SEISMIC RISK ASSESSMENT OF REINFORCED CONCRETE BUILDING USING FEMA P-58 METHODOLOGY

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Approval sheet of the Thesis

This is to certify that we have read this thesis entitled **"Seismic Risk Assessment of Reinforced Concrete Building Using Fema P-58 Methodology"** and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

SEISMIC RISK ASSESSMENT OF REINFORCED CONCRETE BUILDING USING FEMA P-58 METHODOLOGY

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Among natural hazards, earthquakes represent the largest potential source of damage. Observations from past earthquake events indicate that they result in significant losses, both social and financial. As those losses are function of buildings damage, a well-recognized seismic assessment of building performance can help mitigate the effects of devastating earthquakes. The prediction of a building's seismic loss is crucial to its resilience, yet the evaluation process is quite complex. FEMA P-58 is a tool in which a comprehensive procedure is formulated to assess the seismic performance of a building. This tool provides detailed building risk information, such as which components are most likely to be damaged and if applicable, how long it will take to rebuild.

This study focuses on the seismic performance evaluation of an 8-story reinforced concrete building implementing the FEMA P-58 methodology. The building is considered to have symmetrical configuration and for study purposes it is supposed to be located in Portland, USA. The frame elements are characterized by same material properties: the concrete compressive strength is approximately 34.5 MPa and the steel tensile strength is approximately 413.6 MPa. Given the FEMA P-58 facilities, specific fragility groups are first selected. Next, building performance is evaluated following the intensity-based assessment approach. Finally, expected annual losses for the building studied are derived and presented in graphical form.

My research findings indicate that any building detail influences the results of the earthquake consequence. Following the Monte Carlo approach for 500 realizations, the outcome of this study produces a summary of performance group's impact to the overall cost. The results show that the residual drift plays a significant role to the total repair cost, which for approximately 25 of the 500 realizations is judged irreparable. For earthquake intensity used, no collapse occurs, and the post-tensioned flat slabs are predicted to be the primary contributor to repair costs. The integration of FEMA P-58 methodology with structural analysis in SAP2000, give loss prediction results, which can be used to assess the post-earthquake costs of various structures.

Keywords: *FEMA P-58, RC Frame Buildings, Performance Groups, Structural Analysis, Intensity-Based Assessments, Loss Estimation.*

ABSTRAKT

VLERËSIMI I RISKUT SIZMIK TË NDËRTESËS BETONARME DUKE PËRDORUR METODOLOGJINË FEMA P-58

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Ndër rreziqet natyrore, tërmetet paraqesin burimin më të madh potencial të dëmtimit. Vëzhgimet nga ngjarjet e tërmeteve të kaluara tregojnë se ato rezultojnë në humbje të konsiderueshme, si sociale ashtu edhe financiare. Meqenëse kwto humbje janë një funksion i dëmtimit të ndërtesës, një vlerësim sizmik i njohur mirë i performancës së kwsaj ndërtese mund të ndihmojë në zbutjen e efekteve të tërmeteve shkatërruese. Parashikimi i dëmtimit sizmik të një strukture është thelbësor për rezistencën e saj, megjithatë procesi i vlerësimit është mjaft kompleks. FEMA P-58 është një mjet në të cilin është formuluar një procedurë gjithëpërfshirëse për të vlerësuar performancën sizmike të një ndërtese. Ky mjet ofron informacione të hollësishme të riskut të ndërtesës, të tilla si cilët komponentë ka më shumë mundësi të dëmtohen dhe sa kohë do të zgjasë rindërtimi i tyre.

Studimi fokusohet në vlerësimin e performancës sizmike të një ndërtese 8-katëshe beton-arme duke zbatuar metodologjinë e FEMA P-58. Ndërtesa konsiderohet të ketë konfigurim simetrik dhe për qëllime studimi supozohet të jetë e vendosur në Portland, SHBA. Elementet e ramës karakterizohen nga të njëjtat veti materiale: rezistenca në shtypje e betonit është përafërsisht 34.5 MPa dhe rezistenca në tërheqje e celikut është afersisht 413.6 MPa. Sipas lehtësirave që ofron FEMA P-58, në fillim selektohen “fragility groups” (grupim elementesh qe kanë të njëjtat karakteristika dhe nivel dëmtimi në rast tërmeti). Më pas, duke ndjekur “intensity-based assessment approach" (vlerësimi bazuar në intensitet) vlerësohet përformanca e ndërtesës. Në fund humbjet vjetore që llogariten, studiohen dhe paraqiten në formë grafike.

Gjetjet e këtij studimi tregojnë që cdo detaj i ndërtesës influencon në rezultatet që merren nga pasojat e tërmetit. Duke ndjekur "Monte Carlo approach" për 500 realizime, përfundimi i këtij studimi prodhon një përmbledhje të ndikimit që kanë grupet e performancës në koston e përgjithshme. Rezultatet tregojnë se drifti i përhershëm luan një rol të rëndësishëm në koston totale të riparimit, e cila për afro 25 nga 500 realizimet gjykohet e pariparueshme. Për intensitetin e tërmetit të përdorur, nuk ndodh donjë shembje elementi, dhe soletat e sheshta post -tension (post-tensioned flat slabs) parashikohen të jenë kontribuesi kryesor në kostot e riparimit. Integrimi i metodologjisë së FEMA P-58 me analizën strukturore në SAP2000, japin rezultate në parashikimin e humbjeve, të cilat mund të përdoren për të vlerësuar kostot e pas-tërmetit në struktura të ndryshme.

Fjalët kyçe: *FEMA P-58, Ndërtesa me Ramë Betonarme, Grupet e Performancës, Analizë Strukture, Vlerësim Bazuar në Intensitet, Vlerësimi i Humbjeve.*

Dedicated to my family

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CHAPTER 1

INTRODUCTION

1.1 General

Investigations made on post-earthquake sites, have shown that strong ground motions cause losses in a variety of areas. This means that beside the structural collapse or the loss of human's life, earthquakes produce great economic and cultural damage. The evaluation of a building's overall performance necessitates the use of new methods that account for the losses stated above. A methodology that combines ground motion hazard and structural response to make predictions of component-level damage, which are defined in terms of repair costs, repair time, casualties, and building tagging, is called the Performance-based method (FEMA P-58-1, 2018).

Seismic performance-based assessment is a process which uses performance indicators, to achieve the predefined performance objectives for a building construction. The building performance is measured in terms of repair cost, repair time, injuries, or deaths if any. Implementation of this methodology requires effort as it encompasses seismic hazard, structural analysis, and loss models. Also, a detailed model of the building that needs to be analyzed should be clearly defined. To efficiently manage the complexity of this methodology, BIM- based tools, are proposed to manage the information in a single model while reducing the time spent.

FEMA P-58 is a seismic performance assessment methodology used for individual buildings that follows the performance-based earthquake engineering philosophy (Moehle & Deierlein, 2004). Published by the Applied Technology Council (ATC), FEMA P-58 is a 10- year research work which aims to predict the structural behavior through a probabilistic approach. In this tool a comprehensive procedure is formulated to assess the seismic vulnerability of building according to three different types of definition of the seismic action:

• Intensity-based assessment

• Scenario-based assessment

• Time-based assessment (Vielma, et al., 2020).

1.2 Problem Statement

One of the main goals of the performance-based seismic design is to insure the desired overall structural performance through minimization of large seismic induced forces and displacements. Because of complexity of earthquake loads and big data information needed for modeling and analyzing a building, classic design methods are not sufficient enough. Such methods require coordination between parties involved in a building project which make the process even more difficult. For this reason, in this study will be used a combination of PACT tool and SAP2000 software for the performance evaluation of a mid-rise RC building.

As an essential part of the evaluation process, building model requires a detailed definition of every structural and non-structural member, as these should be later quantified in PACT (computational tool provided by FEMA P-58) according to FEMA P-58 methodology. Also, this methodology uses the non-linear static analysis such as pushover analysis and converts it into an IDA curve through SPO2IDA (provided in PACT) procedure. As little information regarding FEMA P-58 Seismic Performance Assessment of Buildings is provided in the literature, this study also describes the necessary concepts and steps needed to make a prediction of the seismic hazard losses and mitigate their risk following this methodology.

1.3 Objective of the study

The main objectives of this study are:

1. To evaluate the seismic vulnerability of a mid-rise structure.
2. To make use of new assessment methodologies, considering not only structural elements but also nonstructural elements.
3. To use seismic performance assessment as a new performance methodology, expressed in terms of potential casualties, repair costs and time, and environmental impacts.
4. To highlight the significance of building importance factor in the seismic assessment of buildings.
5. To develop appropriate evaluation methods ensuring that the structural response allows the preservation of damages so that the losses are minimized.

1.4 **Outline**

Chapter 1 presents an introduction to the topic and to the methodology used, states the problem, and underlines the main purpose of this study. Also, it includes a general summarize of the thesis outline.

Chapter 2 is dedicated to the general overview of FEMA P-58 methodology including the key parameters that should be taken into consideration while evaluating the seismic performance of a building. In addition, some past studies made on the field of performance-based assessment are studied and reviewed.

Chapter 3 provides information regarding the Implementation Guide of FEMA P-58 methodology. This chapter aims to explain the most important steps that enable the application of this performance-based assessment, ranging from building model to the final calculation of the seismic hazard.

Chapter 4 describes the case study used for this thesis. This step has a critical role in FEMA P-58 methodology as it provides significant indicators on the seismic performance.

Chapter 5 deals with the application of intensity-based performance assessment methodology on the previous described case studies. For this assessment, the Performance Assessment Calculation Tool (PACT) is used. Firstly, project information and building characteristics are provided. Then according to fragility specifications, performance groups are defined. Finally, an evaluation of the seismic performance is done based on residual drift fragility.

Chapter 6 highlights the results obtained from this study. The performance of the buildings is calculated in terms of repair or replacement costs, and then a comparison between them is made.

Chapter 7 includes the conclusions gained from this study. Also, it mentions some general recommendations for future application of FEMA- P-58 methodology.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Building acceptance damage criteria and prediction of actual response present concerns that need to be clarified within the earthquake engineering network. In addition, for decision-making purposes, there is a need for alternative ways to encourage cooperation between this network and other parties involved in a construction project. To address these uncertainties and fulfill the performance-based engineering requirements, FEMA developed the next-generation procedures which include a series of projects. The aim of these series is to develop a framework for performance assessment that accounts the effects of earthquake hazards on building response, as well as to create communication model for stakeholders.

Performance-based earthquake engineering (PBEE) implies design, evaluation, construction, monitoring the function and maintenance of engineered facilities whose performance under common and extreme loads responds to the diverse needs and objectives of owners-users and society (Bozorgnia & Bertero, 2004). In 2001, the Applied Technology Council (ATC) and the Federal Emergency Management Agency (FEMA) collaborated to establish Performance-Based Seismic Design Procedures for New and Existing Buildings, in response to the ever-increasing costs of disasters in every country. This project aims to reduce the impact of disasters premising that performance can be predicted and evaluated on a life-cycle rather than only considering the construction costs.

2.2 The Performance-Based Design, FEMA P-58

Originated in the 1990s, Performance-Based Seismic Design (PBSD) is a concept that uses realistic approaches to make prediction of earthquake losses such as human fatalities or economical costs. Considering a range of potential earthquakes, this method permits the design and construction of buildings by giving necessary probabilistic data for specified losses. As a result, during the early stages of a project, engineers and owners collaborate to establish the desired building performance characteristics. In the case of existing buildings, if necessary, this methodology can be used for retrofitting measures (FEMA P-58-1, 2018).

2.2.1 The Performance-Based Design Process

Basic data on the vulnerability of structural and nonstructural elements is required for the implementation of Performance-Based Design. This data information involves laboratory testing of individual components and application of statistical knowledge. The process of determining the performance capabilities of buildings subjected to various seismic hazards is known as performance assessment and it includes structural analysis, damage prediction and probable damage consequences.

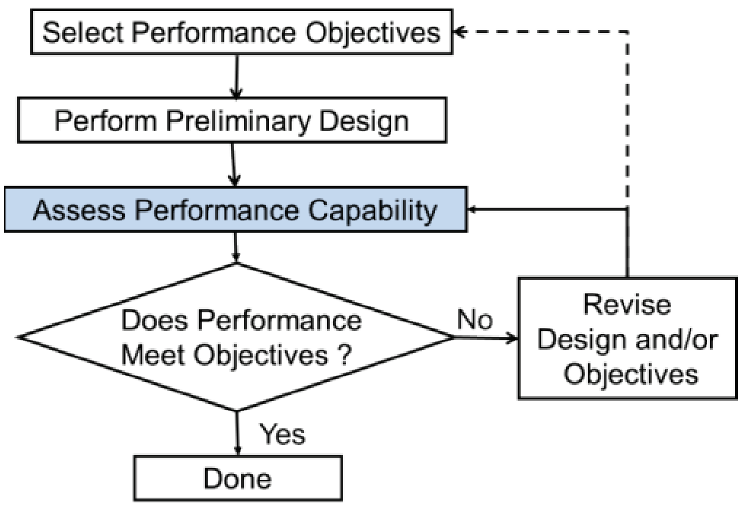


Fig 2. 1: *Flowchart of the performance based design process (FEMA P-58-1, Second Edition)*

As the flowchart in Figure 2.1 implies, the process initiates with selection of one or more performance objectives. Once performance objectives are selected, a preliminary design is developed and then its performance capability is determined. If this performance satisfies the selected performance, the design is adequate. On the other hand, the design must be revised if the assessed performance does not satisfy the desired performance objectives. These steps are iterated until the calculated performance matches the desired performance.

2.2.2 Scope

The scope of this study focuses on the seismic performance assessment methodology, which is just one part of the performance- based design process. The building performance is evaluated by the earthquake damages such as possible injuries, repair cost or time and some environmental impacts. As previously mentioned, this methodology involves data on fragility functions and population models. Some data are provided in PACT tool, but the information is not totally inclusive. Tables below explain data which are provided in this methodology, but performance assessment for other structural systems, occupancies and fragility is also possible. Table 1-1 and Table 1-2, respectively, list structural sytems and building occupancies, for which necessary information have been provided.

Table 2. 1: *Structural Systems and Components for which Fragility and Consequence Data have been Provided on FEMA P-58*

Material	System	Comments
Concrete	Beam-column frames	Conventionally reinforced, with or without modern seismic-resistant detailing
	Shear walls	Shear- or flexurally-controlled, with or without seismic-resistant detailing
	Concrete link beams	Conventionally or diagonal reinforced with modern seismic-resistant detailing
	Slab-column systems	Post-tensioned or conventionally reinforced, with or without slab shear reinforcement
Masonry	Walls	Special or ordinary reinforced masonry walls, controlled by shear or flexure
Steel	Moment frames	Fully restrained, pre- or post-Northridge, Special, Intermediate, and Ordinary detailing
	Concentrically braced frames	"X"-braced, chevron-braced, single diagonals, special, ordinary, or nonconforming detailing
Steel (cont'd)	Buckling-restrained braced frames	"X"-braced, chevron-braced and single diagonals
	Eccentrically braced frames	Flexure or shear links at mid-span of link beam
	Light-framed walls	Structural panel sheathing, steel panel sheathing or diagonal strap bracing
	Conventional floor framing	Concrete-filled metal deck, untopped steel deck, or wood sheathing
Timber	Light-framed walls	Structural panel sheathing, gypsum board sheathing, cement plaster sheathing, let-in bracing, and with or without hold downs

Occupancy	Comment
Commercial Office	None
Education (K-12)	Typical elementary, middle school, high school classrooms
Healthcare	General in-patient hospitals, medical equipment excluded
Hospitality	Hotels and motels
Multi-Unit Residential	Apartments; also applicable to single-family detached housing
Research Laboratories	Special purpose laboratory equipment excluded
Retail	Shopping malls and department stores
Warehouse	Inventory excluded

Table 2. 2: *Building Occupancies for which Nonstructural Component Data and Population Models have been Provided on FEMA P-58*

2.2.3 Limitations

FEMA P-58 work study presents a basic method to analyze the performance of specific structures based on the quantification of probable earthquake damages. One limitation of this methodology is the consideration of consequences both inside and outside the building envelope. Damages on offsite utilities such as power or water supply systems and fire initiation are beyond the scope of this study, but it is possible to develop models in order to assess these additional impacts. Other earthquake impacts are tsunamis, liquefication, landslides or ground fault rupture. Although the methodology provided may be used to examine the consequences of these effects, such an assessment is also outside the scope of the current study work.

Building performance evaluation using this methodology involves uncertainties. The reaction of building elements to earthquake loads may differ from what FEMA indicates. This kind of assessed response occurs regardless of quality of the undertaken measures. The accuracy of performance assessment depends on data calculations which are done by specialized professionals, so FEMA methodology does not provide any warranty regarding the appropriateness of any building performance. To conclude, specialized professionals that use this methodology should consider these limitations as they may have significant effects on decision making actions.

2.2.4 Methodology Volumes Description

The methodology suggested by the Federal Emergency Management Agency is arranged into a set of volumes known as FEMA P-58, Seismic Performance Assessment of Buildings, Methodology, and Implementation. Volumes contain basic explanation of methodology, implementation guidance and supporting electronic tools. A brief description of Volume 1 to Volume 4 is represented below.

Volume 1 – Methodology: FEMA P-58-1, Seismic Performance Assessment of Buildings, Second Edition, is the fundamental outcome of Phase 1 work, which was firstly released in 2012 and updated in 2018. It presents the general methodology for achieving seismic assessments, and describes the development of building information, including response elements amount and environmental impacts data.

Volume 2 – Implementation Guide: FEMA P-58-2, Seismic Performance Assessment of Buildings, also published in 2012 and updated in 2018, gives instructions for using the methodology to conduct a seismic performance assessment. It comprises detailed explanations on how to compile and prepare the essential input data (Applied Technology Council for FEMA, 2018a).

Volume 3 – Supporting Electronic Materials and Background Documentation: FEMA P-58-3, Seismic Performance Assessment of Buildings, consists of a series of electronic products assembled to assist engineers in conducting seismic performance assessments. Published in 2016, this volume incorporates PACT as well as updated fragility data (Applied Technology Council for FEMA, 2018b). Some of documents and electronic tools included are:

- Performance Assessment Calculation Tool (PACT). PACT is an electronic calculating tool and data source for fragility and consequences, enabling probabilistic loss calculations.
- Provided Fragility Data. This component contains products that can help with management and maintenance of fragility functions that are not available in PACT.

- Normative Quantity Estimation Tool which is an Excel file dedicated to nonstructural components estimates.
- Performance Estimation Tool (PET). PET is an Excel file that provides a graphical representation of building's performance results.
- Static Pushover to Incremental Dynamic Analysis (SPO2IDA). SPO2IDA is an Excel file that converts static pushover curves into probability distribution functions according to defined earthquake intensities.
- Collapse Fragility Tool. The Collapse Fragility Tool is an Excel file that produces collapse statistics using a variety of nonlinear dynamic analyses.

Volume 4 – Methodology for Assessing Environmental Impacts: FEMA P-58-4, Seismic Performance Assessment of Buildings describes a methodology to account the environmental impacts of repairing damage due to the induced seismic forces (Applied Technology Council for FEMA, 2018c).

2.3 Past Studies

Numerous studies have been carried out in the past to evaluate the characteristics of the loss assessment context. However, research in the literature is very limited since this methodology is relatively new and real- life applications are found only in the recent years. In the following are described some research studies made on the field of BIM and Seismic Performance – Based Assessment Methods.

"*Fema P58 Seismic Performance Assessment of Buildings*" by R. O. Hamburger (2014), is among the first research paper evidences which describes the result products from the first phase of FEMA P58 project. The intent of this paper is to highlight the methodology implementation to assess the seismic performance of individual buildings expressed by probable repair costs, repair time and casualties. The probable value of an earthquake loss measure is obtained from a complex "triple integral" equation: Performance= $\iiint \{PM| DS\}\{DS| EDPP\}\{EDP|I\}dz$, where:

- PM - the value of a performance measure of a particular damage state, DS;
- EDP (engineering demand parameter) - the value of a response quantity given an intensity of ground motion, I, and the integration occurs over the range of seismic hazards (Hamburger, 2014).

The figure below taken from a conference paper named *"Benchmarking FEMA P-58 performance predictions against observed earthquake data – A preliminary evaluation for the Canterbury earthquake sequence"* by (Baker, Cremen, Giovinazzi, & Seville, 2016) shows the component of FEMA P-58 which combines ground motion hazard, structural response and component damage predictions in order to make predictions of building performance under earthquake loads.

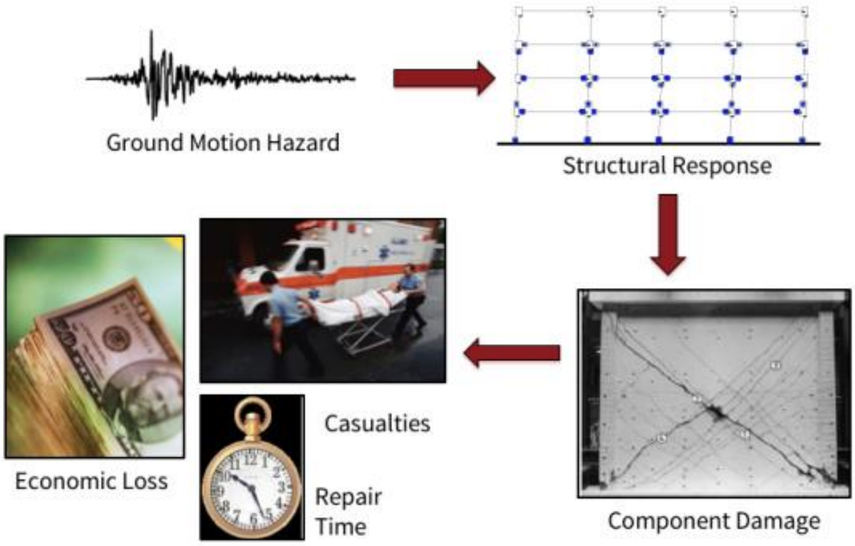


Fig 2. 2: *Components of the FEMA P-58 analysis methodology (figures courtesy Curt Haselon and Ron Hamburger)*

"*A prediction method of building seismic loss based on BIM and FEMA P-58*" by (Zhen X. et al, 2019) is a good study which produces a component-level loss prediction that accounts for a specific region and can be used to evaluate the post-earthquake economical consequences. The framework that authors proposed to predict the seismic loss based on BIM and FEMA P-58 is shown in Fig 2.3.

As we see this framework includes three steps: damage prediction, loss prediction, and result visualization. Firstly using a combination of BIM and FEMA P-58 the seismic damage prediction of each component is done according to the steps:

1. Establish the mapping relationships from BIM components to performance groups (PG) in FEMA P-58.
2. Predict PG damage using FEMA methodology.
3. Perform seismic analysis to obtain Engineering Demand Parameters (EDPs).
4. Mapp back the damages of PG to the BIM components and obtain the damage state (DS) of each component.

Secondly the loss prediction of each component is evaluated as below:

1. Create ontology-based model, to extract measurement data of the components, considering the deduction rules in the local unit-repair cost, from a BIM.
2. Calculate the unit repair cost corresponding to different DSs, based on FEMA P-58 method and finally calculate losses for the entire building.

The final step is to design the visualization to display the spatial distribution of the component damage and loss using BIM technology:

1. Estabish a unified standart for the visualization of damage and loss.
2. Obtain a visualization algorithm of these damages to meet the multiple requirements of observation.
3. Develop a virtual environment (VR) program to allow users observe the detailed information in a virtual walkthrough.

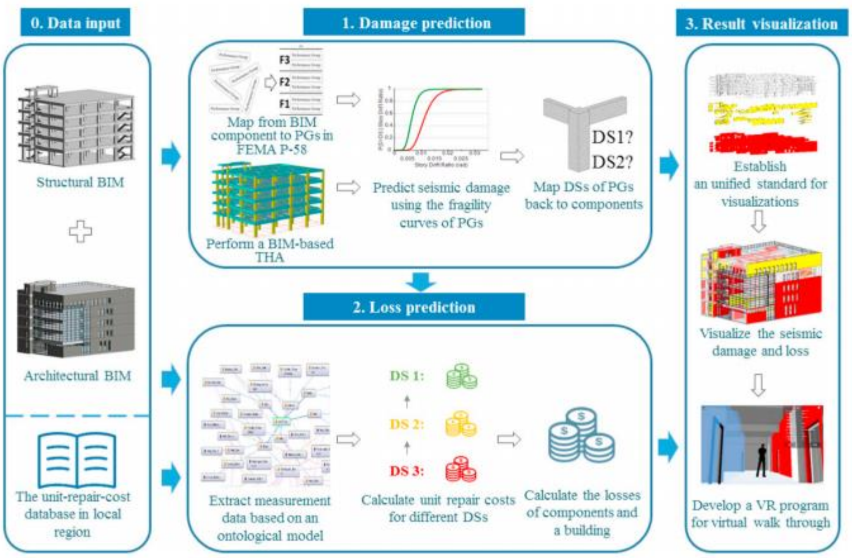


Fig 2. 3: *Framework of this study (Z. Xu, et al., 2019)*

By integrating FEMA P-58 with BIM, the proposed method could save the manual works and help users make a specific repair strategy considering the loss distributions (Zhen, et al., 2019).

Another study presented by D. Cardone (2016) evaluates the seismic performance of typical residential buildings realized in Italy before ‘70s. According to FEMA P-58 the estimation of economic losses in this study is performed in 4 steps:

1. Define the structural response at increasing levels of seismic demands.
2. Estimate the expected damage of structural and nonstrutural elements, from a probabilistic perspective.
3. Evaluate the economic losses to individual components as a function of damage level suffered by each component.
4. Summarize the individual economic losses at the building level and quantify the earthquake damages.

In this paper, specific tools for the performance seismic assessment of the evaluated buildings have been first developed. They include several fragility curves for different damage states of the main structural and non-structural components, and the associated loss functions. The proposed fragility curves and loss functions have been implemented in the Performance Assessment Calculation Tool (PACT) of FEMA P-58. In addition to this evaluation process, pushover analysis has been performed to evaluate collapse fragility curves. Next, an evaluation of the seismic response at different level of hazards is made using the nonlinear response-time history analyses. Referring to the very demanding computational effort, the development of simplified procedures relyng on FEMA P-58 is very useful (Cardone, 2016).

Verki and Aval (2020) made a study in a relatively unexplored application of FEMA P-58. Their research paper is primarily focused on the implementation of this methodology in the developing countries. The main motivation for using FEMA method came from the lack of large seismic intensity information in the developing countries, which make the identification of structural capacities difficult. This paper investigates the available tools and required data within FEMA P-58 method, aiming its application for developing countries which are located in high seismic hazard zones.

To study the seismic performance of sampled structures, the performance assessment calculation tool (PACT) is applied. The inputs in PACT are:

- General building information
- Population model
- Component fragility functions
- Hazard curves of the located zone
- Structural analysis results,

and its outputs are loss curves which show the probability of loss values. The steps followed by this paper for the performance assessment are:

1. Define the performance parameters,
2. Specify fragility curves,
3. Analyze the structure,
4. Generate a probabilistic model,
5. Sum up the loss values and relevant exceedance probabilities for all damage states (DS).

This paper concludes that by applying FEMA P-58 method, it is possible to easily obtain loss curves which lead to better communication between contractors and engineers, different from the past which leads to better decision making on the structural designing process (Verki & Aval, 2020).

In another study mady by J.C. Vielma (2020), is shown the seismic assessment of educational buildings implementing FEMA P-58 jointly with BIM modeling to manage information into a single model. The overall building evaluation process is very complex as it includes the evaluation of every structural and nonstructural element as well as the replacement cost. This evaluation becomes even more difficult counting on educational buildings due to their special contents and high occupancy. For these reasons, the authors have chosen a well-recognized seismic assessment of building performance, such as performance-based method proposed by FEMA. In the figure below it is represented a flowchart of the assessment methodology according to FEMA P-58 which follows these steps:

- Firstly, the building model and the earthquake hazards are defined.
- Based on these the seismic analysis is conducted,
- After the analysis, the fragility functions are developed.
- According to these fragility functions and analysis, the overall building performance is evaluated.

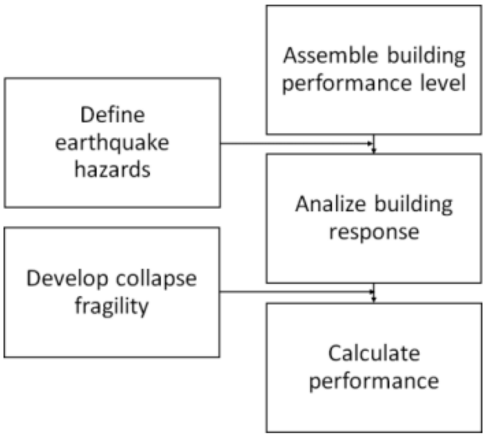


Fig 2. 4: *Flowchart of the assessment methodology according to FEMA P-58*

For this research, three buildings of the Faculty of Civil Engineering in Lisandro Alvarado University, are selected. Buildings are all RC framed structures, but they have different date of construction which means that they were designed according to different building codes. In addition, they have different purposes of use which impacts their occupancy and content. At the end of this study, it is observed that the building designed with the oldest code, has greater vulnerability to strong earthquakes. Coming to the buildings designed according to recent codes it is realized that their performance becomes more satisfactory. The building constructed in 2001 has with no deaths or injuries and the costs associated with the repair post-earthquake actions are relatively low. The main achievement of this work was to produce a reliable loss assessment, aiming to ensure that the structural response allows the preservation of damages so that the losses are minimized (Vielma, et al., 2020).

Recently, Majdi and Said (2021) published a study as a follow-up to prior research papers on the application of FEMA P-58 methodology to educational buildings. The purpose of this study is to evaluate the buildings performance when subjected to earthquake by calculating the losses for eight target intensity levels, using the simplified analysis. For the performance calculation, two research aspects are chosen: the first is direct economic losses (repair costs and time), and the second is social losses (casualties and injuries). After entering all of the relevant structural data into PACT software, the repair cost, repair time, and casualties for all intensity levels are shown graphicalally as in figures 2.5 to 2.8.

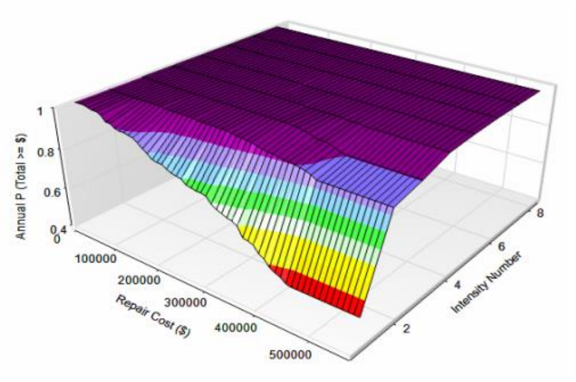


Fig 2. 5: *Repair cost curves*

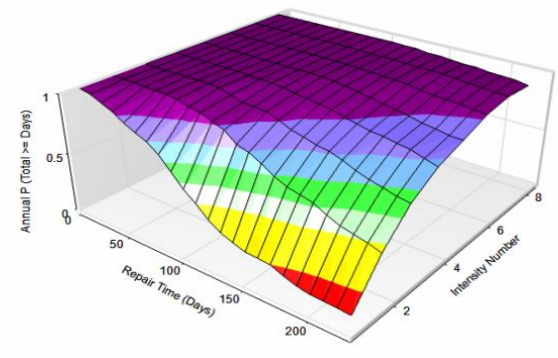


Fig 2. 6: *Repair time curves*

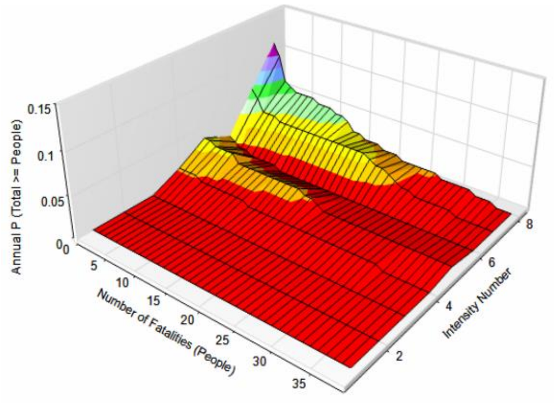


Fig 2. 7: *Fatality curves*

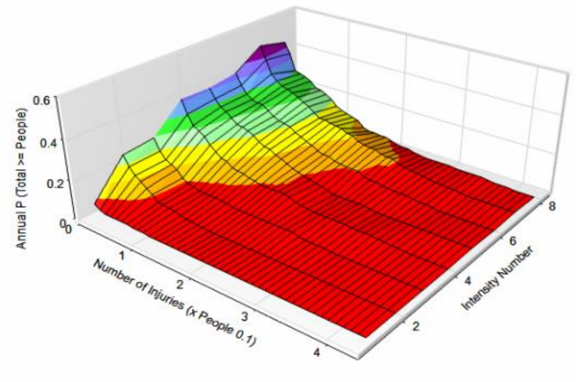


Fig 2. 8: *Injury curves*

Based on the results obtained from this study it can be concluded that every aspect of the case study building, such as its location, analysis method, plan, construction details, and so on, has an impact on the earthquake consequences (Majdi, Said, Vacareanu, & Obied, 2021).

CHAPTER 3

METHODOLOGY

3.1 General

As it was cited on the first chapter, three types of performance assessments can be developed using FEMA P-58 methodology: intensity-based, scenario-based, and time-based assessments.

3.1.1 Scenario-Based Assessments

Scenario-based assessment evaluate the probable building performance assuming that an earthquake of a specific magnitude occurring at a specific location hits the structure. This type of assessment works for buildings that are located near a known active fault. If a historic earthquake event is repeated or predicted to happen, scenario-based assessment is the most suitable evaluation of a building performance. The results of the scenario-based assessments are conditioned by the uncertainty in the intensity assingned to an earthquake scenario.

3.1.2 Time-Based Assessments

Time-based assessments examine a building's performance over a specific length of time, taking into account the probability of all earthquakes that might occur during that timespan. Consequently, it considers uncertainty regarding the magnitude and location of that future earthquake. Assessments focused on a single year are valuable for cost-benefit analyses, whereas assessments spanning longer periods of time are useful for other decision-making. The time period for this evaluation is determined by the decision- maker's objectives.

3.1.1 Intensity-Based Assessments

Intensity-based assessments evaluate a building's performance under the assumption that it would be subjected to an earthquake of a certain magnitude. A 5% damped, elastic, acceleration response spectra is used to define the earthquake intensity. This assessment type can be used to ecaluate the performance of a building given the building code response spectrum or any other response spectrum.

For this thesis study the Intensity-Based Assessments proposed by FEMA P-58 methodology is used. The steps needed for of this method following the simplified analysis on PACT are as below:

- Take the necessary site and building information (3.2)
- Choose the type of the assessment (Section 3.3)
- Compile performance components of the building (3.4)
- Select the appropriate method of building model analysis (3.5)
- Specify the target earthquake ground motion (3.6)
- Analyze the structural response to this earthquake (3.7)
- Enter response data to calculate building performance (3.8)
- Revise results (3.9).

3.2 Site and Building Information

This part of the assessment methodology is very essential, and it includes information on:

- Building location
- The soil profile of the site; shear wave velocity
- Building’s characteristics: designed code, plan/elevation dimensions, vulnerable nonstructural contents etc.

3.3 Choose Assessment Type

For the evaluation of the case study buildings' performances *Intensity-Based Assessment* will be applied. The damages will be expressed as a percentage of the repair costs to the overall replacement cost.

3.4 Compile Performance Components

The following sequence of building information model should be provided:

1. Project information (3.4.1)
2. Building characteristics (3.4.2)
3. Building model of population (3.4.2)
4. Fragility and performance groups (3.4.4)
5. Collapse data information (3.4.5)
6. Residual drift fragility (3.4.6)

3.4.1 Project Information

As shown in Figure 3.1, in the **Project Information** tab, are input basic project information regarding the credentials of project, client and engineer.

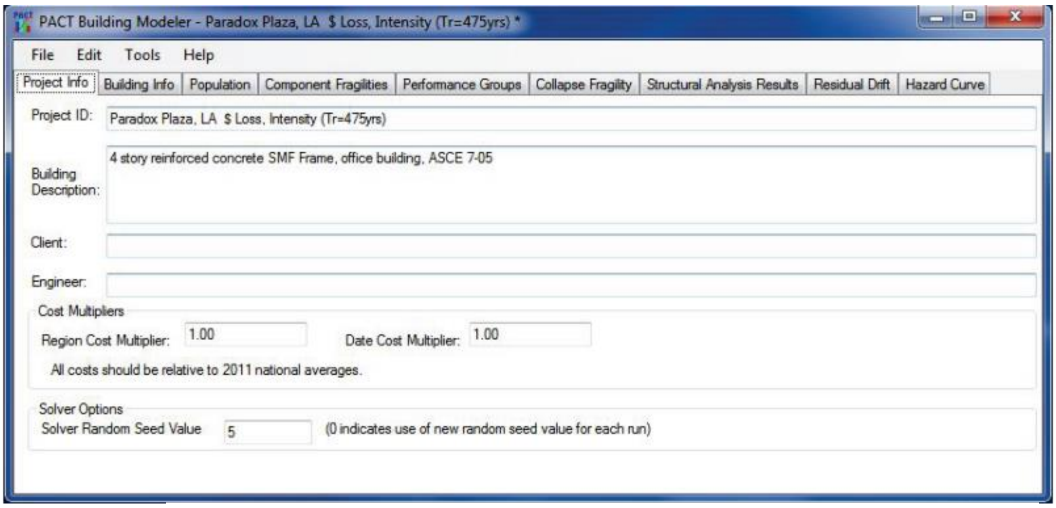


Fig 3. 1: *Example_PACT Project Info tab*

3.4.2 Building Information

The next part of the of the building performance model continues with the **Building Info tab** which includes key building information as in Fig 3.2:

- Stories number,
- Overall replacement cost,
- Replacement time period,
- Replacement cost of core and shell,
- Maximum labors per square foot,
- Total Loss Threshold
- Carbon Emissions Replacement
- Embodied Energy Replacement
- Floor Area
- Floor Height
- Height Factor, used to adjust repair cost accounting the work difficulty on the upper stories.

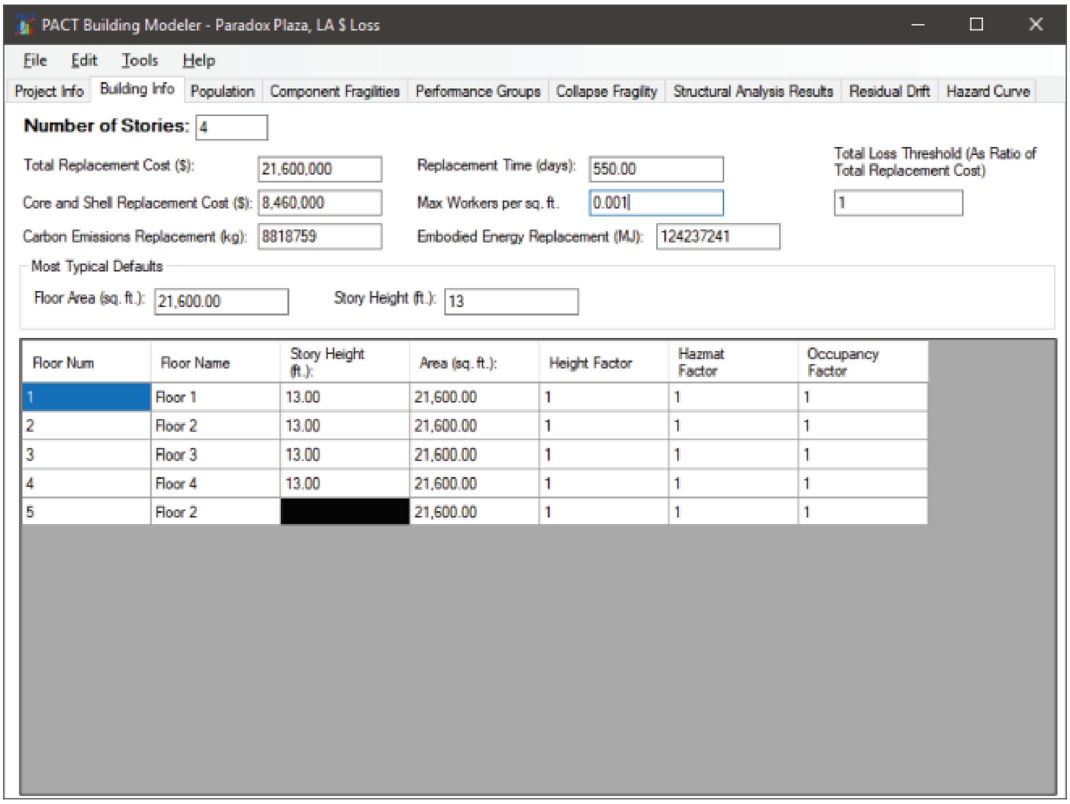


***Fig 3. 2:** Example PACT Building Information tab.*

3.4.3 Population Model

The assessment of casualties requires the definition of the population model, which means, the distribution at different time of residents throughout the building. On PACT are included population models for commercial office, education K-12 (elementary, middle, and high school), healthcare, hospitality, multi-unit residential, research, retail, and warehouse occupancies. The estimation of the repair cost does not require the input of the Population distribution.

3.4.4 Fragility specifications and performance groups

Fragility specifications for both structural and nonstructural components are provided in PACT.

3.4.4.1 Fragility specifications for structural components

Based on the previously described building characteristics, structural components are input to PACT using the Component Fragilities tab as shown in Fig 3.3. This tab lists the most typical specifications ranging from foundation to the floors. PACT includes the following structural components:

A10: Foundations: No fragility group will be selected for foundations since they will be considered non- vulnerable to earthquake damage.

A20: Basement Construction: Select the basement fragility based on the building plan.

B10: Superstructure: This tab is subdivided into fragility groups for every building element. Some of them are listed below:

B101: Floor Construction,

B102: Roof Construction,

B104: Reinforced Concrete Elements.

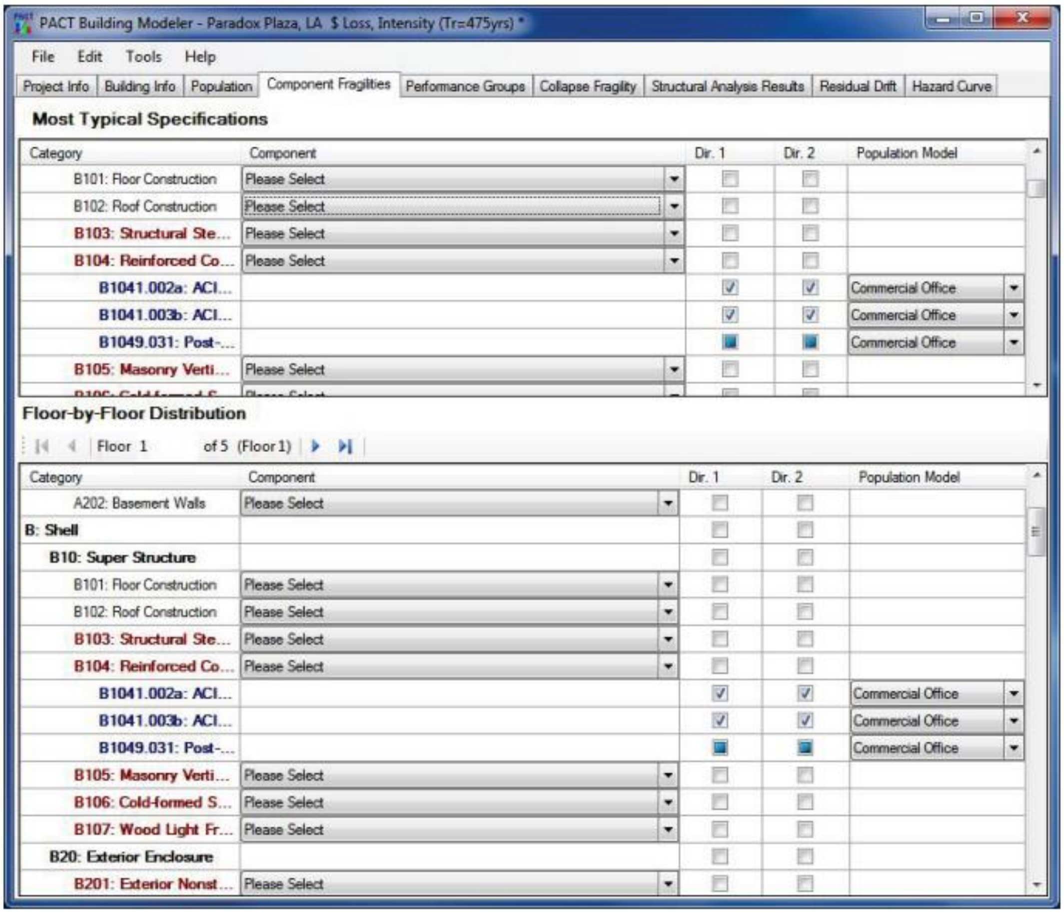


Fig 3. 3: *Example PACT input screen for beam/column joint fragility.*

3.4.4.2 Performance groups for structural components

In this step, the selected fragility groups are quantified by means of the Performance Groups tab. The previously selected structural fragility will appear on this tab, ready to be allocated over each floor level. No dispersion is identified for these components as they are exported directly from the model with precisely known quantities. The definition of the performance groups is iterated on all floors for the two direction and non-directional elements as in Fig 3.4 to Fig 3.6.

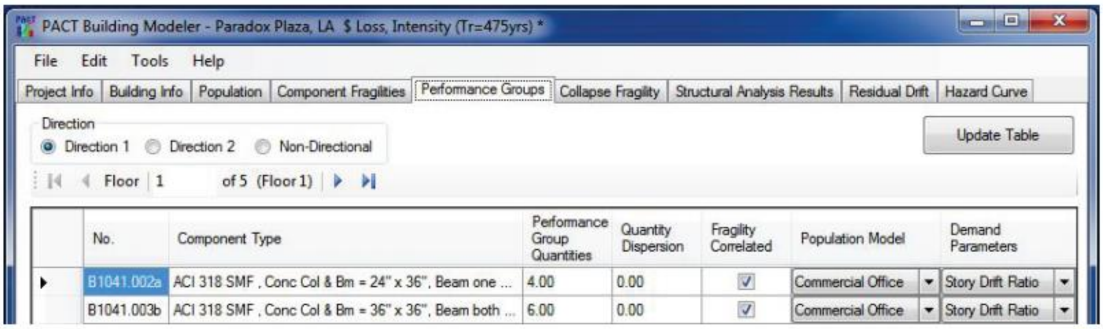


Fig 3. 5: *Example_ PACT entries for structural performance groups, direction 1.*

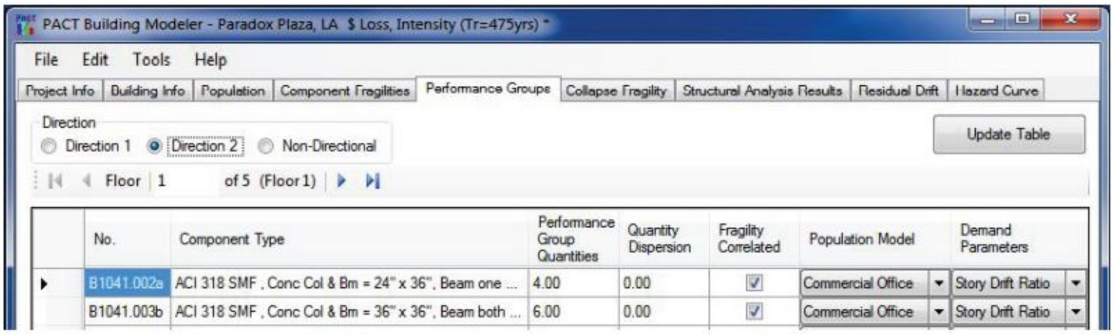


Fig 3. 6: *Example_ PACT entries for structural performance groups, direction 2.*

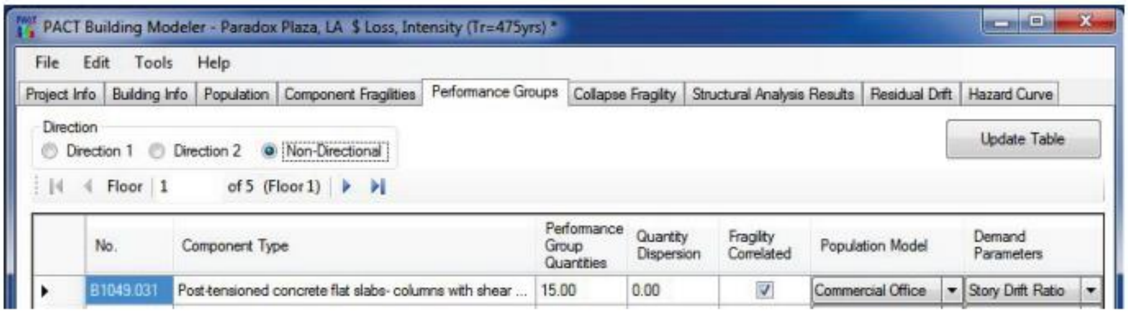
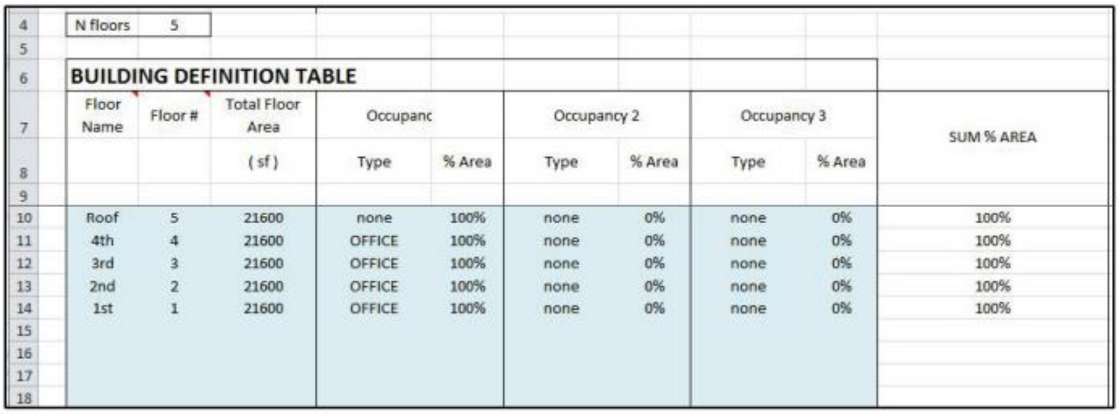


Fig 3. 4: *Example_ PACT entries for structural performance groups, non-directional.*

3.4.4.3 Fragility specifications for non-structural components

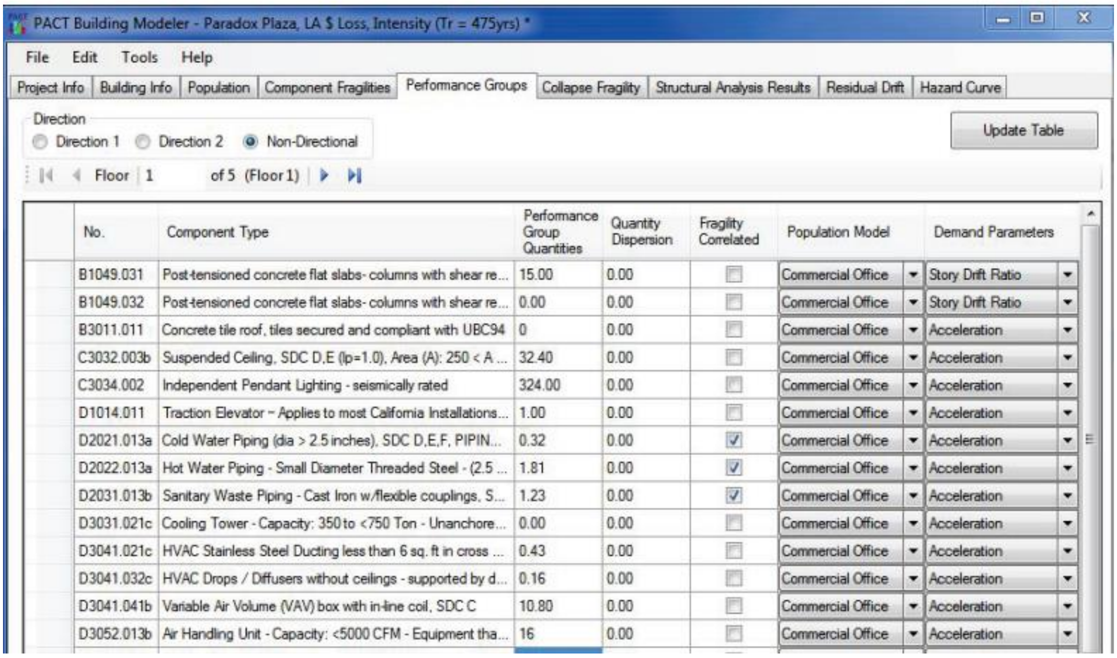
Volume 3 of FEMA P-58 contains the Normative Quantity Estimation Tool, which makes the non-structural components identification process simpler. The tool does not distinguish the damage vulnerability of quantities so users must determine it by themselves. Firstly, the building floors and occupancies are entered into the Building Definition Table in the Normative Quantity Estimation tab as in Fig 3.7.



	N floors	5								
BUILDING DEFINITION TABLE										
Floor Name	Floor #	Total Floor Area (sf)	Occupanc		Occupancy 2		Occupancy 3		SUM % AREA
			Type	% Area	Type	% Area	Type	% Area	
Roof	5	21600	none	100%	none	0%	none	0%	100%
4th	4	21600	OFFICE	100%	none	0%	none	0%	100%
3rd	3	21600	OFFICE	100%	none	0%	none	0%	100%
2nd	2	21600	OFFICE	100%	none	0%	none	0%	100%
1st	1	21600	OFFICE	100%	none	0%	none	0%	100%

Fig 3. 8: *Example_ Normative Quantity Estimation Tool, non-structural list.*

Secondly, to execute the tool to produce a list of nonstructural components Compile button is pressed. Automatically a list of the most probable nonstructural components as in Fig 3.8 is generated. A specific building inventory can be performed in order to account the desired quantities of any building components.



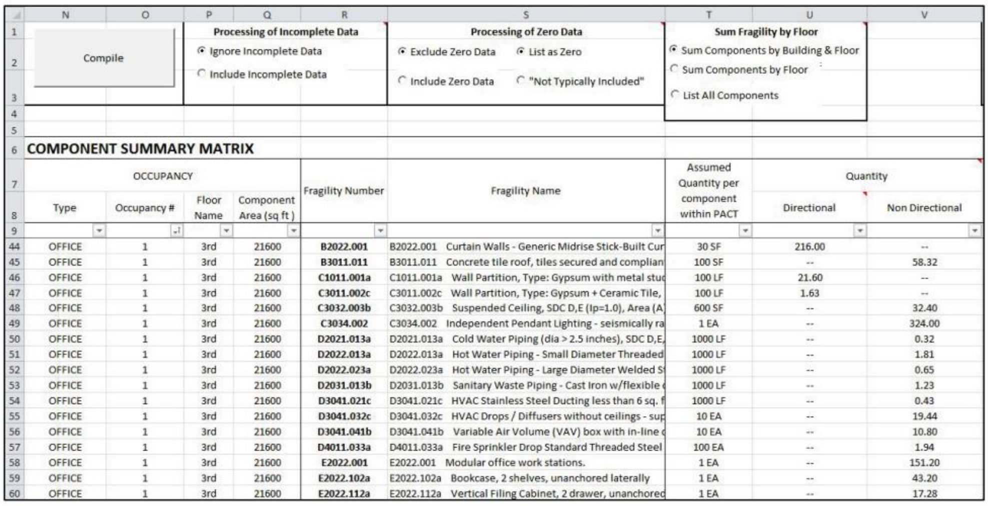
No.	Component Type	Performance Group Quantities	Quantity Dispersion	Fragility Correlated	Population Model	Demand Parameters
B1049.031	Post-tensioned concrete flat slabs- columns with shear re...	15.00	0.00	☐	Commercial Office	Story Drift Ratio
B1049.032	Post-tensioned concrete flat slabs- columns with shear re...	0.00	0.00	☐	Commercial Office	Story Drift Ratio
B3011.011	Concrete tile roof, tiles secured and compliant with UBC94	0	0.00	☐	Commercial Office	Acceleration
C3032.003b	Suspended Ceiling, SDC D,E (Ip=1.0), Area (A): 250 < A ...	32.40	0.00	☐	Commercial Office	Acceleration
C3034.002	Independent Pendant Lighting - seismically rated	324.00	0.00	☐	Commercial Office	Acceleration
D1014.011	Traction Elevator – Applies to most California Installations...	1.00	0.00	☐	Commercial Office	Acceleration
D2021.013a	Cold Water Piping (dia > 2.5 inches), SDC D,E,F, PIPIN...	0.32	0.00	☑	Commercial Office	Acceleration
D2022.013a	Hot Water Piping - Small Diameter Threaded Steel - (2.5 ...	1.81	0.00	☑	Commercial Office	Acceleration
D2031.013b	Sanitary Waste Piping - Cast Iron w/flexible couplings, S...	1.23	0.00	☑	Commercial Office	Acceleration
D3031.021c	Cooling Tower - Capacity: 350 to <750 Ton - Unanchore...	0.00	0.00	☐	Commercial Office	Acceleration
D3041.021c	HVAC Stainless Steel Ducting less than 6 sq. ft in cross ...	0.43	0.00	☐	Commercial Office	Acceleration
D3041.032c	HVAC Drops / Diffusers without ceilings - supported by d...	0.16	0.00	☐	Commercial Office	Acceleration
D3041.041b	Variable Air Volume (VAV) box with in-line coil, SDC C	10.80	0.00	☐	Commercial Office	Acceleration
D3052.013b	Air Handling Unit - Capacity: <5000 CFM - Equipment tha...	16	0.00	☐	Commercial Office	Acceleration

Fig 3. 7: *Example_ Normative Quantity Estimation Tool, non-structural list.*

This information is transferred onto the Performance Groups tabs in PACT similar as the non-structural elements.

3.4.4.4 Performance groups for non-structural components

As the input of the fragility specification data is finished, on Performance Groups tab are additionally identified the non-structural performance groups. An illustration of the example is shown in Fig 3.9.



Compile

Processing of Incomplete Data: Ignore Incomplete Data (selected); Include Incomplete Data

Processing of Zero Data: Exclude Zero Data (selected); List as Zero (selected); Include Zero Data; "Not Typically Included"

Sum Fragility by Floor: Sum Components by Building & Floor (selected); Sum Components by Floor; List All Components

COMPONENT SUMMARY MATRIX

OCCUPANCY				Fragility Number	Fragility Name	Assumed Quantity per component within PACT	Quantity	
Type	Occupancy #	Floor Name	Component Area (sq ft)				Directional	Non Directional
OFFICE	1	3rd	21600	**B2022.001**	B2022.001 Curtain Walls - Generic Midrise Stick-Built Cur	30 SF	216.00	--
OFFICE	1	3rd	21600	**B3011.011**	B3011.011 Concrete tile roof, tiles secured and complian	100 SF	--	58.32
OFFICE	1	3rd	21600	**C1011.001a**	C1011.001a Wall Partition, Type: Gypsum with metal stud	100 LF	21.60	--
OFFICE	1	3rd	21600	**C3011.002c**	C3011.002c Wall Partition, Type: Gypsum + Ceramic Tile,	100 LF	1.63	--
OFFICE	1	3rd	21600	**C3032.003b**	C3032.003b Suspended Ceiling, SDC D,E (Ip=1.0), Area (A	600 SF	--	32.40
OFFICE	1	3rd	21600	**C3034.002**	C3034.002 Independent Pendant Lighting - seismically ra	1 EA	--	324.00
OFFICE	1	3rd	21600	**D2021.013a**	D2021.013a Cold Water Piping (dia > 2.5 inches), SDC D,E,	1000 LF	--	0.32
OFFICE	1	3rd	21600	**D2022.013a**	D2022.013a Hot Water Piping - Small Diameter Threaded	1000 LF	--	1.81
OFFICE	1	3rd	21600	**D2022.023a**	D2022.023a Hot Water Piping - Large Diameter Welded S	1000 LF	--	0.65
OFFICE	1	3rd	21600	**D2031.013b**	D2031.013b Sanitary Waste Piping - Cast Iron w/flexible	1000 LF	--	1.23
OFFICE	1	3rd	21600	**D3041.021c**	D3041.021c HVAC Stainless Steel Ducting less than 6 sq. f	1000 LF	--	0.43
OFFICE	1	3rd	21600	**D3041.032c**	D3041.032c HVAC Drops / Diffusers without ceilings - sup	10 EA	--	19.44
OFFICE	1	3rd	21600	**D3041.041b**	D3041.041b Variable Air Volume (VAV) box with in-line	10 EA	--	10.80
OFFICE	1	3rd	21600	**D4011.033a**	D4011.033a Fire Sprinkler Drop Standard Threaded Steel	100 EA	--	1.94
OFFICE	1	3rd	21600	**E2022.001**	E2022.001 Modular office work stations.	1 EA	--	151.20
OFFICE	1	3rd	21600	**E2022.102a**	E2022.102a Bookcase, 2 shelves, unanchored laterally	1 EA	--	43.20
OFFICE	1	3rd	21600	**E2022.112a**	E2022.112a Vertical Filing Cabinet, 2 drawer, unanchored	1 EA	--	17.28

Fig 3. 9: *Example_ PACT Performance Groups tab, floor 1.*

3.4.5 Collapse Data Information

3.4.5.1 Collapse Fragility

One way to develop collapse fragility is to use the nonlinear static approach as summarized in Section 2.6.2, Volume 1 based on the following steps:

<u>Step 1</u>. In each building direction, construct the mathematical building model. This model will be used for nonlinear static analysis.

<u>Step 2.</u> Perform nonlinear static analysis to identify collapse parameters.

<u>Step 3.</u> Obtain pushover curve Fig 3.10 and obtain the roof drift at which the structure collapse.

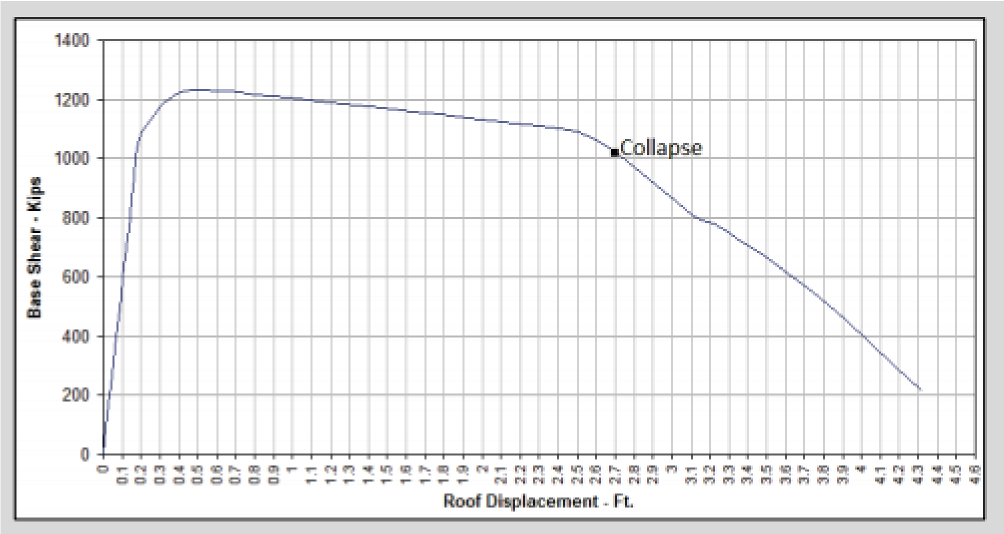


Fig 3. 10: *Example_ Pushover curve obtained by non-linear analysis.*

<u>Step 4.</u> Using the SPO2IDA Tool, convert the pushover curve into an IDA curve. For this approximation are used four control point coordinates as shown in Figure 3.11.

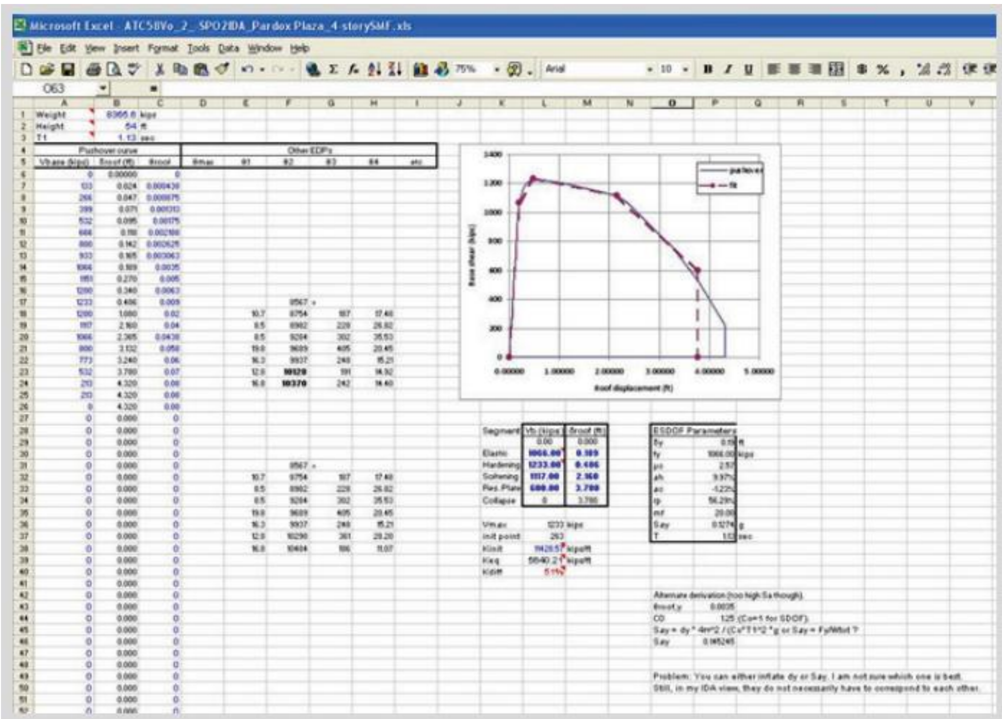


Fig 3. 11: *Example_ SPO2IDA Tool, SPO tab.*

Step 5. Evaluate the SPO2IDA results: S_a (T i) and a dispersion value Fig 3.12.

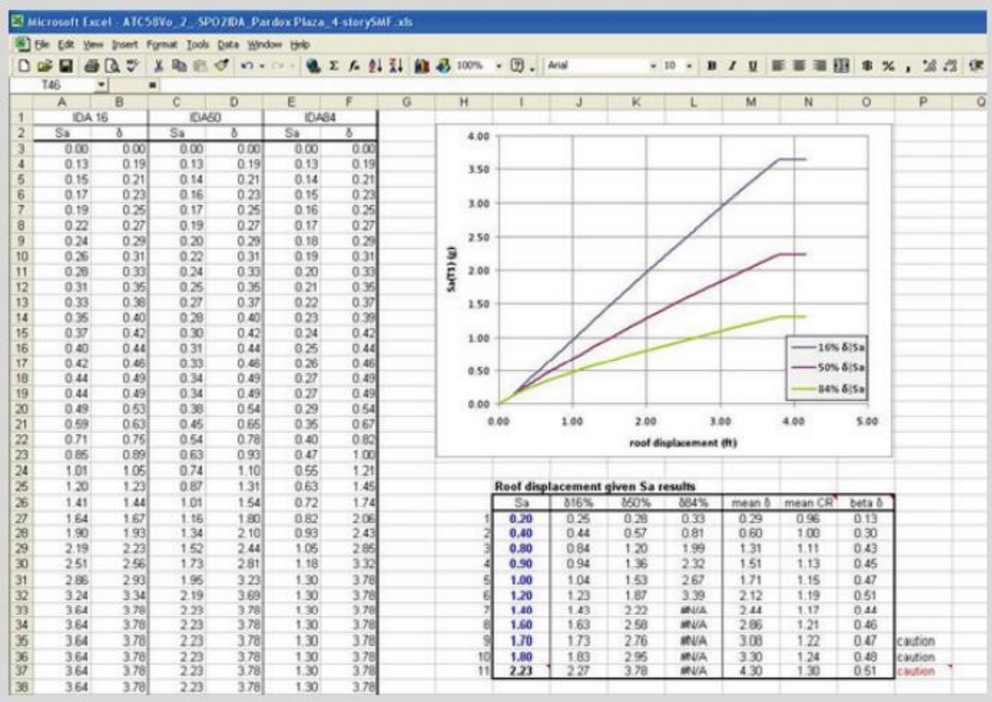


Fig 3. 12: *Example_ SPO2IDA Tool, IDA Outcomes.*

Step 6. Using the Collapse Fragility tab, input the obtained values into PACT, as illustrated in Fig 3.13.

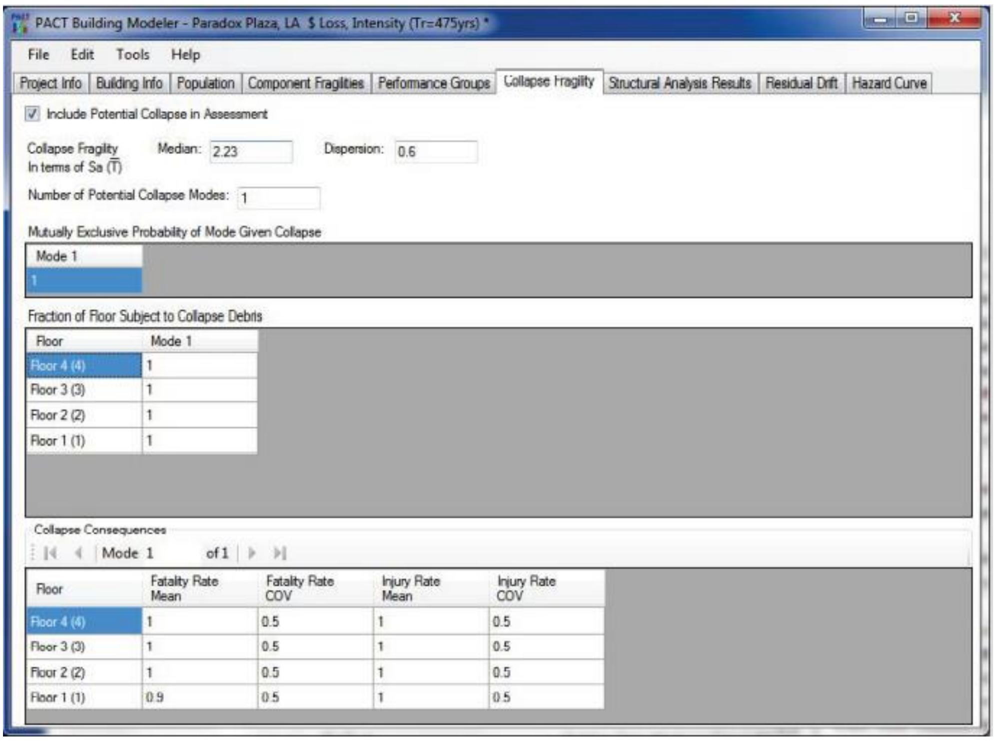


Fig 3. 13: *Example_ PACT Collapse Fragility tab.*

3.4.5.2 Collapse Modes

Analytical information on collapse modes is very limited in this simplified analytical approach. PACT includes a number of independent collapse modes, but to determine the appropriate data judgment thinking should be used. In this thesis study only one mode of collapse is considered.

3.4.6 Residual Drift Fragility

By default, PACT provides residual drift fragility function which can be adjusted to meet the desired requirements. After the analysis is completed, the building median drift ratio demand estimation is entered into the PACT.

3.5 Select the Appropriate Method of Building Model Analysis

The residual drifts, peak transient drift and accelerations median estimates are found by using simplified method. This method involves the use of linear static procedures to create a linear building model.

3.6 Define Earthquake Hazards

To estimate the previous drifts, ground motion parameters: $S_a(T_I^X)$, $S_a(T_I^Y)$, $S_a(T=0)$ should be defined. The following steps are used to obtain these parameters:

Step 1. Perform modal analysis to obtain the fundamental translational building's periods in two orthogonal directions: T_I^X and T_I^Y.

Step 2. Calculate the average period.

Step 3. Obtain the hazard curve of a target earthquake. The basic information needed for generation of the seismic hazard curve are:

- the site location coordinates,
- the average period,
- the class of site soil according to ASCE/SEI.

The Java Ground Motion Calculator offers spectral acceleration curves for different building periods. Figure 3.14 illustrates the inputs and outputs of this tool for an example seismic hazard.

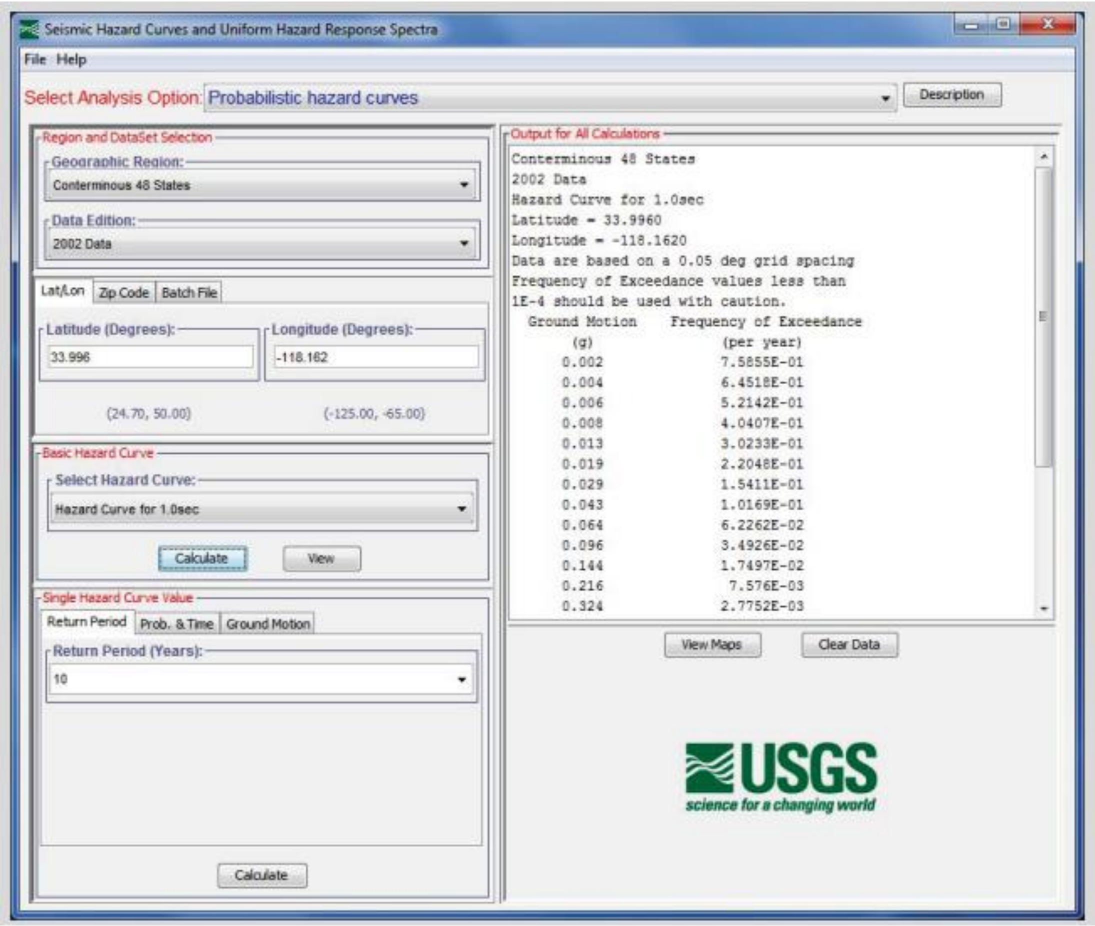


***Fig 3. 14:** Example_ Hazard data on USGS*

3.7 Analyze Building Response

At end of the analysis part of the building response, the following data are obtained:

- Median Story Drift Ratio and Dispersion
- Median Peak Floor Acceleration and Dispersion
- Median Residual Story Drift Ratio and Dispersion

3.8 Input Response Data and Calculate Performance

The procedures used to calculate building performance include generation of simulated demands and computation of types of losses. This technique would ideally require doing a large number of structural assessments to measure uncertainty and examine variability in building performance, which would be challenging to put into practice. A Monte Carlo approach is therefore used to assess a range of possible results given a limited set of inputs. A limited set of studies are utilized to obtain statistical distribution of demands from a series of building response states for a given motion intensity. Statistically consistent demand sets covering many possible building response states are derived from this distribution. Building damage states are determined using these demand sets and fragility functions. Each performance outcome, in terms of a building damage state given one simulated demand set, is called a realization. The performance calculation procedure used to estimate damage in each realization is depicted in the flowchart in Fig 3.15.

Now, proceeding the performance calculations, in the Structural Analysis Results tab on PACT, the residual drifts, peak transient drift and accelerations median estimates input for both directions. To finish the evaluation process, return to the PACT Control Panel and then press the Evaluate Performance button. In this way the tool will run the building model.

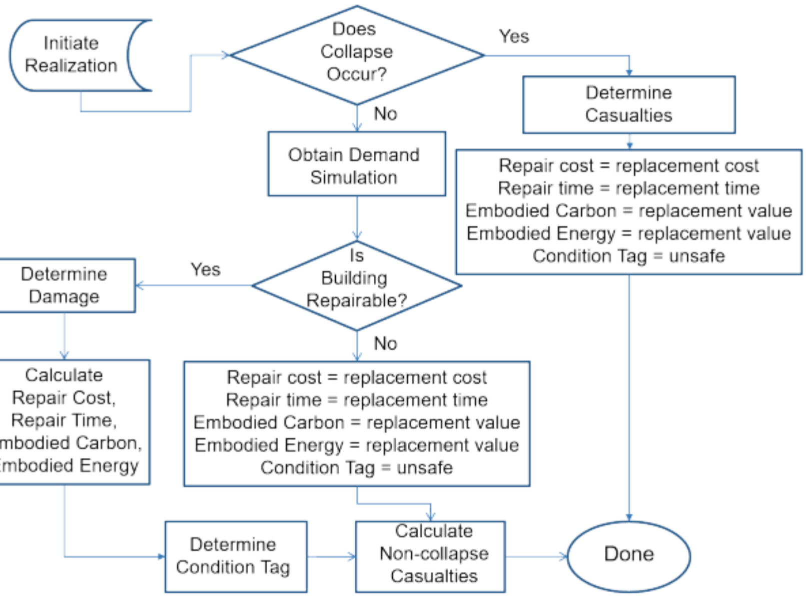


Fig 3. 15: *Performance calculation in each realization (FEMA P-58_Volume1)*

3.9 Review Results

The performance results obtained from PACT can be analyzed in a variety of ways. If it is found that a component has a considerable impact on assessment performance, its replacement with a different configuration may result in a lower overall report cost.

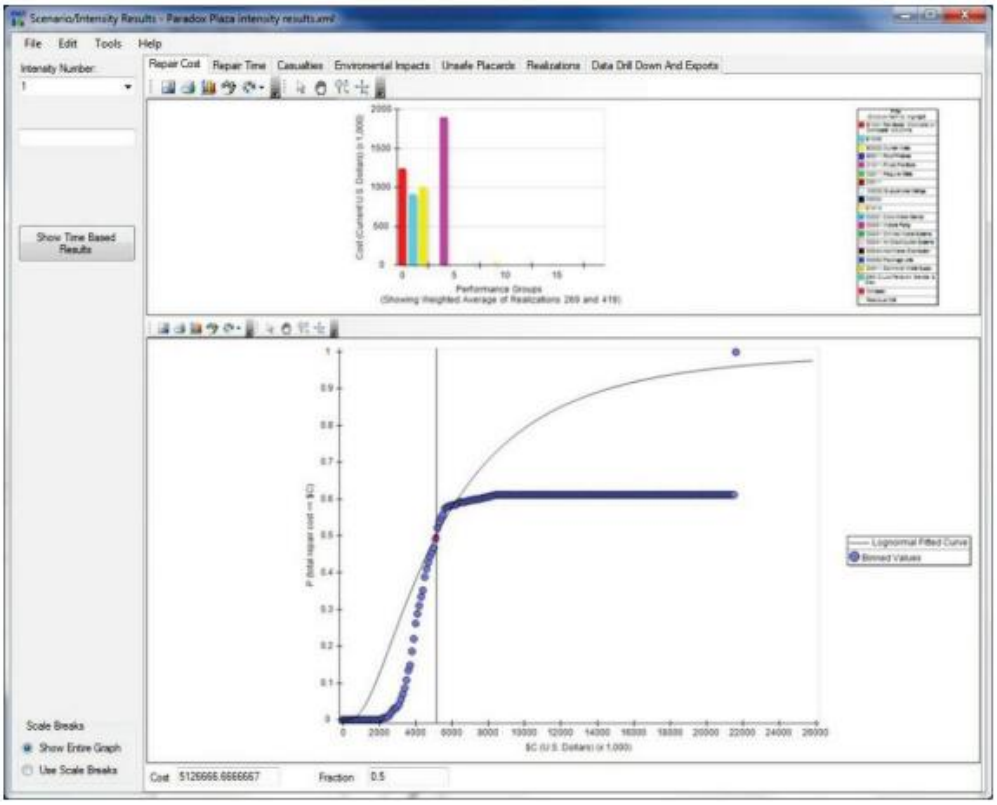


Fig 3. 16: *Example_ PACT Repair Cost tab.*

CHAPTER 4

CASE STUDY DESCRIPTION

4.1 General

This chapter is dedicated to description of the building that will be used for the implementation of FEMA P-58 software package. Informations regarding both structural and non-structural elements as well as the population model data, are explained in detail. For study purposes my case study is a hypothetical structure, as program provided by FEMA(PACT), limits the evaluation to some certain frame sections and materials. For this reason, firsty this structure is analysed and designed as for the requirements and than the seismic evaluation is performed. The program used in this stage is SAP2000 and detailed information about the procedure will be given in the following chapter.

4.2 Description of the Building

The building that will be studied is an eight-story residential building located in Portland, USA. The soil profile according to the ASCE/SEI 7-10 standart is B having a shear wave velocity of 1150 m/s. Structural plan dimensions are 18.7 meters by 13.0 meters. This structure has a regular elevation with floor-to-floor overall height of 3.4 meters. Each story has reinforced concrete special moment frames around the plan, five in x-direction and three in z-direction. For study purposes the plan configuration is symmetrical in both directions with an area of 243.1 m^2 or 2616.7 ft^2.

The figure below represents the typical plan view of the building which is the same for each floor along the building height.

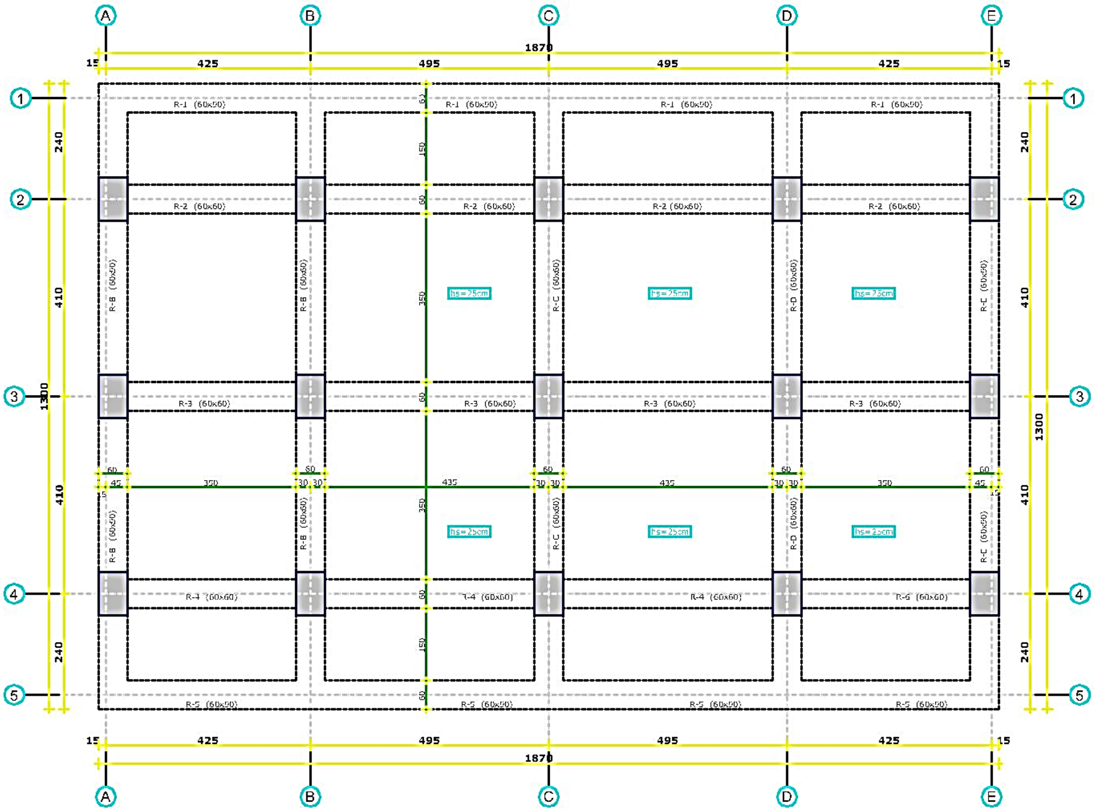


Fig 4. 1: *Plan view of the case study residential building.*

4.3 Structural Members

The structural elements of the building are represented by reinforced concrete beams, columns, and slabs. The material properties for all frame members are the same. The concrete class is approximately 34.5 MPa which according to American standards is 5000 Psi. The steel rebars are of grade 60 which means their strength is approximately 413.6 MPa or 60 ksi. The same material properties are also used for slab element modeling except from the unit weight, which is light, 23kg/m^3.

The structural components are transferred in PACT as fragility specification groups, based on the previously described building characteristics. Appendix A *Structural Component Fragility Specifications* (FEMA P-58-2, 2018) compiles coherent structural fragility specifications for reinforced concrete moment frames. In the paragraphs that follow a detailed description of these elements is represented.

4.3.1 Beams and columns

Columns are the vertical load bearing elements of the structural frame which play an important role in the stability of framed systems. Only one section configuration with 90 cm by 90 cm is used for the columns on this building. Another component of the moment frame is beams element. Beams are the horizontal or sloping bearing elements of the structural system that connect columns and support slabs. For beam element modeling two sections are used. The perimetral beams have a section of 60 cm by 90 cm, while the rest have a section of 60 cm by 60 cm.

The previously described characteristics are used to select the appropriate fragility specifications that will be used by PACT for the seismic evaluation. This evaluation considers the joint connection of the frame elements. These joints are designed such that they do not experience joint failure. For this reason, on Appendix A, ACI 318 Special Moment Frame (SMF) characteristics are judged as the suitable clasification.

Table A-2 Reinforced Concrete Elements (B104)

Material/System	Construction Design Characteristics	Damage Mode, Design Configuration; Other Features	Other/Comments/ Notes	Fragility Classification Number
Reinforced Concrete Moment Frame	ACI 318 Special Moment Frame (SMF)	Beam yield	-	B1041.001a, B1041.001b, B1041.002a, B1041.002b, B1041.003a, B1041.003b
		Weak joints	$\Sigma M_c/\Sigma M_b > 1.2$ $P_u(col) < 0.6 f_c' A_g$ Joint $V/V_n < 1.2$ Compliant transverse reinforcement	B1041.011a, B1041.011b, B1041.012a, B1041.012b, B1041.013a, B1041.013b
	ACI 318 Intermediate Moment Frame (IMF)	Beam or column shear response	Joint shear damage	B1041.021a, B1041.021b, B1041.022a, B1041.022b, B1041.023a, B1041.023b
	ACI 318 Ordinary Moment Frame (OMF)	Beam yield, weak joints	Joint shear damage $\Sigma M_c/\Sigma M_b > 1.2$ $P_u(col) < 0.6 f_c' A_g$	B1041.031a, B1041.031b, B1041.032a, B1041.032b, B1041.033a, B1041.033b
		Column yield Joint shear yield	$\Sigma M_c/\Sigma M_b < 0.8$ Beam, Col: $V_n > V_e$	B1041.041a, B1041.041b, B1041.042a, B1041.042b, B1041.043a, B1041.043b
		Beam yield (flexure or shear) Weak joints	Beam: $V_n < V_e$	B1041.051a, B1041.051b, B1041.052a, B1041.052b, B1041.053a, B1041.053b

Fig 4. 2 *Appendx A_ Structural Component Fragility Specifications (FEMA P-58-2, 2018).*

Based on the above configuration characteristics, the fragility specification for our frame elements is given as the following:

- B1041.001a - one-sided beam/column joints with a 60×60 cm (24×24 inch) size beam.
- B1041.001b - beam/column joints with 60×60 cm (24×36 inch) beams framing the column from all sides.
- B1041.002b - beam/column joints with 60×90 cm (24×36 inch) beams framing the column from all sides.

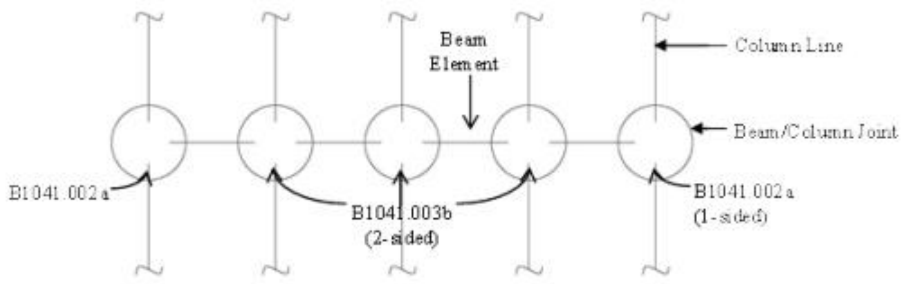


Fig 4. 3: *Reinforced concrete element fragility specification. (FEMA P-58)*

In the following table are summarized the fragility specifications for each joint in both x and y direction, for one floor. Direction 1 is arbitrarily aligned with the North-South axis (y- dir) while entering PACT, and direction 2 is arbitrarily aligned with the East-West building axis (x-dir). Notice that these fragility groups will be the same for other floors.

Table 4. 1: *Fragility Classification for the Beam/Column Joints*

Direction 1	
Joint Location	Fragility Classification Number
A2	B1041.002b
A3	B1041.002b
A4	B1041.002b
B2	B1041.001b
B3	B1041.001b
B4	B1041.001b
C2	B1041.001b
C3	B1041.001b
C4	B1041.001b
D2	B1041.001b
D3	B1041.001b
D4	B1041.001b
E2	B1041.002b
E3	B1041.002b
E4	B1041.002b

Direction 2	
Joint Location	Fragility Classification Number
A2	B1041.001a
B2	B1041.001b
C2	B1041.001b
D2	B1041.001b
E2	B1041.001a
A3	B1041.001a
B3	B1041.001b
C3	B1041.001b
D3	B1041.001b
E3	B1041.001a
A4	B1041.001a
B4	B1041.001b
C4	B1041.001b
D4	B1041.001b
E4	B1041.001a

The table below represents the total quantities of fragility groups ready to be entered on PACT:

Table 4. 2: *Performance Group Quantities for RC Componnents*

Fragility Classification Number	Direction	Quantity Per Floor
B1041.001b	1	9
B1041.002b	1	6
B1041.001a	2	6
B1041.001b	2	9

4.3.2 Slabs

The slab-column joints are another vulnerable reinforced concrete component. Slabs are horizontal elements used to transmit lateral forces to vertical-resisting elements and facilitate functional use of buildings. In the seismic analysis of buildings, the deflections on slabs are considered negligible since they are so small compared with those in the main lateral load resisting constructions. In this way floor slabs are treated as rigid elements. For our case study, the floors and roof are two-way, 25 cm thick, post tensioned flat slabs. Fragility groups B1049.021a to B1049.032 apply to post-tensioned reinforced concrete slab structures. Slab shear reinforcement has been provided at the columns for this case study, and the gravity shear to shear capacity ratio is less than 0.4. As a result, B1049.031 is the most suitable choice.

4.4 **Nonstructural Members**

Nonstructural members play a significant role in seismic assessment, which is often underestimated. *Normative Quantity Estimation Tool*, provided in Volume 3, enables the identification and distribution of the most vulnerable nonstructural components. This tool requires the input of floor quantity, areas, and their occupancies. The execution of this tool according to my case study, produces the following fragility specifications:

- B2022.001 Curtain Walls (Fig.4.6),
- B3011.011 Concrete tile roof,
- C1011.001a Wall Partition, Type: Gypsum with metal studs, Full Height,
- C3011.001a Wall Partition, Type: Gypsum + Wallpaper, Full Height,
- C3032.001a Suspended Ceiling,
- D2021.011a Cold or Hot Potable - Small Diameter Threaded Steel,
- D3041.011a HVAC Galvanized Sheet Metal Ducting (Fig.4.5),
- D3041.031a HVAC Drops / Diffusers in suspended ceilings,
- D3041.041a Variable Air Volume (VAV) box with in-line coil.

For each fragility specification mentioned above, a median estimate of the number of units is given for all directions. The figure below illustrates the outputs of *Normative Quantity Estimation Tool* for the first floor, which is same for every floor:

COMPONENT SUMMARY MATRIX								
OCCUPANCY				Fragility Number	Fragility Name	Assumed Quantity per component within PACT	Quantity	
Type	Occupancy #	Floor Name	Component Area (sq ft)				Directional	Non Directional
APARTMENT	1	2nd	2616.7	**D4011.021a**	D4011.021a Fire Sprinkler Water Piping - Horizontal Mains	1000 LF	--	0.58
APARTMENT	1	2nd	2616.7	**D4011.031a**	D4011.031a Fire Sprinkler Drop Standard Threaded Steel -	100 EA	--	0.31
APARTMENT	1	1st	2616.7	**B2022.001**	B2022.001 Curtain Walls - Generic Midrise Stick-Built Curt	30 SF	13.08	--
APARTMENT	1	1st	2616.7	**B3011.011**	B3011.011 Concrete tile roof, tiles secured and compliant	100 SF	--	8.37
APARTMENT	1	1st	2616.7	**C1011.001a**	C1011.001a Wall Partition, Type: Gypsum with metal stud	100 LF	3.14	--
APARTMENT	1	1st	2616.7	**C3011.001a**	C3011.001a Wall Partition, Type: Gypsum + Wallpaper, Fu	100 LF	1.00	--
APARTMENT	1	1st	2616.7	**C3032.001a**	C3032.001a Suspended Ceiling, SDC A,B,C, Area (A): A < 250	250 SF	--	9.94
APARTMENT	1	1st	2616.7	**C3032.001a**	C3032.001a Suspended Ceiling, SDC A,B,C, Area (A): A < 250	250 SF	--	0.52
APARTMENT	1	1st	2616.7	**D2021.011a**	D2021.011a Cold or Hot Potable - Small Diameter Threade	1000 LF	--	0.28
APARTMENT	1	1st	2616.7	**D3041.011a**	D3041.011a HVAC Galvanized Sheet Metal Ducting less th	1000 LF	--	0.13
APARTMENT	1	1st	2616.7	**D3041.031a**	D3041.031a HVAC Drops / Diffusers in suspended ceilings	10 EA	--	2.09
APARTMENT	1	1st	2616.7	**D3041.041a**	D3041.041a Variable Air Volume (VAV) box with in-line coi	10 EA	--	1.05
APARTMENT	1	1st	2616.7	**D4011.021a**	D4011.021a Fire Sprinkler Water Piping - Horizontal Mains	1000 LF	--	0.58
APARTMENT	1	1st	2616.7	**D4011.031a**	D4011.031a Fire Sprinkler Drop Standard Threaded Steel -	100 EA	--	0.31

Fig 4. 4: *Normative Quantity Estimation tool, Component Summary Matrix, list of nonstructural elements.*

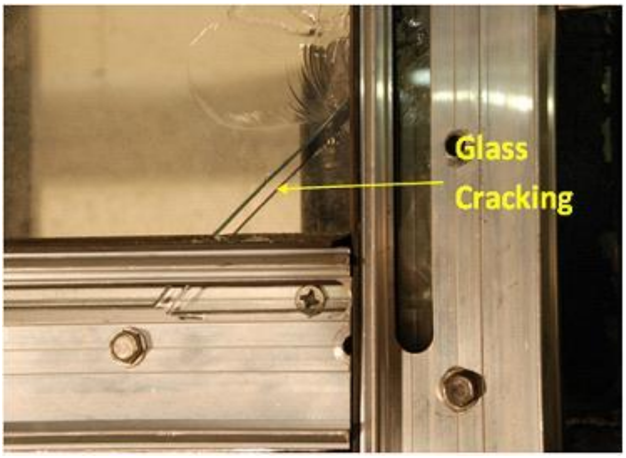


Fig 4. 5: *Curtain Walls*

Fig 4. 6: *HVAC Galvanized Sheet*

CHAPTER 5

BUILDING MODELING, ANALYSIS AND DESIGN IN SAP2000

All the calculations required for this study are performed on SAP2000 (CSI, 2016). This software incorporates modeling, analysis, design, and reporting into a single user interface. These features, introduced on our structure, are explained in the preceding sections.

5.1 SAP2000 Software

SAP2000 is general-purpose civil-engineering software produced by Computer and Structures, Incorporated (CSI), a structural and earthquake engineering company. This software enables advanced analytical techniques, to be used for the analysis and design of any type of structural system. SAP2000 is a finite element software which performs static or dynamic, linear, or nonlinear analysis, including large deformation analysis, Eigen and Ritz analyses, buckling analysis, progressive collapse analysis, support plasticity and nonlinear segmental construction analysis etc. Within this software are integrated design codes: Eurocodes, AASHTO specifications, ACI and AISC building codes etc, making it a powerful design tool. Furthermore, SAP2000 gives a diverse material options ranging from concrete to steel and composite structures.

5.2 Modelling, Analysis, and Design on SAP2000

The structural modeling process is simplified due to built-in modeling templates, controls, and features. In the following paragraphs will be illustrated with figures all the material and sections definitions, the load cases, and combinations, as well as the necessary steps needed for the pushover analysis of our case study building.

5.2.1 Material and Section Properties

SAP2000 has a built-in library of standard concrete, steel, and composite material properties. Also, users can create new material properties in order to meet their requirements. To define the properties of a material, select the Define menu and then click on Materials. For this case study three types of materials are used.

The first material is concrete that will be used on the entire structural framing system. This material has a strength of approximately 34.5 MPa or 5000 Psi. The figure below represents the *Define Material* window from SAP2000 in which are shown some other characteristics of the created material.

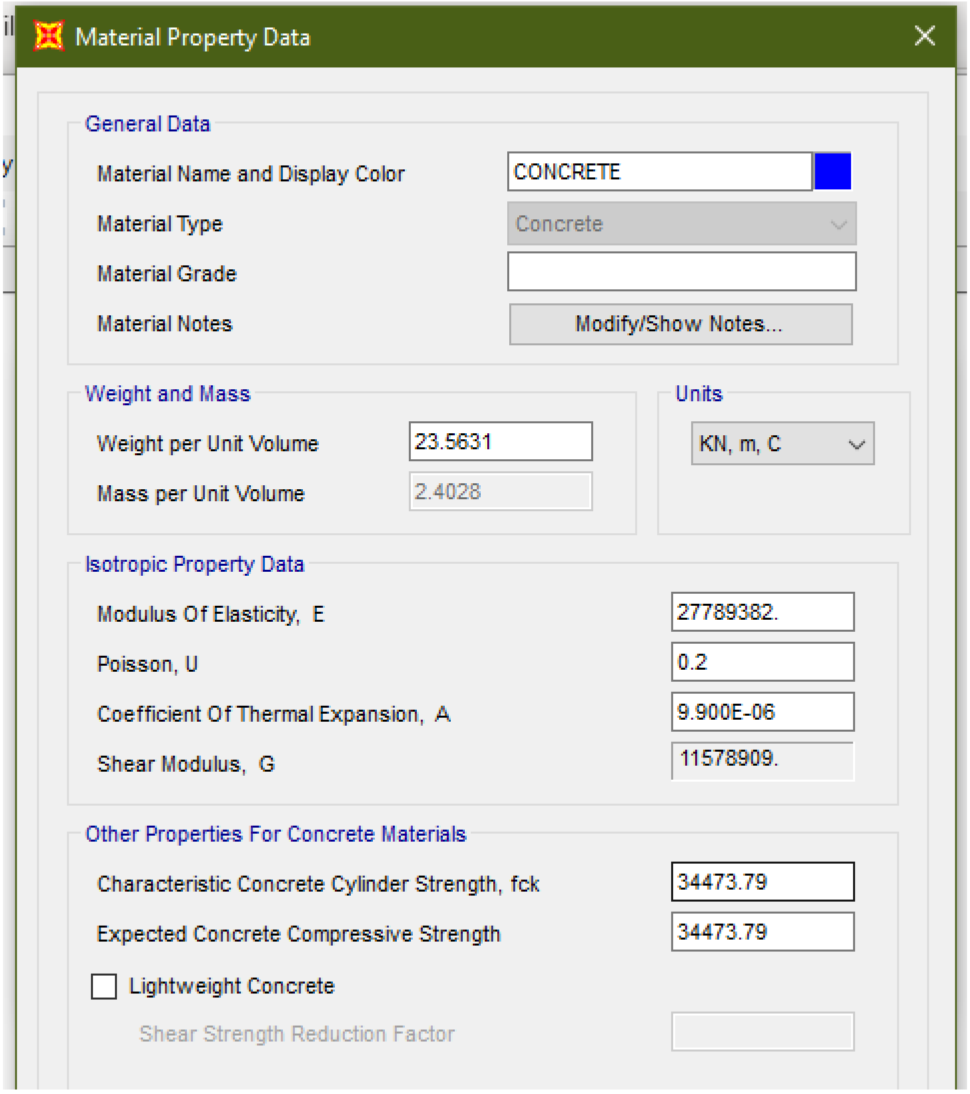


Fig 5. 1: *Material 1_ (SAP2000)*

The same concrete strength but this time with less unit weight is created for slab modelling (Fig 5.2).

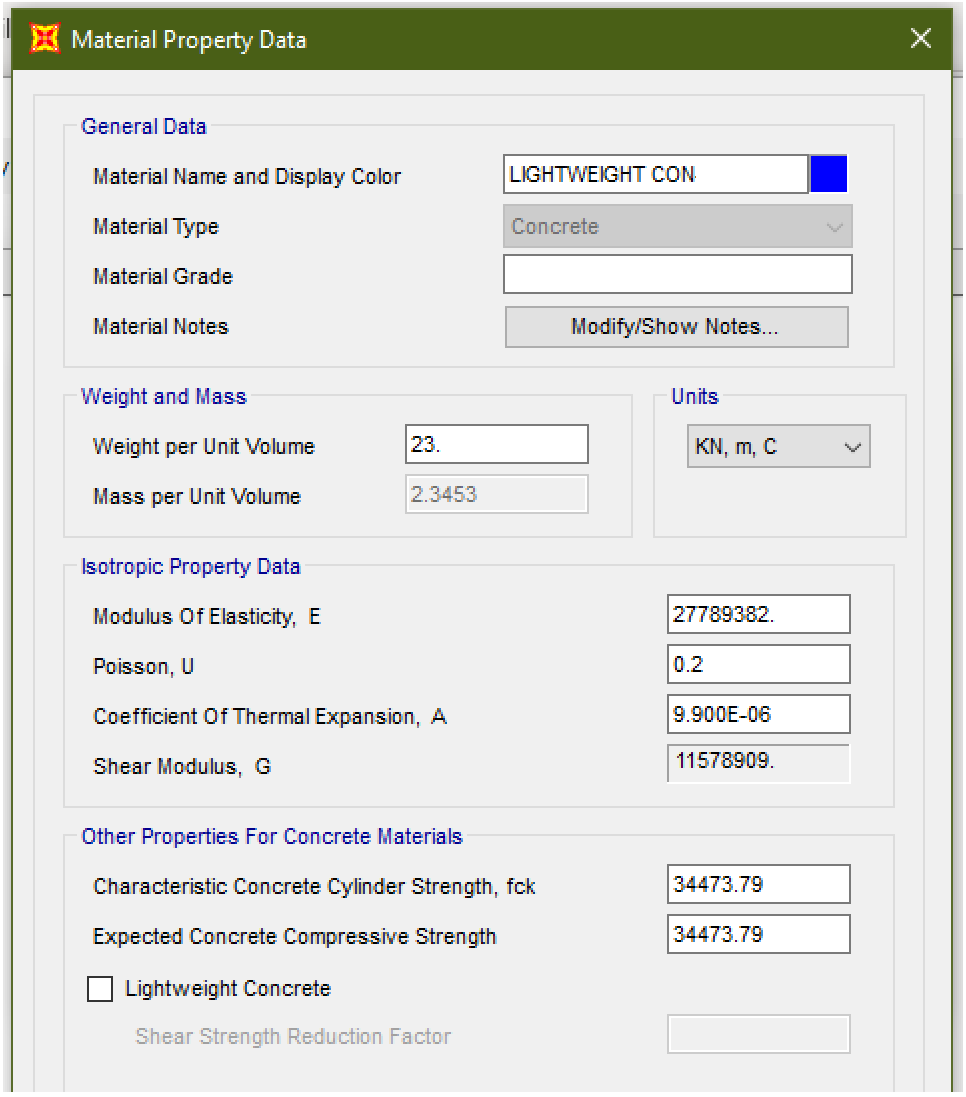


Fig 5. 2: *Material 2_ (SAP2000)*

For the steel part of the RC frame a Grade-60 steel is used. This material has a 413.6 MPa (60 ksi) yield strength (Fig 5.3).

The defined materials will be used to define the properties of beam, column, and slab sections. SAP2000 assumes the loads acting on a structure include the weight of each material. For this reason, unit weight of elements composed with these materials is not calculated.

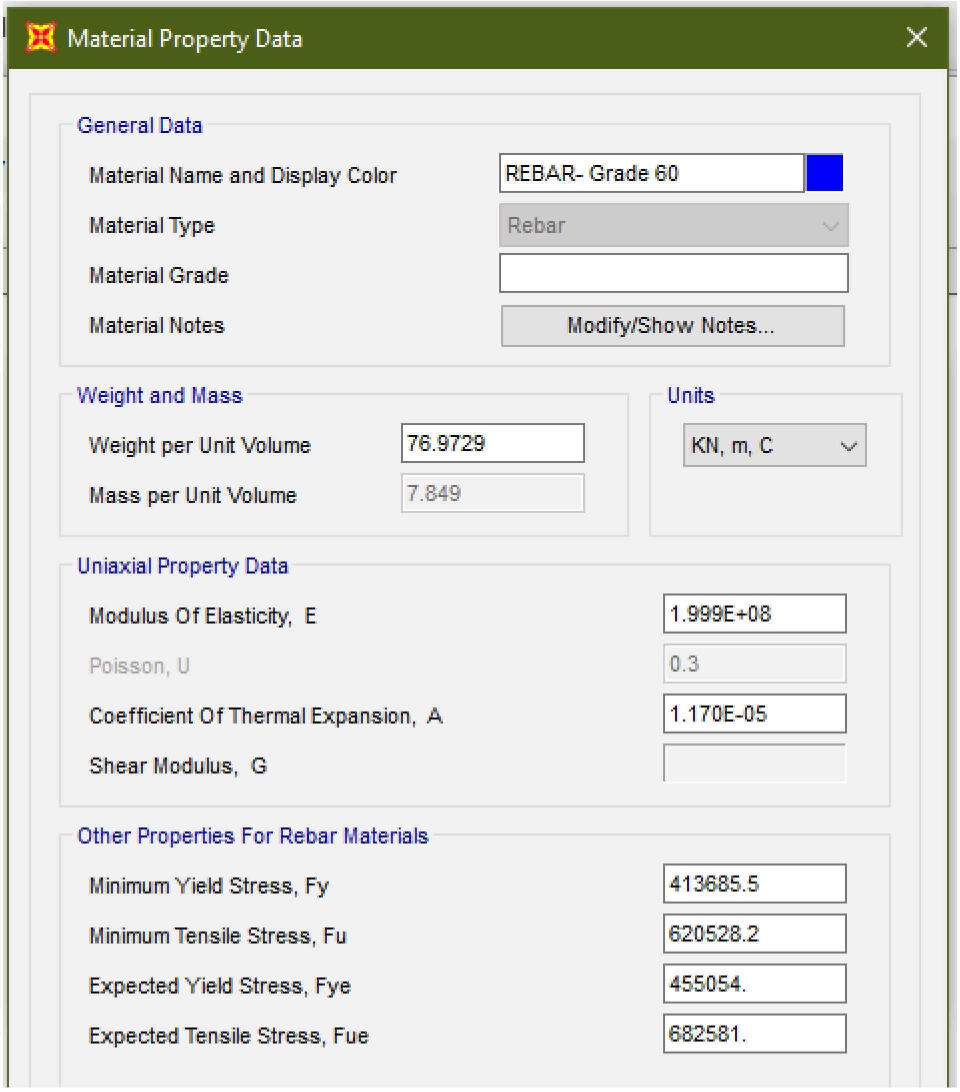


Fig 5. 3: *Material 3_ (SAP2000)*

As mentioned on the previous chapters three sections are used for the structural frame. To define the cross-section properties of these elements, click on the Define menu, click on Section Properties, then Frame Sections. For these sections, the *CONCRETE-5000Psi* is assigned. To model slab element, same steps are used but this time select the Area Sections. Slab thickness is 25 cm and *LIGHTWEIGHT CON-5000Psi* is used (Fig 5.4).

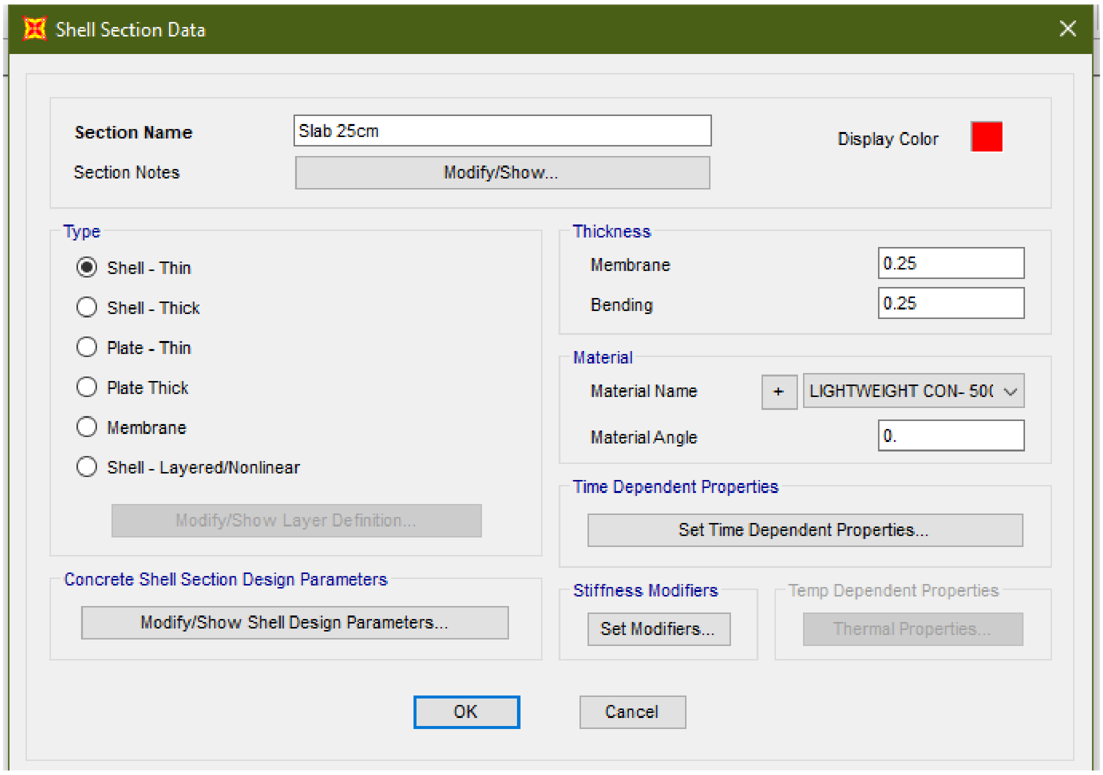


Fig 5. 4: *Material 4_ (SAP2000)*

5.2.2 Load Cases and Combinations

In this session will be explained the types of loads that will be used for the structural analysis as well as their combinations. Firstly, the loads that will act on the structure will be declared. As illustrated in Fig 5.5 these load patterns are:

- The self-weight of the structure
- The live loads: 1.92 kN/m^2
- The weight of finishes: 1.53 kN/m
- Walls's weight
    - Internal walls: 8.7 kN/m
    - External wall: 12.43 kN/m
- Earthquake loads on x and y direction.

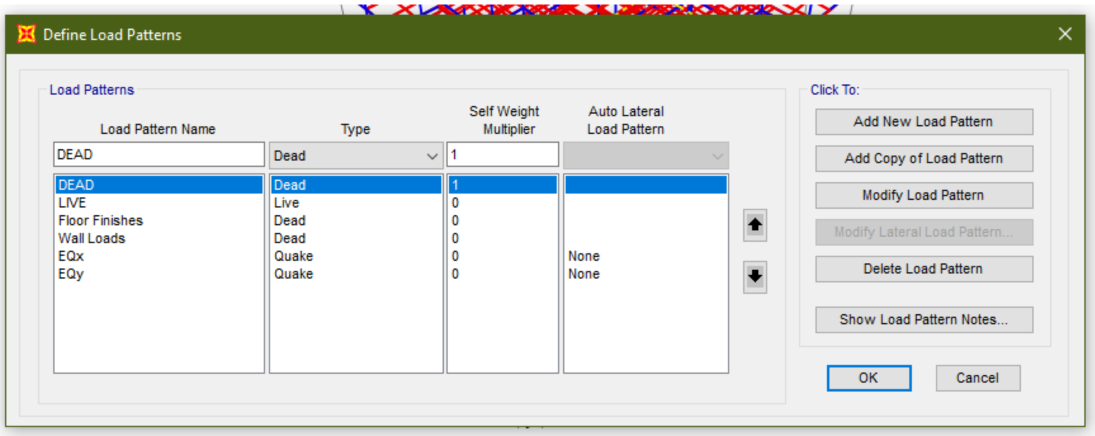


Fig 5. 5: *Types of Load Patterns*

For the earthquake loads pattern, firstly, a response spectrum function should be defined. To define this function, go to Define, Functions, Response Spectrum. The soil type for our study will be B, with a behavior factor, q= 4.68 and a_g/g=025.

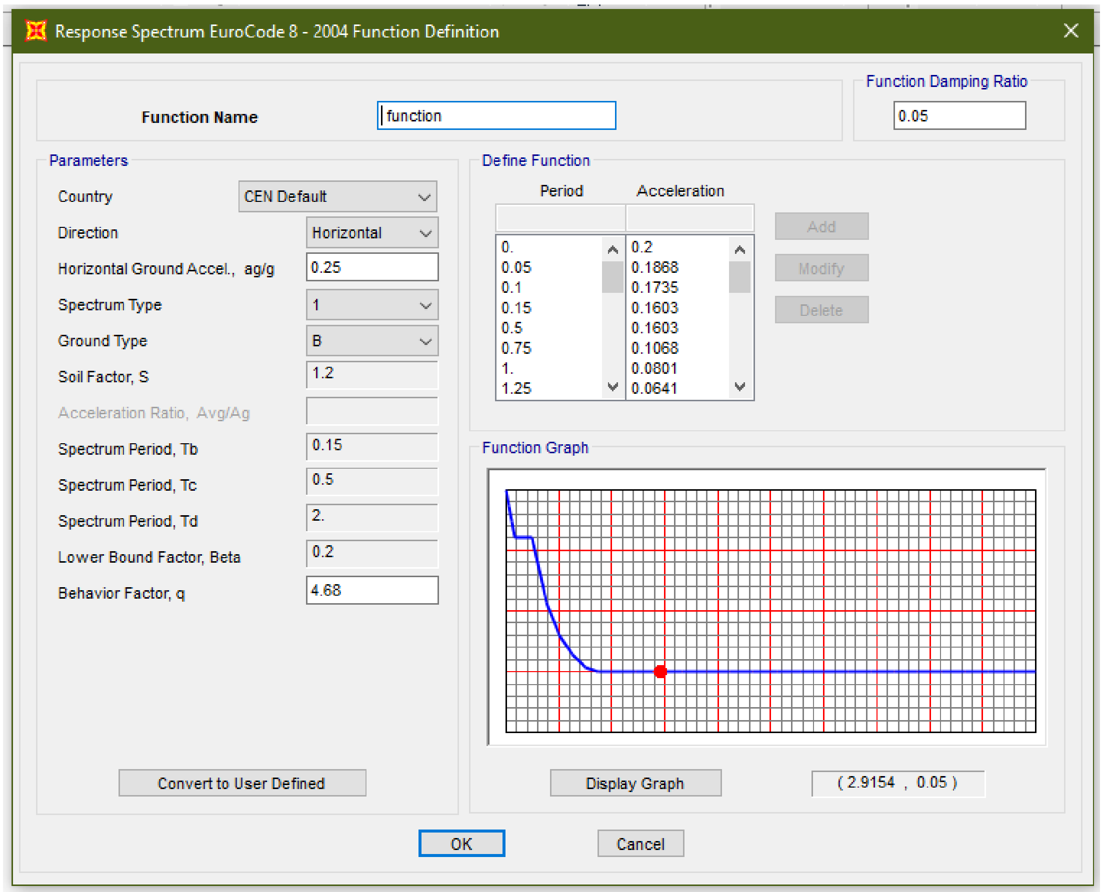


Fig 5. 6: *Response Spectrum Function*

According to Eurocodes, three types of load combinations are used in this structural analysis (Fig 5.7).

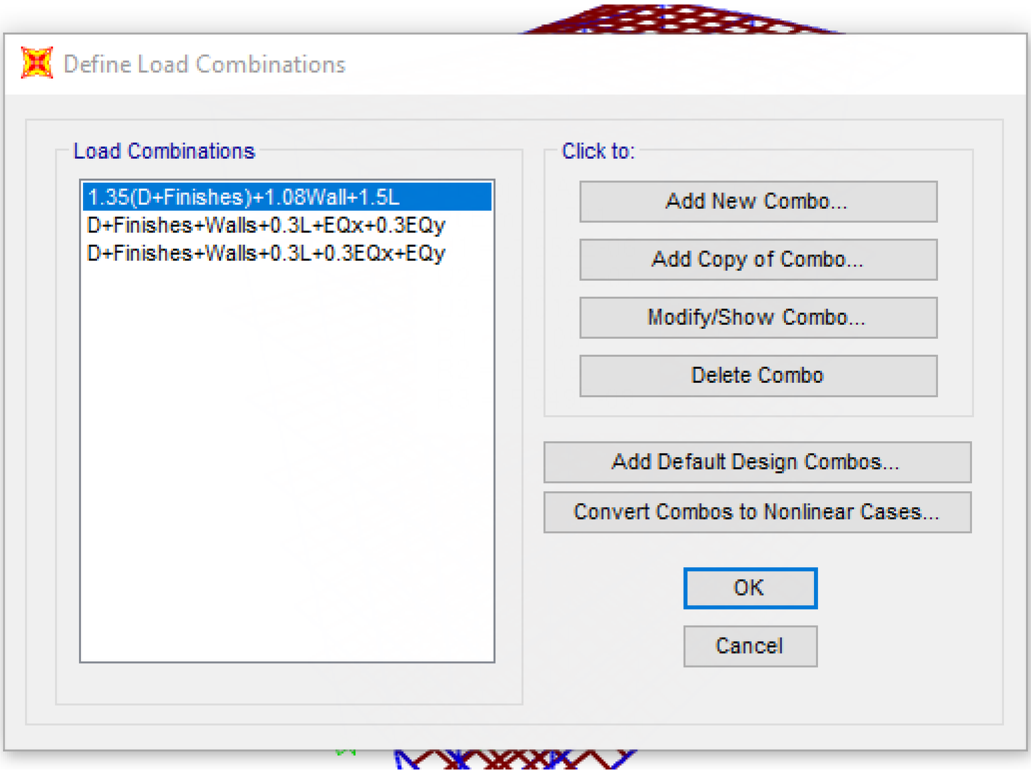


Fig 5. 7: *Load Combinations*

After all the load cases were assigned to the structural members respectively, Run the analysis and then design this structure accordingly. For the structural design, on SAP2000, Eurocode 2-2004 is selected. The next step of this study is the *Pushover Analysis*, which will be performed based on the obtained results.

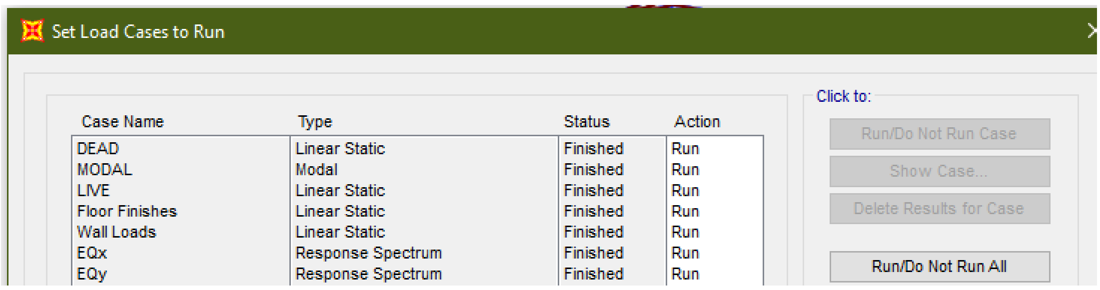


Fig 5. 8: *Run Analysis*

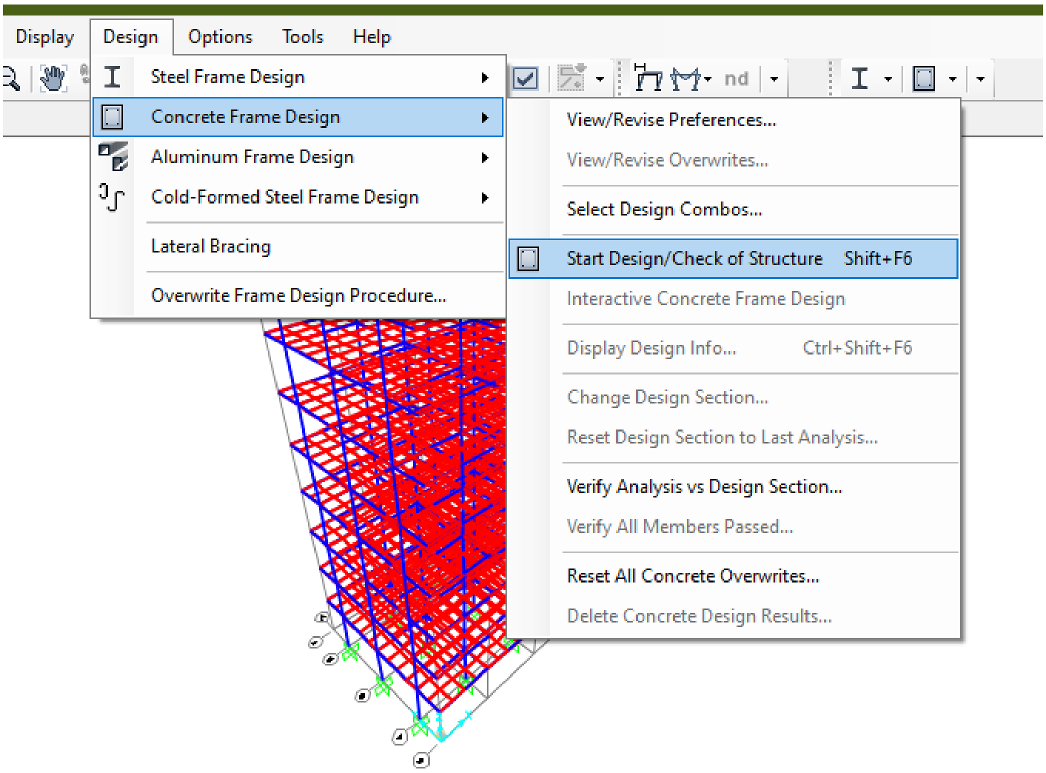


Fig 5. 9: *Design Options*

5.3 Pushover Analysis

Pushover analysis is a nonlinear, static method in which the magnitude of structural loading is incrementally increased according to a predefined manner. Poor links and failure modes of the structure are found out as this magnitude increases. This procedure is used to estimate the structure's strength capacity beyond its elastic limit (also known as the Limit State) and up to its ultimate strength in the post-elastic range. The possible vulnerable points on a structure are predicted by monitoring the members through the hinges.

Hinges are points on a structure where cracking and yielding are mostly expected to occur, resulting in high flexural (or shear) displacement as the structure reaches its ultimate strength under cyclic loading. During a seismic event, at these locations of the actual building, cross diagonal cracks are likely to appear. They are positioned at the either ends of beams and columns, with the cracks being at a small distance from the joint. Consequently, the same position of hinges at beams and columns is inserted on the corresponding computer analysis model (SAP2000 in this case).

Pushover analysis capabilities are fully integrated in SAP2000 program, so it allows the implementation of the pushover procedures as prescribed in the ATC-40 and FEMA-273 documents. Below are briefly described the steps involved in the pushover analysis:

1. Create the basic computer model (as previously explained).
2. Locate the pushover hinges on the model by selecting members and assigning them the hinge properties.
   - In this case hinges are located at 0.05 and 0.95 distance from the beam- columns joint.
   - P-M2-M3 hinges are assigned to columns as they are subjected to axial force (P), bending moment about y-axis (M2), and bending moment about x-axis (M3).
   - For beams, M2-M3 hinges are assigned as they are only subjected to bending moments about x and y axis.
3. Define the pushover load cases. In SAP2000 more than one pushover load case can be run in the same analysis. Pushover load cases can be controlled by defined force level or displacement.
   - As the starting pushover forces for this case are used the gravity loads which are now set to non-linear static. Then two other non-linear load cases *PushX* and *PushY* are created to continue the pushover analysis.
4. Run the above non-linear static analysis.
5. Display the pushover curve as shown in Fig. 5.10.

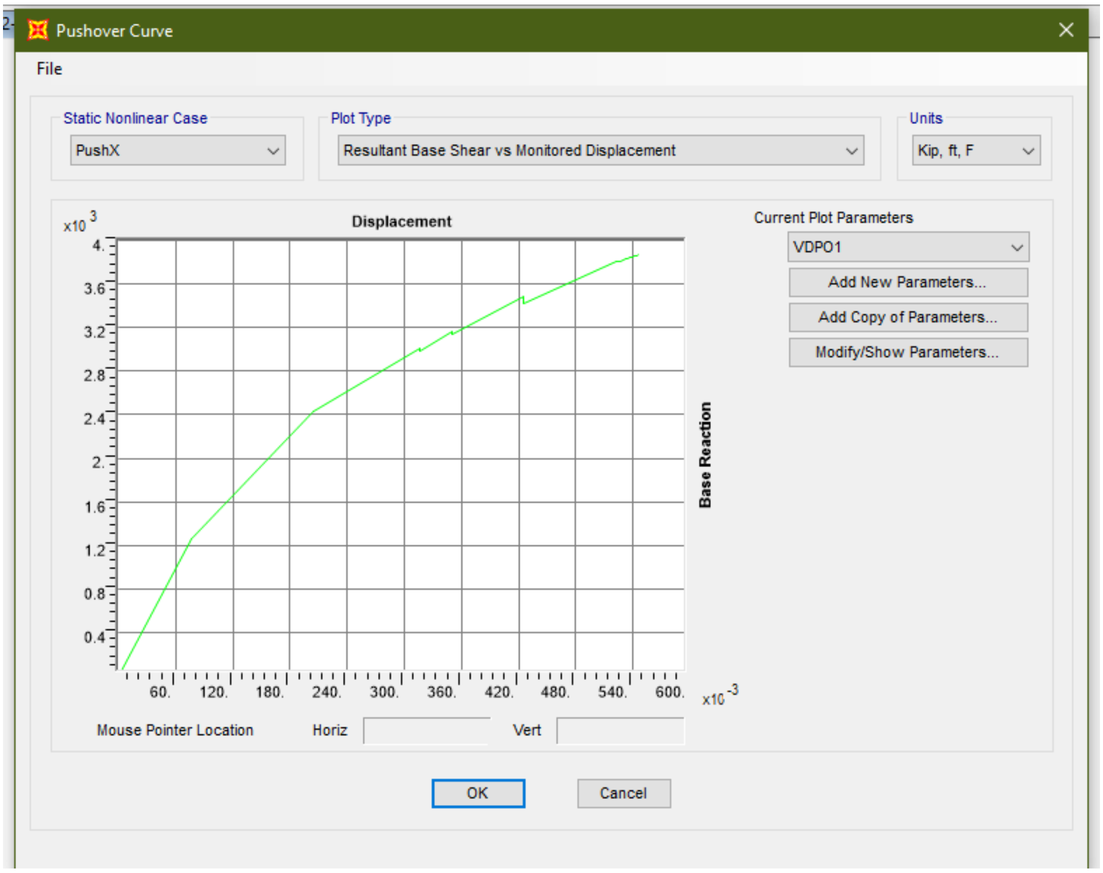


Fig 5. 10: *Pushover Curve obtained by the pushover analysis.*

The coordinates of the pushover curve, the building height, building weight and fundamental building period, will be input into the SPO2IDA Tool (part of FEMA P-58 Volumes) to further continue with the seismic evaluation.

From SAP2000 software analysis the following outputs are obtained:

- Building weight= 30823.33kN (6929.366 kips)
- Building height= 27.2m (89.2 ft)
- T_x= 0.724 sec
- T_y= 0.705 sec
- $\bar{T}$ = 0.714 sec

CHAPTER 6

SEISMIC EVALUATION USING PACT

In this chapter are organized the steps conducted for the intensity-based performance assessment of the case study. The evaluation is done through PACT platform, considering the necessary work needed to get a median repair cost estimate for a ground shaking with a return period of 475 years.

6.1 PACT Platform

PACT is an electronic calculating tool that executes the FEMA P-58 methodology's probabilistic calculations and loss accumulation. Within this platform are reposed fragility data as well as a collection of utilities for specifying building properties. PACT can be used for scenario-based, intensity-based, and time-based loss calculations and it can address results from both nonlinear response history analyses and simplified analyses. The fundamental PACT's functions are:

- Organizing building data, fragility functions, and demand parameters.
- Calculating losses, such as maintenance costs, and casualty estimates.
- Providing details on performance group losses from the above calculations.

6.2 Step by step evaluation

In chapter 3, dedicated to the methodology outline of the case study, were explained the steps needed for the seismic evaluation. Now, according to the previously described steps, the corresponding building data information, will be implemented in PACT. PACT has nine tools specified as the following: Project Info, Building Info, Population, Component Fragilities, Performance Groups, Collapse Fragility, Structural Analysis Results, Residual Drifts, and Hazard Curves.

6.2.1 Building Information

Building Information tool is used to enter basic building information required to estimate seismic loss. The data required on this section are summarized on the table below:

BUILDING INFORMATION		
Number of Stories	8	
Total replacement cost	5233400	$
Replacement Time	1095	days
Core & Shell Replacement Cost	194480	$
Max Workers per Square Foot	0.001	
Carbon Emissions Replacement	2462076.8	kg
Embody Energy Replacement	34070623.4	MJ
Floor Area	243.1	m^2
Floor Height	3.4	m

Table 6. 1: *Building Information*

The calculations input on PACT are shown in the figure:

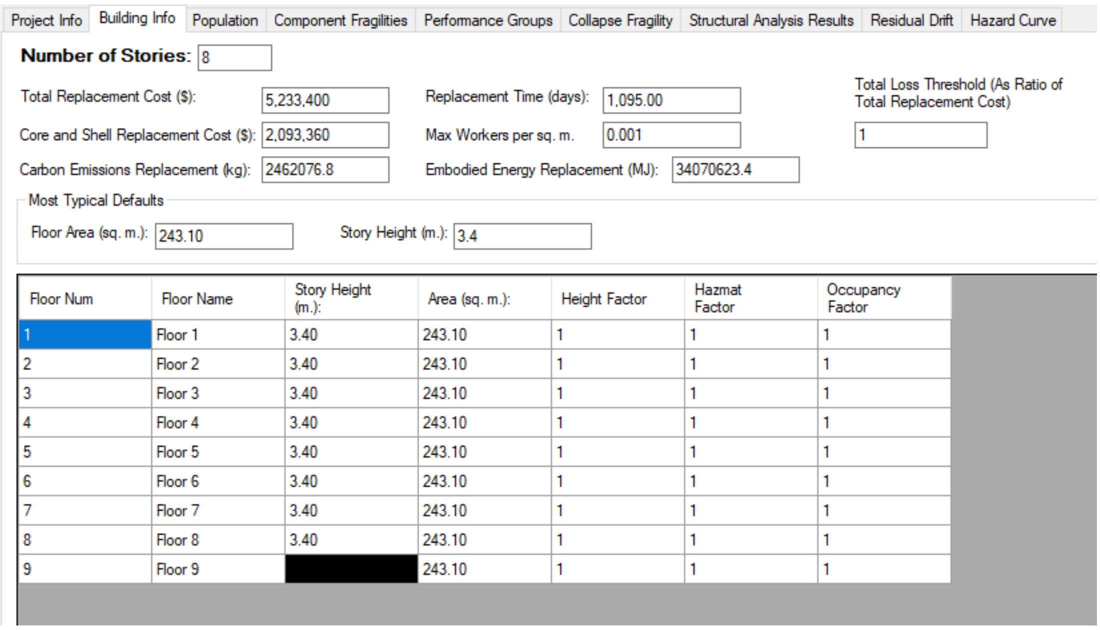


Fig 6. 1: *PACT Building Information tab.*

6.2.2 Population Model

A variety of building population models are offered by PACT. To calculate casualties, users must establish the population model, which is the distribution of occupants across the building at different times of day. PACT includes population models for commercial office, education K-12 (elementary, middle, and high school), healthcare, hospitality, multi-unit residential, research, retail, and warehouse occupancies. Each population model can be modified to reflect any month variation. Our case study is a residential building so multi-unit residential population model fits best. Fig.6.2 shows the population hourly distribution of people per 1000 square feet on weekdays and weekends.

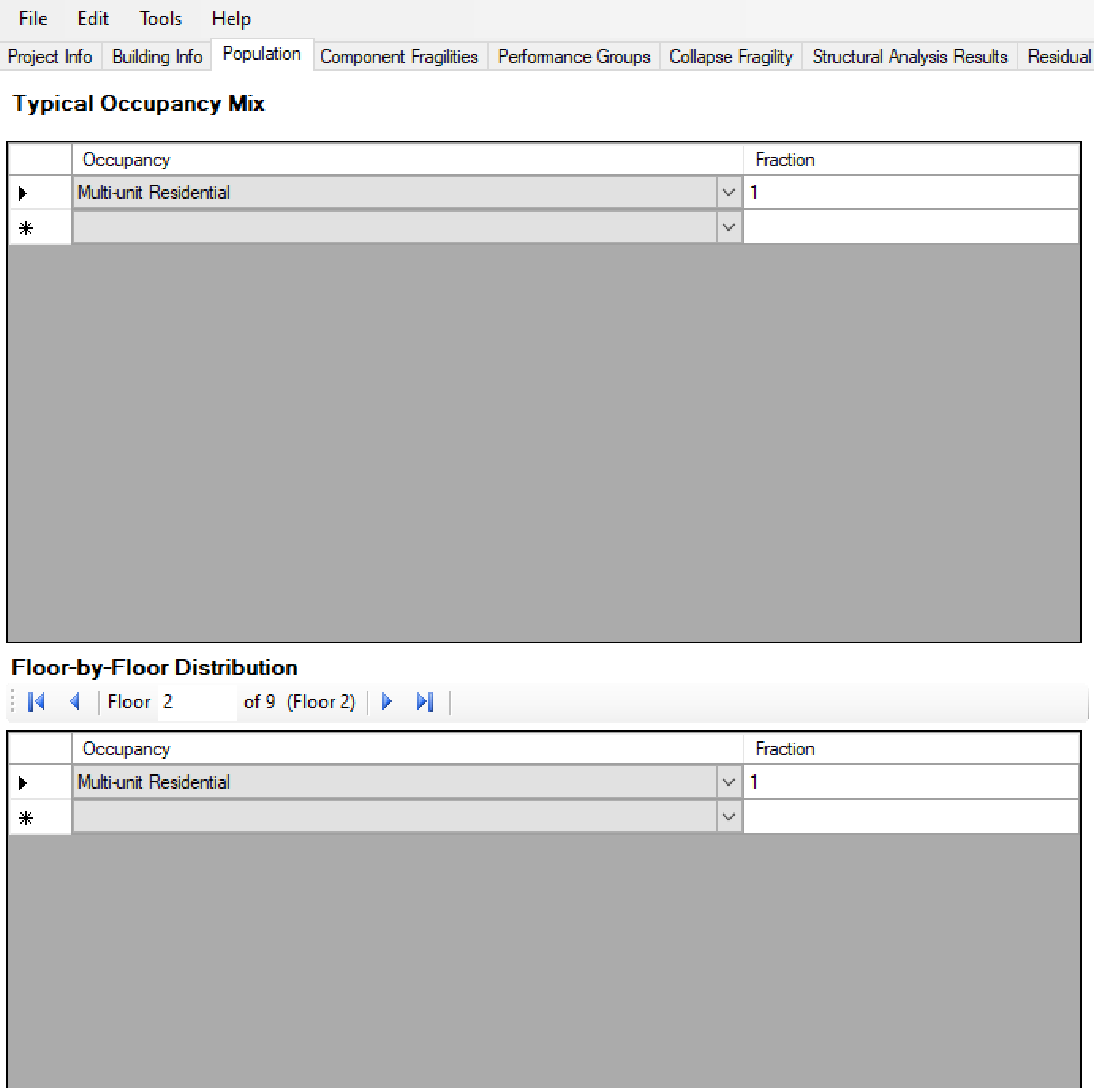


***Fig 6. 2:** PACT Population tab, multi-unit residential occupancy (1)*

Population Model Name: Multi-unit Residential

Peak number of occupants per 1000sf: 3.1

Population Dispersion: 0.2

Day of the Week | Month | Graph

Hour	Weekdays	Weekend
12:00 AM	100%	100%
1:00 AM	100%	100%
2:00 AM	100%	100%
3:00 AM	100%	100%
4:00 AM	100%	100%
5:00 AM	100%	100%
6:00 AM	80%	100%
7:00 AM	60%	100%
8:00 AM	40%	100%
9:00 AM	20%	75%
10:00 AM	20%	50%
11:00 AM	20%	50%
12:00 PM	20%	50%
1:00 PM	20%	50%
2:00 PM	25%	50%
3:00 PM	30%	50%
4:00 PM	35%	50%
5:00 PM	50%	50%
6:00 PM	67%	50%
7:00 PM	84%	50%
8:00 PM	100%	50%
9:00 PM	100%	75%
10:00 PM	100%	100%

Fig 6. 3: *PACT Population tab, multi-unit residential occupancy (2)*

6.2.3 Fragility Specifications and Performance Groups

The fragility specification describes the demand parameter that predicts damage, as well as the types of damage that can occur. Also, they give information on fragility and consequence functions. Fragility functions indicate the likelihood of each damage state occurring as a function of demand, whereas consequence functions provide the probable values of loss that would happen as a consequence of each damage state.

The number, vulnerability, and distribution of potentially damaging components and contents must all be determined based on the building's features. This process is divided as below:

1. Determination of the required fragility specifications for each floor, and
2. Determination of the component's quantity for each performance groups at each floor level.

In pact, the quantity and distribution of damageable components complying to the fragility specifications is entered through the performance groups. A performance group is a set of components that are all characterized by the same fragility group which will face the same demand.

In chapter 4 and 5 are described the case study section materials and geometry which now will be used for the identification of component fragilities. The figure below, taken from PACT tool, lists both structural and non-structural component fragilities used for the seismic evaluation of the structure.

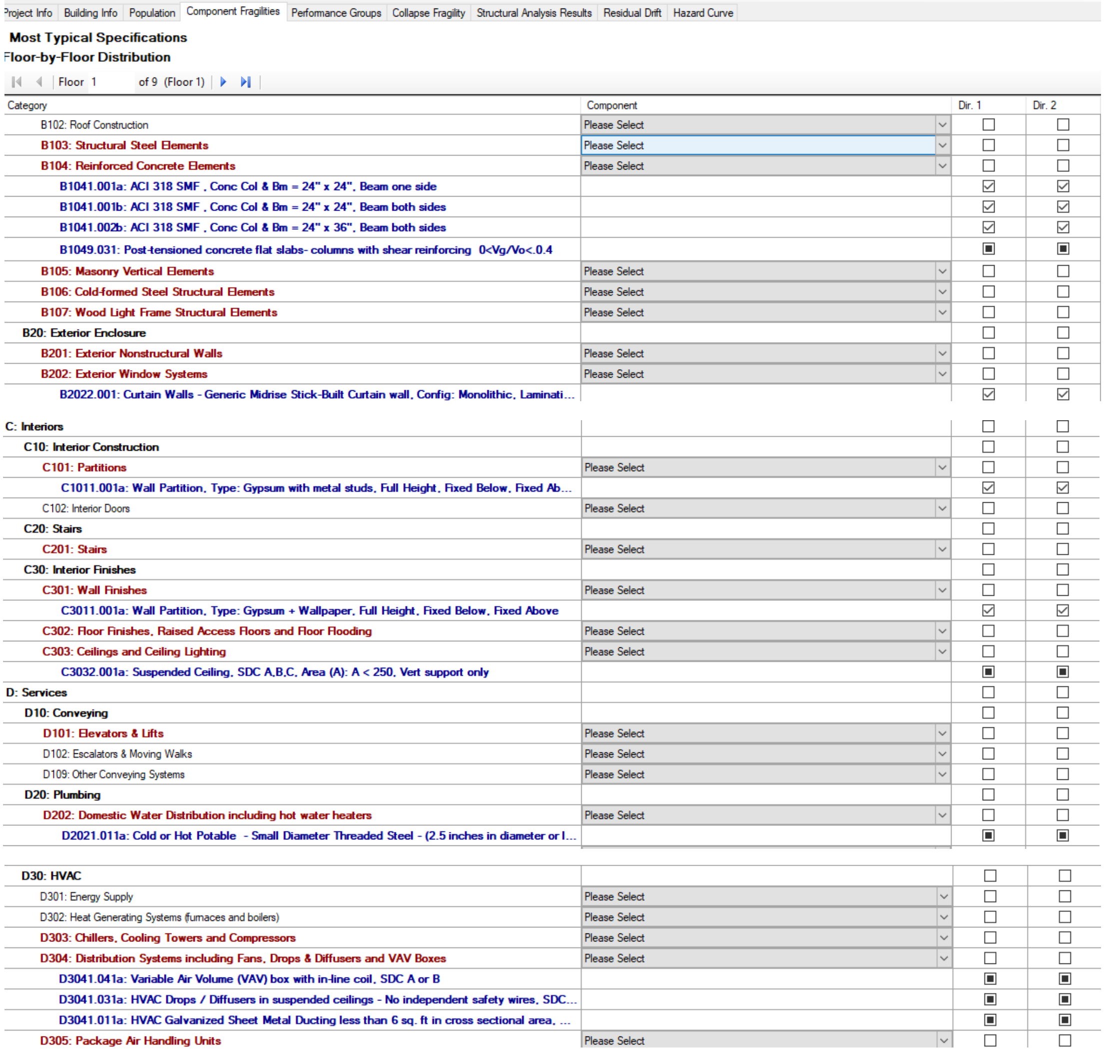
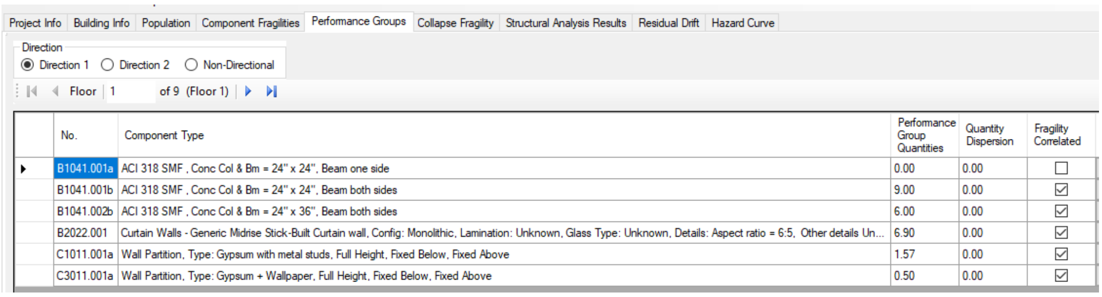


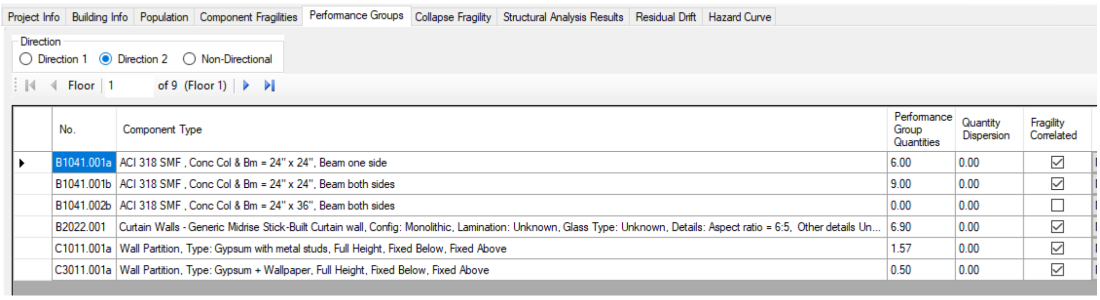
Fig 6. 4: *PACT input screen for fragility components*

For each of the pre-selected parameters, the number of components in each building direction is entered in the Performance Groups tab. The procedure of performance group defining is repeated for each floor. Fig 6.5 to 6.7 illustrate data input for direction 1, direction 2, and non-directional fragility specifications on the first floor.



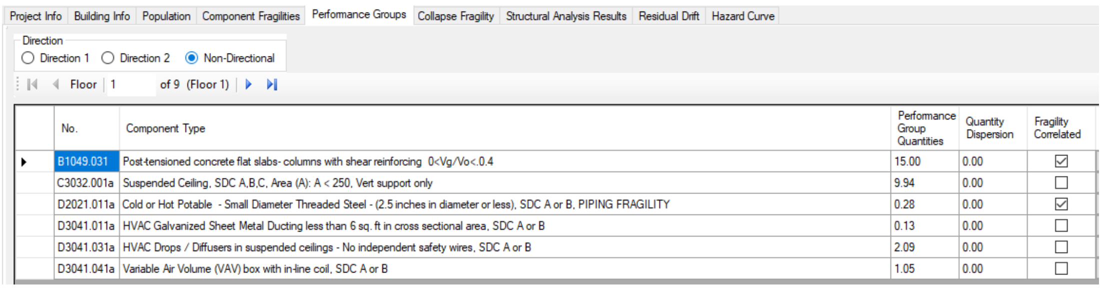
No.	Component Type	Performance Group Quantities	Quantity Dispersion	Fragility Correlated
B1041.001a	ACI 318 SMF , Conc Col & Bm = 24" x 24", Beam one side	0.00	0.00	☐
B1041.001b	ACI 318 SMF , Conc Col & Bm = 24" x 24", Beam both sides	9.00	0.00	☑
B1041.002b	ACI 318 SMF , Conc Col & Bm = 24" x 36", Beam both sides	6.00	0.00	☑
B2022.001	Curtain Walls - Generic Midrise Stick-Built Curtain wall, Config: Monolithic, Lamination: Unknown, Glass Type: Unknown, Details: Aspect ratio = 6:5, Other details Un...	6.90	0.00	☑
C1011.001a	Wall Partition, Type: Gypsum with metal studs, Full Height, Fixed Below, Fixed Above	1.57	0.00	☑
C3011.001a	Wall Partition, Type: Gypsum + Wallpaper, Full Height, Fixed Below, Fixed Above	0.50	0.00	☑

Fig 6. 5: *1st floor PACT entries of performance groups, direction 1.*



No.	Component Type	Performance Group Quantities	Quantity Dispersion	Fragility Correlated
B1041.001a	ACI 318 SMF , Conc Col & Bm = 24" x 24", Beam one side	6.00	0.00	☑
B1041.001b	ACI 318 SMF , Conc Col & Bm = 24" x 24", Beam both sides	9.00	0.00	☑
B1041.002b	ACI 318 SMF , Conc Col & Bm = 24" x 36", Beam both sides	0.00	0.00	☐
B2022.001	Curtain Walls - Generic Midrise Stick-Built Curtain wall, Config: Monolithic, Lamination: Unknown, Glass Type: Unknown, Details: Aspect ratio = 6:5, Other details Un...	6.90	0.00	☑
C1011.001a	Wall Partition, Type: Gypsum with metal studs, Full Height, Fixed Below, Fixed Above	1.57	0.00	☑
C3011.001a	Wall Partition, Type: Gypsum + Wallpaper, Full Height, Fixed Below, Fixed Above	0.50	0.00	☑

Fig 6. 6: *1st floor PACT entries of performance groups, direction 2.*



No.	Component Type	Performance Group Quantities	Quantity Dispersion	Fragility Correlated
B1049.031	Post-tensioned concrete flat slabs- columns with shear reinforcing 0<Vg/Vo<0.4	15.00	0.00	☑
C3032.001a	Suspended Ceiling, SDC A,B,C, Area (A): A < 250, Vert support only	9.94	0.00	☐
D2021.011a	Cold or Hot Potable - Small Diameter Threaded Steel - (2.5 inches in diameter or less), SDC A or B, PIPING FRAGILITY	0.28	0.00	☑
D3041.011a	HVAC Galvanized Sheet Metal Ducting less than 6 sq. ft in cross sectional area, SDC A or B	0.13	0.00	☐
D3041.031a	HVAC Drops / Diffusers in suspended ceilings - No independent safety wires, SDC A or B	2.09	0.00	☐
D3041.041a	Variable Air Volume (VAV) box with in-line coil, SDC A or B	1.05	0.00	☐

Fig 6. 7: *1st floor PACT entries of performance groups, non-directional.*

6.2.4 Collapse Fragility Analysis

A building collapse fragility function must be established after the building performance model is entered into PACT to allow for the assessment of casualties. The collapse fragility function is a function of ground motion intensity that represents the probability of a structure collapsing in one or more modes. In this case the nonlinear static approach is used to develop collapse fragility. The method relies on incremental dynamic analysis (IDA) curves derived from nonlinear single-degree-of-freedom models, which may be accessed using the Static Pushover 2 Incremental Dynamic Analysis (SP2OIDA) Tool.

Firstly, the nonlinear static analysis of the building is performed to develop the pushover curve. The steps needed for the pushover analysis and pushover curve have been explained in Section 5.3. As the pushover curve is obtained, its coordinates (Table 6.2), as well as the building height, weight, and fundamental building period, are then entered into the SPO2IDA Tool. To approximate the pushover curve, four control points, as shown, are used.

Fig 6. 8: *Hypothetical SPO2IDA idealized pushover curve*

The elastic section is defined as the segment from the ordinate to point 1. Point 1 is referred to as the yield point. The hardening segment is defined from point 1 to point 2, with point 2 being the point of peak strength. The softening branch goes from point 2 to point 3, with point 3 marking the start of the residual strength response. The residual strength plateau is represented by the segment from points 3 to 4. The ultimate deformation upon collapse is represented by point 4.

Following the above logic, in Fig 6.9 is shown the idealization of the pushover curve. Then, SPO2IDA is executed, and the median collapse capacity extracted. On the IDA results tab are provided the results of the SPO2IDA evaluation (Fig 6.10). The collapse fragility is thus defined as having a median value $S_a(T)$ of 7.65g.

***Table 6. 2** Pushover curve coordinates into the SPO2IDA Tool.*

Pushover curve		
Vbase (kips)	δroof (ft)	θroof
0.000	0	0
64.300	0.004198	0.00588
102.893	0.65562	0.00735
231.511	1.177	0.0132
270.096	1.445	0.0162
308.682	1.704	0.0191
385.852	2.096	0.0235
450.160	2.426	0.0272
475.884	2.685	0.0301
540.192	2.890	0.0324
604.502	3.211	0.036
643.086	3.479	0.039
707.395	3.800	0.0426
797.427	4.201	0.0471
861.736	4.594	0.0515
913.183	5.049	0.0566
990.350	5.379	0.0603
1067.524	5.771	0.0647
1131.832	6.164	0.0691
1196.141	6.494	0.0728
1273.311	6.949	0.0779
1350.480	7.546	0.0846
1363.340	7.805	0.0875
1401.929	8.260	0.0926
1440.510	8.661	0.0971
1517.684	9.312	0.1044
1556.270	9.705	0.1088
1633.440	10.427	0.1169
1672.020	10.758	0.1206
1684.887	11.088	0.1243
1749.196	11.542	0.1294
1813.500	12.069	0.1353
1852.090	12.524	0.1404
1877.800	12.925	0.1449
1916.390	13.380	0.15
1942.120	13.639	0.1529
1967.840	13.969	0.1566
2057.877	14.433	0.1618
2096.460	14.950	0.1676
2173.630	15.610	0.175
2212.210	16.002	0.1794
2237.940	16.333	0.1831
2302.250	16.859	0.189
2327.970	17.314	0.1941
2392.280	17.902	0.2007
2456.590	18.759	0.2103
2469.450	19.294	0.2163
2546.620	20.204	0.2265
2559.480	20.730	0.2324
2610.930	21.185	0.2375
2623.790	21.845	0.2449
2675.241	22.434	0.2515
2700.964	23.023	0.2581
2739.549	23.674	0.2654
2764.273	24.004	0.2691
2790.996	24.530	0.275
2829.852	25.119	0.2816
2855.305	25.583	0.2868
2909.367	26.742	0.2998
2990.353	27.929	0.3131
3102.890	29.721	0.3332
3195.040	30.997	0.3475

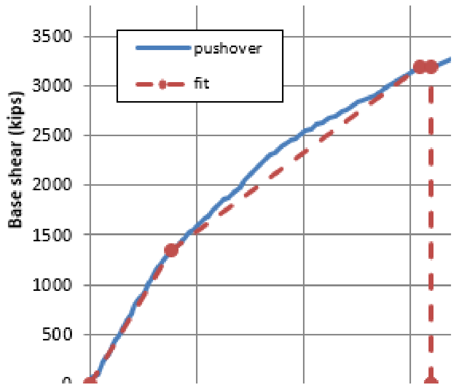


***Fig 6. 9:** Idealization of the Pushover curve*

Roof displacement given Sa results

	Sa	δ16%	δ50%	δ84%	mean δ	mean CR
1	0.03	0.13	0.13	0.13	0.13	1.00
2	0.06	0.26	0.26	0.26	0.26	1.00
3	0.09	0.38	0.38	0.38	0.38	1.00
4	0.12	0.51	0.51	0.51	0.51	1.00
5	0.15	0.64	0.64	0.64	0.64	1.00
6	0.18	0.77	0.77	0.77	0.77	1.00
7	0.21	0.89	0.89	0.89	0.89	1.00
8	0.24	1.02	1.02	1.02	1.02	1.00
9	0.27	1.15	1.15	1.15	1.15	1.00
10	0.28	1.19	1.19	1.19	1.19	1.00
11	7.65	25.27	32.00	#NUM!	32.90	1.01

Instructions | SPO | IDA results | IDA calcs | GUI

Fig 6. 10: *The results of the SPO2IDA evaluation*

6.2.5 Define Earthquake Hazards

The earthquake intensity required for the intensity-based assessments can be defined by any 5% damped, elastic, horizontal acceleration response spectrum. A set of *n* scaled ground motions are involved for the target acceleration response spectrum. To obtain the ground motion parameter values for the seismic evaluation of the case study building, Unified Hazard Tool (https://earthquake.usgs.gov/hazards/interactive/) is used (Fig 6.11). For the target intensity, an earthquake with an average return period of 475 years is applied.

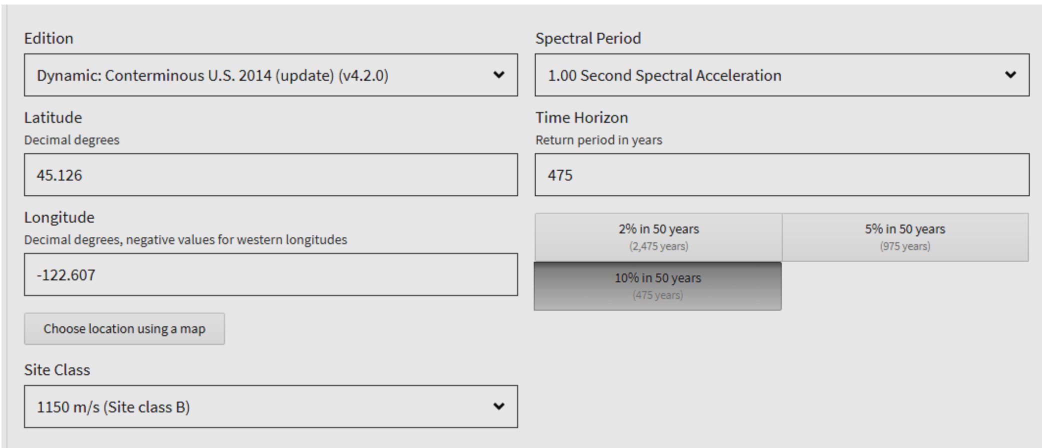


Fig 6. 11: *The values entered on Unified Hazard Tool*

From this tool we obtain the Hazard Response Spectrum and take $S_a(1s) = 0.0852g$.

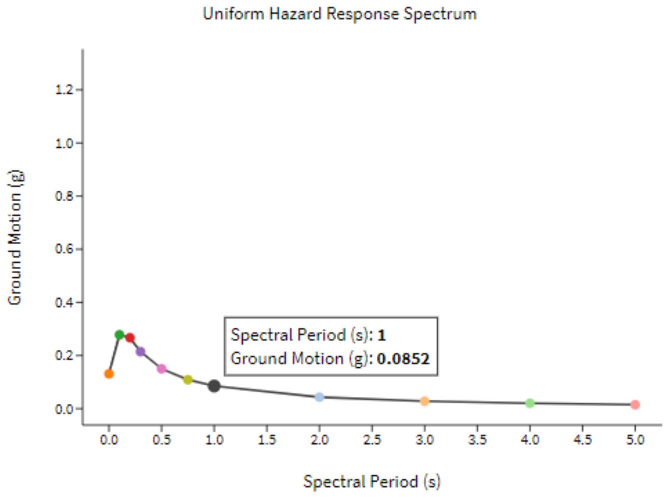


Fig 6. 12: *Hazard Response Spectrum for T=1s*

For structures in the period range of 0.7 to 2.0 seconds, the spectral acceleration corresponding to a specific period is obtained from the formula:

$$S_a(T) = \frac{S_a(1.0)}{T}$$

$$S_a(0.714) = \frac{0.0852}{0.714} = 0.12g$$

This website can also be used to generate the peak ground acceleration for a return period of 475 years, which at the site is 0.131g, as shown in Fig 6.13.

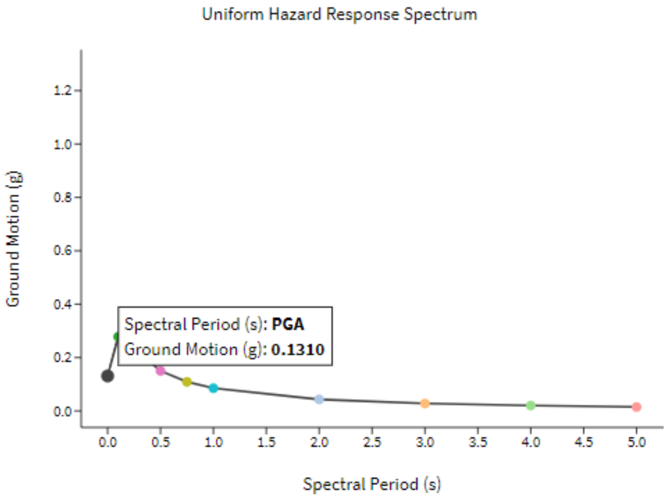


Fig 6. 13: *Hazard Response Spectrum for PGA*

6.2.6 Analyze Building Response

Using the simplified analysis approach, median estimates and dispersions of peak transient drift ratio, peak floor acceleration, and residual drift ratio are calculated.

For the estimation of the story drift ratio, firstly the displacements of each story from SAP2000 are obtained. The story displacements and corresponding drift ratios are summarized in the table below:

Table 6. 3: *Results from SAP2000 and Drift Ratios*

Story	Displacement(inch)	Drift(inch)	Drift Ratios
1	1.44586325	1.445863	0.0108021
2	2.89782885	1.451966	0.0108477
3	4.04011003	1.142281	0.0085340
4	4.89109258	0.850983	0.0063577
5	5.55144559	0.660353	0.0049335
6	6.03719265	0.485747	0.0036290
7	6.3554991	0.318306	0.0023781
8	6.53908141	0.183582	0.0013716

Following the instructions from Volume 1 of FEMA P-58, median estimate of story drift ratios Δ_i* at each story are determined. To correct for the inelastic behavior the Equation 5-10 is used:

$$\Delta_i^* = H_{\Delta i^*}(S, T, h_i, H) \times \Delta_i \quad i = 1 \text{ to } N, \qquad \text{(Equation 1)}$$

Where $H_{\Delta i}$ (S, T, h_i, H), drift modification factor, is calculated using the Equation 5-11 (Volume 1):

$$\ln(H_{\Delta i}) = a_0 + a_1 T_1 + a_2 S + a_3 \frac{h_{i+1}}{H} + a_4 \left(\frac{h_{i+1}}{H}\right)^2 + a_5 \left(\frac{h_{i+1}}{H}\right)^3, \qquad \text{(Equation 2)}$$

S ≥1, i =1 to N, with T_1=0.714 s, H= 1070.8 inches.

The Correction Factors for Story Drift Ratio, a_0 through a_5, are found at Table 5-4 in Volume 1. For a 4-story moment frame structure, the coefficients are as follows:

$a_0 = 0.75$, $a_1 = -0.044$, $a_2 = -0.010$, $a_3 = -2.58$, $a_4 = 2.30$, $a_5 = 0.0$

Table 6. 4: *Volume 1, Table 5-4 Correction Factors for Story Drift Ratio, 2-Story to 9-Story Buildings*

Demand	Frame Type	a_0	a_1	a_2	a_3	a_4	a_5
Story drift ratio	Steel EBF[1]	0.90	-0.12	0.012	-2.65	2.09	0
	Steel SCBF[2]	0.75	0.18	-0.042	-2.45	1.93	0
	Steel BRBF[3]	0.33	0.14	-0.059	-0.68	0.56	0
	Moment Frame[4]	0.75	-0.044	-0.010	-2.58	2.30	0
	Wall	0.92	-0.036	-0.058	-2.56	1.39	0

$$S = \frac{S_a(T_1)W}{V_{y1}} \quad \text{(Equation 3)}$$

In this case, $S_a(T_1) = 0.12g$; W = 6929.36 kips and the value of V_{y1} is taken from the Pushover Analysis Idealization Curve on SPO2IDA as 1350.48 kips.

$$S = \frac{0.12 * 6929.36}{135048} = 0.62$$

The calculation for converting peak story drift ratio to a median estimate of peak story drift ratio is tabulated in table below:

Table 6. 5: *Estimates of Median Story Drift Ratio*

Story	Δi	$\frac{h_i}{H}$	$\ln H_{\Delta i}$	$H_{\Delta i}$	Δ_i^*
1	0.01080	0.125	0.425808	1.530808	0.016536
2	0.01085	0.250	0.211126	1.23506	0.013398
3	0.00853	0.375	0.068318	1.070703	0.009137
4	0.00636	0.50	-0.00262	0.997386	0.006341
5	0.00493	0.625	-0.00168	0.998324	0.004925
6	0.00363	0.75	0.071136	1.073725	0.003897
7	0.00238	0.875	0.215823	1.240874	0.002951
8	0.00137	1	0.432384	1.540907	0.002113

The final step of this analysis is to assign dispersions. From Table 3-4 (Volume 2) with T = 0.714s and S = 0.62, β_{SD} is 0.27.

Table 6. 6: *Volume 2, Table 3-4 Default Dispersions for Story Drift*

T_1 (sec)	$S = \frac{S_a(T_1)W}{V_{y1}}$	$\beta_{a\Delta}$	β_m	β_{SD}
0.5	≤1.00	0.1	0.25	0.27
	2	0.35	0.25	0.43
	4	0.4	0.35	0.53
	6	0.45	0.50	0.67
	≥8	0.45	0.50	0.67
0.75	≤1.00	0.1	0.25	0.27
	2	0.35	0.25	0.43
	4	0.4	0.35	0.53
	6	0.45	0.50	0.67
	≥8	0.45	0.50	0.67

6.2.7 Input Response Data and Calculate Performance

To conclude the evaluation process, in the Structural Analysis Results tab are input the final data estimates. Firstly, in this tab it is required to select the assessment and the analysis type. As mentioned throughout this study, the Intensity-based assessment following the simplified method is performed. Next the median demand estimate for drift ratio is input for story. Figure below shows the inputs of the peak residual drift ratio and its associated dispersion.

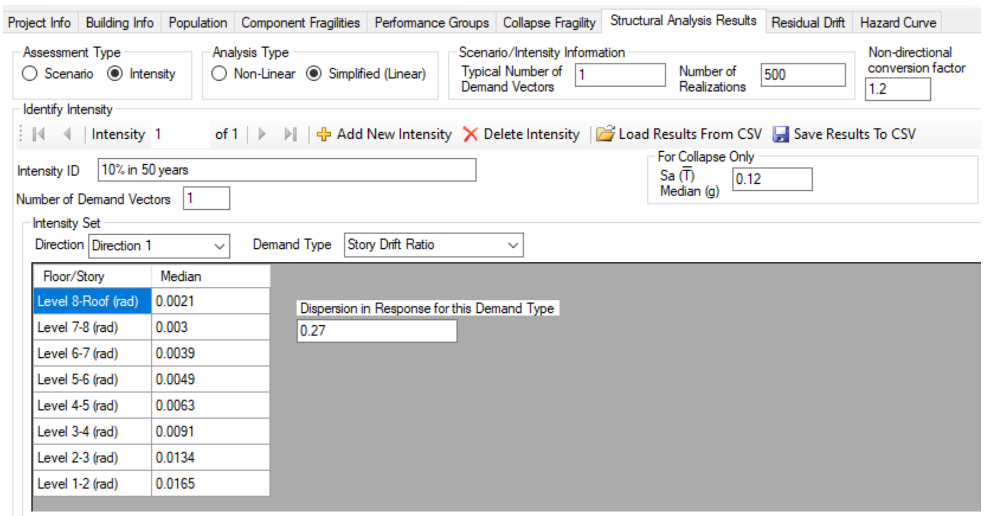


Fig 6. 14: *Inputs on Structural Analysis Results tab.*

After the Structural Analysis is completed the estimated median and the maximum building residual drift ratio and dispersion are input into the PACT Residual Drift tab. The median residual drift ratio at which damage will be regarded irreparable, considering the story drift at yield point, is set to 0.0846.

$$\frac{90.6}{1070.4} = 0.846$$

In the bottom row of this tab corresponding to the intensity used, the maximum residual drift of 0.036 with a dispersion of 0.27 is also entered. Upon completion of the last inputs, the PACT evaluation execution will begin. This is done by returning to the PACT Control Panel and pressing the Evaluate Performance button.

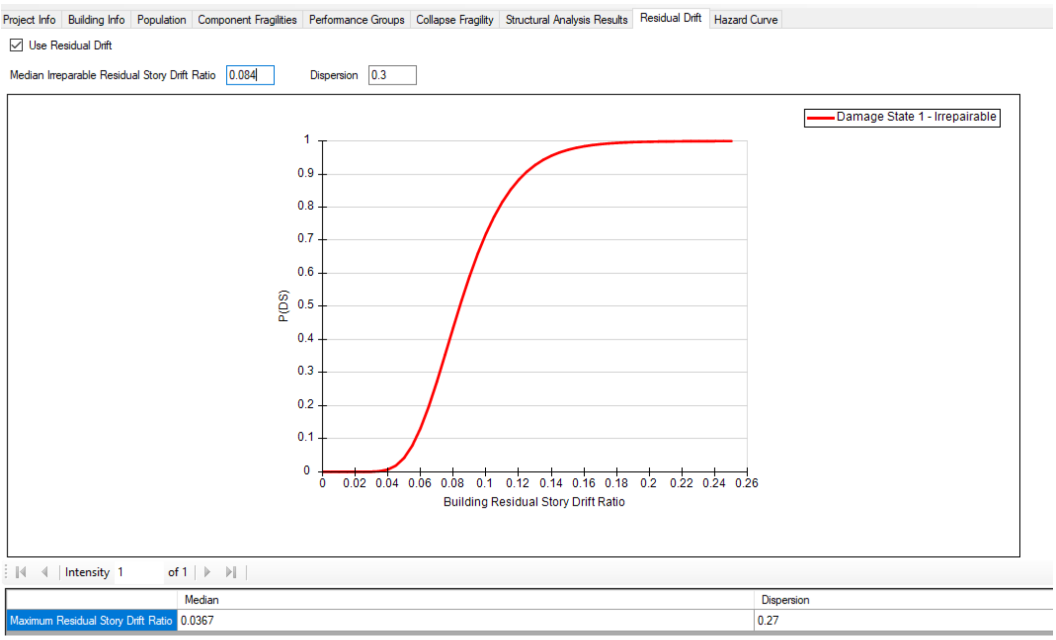


Fig 6. 15: *PACT Residual Drift tab.*

CHAPTER 7

INTERPRETATIONS AND RESULTS

The results of the performance assessment using the PACT tool are presented in this chapter. PACT offers a variety of options for viewing assessment results which will be shown within this chapter. These results can be reviewed at the PACT Control Panel by pressing the Examine Results button.

7.1 Review Results

On PACT results can be sorted by performance group, direction, story level, and realization. Figure 7.1 provides illustrative results of the PACT outputs for the case study intensity-based assessment. As it is shown, the estimated median repair cost is $389,795.9 which means 7.45% of the example building's total replacement cost. The contribution to repair cost due to each performance group is shown in the upper portion of the Repair Cost tab.

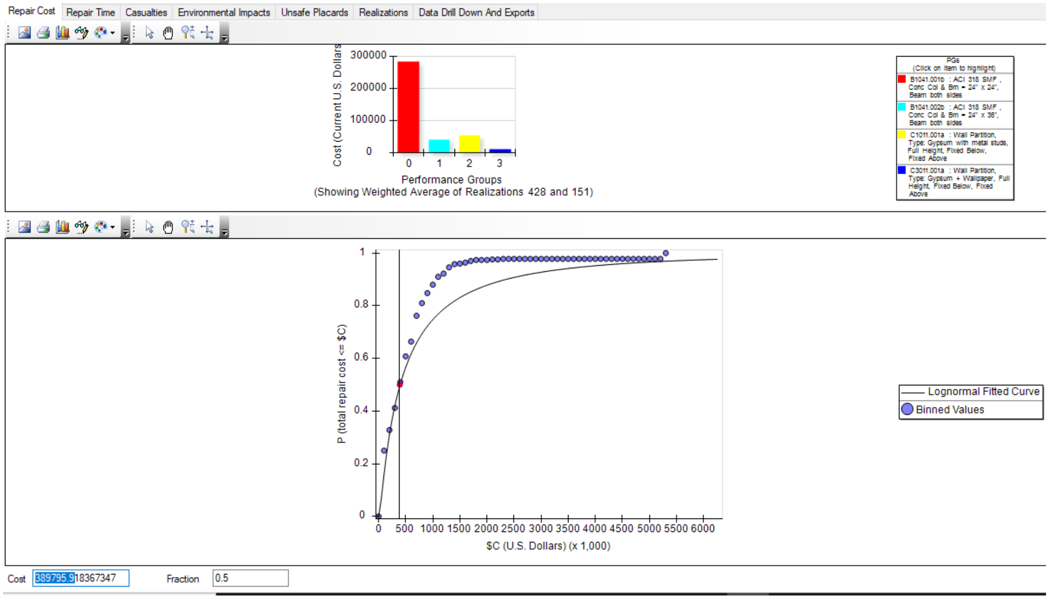


Fig 7. 1: *PACT Repair Cost tab.*

By selecting the Realizations button, a summary of performance group impact to the overall cost for each realization is represented as in the Fig 7.2. This figure indicates that residual drift plays a significant role to the total repair cost, which for approximately 25 of the 500 realizations is judged irreparable.

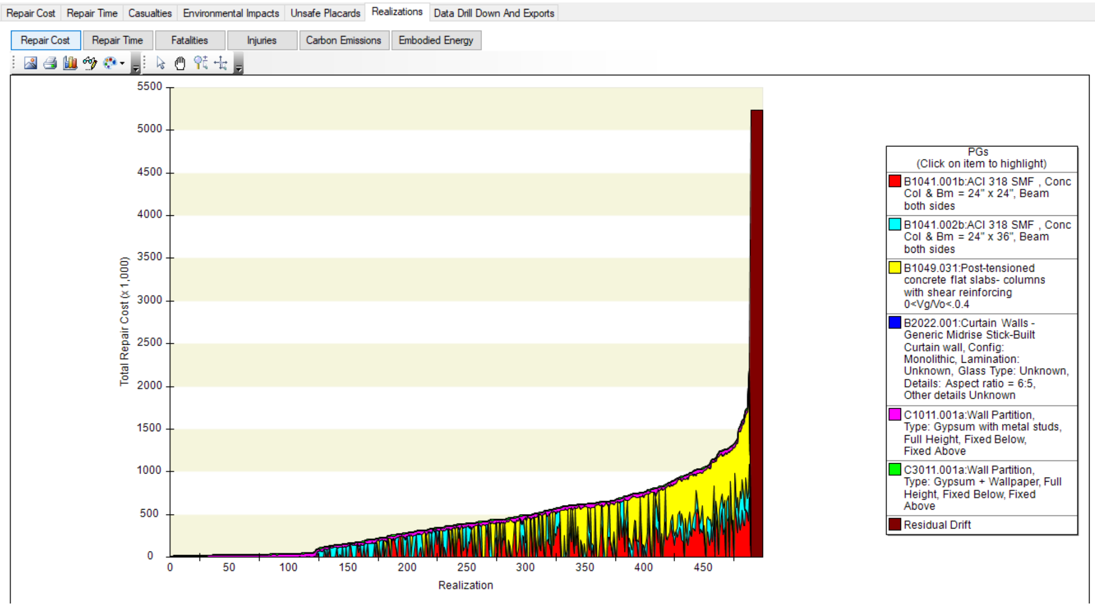


Fig 7. 2: *PACT Repair Cost tab with realizations.*

For this intensity, as shown, there is no collapse in any of realizations. The post-tensioned flat slabs are predicted to be the primary contributor to repair costs. For such cases, the replacement with an alternate component, if judged sufficient by the engineers, potentially lowers the entire cost of the report. The model can be rerun on PACT after such revision. Figures 7.3 to 7.5 show the graphical representation of repair time, fatalities, and injuries for each realization.

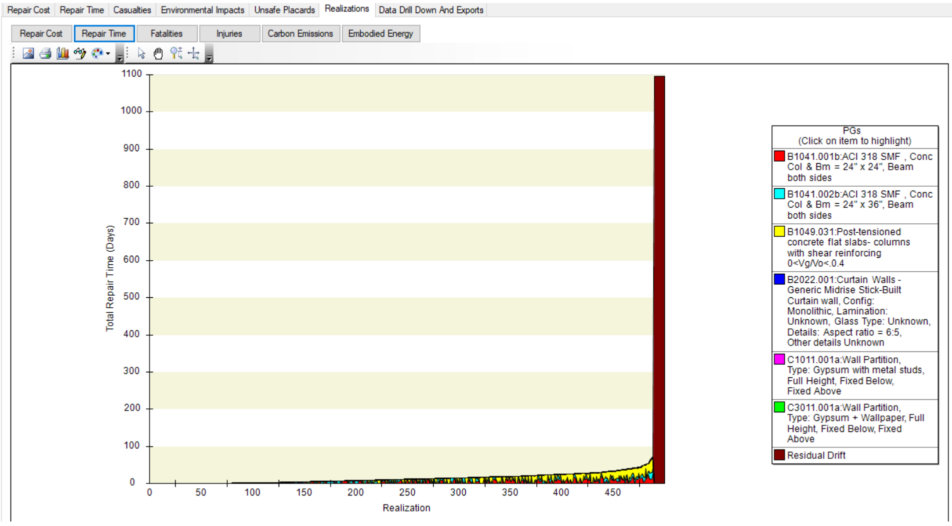


***Fig 7. 3:** PACT Repair time tab with realizations.*

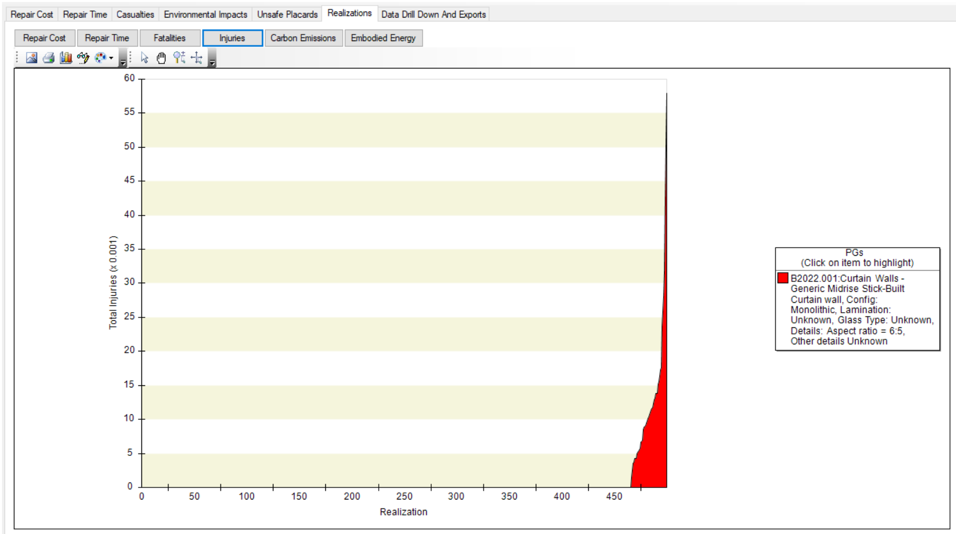


***Fig 7. 5:** PACT Fatalities tab with realizations.*

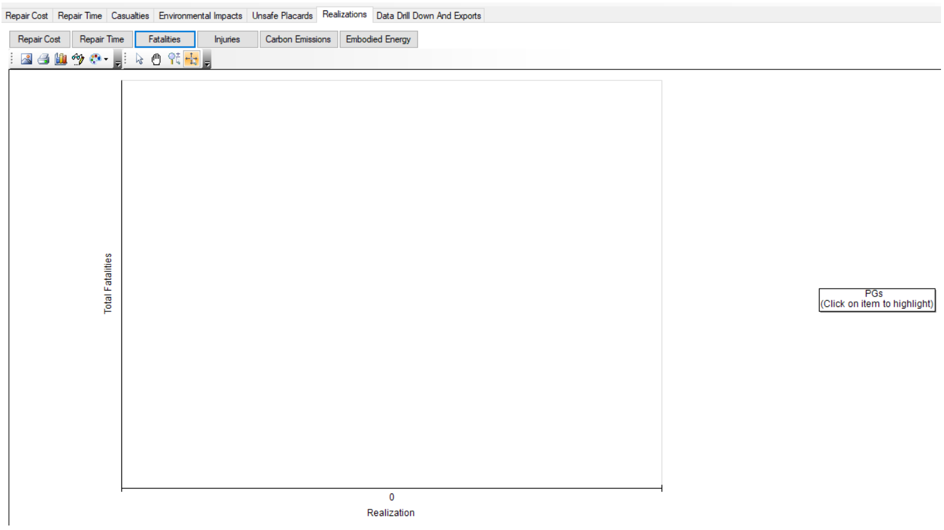


***Fig 7. 4:** PACT Injuries tab with realizations.*

CHAPTER 8

SUMMARY AND CONCLUSIONS

This study is focused on the basic concepts of seismic evaluation of RC buildings based on FEMA P-58 methodology. Appropriate decision making before earthquake occurrence, is a direct benefit of the followed methodology. Therefore, economical losses are reduced, and injuries or deaths are prevented at some high levels of accuracy.

8.1 Summary

In this thesis, FEMA P-58 methodology is used to estimate the earthquake losses for an eight-storey hypothetical building. The building used as a case study, is modeled as a RC frame structure and it is designed according to Eurocodes on SAP2000. For the seismic performance assessment, several fragility functions of the main structural and non-structural components provided on PACT are selected. To evaluate the collapse fragility curves, the nonlinear static approach is used. Firstly, the pushover analysis is performed and then the coordinates of the pushover curve are input into the SPO2IDA Tool for the linear approximation of the pushover curve. Next, as the Intensity-Based Performance assessment has been carried out, a target intensity given as earthquake ground shaking is chosen. Finally, the building's response is analyzed in order to determine the extent of the damage. The losses are then expressed in terms of casualties, repair cost, repair time, embodied energy, and carbon, considering different sources of uncertainties.

8.2 Conclusions

By integrating FEMA P-58 with structural analysis in SAP2000, loss prediction results are produced, which can be used to assess the post-earthquake economic resilience of various structures. PACT is a user-friendly tool which makes the obtained results very clear to the owner and decision makers. This methodology indicates that any building detail influences the results of the earthquake consequences. The results from this study are highlighted as following:

1. Repair cost is $389,795.9, (7.5% of building's total replacement cost), taking into account the estimated median repair cost for given intensity.
2. Repair time, by using similar approach as in the repair cost, is about 9.32 days.
3. Casualties: On the case study structure, no deaths or injuries are annualized for the used intensity.

8.3 Limitations and Recommendations for future research

For a well organization of all the activities involved on the evaluation of the seismic vulnerability of buildings, a BIM platform it is suggested for implementation. As a result, the performance groups are correctly located, allowing for precise damage determination under a particular scenario.

BIM has made the implementation of the FEMA P58 methodology more efficiently and accurately but there is a limitation in terms of the utilised programes. It would be great if there was compatibility between the program used to model the building and the program that does the seismic evaluation. This would save the working time and reduce the possibilities of making mistakes in the structural detail's generation process, which is essential for the analysis.

PACT provides a huge list of component fragility specifications, but it should be emphasized that the list does not contain all potentially vulnerable building components. Users must carefully identify any potentially damaging building feature that is not included in PACT. Also, there is a limitation in the geometry of the sections used for building elements. Only three types of cross sectons are provided for the RC frame on the PACT library. Although users can modify the provided fragility specification to reflect the actual section size, this degree of precision is seldom justified. A detailed study on the behaviour of various frame elements that involves the development of fragility curves, could contribute for a better structural model idealization.

The seismic performance assessment requires a realistic estimation of building conditions and components. This study evaluates the sesismic vulnerability of a building located on USA as proper hazard maps are not easily generated for Albanian seismicity. Furthermore, the cost values reflect the USA construction practice, so the implementation of FEMA P-58 to other territories logically requires conversion factors. Counting the limited number of research studies available in the literature, a beneficial study could be done to adapt FEMA P-58 to local conditions.

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