APPLICATION OF INCREMENTAL DYNAMIC ANALYSIS FOR SEISMIC PERFORMANCE ASSESSMENT OF A PREMODERN RC TEMPLATE BUILDING IN ALBANIA

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Approval sheet of the Thesis

This is to certify that we have read this thesis entitled **“Application of Incremental Dynamic Analysis for Seismic Performance Assessment of a Premodern RC Template Building in Albania”** 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

APPLICATION OF INCREMENTAL DYNAMIC ANALYSIS FOR SEISMIC PERFORMANCE ASSESSMENT OF A PREMODERN RC TEMPLATE BUILDING IN ALBANIA

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Albania is a country prone to earthquakes due to its location in a seismically active region, where the convergence of the tectonic plates often results in severe geological dynamics. The November 2019 earthquake emphasized the need to improve performance evaluation methods, due to the fact that many premodern buildings were severely damaged. This study evaluates the seismic performance of a template reinforced concrete building which is chosen to represent the commonly constructed designs with premodern codes during the 1980s in Albania. The building's seismic performance is evaluated by conducting a modern approach known as Incremental Dynamic Analysis (IDA). This analysis is performed using a series of dynamic time history analyses, simulating the effects of various intensity scales from a set of 20 ground motion records on the horizontal and vertical direction of the structure. For each ground motion, the IDA curves are constructed, and the limit states including Immediate Occupancy (IO), Collapse Prevention (CP) and Global Instability (GI) performance levels are allocated. To statistically categorize the generated data of the multi – record IDA curves, three percentile curves are obtained as 16%, 50% and 84%. In the end, the results from the demand calculations are evaluated to determine if they exceed or meet the performance point derived from probabilistic seismic hazard maps for the most seismically active region in the country.

Keywords: *RC template building, Incremental Dynamic Analysis, Seismic Performance Assessment, Premodern Codes, Zeus-NL, Limit States*

ABSTRAKT

APLIKIMI I ANALIZËS DINAMIKE RRITËSE PËR VLERËSIMIN E PERFORMANCËS SIZMIKE TË NJË NDËRTESË SHABLLON TË VJETËR BETON-ARME NË SHQIPËRI

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Master Shkencor, Departamenti i Inxhinierisë së Ndërtimit

Udhëheqësi: Dr. Marsed Leti

Shqipëria është një vend i prirur për tërmete për shkak të vendndodhjes së saj në një rajon sizmik, ku përplasja e pllakave tektonike shpesh rezulton në dinamika gjeologjike të ndjeshme. Tërmeti i nëntorit 2019 theksoi nevojën për të përmirësuar metodat e vlerësimit të performancës së ndërtesave, për shkak se shumë prej tyre pësuan dëmtime të rënda. Ky studim vlerëson performancën sizmike të një ndërtese beton-arme, e cila është zgjedhur për të përfaqësuar projektet e ndërtuara gjerësisht sipas kodeve të vjetra të ndërtimit gjatë viteve 1980 në Shqipëri. Performanca sizmike e ndërtesës vlerësohet duke përdorur një procedurë moderne të njohur si Analiza Dinamike Rritëse (IDA). Kjo analizë zhvillohet duke përdorur një seri analizash time-history, dhe duke simuluar efektet e intensiteteve të ndryshme nga një set prej 20 tërmetesh në drejtimin horizontal dhe vertikal të strukturës. Për çdo tërmet, ndërtohen kurbat IDA dhe caktohen kufijtë e performancës përfshirë Okupimin e Menjëhershëm (IO), Parandalimin e Rënies (CP) dhe Nivelin e Paqëndrueshmërisë Globale (GI). Për të kategorizuar në mënyrë statistikore të dhënat e gjeneruara të kurbave IDA, merren tre kurba të shprehura në përqindje 16%, 50% dhe 84%. Në fund, rezultatet vlerësohen për të përcaktuar nëse ato tejkalojnë ose përmbushin limitin e performancës të përcaktuar nga hartat probabilistike të rrezikut sizmik për rajonet më aktive të vendit.

Fjalët kyçe: *Ndërtesë beton-arme shabllon, Analiza Dinamike Rritëse, Vlerësimi i Performancës Sizmike, Kode paramoderne, Zeus-NL, Kufijtë e Performancës*

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

In Albania, a significant proportion of the population resides in masonry buildings constructed between 1970 and 1990, a period characterized by outdated building codes that lacked strict seismic regulations. During this era, the building code KTP-9-78 [1] was focused on designing buildings that resist only vertical loads. It was not until the introduction of the seismic code KTP-N2-89 in 1989 [2], that seismic considerations were implemented. Hence, buildings from this period are especially vulnerable to the impact of earthquakes.

Albania is located in the Balkans region, which has the highest seismicity in Europe, and the country has experienced several significant earthquakes in the past years [3]. Ensuring the structural integrity of these buildings during such events is one of the most important issues in the earthquake engineering community.

The most recent significant earthquake occurred on November 26, 2019, registering a Richter magnitude of 6.4. It struck the central western region of Albania, with the epicenter located offshore, northwest of Durrës. This devastating event resulted in 51 fatalities and injured over 3,000 individuals [4]. The structures that were reported to be the most damaged were those built during the communist era according to old building codes [5, 6]. After the earthquake, numerous field missions were organized to conduct structural and geotechnical inspections on these buildings. It was found that many exhibited critical deficiencies, including low-quality materials and insufficient shear reinforcement, as they were mass-constructed during the communist era to minimize architectural costs [6].

For this study, one of these templates from the 1980s era found under the name of “BANESA TIP PËR QYTETE ME SIZMICITET 7-8 BALLË” is selected. The assessment of structural performance is known to be a challenging task. Thus, this study aims to utilize a modern analysis methodology called Incremental Dynamic Analysis (IDA) [7].

1.2 Thesis Objective

This study focuses on the assessment of the seismic performance of a template reinforced concrete building using Incremental Dynamic Analysis. The selected building represents typical design templates commonly constructed in Albania during the 1980s. Blueprints for this building were obtained from the Central Technical Archive of Construction (AQTN) [8].

Incremental Dynamic Analysis is a modern approach that allows precise demand calculation [7]. It is also known as a dynamic pushover analysis, and it can replicate a series of time history analyses under a set of different ground motions by scaling the intensity measure until global instability is achieved.

The methodology involves a step-by-step guide on constructing the IDA curves, and a definition of limit states once the capacity curves are generated. The IDA analyses progress from capturing elastic behavior to exploring potential structural instability or collapse [9].

The IDA curves generated from the analyses are summarized at key percentiles 16%, 50% (median) and 84% to provide a probabilistic understanding of structural performance across the various ground motion scenarios.

An important aspect of this study is comparing the demand results to the hazard maps of Albania to evaluate the building's performance considering the region's PGA values. The residential building should normally satisfy the Life Safety (LS) performance level. However, due to the complex nature of the IDA curves, calculating the LS limit state requires significant effort. Therefore, the Immediate Occupancy (IO) limit state is used as a guideline while comparing the results to a performance point derived from Albania's probabilistic hazard maps.

The study gathers results from the analyses, offering meaningful insights into the seismic performance of the chosen template reinforced concrete building in Albania.

1.3 Scope of works

The first step involves selecting a template that represents commonly designed reinforced concrete buildings during the 1980s era in many regions of Albania. The chosen template is a five-story residential building with symmetrical frames and no shear walls. Given the significant impact of the building's total mass in nonlinear dynamic analyses, the next phase involves careful calculations of the dead and live loads for each element in the building frame. Following these preliminary steps, a set of 20 ground motion records is selected to represent a range of seismic scenarios.

Frames are selected for both the X and Y directions of the building and analytically modeled using ZeusNL software. To assess seismic performance, a series of Incremental Dynamic Analyses are conducted, revealing the seismic vulnerability of the frames and their behavior as they progress from elastic to global instability.

The results from these analyses are grouped into fractiles, which are statistical representations of the structure's seismic response. The generated data helps to evaluate how often certain levels of demand are exceeded.

The calculated Immediate Occupancy performance level of the curves is then compared to thresholds derived from the probabilistic seismic hazard maps of Albania. Given that Albania is located in the Balkans, a region with moderate to high seismicity, this comparison is crucial for understanding how well the structures can withstand potential earthquakes.

1.4 Organization of the thesis

This thesis is divided into 7 chapters. The organization is done as follows:

Chapter 1 raises the challenges that the earthquake engineering community faces in the assessment of structural behavior under ground motion. It discusses how the November 2019 earthquake in Albania raised the urgent need to establish seismic performance evaluation methods, given that many buildings were constructed without adequate seismic regulations. Additionally, it introduces a modern methodology, the

Incremental Dynamic Analysis (IDA), which has been previously validated to yield more precise results for seismic evaluation in comparison to conventional analyses. This chapter presents the thesis objective and scope of works. The introduction outlines all the issues that are to be discussed in other chapters of the study.

Chapter 2 lays down the existing literature for Incremental Dynamic Analysis (IDA). It introduces two key concepts: Intensity Measure (IM) to describe ground motion scaling, and Damage Measure (DM) to measure structural response. Together, they form the IDA curve, showing how a structure behaves at varying intensities of ground motion, from elasticity to instability. The most common algorithms used to construct the curves are briefly introduced. The general principles for defining limit-states and estimating capacities are explored, along with methods to summarize multi-record IDA studies.

Chapter 3 walks through the practical application of Incremental Dynamic Analysis (IDA) using a 5-story residential building as a case. It guides readers step-by-step, from selecting ground motion measures to defining limit-states and estimating capacities. The methodology concludes by integrating IDA results with Probabilistic Seismic Hazard Analysis (PSHA) to assess seismic risk.

Chapter 4 includes all the data and information regarding the selected building for this case study. It offers insights into the properties of each structural element.

Chapter 5 provides a condensed manual for the ZeusNL software used in the study, outlining its evolution, key modules, and operational principles. It offers insights into the software's history, core functionalities like nodes, data processing and visualization. The chapter explains how the software processes input data, how sections and materials are incorporated into the structural model and produces analytical outputs.

Chapter 6 includes all the results collected from the previous chapters. The outcomes of all the work done are further discussed in this part of the study.

Chapter 7 restates the importance of the seismic performance evaluation of old buildings in Albania and summarizes the study. It also leaves room for comments and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Performance-Based Earthquake Engineering

Performance-Based Earthquake Engineering (PBEE) is a comprehensive approach that evaluates the earthquake resistance of buildings through a systematic and quantifiable framework [10]. Unlike traditional seismic design codes, it considers a spectrum of performance levels and assessing the possible outcomes of seismic events on structures. Building performance, within the context of PBEE, can be evaluated by examining various factors that affect the safety of occupants during and after seismic events. These factors include the expenses and practicality associated with returning the building to its condition before the earthquake, the duration needed for restoration, and the wider financial, architectural, or cultural implications that come with the event [11].

One crucial aspect of PBEE is the establishment of Building Performance Levels, which serve as benchmarks to categorize the extent of damage a structure might incur during an earthquake. These levels are crucial to determining rehabilitation objectives, providing a range of solutions to meet specific structural and societal needs. The selection of appropriate performance levels ensures a thorough understanding of seismic risks, allowing for more precise and effective earthquake-resistant design strategies [12].

2.1.1. Seismic demand and capacity

Understanding the relationship between demand and capacity is important when evaluating a building’s earthquake resistance. Seismic demand represents the magnitude of seismic forces or deformations that a structure experiences during seismic activity. Various factors shape seismic demand, including the severity and duration of ground motion, earthquake attributes, and the structure's location and type. It is essentially the "demand" that the earthquake places on the structure. Seismic capacity refers to the building’s capability to withstand seismic stresses and strains. It is a measure of the structure's strength, stiffness, and ductility. The capacity is determined by the design and construction choices made for the structure, including the materials used, the structural system employed, and the detailing of connections. Essentially, it represents the structure's “capacity” to endure the seismic demand. If the demand surpasses this capability, the structure may incur damage or fail. Therefore, earthquake engineers strive to design structures with sufficient capacity to withstand the expected seismic demand. This is often expressed in terms of a safety margin, where the capacity is designed to be greater than the expected demand.

Visually, the point where the demand curve intersects with the capacity envelope offers valuable insights into the seismic behavior of a structure [13].

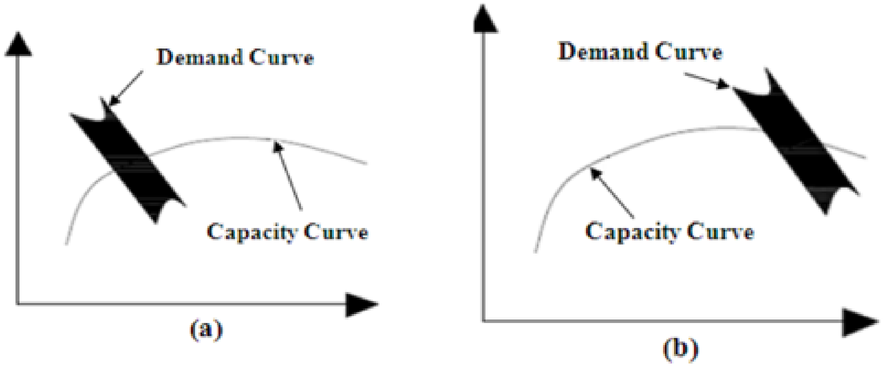


Figure 1. Demand versus capacity curves [13]

When the demand curve crosses paths with the capacity envelope within the elastic range, as depicted in *Figure 1a*, it indicates that the building that is being examined has good robustness against seismic forces. This suggests that the building exhibits enough flexibility and stiffness to endure the seismic vibrations without undergoing significant damage. On the other hand, if the demand curve intersects the capacity curve beyond the elastic limit, as illustrated in *Figure 1b*, means that the structure is not going to perform well during ground shaking. This scenario suggests that the structure is operating close to its limit, and there is limited margin for absorbing additional seismic forces. In such cases, it becomes crucial to consider seismic retrofitting or rehabilitation measures to enhance the structure's resilience and prevent collapse.

2.1.2. P-Delta Effect on Structures

In discussions concerning the P-delta effect, when a structure deforms under the influence of vertically and horizontally applied loads, the resulting shape can lead to additional bending moments. These additional moments, known as P-delta moments, arise due to the interaction between the deformed shape of the structure and the applied loads [12]. They contribute to the overall structural response and should be considered, especially when analyzing structures in dynamic approaches, to accurately predict the behavior of the structure.

The analysis that does not consider the P-delta effect is called "first order analysis," while the one considering it is termed "second order analysis." The P-delta effect adds an extra moment which is generated by the bent shape of an element, alongside the initial moment based on the non-deformed shape. In simpler terms, during static analysis (when we're looking at how a structure behaves when loads are not changing), the P-delta effect usually makes the building sway more to the side. But when we're analyzing how the building responds to changing loads (dynamic analysis), the P-delta effect can make the sway stronger or weaker. It depends on how the loads change over time and how quickly the building naturally vibrates. This effect can have a big impact, pushing the structure's response beyond its usual limits [14].

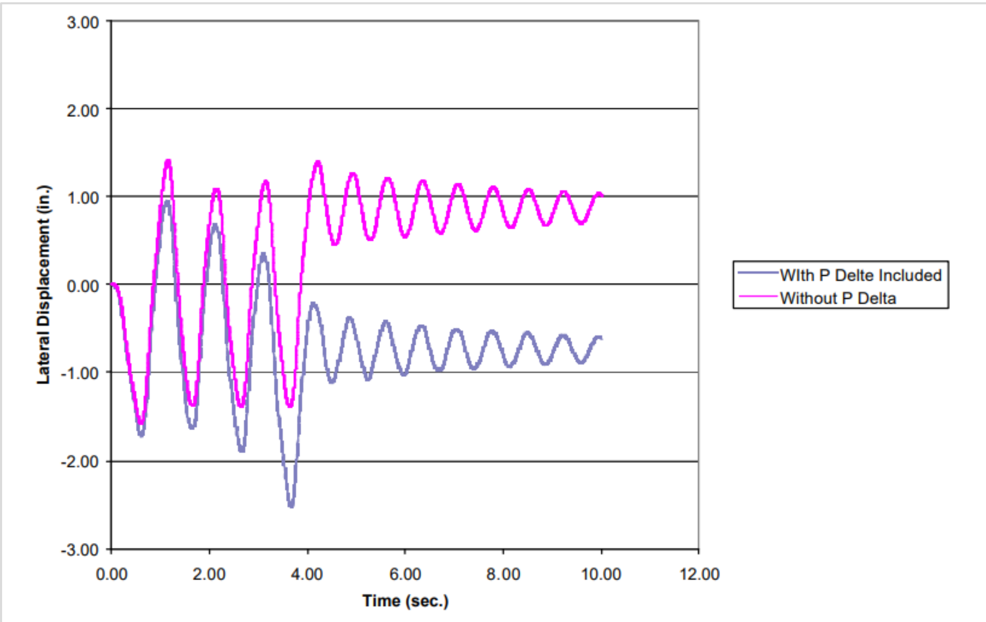


Figure 2. P-Delta Effect on Structure Responses [14]

When buildings face earthquakes and are designed to allow yielding under the shaking, it is really important to consider the P-delta effect in the analysis. This means we need to take into account how the building's shape changes as it bends. We do this by adjusting the stiffness of the building, which we call geometric stiffness.

2.1.3. Building Performance Levels

Performance-based seismic engineering is mainly concerned with establishing limit states to indicate varying levels of structural performance, such as material strains, rotations, displacements. Seismic rehabilitation codes such as ASCE 41-06 [15] and FEMA 356 [12] evaluate three important damage levels:

At the Immediate Occupancy (IO) level, structures may exhibit minor cracks in non-structural elements, however they are considered as safe for occupancy. At this level, the structure is easily repairable.

Progressing to the Life Safety (LS) level, structures are designed to maintain stiffness and strength across all stories, with a consideration for permanent drift. In such cases, even if repair is possible, the total cost may not significantly differ from complete reconstruction.

Lastly, the Collapse Prevention (CP) level signifies structures with minimal stiffness and strength in all stories, where columns and walls maintain functionality, though non-structural components may suffer damage, bringing the building close to collapse [15]. The construction is not safe for re-occupancy and could not be technically practical to repair, according to FEMA 356 [12].

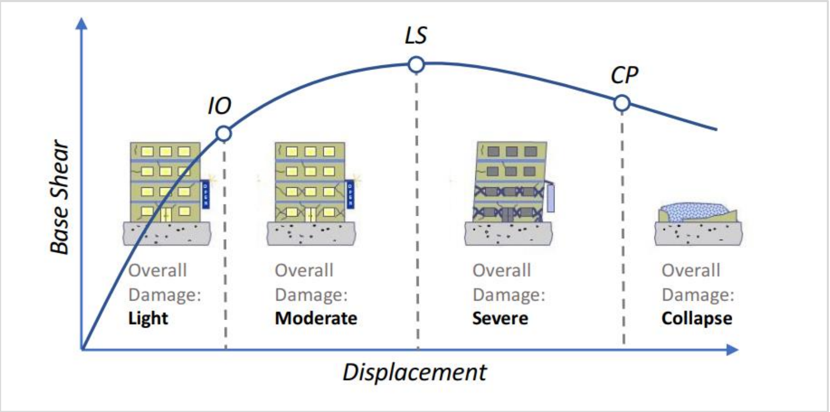


Figure 3. Limit states of a building [16]

This seismic code further provides specified rotations at these levels, serving as critical acceptance criteria during the evaluation of reinforced concrete elements through both linear and nonlinear procedures. As such, the ASCE 41-06 code [15] not only establishes a damage classification system but also offers quantifiable metrics to guide engineers in assessing the seismic performance of structures across these states.

2.2 Nonlinear Analyses

Nonlinear analyses are a key component in earthquake engineering, serving as a fundamental tool to assess the structural response beyond the elastic limit. These analytical approaches address the materials' nonlinearity, offering a more realistic illustration of a structure's behavior under seismic loading. In earthquake engineering, two primary types of nonlinearities are considered.

2.2.1. Nonlinear Static Analyses

Static nonlinear analysis is commonly performed through pushover analysis. Pushover analysis involves applying lateral loads incrementally, allowing engineers to observe the progression of deformations and assess the structure's response at various performance levels until global failure is reached [13]. This method provides valuable insights into potential failure mechanisms, allowing for the identification of weak points and informing the development of effective retrofitting strategies. Pushover curves is plotted using the base shear versus the global drift in the vertical and horizontal axis respectively.

2.2.2 Nonlinear Dynamic Analyses

On another note, dynamic nonlinear analyses simulate the structure's response over time using actual earthquake ground motion records. Unlike static analysis methods, time history analysis considers the time-varying nature of seismic forces, providing a more realistic representation of structural behavior during an earthquake. This approach involves applying the recorded ground motion data to the structure, allowing engineers to assess dynamic effects, such as inertial forces and damping, on the building's response. Time history analysis is particularly valuable for capturing the intricate and often complex interactions between the structure and the ground motion, enabling a comprehensive understanding of how a building behaves under different seismic conditions [17]. This method is crucial in Performance-Based Earthquake Engineering (PBEE) as it facilitates the prediction of structural responses at various damage states, assisting in setting performance goals and seismic design standards. Time history analysis thus stands as an essential tool in ensuring the seismic resilience of structures by offering a detailed and accurate assessment of their behavior under realistic seismic conditions.

While nonlinear analysis provides invaluable insights, it comes with challenges. The computational demands of nonlinear analysis necessitate advanced numerical techniques and powerful computing resources. Ongoing research in this field aims to improve modeling techniques by incorporating refined constitutive models and enhancing computational efficiency.

2.2.2.1 Incremental Dynamic Analysis (IDA)

Incremental Dynamic Analysis (IDA) is a valuable method for evaluating how structures respond to earthquakes. It assists in understanding how a building behaves at different levels of earthquake intensity. Introduced by Vamvatsikos and Cornell [7], IDA involves running computer simulations of a building's response to many earthquake scenarios, each with different levels of shaking. This process covers everything from small vibrations to the worst possible shaking. IDA gives a detailed understanding of how buildings perform by estimating what's called "demand" given the intensity of shaking. This helps set safety goals like making sure a building is safe to occupy right after an earthquake or preventing it from collapsing. IDA is useful for deciding how to make buildings stronger against earthquakes through methods like retrofitting or repairs.

The key objectives of Incremental Dynamic Analysis (IDA) include:

- Examining how a structure responds across various levels of ground motion intensity, from elasticity to dynamic instability.

- Getting a clearer understanding of how buildings react when there are rare or very strong earthquakes.
- Figuring out how buildings react when the intensity of the earthquakes gets progressively higher, like noticing how they bend more or when they start to weaken.
- Producing estimates of a structure's dynamic capacity to withstand seismic forces across different intensity levels.
- Evaluating the stability or variability of structural response and demands across multiple earthquake data sets [7]

The application of IDA encompasses several pivotal steps. Initially, constructing a comprehensive computer model of the building capable of accurately simulating bending and torsional behavior similar to real-world scenarios. Then, finding a collection of seismic recordings. Following this, determining the magnitude of each earthquake by adjusting their scales accordingly. Proceeding, conducting simulations of the building's reaction to each seismic event. Lastly, processing the generated data to develop graphical representations illustrating the extent of potential structural damage measured by the Damage Measure (DM) parameter across varying seismic intensities measured by an Intensity Measure (IM).

While IDA involves complexities, advancements such as the hunt & fill algorithm contribute to computational efficiency. This algorithm optimally selects record scaling levels, minimizing the number of required runs and ensuring accuracy. The IDA process is automated, making it user-friendly and allowing for seamless integration with existing analysis programs.

2.2.2.1.1 Fundamentals of IDA

In 2002, Greek researcher Dimitrios Vamvatsikos and American researcher, Stanford University professor C. Allin Cornell, jointly authored a seminal research article on Incremental Dynamic Analysis (IDA) [7]. This comprehensive work delved into the foundational principles, key concepts, and terminology of the method, offering a thorough exploration that became a cornerstone reference in the field of structural engineering dynamics and seismic risk assessment. Incremental Dynamic Analysis curves are divided in two groups, the single record IDA and multiple record IDA.

2.2.2.1.1.1 Single Record IDA

As a first step, all the terms that are needed should be clearly defined, and the methodology should be started using the concept of scaling an acceleration time history as a basic building block for this approach.

Definition 1: The SCALE FACTOR (SF) is a non-negative scalar λ that produces a scaled accelerogram applied to the natural acceleration time history. $\lambda = 1$ signifies the natural accelerogram, while for $\lambda < 1$ the accelerogram is scaled down, oppositely for the $\lambda > 1$ the accelerogram is scaled up.

Definition 2: INTENSITY MEASURE (IM) is a non-negative scalar IM that depends on the unscaled accelerogram and monotonically increases with a factor λ. The IM values are proportional to the SF since IM = λ. Examples of the IMs are the peak ground acceleration, 5% damped spectral acceleration and the reduction factor (R).

Definition 3: DAMAGE MEASURE (DM) or also known as Structural State Variable, is a non-negative scalar parameter (DM) that characterizes the response of the structural model under the applied seismic loading. Based on the user's preferences, DM can be obtained as: maximum base shear, node rotation, maximum story ductility, roof drift, global drift, interstory drift etc.

Now we are able to define the IDA.

Definition 4: SINGLE RECORD IDA often referred to as Dynamic Pushover (DPO) or simply Incremental Dynamic Analysis (IDA), involves a systematic series of time history analyses performed under various accelerograms. These accelerograms represent ground motion records scaled to various levels of intensity, typically quantified by Intensity Measures (IM). Each analysis incrementally increases the intensity of the applied ground motion, pushing the structure beyond its elastic limit and progressing towards global collapse. This iterative process allows engineers to capture the evolving structural response under realistic seismic loading conditions, recording DM values for each IM step.

Definition 5: IDA CURVE is a graphical representation of the damage measure variable (DM) plotted against one or more Intensity Measures (IMs) that define the scaled accelerogram applied. These curves can be depicted in two or more dimensions based on the number of IMs used, typically with at least one being scalable. In conventional two-dimensional plots, the IM, smiliar to "force," is presented on the vertical axis, while the DM is on the horizontal axis, resembling stress-strain or force-deformation graphs.

2.2.2.1.1.2 Multiple Record IDA

Definition 1: MULTI RECORD IDA involves conducting several individual IDAs on the same structural model, each using a different accelerogram, to comprehensively capture the range of potential responses influenced by the choice of ground motion record. All Incremental Dynamic Analysis curves can be plotted on the same graph, as shown in *Figure 4.*

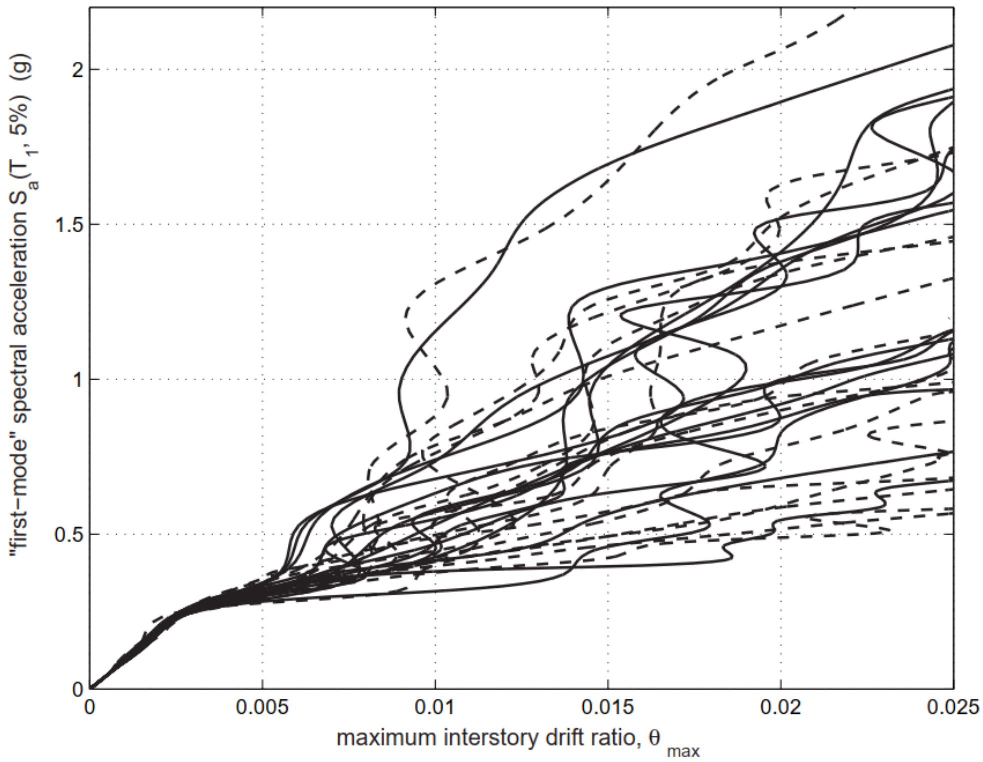


Figure 4. Thirty IDA curves plotted in the same graph

Definition 2: An IDA CURVE SET is a compilation of IDA curves for a single structural model subjected to varied accelerograms, that are all parameterized on the same IMs and DM values.

For each curve, it displays a specific outcome based on the structural model and ground motion record. However, to consider the randomness associated with potential ground motion records a building might encounter, probabilistic characterization is necessary. To represent the overall trend and variability within the dataset, engineers combine the IDA curves into percentiles such as the 16%, 50%, and 84% fractiles, as illustrated in *Figure 5.*

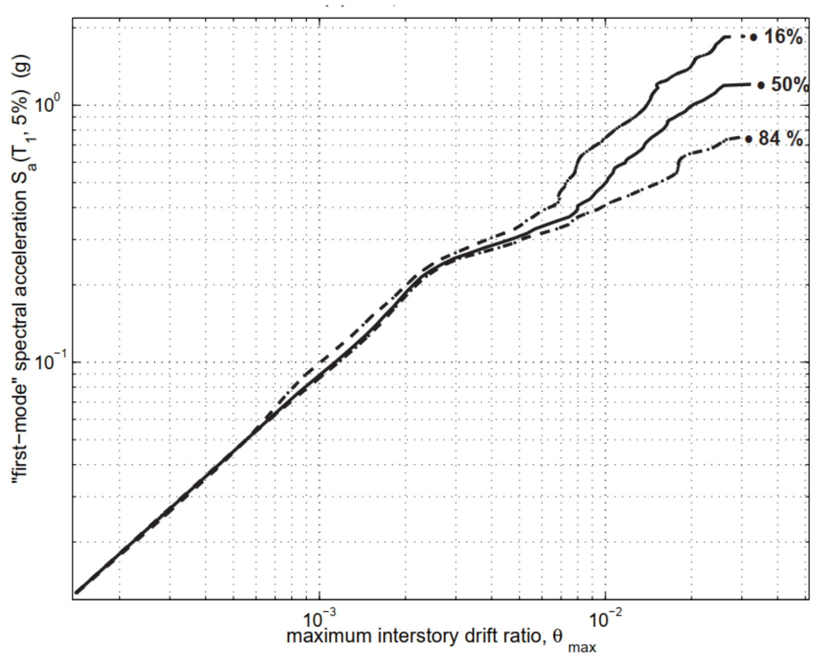


Figure 5. 16%, 50% and 84% IDA percentiles

2.2.2.1.2 General Properties

In an IDA study, when different ground motions are applied to a structural model, they often produce varied capacities that are hard to anticipate beforehand. For example, *Figure 6* shows different behaviors of a 5-story frame, progressing from slow weakening to extreme weaving behavior. Each graph shows how the structure responds to different ground motions at various intensities, and they are both similar and different in interesting ways. All curves start with a linear elastic region that ends when the structure's elements stop being elastic. This segment's slope, called "stiffness," may vary slightly between ground motions but remains the same for similar systems. At the other end of the curves, they stop at different intensity levels. Some curves sharply soften and collapse, while others follow a pattern of softening and hardening, where the rate of damage accumulation may increase or decrease. Eventually, if the model allows, a final softening occurs, indicating dynamic instability. This behavior is observable across various intensity measures and demand measures [7].

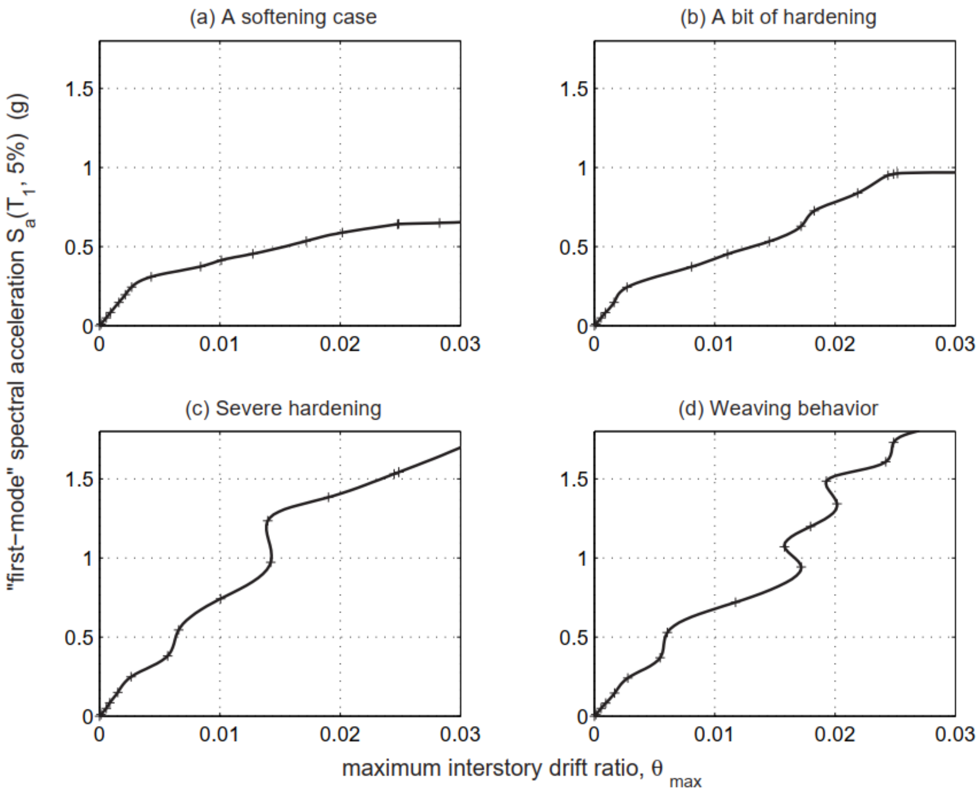


Figure 6. IDA curves for a 5-story steel braced frame subjected to 4 different records

Another interesting structural behavior that has been observed is that of multi storey buildings. *Figure 7* shows the IDA curve for each floor level of a 5-storey structure. In this case it can be observed that the curve of the second floor goes under extreme softening and later on acts as fuse for the above stories. In IDA curves, hardening isn't new, but it's still surprising that a system might show less damage even when the earthquake gets stronger. This happens because weaker cycles early in the earthquake can cause damage, making the structure stronger for later, stronger cycles.

In tall buildings, one floor might yield early, protecting the ones above it. Even simple structures can show this, becoming less responsive to stronger earthquakes after yielding early.

Sometimes, a structure might seem like it's going to collapse at one intensity but then still stands at a higher one, showing a lot of damage but not collapsing. As IDA curves get more complicated, we can see them as mathematical functions, where each intensity measure (IM) gives one damage measure (DM), but each DM might come from different IMs. These curves aren't always smooth or continuous because they can have sharp changes due to collapses and recoveries. As the intensity of the earthquake simulation increases, weaker responses at the beginning of the recorded history may become strong enough to cause damage, like bending or breaking. This changes how the building behaves for stronger shaking later on. In tall buildings, stronger shaking might cause one floor to bend or break first, acting as a safeguard to protect the floors above it [7].

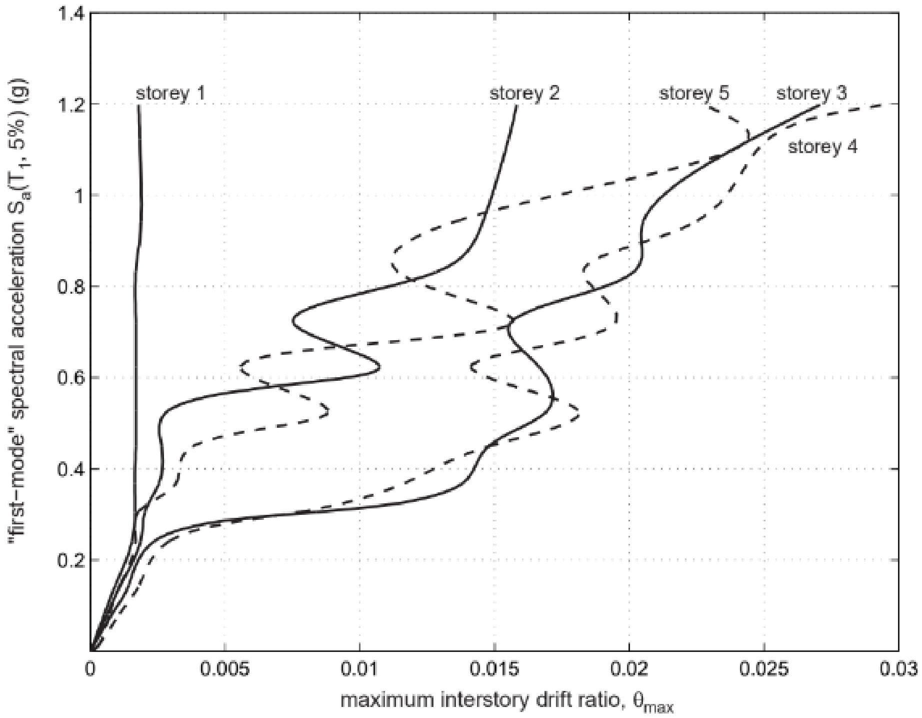


Figure 7. IDA curves of peak interstory drifts for each floor for 5-story steel braces frame

2.2.2.1.2 Determination of Capacity and Limit States

In Performance Based Earthquake Engineering (PBEE), IDA is known as a good alternative analysis to assess how buildings respond to seismic events. These curves are crucial for establishing performance levels, which indicate the building's ability to withstand earthquakes without sustaining significant damage or collapsing. However, determining these performance levels is not a straightforward task [7]. There are two primary approaches:

The *DM-based rule* involves setting criteria based on observable structural damage, such as deformation or cracking. This method is relatively straightforward to implement and interpret, making it accessible for engineers. However, it may not capture all aspects of structural behavior accurately, leading to potential oversights in assessing building performance.

The *IM-based rule* follows what's called the 20% tangent slope method. In simpler terms, we look at the curve and find the last point where the slope of a line touching the curve is 20% of the slope at the beginning. This point is then marked as the capacity point. While this method provides a more comprehensive understanding of the building's behavior under different seismic conditions, it is complex and requires customization for each building based on its structural characteristics and geographical location.

Engineers often combine these approaches to develop comprehensive guidelines for assessing building performance during earthquakes. It has been concluded that Immediate Occupancy (IO) level usually belongs to 0.5% of the DM value for a maximum global drift ratio example in premodern buildings (θ_{max} = 0.5%).

Collapse Prevention (CP) will occur at the 20% tangent of the elastic slope in a range of DM values beginning from the IO point to θ_{max} = 10%. In cases when there are multiple points satisfying such a rule, as illustrated in *Figure 8*, we take the first second point where the slope is 20% due to extreme hardening.

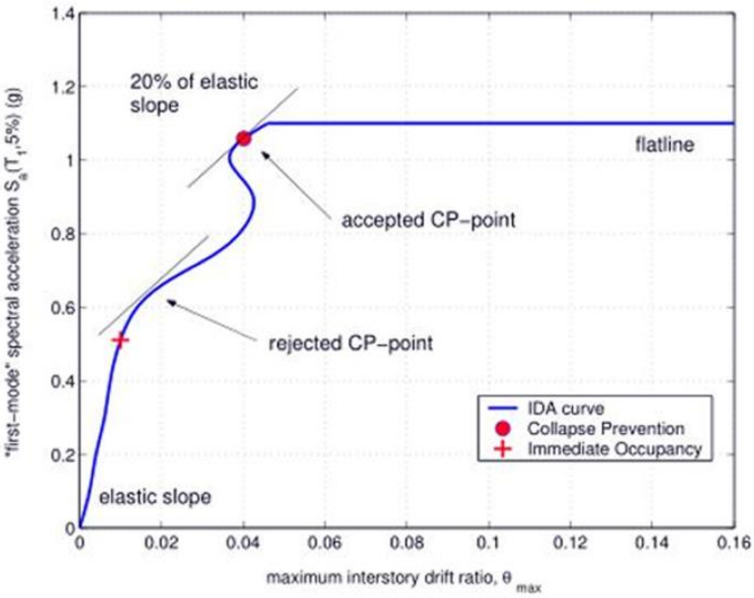


Figure 8. Limit states defined on the IDA curve

There are also cases of resurrection which causes the appearance of a second, fake flatline, and as a result, two or more points satisfy the 20% slope approach. In that situation, the first flatline is taken into consideration and the region above it is ignored, as shown in *Figure 9*. Finally, Global Instability (GI) point is marked at the start of when the IDA curve softens and the flatline is reached [18].

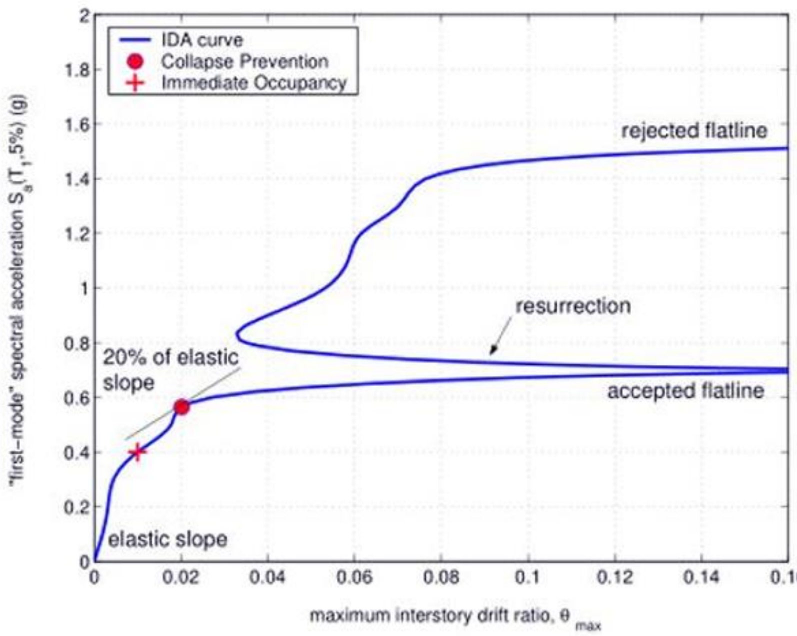


Figure 9. Limit states defined on the IDA curve in the case of resurrection

2.2.2.1.3 IDA VS Nonlinear Static Pushover

Both Incremental Dynamic Analysis (IDA) and Static Pushover (SPO) are incremental analyses, thus examining the similarities and dissimilarities between these curves will be important. Since the incremental loading is applied to the same structural model, it is expected that there will be some correlation in the results between both analysis curves.

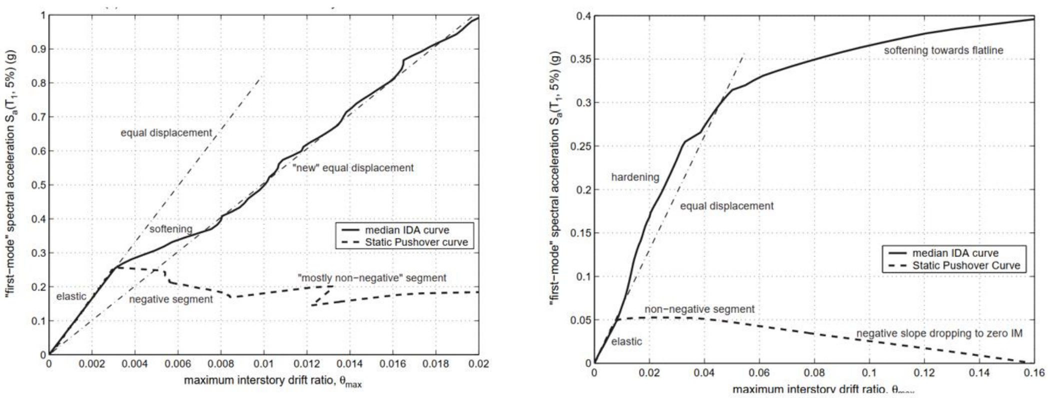


Figure 10. The median IDA versus the Static Pushover curve for (left) a T_1 = 4 sec, 20storey steel moment-resisting frame with ductile connections and (right) a T_1=1.8 sec, 5storey steel braced frame

When we compare the two curves, we notice that they often have similar patterns:

The beginning part, where the building behaves elastically, matches well. After that, there's a part where the SPO's stiffness reduces, which correlates with a phase in the IDA where the building behaves almost elastically. If the SPO's slope becomes negative, it means the building's response might lead to collapse in the IDA unless there's a positive part in the SPO to stop it. Finally, if there's a non-negative part in the SPO after a negative slope, it appears as a modified version of the previous elastic phase in the IDA, but with lower stiffness.

Overall, both IDA and static pushover give similar values as belongs to damage measure DM. Different results are observed for intensity measures (IM) when IDA gives much higher results than static pushover one. However, researchers have concluded that IDA provides more accuracy than the other analyses, and comparisons have shown that the static pushover curves tend to underestimate or overestimate the performance of the structure [7].

2.2.2.1.4 IDA Algorithms

Despite the simplicity of the theoretical concept behind an Incremental Dynamic Analysis (IDA) study, conducting one can be quite resource-intensive. Due to the high computer processing power that is required for each dynamic nonlinear run, it's necessary to formulate algorithms that carefully select discrete Intensity Measures (IM) values to create IDA curves efficiently. The goal is to strike a balance between achieving a high resolution of demand and capacity on the curve. Demand resolution involves evenly spacing points along the curve to avoid gaps larger than a certain tolerance, while capacity resolution requires concentrating points around the flatline to accurately bracket it. In a multi-record IDA study, there are advantages to adjusting the grid of points based on information from previous results.

There are two types of algorithms used to construct IDA Curves: stepping algorithm and the hunt & fill tracing algorithm [7].

STEPPING ALGORITHM is used to incrementally increase the Intensity Measure (IM) by a constant step until collapse is reached, thereby creating a uniformly spaced grid of points on the curve.

repeat

  select an initial IM value

  increase the IM by a predefined step

  scale record, run analysis, and extract DMs

until collapse is reached, either by satisfying a collapse rule or by failing to converge to a solution.

The stepping algorithm is one of the simplest approaches, where IM is increased by a constant step until collapse. However, its efficiency depends heavily on the choice of the step size and can lead to unbalanced distribution of runs along the curve. To improve upon this, enhancements such as allowing step increases and adding step-reducing routines have been proposed. Another strategy is the hunt & fill tracing algorithm, which combines larger leaps to bracket the IM parameter space with subsequent gap-filling to improve both capacity and demand resolution.

HUNT & FILL TRACING ALGORITHM is used to efficiently locate the capacity and improve both demand and capacity resolution by strategically increasing steps and filling in gaps.

Hunting Phase

increase IM by a step

scale record, run analysis, and extract the DMs

increase step

repeat steps 1-3 until collapse is reached

Step-Reducing Routine (Bisection):

select an IM value in the gap between the highest non-collapsing and lowest non-collapsing IMs.

scale the record, run the analysis, and extract the DMs.

repeat until the difference between the highest collapsing and lowest non-collapsing IM-gap is less than a predefined tolerance.

This algorithm aims to strike a balance between demand and capacity resolution by adjusting the step size dynamically. However, it may require additional computational resources and careful tuning of parameters to ensure efficiency and accuracy. Regardless of the approach used, it's crucial to ensure a dense enough grid of IM values to accurately detect any structural resurrections that may occur before the final flatline.

2.3 Seismic Hazard of Albania

The seismic hazard of Albania is a critical factor in the design of earthquake-resistant structures. It has a long history of seismic activity, necessitating a huge amount of data collection and mapping. Continuous improvement of procedures for defining seismic hazard at both regional and local levels is essential to optimize these designs. Key elements in defining seismic action in design codes include reference motion and detailed characterization of soil conditions. Recently, a new probabilistically based seismic hazard map of Albania was developed by the

Seismological Institute, highlighting the need to update the site-dependent spectral response parameters in the current Albanian seismic code KTP-N.2-89. This update is necessary as the current procedures are not based on the Probabilistic Seismic Hazard Analysis (PSHA) approach, widely accepted for its comprehensive methodology [19].

Seismic hazard analysis assesses the potentially damaging phenomena to which a region or facility may be subjected during its useful life. The primary methods used today are deterministic and probabilistic approaches, with PSHA being the most widespread. The PSHA, first proposed by Cornell in 1968 [20], evaluates the probability that a ground motion parameter will be exceeded within a specific time period. This analysis can result in hazard curves or maps showing spatial variability for a given return period.

2.3.1 Probabilistic Seismic Hazard Analysis (PSHA)

The PSHA method for calculating seismic hazard in Albania involves several key steps [3]:

- ❖ Earthquake Catalogues: Collecting comprehensive data on past seismic events is crucial. This includes information from both historical records and modern instruments.
- ❖ Characterization of Seismic Source Zones: Identifying seismic source zones and their parameters helps in understanding potential earthquake-generating faults.
- ❖ Strong Seismic Ground Motion: Selecting appropriate attenuation relationships to estimate ground motion intensity is vital for accurate hazard assessment.
- ❖ Computation of Seismic Hazard: Determining the annual frequency of exceedance for ground motion parameters like peak ground acceleration (PGA), peak ground velocity (PGV), or spectral acceleration (SA) forms the basis of probabilistic analysis.

Recent studies and the development of a new probabilistic seismic hazard map mark significant progress in Albania's seismic hazard assessment. These developments are aimed at revising the seismic coefficients in the current Albanian seismic code and adopting a new code aligned with the Eurocode 8 (EC8) [21] approach. This modern approach will incorporate site-specific response parameters, resonance effects, and liquefaction susceptibility, providing a more robust framework for the design of earthquake-resistant structures.

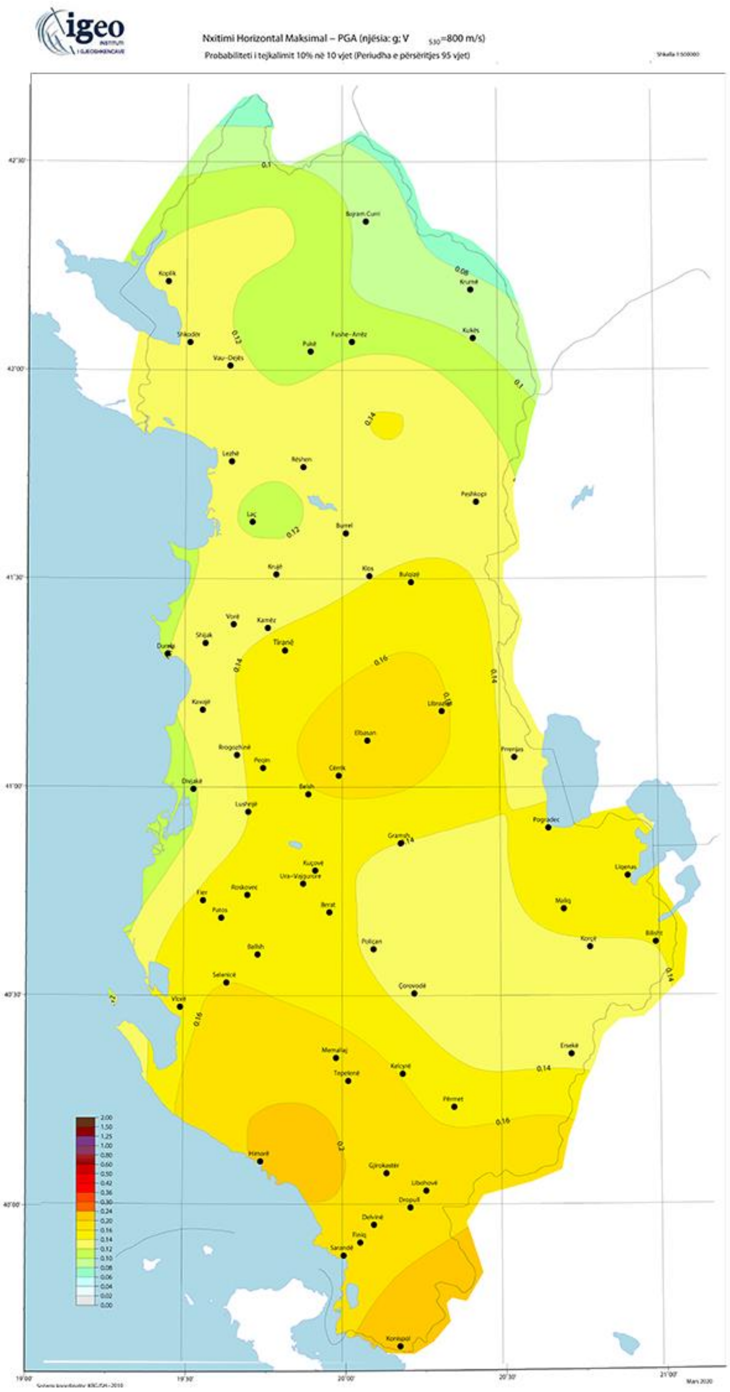


Figure 11. Probabilistic seismic hazard map for horizontal PGA, with the return period of 95 years, for hard rock conditions (Vs30 ≥ 800 m/sec) [22]

The seismic hazard map of Albania for a return period of 95 years is a culmination of extensive research conducted by the Department of Seismology at the Institute of Geosciences (IGJEO), part of the Polytechnic University of Tirana. This map builds on previous work which has incorporated results from the NATO project "SPS 984374" (2012-2015) and subsequent re-evaluations.

The map for the 95-year return period is shown in *Figure 11* and it provides critical insights for long-term seismic risk assessment and infrastructure resilience. It outlines the expected peak ground acceleration (PGA) levels across different regions of Albania, helping to inform guidelines for building performance. For instance, reinforced concrete buildings should meet safety standards such as Immediate Occupancy (IO) for a return period of 95 years, Life Safety (LS) for a return period of 475 years and should meet the Collapse Prevention (CP) limit state at return periods of 2475 years, ensuring structural integrity in the face of significant seismic events [22].

CHAPTER 3

METHODOLOGY

3.1 General

In this study, Incremental Dynamic Analysis (IDA) is conducted on a template reinforced concrete building constructed without adequate seismic regulations. This involves performing multiple analyses using moment-resisting frames specifically developed for this typical building design in Albania. The process begins with an eigenvalue analysis conducted through Zeus-NL software [23] to determine the dynamic characteristics of the building. This preliminary analysis serves as an initial validation tool for the analytical models, ensuring that the calculated periods are accurate and that the masses are correctly assigned to the frame elements.

Following the eigenvalue analysis, dynamic pushover analyses are executed using a range of input ground motions to evaluate the building's response under various seismic scenarios with increasing levels of severity. The immediate occupancy limit states of the template model are then compared with the seismic demands at one of the most affected areas by earthquakes to assess the building's overall seismic performance.

All the results generated from these detailed analyses, including the evaluation of capacities, limit states, and seismic demands, are further discussed in Chapter 6.

3.2 Preparing the Structural Model

The building used in this study is selected to represent premodern reinforced concrete building templates that are continuously threatened by moderate to strong earthquakes in Albania. The selected building has two symmetrical axes and features a typical reinforced concrete moment-resisting frame system without shear walls in any direction. A plan view of the selected building along with details for each structural member is provided in Chapter 5. For ease of study, the building is prepared using 2D reinforced concrete moment resisting frames in longitudinal and transverse direction.

Due to the varying column dimensions and reinforcement across different story levels, there should be a corresponding configuration in the element connectivity with its respective material and cross section for each type of column. Moreover, considering that each element in Zeus-NL is divided into four sections and the fact that this software operates with nodes, significant manual effort is required to adjust the data for each element and integrate it into the building model. This process becomes time-consuming due to the large number of elements and inputs involved.

To simplify this task, Microsoft Excel is utilized. As shown in *Table 1*, element locations are determined by filtering columns such as "bay," "story," and "frame" in a table. For instance, an element labeled "col1211" with a "CCS12" cross-section is positioned at the 1st bay, 1st frame, and 2nd story of the building model.

Table 1. Configuration of frame elements using Excel

Element Number	***Element Class***	***Nodes***	***bay***	***story***	***frame***
col1111	CCS12	n111 n111-y1 nsn1001	1	1	1
col1112	CCS12	n111-y1 n111-y2 nsn1001	1	1	1
col1113	CCS12	n111-y2 n111-y3 nsn1001	1	1	1
col1114	CCS12	n111-y3 n121 nsn1001	1	1	1
col1211	CCS12	n121 n121-y1 nsn1001	1	2	1
bmx1211	BCS12	n121 n121-x1 nsn1001	1	2	1

Once all members have been assigned and linked to their respective cross-sections and positions in the frame, it is crucial to assign masses to each member. Since Zeus-NL is designed to analyze moment frame structures only, it cannot model slab elements. Therefore, the loads coming from the slabs must be hand-calculated and assigned as distributed loads over the beams.

The user has the option to either leave these as distributed masses or to consolidate all the loads from the slabs, beams, columns, and partition walls into lumped masses. These lumped masses can then be assigned to each column and support point of the structure. This flexibility allows for a more accurate representation of the building's load distribution, ensuring that the seismic analysis reflects the true behavior of the structure under seismic forces.

Another important step that needs to be considered is to verify the structure for potential modeling mistakes. This is done using Zeus-view, a software which is automatically installed alongside the Zeus NL program. Zeus-view enables the structural model to be exported in a .dxf format, compatible with AutoCAD. It offers advanced visualization capabilities, allowing users to navigate through the three-dimensional structural model with ease. Users can zoom in for precise examination of dimensions and inspect every component thoroughly in AutoCAD’s workplace.

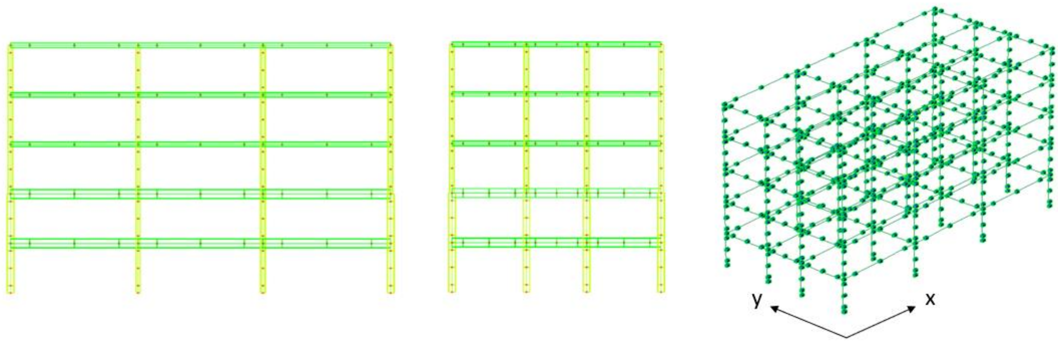


Figure 12. Frame in X direction (left), frame in Y direction (middle) and building in 3D View (right)

Figure 12 illustrates the template building’s structural layout with three views: the X direction view on the left, the Y direction view on the middle and a 3D perspective view on the right. The X and Y direction views are generated in AutoCAD’s workplace using the feature Zeus-view, which clearly shows the changes in beam and column cross sections across different story levels.

The 3D perspective on the right is generated by Zeus-NL and highlights only the elements and nodes, indicating that each element is subdivided into four parts, represented by small dots.

3.3 Ground Motions

The primary objective of this study is to evaluate the seismic performance of a template RC building under a range of seismic scenarios by conducting dynamic pushover analyses. Each selected earthquake applied to the building is characterized by increasing levels of severity.

Existing literature recommends employing ten to twenty earthquake records to ensure adequate results of capacity while focusing on estimating seismic demand [24]. Therefore, twenty response spectra compatible ground motions with peak ground accelerations from 0.042g to 3.500g were considered in this study. They are presented with details in *Table 2.*

Table 2. Earthquake acceleration records used in the study and their characteristics

No	Event	Year	Station	Ø°	Soil	M	R (km)	PGA (g)
1	Corinth	1981	Greece, Corinth	0	C	6.6	19.9	0.264
2	Kocaeli	1999	Turkey, Duzce	180	C	7.1	1.60	0.427
3	Erzincan	1992	Turkey, Erzincan	90	C	6.7	8.90	0.488
4	Friuli	1976	Italy, Tolmezo	270	B	6.5	20.2	0.345
5	Imperial Valley	1979	Chihuahua	282	C,D	6.5	28.7	0.254
6	Imperial Valley	1979	Plaster City	45	C,D	6.5	31.7	0.042
7	Imperial Valley	1979	Westmoreland Fire Station	90	C,D	6.5	15.1	0.074
8	Loma Prieta	1989	Agnews State Hospital	90	C,D	6.9	28.2	0.159
9	Loma Prieta	1989	Coyote Lake Dam Downstr.	285	B,D	6.9	22.3	0.179
10	Loma Prieta	1989	Hollister South & Pine	0	D	6.9	28.8	0.371
11	Loma Prieta	1989	Sunnyvale Colton Ave	270	C,D	6.9	28.8	0.207
12	Loma Prieta	1989	WAHO	0	D	6.9	16.9	0.370
13	Loma Prieta	1989	WAHO	90	D	6.9	16.9	0.638
14	Northridge	1994	LA, Baldwin Hills	90	B	6.7	31.3	0.239
15	Northridge	1994	LA, Hollywood Storage FF	360	C,D	6.7	25.5	0.358
16	San Fernando	1971	LA, Hollywood Stor. Lot	180	C,D	6.6	21.2	0.174
17	San Fernando	1971	LA, Hollywood Stor. Lot	90	C,D	6.6	21.2	0.210
18	Spitak	1988	Armenia, Gukasian	90	C	6.8	36.1	0.207
19	Superst. Hill	1987	Wildlife Liq. Array	360	C,D	6.7	24.4	0.200
20	Tabas	1978	Iran, Dayhook	280	B	7.4	20.6	3.500

The ground motion data are sourced from reputable institutions such as the Pacific Earthquake Engineering Research Centre (PEER) [25] and the U.S Geological Survey (USGS) [26].

3.4 Nonlinear analyses procedure

Buildings designed for seismic safety using linear analysis methods often experience significant nonlinear deformations during earthquakes. Linear analysis, which assumes that material properties and structural responses remain proportional to applied loads, fails to accurately predict the actual behavior of structures under severe seismic conditions. Therefore, to capture the true response of buildings during such events, nonlinear analysis is preferred.

Nonlinear analysis considers the complexities of real-world structural behavior, including material nonlinearity, geometric nonlinearity, and the interaction between different structural components. This type of analysis allows engineers to predict how buildings will behave when subjected to forces beyond their elastic limits. Despite being more complex and time-consuming, nonlinear analyses have become more accessible with advancements in computational technology and software development. There are now many modern applications and software tools that have made it easier to perform these analyses efficiently.

The most complex yet accurate form of nonlinear analysis is nonlinear dynamic analysis. This method involves applying actual or simulated earthquake ground motions to a structural model and observing its response over time.

In this section, we will outline the step-by-step procedure for applying Incremental Dynamic Analysis (IDA), a modern approach used to assess the vulnerability of a selected building under a specified set of ground motions.

3.4.1. Eigenvalue analysis

To determine the dynamic characteristics of the five-story structural model, including eigenperiods and mode shapes, an eigenvalue analysis must be conducted. This analysis is performed twice for each frame: first with dead and live loads applied as lumped masses to the structure, and then with these same loads applied as distributed loads over each beam of the frame. This comparative approach allows for assessing the correlation between the two methods, with expectedly similar results.

Once the analysis is completed, typically taking only a few seconds due to its eigenvalue nature, the deformed shape viewer is utilized to open the analysis' .num file. A list of the converged eigenmodes will be displayed, and each can be selected to view its corresponding mode shape by clicking the "View Shape" button. Users have the flexibility to copy, print, or modify the appearance of the generated 3D plots.

Figure 13 illustrates the ten periods of the horizontal frame using lumped masses. Chapter 6 will showcase and analyze results for the frames in both directions, for both cases (lumped masses vs distributed masses) with detailed comparison and further elaboration. As will be demonstrated, there is minimal difference between the periods observed in the two cases, indicating a high degree of similarity between the mass assignment methods.

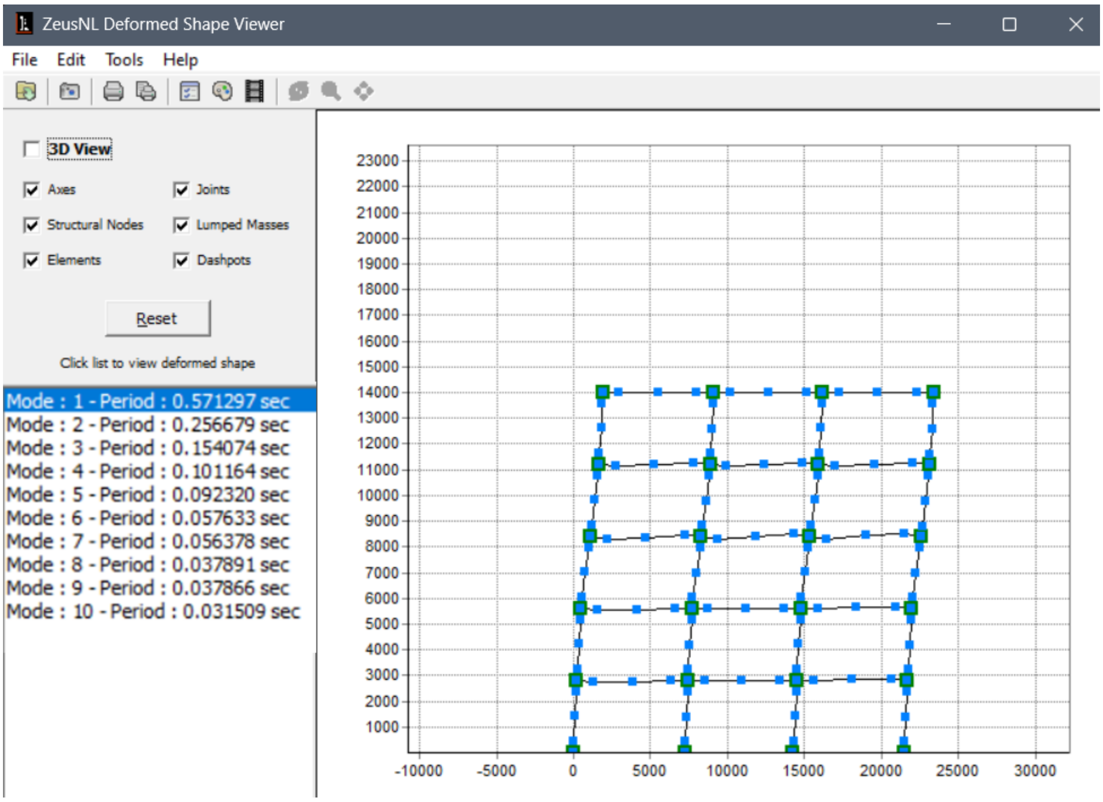


Figure 13. Eigenvalue analysis results on the x direction frame using Lmass

3.4.2. Dynamic Time History Analysis

Given that the primary focus of this study is a compilation of numerous dynamic time history analyses until global instability is reached, it's crucial to understand the mechanics of a single Dynamic Time History Analysis. The chosen accelerograms for the Dynamic Time History Analysis correspond to the seismic activity records shown in *Table 2*. The time and acceleration data for each earthquake record are arranged in a text file, formatted in a tabular layout and then imported into the ZeusNL software for further processing. Once the acceleration values are prescribed into the 2D frame model, the analysis begins its execution. Post-Processor serves as a pivotal tool, facilitating the generation of the analytical results.

The purpose of this analysis is to plot the interstory drift over time, specifically measuring the drift between the top left node and the bottom left node of the frame. To ensure an accurate representation, the settings are configured with "time" on the x-axis and "interstory drift" on the y-axis. In this context, the interstory drift corresponds to the seismic displacement (Ux). The resulting curve, which illustrates the building's response to seismic activity, is shown in *Figure 14*.

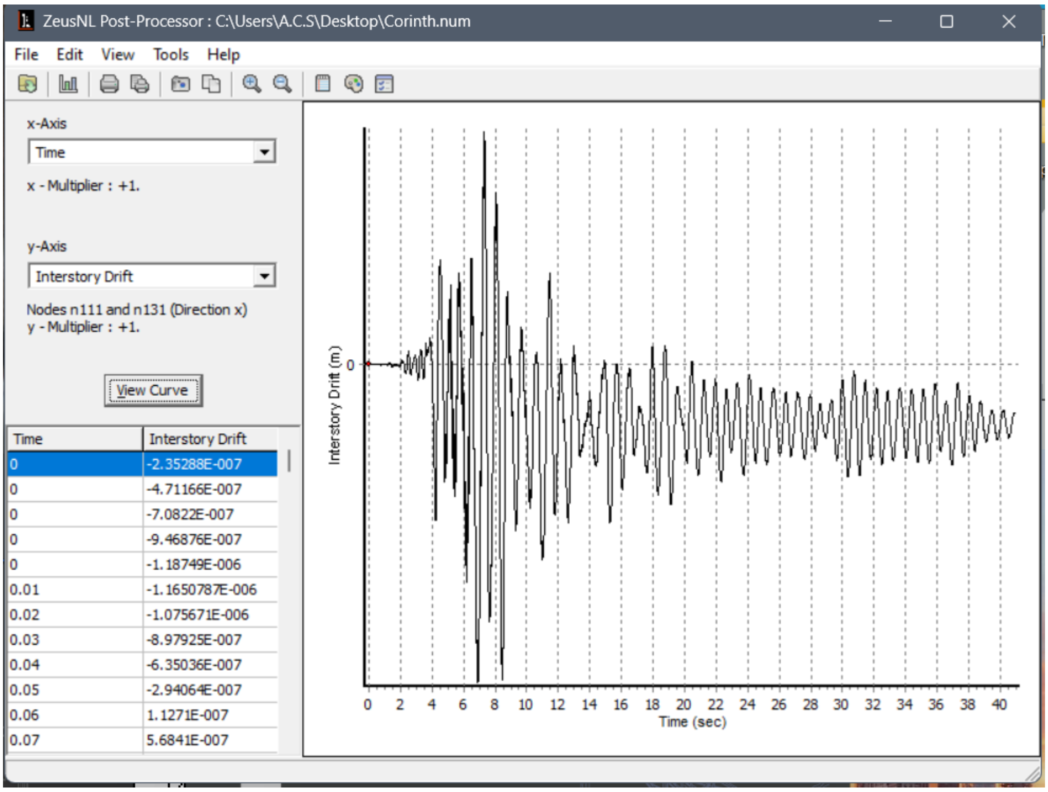


Figure 14. Performing Time History analyses with Zeus-NL

3.4.3. Incremental Dynamic Analysis

The focus shifts to the construction of a single IDA curve, an important seismic performance assessment tool within structural engineering analyses. This dynamic pushover approach emerges as a modern technique, where the selected 2D frame undergoes stimulation from the same seismic motion input, scaled to the intensity measure of each record.

Even though executing dynamic pushover analyses is considered to be time-consuming, the ZBeer utility facilitates the entire procedure by automatically scaling the input record for a series of scaling factors, collecting the requested response parameters and plotting the dynamic pushover points. After the building model and its respective loads are uploaded, the user has the option to choose monitoring parameters, which in this case are base shear (V) and drift (d). Horizontal forces (Vi) from support nodes are added and plotted against the displacement (or rotation) difference between a top story node and one at the base of the structure (global drift). Subsequently, the curve is generated, as shown in *Figure 15.*

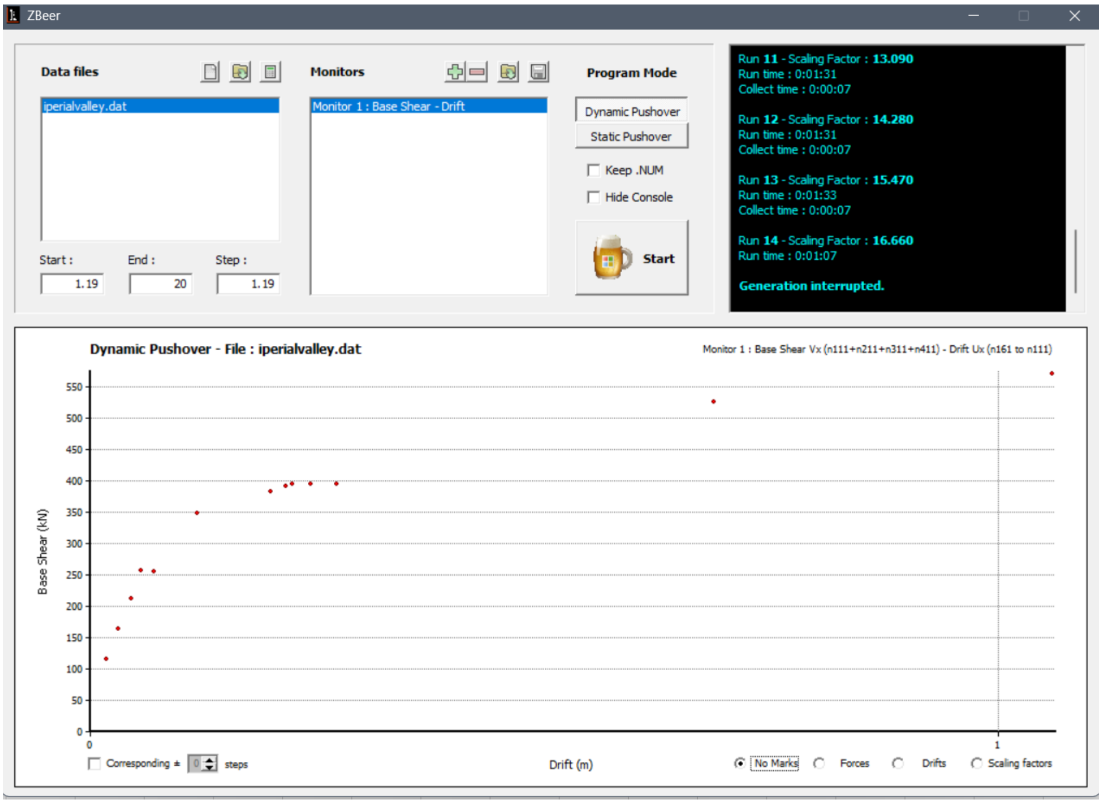


Figure 15. Performing Incremental Dynamic Analysis with Zeus-NL for record #6

3.5 Selection of IM and DM

To effectively interpret the results of the IDA analysis, users must select suitable IM and DM parameters. Considering prior research [7, 9], the preference for the intensity measure is employing the 5% damped first mode spectral acceleration, $Sa_{(T1,5\%)}$, coupled with the maximum global drift, Θ_{max}, for the damage measure when plotting IDA curves. The maximum global drift will be determined as the top node's maximum drift relative to the bottom node, divided by the building's height.

3.6 Construction of a single IDA Curve

To construct an IDA curve while avoiding to perform extra analyses, previous studies have typically employed the hunt and fill algorithms [7]. However, in this study, spline interpolation has been used, facilitated through Microsoft Excel, which yields smooth and easily interpretable curves. As illustrated in *Figure 16*, the dots represent data points derived from dynamic analyses, while the line signifies the interpolation from these data points. As it can be seen, the curve progresses to a "flatline" after an intensity measure of 0.7g, indicating global instability where the structure responds with "infinite" Θ_{max} values.

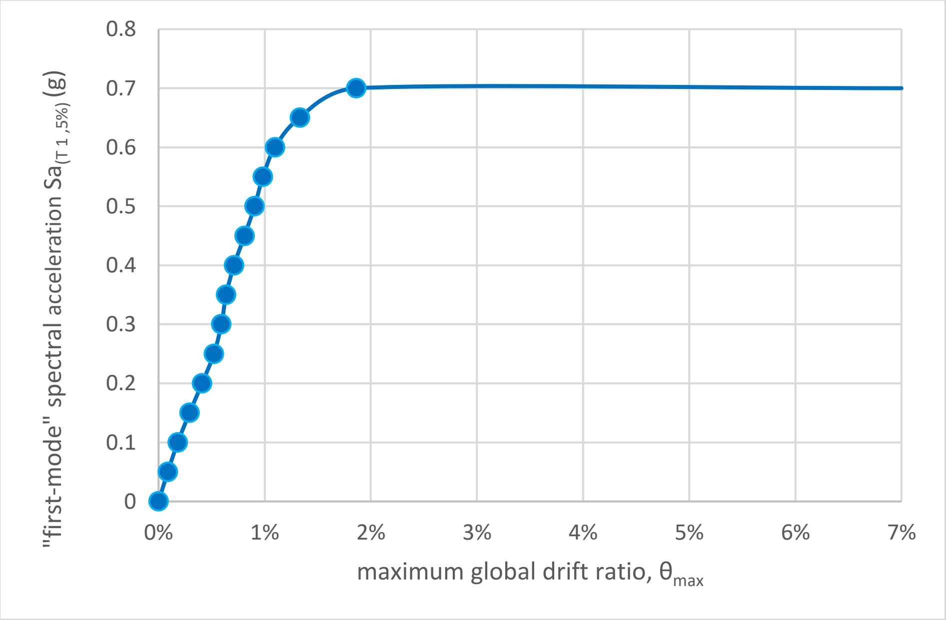


Figure 16. The spline interpolation of dynamic analysis points for earthquake record #1 (horizontal frame)

3.7 Determination of Limit States

In order to get more insights into the structural model's seismic vulnerability, it is important to establish limit states and to properly allocate them in the generated curves. In Performance-Based Earthquake Engineering (PBEE), engineers rely on Incremental Dynamic Analysis (IDA) curves to evaluate how buildings respond to seismic events, crucial for determining the structures' earthquake resilience levels [27]. However, the process of determining these levels isn't straightforward.

There are three limit states considered in this study: Immediate Occupancy (IO) and Collapse Prevention (CP), as defined in FEMA guidelines [28], along with Global Instability (GI), as suggested in prior research [18].

Immediate Occupancy is an important limit state which aims to ensure the structure remains functional and safe for occupancy immediately following a seismic event. Setting this limit state is different across building types. Different authors suggest Immediate Occupancy (IO) be set to 1% of Damage Measure (DM) for modern buildings, but this percentage has been reduced to 0.5% for premodern ones, as in this paper [29]. The IO limit state is defined with a "plus" sign on the IDA curve of record #1 shown in *Figure 17.*

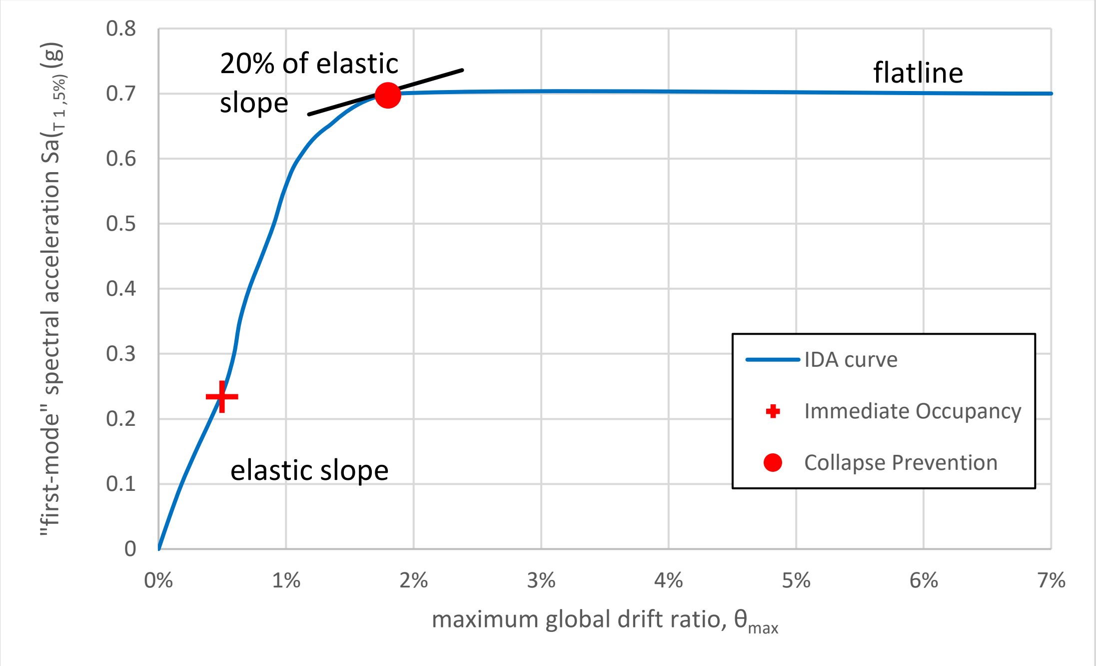


Figure 17. The limit-states, as defined on the IDA curve of record #1 for the horizontal frame

The collapse prevention point is pinpointed on the IDA curve when 20% of the elastic slope is attained or when DM reaches 10%, whichever comes first in terms of IM. This is shown by a red circle on the IDA curve of record #1 in *Figure 17*. To conclude, the limit state of Global Instability is defined when the flatline is attained [12]. This happens when significantly large DM values are generated, triggered by even minor increments in the IM.

Due to the complexity of IDA curves and the various shapes that they can take, there can be cases where multiple points may satisfy the Collapse Prevention (CP) criteria. In that case, all points within the specified range should be carefully studied in order to determine the most appropriate one. The last point with the 20% slope in the curve before reaching the 10% DM value will be taken into consideration [12].

A practical illustration of such an occurrence is shown in *Figure 18* for the IDA curve derived from record #13 Loma Prieta for the horizontal frame configuration. Here, the initial 20% slope is disregarded and the final 20% slope point appearing on the same curve is the accepted CP point.

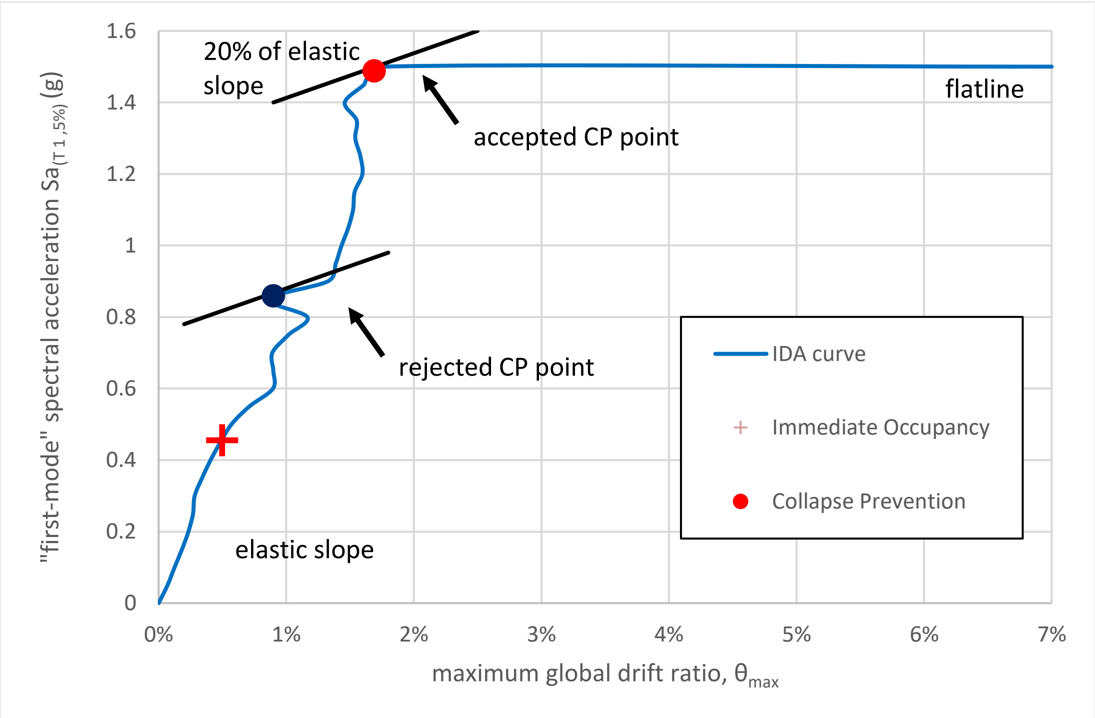


Figure 18. The limit-states, as defined on the IDA curve of record #13

Another phenomenon that requires careful consideration is known as structural resurrection. This phenomenon occurs when the structural response curve undergoes extreme hardening, making it appear like it is approaching the start of global collapse. However, as the intensity measures (IM) continue to increase, the structural system exhibits a surprising resilience, rebounding in terms of damage measures (DM), despite displaying a high level of response. This resilience is often characterized by the occurrence of multiple flatlines in the response curve.

In such cases, where several flatlines appear, it is important to distinguish the realistic response from the unusual ones. Typically, the initial flatline is accepted as indicative of the true structural behavior, while the following ones are disregarded as they do not yield reliable results. This phenomenon is demonstrated in *Figure 19.*

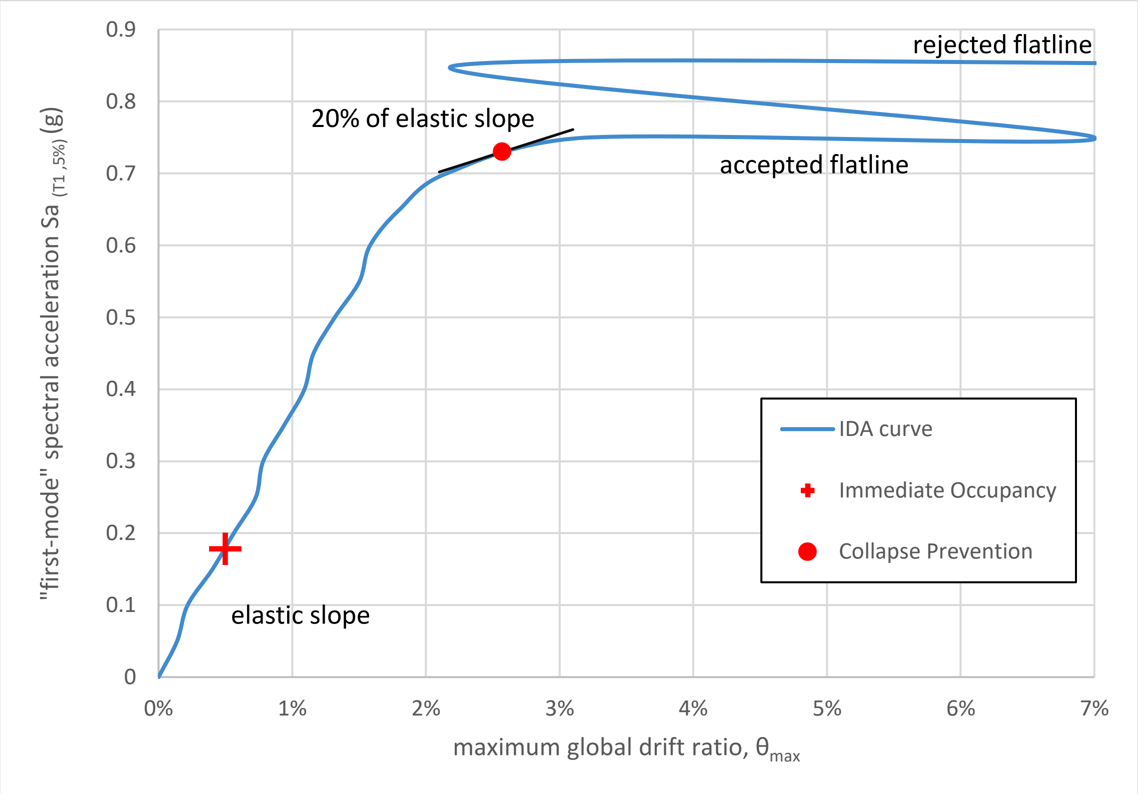


Figure 19. The limit-states, as defined on the IDA curve of record #19

3.8 Multi-record IDA

As it has been acknowledged by now, relying solely on a single ground motion record does not capture the full spectrum of potential structural responses during seismic events. Each single-record IDA curve highly depends on the ground motion record that is chosen.

To address this limitation, it is recommended to subject the structural model to a suite of ground motion records. *Figure 20* shows an IDA curve set or rather known as a multi-record IDA study using all twenty ground motion records for the frame in the X direction.

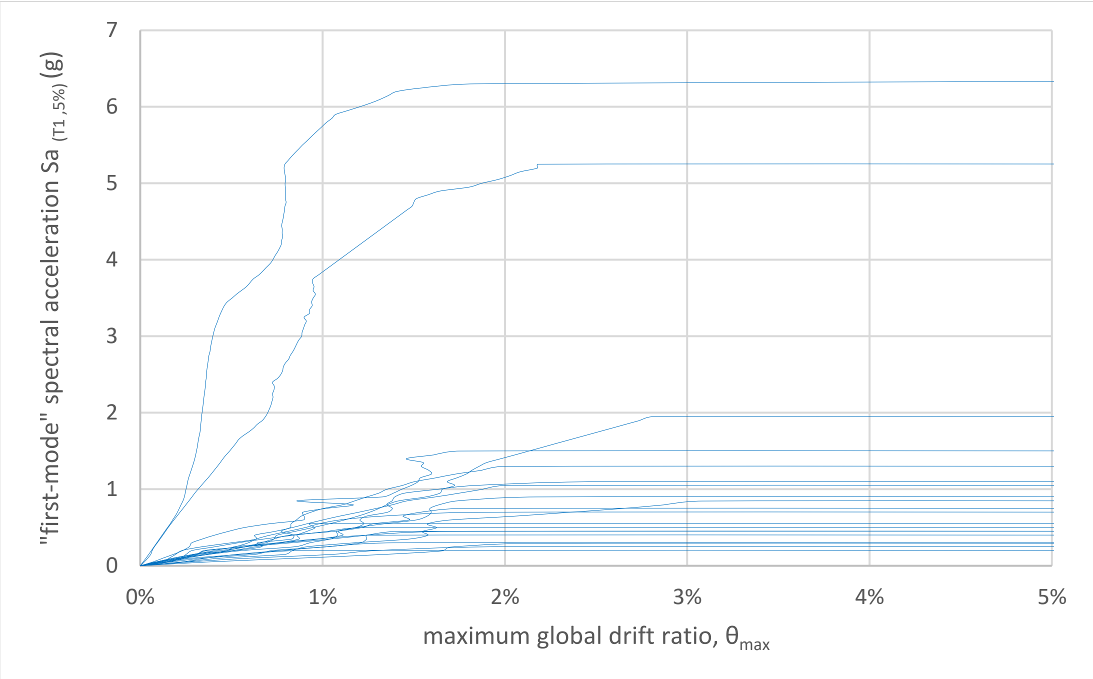


Figure 20. All twenty IDA curves for the frame in X direction

3.9 Summarize the IDAs into 16%, 50%, 84% fractiles

Following established methodologies from proposed literature [13], it has been chosen to compute the 16%, 50%, and 84% percentile values. Using interpolation techniques, fractile values of Intensity Measures (IM) and Damage Measures (DM) are combined to construct the IDA fractile curves from 20 earthquake records given in this paper. Interpreting these fractiles simplifies the process of extracting essential information from demand calculations. Each curve reflects a certain probabilistic outcome based on the structural model and ground motion record. It's essential to study this probabilistic characterization to handle the randomness linked to potential ground motion scenarios.

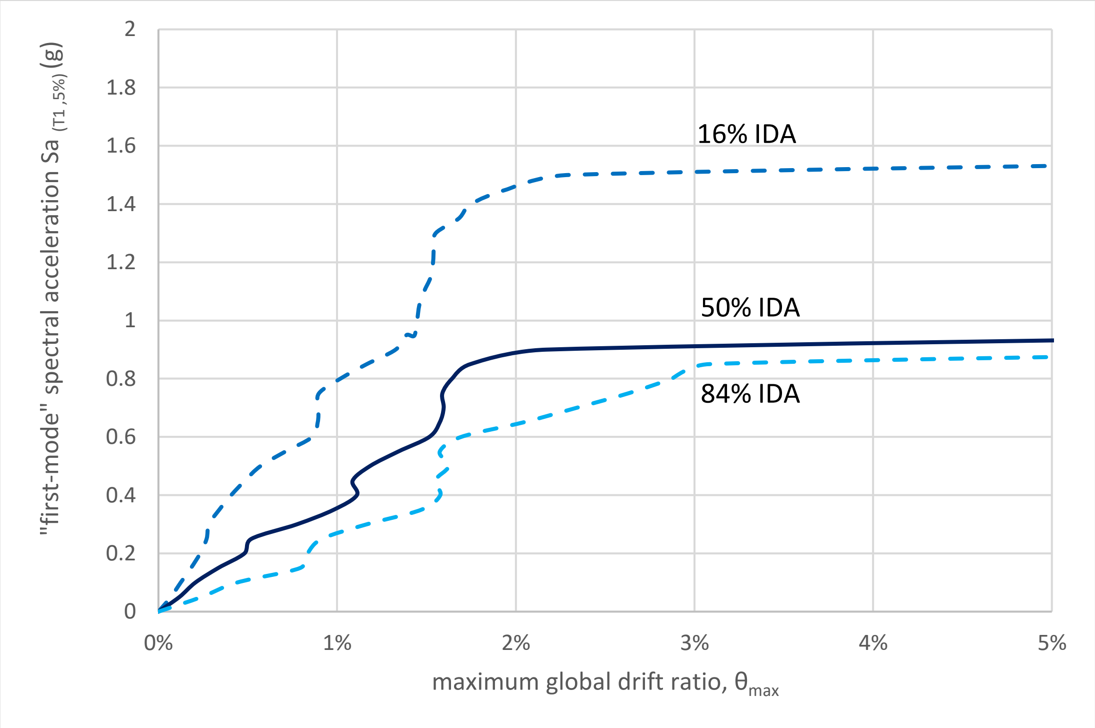


Figure 21. IDA fractiles generated for the frame in X direction

CHAPTER 4

CASE STUDY BUILDING

4.1 General

In this chapter, insights are provided into the selected building for the study. The building under examination is part of the template buildings category developed during the communism era in Albania and is found under the name “BANESA TIP PËR QYTETE ME SIZMICITET 7-8 BALLË”. These types of buildings were mass constructed throughout Albania’s region in multiple cities with the same structural configurations in order to minimize architectural expenses and construction time. For this reason, examining just one template building for study effectively represents a large number of residential structures across our country.

The blueprints are sourced from "ARKIVI QËNDROR TEKNIK I NDËRTIMIT (AQTN)" in Tirana, Albania. Established in accordance with DCM No.377 dated 26.07.1993 and based on the law of the People's Assembly No.7726 dated 29.06.1993, AQTN functions as the Central Technical Archive of Construction. It has been collecting construction documents since 1911 until 1990 [8]. The building's characteristics and features are carefully outlined and supported with visual representations in the form of tables and figures in the following sections.

4.2 Description of the Building

The overall height of the five-story building is 14 meters, with regular story height, each 2.8 meters. It is composed of four frames in the X-direction and four frames in the Y-direction. *Figure 22* demonstrates the elevation profile of the building in each axis. The upcoming sections will present detailed information about the element types, materials, column and beam cross-section and finally the reinforcement used to model the structural model.

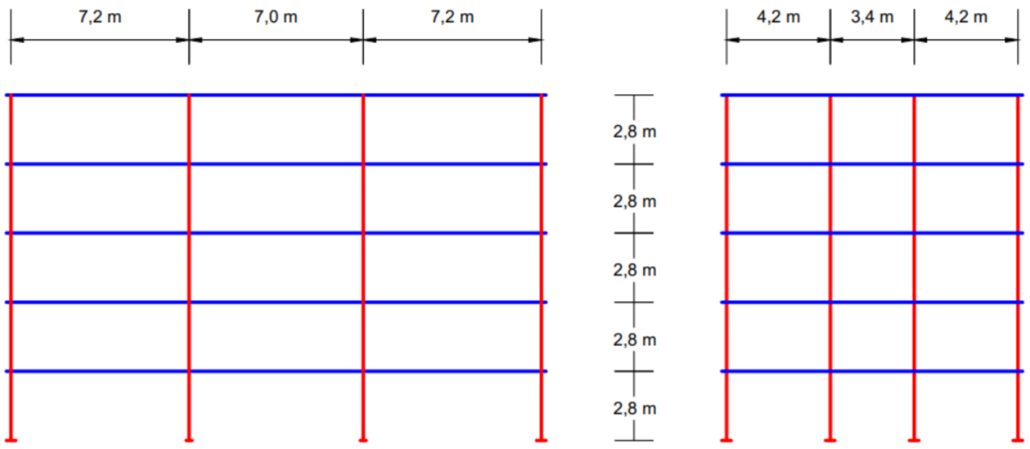


Figure 22. Structure elevation in X-direction (left) and Y-direction (right)

The selected building's plan configuration spans 21.50 meters along the X-axis and 11.80 meters along the Y-axis. The building has four frames in the longer direction and four frames in the shorter direction as shown in *Figure 23.* The plan area measures 253.70 m^2 and is symmetrical in both directions, which prevents the development of torsional effects.

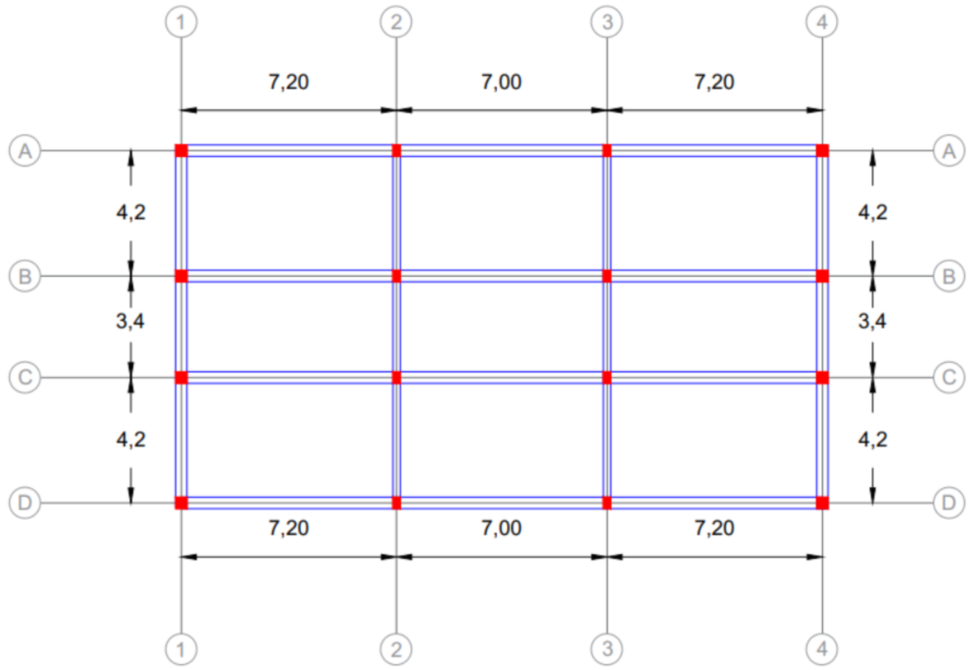


Figure 23. Plan view of the selected building (Units given in meters)

4.3 Material Classes

According to the details on the blueprint, the concrete class is specified as M200 [8]. The use of the letter "M" into concrete terminology dates back to the construction practices of the Union of Soviet Socialist Republics (USSR), where it denotes the compressive strength of concrete in cubic tests [30]. It is converted to C16/20 by considering Eurocode standards [31]. As for the steel used for the reinforcement of the structural elements, the blueprint characterizes it as (Ç3). This is converted to a Yield strength f_{yk} = 320 MPa according to European standards [32].

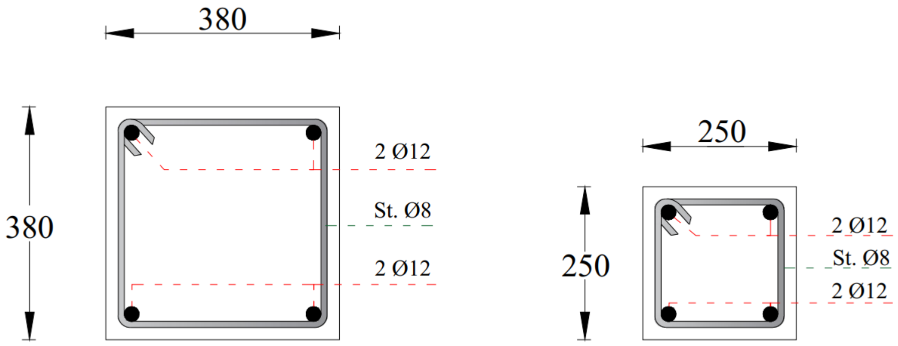
4.4 Structural Members

4.4.1 Columns

Columns are the vertical load carrying elements which play the vital role in the building performance. In this study, three types of element configurations are used to model the columns of the building.

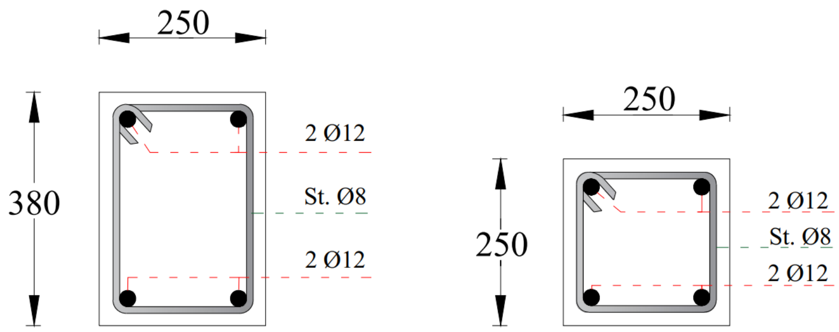
The first type of column element is composed of 4 Ø12 steel bars and has the dimensions of 38 cm by 38 cm. This element is used to model the outer columns for the first two floors of the structure. The second configuration will have 25 cm by 25 cm dimensions and will use 4 Ø12 steel bars to model the rest of the outer columns, from third story till the fifth one. The third element has 25 cm by 38 cm dimensions and uses 4 Ø12 reinforcement to model the inner columns of the building up to the second floor, whereas from 3rd story to 5th one, the reinforcement remains the same but the dimensions of the column become 25 cm by 25 cm.

Details are tabulated as shown in the *Table 3* whereas *Figure 24* and *Figure 25* demonstrate all four column elements used in this study. Units are in mm.



a) b)

Figure 24. Outer columns - a) Lower stories, b) Upper stories



a) b)

Figure 25. Inner columns - a) Lower stories b) Upper stories

Table 3. Column details

Column Type	***Column Size***	***Longitudinal reinforcement (No. of bars / bar size)***	***Trasverse reinforcement (bar size / spacing)***	***Floor Level***
Type 1	38 * 38 cm	4 Ø12	Ø8 at 10cm/20cm	1-2
Type 2	25 * 38 cm	4 Ø12	Ø8 at 10cm/20cm	1-2
Type 3	25 * 25 cm	4 Ø12	Ø8 at 10cm/20cm	3-5

4.4.2 Beams

Beams are the horizontal load carrying members which transfer the weight from slab to columns. For the purpose of this study there are selected three types of beam elements. Depending on the story level, the dimensions and the reinforcement of the beams will change. The selected structural model is composed of beams with dimensions 50 cm by 38 cm whose reinforcement consists of 4 Ø10 upper longitudinal steel bars and 6 Ø20 lower longitudinal steel bars for some of the beams of the first two stories. The rest of the beams in the first two floor levels are composed with 3 Ø10 and 4 Ø12 longitudinal steel bars. These configurations become 6 Ø12 for all of the beams in the third to fifth floor level. *Figure 26* and *Figure 27* demonstrate the cross sections of the beams and their reinforcement used for the selected building.

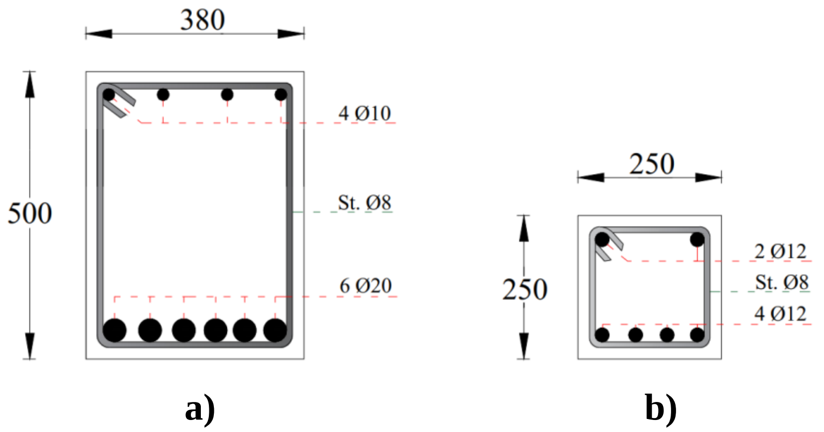


Figure 26. Beam cross sections - a) Lower stories b) Upper stories

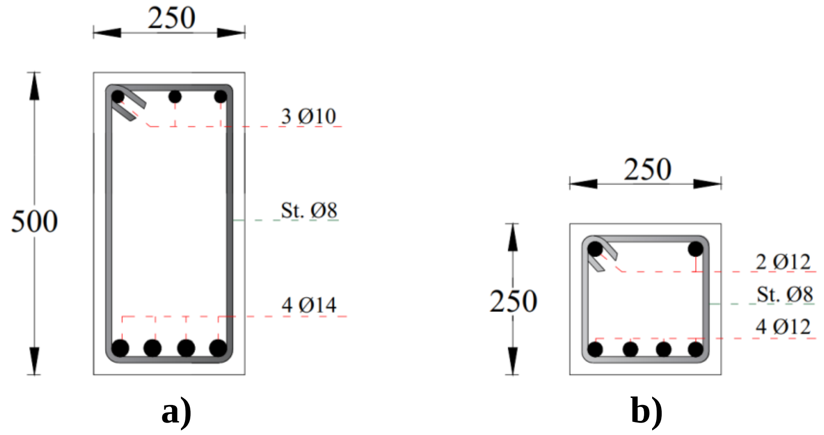


Figure 27. Beam cross sections - a) Lower stories b) Upper stories

Table 4 summarizes the cross-sectional dimensions and reinforcement used for the beam elements.

Table 4. Beam details

Beam Type	*Beam Size*	*Longitudinal reinforcement (No. of bars / bar size)*	*Trasverse reinforcement (bar size / spacing)*	*Floor Level*
Type 1	38 * 50 cm	4 Ø10 upper, 6 Ø20 lower	Ø8 at 10cm/20cm	1-2
Type 2	25 * 50 cm	3 Ø10 upper, 4 Ø14 lower	Ø8 at 10cm/20cm	1-2
Type 3	25 * 25 cm	6 Ø12	Ø8 at 10cm/20cm	3-5

4.4.3 Slabs

The software chosen for the analyses, Zeus-NL, is limited to modeling only moment frame structures and does not support slab elements. However, considering the mass of the building is significant in dynamic analyses, it's important not to overlook the contribution of the loads coming from the slabs. Therefore, it's necessary to calculate the self-weight of the elements by hand.

In the selected structural model, all the slabs were determined to be two-way slabs, which means that their weight is determined and uniformly distributed onto the beam elements. The dead and live loads are computed based on their respective coefficients. During calculation stage, slabs are assumed to be 15 cm thick concrete layers.

Figure 28 shows a visualization of the distribution of slab weight over beams.

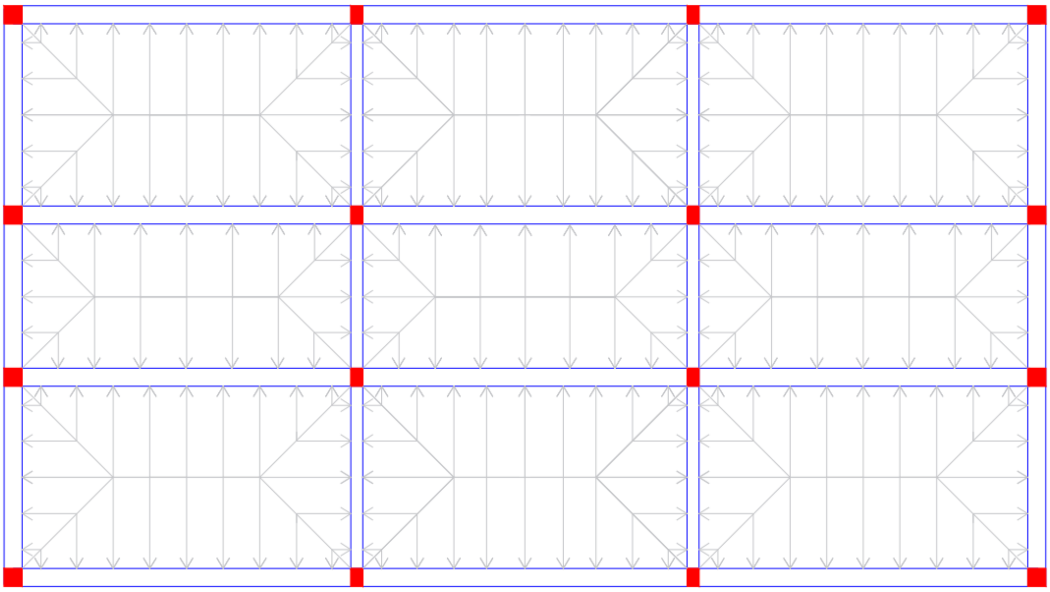


Figure 28. Slab weight distribution

CHAPTER 5

MODELLING WITH ZEUS NL

5.1 Zeus-NL Software

Zeus Nonlinear (ZeusNL) is a software specifically developed for earthquake engineering applications. It uses the fiber approach and offers a significant advancement in the field of Finite Element analysis, revolutionizing traditional approaches to structural analysis. ZeusNL makes it easy and efficient to do different types of complex structural analyses, like dynamic time-history, pushover, and eigenvalue analyses. It comes with concrete and steel material models ready to use, along with lots of 3D building parts and pre-defined shapes. With ZeusNL, the user can simulate structures accurately, taking into account things like how they bend and the P-delta effect.

Among its numerous features, ZeusNL offers a set of templates for each analysis, granting users full control over material models, section types, nodes, elements, restraints, and loads. Developed by Elnashai et al. at the Mid-America Earthquake Center, University of Illinois at Urbana-Champaign, ZeusNL stands out for its capability to run multiple static and dynamic analyses simultaneously. It excels in applying constant or variable forces, displacements, and accelerations, ensuring precise predictions of structural behavior under diverse loading conditions.

5.2 Modelling in Zeus-NL

ZEUS-NL software has been used in many previous studies to accurately investigate how residential reinforced concrete structures perform under seismic loads [33, 34, 35]. During ZEUS-NL modelling, every structural member is constructed using multiple cubic elasto-plastic elements. These elements proficiently portray the distribution of inelastic behavior within the member's cross-section and along its length through the fiber modeling approach [23].

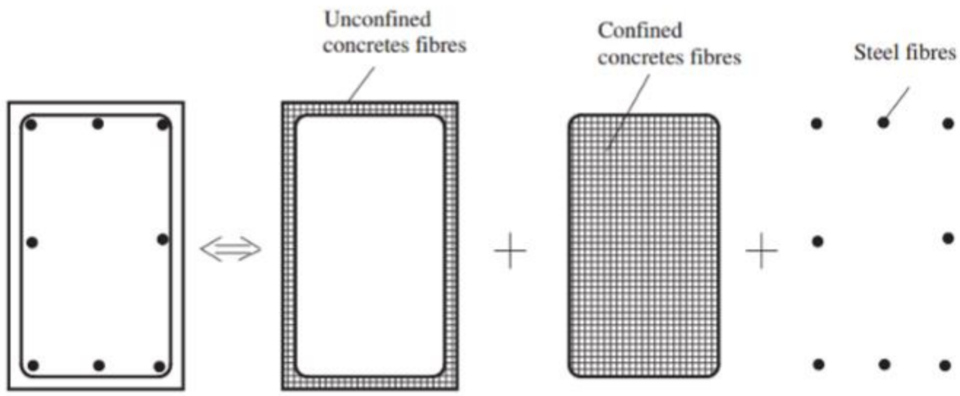


Figure 29. Decomposition of a RC rectangular section

5.2.1 Analyses

The Zeus-NL software offers a comprehensive range of analyses, including dynamic time-history, static time-history, conventional pushover, adaptive pushover, and eigenvalue analyses. These analyses are shown in the dropdown in *Figure 30* which displays the main window upon initiating a new project, with the available analyses conveniently presented at the bottom.

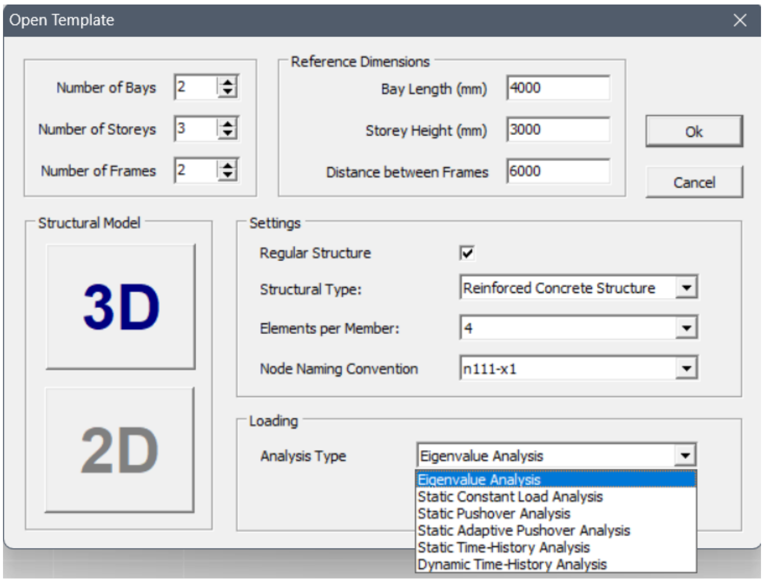


Figure 30. Zeus NL's new project window

Additionally, there is an option labeled "Regular Structure." When selected, the length of bays and the spacing between frames are automatically set to uniform values specified for each. If left unchecked, a window prompts the user to modify individual bay lengths and frame spacings according to their preferences. This customization is facilitated through adjusting ratios in the "Ratios to Reference Dimensions" window.

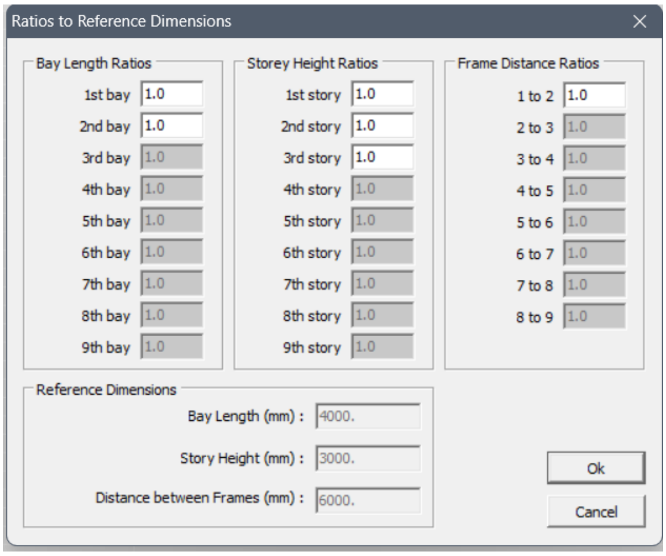


Figure 31. Ratios to reference dimensions for irregular models

5.2.2 Materials

The "Materials" module is the first section that appears in the ribbon above the workplace of Zeus-NL software, accompanying other customizable features within the application, as seen in *Figure 32*. This software offers a material library where users can select materials for their modelling needs. The material types offered are:

- **stl1:** Linear elastic model
- **stl2:** Ramberg-Osgood model with Masing type hysteresis curve
- **stl3:** Menegotto-Pinto model with isotropic strain-hardening
- **con1:** Trilinear concrete model
- **con2:** Uniaxial constant confinement concrete model
- **con3:** Uniaxial variable confinement concrete model
- **con4:** Sheikh-Uzumeri model

- **ecc:** Model for Engineered Cementitious Composite (ECC) materials
- **frp1:** Uniaxial constant fiber-reinforced plastic confined concrete model

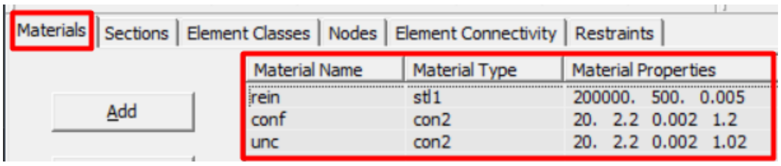


Figure 32. Materials module in Zeus-NL

Users can easily modify material properties by selecting different materials from the library, adjusting them to the requirements of their case study. Within the "material window," all necessary material details are presented. For instance, when steel is chosen, users can adjust parameters such as Young's Modulus or Yield Strength, as illustrated in *Figure 33.*

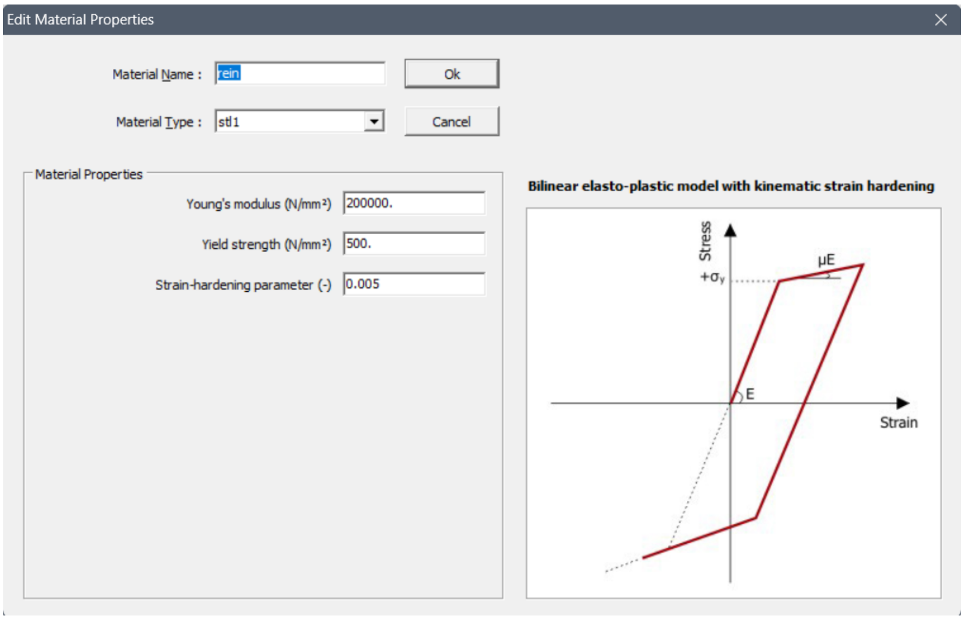


Figure 33. The Material Properties dialog box

These materials can later be edited in the sections module to define section properties. It should be noted that there are limitations on naming conventions; special characters such as #, & or space should be avoided, and names should not exceed eight characters, a rule also applicable when saving files.

5.2.3 Sections

In this section, users can define the properties of their structural model's elements' cross sections, with 14 options like steel, reinforced concrete (RC), and composite sections. Each section comes with a name and dimensions. For RC sections, users can also set the size and position of reinforcing bars. When a rectangular cross-section used for an RC structure is needed, since both sides are symmetrical, the location of the steel bars in one quarter of the cross-section is sufficient. The rest of the configuration is handled passively by the program, automatically generated.

Like with materials, sections can be copied, pasted, and edited. If users need to change a section, they can do so by clicking "Edit". This opens a window where they can modify the section's name, materials, dimensions, and reinforcement details. The program provides visual cues, like red lines, to show changes made to dimensions. When users are satisfied with their changes, they can click "Ok" to finalize the section settings.

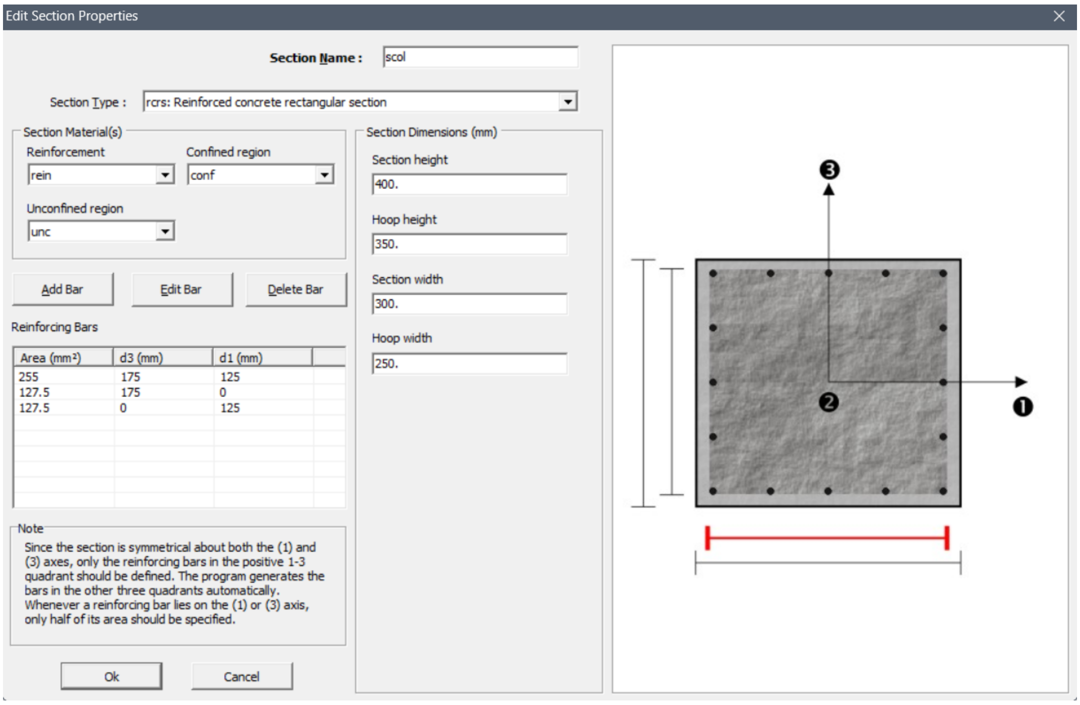


Figure 34. The Section Properties dialog box

5.2.4 Element Classes

The ZeusNL element library includes different types of elements used for modeling different parts of a structure. This includes elements for structural components like beams and columns, non-structural elements like mass and damping, and boundary conditions like supports and joints. Here's a breakdown of the different types of elements available:

- **Cubic:** This is a cubic elasto-plastic 3D beam-column element.
- **Joint:** This is a 3D joint element featuring uncoupled axial, shear, and moment actions.
- **Lmass:** This element represents a lumped (concentrated) mass element, primarily used in dynamic and eigenvalue analyses.
- **Dmass:** This is a cubic distributed mass element.
- **Ddamp:** This element is a dashpot (concentrated) viscous damping element, utilized in dynamic analysis.
- **Rdamp:** This element models Rayleigh damping for dynamic analysis.

It's important to understand the difference between element types and element classes in ZeusNL. Element types refer to the different kinds of elements you can use in your project, while element classes group properties specific to a particular type of element. In a ZeusNL project, you might have multiple classes of the same element type. For example, you could have two classes of cubic elements labeled "col" and "beam," or three classes of lmass elements labeled "mass1," "mass2," and "mass4."

These element classes are crucial for defining how elements connect to each other in the overall structure, especially when setting up the mesh configuration. Additionally, there are two important methods for simulating the weight of elements: Lmass and Dmass elements represent lumped mass and distributed mass, respectively. These methods help account for the weight of elements like slabs and walls that can't be directly modeled in ZeusNL. Lump mass is particularly important for eigenvalue analyses, which determine how quickly the structure vibrates.

5.2.5 Nodes

Once the user has defined the element classes, they move on to setting up the mesh for the model. In the Nodes module, there's a list of nodes along with a 3D plot of the structure, which helps users visualize and understand the model better. Most nodes are structural, meaning they contribute to the building's strength, but some are non-structural and serve other purposes.

For certain types of elements like cubic, joint, dmass, and rdamp, an additional third node is needed along with the two end nodes. This extra node helps accurately position the element in space. Together, the end nodes and the third node form a plane in 3D space, with the section's strong axis aligned with this plane. In the Nodes module, users have options like Add, Remove, and Edit, as well as an Incrementation button, which lets them create new nodes in a repetitive way.

5.2.6 Element Connectivity

In this section, all the defined materials, sections, loads, masses, and nodes, are connected with one another and assigned to their corresponding positions in the structural model. This crucial step ensures that every element of the model is accurately defined and aligned, laying the foundation for an effective structural analysis.

By default, each element in the model is assigned a unique identifier following a specific format. For example, "col111" indicates a column, with the numbers denoting its location within the structure. Similarly, "bmx234" signifies a beam oriented in the X direction, positioned in the 2^{nd} frame and 4^{th} bay, and located on the second story of the building.

The numbering convention differs slightly for columns and beams. For columns, the numbering starts from the ground level, with 1 indicating the first story above the ground. However, for beams, the numbering begins from the base floor, so a beam on the second story is assigned a number 2.

Additionally, non-structural nodes assist in visualizing the location of elements in the 3D view, providing a plan for element placement. For lumped mass elements, only the node where the mass is applied is necessary, while for distributed mass elements, two end nodes are required to define where the distributed load is applied along the element.

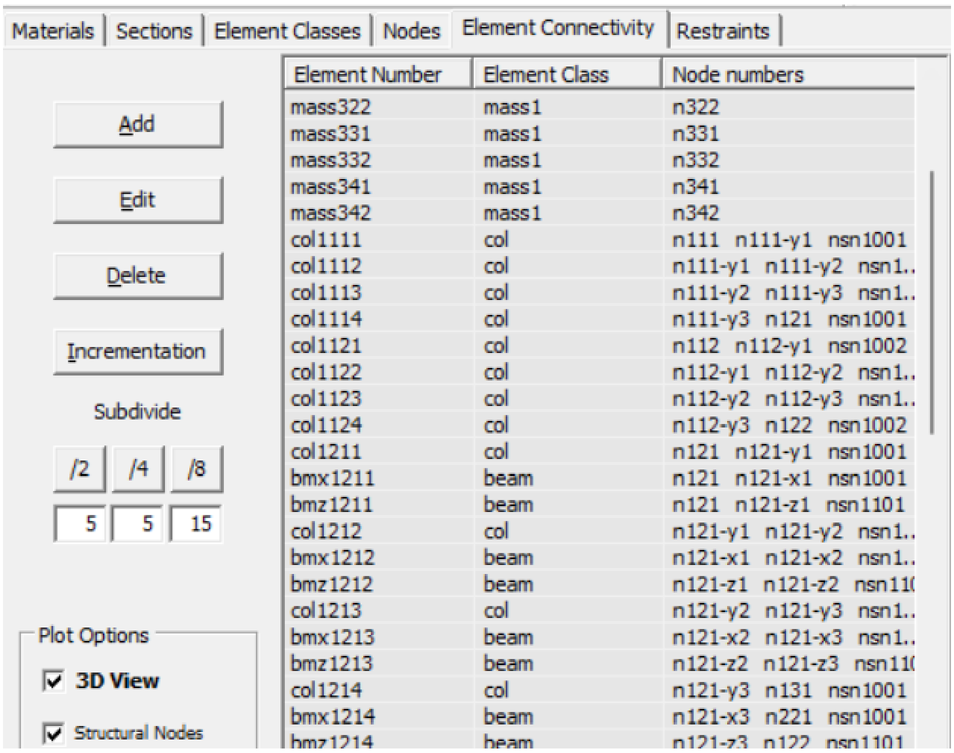


Figure 35. Element connectivity example

5.2.7 Restraints

Users can define restrained nodes effortlessly by selecting them and clicking the Edit button. Although the process is straightforward, it's important to highlight a crucial aspect regarding restraints.

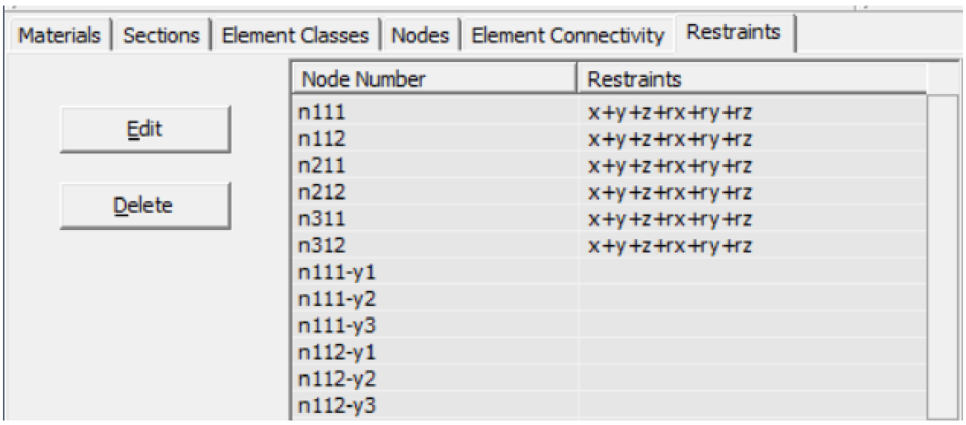


Figure 36. Nodes and their restraints example

During dynamic analysis, the degrees of freedom (DOF) that are restricted at the supports, especially in the direction of the earthquake, must be freed. This means that the restrained DOFs of the supports in the model usually include y, z, rx, ry, and rz, but not x (where x denotes the direction of the earthquake).

In simpler terms, when there is a simulation of how a building responds to an earthquake, it needs to be allowed to move sideways (x-direction) at the supports so that the user can see how it reacts to the shaking. This restraind modification ensures that the structure can respond appropriately to seismic forces without being overly constrained.

CHAPTER 6

INTERPRETATION OF RESULTS

6.1 General

This chapter provides results of all the analyses that have been conducted in order to assess the performance of a template RC building under seismic loads. For each analysis performed there are two sets of results, one for each frame in both directions.

6.1.1 Eigenvalue analysis

For this study, the eigenvalue analysis is chosen as the initial analysis to be performed. The results that are gained from this analysis are important, as they provide the period of the structure. This way the user can check if the mass distribution is assigned properly. The analysis is conducted twice for each frame: firstly, with masses allocated as lumped points on each support, and secondly, with masses distributed evenly across each beam. The results are presented in *Table 5*.

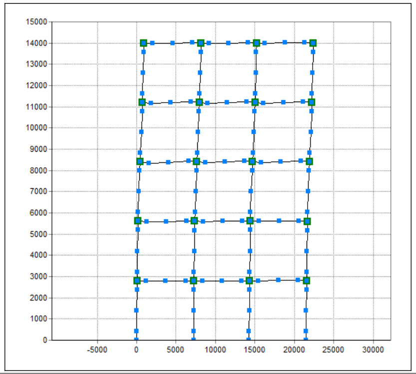
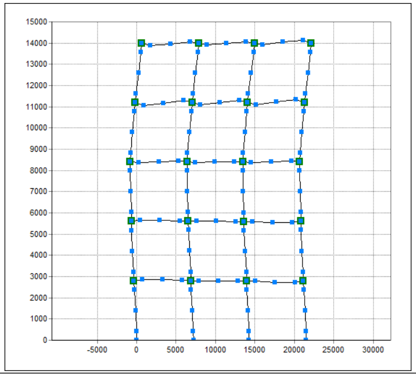
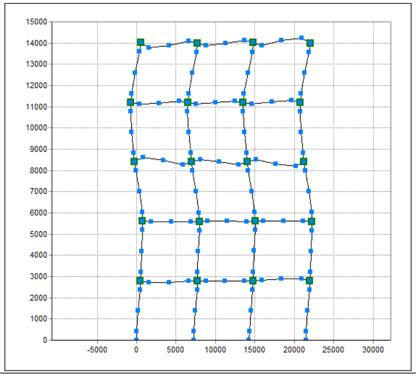
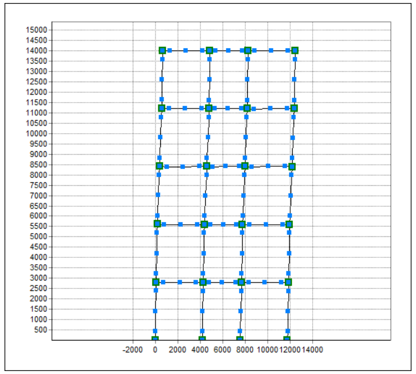
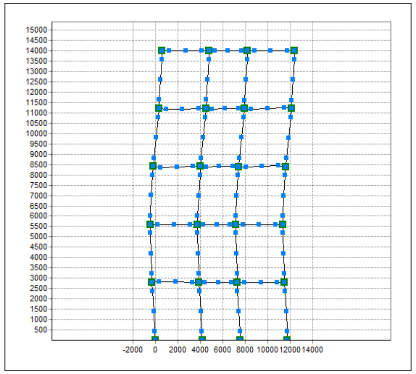
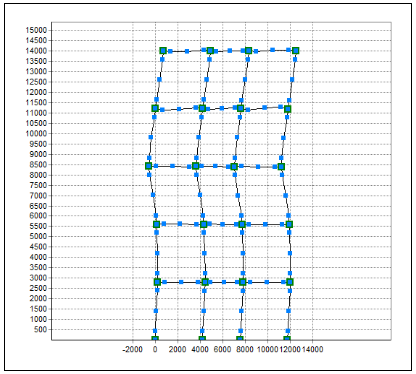
Table 5. Comparison of the fundamental periods of vibration for the frames in both directions

Mode	***X-direction***		***Y-direction***	
	Period [Lmass]	***Period [Dmass]***	***Period [Lmass]***	***Period [Dmass]***
1	0.571297	0.599714	0.536818	0.552121
2	0.256679	0.253462	0.241725	0.269344
3	0.154074	0.164512	0.148002	0.173766
4	0.101164	0.109475	0.099799	0.116313
5	0.09232	0.098015	0.089872	0.098367

As illustrated, the Lmass configuration tends to have slightly shorter periods compared to the Dmass configuration. Despite this difference, the periods for both cases closely align in both frames under examination. This initial verification step is important because it ensures the accuracy of the load distributions, making it possible to advance to the next phase of analysis.

Table 6 presents the deformed shapes of the frames in both the X and Y directions for the first three vibration modes. This illustration provides an exaggerated view of the frames' behavior under seismic loading conditions. The periods in Y direction are shorter than those in X direction but with very little difference in value. This consistency across different modes and directions proves that the total mass of each frame has been accurately calculated.

Table 6. Deformed shapes of the frames in both directions

Zeus-NL	**Mode 1**	**Mode 2**	**Mode 3**
X-direction	**Deformed Shape (MODAL) ; T=0.571297** 	**Deformed Shape (MODAL) ; T=0.256679** 	**Deformed Shape (MODAL) ; T=0.154074** 
Y-direction	**Deformed Shape (MODAL) ; T=0.536818** 	**Deformed Shape (MODAL) ; T=0.241725** 	**Deformed Shape (MODAL) ; T=0.148002** 

6.1.2 Incremental Dynamic Analysis

The selected frames of the building are modeled using moment frames to represent their structural behavior in both the horizontal (X) and vertical (Y) directions. The Incremental Dynamic Analysis (IDA) is entirely automated and easily carried out using Zeus-NL software, increasing the intensity measure step by step by a factor of 0.05g until numerical convergence is reached. The analysis covers an entire range of structural response for each ground motion record, beginning from elastic response to yielding and then finally reaching global instability. The resulting IDA curves plot intensity measure (first-mode spectral acceleration) against damage measure (global drift ratio) in a 2D graph.

The two frames undergo an extensive series of over a thousand nonlinear dynamic analyses in order to generate the IDA curves. The IDA analysis, known for its comprehensive insights into predicting structural behavior under varying ground motion conditions, is time-consuming and requires significant computer processing power due to the complexities involved [9].

The post-processing of the generated data is just as important as running the analysis. After extracting the Intensity Measure (IM) and Damage Measure (DM) values from each analysis, a voluminous set of data points emerges, each requiring careful handling and analysis. To effectively visualize and interpret these results, Microsoft Excel 2013 is utilized. Using the spline interpolation effectively reduces the scatter of data points, making it easy to observe any changes in structural response.

Figures 37-44 illustrate the IDA curves generated under a set of 20 ground motion records detailed in *Table 2*, together with their limit states and IDA fractiles.

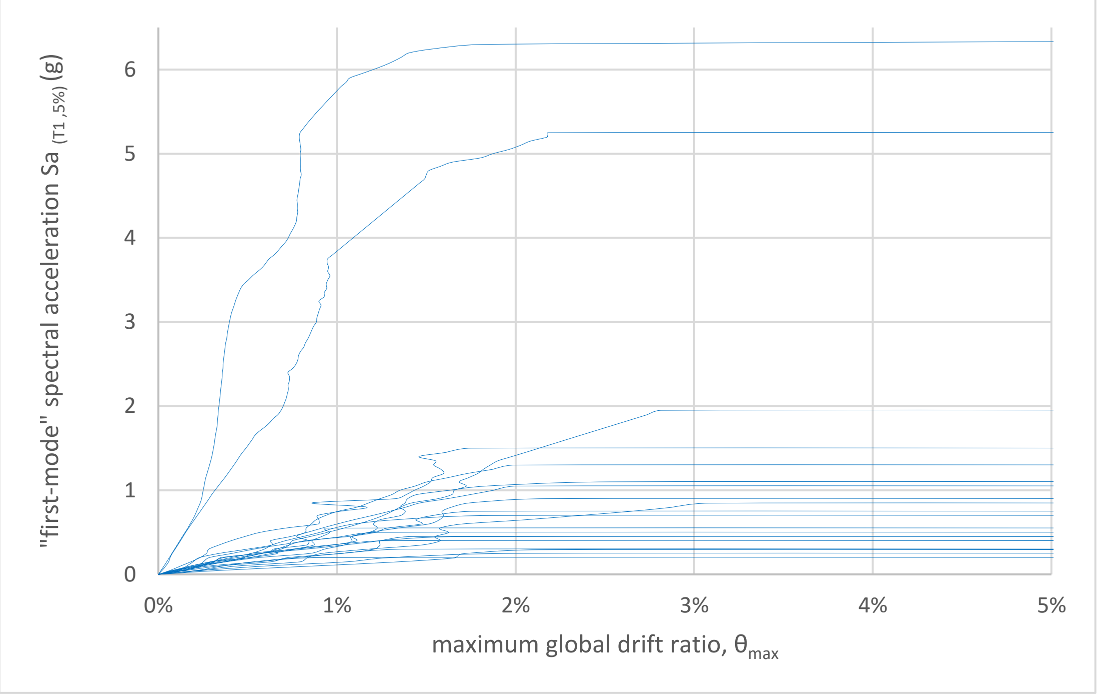


Figure 37. Twenty IDA curves for the building in X-direction

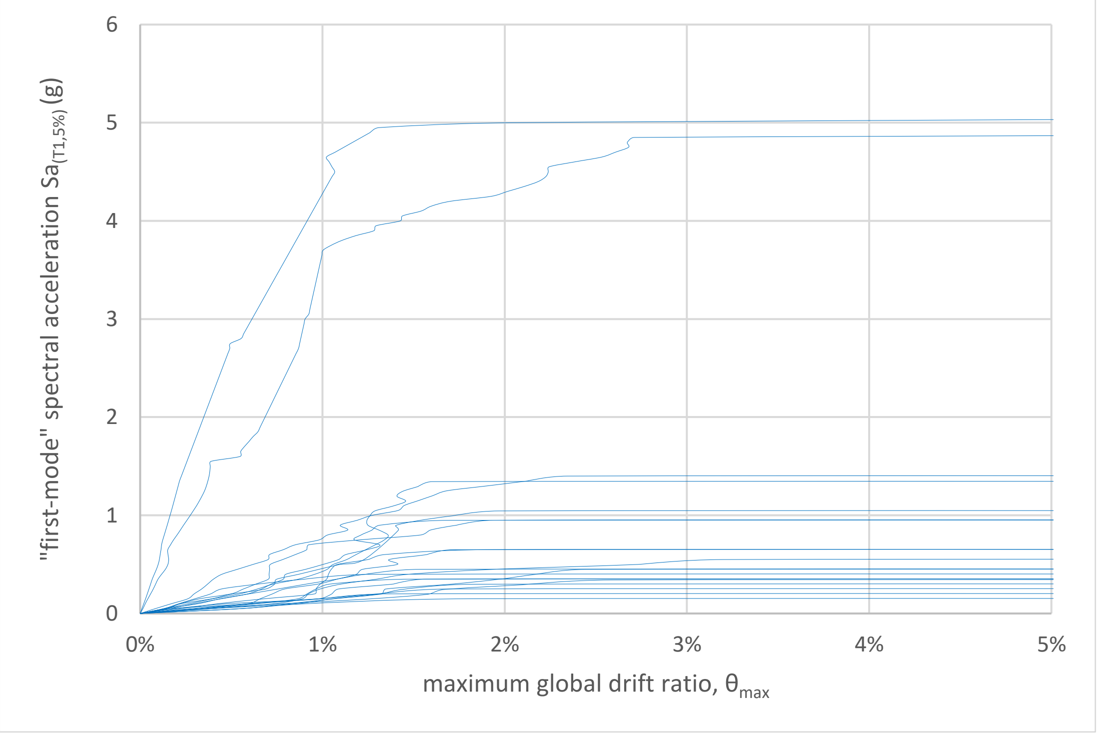


Figure 38. Twenty IDA curves for the building in Y-direction

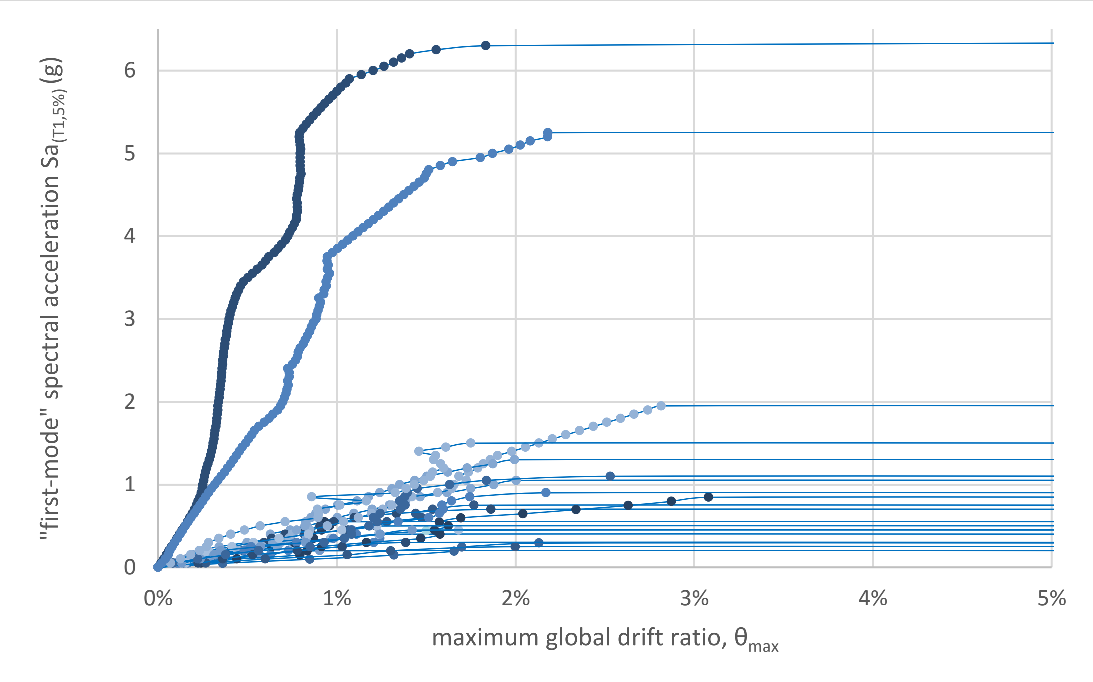


Figure 39. Twenty IDA curves for the building in X-direction presented with data points which show how many analyses it takes to generate each curve

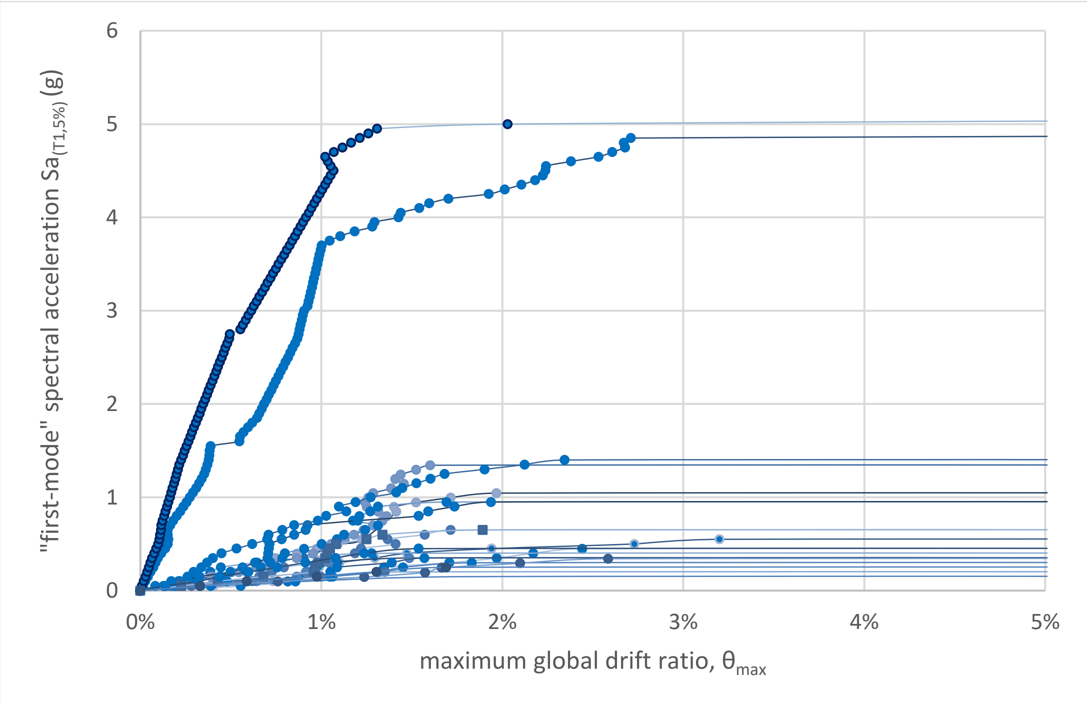


Figure 40. Twenty IDA curves for the building in Y-direction presented with data points which show how many analyses it takes to generate each curve

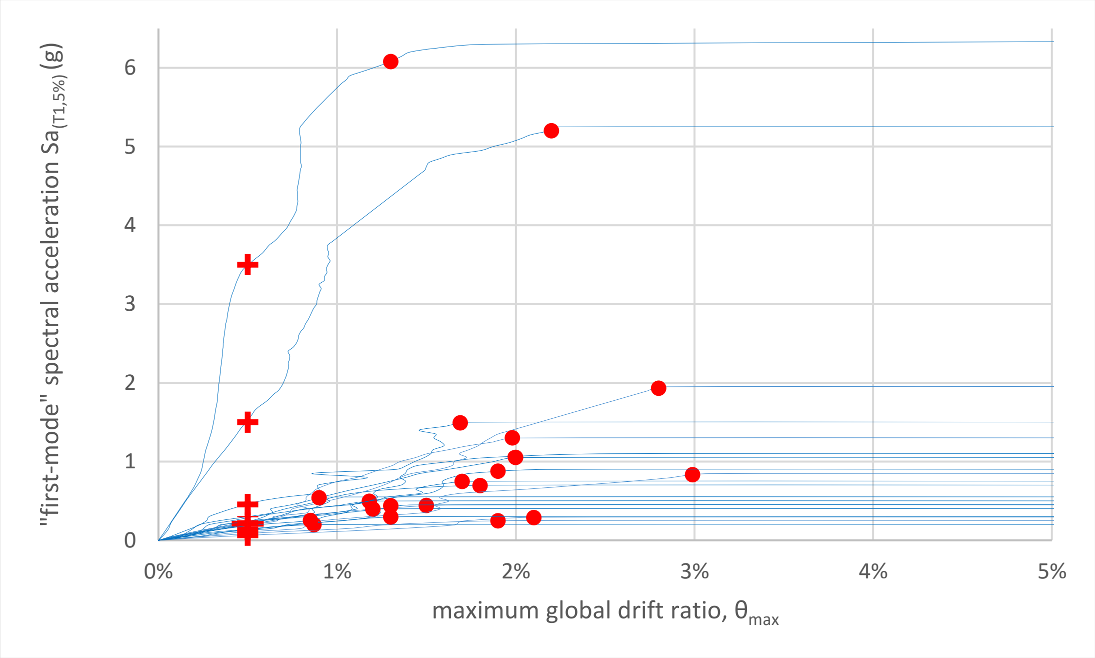


Figure 41. Twenty IDA curves and associated limit-state capacities for the building in X-direction. The Immediate Occupancy (IO) limit is represented by plus sign, Collapse Prevention (CP) limit is represented by dots and global instability (GI) with flatlines

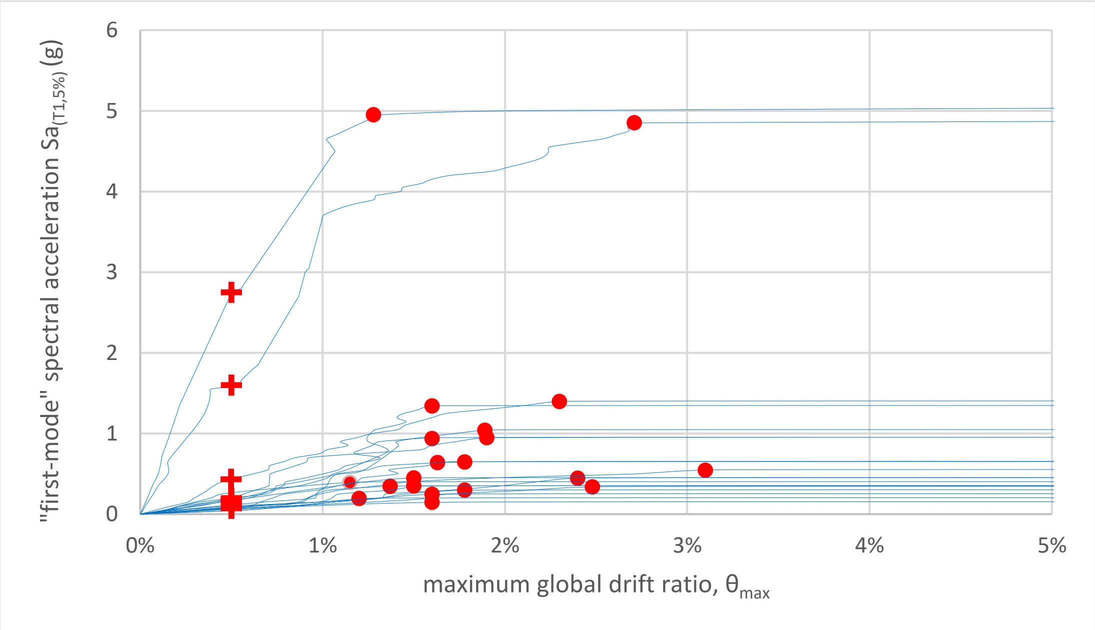


Figure 42. Twenty IDA curves and associated limit-state capacities for the building in Y-direction. The Immediate Occupancy (IO) limit is represented by plus sign, Collapse Prevention (CP) limit is represented by dots and global instability (GI) with flatlines

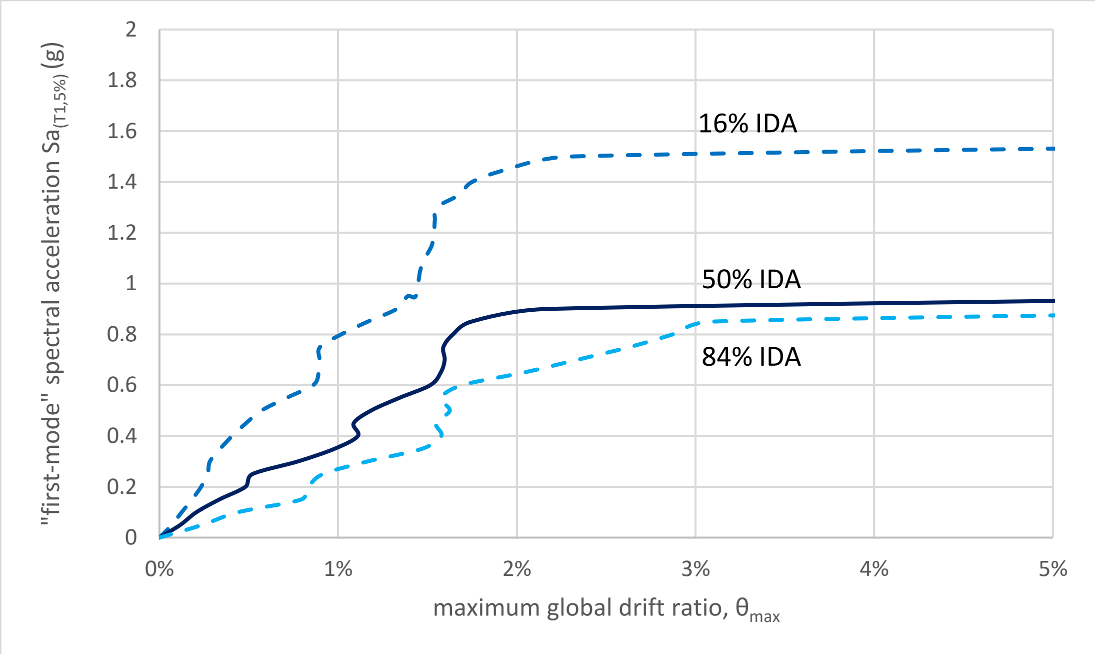


Figure 43. The summary of the IDA curves into their 16%, 50% and 84% fractiles for the frame in X-direction

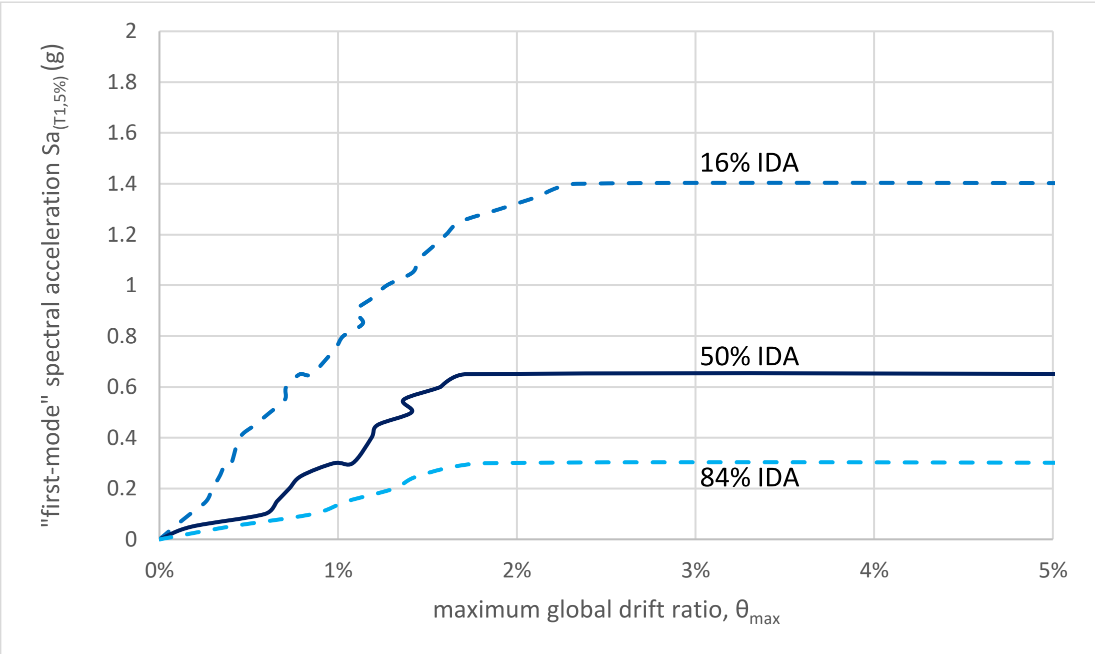


Figure 44. The summary of the IDA curves into their 16%, 50% and 84% fractiles for the frame in Y-direction

As shown in *Figures 37-42*, the seismic performance of each frame is presented through twenty IDA curves plotted together on a single graph. To ensure a clearer interpretation of results, various presentation techniques of the graphs are employed. *Figures 37 and 38* show IDA curves in their simplest form, represented by smooth lines, enabling easy observation of their progression from elastic behavior to eventual softening, concluding with a flatline indicating global instability or collapse.

In *Figures 39 and 40*, the curves are accompanied by their respective data points, highlighting the number of runs required to construct each curve. This visualizes the extensive effort involved, with hundreds of points needed for each analysis.

Figures 41 and 42 illustrate the positions of limit states as data points. The immediate occupancy level is indicated by a plus "+" sign when the damage measure (DM) parameter reaches 0.5%. Collapse prevention is denoted by a dot "•" sign, while global instability is represented by flatlines.

Lastly, *Figures 43 and 44* showcase fractiles for each set of IDA curves, summarizing them into 16%, 50%, and 84% fractiles. These IDA fractiles provide further insights into the structural performance of the building, offering a comprehensive overview of its behavior under varying loading conditions.

6.1.3 IDA Fractiles

After generating the IDA curves for each record, it is suggested in previous studies [7, 9, 27] that the best method to evaluate the statistical distribution of response relative to the input is to summarize the curves into 16%, 50%, and 84% fractiles. These fractiles, just like the initial curves, represent various levels of structural response, including immediate occupancy, collapse prevention, and global instability, visually depicted on dynamic pushover curves.

By summarizing the data of the limit states for each fractile, we obtain interpolated values that generate the 16%, 50%, and 84% limit states of the IDA curves, as shown in *Figures 45 and 46*. For example, when observing the behavior of the frame in X-direction given $Sa_{(T1;5\%)}$ = 0.2 g, the 16% of records produce a maximum drift ratio of 0.2%, 50% of records produce 0.5% global drift, and 84%

produce 0.8% global drift. These fractiles can also be used inversely; for instance, to generate a demand of θ_{max} = 1.8%, 84% of records need to be scaled at $Sa_{(T1;5\%)} \geq 0.6$ g, 50% at $Sa_{(T1;5\%)} \geq 0.85$ g, and 16% at $Sa_{(T1;5\%)} \geq 1.45$ g.

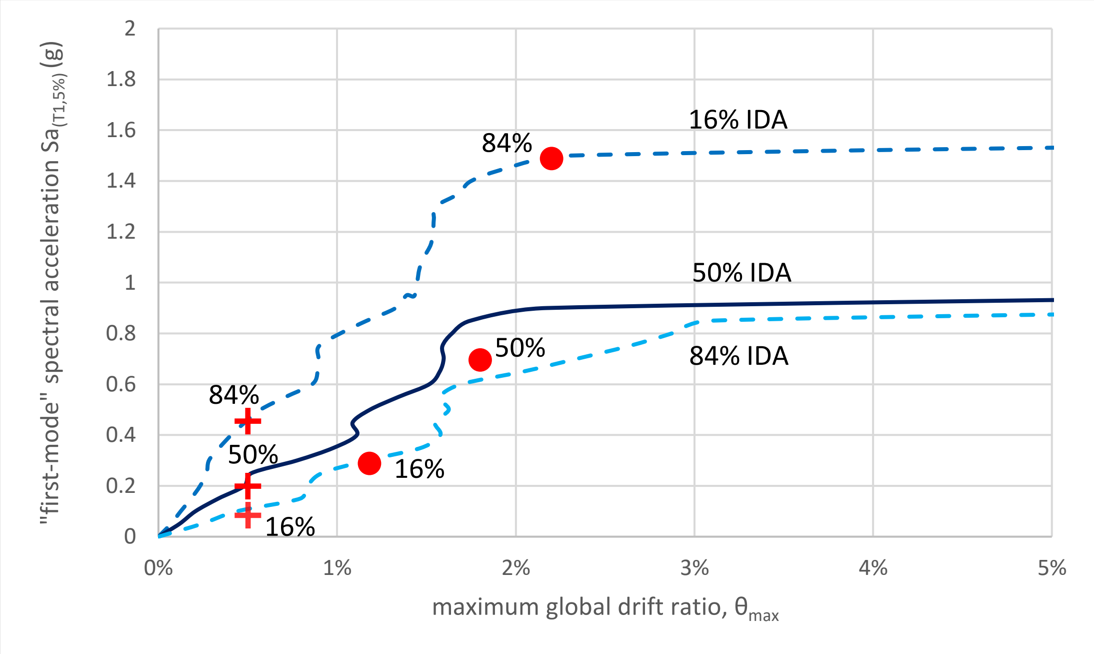


Figure 45. IDA fractiles shown as 16%, 50%, 84% together with limit-states summarized for the X-direction frame

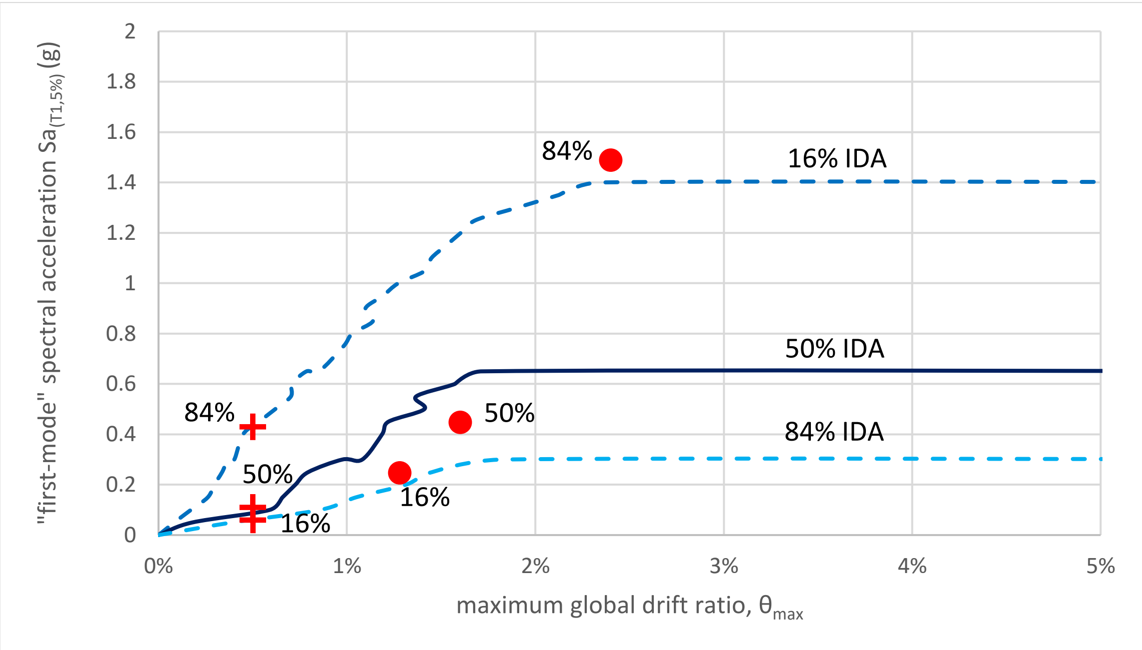


Figure 46. IDA fractiles shown as 16%, 50%, 84% together with limit-states summarized for the Y-direction frame

Limit states, including Immediate Occupancy (IO), Collapse Prevention (CP), and Global Instability (GI), are crucial benchmarks for assessing structural performance. These are consolidated in *Table 7 and 8*, where the intensity measure (IM) parameter is defined as "first-mode spectral acceleration," and the damage measure is designated as "maximum global drift ratio."

As illustrated, the collapse prevention limit states are all set below 10% of the global drift ratio to ensure structural safety before potential collapse, following FEMA 356 guidelines. The global instability level signifies total building collapse, with the corresponding "+∞" value for the damage measure parameter when reached.

Table 7. The numerical values of $Sa_{(T1,5\%)}$ and θ_{max} for each of the limit states in X direction

No	***Sa (T1,5%) (g)***			***ϑ_{max}***		
	IO	**CP**	**GI**	**IO**	**CP**	**GI**
1	0.234	0.697	0.7	0.50%	1.80%	+∞
2	0.137	0.199	0.2	0.50%	0.87%	+∞
3	0.064	0.29	0.3	0.50%	2.10%	+∞
4	0.22	1.93	1.95	0.50%	2.80%	+∞
5	0.1	0.833	0.85	0.50%	2.99%	+∞
6	0.21	1.297	1.3	0.50%	1.98%	+∞
7	0.085	0.248	0.25	0.50%	1.90%	+∞
8	0.281	0.497	0.5	0.50%	1.18%	+∞
9	0.235	0.881	0.9	0.50%	1.90%	+∞
10	0.137	0.295	0.3	0.50%	1.30%	+∞
11	0.232	0.443	0.45	0.50%	1.32%	+∞
12	0.183	1.06	1.1	0.50%	1.99%	+∞
13	0.455	1.489	1.5	0.50%	1.69%	+∞
14	1.5	5.2	5.23	0.50%	2.20%	+∞
15	0.19	0.54	0.55	0.50%	0.90%	+∞
16	0.302	1.04	1.051	0.50%	2.00%	+∞
17	0.201	0.746	0.75	0.50%	1.70%	+∞
18	0.051	0.58	0.6	0.50%	2.20%	+∞
19	0.125	0.397	0.4	0.50%	1.20%	+∞
20	3.503	6.08	6.1	0.50%	1.30%	+∞

Table 8. The numerical values of $Sa_{(T1,5\%)}$ and θ_{max} for each of the limit states in Y direction

No	***Sa (T1,5%) (g)***			***ϑmax***		
	IO	**CP**	**GI**	**IO**	**CP**	**GI**
1	0.171	0.448	0.45	0.50%	1.50%	+∞
2	0.085	0.247	0.25	0.50%	1.60%	+∞
3	0.072	0.337	0.35	0.50%	2.48%	+∞
4	0.433	1.395	1.4	0.50%	2.30%	+∞
5	0.115	0.645	0.65	0.50%	1.78%	+∞
6	0.203	0.944	0.95	0.50%	1.90%	+∞
7	0.084	0.195	0.2	0.50%	1.20%	+∞
8	0.11	0.348	0.35	0.50%	1.50%	+∞
9	0.085	0.641	0.65	0.50%	1.63%	+∞
10	0.061	0.298	0.3	0.50%	1.78%	+∞
11	0.075	0.347	0.35	0.50%	1.37%	+∞
12	0.17	0.938	0.95	0.50%	1.60%	+∞
13	0.18	1.34	1.35	0.50%	1.60%	+∞
14	2.75	4.95	5	0.50%	1.28%	+∞
15	0.19	1.042	1.05	0.50%	1.89%	+∞
16	0.265	0.394	0.4	0.50%	1.15%	+∞
17	0.062	0.544	0.55	0.50%	3.10%	+∞
18	0.043	0.445	0.45	0.50%	2.40%	+∞
19	0.044	0.147	0.15	0.50%	1.60%	+∞
20	1.602	4.865	4.9	0.50%	2.71%	+∞

6.1.4 Evaluation of the structural performance

As described in Chapter 2.3, a key goal of performance assessment for reinforced concrete buildings is to ensure the Life Safety (LS) limit state is maintained for earthquakes with a 475-year return period. However, identifying this limit state on the IDA curves is a complex process. As the calculation of LS in each IDA curve requires further research, in this thesis the focus shifts to evaluation the performance of the building in terms of immediate occupancy. This task is achieved by comparing the immediate occupancy values obtained from the IDA curves with the PGA for a return period of 95 years.

As seen in *Figures 47 and 48*, comparisons are provided, illustrating how the IO limit states of the IDA curves align with the threshold PGA value selected as 0.12g, based on the recent seismic events in our country. There is a graphical representation of bars for each earthquake record to illustrate the IO values shown in *Figures 47 and 48*. To check whether the buildings meet the IO performance level, there is a red line positioned at 0.12g that represents the threshold derived from the hazard map.

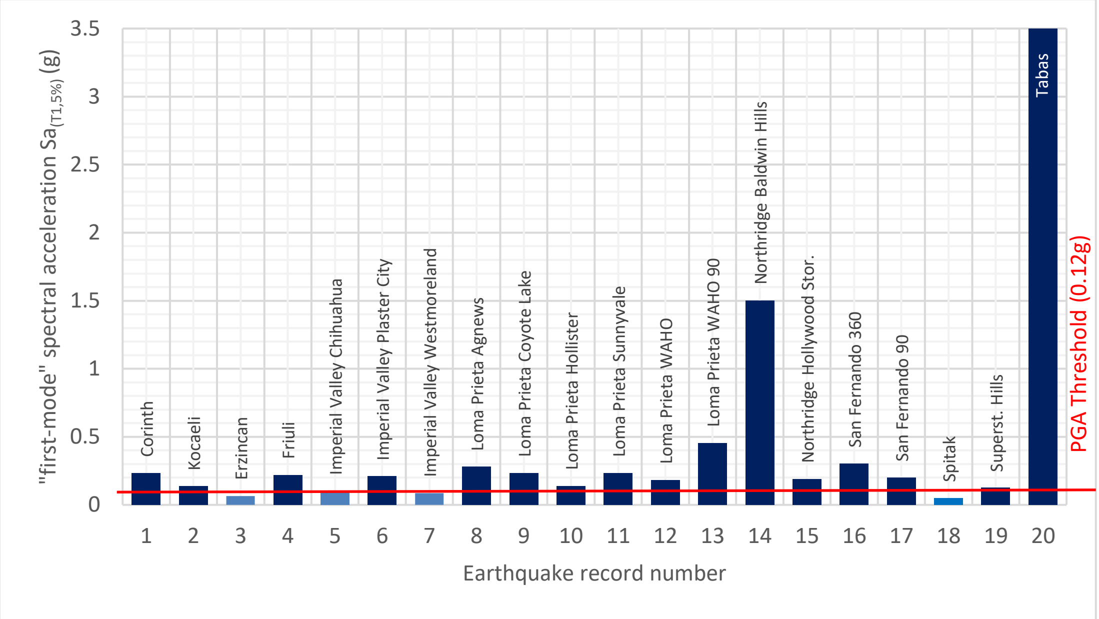


Figure 47. The earthquake records violating IO limit state for the X-direction frame

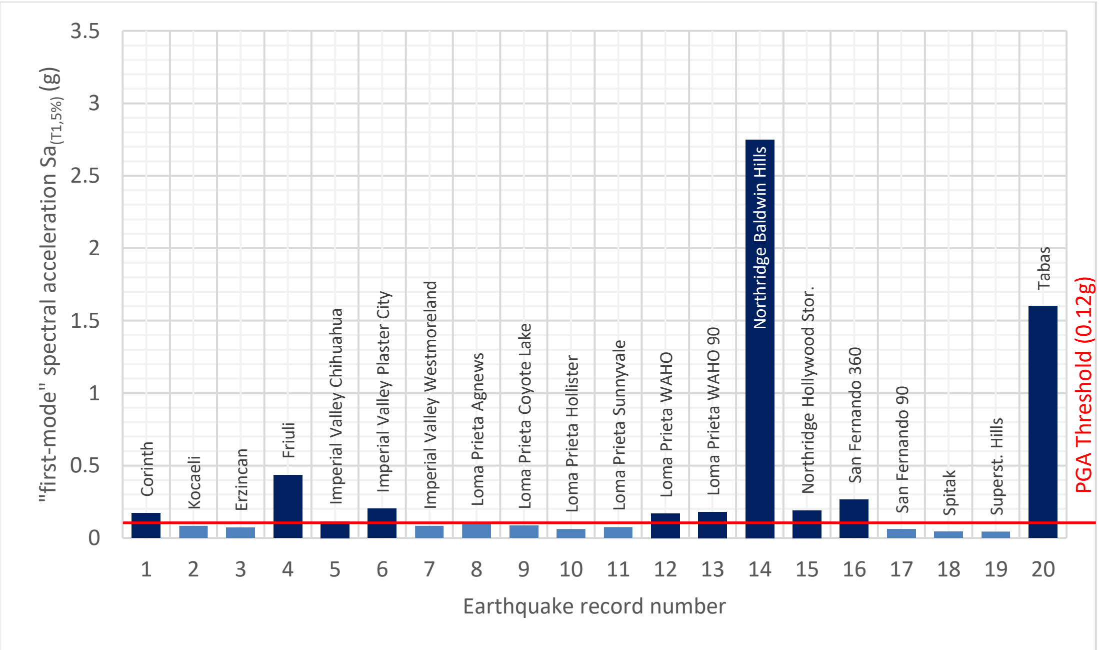


Figure 48. The earthquake records violating IO limit state for the Y-direction frame

As seen, immediate occupancy is ensured in 16 out of 20 records considered in this study for the horizontal frame, and in 10 out of 20 records for the vertical frame. For the X direction frame, IO is exceeded by four earthquake records, including Erzincan – Turkey, Imperial Valley – Chihuahua, Imperial Valley – Westmoreland Fire Station and Spitak – Armenia. The IO limit is exceeded in 10 out of 20 records for the frame in Y direction, including Kocaeli – Turkey, Duzce, Erzincan – Turkey, Imperial Valley – Westmoreland Fire Station, Loma Prieta - Agnews State Hospital, Loma Prieta – Coyote Lake Dam Downstr., Loma Prieta – Hollister South & Pine, Loma Prieta – Sunnyvale Colton Ave, San Fernando – LA, Hollywood Stor. Lot, Spitak – Armenia, Gukasian and Superstition Hills – Wildlife Liq. Array.

The rest of these records must be increased to higher intensities to violate the immediate occupancy of the building. From this point of view, the performance of the building in X direction is better compared to the other direction.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 General

This study evaluates the structural performance of a premodern template reinforced concrete building using a modern nonlinear analysis method known as Incremental Dynamic Analysis (IDA). The building, characterized by a symmetrical horizontal plan configuration and absence of shear walls, is composed of reinforced concrete members with a concrete strength of f_c = 16 MPa and steel class f_y = 320 MPa.

To evaluate the seismic performance of the building, ZeusNL software is employed. Eigenvalue analysis provides results for proper modal mass assignment, period verification, and a comparison between the mass distribution methods used on the frame elements. Incremental dynamic analysis utilizes twenty ground motion records ranging from 0.042g to 3.5g peak ground acceleration and generates the dynamic pushover curves (IDA curves). These curves are then post-processed and categorized into 16%, 50%, and 84% fractiles, providing probabilistic insights into seismic performance.

Moreover, Immediate Occupancy, Collapse Prevention, and Global Instability limit states are calculated and allocated for each IDA curve and fractile, enhancing the understanding of structural behavior. The methodology employed in generating, interpolating, and illustrating the IDA curves, as well as determining the limit states and summarizing the IDA fractiles, is outlined step by step in this study.

7.2 Conclusions

This study investigated the performance of a premodern template reinforced concrete building that is widely found in many regions of Albania, using a modern approach of nonlinear dynamic analysis. All the analyses that have been performed in this study have been performed using the ZEUS NL software. Based on the values gathered from the analyses, the following conclusions were drawn:

1. The software Zeus NL, unlike other structural performance assessment softwares such as SAP2000 or ETABS, does not calculate the self-weight of slabs, frame elements and walls during its analyses. Hence, these loads must be calculated by the users themselves and assigned onto the members as either point loads over supports or distributed loads over beams. Both cases are applied in this paper to see the similarities and dissimilarities, and from the eigenvalues analysis it is observed that both cases give similar results while estimating the period of the structures.

2. Incremental Dynamic Analyses (IDA) for each frame under twenty ground motions are conducted. The resulting IDA curves are presented in this report in various formats in order to offer clear insights into structural behavior changes. These illustrations range from smooth line curves showcasing IDA variations to dot representations highlighting each incremental step, making it easy for the user to visually interpret the iterations leading to global instability. Then, the IDA results are summarized into 16%, 50%, and 84% fractiles. Limit states including Immediate Occupancy (IO), Collapse Prevention (CP), and Global Instability (GI) are allocated on the curves following FEMA guidelines. To investigate structural performance under nonlinear dynamic analysis, the structural models in both the X and Y directions are compared. The examination of the generated IDA curves enables the identification of earthquake records triggering structural limit states earlier than anticipated. The analysis reveals that certain earthquake records, including Imperial Valley - Westmoreland Fire Station, Tabas - Iran, and Kocaeli - Turkey, Duzce, induce structural failure earlier than others. This leads to the conclusion that inherent characteristics of the accelerogram and resonance effects may significantly influence structural performance.

3. Finally, the Immediate Occupancy (IO) limit states from the Incremental Dynamic Analysis (IDA) curves are compared to a 0.12g peak ground acceleration (PGA) threshold derived from the probabilistic seismic hazard maps of Albania for a return period of 95 years. The comparison reveals that the seismic performance of the structure is inadequate. For the frame in the X direction, 20% of the earthquake records exceed the IO limit, while for the frame in the Y direction, this limit state is exceeded

by 50% of the records. This inadequate performance may be due to factors such as the absence of shear walls or other critical design elements.

Although the target of this study is to determine the percentage of earthquakes that violate the life safety (LS) limit state to assess building performance, IO levels are used as a guideline for future research until LS values can be calculated. Ideally, performance assessment should include calculated LS limit states, underscoring the need for further studies to ensure structures meet desired safety standards under different seismic conditions.

7.3 Recommendations for future research

The current study focuses on a specific template reinforced concrete building prevalent in Albania. Further exploration into diverse building typologies and materials, as well as advanced analysis methodologies, can offer more insight into seismic design and retrofitting practices. This section outlines key recommendations for future research endeavors.

1. While the current study focuses on a template reinforced concrete, 5-story residential building designed according to outdated building codes, future research could broaden its scope to focus on other types of structures such as bridges, hospitals, schools, mosques, or public institutions. Analyzing the seismic performance of these diverse structures could provide valuable insights into their vulnerability and aid in developing targeted retrofitting strategies.

2. The building used in this study is symmetrical without structural irregularities. Future research could explore structures with asymmetrical layouts, varying floor heights, or the inclusion of architectural features that may impact seismic response. Utilizing advanced nonlinear analysis techniques like Incremental Dynamic Analysis (IDA) would be beneficial in assessing the performance of such structures under seismic loading.

3. While the current study focuses on reinforced concrete structures, future research could investigate the seismic performance of steel structures in Albania and

neighboring countries. Comparing the behavior of steel structures to reinforced concrete ones could offer valuable insights into the effectiveness of different building materials and construction techniques in mitigating seismic risks.

4. Given the absence of shear walls in the analyzed building, future research could explore the influence of different structural systems and material properties on seismic performance. This could involve studying buildings with shear walls, moment frames, or hybrid systems to assess their effectiveness in resisting seismic loads.

5. A deeper investigation into Incremental Dynamic Analysis (IDA) combined with Performance-Based Earthquake Engineering (PBEE) methodologies could enhance our understanding of seismic risk assessment and performance evaluation. In this study, the Life Safety limit state was not calculated due to the complexity of the IDA curves and the significant effort required to determine this limit state accurately. Future research could focus on calculating and incorporating the Life Safety limit state within the IDA curves. By doing so, researchers could compare the results with thresholds derived from seismic hazard maps of Albania, specifically for a return period of 475 years.

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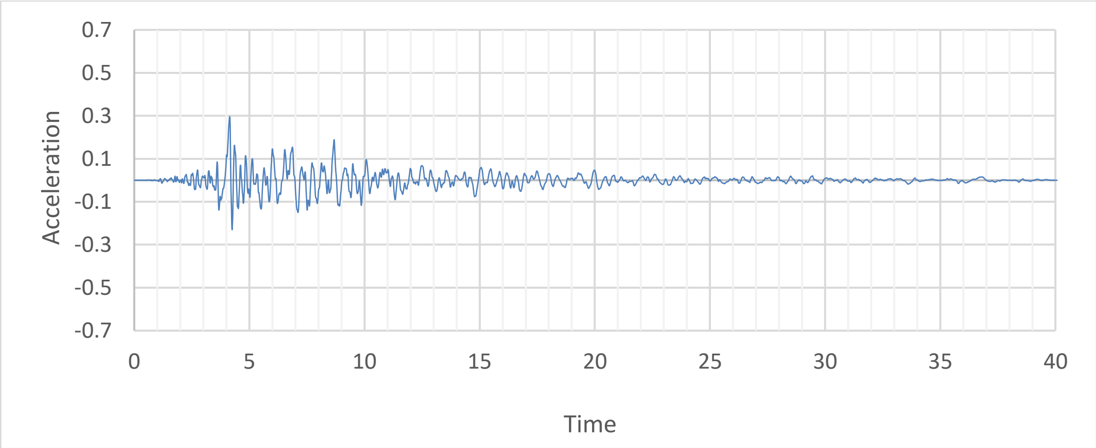
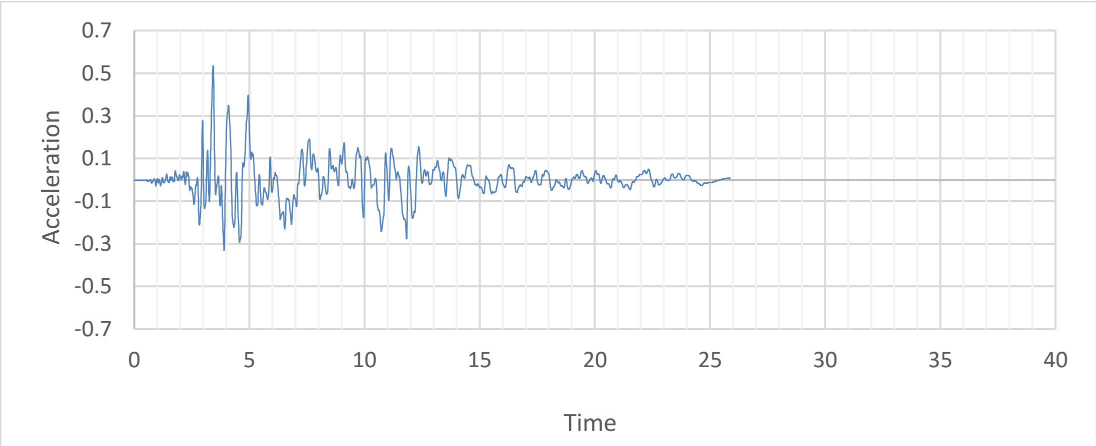
APPENDIX A

EARTHQUAKE ACCELEROGRAMS

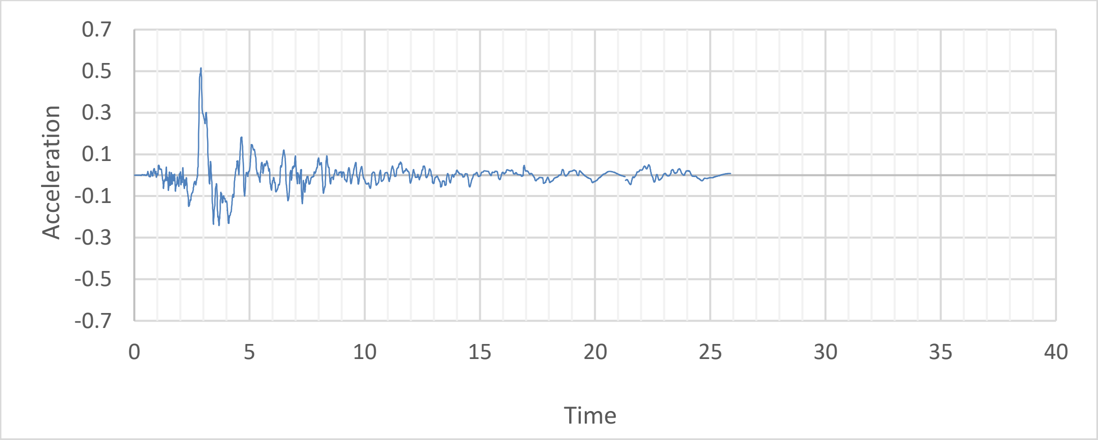
The twenty accelerograms used for IDA analysis are presented below and plotted as “Acceleration (g)” versus “Time (sec)”. Details for each earthquake record are presented in *Table 2*.



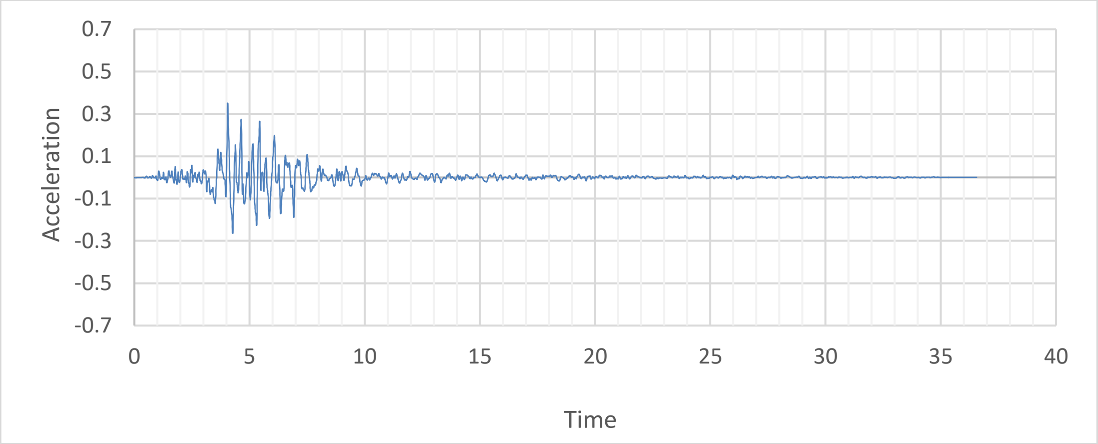
No.1: Corinth – Greece, Corinth



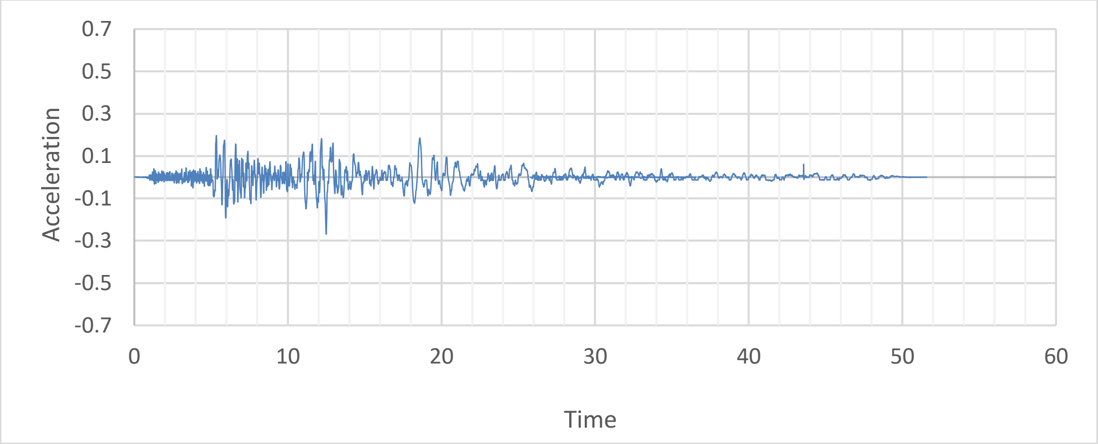
No.2: Kocaeli – Turkey, Duzce



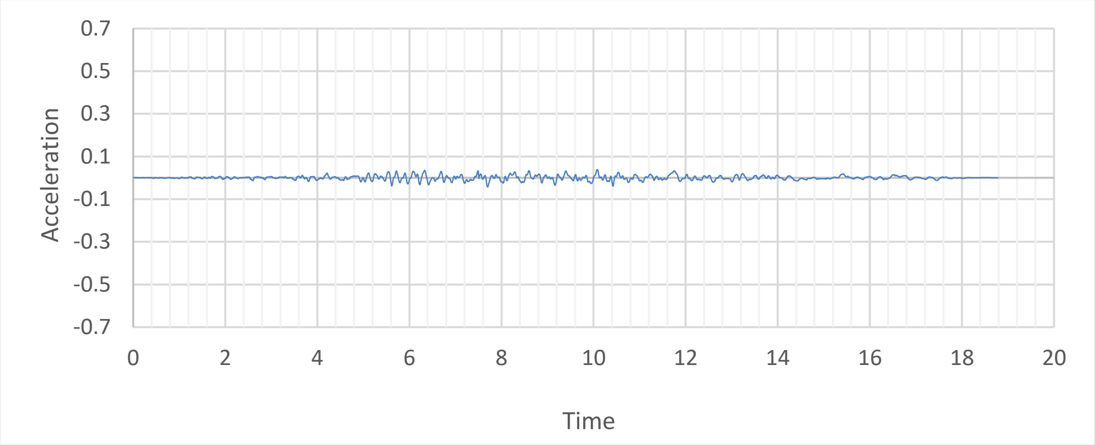
No.3: Erzincan – Turkey, Erzincan



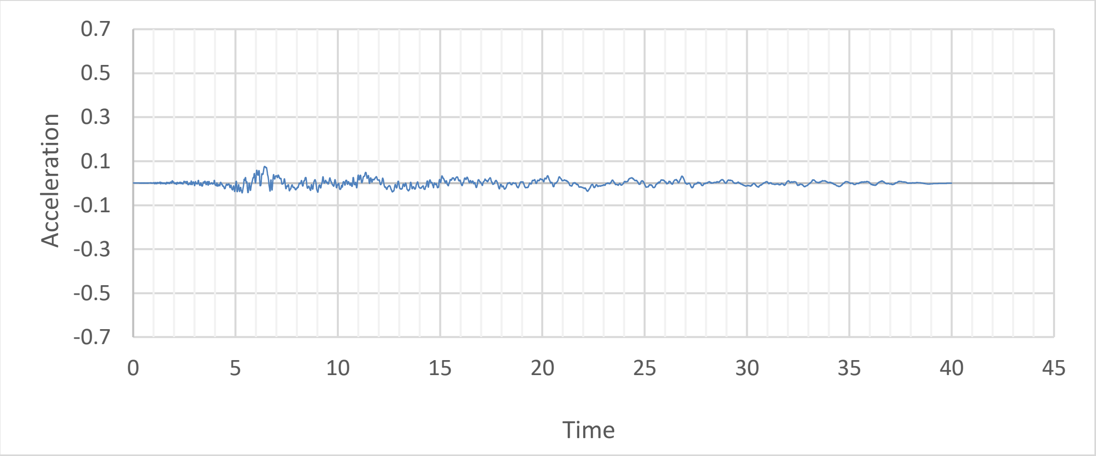
No.4: Friuli – Italy, Tolmezo



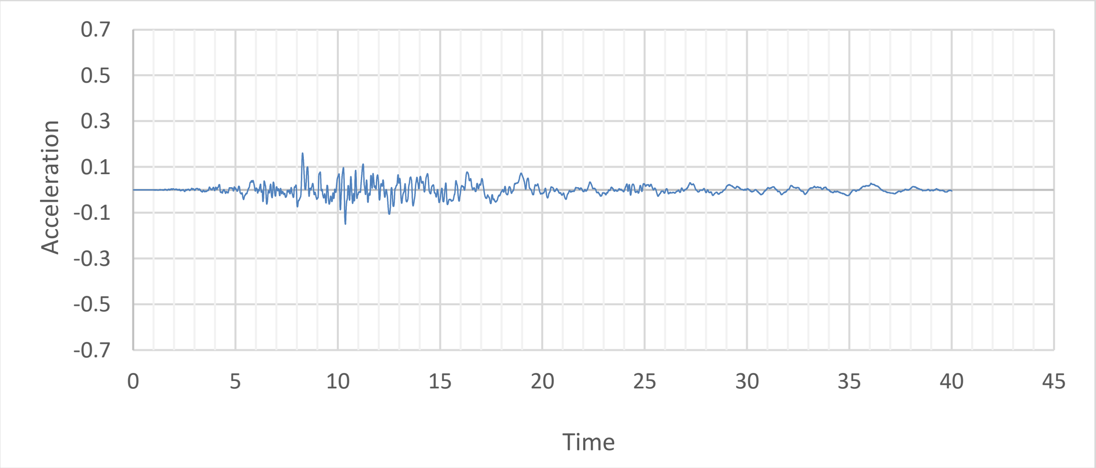
No.5: Imperial Valley – Chihuahua



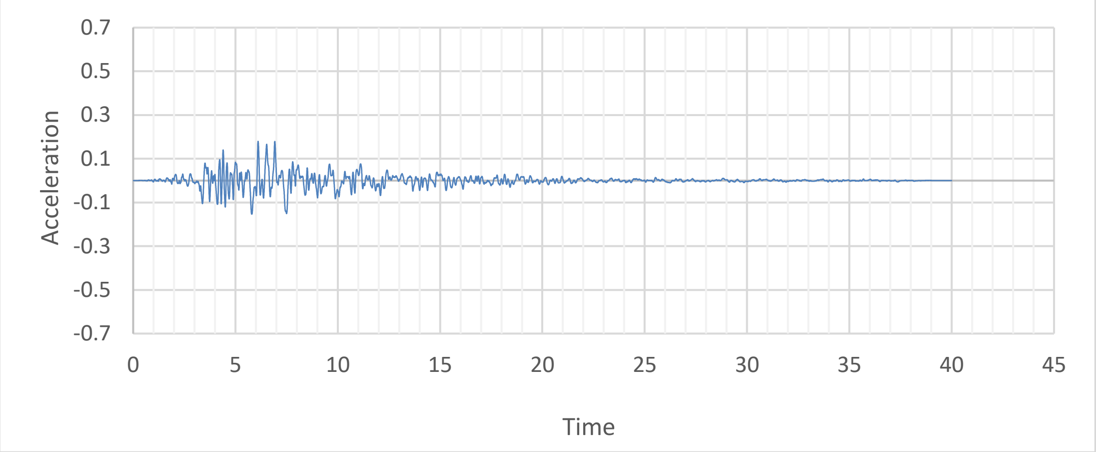
No.6: Imperial Valley – Plaster City



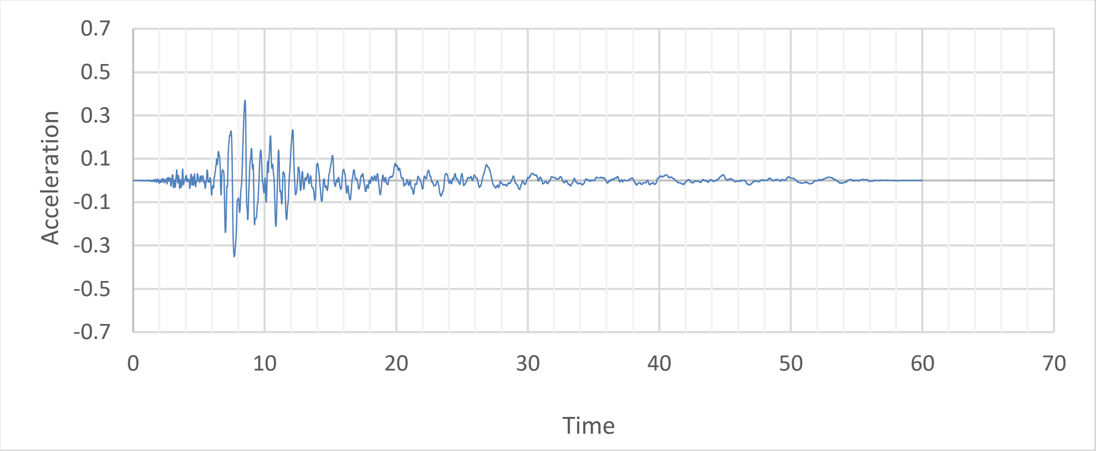
No.7: Imperial Valley – Westmoreland Fire Station



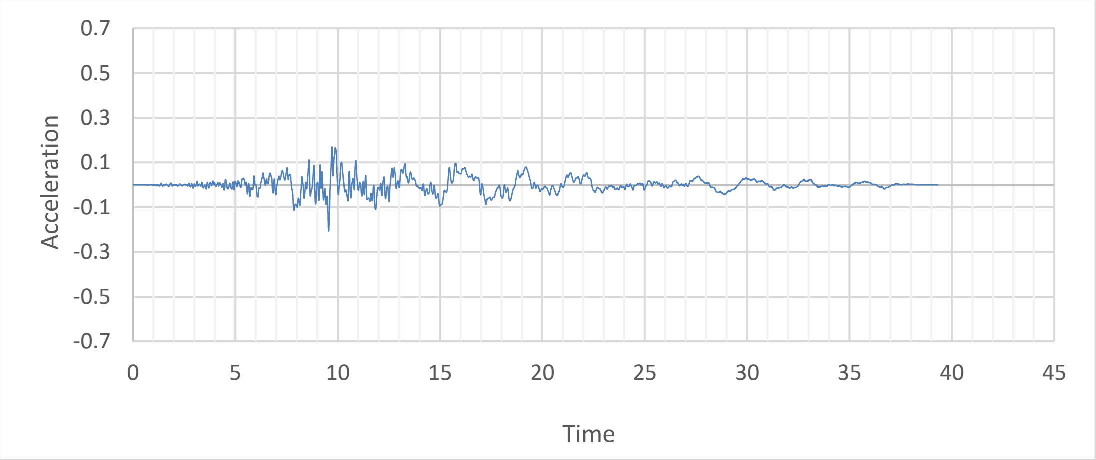
No.8: Loma Prieta – Agnews State Hospital



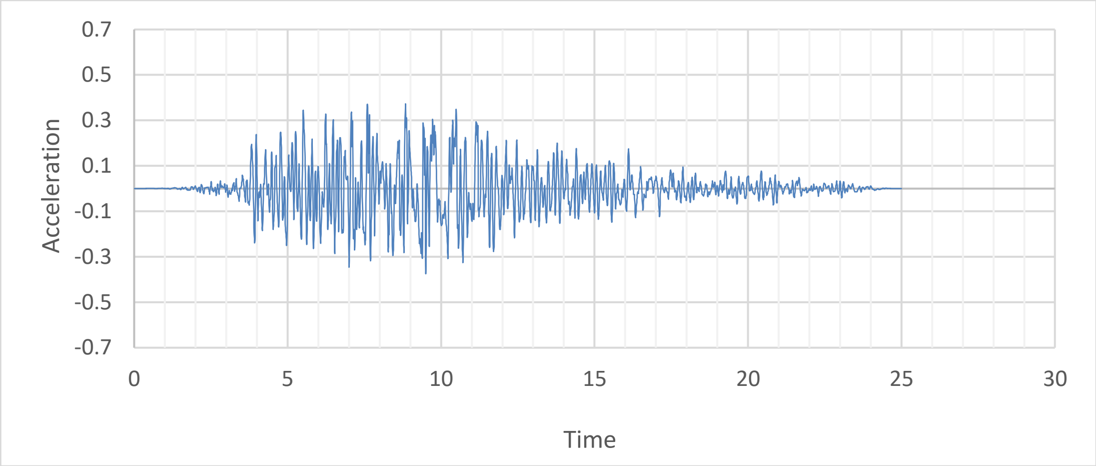
No.9: Loma Prieta – Coyote Lake Dam Downstr



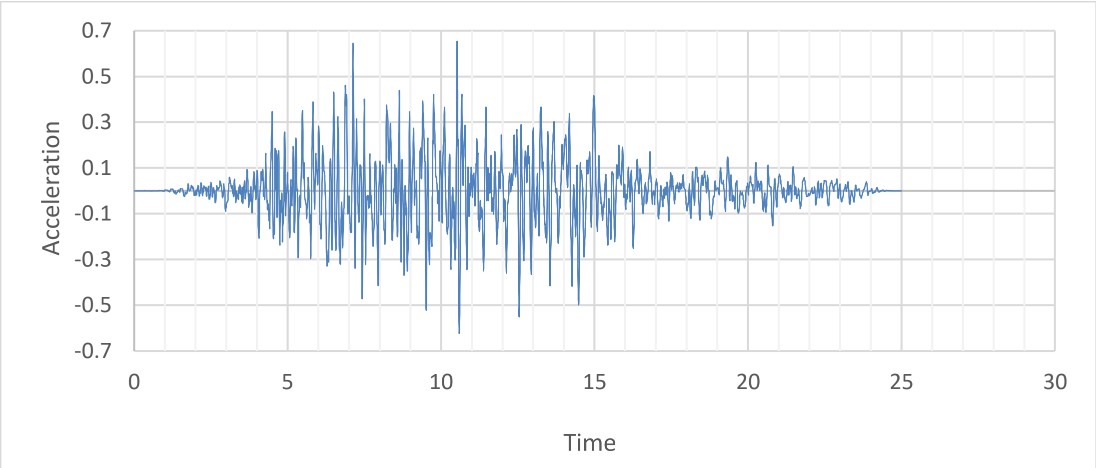
No.10: Loma Prieta – Hollister South & Pine



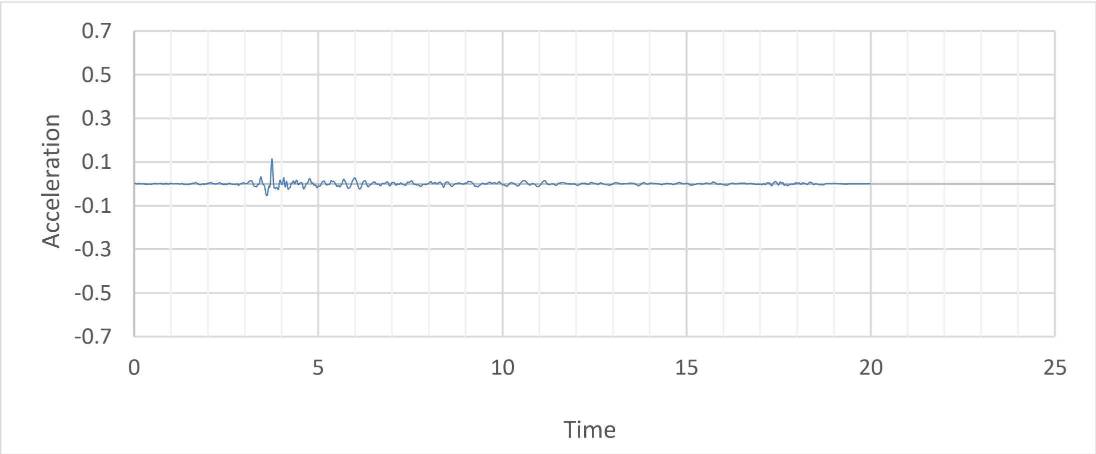
No.11: Loma Prieta – Sunnyvale Colton Ave



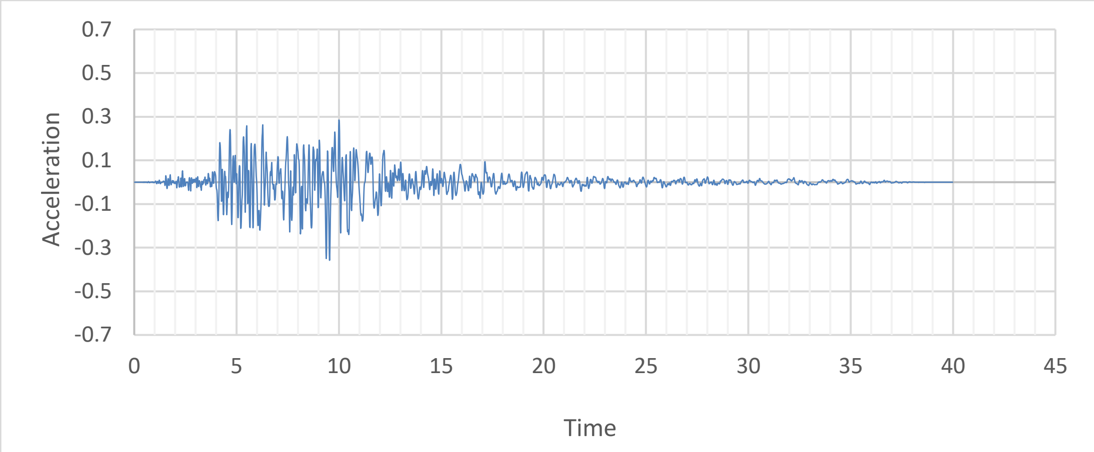
No.12: Loma Prieta – WAHO 0



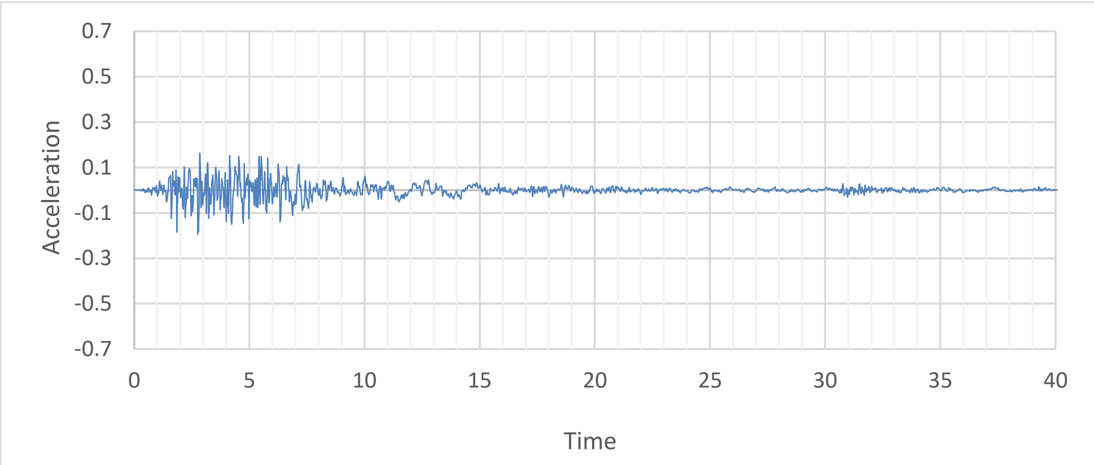
No.13: Loma Prieta – WAHO 90



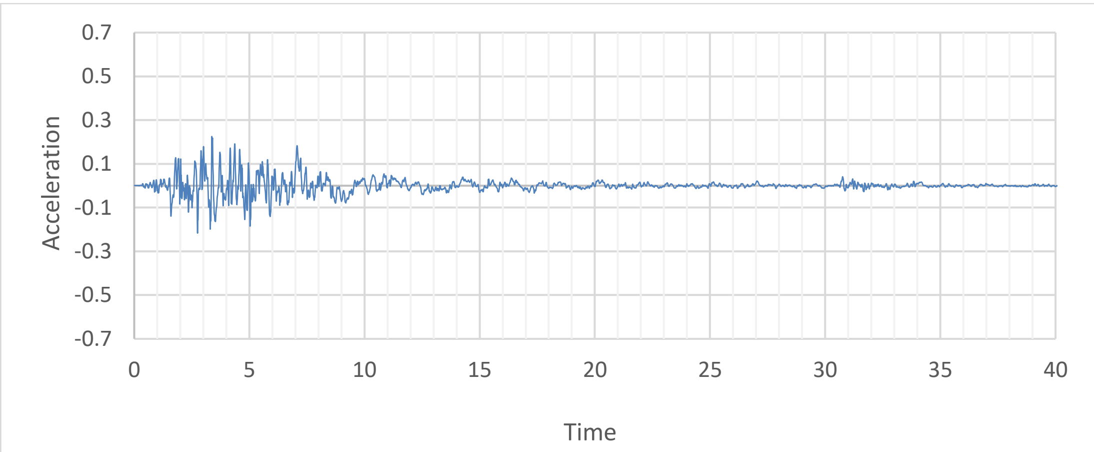
No.14: Northridge – LA, Baldwin Hills



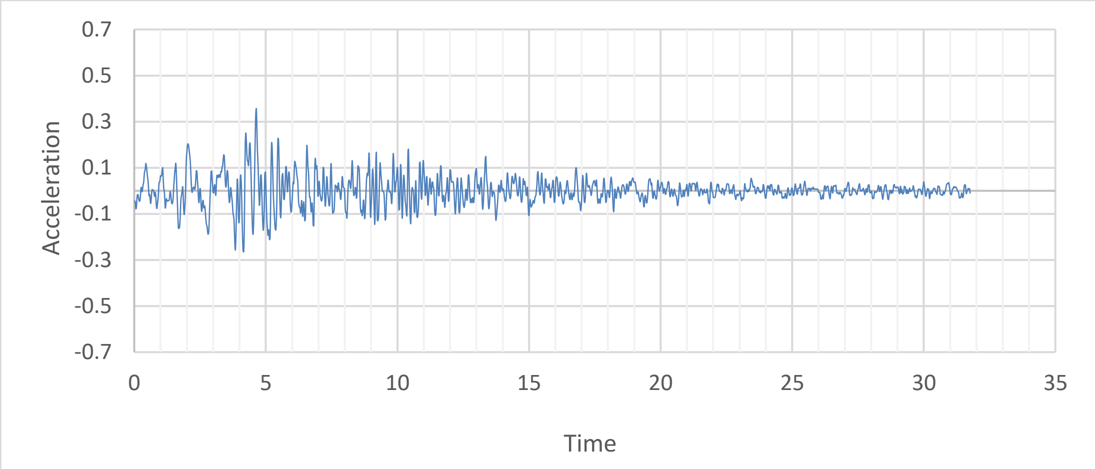
No.15: Northridge – LA, Hollywood Storage FF



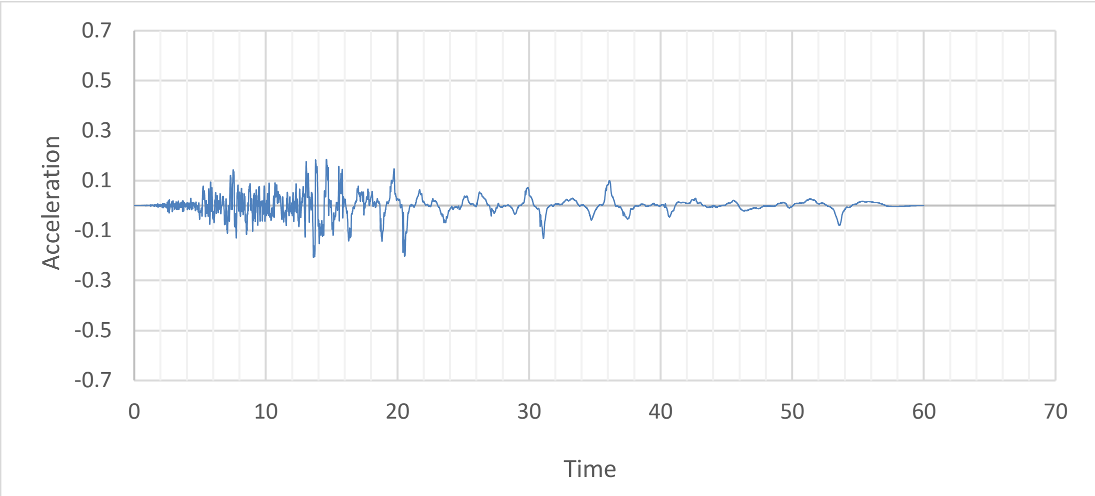
No.16: San Fernando – LA, Hollywood Storage Lot 180



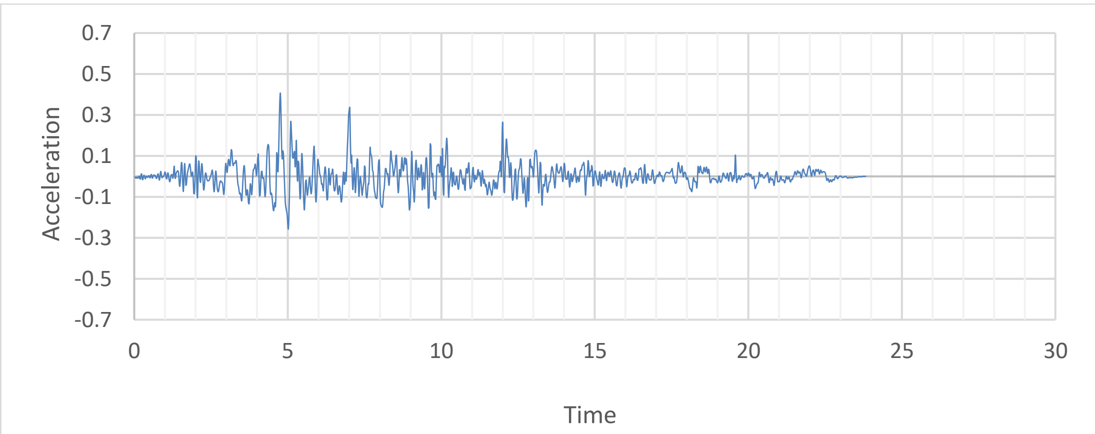
No.17: San Fernando – LA, Hollywood Storage Lot 90



No.18: Spitak – Armenia, Gukasian



No.19: Superstition Hills – Wildlife Liq. Array



No.20: Tabas – Iran, Dayhook