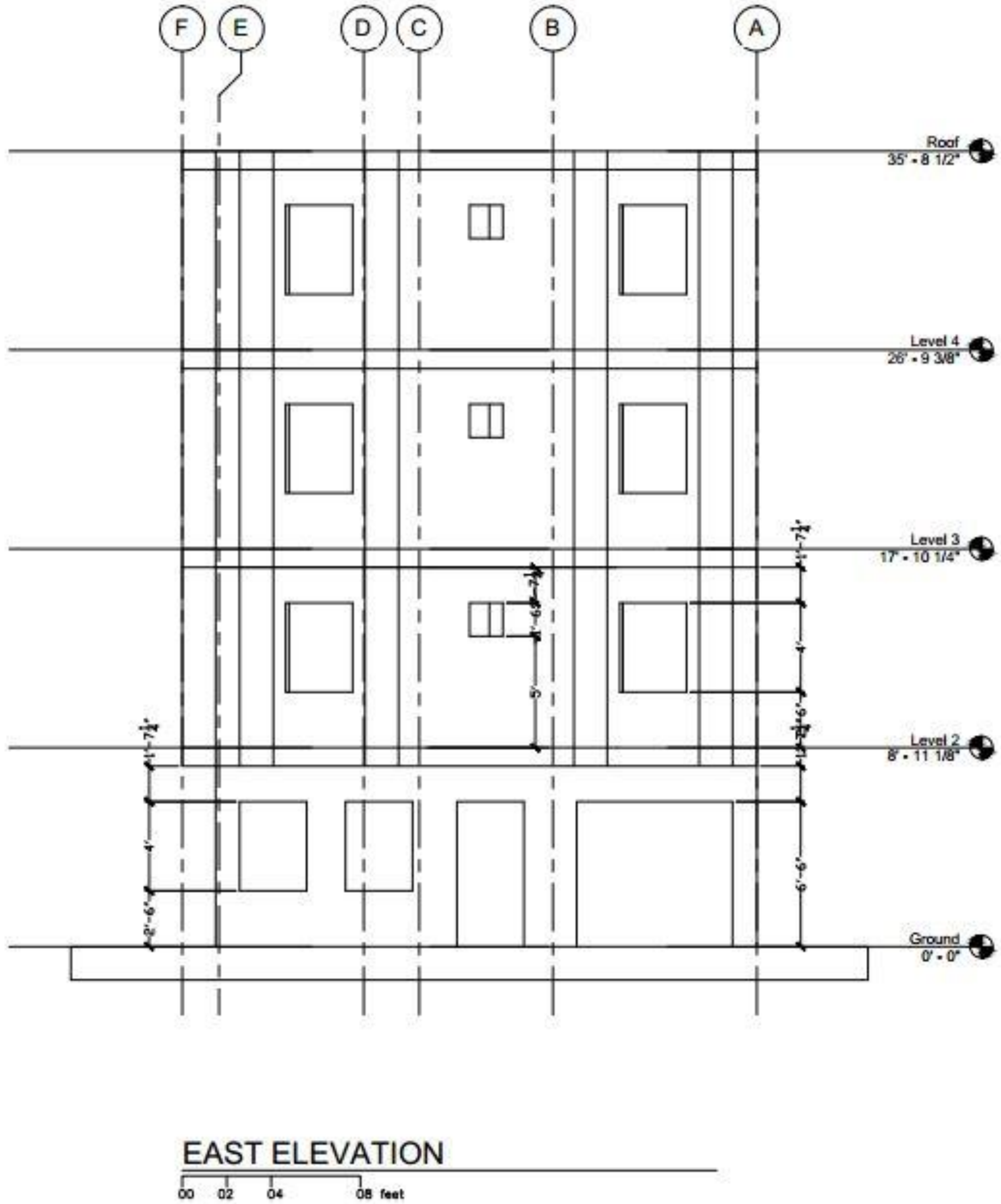
## A3.2: South elevation



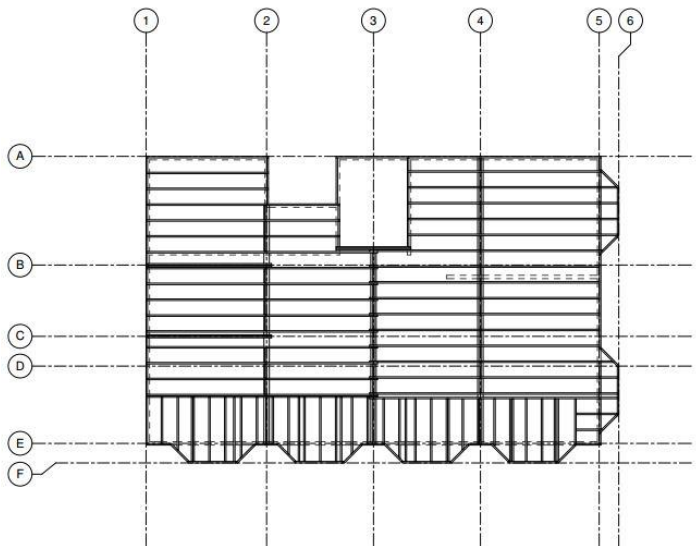
## A3.3: West elevation



## A3.4: East elevation

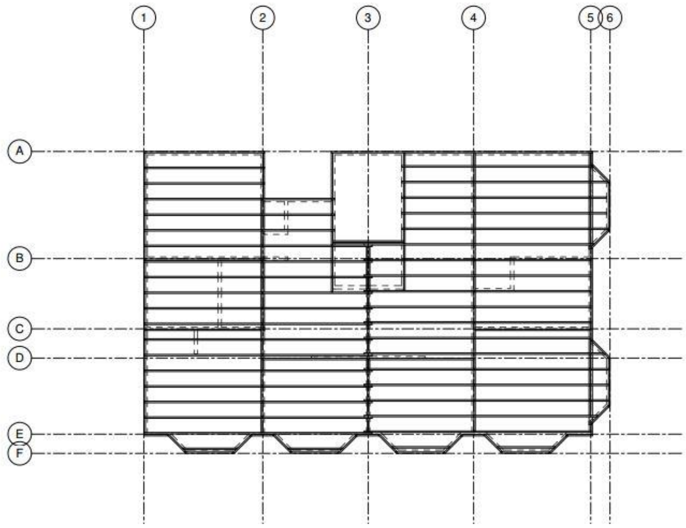


## A4.1: Level 2 framing



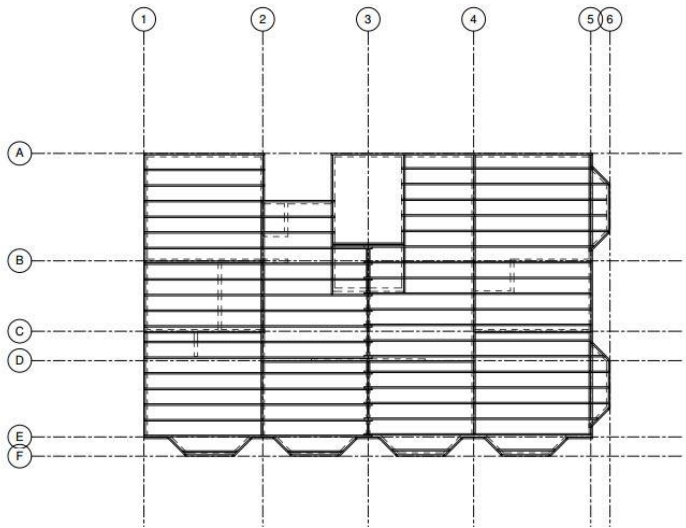

| Structural Framing Level 2 Framing | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| 2x10 | 1 | DF-L #2 | 0' - 9 3/4" |
| 2x10 | 1 | DF-L #2 | 0' - 11 1/4" |
| 2x10 | 1 | DF-L #2 | 0' - 11 1/2" |
| 2x10 | 10 | DF-L #2 | 1' - 1" |
| 2x10 | 1 | DF-L #2 | 1' - 1 1/4" |
| 2x10 | 1 | DF-L #2 | 1' - 1 5/8" |
| 2x10 | 53 | DF-L #2 | 1' - 2 1/2" |
| 2x10 | 4 | DF-L #2 | 1' - 2 3/4" |
| 2x10 | 3 | DF-L #2 | 2' - 0 5/8" |
| 2x10 | 1 | DF-L #2 | 2' - 1" |
| 2x10 | 1 | DF-L #2 | 2' - 2 1/8" |
| 2x10 | 12 | DF-L #2 | 2' - 3" |
| 2x10 | 1 | DF-L #2 | 2' - 3 1/8" |
| 2x10 | 1 | DF-L #2 | 3' - 5 1/2" |
| 2x10 | 4 | DF-L #2 | 3' - 9 1/4" |
| 2x10 | 1 | DF-L #2 | 3' - 10 1/8" |
| 2x10 | 2 | DF-L #2 | 3' - 10 1/2" |
| 2x10 | 5 | DF-L #2 | 3' - 10 3/4" |
| 2x10 | 1 | DF-L #2 | 3' - 10 7/8" |
| 2x10 | 6 | DF-L #2 | 4' - 2 3/8" |
| 2x10 | 1 | DF-L #2 | 4' - 3 7/8" |
| 2x10 | 1 | DF-L #2 | 4' - 5 7/8" |
| 2x10 | 1 | DF-L #2 | 4' - 9 3/8" |
| 2x10 | 1 | DF-L #2 | 4' - 9 7/8" |
| 2x10 | 1 | DF-L #2 | 5' - 0 3/8" |
| 2x10 | 1 | DF-L #2 | 5' - 1 3/8" |
| 2x10 | 11 | DF-L #2 | 5' - 3 1/4" |
| 2x10 | 10 | DF-L #2 | 5' - 4 3/4" |
| 2x10 | 2 | DF-L #2 | 6' - 3 1/2" |
| 2x10 | 1 | DF-L #2 | 8' - 0 5/8" |
| 2x10 | 3 | DF-L #2 | 10' - 3 1/2" |
| 2x10 | 4 | DF-L #2 | 10' - 5 1/4" |
| 2x10 | 3 | DF-L #2 | 16' - 3 1/2" |
| 2x10 | 1 | DF-L #2 | 16' - 4 3/8" |
| 2x10 | 4 | DF-L #2 | 17' - 8" |
| 2x10 | 6 | DF-L #2 | 19' - 4 1/4" |
| 2x10 | 11 | DF-L #2 | 19' - 5 3/4" |
| 2x10 | 1 | DF-L #2 | 19' - 7 5/8" |
| 2x10 | 1 | DF-L #2 | 20' - 6 5/8" |
| 2x10 | 3 | DF-L #2 | 20' - 10 1/4" |
| 2x10 | 1 | DF-L #2 | 22' - 3 1/2" |
| 4x6 | 4 | DF-L #1 | 7' - 0 1/8" |
| 6x12 | 1 | DF-L #1 | 16' - 3 1/2" |
| 6x12 | 1 | DF-L #1 | 20' - 3 1/2" |
| 6x12 | 1 | DF-L #1 | 24' - 3 1/2" |

## A4.2: Level 3 framing



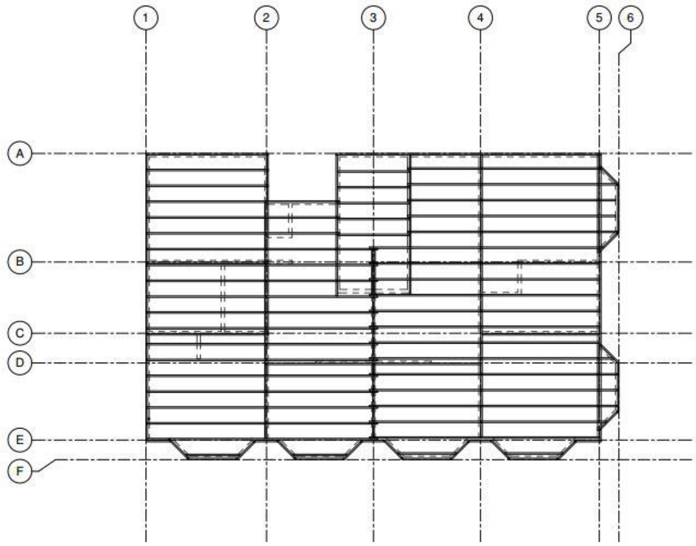

| Structural Framing Level 3 Framing | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| 2x10 | 1 | DF-L #2 | 0' - 11 1/2" |
| 2x10 | 15 | DF-L #2 | 1' - 1" |
| 2x10 | 1 | DF-L #2 | 1' - 1 5/8" |
| 2x10 | 77 | DF-L #2 | 1' - 2 1/2" |
| 2x10 | 3 | DF-L #2 | 2' - 0 5/8" |
| 2x10 | 1 | DF-L #2 | 2' - 1" |
| 2x10 | 12 | DF-L #2 | 2' - 3" |
| 2x10 | 1 | DF-L #2 | 2' - 3 1/8" |
| 2x10 | 1 | DF-L #2 | 3' - 10 1/2" |
| 2x10 | 6 | DF-L #2 | 4' - 2 3/8" |
| 2x10 | 2 | DF-L #2 | 4' - 8 1/4" |
| 2x10 | 2 | DF-L #2 | 4' - 11 1/4" |
| 2x10 | 2 | DF-L #2 | 6' - 0 1/2" |
| 2x10 | 1 | DF-L #2 | 8' - 0 5/8" |
| 2x10 | 2 | DF-L #2 | 8' - 11 1/2" |
| 2x10 | 3 | DF-L #2 | 9' - 10 1/2" |
| 2x10 | 3 | DF-L #2 | 10' - 3 1/2" |
| 2x10 | 3 | DF-L #2 | 16' - 3 1/2" |
| 2x10 | 1 | DF-L #2 | 16' - 4 3/8" |
| 2x10 | 2 | DF-L #2 | 17' - 6" |
| 2x10 | 2 | DF-L #2 | 17' - 8" |
| 2x10 | 7 | DF-L #2 | 19' - 4 1/4" |
| 2x10 | 13 | DF-L #2 | 19' - 5 3/4" |
| 2x10 | 1 | DF-L #2 | 19' - 7 5/8" |
| 2x10 | 1 | DF-L #2 | 19' - 11 5/8" |
| 2x10 | 1 | DF-L #2 | 20' - 6 5/8" |
| 2x10 | 3 | DF-L #2 | 20' - 10 1/4" |
| 2x10 | 1 | DF-L #2 | 22' - 3 1/2" |
| 4x4 | 1 | DF-L #1 | 7' - 1 7/8" |
| 4x12 | 1 | DF-L #1 | 3' - 0" |
| 4x12 | 1 | DF-L #1 | 3' - 9" |
| 4x12 | 1 | DF-L #1 | 6' - 3 1/2" |
| 4x12 | 2 | DF-L #1 | 7' - 4 5/8" |

## A4.3: Level 4 framing



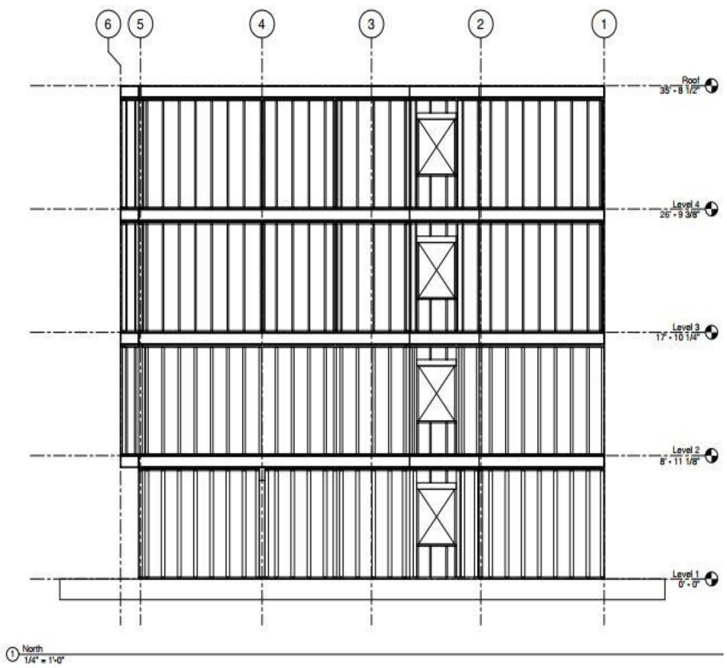

| Structural Framing Level 4 Framing | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| 2x10 | 1 | DF-L #2 | 0' - 11 1/2" |
| 2x10 | 15 | DF-L #2 | 1' - 1" |
| 2x10 | 1 | DF-L #2 | 1' - 1 5/8" |
| 2x10 | 77 | DF-L #2 | 1' - 2 1/2" |
| 2x10 | 3 | DF-L #2 | 2' - 0 5/8" |
| 2x10 | 1 | DF-L #2 | 2' - 1" |
| 2x10 | 12 | DF-L #2 | 2' - 3" |
| 2x10 | 1 | DF-L #2 | 2' - 3 1/8" |
| 2x10 | 1 | DF-L #2 | 3' - 10 1/2" |
| 2x10 | 6 | DF-L #2 | 4' - 2 3/8" |
| 2x10 | 2 | DF-L #2 | 4' - 8 1/4" |
| 2x10 | 2 | DF-L #2 | 4' - 11 1/4" |
| 2x10 | 2 | DF-L #2 | 6' - 0 1/2" |
| 2x10 | 1 | DF-L #2 | 8' - 0 5/8" |
| 2x10 | 2 | DF-L #2 | 8' - 11 1/2" |
| 2x10 | 3 | DF-L #2 | 9' - 10 1/2" |
| 2x10 | 3 | DF-L #2 | 10' - 3 1/2" |
| 2x10 | 3 | DF-L #2 | 16' - 3 1/2" |
| 2x10 | 1 | DF-L #2 | 16' - 4 3/8" |
| 2x10 | 2 | DF-L #2 | 17' - 6" |
| 2x10 | 2 | DF-L #2 | 17' - 8" |
| 2x10 | 7 | DF-L #2 | 19' - 4 1/4" |
| 2x10 | 13 | DF-L #2 | 19' - 5 3/4" |
| 2x10 | 1 | DF-L #2 | 19' - 7 5/8" |
| 2x10 | 1 | DF-L #2 | 19' - 11 5/8" |
| 2x10 | 1 | DF-L #2 | 20' - 6 5/8" |
| 2x10 | 3 | DF-L #2 | 20' - 10 1/4" |
| 2x10 | 1 | DF-L #2 | 22' - 3 1/2" |
| 4x4 | 1 | DF-L #1 | 7' - 1 7/8" |
| 4x12 | 1 | DF-L #1 | 3' - 0" |
| 4x12 | 1 | DF-L #1 | 3' - 9" |
| 4x12 | 1 | DF-L #1 | 6' - 3 1/2" |
| 4x12 | 2 | DF-L #1 | 7' - 4 5/8" |

## A4.4: Roof framing



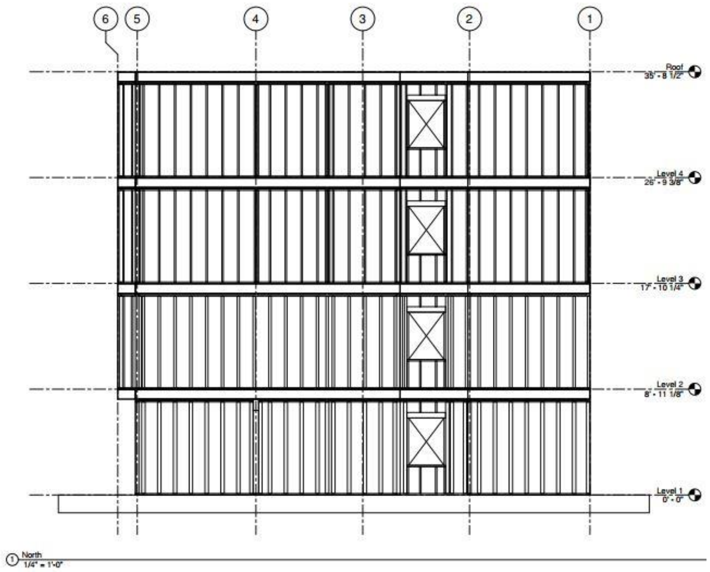

| Structural Framing Roof Framing | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| 2x10 | 1 | DF-L #2 | 0' - 11 1/2" |
| 2x10 | 15 | DF-L #2 | 1' - 1" |
| 2x10 | 1 | DF-L #2 | 1' - 1 5/8" |
| 2x10 | 77 | DF-L #2 | 1' - 2 1/2" |
| 2x10 | 3 | DF-L #2 | 2' - 0 5/8" |
| 2x10 | 1 | DF-L #2 | 2' - 1" |
| 2x10 | 11 | DF-L #2 | 2' - 3" |
| 2x10 | 1 | DF-L #2 | 2' - 3 1/8" |
| 2x10 | 1 | DF-L #2 | 3' - 10 1/2" |
| 2x10 | 6 | DF-L #2 | 4' - 2 3/8" |
| 2x10 | 2 | DF-L #2 | 4' - 8 1/4" |
| 2x10 | 1 | DF-L #2 | 4' - 9 5/8" |
| 2x10 | 2 | DF-L #2 | 4' - 11 1/4" |
| 2x10 | 5 | DF-L #2 | 6' - 0 1/2" |
| 2x10 | 1 | DF-L #2 | 8' - 0 5/8" |
| 2x10 | 2 | DF-L #2 | 8' - 11 1/2" |
| 2x10 | 1 | DF-L #2 | 9' - 9 1/2" |
| 2x10 | 2 | DF-L #2 | 9' - 10 1/2" |
| 2x10 | 3 | DF-L #2 | 10' - 3 1/2" |
| 2x10 | 3 | DF-L #2 | 16' - 3 1/2" |
| 2x10 | 1 | DF-L #2 | 16' - 4 3/8" |
| 2x10 | 2 | DF-L #2 | 17' - 6" |
| 2x10 | 2 | DF-L #2 | 17' - 8" |
| 2x10 | 7 | DF-L #2 | 19' - 4 1/4" |
| 2x10 | 13 | DF-L #2 | 19' - 5 3/4" |
| 2x10 | 1 | DF-L #2 | 19' - 7 5/8" |
| 2x10 | 1 | DF-L #2 | 19' - 11 5/8" |
| 2x10 | 1 | DF-L #2 | 20' - 6 5/8" |
| 2x10 | 3 | DF-L #2 | 20' - 10 1/4" |
| 2x10 | 1 | DF-L #2 | 22' - 1 1/2" |
| 4x4 | 1 | DF-L #1 | 7' - 1 7/8" |
| 4x12 | 1 | DF-L #1 | 3' - 0" |
| 4x12 | 1 | DF-L #1 | 3' - 9" |
| 4x12 | 1 | DF-L #1 | 6' - 3 1/2" |
| 4x12 | 2 | DF-L #1 | 7' - 4 5/8" |

# A5.1: North elevation framing



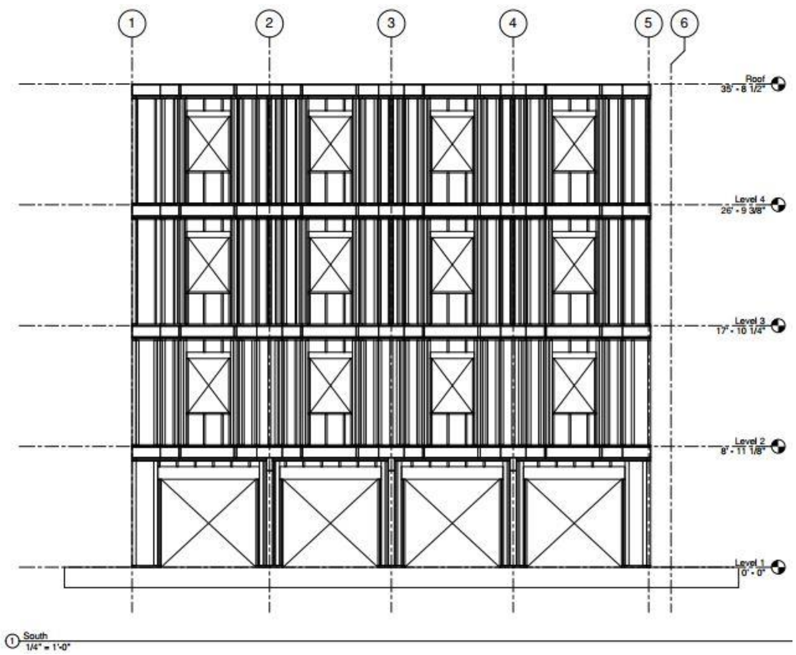

| Structural Framing North Elevation | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| Level 1-North | | | |
| 2x4 | 4 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 8 | DF-L Stud | 2' - 3" |
| 2x4 | 2 | DF-L Stud | 3' - 3" |
| 2x4 | 2 | DF-L Stud | 3' - 8 1/2" |
| 2x4 | 6 | DF-L Stud | 4' - 0" |
| 2x4 | 2 | DF-L Stud | 5' - 7 1/2" |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 5' - 11" |
| 2x4 | 1 | DF-L Stud | 6' - 0" |
| 2x4 | 1 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 2 | DF-L Stud | 8' - 0" |
| 2x4 | 1 | DF-L Stud | 9' - 7 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 11" |
| 2x4 | 2 | DF-L Stud | 10' - 3 1/2" |
| 2x4 | 1 | DF-L Stud | 11' - 7 1/2" |
| 2x4 | 1 | DF-L Stud | 22' - 0" |
| 4x4 | 39 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 2 | DF-L #1 | 3' - 3" |
| 4x6 | 2 | DF-L #1 | 7' - 0 1/8" |
| Level 2-North | | | |
| 2x4 | 4 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 1 | DF-L Stud | 1' - 8 1/2" |
| 2x4 | 8 | DF-L Stud | 2' - 3" |
| 2x4 | 2 | DF-L Stud | 3' - 3" |
| 2x4 | 1 | DF-L Stud | 3' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 3' - 9" |
| 2x4 | 6 | DF-L Stud | 4' - 0" |
| 2x4 | 1 | DF-L Stud | 4' - 0 1/2" |
| 2x4 | 3 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 6' - 0" |
| 2x4 | 2 | DF-L Stud | 7' - 0 3/8" |
| 2x4 | 1 | DF-L Stud | 8' - 2" |
| 2x4 | 1 | DF-L Stud | 9' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 10' - 0" |
| 2x4 | 2 | DF-L Stud | 10' - 3 1/2" |
| 2x4 | 1 | DF-L Stud | 11' - 9" |
| 2x4 | 2 | DF-L Stud | 21' - 8 1/2" |
| 3x4 | 39 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 2 | DF-L #1 | 3' - 3" |

# A5.2: North elevation framing



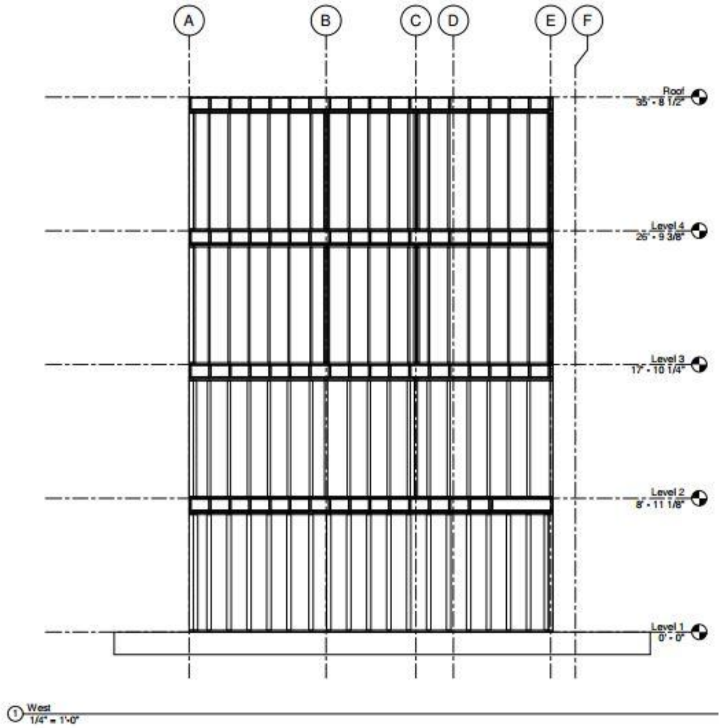

| Structural Framing North Elevation | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| Level 3-North | | | |
| 2x4 | 4 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 1 | DF-L Stud | 1' - 8 1/2" |
| 2x4 | 8 | DF-L Stud | 2' - 3" |
| 2x4 | 2 | DF-L Stud | 3' - 3" |
| 2x4 | 1 | DF-L Stud | 3' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 3' - 9" |
| 2x4 | 6 | DF-L Stud | 4' - 0" |
| 2x4 | 1 | DF-L Stud | 4' - 0 1/2" |
| 2x4 | 3 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 6' - 0" |
| 2x4 | 2 | DF-L Stud | 7' - 0 3/8" |
| 2x4 | 50 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 8' - 2" |
| 2x4 | 1 | DF-L Stud | 9' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 10' - 0" |
| 2x4 | 2 | DF-L Stud | 10' - 3 1/2" |
| 2x4 | 1 | DF-L Stud | 11' - 9" |
| 2x4 | 2 | DF-L Stud | 21' - 8 1/2" |
| 4x6 | 2 | DF-L #1 | 3' - 3" |
| Level 4-North | | | |
| 2x4 | 4 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 1 | DF-L Stud | 1' - 8 1/2" |
| 2x4 | 8 | DF-L Stud | 2' - 3" |
| 2x4 | 2 | DF-L Stud | 3' - 3" |
| 2x4 | 1 | DF-L Stud | 3' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 3' - 9" |
| 2x4 | 6 | DF-L Stud | 4' - 0" |
| 2x4 | 1 | DF-L Stud | 4' - 0 1/2" |
| 2x4 | 3 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 6' - 0" |
| 2x4 | 2 | DF-L Stud | 7' - 0 3/8" |
| 2x4 | 50 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 8' - 2" |
| 2x4 | 1 | DF-L Stud | 9' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 10' - 0" |
| 2x4 | 2 | DF-L Stud | 10' - 3 1/2" |
| 2x4 | 1 | DF-L Stud | 11' - 9" |
| 2x4 | 2 | DF-L Stud | 21' - 8 1/2" |
| 4x6 | 2 | DF-L #1 | 3' - 3" |

# A5.3: South elevation framing



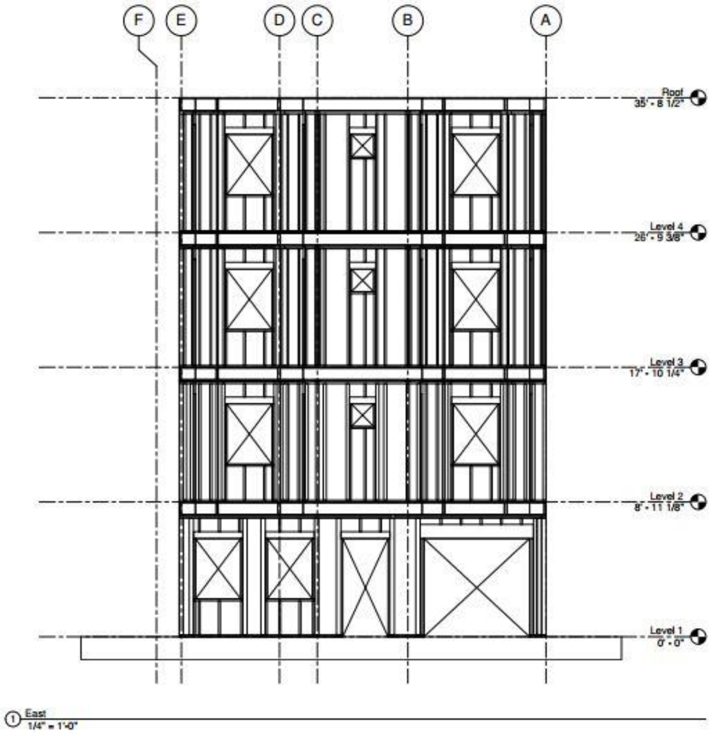

| Structural Framing South Elevation | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| Level 1-South | | | |
| 2x4 | 22 | DF-L Stud | 0' - 4 7/8" |
| 2x4 | 1 | DF-L Stud | 1' - 10 1/4" |
| 2x4 | 3 | DF-L Stud | 2' - 0" |
| 2x4 | 1 | DF-L Stud | 2' - 1 3/4" |
| 2x4 | 16 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 6 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 4 | DF-L Stud | 8' - 6 1/2" |
| 2x4 | 2 | DF-L Stud | 9' - 7 1/2" |
| 2x4 | 2 | DF-L Stud | 9' - 11" |
| 4x4 | 10 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 3 | DF-L #1 | 7' - 0 1/8" |
| 4x12 | 4 | DF-L #1 | 7' - 6" |
| Level 2-South | | | |
| 2x4 | 3 | DF-L Stud | 0' - 9 1/2" |
| 2x4 | 8 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 3 | DF-L Stud | 1' - 2 1/2" |
| 2x4 | 3 | DF-L Stud | 2' - 1" |
| 2x4 | 1 | DF-L Stud | 2' - 2 3/8" |
| 2x4 | 2 | DF-L Stud | 2' - 2 1/2" |
| 2x4 | 16 | DF-L Stud | 2' - 3" |
| 2x4 | 6 | DF-L Stud | 2' - 3 1/2" |
| 2x4 | 24 | DF-L Stud | 2' - 5" |
| 2x4 | 4 | DF-L Stud | 3' - 3" |
| 2x4 | 8 | DF-L Stud | 4' - 0" |
| 2x4 | 12 | DF-L Stud | 4' - 3 1/2" |
| 3x4 | 50 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 4 | DF-L #1 | 3' - 3" |
| Level 3-South | | | |
| 2x4 | 3 | DF-L Stud | 0' - 9 1/2" |
| 2x4 | 8 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 3 | DF-L Stud | 1' - 2 1/2" |
| 2x4 | 3 | DF-L Stud | 2' - 1" |
| 2x4 | 1 | DF-L Stud | 2' - 2 3/8" |
| 2x4 | 2 | DF-L Stud | 2' - 2 1/2" |
| 2x4 | 16 | DF-L Stud | 2' - 3" |
| 2x4 | 6 | DF-L Stud | 2' - 3 1/2" |
| 2x4 | 24 | DF-L Stud | 2' - 5" |
| 2x4 | 4 | DF-L Stud | 3' - 3" |
| 2x4 | 8 | DF-L Stud | 4' - 0" |
| 2x4 | 12 | DF-L Stud | 4' - 3 1/2" |
| 2x4 | 57 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 4 | DF-L #1 | 3' - 3" |
| Level 4-South | | | |
| 2x4 | 3 | DF-L Stud | 0' - 9 1/2" |
| 2x4 | 8 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 3 | DF-L Stud | 1' - 2 1/2" |
| 2x4 | 3 | DF-L Stud | 2' - 1" |
| 2x4 | 1 | DF-L Stud | 2' - 2 3/8" |
| 2x4 | 2 | DF-L Stud | 2' - 2 1/2" |
| 2x4 | 16 | DF-L Stud | 2' - 3" |
| 2x4 | 6 | DF-L Stud | 2' - 3 1/2" |
| 2x4 | 24 | DF-L Stud | 2' - 5" |
| 2x4 | 4 | DF-L Stud | 3' - 3" |
| 2x4 | 8 | DF-L Stud | 4' - 0" |
| 2x4 | 12 | DF-L Stud | 4' - 3 1/2" |
| 2x4 | 57 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 4 | DF-L #1 | 3' - 3" |

# A5.4: West elevation framing



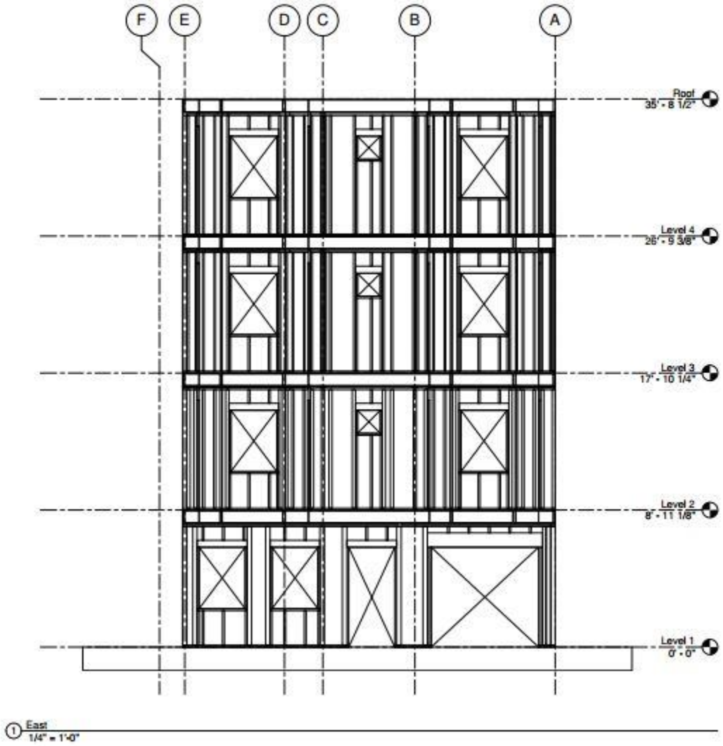

| Structural Framing West Elevation | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| Level 1-West | | | |
| 2x4 | 1 | DF-L Stud | 8' - 0" |
| 2x4 | 1 | DF-L Stud | 16' - 0" |
| 2x4 | 2 | DF-L Stud | 23' - 8 1/2" |
| 4x4 | 19 | DF-L Stud | 7' - 8 5/8" |
| Level 2-West | | | |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 8' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 0" |
| 2x4 | 2 | DF-L Stud | 24' - 0" |
| 3x4 | 20 | DF-L Stud | 7' - 8 5/8" |
| Level 3-West | | | |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 26 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 8' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 0" |
| 2x4 | 2 | DF-L Stud | 24' - 0" |
| Level 4-West | | | |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 26 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 8' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 0" |
| 2x4 | 2 | DF-L Stud | 24' - 0" |

# A5.5: East elevation framing



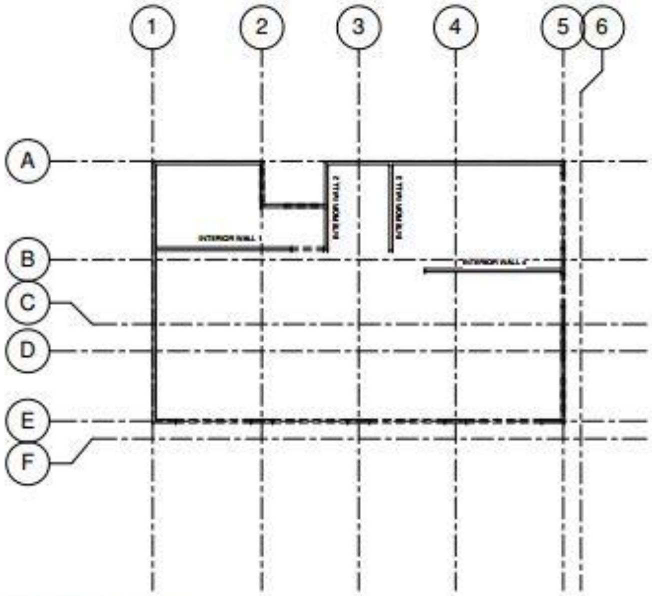

| Structural Framing East Elevation | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| Level 1-East | | | |
| 2x4 | 5 | DF-L Stud | 0' - 4 7/8" |
| 2x4 | 1 | DF-L Stud | 0' - 9 1/2" |
| 2x4 | 7 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 8 | DF-L Stud | 2' - 3" |
| 2x4 | 1 | DF-L Stud | 2' - 4 1/2" |
| 2x4 | 2 | DF-L Stud | 3' - 3" |
| 2x4 | 4 | DF-L Stud | 4' - 0" |
| 2x4 | 6 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 10' - 0" |
| 2x4 | 1 | DF-L Stud | 10' - 10" |
| 2x4 | 1 | DF-L Stud | 13' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 24' - 0" |
| 3x4 | 1 | DF-L Stud | 7' - 8 5/8" |
| 4x4 | 9 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 3 | DF-L #1 | 3' - 3" |
| 4x12 | 1 | DF-L #1 | 7' - 6" |
| Level 2-East | | | |
| 2x4 | 4 | DF-L Stud | 0' - 8" |
| 2x4 | 5 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 2 | DF-L Stud | 0' - 11 1/2" |
| 2x4 | 1 | DF-L Stud | 1' - 1" |
| 2x4 | 1 | DF-L Stud | 1' - 2 1/2" |
| 2x4 | 2 | DF-L Stud | 1' - 6" |
| 2x4 | 1 | DF-L Stud | 1' - 9" |
| 2x4 | 4 | DF-L Stud | 2' - 0" |
| 2x4 | 8 | DF-L Stud | 2' - 3" |
| 2x4 | 8 | DF-L Stud | 2' - 5" |
| 2x4 | 2 | DF-L Stud | 3' - 3" |
| 2x4 | 4 | DF-L Stud | 4' - 0" |
| 2x4 | 6 | DF-L Stud | 4' - 3 1/2" |
| 2x4 | 3 | DF-L Stud | 4' - 9" |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 8 | DF-L Stud | 7' - 0 3/8" |
| 2x4 | 1 | DF-L Stud | 7' - 7 3/8" |
| 2x4 | 1 | DF-L Stud | 8' - 3 1/2" |
| 3x4 | 28 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 1 | DF-L #1 | 1' - 9" |
| 4x6 | 2 | DF-L #1 | 3' - 3" |

# A5.6: East elevation framing



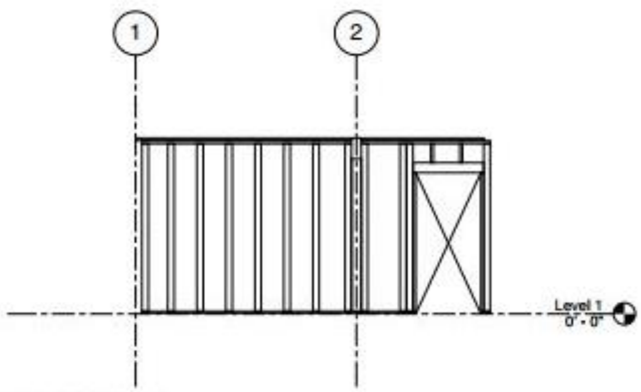

| Type | Count | Material Grade | Cut Length |
|---|---|---|---|
| **Level 3-East** | | | |
| 2x4 | 4 | DF-L Stud | 0' - 8" |
| 2x4 | 5 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 2 | DF-L Stud | 0' - 11 1/2" |
| 2x4 | 1 | DF-L Stud | 1' - 1" |
| 2x4 | 1 | DF-L Stud | 1' - 2 1/2" |
| 2x4 | 2 | DF-L Stud | 1' - 6" |
| 2x4 | 1 | DF-L Stud | 1' - 9" |
| 2x4 | 4 | DF-L Stud | 2' - 0" |
| 2x4 | 8 | DF-L Stud | 2' - 3" |
| 2x4 | 8 | DF-L Stud | 2' - 5" |
| 2x4 | 2 | DF-L Stud | 3' - 3" |
| 2x4 | 4 | DF-L Stud | 4' - 0" |
| 2x4 | 6 | DF-L Stud | 4' - 3 1/2" |
| 2x4 | 3 | DF-L Stud | 4' - 9" |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 8 | DF-L Stud | 7' - 0 3/8" |
| 2x4 | 1 | DF-L Stud | 7' - 7 3/8" |
| 2x4 | 34 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 8' - 3 1/2" |
| 4x6 | 1 | DF-L #1 | 1' - 9" |
| 4x6 | 2 | DF-L #1 | 3' - 3" |
| **Level 4-East** | | | |
| 2x4 | 4 | DF-L Stud | 0' - 8" |
| 2x4 | 5 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 2 | DF-L Stud | 0' - 11 1/2" |
| 2x4 | 1 | DF-L Stud | 1' - 1" |
| 2x4 | 1 | DF-L Stud | 1' - 2 1/2" |
| 2x4 | 2 | DF-L Stud | 1' - 6" |
| 2x4 | 1 | DF-L Stud | 1' - 9" |
| 2x4 | 4 | DF-L Stud | 2' - 0" |
| 2x4 | 8 | DF-L Stud | 2' - 3" |
| 2x4 | 8 | DF-L Stud | 2' - 5" |
| 2x4 | 2 | DF-L Stud | 3' - 3" |
| 2x4 | 4 | DF-L Stud | 4' - 0" |
| 2x4 | 6 | DF-L Stud | 4' - 3 1/2" |
| 2x4 | 3 | DF-L Stud | 4' - 9" |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 8 | DF-L Stud | 7' - 0 3/8" |
| 2x4 | 1 | DF-L Stud | 7' - 7 3/8" |
| 2x4 | 34 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 8' - 3 1/2" |
| 4x6 | 1 | DF-L #1 | 1' - 9" |
| 4x6 | 2 | DF-L #1 | 3' - 3" |

# 6.1: Level 1 interior walls framing

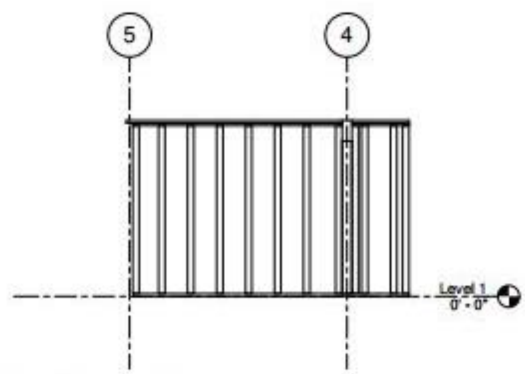



① Level 1 Interior Wall Key
1/8" = 1'-0"

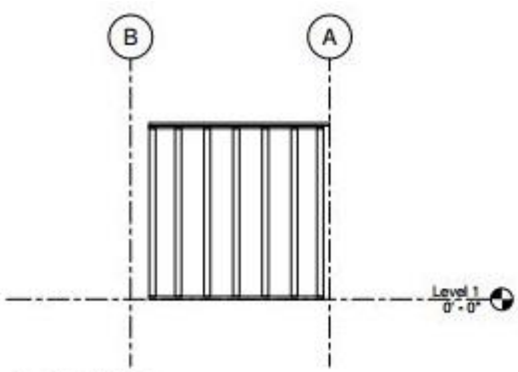
| Structural Framing Level 1 Interior Walls | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| Level 1-Interior Wall 1 | | | |
| 2x4 | 1 | DF-L Stud | 0' - 5" |
| 2x4 | 2 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 1 | DF-L Stud | 5' - 7 1/2" |
| 2x4 | 1 | DF-L Stud | 5' - 11" |
| 2x4 | 2 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 7 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 11" |
| 2x4 | 1 | DF-L Stud | 12' - 7" |
| 4x4 | 11 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 1 | DF-L #1 | 3' - 3" |
| 4x6 | 1 | DF-L #1 | 7' - 0 1/8" |
| Level 1-Interior Wall 2 | | | |
| 2x4 | 1 | DF-L Stud | 4' - 0" |
| 4x4 | 4 | DF-L Stud | 7' - 8 5/8" |
| Level 1-Interior Wall 3 | | | |
| 2x4 | 2 | DF-L Stud | 8' - 0" |
| 2x4 | 1 | DF-L Stud | 8' - 3 1/2" |
| 4x4 | 7 | DF-L Stud | 7' - 8 5/8" |
| Level 1-Interior Wall 4 | | | |
| 2x4 | 2 | DF-L Stud | 2' - 7 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 7 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 11" |
| 2x4 | 1 | DF-L Stud | 12' - 8 1/2" |
| 4x4 | 12 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 1 | DF-L #1 | 7' - 0 1/8" |



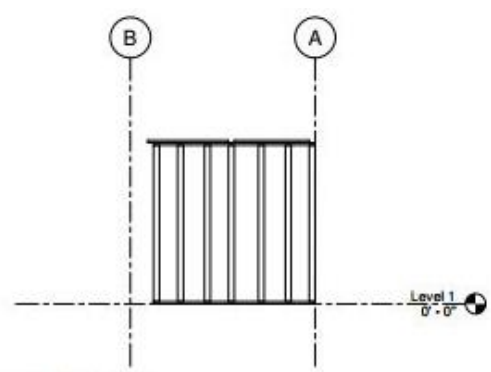

② Level 1 Interior Wall 1
1/4" = 1'-0"




⑤ Level 1 Interior Wall 4
1/4" = 1'-0"

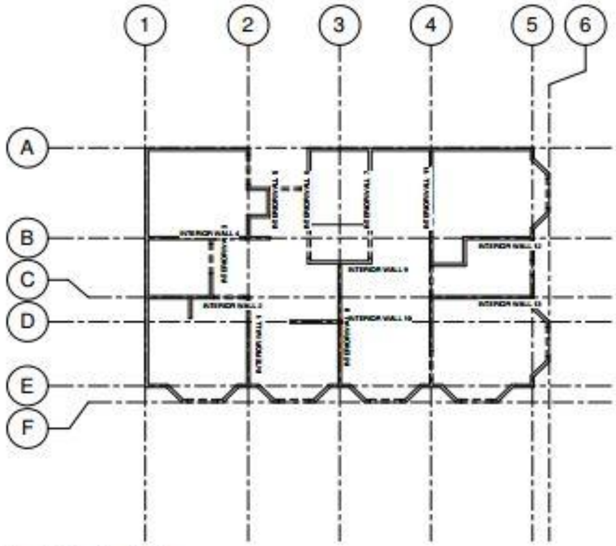



④ Level 1 Interior Wall 3
1/4" = 1'-0"

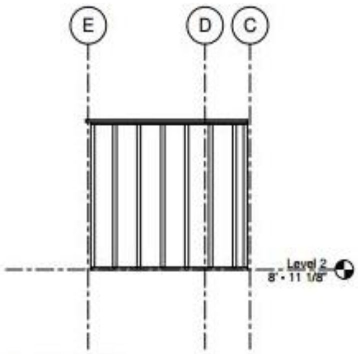



③ Level 1 Interior Wall 2
1/4" = 1'-0"

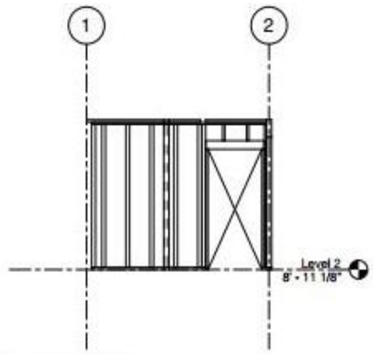
# A6.2: Level 2 interior walls framing



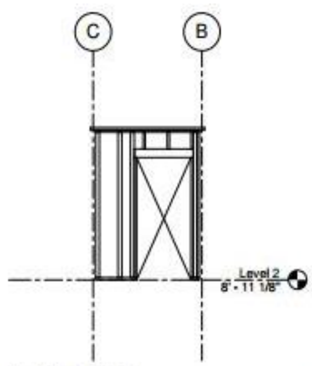

① Level 2 Floor Plan Wall Key
1/8" = 1'-0"



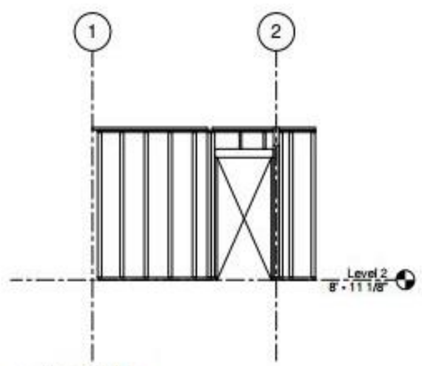

② Level 2 Interior Wall 1
1/4" = 1'-0"




③ Level 2 Interior Wall 2
1/4" = 1'-0"



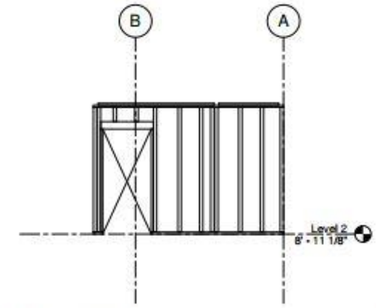

④ Level 2 Interior Wall 3
1/4" = 1'-0"



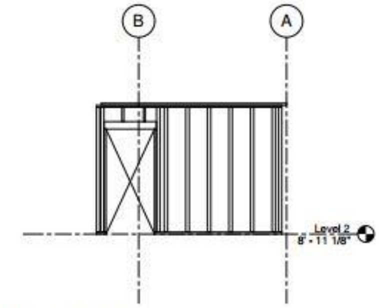

⑤ Level 2 Interior Wall 4
1/4" = 1'-0"

| Structural Framing Level 2 Interior Walls | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| Interior Wall 1 | | | |
| 2x4 | 2 | DF-L Stud | 8' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 0" |
| 3x4 | 8 | DF-L Stud | 7' - 8 5/8" |
| Interior Wall 2 | | | |
| 2x4 | 1 | DF-L Stud | 0' - 6 1/2" |
| 2x4 | 2 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 1 | DF-L Stud | 1' - 9" |
| 2x4 | 2 | DF-L Stud | 2' - 0" |
| 2x4 | 1 | DF-L Stud | 2' - 3 1/2" |
| 2x4 | 1 | DF-L Stud | 3' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 4' - 3 1/2" |
| 2x4 | 2 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 6' - 5 1/2" |
| 2x4 | 1 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 9' - 8 1/2" |
| 3x4 | 11 | DF-L Stud | 7' - 8 5/8" |
| 4x4 | 1 | DF-L #1 | 7' - 0 3/8" |
| 4x6 | 1 | DF-L #1 | 3' - 3" |
| Interior Wall 3 | | | |
| 2x4 | 1 | DF-L Stud | 0' - 5 1/2" |
| 2x4 | 3 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 1 | DF-L Stud | 2' - 3" |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 6' - 3 1/2" |
| 2x4 | 2 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 7' - 8 5/8" |
| 3x4 | 4 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 1 | DF-L #1 | 3' - 3" |
| Interior Wall 4 | | | |
| 2x4 | 2 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 2 | DF-L Stud | 2' - 0" |
| 2x4 | 1 | DF-L Stud | 2' - 5" |
| 2x4 | 1 | DF-L Stud | 3' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 6' - 4" |
| 2x4 | 2 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 6' - 7" |
| 2x4 | 1 | DF-L Stud | 9' - 8 1/2" |
| 3x4 | 10 | DF-L Stud | 7' - 8 5/8" |
| 4x4 | 1 | DF-L #1 | 7' - 0 3/8" |
| 4x6 | 1 | DF-L #1 | 3' - 3" |
| Interior Wall 5 | | | |
| 2x4 | 1 | DF-L Stud | 1' - 8 1/2" |
| 2x4 | 2 | DF-L Stud | 1' - 11 1/2" |
| 2x4 | 2 | DF-L Stud | 2' - 0" |
| 2x4 | 1 | DF-L Stud | 2' - 2 1/2" |
| 2x4 | 2 | DF-L Stud | 2' - 6" |
| 2x4 | 1 | DF-L Stud | 3' - 1" |
| 2x4 | 2 | DF-L Stud | 7' - 0 3/8" |
| 3x4 | 9 | DF-L Stud | 7' - 8 5/8" |

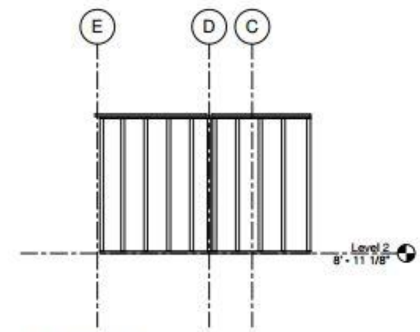
## A6.3: Level 2 interior walls framing



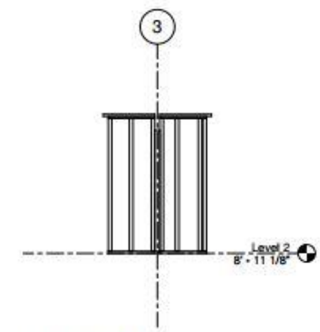

7 Level 2 Interior Wall 6
1/4" = 1'-0"



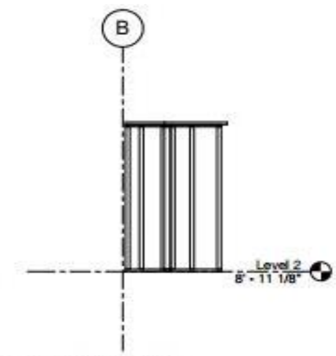

8 Level 2 Interior Wall 7
1/4" = 1'-0"




9 Level 2 Interior Wall 8
1/4" = 1'-0"



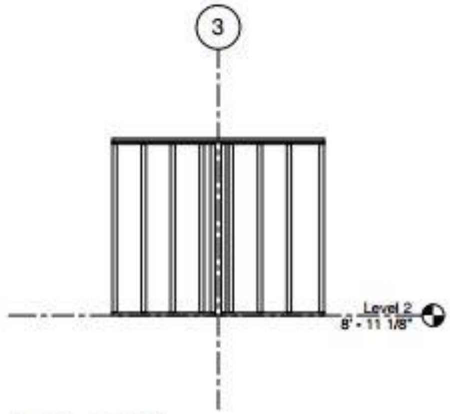

10 Level 2 Interior Wall 9
1/4" = 1'-0"



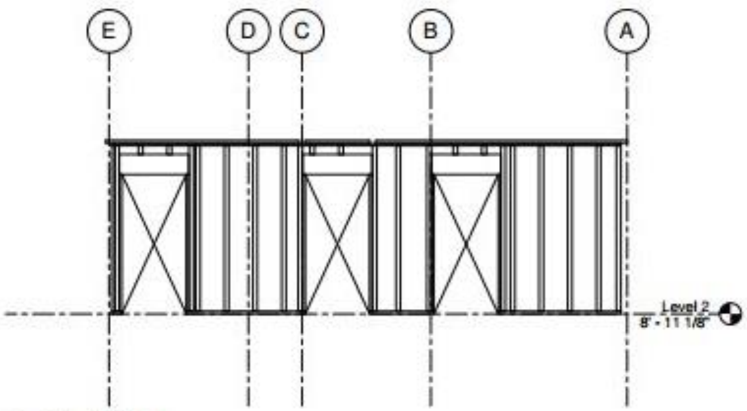

6 Level 2 Interior Wall 5
1/4" = 1'-0"

| Structural Framing Level 2 Interior Walls | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| Interior Wall 6 | | | |
| 2x4 | 1 | DF-L Stud | 0' - 7" |
| 2x4 | 2 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 7' - 2" |
| 3x4 | 2 | DF-L Stud | 0' - 10 5/8" |
| 3x4 | 6 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 1 | DF-L #1 | 3' - 3" |
| Interior Wall 7 | | | |
| 2x4 | 1 | DF-L Stud | 0' - 7" |
| 2x4 | 2 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 2 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 7' - 10 1/2" |
| 2x4 | 2 | DF-L Stud | 11' - 5 1/2" |
| 3x4 | 10 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 1 | DF-L #1 | 3' - 3" |
| Interior Wall 8 | | | |
| 2x4 | 1 | DF-L Stud | 5' - 9" |
| 2x4 | 1 | DF-L Stud | 6' - 6" |
| 2x4 | 2 | DF-L Stud | 12' - 3" |
| 3x4 | 11 | DF-L Stud | 7' - 8 5/8" |
| Interior Wall 9 | | | |
| 2x4 | 2 | DF-L Stud | 2' - 8 1/2" |
| 2x4 | 2 | DF-L Stud | 3' - 0" |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 3x4 | 7 | DF-L Stud | 7' - 8 5/8" |
| 4x4 | 1 | DF-L #1 | 7' - 0 3/8" |

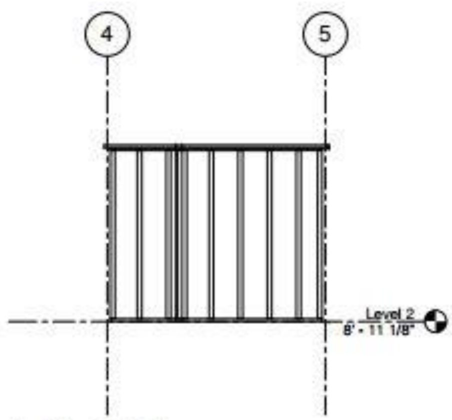
# A6.4: Level 2 interior walls framing



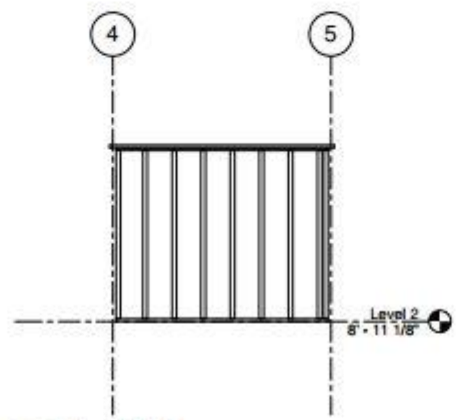

(1) Level 2 Interior Wall 10
1/4" = 1'-0"




(2) Level 2 Interior Wall 11
1/4" = 1'-0"




(3) Level 2 Interior Wall 12
1/4" = 1'-0"



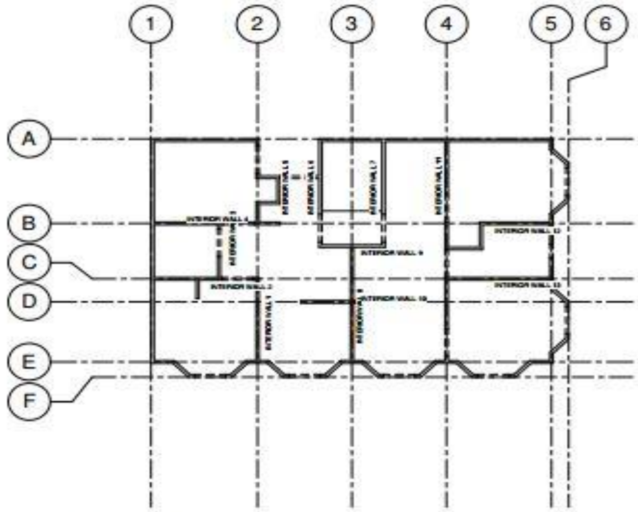

(4) Level 2 Interior Wall 13
1/4" = 1'-0"

Structural Framing Level 2 Interior Walls

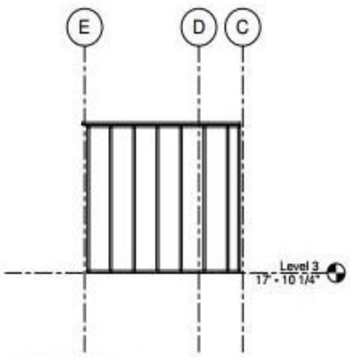
| Type | Count | Material Grade | Cut Length |
|---|---|---|---|
| Interior Wall 10 | | | |
| 2x4 | 4 | DF-L Stud | 4' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 8 1/2" |
| 3x4 | 10 | DF-L Stud | 7' - 8 5/8" |
| Interior Wall 11 | | | |
| 2x4 | 1 | DF-L Stud | 0' - 5 1/2" |
| 2x4 | 2 | DF-L Stud | 3' - 0" |
| 2x4 | 1 | DF-L Stud | 5' - 6 1/2" |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 6 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 9' - 0" |
| 2x4 | 1 | DF-L Stud | 11' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 23' - 8 1/2" |
| 3x4 | 6 | DF-L Stud | 0' - 4 7/8" |
| 3x4 | 16 | DF-L Stud | 7' - 8 5/8" |
| 4x12 | 3 | DF-L #1 | 3' - 3" |
| Interior Wall 12 | | | |
| 2x4 | 3 | DF-L Stud | 2' - 8 1/2" |
| 2x4 | 3 | DF-L Stud | 3' - 3 1/2" |
| 2x4 | 2 | DF-L Stud | 6' - 5" |
| 2x4 | 1 | DF-L Stud | 7' - 0" |
| 3x4 | 13 | DF-L Stud | 7' - 8 5/8" |
| Interior Wall 13 | | | |
| 2x4 | 2 | DF-L Stud | 9' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 10' - 3 1/2" |
| 3x4 | 9 | DF-L Stud | 7' - 8 5/8" |

# A6.5: Level 3 and 4 interior walls framing

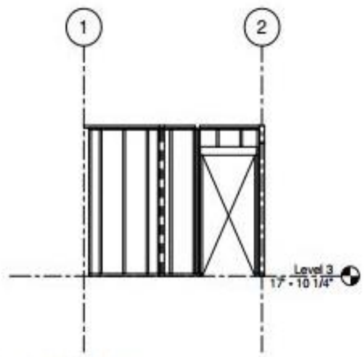
| Structural Framing Level 3 and 4 Interior Walls | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| Interior Wall 1 | | | |
| 2x4 | 8 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 2 | DF-L Stud | 8' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 9' - 0" |
| Interior Wall 2 | | | |
| 2x4 | 1 | DF-L Stud | 0' - 6 1/2" |
| 2x4 | 2 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 1 | DF-L Stud | 1' - 9" |
| 2x4 | 2 | DF-L Stud | 2' - 0" |
| 2x4 | 1 | DF-L Stud | 2' - 3 1/2" |
| 2x4 | 1 | DF-L Stud | 3' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 4' - 3 1/2" |
| 2x4 | 2 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 6' - 5 1/2" |
| 2x4 | 15 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 9' - 8 1/2" |
| 4x4 | 1 | DF-L #1 | 7' - 0 3/8" |
| 4x6 | 1 | DF-L #1 | 3' - 3" |
| Interior Wall 3 | | | |
| 2x4 | 1 | DF-L Stud | 0' - 5 1/2" |
| 2x4 | 3 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 1 | DF-L Stud | 2' - 3" |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 6' - 3 1/2" |
| 2x4 | 2 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 5 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 1 | DF-L #1 | 3' - 3" |
| Interior Wall 4 | | | |
| 2x4 | 2 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 2 | DF-L Stud | 2' - 0" |
| 2x4 | 1 | DF-L Stud | 2' - 5" |
| 2x4 | 1 | DF-L Stud | 3' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 6' - 4" |
| 2x4 | 2 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 6' - 7" |
| 2x4 | 11 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 9' - 8 1/2" |
| 4x4 | 1 | DF-L #1 | 7' - 0 3/8" |
| 4x6 | 1 | DF-L #1 | 3' - 3" |
| Interior Wall 5 | | | |
| 2x4 | 1 | DF-L Stud | 1' - 8 1/2" |
| 2x4 | 2 | DF-L Stud | 1' - 11 1/2" |
| 2x4 | 2 | DF-L Stud | 2' - 0" |
| 2x4 | 1 | DF-L Stud | 2' - 2 1/2" |
| 2x4 | 2 | DF-L Stud | 2' - 6" |
| 2x4 | 1 | DF-L Stud | 3' - 1" |
| 2x4 | 2 | DF-L Stud | 7' - 0 3/8" |
| 2x4 | 10 | DF-L Stud | 7' - 8 5/8" |



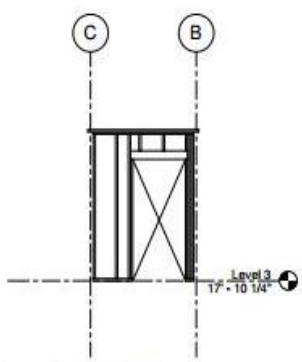

11 Level 3 and 4 Floor Plan Wall Key
1/8" = 1'-0"



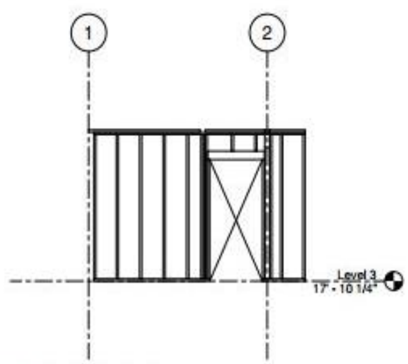

1 Level 3 or 4 Interior Wall 1
1/4" = 1'-0"



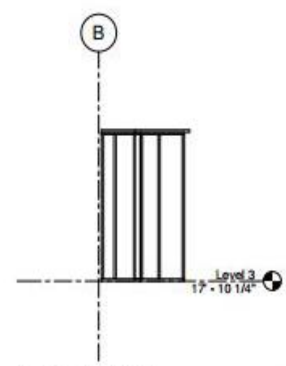

2 Level 3 or 4 Interior Wall 2
1/4" = 1'-0"




3 Level 3 or 4 Interior Wall 3
1/4" = 1'-0"



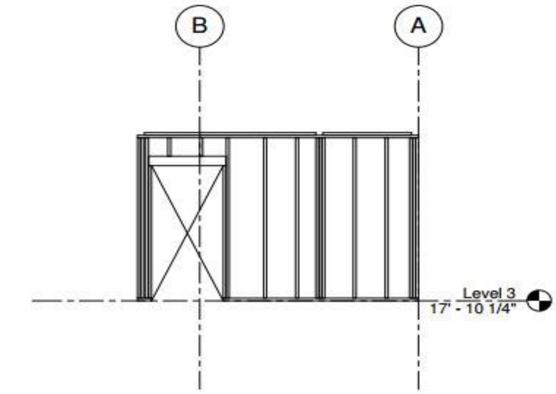

4 Level 3 or 4 Interior Wall 4
1/4" = 1'-0"



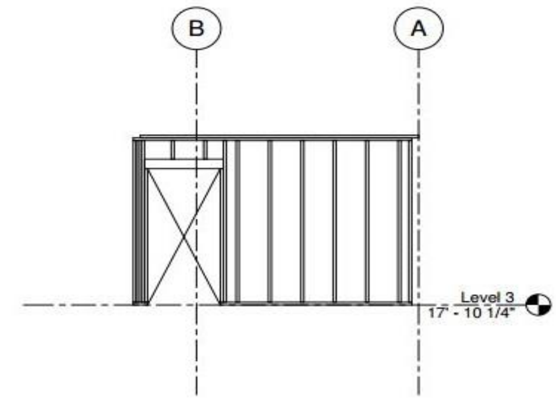

5 Level 3 or 4 Interior Wall 5
1/4" = 1'-0"

## A6.6: Level 3 and 4 interior walls framing

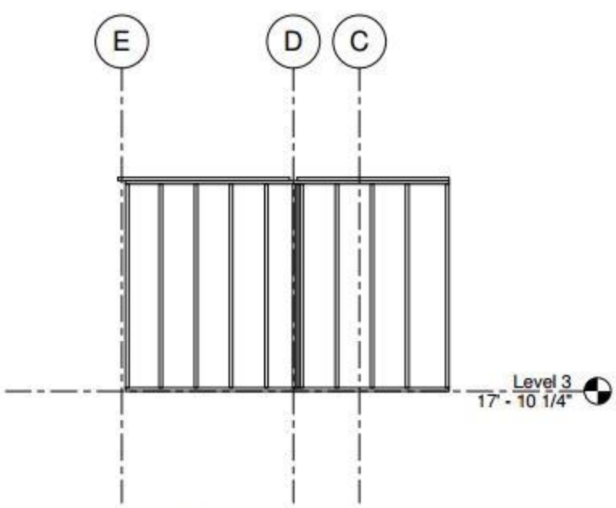
| Structural Framing Level 3 and 4 Interior Walls | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| Interior Wall 6 | | | |
| 2x4 | 1 | DF-L Stud | 0' - 7" |
| 2x4 | 2 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 2 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 1 | DF-L Stud | 7' - 2" |
| 2x4 | 6 | DF-L Stud | 7' - 8 5/8" |
| 4x6 | 1 | DF-L #1 | 3' - 3" |
| Interior Wall 7 | | | |
| 2x4 | 1 | DF-L Stud | 0' - 7" |
| 2x4 | 2 | DF-L Stud | 0' - 10 5/8" |
| 2x4 | 2 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 11 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 7' - 10 1/2" |
| 2x4 | 2 | DF-L Stud | 11' - 5 1/2" |
| 4x6 | 1 | DF-L #1 | 3' - 3" |
| Interior Wall 8 | | | |
| 2x4 | 1 | DF-L Stud | 5' - 9" |
| 2x4 | 1 | DF-L Stud | 6' - 6" |
| 2x4 | 13 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 2 | DF-L Stud | 12' - 3" |
| Interior Wall 9 | | | |
| 2x4 | 2 | DF-L Stud | 2' - 8 1/2" |
| 2x4 | 2 | DF-L Stud | 3' - 0" |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 7 | DF-L Stud | 7' - 8 5/8" |
| 4x4 | 1 | DF-L #1 | 7' - 0 3/8" |



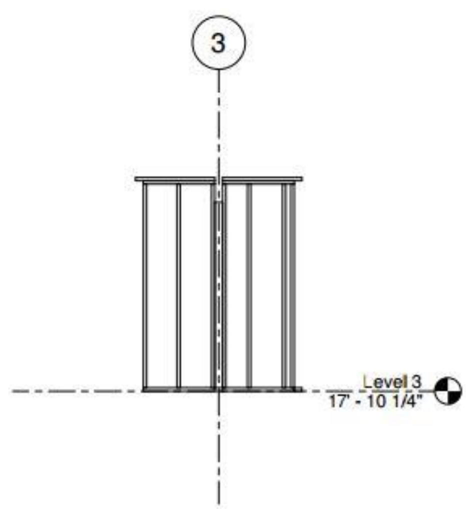

6 Level 3 or 4 Interior Wall 6
1/4" = 1'-0"




7 Level 3 or 4 Interior Wall 7
1/4" = 1'-0"

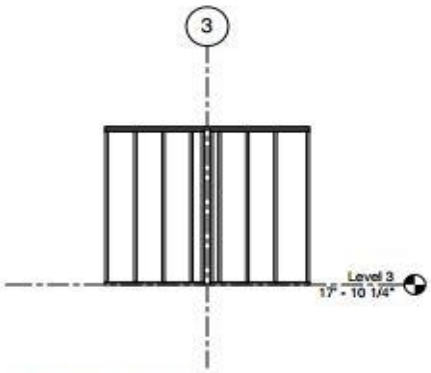



8 Level 3 or 4 Interior Wall 8
1/4" = 1'-0"



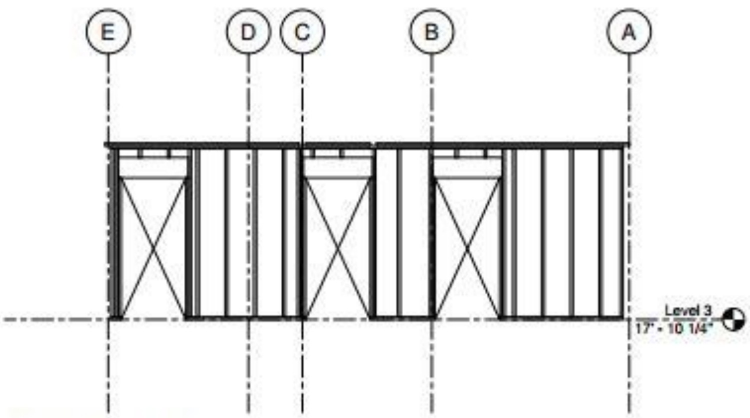

9 Level 3 or 4 Interior Wall 9
1/4" = 1'-0"

## A6.7: Level 3 and 4 interior walls framing

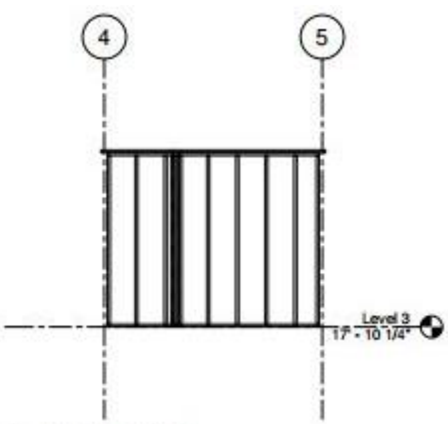



(1) Level 3 or 4 Interior Wall 10
1/4" = 1'-0"

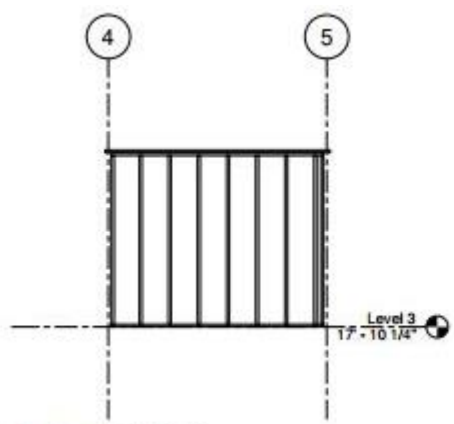
| Structural Framing Level 3 and 4 Interior Walls | | | |
|---|---|---|---|
| Type | Count | Material Grade | Cut Length |
| Interior Wall 10 | | | |
| 2x4 | 4 | DF-L Stud | 4' - 8 1/2" |
| 2x4 | 10 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 9' - 8 1/2" |
| Interior Wall 11 | | | |
| 2x4 | 6 | DF-L Stud | 0' - 4 7/8" |
| 2x4 | 1 | DF-L Stud | 0' - 5 1/2" |
| 2x4 | 2 | DF-L Stud | 3' - 0" |
| 2x4 | 1 | DF-L Stud | 5' - 6 1/2" |
| 2x4 | 1 | DF-L Stud | 5' - 8 1/2" |
| 2x4 | 6 | DF-L Stud | 6' - 4 1/2" |
| 2x4 | 18 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 1 | DF-L Stud | 9' - 0" |
| 2x4 | 1 | DF-L Stud | 11' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 23' - 8 1/2" |
| 4x12 | 3 | DF-L #1 | 3' - 3" |
| Interior Wall 12 | | | |
| 2x4 | 3 | DF-L Stud | 2' - 8 1/2" |
| 2x4 | 3 | DF-L Stud | 3' - 3 1/2" |
| 2x4 | 2 | DF-L Stud | 6' - 5" |
| 2x4 | 1 | DF-L Stud | 7' - 0" |
| 2x4 | 17 | DF-L Stud | 7' - 8 5/8" |
| Interior Wall 13 | | | |
| 2x4 | 9 | DF-L Stud | 7' - 8 5/8" |
| 2x4 | 2 | DF-L Stud | 9' - 8 1/2" |
| 2x4 | 1 | DF-L Stud | 10' - 3 1/2" |




(2) Level 3 or 4 Interior Wall 11
1/4" = 1'-0"




(3) Level 3 or 4 Interior Wall 12
1/4" = 1'-0"




(4) Level 3 or 4 Interior Wall 13
1/4" = 1'-0"

## Appendix B

Table of Contents

# B2.1: Details LCA results of retrofitted building of different LCA phases

| | | PRODUCT (A1 to A3) | | | CONSTRUCTION PROCESS (A4 & A5) | | | USE (B2, B4 & B6) | | | | END OF LIFE (C1 to C4) | | | BEYOND BUILDING LIFE (D) | | | TOTAL EFFECTS | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **LCA Measures** | **Unit** | Manufacturing | Transport | **Total** | Construction-Installation Process | Transport | **Total** | Replacement Manufacturing | Replacement Transport | Operational Energy Use Total | **Total** | De-construction, Demolition, Disposal & Waste Processing | Transport | **Total** | BBL Material | BBL Transport | **Total** | **A to C** | **A to D** |
| Global Warming Potential | kg $CO_2$ eq | 2.71E+04 | 9.90E+02 | **2.81E+04** | 2.17E+03 | 1.26E+04 | **1.48E+04** | 5.74E+03 | 1.99E+03 | 7.81E+10 | **7.81E+10** | 1.28E+03 | 5.06E+02 | **1.78E+03** | -2.45E+04 | 0.00E+00 | **-2.45E+04** | **7.81E+10** | **7.81E+10** |
| Acidification Potential | kg $SO_2$ eq | 1.62E+02 | 1.01E+01 | **1.72E+02** | 1.62E+01 | 1.44E+02 | **1.60E+02** | 4.92E+01 | 2.21E+01 | 6.30E+08 | **6.30E+08** | 1.79E+01 | 4.87E+00 | **2.27E+01** | 1.44E+00 | 0.00E+00 | **1.44E+00** | **6.30E+08** | **6.30E+08** |
| HH Particulate | kg PM2.5 eq | 9.42E+01 | 5.25E-01 | **9.47E+01** | 3.31E+00 | 6.94E+00 | **1.02E+01** | 5.48E+01 | 1.11E+00 | 4.20E+07 | **4.20E+07** | 5.88E-01 | 2.70E-01 | **8.58E-01** | 6.30E-01 | 0.00E+00 | **6.30E-01** | **4.20E+07** | **4.20E+07** |
| Eutrophication Potential | kg N eq | 2.30E+01 | 6.29E-01 | **2.36E+01** | 1.55E+00 | 8.92E+00 | **1.05E+01** | 1.43E+00 | 1.37E+00 | 6.10E+06 | **6.10E+06** | 1.10E+00 | 3.03E-01 | **1.41E+00** | 7.38E-02 | 0.00E+00 | **7.38E-02** | **6.10E+06** | **6.10E+06** |
| Ozone Depletion Potential | kg CFC-11 eq | 3.92E-04 | 3.56E-08 | **3.92E-04** | 1.73E-05 | 4.99E-07 | **1.78E-05** | 4.12E-05 | 7.85E-08 | 1.09E-01 | **1.09E-01** | 5.46E-08 | 1.77E-08 | **7.22E-08** | 0.00E+00 | 0.00E+00 | **0.00E+00** | **1.10E-01** | **1.10E-01** |
| Smog Potential | kg O3 eq | 1.99E+03 | 3.22E+02 | **2.31E+03** | 2.56E+02 | 4.61E+03 | **4.86E+03** | 4.71E+02 | 7.05E+02 | 1.64E+09 | **1.64E+09** | 5.87E+02 | 1.54E+02 | **7.40E+02** | 1.45E+01 | 0.00E+00 | **1.45E+01** | **1.64E+09** | **1.64E+09** |
| Total Primary Energy | MJ | 4.03E+05 | 1.44E+04 | **4.17E+05** | 3.40E+04 | 1.82E+05 | **2.16E+05** | 1.19E+05 | 2.89E+04 | 1.42E+12 | **1.42E+12** | 1.91E+04 | 7.38E+03 | **2.65E+04** | 2.87E+03 | 0.00E+00 | **2.87E+03** | **1.42E+12** | **1.42E+12** |
| Non-Renewable Energy | MJ | 2.94E+05 | 1.44E+04 | **3.09E+05** | 2.65E+04 | 1.82E+05 | **2.08E+05** | 1.09E+05 | 2.88E+04 | 1.34E+12 | **1.34E+12** | 1.91E+04 | 7.38E+03 | **2.64E+04** | 2.87E+03 | 0.00E+00 | **2.87E+03** | **1.34E+12** | **1.34E+12** |
| Fossil Fuel Consumption | MJ | 2.68E+05 | 1.44E+04 | **2.83E+05** | 2.53E+04 | 1.82E+05 | **2.07E+05** | 1.05E+05 | 2.88E+04 | 1.29E+12 | **1.29E+12** | 1.90E+04 | 7.37E+03 | **2.64E+04** | 5.77E+03 | 0.00E+00 | **5.77E+03** | **1.29E+12** | **1.29E+12** |

## B2.2: Details LCA results of retrofitted CLT retrofit (FEMA P-807) of different LCA phases

| | | PRODUCT (A1 to A3) | | | CONSTRUCTION PROCESS (A4 & A5) | | | USE (B2, B4 & B6) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **LCA Measures** | **Unit** | Manufacturing | Transport | **Total** | Construction-Installation Process | Transport | **Total** | Replacement Manufacturing | Replacement Transport | Operational Energy Use Total | **Total** |
| Global Warming Potential | kg $CO_2$ eq | 4.41E+02 | 6.88E-01 | **4.42E+02** | 1.25E+01 | 1.90E+02 | **2.02E+02** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Acidification Potential | kg $SO_2$ eq | 2.46E+00 | 6.97E-03 | **2.47E+00** | 1.39E-01 | 2.32E+00 | **2.46E+00** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| HH Particulate | kg PM2.5 eq | 1.56E+00 | 3.71E-04 | **1.56E+00** | 1.88E-02 | 1.02E-01 | **1.20E-01** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Eutrophication Potential | kg N eq | 1.01E-01 | 4.33E-04 | **1.02E-01** | 8.14E-03 | 1.44E-01 | **1.52E-01** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Ozone Depletion Potential | kg CFC-11 eq | 4.35E-07 | 2.50E-11 | **4.35E-07** | 4.70E-09 | 7.58E-09 | **1.23E-08** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Smog Potential | kg O3 eq | 3.76E+01 | 2.21E-01 | **3.78E+01** | 4.17E+00 | 7.47E+01 | **7.89E+01** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Total Primary Energy | MJ | 1.23E+04 | 1.00E+01 | **1.23E+04** | 2.43E+02 | 2.70E+03 | **2.95E+03** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Non-Renewable Energy | MJ | 8.26E+03 | 1.00E+01 | **8.27E+03** | 2.03E+02 | 2.70E+03 | **2.91E+03** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Fossil Fuel Consumption | MJ | 5.07E+03 | 9.99E+00 | **5.08E+03** | 1.71E+02 | 2.70E+03 | **2.87E+03** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |

| | | END OF LIFE (C1 to C4) | | | BEYOND BUILDING LIFE (D) | | | TOTAL EFFECTS | |
|---|---|---|---|---|---|---|---|---|---|
| **LCA Measures** | **Unit** | De-construction, Demolition, Disposal & Waste Processing | Transport | **Total** | BBL Material | BBL Transport | **Total** | **A to C** | **A to D** |
| Global Warming Potential | kg $CO_2$ eq | 3.87E+01 | 4.28E+00 | **4.30E+01** | -5.07E+02 | 0.00E+00 | **-5.07E+02** | **6.87E+02** | **1.80E+02** |
| Acidification Potential | kg $SO_2$ eq | 4.48E-01 | 4.12E-02 | **4.89E-01** | 5.46E-02 | 0.00E+00 | **5.46E-02** | **5.42E+00** | **5.48E+00** |
| HH Particulate | kg PM2.5 eq | 4.90E-02 | 2.28E-03 | **5.13E-02** | 2.39E-02 | 0.00E+00 | **2.39E-02** | **1.74E+00** | **1.76E+00** |
| Eutrophication Potential | kg N eq | 2.49E-02 | 2.56E-03 | **2.75E-02** | 2.80E-03 | 0.00E+00 | **2.80E-03** | **2.81E-01** | **2.84E-01** |
| Ozone Depletion Potential | kg CFC-11 eq | 1.38E-09 | 1.49E-10 | **1.53E-09** | 0.00E+00 | 0.00E+00 | **0.00E+00** | **4.48E-07** | **4.48E-07** |
| Smog Potential | kg O3 eq | 1.30E+01 | 1.30E+00 | **1.43E+01** | 5.52E-01 | 0.00E+00 | **5.52E-01** | **1.31E+02** | **1.32E+02** |
| Total Primary Energy | MJ | 6.02E+02 | 6.24E+01 | **6.65E+02** | 1.09E+02 | 0.00E+00 | **1.09E+02** | **1.59E+04** | **1.60E+04** |
| Non-Renewable Energy | MJ | 5.86E+02 | 6.24E+01 | **6.48E+02** | 1.09E+02 | 0.00E+00 | **1.09E+02** | **1.18E+04** | **1.19E+04** |
| Fossil Fuel Consumption | MJ | 5.77E+02 | 6.23E+01 | **6.39E+02** | 2.19E+02 | 0.00E+00 | **2.19E+02** | **8.58E+03** | **8.80E+03** |

## B2.3: Details LCA results of retrofitted SMF retrofit (FEMA P-807) of different LCA phases

| | | PRODUCT (A1 to A3) | | | CONSTRUCTION PROCESS (A4 & A5) | | | USE (B2, B4 & B6) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **LCA Measures** | **Unit** | Manufacturing | Transport | **Total** | Construction-Installation Process | Transport | **Total** | Replacement Manufacturing | Replacement Transport | Operational Energy Use Total | **Total** |
| Global Warming Potential | kg $CO_2$ eq | 8.84E+02 | 1.11E+01 | **8.95E+02** | 2.04E+01 | 1.87E+02 | **2.07E+02** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Acidification Potential | kg $SO_2$ eq | 4.15E+00 | 1.07E-01 | **4.25E+00** | 1.98E-01 | 2.48E+00 | **2.68E+00** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| HH Particulate | kg PM2.5 eq | 4.37E+00 | 5.91E-03 | **4.38E+00** | 6.61E-02 | 9.54E-02 | **1.62E-01** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Eutrophication Potential | kg N eq | 1.71E-01 | 6.65E-03 | **1.78E-01** | 1.32E-02 | 1.53E-01 | **1.66E-01** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Ozone Depletion Potential | kg CFC-11 eq | 7.40E-08 | 3.88E-10 | **7.44E-08** | 2.53E-09 | 7.48E-09 | **1.00E-08** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Smog Potential | kg O3 eq | 4.91E+01 | 3.38E+00 | **5.25E+01** | 5.42E+00 | 8.03E+01 | **8.57E+01** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Total Primary Energy | MJ | 1.80E+04 | 1.62E+02 | **1.81E+04** | 4.09E+02 | 2.62E+03 | **3.02E+03** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Non-Renewable Energy | MJ | 1.65E+04 | 1.62E+02 | **1.67E+04** | 3.34E+02 | 2.61E+03 | **2.95E+03** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Fossil Fuel Consumption | MJ | 9.49E+03 | 1.62E+02 | **9.65E+03** | 2.62E+02 | 2.61E+03 | **2.87E+03** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |

| END OF LIFE (C1 to C4) | | | BEYOND BUILDING LIFE (D) | | | TOTAL EFFECTS | |
|---|---|---|---|---|---|---|---|
| De-construction, Demolition, Disposal & Waste Processing | Transport | **Total** | BBL Material | BBL Transport | **Total** | **A to C** | **A to D** |
| 6.04E+01 | 1.92E+00 | **6.23E+01** | -1.74E+02 | 0.00E+00 | **-1.74E+02** | **1.17E+03** | **9.91E+02** |
| 5.76E-01 | 1.86E-02 | **5.95E-01** | 1.26E-01 | 0.00E+00 | **1.26E-01** | **7.52E+00** | **7.65E+00** |
| 1.18E-01 | 1.02E-03 | **1.19E-01** | 5.51E-02 | 0.00E+00 | **5.51E-02** | **4.66E+00** | **4.72E+00** |
| 2.76E-02 | 1.15E-03 | **2.88E-02** | 6.46E-03 | 0.00E+00 | **6.46E-03** | **3.73E-01** | **3.79E-01** |
| 1.79E-09 | 6.72E-11 | **1.86E-09** | 0.00E+00 | 0.00E+00 | **0.00E+00** | **8.63E-08** | **8.63E-08** |
| 1.41E+01 | 5.85E-01 | **1.46E+01** | 1.27E+00 | 0.00E+00 | **1.27E+00** | **1.53E+02** | **1.54E+02** |
| 9.70E+02 | 2.81E+01 | **9.98E+02** | 2.51E+02 | 0.00E+00 | **2.51E+02** | **2.22E+04** | **2.24E+04** |
| 9.26E+02 | 2.80E+01 | **9.54E+02** | 2.51E+02 | 0.00E+00 | **2.51E+02** | **2.06E+04** | **2.08E+04** |
| 9.01E+02 | 2.80E+01 | **9.29E+02** | 5.04E+02 | 0.00E+00 | **5.04E+02** | **1.34E+04** | **1.40E+04** |

## B2.4: Details LCA results of retrofitted SMF retrofit (PBRS) of different LCA phases

| | | PRODUCT (A1 to A3) | | | CONSTRUCTION PROCESS (A4 & A5) | | | USE (B2, B4 & B6) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **LCA Measures** | **Unit** | Manufacturing | Transport | **Total** | Construction-Installation Process | Transport | **Total** | Replacement Manufacturing | Replacement Transport | Operational Energy Use Total | **Total** |
| Global Warming Potential | kg $CO_2$ eq | 4.63E+03 | 1.99E+01 | **4.65E+03** | 8.71E+01 | 8.66E+02 | **9.53E+02** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Acidification Potential | kg $SO_2$ eq | 2.07E+01 | 1.92E-01 | **2.09E+01** | 7.59E-01 | 1.16E+01 | **1.24E+01** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| HH Particulate | kg PM2.5 eq | 2.21E+01 | 1.06E-02 | **2.22E+01** | 2.74E-01 | 4.38E-01 | **7.12E-01** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Eutrophication Potential | kg N eq | 6.52E-01 | 1.19E-02 | **6.64E-01** | 4.36E-02 | 7.19E-01 | **7.63E-01** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Ozone Depletion Potential | kg CFC-11 eq | 2.77E-07 | 6.95E-10 | **2.77E-07** | 6.82E-09 | 3.47E-08 | **4.15E-08** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Smog Potential | kg O3 eq | 2.28E+02 | 6.05E+00 | **2.34E+02** | 1.99E+01 | 3.78E+02 | **3.98E+02** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Total Primary Energy | MJ | 9.01E+04 | 2.90E+02 | **9.04E+04** | 1.61E+03 | 1.21E+04 | **1.37E+04** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Non-Renewable Energy | MJ | 8.75E+04 | 2.90E+02 | **8.78E+04** | 1.48E+03 | 1.21E+04 | **1.36E+04** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |
| Fossil Fuel Consumption | MJ | 4.95E+04 | 2.89E+02 | **4.98E+04** | 1.09E+03 | 1.21E+04 | **1.31E+04** | 0.00E+00 | 0.00E+00 | 0.00E+00 | **0.00E+00** |

| END OF LIFE (C1 to C4) | | | BEYOND BUILDING LIFE (D) | | | TOTAL EFFECTS | |
|---|---|---|---|---|---|---|---|
| De-construction, Demolition, Disposal & Waste Processing | Transport | **Total** | BBL Material | BBL Transport | **Total** | **A to C** | **A to D** |
| 2.97E+02 | 4.02E+00 | **3.01E+02** | -1.15E+02 | 0.00E+00 | **-1.15E+02** | **5.91E+03** | **5.79E+03** |
| 2.69E+00 | 3.89E-02 | **2.73E+00** | 6.76E-01 | 0.00E+00 | **6.76E-01** | **3.61E+01** | **3.68E+01** |
| 6.27E-01 | 2.14E-03 | **6.30E-01** | 2.96E-01 | 0.00E+00 | **2.96E-01** | **2.35E+01** | **2.38E+01** |
| 1.23E-01 | 2.42E-03 | **1.25E-01** | 3.47E-02 | 0.00E+00 | **3.47E-02** | **1.55E+00** | **1.59E+00** |
| 8.40E-09 | 1.40E-10 | **8.54E-09** | 0.00E+00 | 0.00E+00 | **0.00E+00** | **3.28E-07** | **3.28E-07** |
| 6.20E+01 | 1.23E+00 | **6.32E+01** | 6.83E+00 | 0.00E+00 | **6.83E+00** | **6.94E+02** | **7.01E+02** |
| 4.81E+03 | 5.86E+01 | **4.87E+03** | 1.35E+03 | 0.00E+00 | **1.35E+03** | **1.09E+05** | **1.10E+05** |
| 4.57E+03 | 5.86E+01 | **4.63E+03** | 1.35E+03 | 0.00E+00 | **1.35E+03** | **1.06E+05** | **1.07E+05** |
| 4.44E+03 | 5.85E+01 | **4.50E+03** | 2.71E+03 | 0.00E+00 | **2.71E+03** | **6.74E+04** | **7.02E+04** |

## Appendix C

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**C2.1: Bill of materials of unretrofitted building**

| Material | Unit | Total Quantity |
|---|---|---|
| #15 Organic Felt | 100sf | 26.5059 |
| 1/2" Regular Gypsum Board | sf | 11,969.1681 |
| 6 mil Polyethylene | sf | 1,479.3280 |
| Air Barrier | sf | 4,534.7455 |
| Blown Cellulose | sf (1") | 24,494.2325 |
| Concrete Benchmark 4000 psi | yd3 | 45.1755 |
| Double Glazed Hard Coated Argon | sf | 431.1098 |
| Expanded Polystyrene | sf (1") | 1,071.4396 |
| Galvanized Sheet | Tons (short) | 0.1687 |
| Glass Based shingles 30yr | 100sf | 19.5306 |
| Glass Fibre | lbs | 2,777.8212 |
| Glazing Panel | Tons (short) | 1.5873 |
| Joint Compound | Tons (short) | 1.2233 |
| Laminated Veneer Lumber | ft3 | 47.0815 |
| Large Dimension Softwood Lumber, kiln-dried | Mbfm large dimension | 6.6922 |
| Nails | Tons (short) | 0.4956 |
| Paper Tape | Tons (short) | 0.0140 |
| Polyiso Foam Board (unfaced) | sf (1") | 588.4401 |
| PVC Window Frame | lbs | 862.7736 |
| Rebar, Rod, Light Sections | Tons (short) | 0.8693 |
| Roofing Asphalt | lbs | 90.9091 |

| | | |
|---|---|---|
| Screws Nuts & Bolts | Tons (short) | 0.3994 |
| Small Dimension Softwood Lumber, kiln-dried | Mbfm small dimension | 14.4610 |
| Softwood Plywood | msf (3/8") | 15.5166 |
| Solvent Based Alkyd Paint | Gallons (us) | 2.8704 |
| Spruce Wood Bevel Siding | sf | 9,404.6381 |
| Water Based Latex Paint | Gallons (us) | 440.1054 |
| Welded Wire Mesh / Ladder Wire | Tons (short) | 0.0600 |

**C2.2: Bill of materials of SMF (FEMA P-807)**

| Material | Unit | Total Quantity |
|---|---|---|
| Bolts, Fasteners, Clips | Tons (short) | 0.0093 |
| Softwood Plywood | msf (3/8") | 0.6510 |
| Steel Plate | Tons (short) | 0.0172 |
| Wide Flange Sections | Tons (short) | 0.9595 |

**C2.3: Bill of materials of SMF (PBSR)**

| Material | Unit | Total Quantity |
|---|---|---|
| Bolts, Fasteners, Clips | Tons (short) | 0.0361 |
| Softwood Plywood | msf (3/8") | 1.1655 |
| Steel Plate | Tons (short) | 0.0707 |

| | | |
|---|---|---|
| Wide Flange Sections | Tons (short) | 5.2318 |

**C2.4: Bill of materials of CLT (FEMA P-807)**

| Material | Unit | Total Quantity |
|---|---|---|
| Cross Laminated Timber | ft3 | 48.8133 |
| Rebar, Rod, Light Sections | Tons (short) | 0.0099 |
| Wide Flange Sections | Tons (short) | 0.3535 |