

SCALING OF INPUT SEISMIC ENERGY OF SDOF SYSTEMS THROUGH
EXPERIMENTAL AND ANALYTICAL INVESTIGATION

by

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ABSTRACT

SCALING OF INPUT SEISMIC ENERGY OF SDOF SYSTEMS THROUGH EXPERIMENTAL AND ANALYTICAL INVESTIGATION

In this study, two steel hollow section specimens and two aluminum hollow section specimens with different length and cross-sectional dimensions were used. In the analytical part, spectral input energy of these specimens was calculated with ten different periods under San Salvador, Loma Prieta and Erzincan ground motion records in elastic range. The scale factor for spectral input energy between specimens were calculated with seven different cases in terms of length, cross-sectional dimension and material properties. For each defined binary state, input energy scale factor was determined based on material elasticity modulus ratio, length ratio and period ratio between the specimens. In those seven different binary states, spectral input energy values were proportioned and scale factor for input energy was determined. Steel and aluminum specimens' numerical models were constructed using SAP2000 Structural Analysis software and their corresponding energy values for each period under defined earthquake ground motion were calculated. Spectral energy values were compared with existing mass-normalized input energy spectra (Dindar, 2015) based on earthquake properties. Experimental studies were carried out with four specimens, three different periods and under three different earthquake ground motion records by using shake table. Spectral input energy for each specimen was calculated from the experimental data. Numerical modelling results for spectral input energy values were compared with experimental results and they all showed good agreement. Also, experimental and analytical studies showed that scale factor for spectral input energy is equal to mass scale factor between the specimens for a given ground motion data.

ÖZET

DENEYSEL VE ANALİTİK ÇALIŞMAYLA TEK SERBESTLİK DERECELİ SİSTEMLERİN YAPIYA GELEN SİSMİK ENERJİSİNİN ÖLÇEKLENDİRİLMESİ

Bu çalışmada, boyları ve kesit boyutları farklı olan iki çelik ve iki alüminyum kutu profil numuneler kullanıldı. Kullanılan numunelerin spektral girdi enerjileri analitik çalışmada on farklı periyotta San Salvador, Loma Prieta ve Erzincan depremi altında elastik bölgede hesaplandı. Numuneler arasındaki giren enerji oranının ölçek faktörü yedi farklı iki durumlarla boy, kesit boyutlarına ve malzeme türüne bağlı olarak hesaplandı. Her ikili durum için, spektral giren enerji ölçek faktörü malzeme elastik modülü oranı, uzunluk oranı ve periyot oranlarına bağlı olarak hesaplandı. Yedi farklı ikili durumlarda elde edilen yapıya gelen enerji değerleri kendi içlerinde oranlanmıştır ve giren enerji için ölçek faktörü belirlendi. Çelik ve alüminyum numunelerin modellemeleri SAP2000 programıyla yapıldı ve enerji değerleri bu programla hesaplanarak bulundu. Spektral enerji değerleri deprem özelliklerine göre Dindar (2015) giren enerji spektrum eğrisi ile karşılaştırıldı. Deneysel çalışmalar dört numune için üç farklı periyot ve tanımlanan üç farklı deprem altında sarsma masası kullanılarak yapıldı. Her numunenin spektral giren enerji değeri deney sonucundan hesaplandı. Numerik hesaplama sonucu spektral giren enerji değeri deneysel hesaplama sonucu giren enerjiyle karşılaştırıldı ve uyumluluk gösterdiler. Ayrıca, analitik çalışmalar ve deneysel çalışmalar giren enerji için ölçek faktörünün aynı yer hareketi altında numuneler arasındaki kütle ölçek faktörüne eşit olduğunu göstermiştir.

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LIST OF SYMBOLS

c	Damping coefficient
E_a	Absorbed energy
E_d	Damping energy
E_l	Input energy
E_k	Kinetic energy
E_p	Plastic energy
E_s	Strain energy
f_s	Restoring force
f_y	Yielding stress
F	Force
J	Joule
k	Stiffness
m	Mass
M	Moment
R	Force Reduction Factor
TD	Natural Period of Damped Vibration
T_n	Natural period

LIST OF ACRONYMS/ABBREVIATIONS

2D	Two Dimensional
ADS	Acceleration Design Spectrum
ARS	Acceleration Response Spectrum
ASCE	American Society of Civil Engineering
ASD	Allowable Stress Design
EDB	Energy-Based Design
EQM	Equation of Motion
EFF	Elastic Perfectly Plastic
ITU	Istanbul Technical University
MDOF	Multi Degrees of Freedom
NA	Not Available
PGA	Peak Ground Acceleration
RC	Reinforced Concrete
SDOF	Single Degree of Freedom

1. INTRODUCTION

1.1. General

Earthquake is a natural disaster that results collapse of the structures and loss of lives. Protection of occupants against injury or loss of life is the main objective in the design earthquake-resistant structures (Gioncu *et al.*, 2010). Damage level of the earthquake could not be prevented exactly. However, earthquake-resistant structures could be constructed to reduce the level of damage. Seismic demand of the ground motion and seismic capacity of the structure determine how the structure resists against earthquake.

Seismic design is a crucial part of the structural design to evaluate the responses of building under earthquake loading. Seismic analysis gives the dynamic responses such as displacement, velocity and acceleration of structures under seismic action. The responses of the building under seismic load effect depend on characteristics of the ground motion, dynamic properties of the structure, characteristics of the structural materials and type of foundation (Gioncu *et al.*, 2010).

The designed structures are expected to resist earthquakes with little effect and without any significant damage, or to resist moderate level with some non-structural damage and reparable structural damage, or to resist high level of earthquake without collapse (Gioncu *et al.*, 2010).

Some procedures and guidelines were developed to evaluate the existing building behavior under seismic load and design the structures to resist ground motion loadings. These conventional methods are basically forced-based design and displacement-based design including performance-based approach methods. However, still there are many shortcomings of these procedures in terms of evaluation of the seismic behavior of the structure. The damage level of the earthquake does not only depend on the strength and displacement parameters of the structure, but also mainly depends on the hys-

teretic behavior and energy dissipation mechanism of the structure, which is related to plastic deformation and ductility of the structures. Researchers discovered that earthquake records having same elastic acceleration response spectrum could produce different energy levels imparted into the structural system and thus distributed with different dissipation mechanism within the structure. Therefore, energy-based analysis and design philosophy has gained some momentum over the past decade.

1.2. Current Design Methods

1.2.1. Force-Based Method

Force-based method is included in FEMA 1997, UBC2000 and ABYYHY 2007 codes and it is used to calculate the dynamic response of the structures.

The force-based design approach uses elastic model for the analysis, has a stiffness equal to the initial stiffness of the design structure. By calculating the period of the structural system, elastic seismic demand force in terms of acceleration is calculated (Rahman *et al.*, 2011). Force-based design is a seismic design methodology that uses lateral forces as design parameter to predict the seismic demand of the structure. However, lateral displacements are important in order to determine the level of damage on the structure. Force-based design controls the displacements at the end of the design thus it cannot predict the potential damage of the earthquake. In other words, Force-Based Design method does not provide the appropriate ways for the concepts of performance-based Earthquake Engineering (Bertero and Bertero, 2002). Performance levels must be defined in terms of displacements, as damage is better correlated to displacements rather than forces.

For the inelastic calculation, force-based design uses the R factor which is the strength reduction factor and it is related to ductility (μ) and period of the structure (T_n). Obtained elastic force is reduced by a reduction factor for inelastic calculations. It uses elastic forces as the basic design process. It does not consider the hysteric behavior of the systems during nonlinear analysis range.

Also, this method considers only the maximum response of the structure that is, it neglects the cumulative damage effect of the seismic loading due to ground motion's duration and frequency content. The other deficiency of this method is that the seismic force is calculated based on the period of the structure and the period of the structure is calculated with the rigidity of the structure that is based on the size of the members. Thus, if the size of the structure changes from preliminary design, design forces will be re calculated. It could be concluded that the force-based design method is not appropriate method to design structures as earthquake resistant.

1.2.2. Displacement-Based Method

Displacement-based design begins with the estimate of the dimensions of the elements and estimate of the stiffness of the structure. By using stiffness of the structure, the period of the system could be determined, and then the strength of the system could be evaluated. After calculation of seismic forces, the structure is analyzed under seismic forces, then the displacement values of the structure are calculated. When the displacement is compared with allowed displacement values, design is completed. Otherwise, structure dimension changes and steps are repeated. The displacement parameter is important to design structure as earthquake resistant structures. That means, design forces are recalculated based on the new dimensions of the elements. Although this design method used in earthquake resistant analysis, it cannot truly represent the earthquake problems. It is explained in below flow chart in Figure 1.1.

To evaluate the seismic performance of a structure, deformation is an important parameter it empathizes that the realistic displacement demand of the structure. The direct displacement-based design (DDBD) (Kowalsky *et al.*, 1994) is one of the performance-based design approaches for design of the structures under seismic loading. Contrary to the force-based design method, design forces are calculated with the desired performance level based on the inelastic response of the structural system.

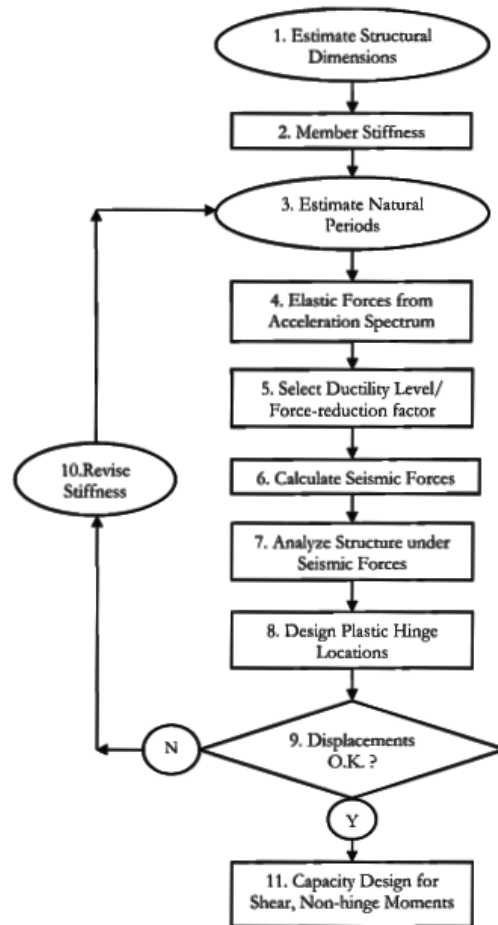


Figure 1.1. Force Based Design Process.

The displacement response design method is considered to offer the following advantages with respect to the spectral acceleration response design method (Medhekar and Kennedy, 2000).

- Target displacement criteria are selected for the serviceability and ultimate limit states, and thus the damage control is achieved directly.
- Strength and stiffness of the lateral load resisting system are chosen to satisfy the desired deformation criteria.
- The estimation of the fundamental period of the structure is not required for the preliminary design.
- The displaced shape may be explicitly linked to the member ductility demands (Gioncu *et al.*, 2010).

While force-based seismic design characterizes a structure in terms of elastic, pre-yield properties (initial stiffness, elastic damping), displacement-based method characterizes the structure by secant stiffness at maximum displacement and a level of equivalent viscous damping, representative of the combined elastic, damping and the hysteretic energy absorbed during inelastic response (Priestley *et al.*, 2007).

Priestly and Calvi (1997) developed this method for both single degree of freedom (SDOF) system and multi degree of freedom (MDOF) system. Their method begins with preliminary design with the estimation of dimensions and continue with pushover analysis that results in yield and ultimate displacement of the system. Capacity curve, and acceleration and displacement spectra are formed. By using capacity curve (top displacement-base shear) and response spectrum, which are acceleration and displacement spectra, target displacement is determined.

Performance of the structural systems is determined by the damage of the structural members and the damage of the structural members is determined by the deformation capacity of the structural members. (Hayder J JUDI 1, Barry J DAVIDSON 2 And Richard C FENWICK 3). This means that the displacement capacity of the members is the main parameter for the design of the structures. The deformation capacity of the structural members is an important parameter for the seismic design of the structure. Performance of the structure under earthquake is determined by deformation capability of its members. In contrast to force-based design, displacement based design approach that designs the structure for a given target displacement can control the potential damages (Yavas, Altug, 2004).

Based on the force-based design methodology, by using period and ductility capacity strength and displacement are determined. In direct displacement-based method, displacement and ductility demands are used and then period and strength of the structure are calculated (Fajfar, 1999). However, for the design of the members, these methods have shortcomings. They do not include duration and the frequency content of the ground motions, dissipation mechanism of the structures that are the main reasons of the accumulated damage occurred in the members.

1.3. Introduction to Energy-Based Method

Energy concept is the main parameter to truly determine the seismic demands and design of the structural members. Housner (1998) focused on the energy-based design methodology to design structures to resist severe earthquakes. Energy-based seismic design philosophy focuses on the seismic behavior of the structure that defines how the input energy of the ground motion is absorbed and dissipated by the structure.

Energy-based design method is correlated with energy parameters, which are magnitude of the ground motion record, soil type and distance to fault. These parameters affect the response of the structures against dynamic loading. Input energy spectra from energy-based design method contains the defined parameters to design safe structures. Thus, instead of the response spectra used with current design methods, input energy spectrum is proposed for design of the structures (Decanini, and Mollaioli, 2001). To design earthquake-resistant structures, besides the strength and the deformation capacities, structures must have enough energy dissipation capacity in terms of plastic deformation and viscous damping. Peak ground acceleration defines the severity of the ground motion at a specific site, but it is a poor parameter to calculate the amount of the energy imparted to a structure and damage potential of the earthquake. Damage potential of an earthquake ground motion is determined by the amount of the energy imparted into the structure. The input energy is dissipated by inelastic deformation and by damping and displacement ductility of the structure. Energy-Based Seismic Design emphasizes on the seismic behavior of the structure in terms of how input energy, which is originated from ground motion, is absorbed and also dissipated by the structure.

Energy imparted into the linear elastic system at the end of the ground motion is represented by function of its natural frequency and damping (Zahrah *et al.*, 1984).

Thus, the major difference between energy-based method and the other methods, which are force-based and displacement-based methods including performance-based design, is the consideration of the energy dissipating mechanism of the structure. Also,

this method covers the ground motion records, duration of earthquake and frequency content of the earthquake whereas they are not covered in response spectra analysis.

Energy dissipating mechanism controls the structural damages during earthquake ground motion. Total energy dissipating capacity must be greater than the input energy of the expected earthquake so that the structure surviving the earthquake. (Lieping *et al.*, 2009). By this method, structures could resist against any severe earthquakes. During the energy-based design process, demand of the total input energy (E_i) and hysteresis energy (E_H) is considered. Energy-based approach shows how to control and calculate energy dissipation of the structure

Earthquake load effect refers to the input energy, while energy absorption capacity refers to structural resistance to dynamic loading.

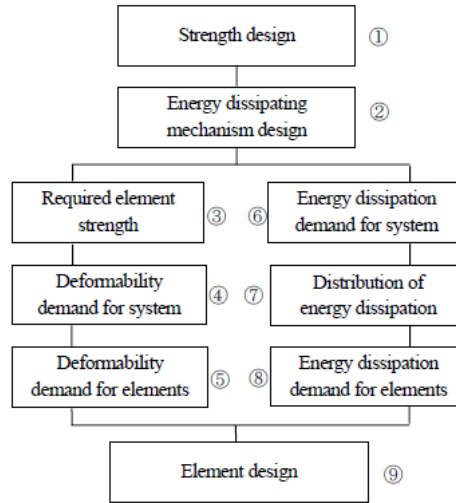


Figure 1.2. Framework of energy-based seismic design (Ye, 2009).

Figure 1.2 shows that following steps 1-2-3-4-5-9 describe the current displacement-based design methodology, and following steps 1-2-6-7-8-9 describe the energy-based design methodology (Ye, 2009). In addition to these, energy is defined as the area under the force-displacement curve of the structure. Two similar structures could have equal yield and displacement capacities, but energy dissipation mechanism could be different

due to structural system's constitutive behavior, that is, structures could absorb same energy but dissipate different energy amounts. Energy dissipation determines directly the damage on the structure. (Paek an dang, 1985). As a result, for the design of the earthquake resistant structures, seismic analysis considers force-deformation capacity and energy dissipation capacity of structural elements.

Dindar (2015) developed energy demand spectra based on the soil parameters, ground motion intensity and frequency content of the earthquake. This derived spectrum includes input energy spectra and plastic energy spectra for different soil types. Analytical calculation and experimental results were compared with these spectra.

1.4. Literature Review

Research in dimensional analysis for the energy-based design is not yet done in terms of both quantitative and experimental studies. Only Kuawamura (1989) stated that the input energy is less affected by restoring force characteristics of the structures and mainly affected by fraction of the critical damping of the structures. Kuawamura (1989) defines mass normalized input energy formula as the following.

Input energy depends on the structure's period and its equivalent velocity spectrum of the structure. While structures have same spectral velocity, mass-normalized input energies are equal. There is no study found in the literature for the determination of scale factor formula for spectral input energy between SDOF systems.

$$E_1 = \frac{1}{2}mV_E^2 \quad (1.1)$$

$$\frac{E_1}{m} = \frac{1}{2}V_E^2 \quad (1.2)$$

1.5. Research Rational

Energy-based design method considers seismic behavior of the structure based on energy concept. Experimental research gives more reliable information about the response of the structure under ground motion record to calculate the energy terms. But, experimental research on large-scale specimens are difficult to conduct. Thus, there should be a scale factor between the main structure and its prototype to calculate the energy terms. Using different material, mass and dimensional properties, input energy of the main structure energy could be easily calculated from its small-scale counterpart. This requires that the scale factor for energy term between prototype and the main structure should be derived. Scale factor is an important parameter to save time during energy design and analysis of the systems. This study focuses on that scaling of spectral input energy is possible through dimensional analysis.

1.6. Objective and Scope of the Study

Having considered the above literature review, no study focused on the dimensional analysis of energy-based design of the structural elements in detail. In this study, dimensional and scale analyses are applied to energy-based design principle in order to determine formulations for a scale factor of spectral input energy. In this study, input energy values were calculated for linear elastic SDOF systems.

This study aims to apply the dimensional analysis method to derive the scale factor for input energy terms with different material and length properties of specimens for SDOF systems. Experiments were carried out with hollow cross section aluminum and steel columns with two different dimensions to verify the theoretical calculation. Analytically and experimentally, energy value comparison will be made between large and small scale SDOF structures and their energy terms due to scaling effect were analyzed. Input energy data were analyzed for the seven cases with binary states in elastic range. Based on the dimensional analysis, the generalized formula for input energy was developed for elastic case only. The best fitting dimensional analysis equation for input energy is derived as a result of this study for input energy term, from prototype

energy actual structure energy could be easily calculated.

The scope of this study is limited to SDOF specimens of rectangular hollow section steel and aluminum columns in two-dimensional motion plane. Their modulus of elasticities and lengths are main parameters. Four different elements were used and ten different periods were used during analytical study. To calculate the input energy terms of the all elements, SAP2000 software and produced MATLAB code used. Energy values of the elements are calculated for elastic cases. Lateral deformations were calculated only considering the bending behavior, shear effect and axial load effect did not considered. Based on each defined period, specimens were modelled by SAP2000 software as cantilever column defining length and material modulus of elasticity value and input energy (E_1) value were generated. By using four different specimens, based on the material type and length of each specimen, seven different cases were created that were used for both elastic analysis shown in Table 1.2 Material cross section dimensions were determined by selected length ratio as two. Table 1.1 shows the material cross section dimensions.

Table 1.1. Material Cross Section Dimension.

SPECIMEN	B(mm) (width)	H(mm) (depth)	T(mm) (thickness)
ST80/40/2	40	80	2
AL80/40/2	40	80	2
ST40/20/1	20	40	1
AL40/20/1	20	40	1

Based on the defined seven cases in Table 1.2, results for each elastic case, input energy scale factor is generated by scaled specimen dimension parameters. Length ratio is defined as $\lambda_{|L|}$ and modulus of elasticity ratio defined as λ_E . Here, ST stands for Steel and AL stands for aluminum.

Table 1.2. Cases with Binary State for Scale Analysis.

CASES FOR RATIO ANALYSIS		(λ_L)	(λ_E)
Case 1	ST80/40/2-AL80/40/2	1.00	2.89
Case 2	ST40/20/1-AL40/20/1	1.00	2.89
Case 3	ST80/40/2-ST40/20/1	2.00	1.00
Case 4	AL80/40/2-AL40/20/1	2.00	1.00
Case 5	ST80/40/2-AL40/20/1	2.00	2.89
Case 6	AL80/40/2-ST80/40/2	1.00	0.35
Case 7	AL80/40/2-ST40/20/1	2.00	0.35

1.7. Organization of The Thesis

This thesis consists of six chapters. The first chapter covers the introduction, literature review and scope of the research. Chapter 2 includes the energy-based approach and formulation of the energy balance equation. This chapter also describes the energy terms and describes how to generate the energy terms of the structure by using energy balance equation. Chapter 3 consists of analytical study part of the thesis. As first part, it mentions dimensional analysis method and analytical steps of dimensional analysis methods. Numerical model input energy analysis results were included into this chapter. Also, Dindar (2015) energy spectrum was explained and the results of input energy of specimens derived from Dindar spectrum were compared with numerical modelling results. At the end of the chapter, dimensional analysis results of numerical modelling and Dindar spectrum were presented. Chapter 4 discusses experimental part of the research that defines experimental set-up and results of this experimental study. Chapter 5 gives information about comparison between numerical analysis results and experimental results. Chapter 6 is consisting of conclusion and recommendation for future researches.

2. ANALYTICAL ANALYSIS OF DERIVATION OF ENERGY TERMS USING ENERGY BALANCE EQUATION

This chapter describes the energy responses of the SDOF systems that are exposed to the ground motion loads. It also includes derivation of the energy terms using the energy balance equation for SDOF systems. Plastic and elastic energy terms are derived from energy balance equation.

2.1. Energy Balance Equation

During the dynamic motion, part of the absorbed energy is stored temporarily in the structure in the form of kinetic and strain energy, and the rest is dissipated by damping and inelastic deformation within the structure.

As in the case of a linear elastic structure, damping has little effect on the amount of energy imparted into the structure by ground motion. While damping and ductility have a small effect on the amount of energy imparted to a structure, they greatly influence the manner in which that energy is dissipated (Zahrah, Hall, 1984). Thus input energy values calculated with linear elastic case are similar with results of elastic perfectly plastic behavior model energy spectrum values. SDOF system subjected to the ground motion load is shown in Figure 2.1.

During any earthquake motion, internal and external forces are in balance, so that work done by the internal and external forces should be in balance as well. That means, energy balance could be directly formulated by the equation of motion of the SDOF system (Dindar, 2009; Akiyama, 1985). Equation of motion of the SDOF system could be described by the absolute and relative motions terms. Absolute motion is the displacement of the system with respect to the ground, whereas relative motion term is the point of initial position at rest.

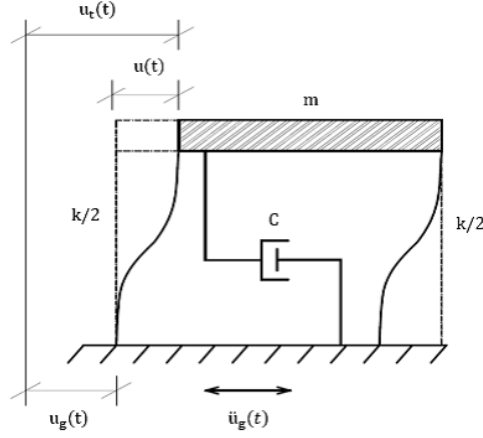


Figure 2.1. SDOF System Subjected to Ground Motion.

The equation of motion of SDOF system is as follows;

$$m \ddot{u}(t) + c \dot{u}(t) + f_s(u(t), \dot{u}(t)) = 0 \quad (2.1)$$

where m is the mass of the system, c is the damping factor of the system and f_s is the restoring force of the system.

$\ddot{u}_t(t)$, $\ddot{u}(t)$, $u(t)$ are the responses of the SDOF system. $\ddot{u}_t(t)$ is the total acceleration, $\dot{u}(t)$ is the total velocity and $u_t(t)$ is the total displacement that consists of the ground displacement $u_g(t)$ and relative displacement $u(t)$ of the SDOF system as follows;

$$u_t(t) = u_g(t) + u(t) \quad (2.2)$$

Equation 2.2 is inserted into the Equation 2.1, and the equation of motion of the SDOF becomes;

$$m \ddot{u}(t) + c \dot{u}(t) + f_s(u(t), \dot{u}(t)) = -m \ddot{u}_g(t) \quad (2.3)$$

where, $\ddot{u}_g(t)$ is the acceleration of the ground motion, $m \ddot{u}(t)$ is the represents the inertia force due to the mass, $c \dot{u}(t)$ is the represents damping force due to internal the friction

of structural members, $f_s(u(t), \dot{u}(t))$ is the represents the restoring force of the system. If the system response is in elastic range, this term becomes, $ku(t)$ where k is the initial stiffness of the system. The equation of motion formula is shown as Equation 2.4.

$$m \ddot{u}(t) + c \dot{u}(t) + ku(t) = -m\ddot{u}_g(t) \quad (2.4)$$

where $m\ddot{u}_g(t)$ represents external force acting on the structure.

In case of the ground motion loading, the equation of motion includes response of the structure as displacement, velocity, acceleration of a system and also excitation of the ground motion. The potential damage of the ground motion is determined by the extreme values of the exposed ground motion time history data. Severity of the earthquake especially is determined by peak ground acceleration (PGA) or peak ground velocity (PGV) of ground motion (Kramer, 1990). That is, PGA is a poor parameter to calculate the amount of the energy imparted into the structure and damage potential of the earthquake. Damage potential of an earthquake ground motion is determined by relationship between the amount of the energy imparted into the structure, and the amount of energy dissipated by inelastic deformation and by damping and displacement ductility of the structure. Energy imparted into the linear elastic system at the end of the ground motion is represented by a function of its natural frequency and damping (Zahrah *et al.*, 1984). The damage level of the earthquake also depends on the energy dissipating mechanism of the system and the input energy (E_i) of the ground motion. Energy dissipating mechanism is the ability of the structural system to dissipate the input energy of the ground motion.

2.1.1. Derivation of Absolute and Relative Energy Equations

Uang and Bertero (1988) have derived the two energy equations namely the absolute and relative energy equations. The energy balance equation could be written by the absolute responses of the motion and relative responses of the motion of the system according to Uang and Bertero (1990). The only difference between two formulas is the kinetic energy and input energy term.

Absolute input energy refers to work done by the total base shear at the foundation level (Bertero and Uang, 1992).

The integration of the Equation 2.1 with respect to the relative displacement of the system $u(t)$ give rise to the energy balance equation as follows;

$$\int m\ddot{u}_t(t)du + \int c\dot{u}(t)du + \int f_s du = 0 \quad (2.5)$$

Based on the $u_t(t) = u_g(t) + u(t)$, Equation 2.5 could be shown as Equation 2.6;

$$\int m\ddot{u}_t(t)du_t + \int c\dot{u}(t)du + \int f_s du = \int m\ddot{u}_t(t)du_g \quad (2.6)$$

The Equation 2.6 is defined as absolute energy equation. The terms of this equation are; $\int m\ddot{u}_t(t)du_t$ represents the absolute kinetic energy term, $\int c\dot{u}(t)du$ represents the damping energy term, $\int f_s du$ represents absorbed energy term, $\int m\ddot{u}_t(t)du_g$ represents absolute input energy term. Equation 2.1 is written in terms of the energy components as;

$$E_k + E_d + E_a = E_i \quad (2.7)$$

where E_a is the term includes both elastic and plastic strain energy. That is;

$$E_a = E_s + E_p \quad (2.8)$$

where E_s is the elastic strain energy (potential energy), E_p is the plastic strain energy.

Figure 2.2 shows that earthquake load on a fixed base SDOF system. The integration of the Equation 2.3 with respect to the displacement of the system $u(t)$ results in relative energy formula as follows;

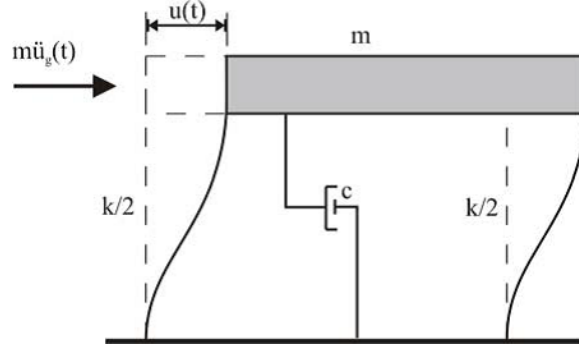


Figure 2.2. Fixed Base SDOF system.

$$\int m \ddot{u}(t) du + \int c \dot{u}(t) du + \int f_s du = \int m \ddot{u}_g(t) du \quad (2.9)$$

where $\int m \ddot{u}(t) du$ represents the relative kinetic energy term, $\int c \dot{u}(t) du$ represents the damping energy term, $\int f_s du$ represents the absorbed energy term, $\int m \ddot{u}_g(t) du$ represents the relative input energy term. That is the work done by the equivalent force $-m\ddot{u}_g$ on a fixed base system in Figure 2.2.

Equation 2.9 is written in terms of energy components as;

$$E_k' + E_d + E_a = E_i' \quad (2.10)$$

where E_a is the term includes both elastic and plastic strain energy. That is;

$$E_a = E_s + E_p \quad (2.11)$$

where E_s is elastic strain energy, E_p is the plastic strain energy.

In this research, for all dimensional analysis, relative energy terms are used to get the scale factor for input energy and plastic energy terms between different specimens. During this study, relative kinetic energy term that is shown in Equation 2.10 as E_k' will be used as E_k and also, relative input energy term that is shown in Equation 2.10

as $E'_{|l|}$, will be used as $E_{|l|}$.

2.2. Concept and Formulation of Energy Components

Energy components are related to the dynamic characteristics of the structures and earthquake ground motion record characteristics. The input energy is defined as imparted energy into the structure consists of two parts as recoverable and irrecoverable energies, as shown in Figure 2.3;

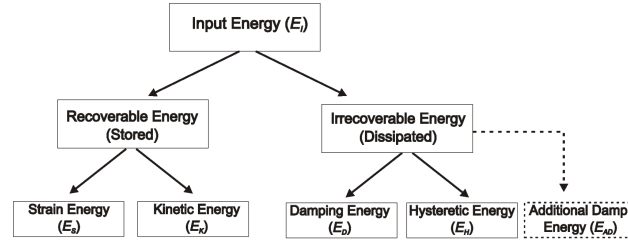


Figure 2.3. Energy Terms (Dindar, 2009).

The elastic strain and kinetic energies are named as recoverable (stored) energy while damping and hysteretic energies are named as irrecoverable (dissipated) energy. At the end of the motion, system is able to recover the elastic strain energy and kinetic energy, but it cannot recover the damping energy and hysteretic energy. Damping and hysteretic energy increase during the ground motion, elastic strain energy and kinetic energy decrease at the end of the motion. Damping energy and hysteretic energy represent the energy dissipation mechanism of the system. Energy dissipation mechanism is directly related to the damage occurred in the member of the structure. Thus, damping energy and hysteretic energy analysis are crucial part for the energy-based design of the structures.

The physical meaning of each energy components in Equation 2.9 is expressed briefly in the following subsections.

2.2.1. Input Energy

Earthquake input energy is related to the magnitude of the ground motion record, distance from the seismic source, soil type, focal mechanism, frequency of the ground motion record (Decanini, Mollaioli, 1998).

Relative input energy is known as the work done by the equivalent force $-m\ddot{u}_g$ on a fixed base system like in Figure 2.4. It could be defined as energy imparted into the structure. The relative input energy is derived from right hand side of the Equation 2.9. That is, input energy is the integration of the structural velocity times the ground acceleration (Dander, 2009).

$$E_i = - \int m\ddot{u}_g(t)du = - \int m\ddot{u}_g(t)du \frac{dt}{dt} = -m \int \ddot{u}_g(t) \dot{u} dt \quad (2.12)$$

2.2.2. Kinetic Energy

Kinetic energy is known as energy of motion. It depends on mass and velocity of an object. The formula of the kinetic energy is derived as;

$$\begin{aligned} E_K &= \int m \ddot{u}(t)du = \int m \ddot{u} \frac{dt}{dt} du = \int m \dot{u} \ddot{u} dt \\ &= \int m \dot{u} \frac{d\dot{u}}{dt} dt = m \int \dot{u} d\dot{u} = \frac{m\dot{u}^2}{2} \end{aligned} \quad (2.13)$$

2.2.3. Damping Energy

Damping is the energy dissipating mechanism of a structure under dynamic loading. At the end of the motion in elastic case, the damping energy reaches the value equal to the input energy while kinetic and elastic strain energy decreases (Dindar, 2009). Damping energy formula is derived from Equation 2.9 as follows;

$$E_d = \int c \dot{u} du \frac{dt}{dt} = c \int \dot{u}^2 dt \quad (2.14)$$

2.2.4. Absorbed Energy

Absorbed energy is defined as sum of elastic strain energy and plastic strain energy. Elastic strain energy and plastic strain energy are worked together in plastic range of the system behavior. Plastic strain energy does not exist in elastic range. The absorbed energy formula is derived from Equation 2.9 as follows;

$$E_a = \int f_s(t) du = \int f_s(t) du \frac{dt}{dt} = \int f_s(t) \dot{u} dt \quad (2.15)$$

Elastic strain energy is described as potential energy, that is, energy stored in the structure due to elastic deformation. Uang and Bertero (1990) formulated the strain energy in terms of the elastic stiffness k of the system as follows;

$$E_s = \frac{f_s(t)^2}{2k} \quad (2.16)$$

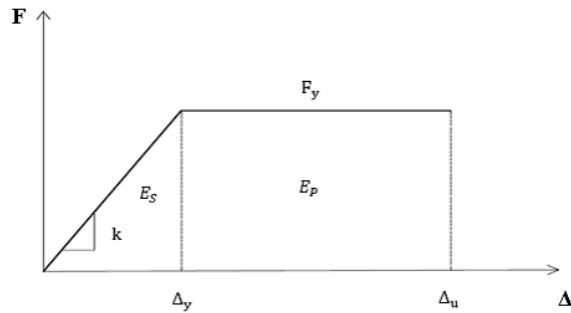


Figure 2.4. Elastic and Plastic Strain Energy.

Figure 2.4 shows plastic and elastic energy part on representative force - displacement curve. Elastic strain energy is shown in elastic range of the system behavior. In elastic range, force displacement curve of the system is in a linear form. The area under the force displacement curve of the system give the elastic strain energy of the system

in elastic range, formula as follows;

$$E_s = \frac{1}{2}F\Delta = \frac{1}{2}k\Delta^2 \quad (2.17)$$

Plastic strain energy is the dissipated energy due to the plastic deformation of the system in plastic range. Plastic energy term is considered as cumulative. The formula of the plastic strain energy is derived from the energy balance equation as follows;

$$E_p = E_i - (E_K + E_d + E_s) \quad (2.18)$$

The traditional method to calculate the plastic energy of the system is to calculate the closed area of the force-displacement hysteresis curve of the system (Mahin and Bertero, 1981).

3. ANALYTICAL STUDY

3.1. Dimensional Analysis Method

Mathematical equations represent the relationships between relevant properties of the system. These equations consist of variables and parameters. The variables could have dependent and independent variables. Two systems with same parameters coincide are called similar and they differ only in scale. Most importantly, Buckingham's theorem (dimensional analysis) describes the relation between the number of variables and fundamental dimensions.

Dimensional analysis could be applied between the similar systems that have same dependent variables with same independent variables. By dimensional analysis, between similar systems, the similarity between dependent variables could be easily described by similar independent variables. The scale factor of the common dependent variable between similar system could be found by dimensional analysis of independent variables. It is a method that converts physical problems to simplest problem. Bridgman (1969) explains as: "The principal use of dimensional analysis is to deduce from a study of the dimensions of the variables in any physical system certain limitations on the form of any possible relationship between those variables. The method is of great generality and mathematical simplicity".

The variables or parameters in a model refers to the physical properties have physical dimensions. The common dimensions of base physical quantities used in equation are shown in Table 3.1.

Table 3.1. Common Dimensions of Base Physical Quantities in SI Units.

Quantity	SI Name	SI Symbol
Length, L	meter	m
Time, t	second	s
Mass, m	kilogram	kg

Dimensional analysis represents equations and quantities without numerical values of these quantities. The general physical quantities are represented in Table 3.3. Each physical quantity has dimension independent from the unit. Dimensions of each physical quantity, are derived by using base quantity dimension.

Table 3.2. Derived Quantities (Sonin, 2007).

Quantity	Defining equation/ law	Dimension	Dimensional Symbol	Name
area	$A = \int dx dy$	L^2	M^2	...
volume	$V = \int dx dy dz$	L^3	m^3	...
frequency	$f = 1/\tau$	t^{-1}	s^{-1}	hertz (Hz)
velocity	$v = dx/dt$	Lt^{-1}	ms^{-1}	...
acceleration	$a = d^2x/dt^2$	Lt^{-2}	ms^{-2}	...
density	$\rho = M/V$	ML^{-3}	$kg\ m^{-3}$	...
force	$F = Ma$	MLt^{-2}	$kg\ m\ s^{-2}$	newton (N)
stress/pressure	$p = F/A$	$ML^{-1}t^{-2}$	$N\ m^{-2} = kg\ m^{-1}s^{-2}$	pascal (Pa)
work/energy	$W = \int F dx$	ML^2t^{-2}	$Nm = kg\ m^2s^{-2}$	Joule (J)
torque	$T = Fl$	ML^2t^{-2}	$N\ n = kg\ m^2s^{-2}$	...
power	dW/dt	ML^2t^{-3}	$Js^{-1} = kg\ m^2s^{-3}$	watt (W)
charge	$Q = \int I dt$	IT	As	coulomb C

The dimension of any derived physical quantity is a product of powers of the base quantity dimensions. As a result of dimensional analysis, the physical quantity exists independent from unit. Dimensions of physical quantities are shown in Table 3.2.

First step of the dimensional analysis is to determine the physical quantities in equation and then determine the dimension of these physical quantities. By using basic dimension of quantities, dimensional analysis of equation is derived. Scale analysis is a reduction of the parameters in the equation that is the summary of the physical quantities, the last position of the equation in terms of the dimension of the physical quantity.

Table 3.3. Dimensions of Physical Quantities.

Quantity	Dimension
Area	L^2
Volume	L^3
Velocity	L/T
Acceleration	L/T^2
Mass Density	M/L^3
Mechanical Energy	ML^2 /T^2

Dimensional analysis covers the scale analysis. Scaling reduces the number of parameters of any equation. Scaling is an important way to simplify the equation, it is a way to express the relationship between variables of similar systems. Thus, it is a powerful to analyze a model without solving the model explicitly. Scale analysis describes how the system depends on the parameters of its relevant equation and what is the relationship of the common variables between similar system. By using scale analysis for similar systems, scale factor of same dependent variables of these systems can be derived. This method also saves the time, cost and energy.

3.2. Dimensional Analysis Steps for Energy Based Design Method

Dimensional analysis is a mathematical method that figures out the relationship between common dependent variables of actual structure and its prototype. In terms of the energy-based design method, dimensional analysis techniques could be used to derive the input energy scale factor equation between scaled specimens. Energy terms depend on response parameters of the system under dynamic loading. Energy is defined as force times displacement. Force is also depending on mass and acceleration. Relationship between common variables is analyzed to derive the dimensional analysis expression of the energy. The variable parameters of the specimens are described as geometric scale ($\lambda_{|L|}$) and material scale (λ_E) based on length ratio and the modulus of the elasticity ratio of the specimens. All other parameters of the specimens are

represented with these defined two input parameters.

The natural period of a SDOF is defined in Equation 3.1;

$$T = 2\pi\sqrt{\frac{m}{k}} \quad (3.1)$$

where k is the stiffness of the specimen and m is the mass of the specimen. Specimens were analyzed as fixed based and cantilever column. Thus, the stiffness of the specimen is formulated as;

$$k = \frac{3EI}{L^3} \quad (3.2)$$

$$I = \frac{bh^3}{12} \quad (3.3)$$

where E is the modulus of elasticity of the specimen, I is the moment of inertia of the specimen, L is the length of the specimen and are, b and h is the are cross-sectional dimensions of the specimen. The period scale factor, λ_T is the consists of stiffness scale factor which, λ_k is the mass scale factor, λ_m is the stiffness scale factor, λ_k is the consists of modulus of elasticity scale factor λ_E is the length scale factor λ_L is the moment of inertia scale factor, (λ_I)is the thus, Equation 3.1 is written as in Equation 3.4;

$$\lambda_T = \sqrt{\frac{\lambda_m}{\lambda_k}} \quad (3.4)$$

Equation 3.5 inertia scale factor λ_I that is derived from scale factor of cross section dimensions.

$$\lambda_I = \lambda_b \lambda_h^3 \quad (3.5)$$

Cross-sectional dimensions of specimens were defined with length scale factor (λ_L) since they have similar dimensional properties with length. That means, the length ratio between the two different specimens also refers to ratio between cross-sectional dimensions (b and h). Dimension of the cross sections are written as;

$$\lambda_h = \lambda_L \quad (3.6)$$

$$\lambda_b = \lambda_L \quad (3.7)$$

By substituting Equation 3.6 and Equation 3.7 moment of inertia scale factor is derived as;

$$\lambda_I = \lambda_L^4 \quad (3.8)$$

From Equation 3.2 the stiffness scale factor could be written as;

$$\lambda_k = \frac{\lambda_E \lambda_I}{\lambda_L^3} \quad (3.9)$$

Substituting Equation 3.9 into Equation 3.4) the period scale factor is derived as;

$$\lambda_T = \sqrt{\frac{\lambda_m \lambda_L^3}{\lambda_E \lambda_I}} \quad (3.10)$$

From Equation 3.10 mass scale factor (λ_m) is written as;

$$\lambda_m = \frac{\lambda_E \lambda_I}{\lambda_L^3} \lambda_T^2 \quad (3.11)$$

Since the cross-sectional dimensions are proportional to the length ratio of the specimen, inertia scale factor is the forth degree of length scale factor from Equation

3.8. Thus, from Equation 3.9 stiffness scale factor λ_k is expressed as;

$$\lambda_k = \frac{\lambda_E \lambda_L^4}{\lambda_L^3} = \lambda_E \lambda_L \quad (3.12)$$

Substituting Equation 3.10 into Equation 3.4, the natural period scaling factor is derived as;

$$\lambda_T = \sqrt{\frac{\lambda_m}{\lambda_E \lambda_L}} \quad (3.13)$$

Equation 3.13 can be written as;

$$\lambda_T^2 = \frac{\lambda_m}{\lambda_E \lambda_L} \quad (3.14)$$

From the Equation 3.14 mass scale factor, λ_m , is derived as;

$$\lambda_m = \lambda_E \lambda_L \lambda_T^2 \quad (3.15)$$

The mass is formulated as density times volume, so mass scale factor is also defined as

$$\lambda_m = \lambda_\rho \lambda_L^3 \quad (3.16)$$

Where is the density scale factor. If Equation 3.15 is inserted in Equation 3.16, density scale factor is expressed as;

$$\lambda_\rho = \frac{\lambda_m}{\lambda_L^3} = \frac{\lambda_T^2 \lambda_E \lambda_L}{\lambda_L^3} = \frac{\lambda_T^2 \lambda_E}{\lambda_L^2} \quad (3.17)$$

Gravitational acceleration is defined as meter per square of second. Thus, the gravitational acceleration scale factor is λ_g defined as;

$$\lambda_g = \frac{\lambda_L}{\lambda_T^2} \quad (3.18)$$

From Equation 3.18 period scale factor could be defined as;

$$\lambda_T^2 = \frac{\lambda_L}{\lambda_g} \quad (3.19)$$

Substituting Equation 3.19 into Equation 3.17, density scale factor, λ_ρ , could be expressed as;

$$\lambda_\rho = \frac{\lambda_L \lambda_E}{\lambda_g \lambda_L^2} = \frac{\lambda_E}{\lambda_g \lambda_L} \quad (3.20)$$

By inserting Equation 3.20 into the Equation 3.16, mass scale factor is expressed as;

$$\lambda_m = \frac{\lambda_E}{\lambda_g \lambda_L} \lambda_L^3 = \frac{\lambda_E}{\lambda_g} \lambda_L^2 \quad (3.21)$$

The energy is expressed as force times distance, force is defined as mass times acceleration. Since L is evaluated as displacement dimension. The energy scale factor could be expressed as by using Equation 3.14;

$$\lambda_e = \lambda_m \lambda_a \lambda_L = \lambda_E \lambda_L^3 \quad (3.22)$$

Mass scale factor is

$$\lambda_m = \frac{\lambda_E \lambda_I}{\lambda_L^3} \lambda_T^2 \quad (3.23)$$

Stiffness scale factor is

$$\lambda_k = \frac{\lambda_E \lambda_I}{\lambda_L^3} \quad (3.24)$$

Period scale factor is

$$\lambda_T = \sqrt{\frac{\lambda_m}{\lambda_k}} \quad (3.25)$$

If displacement scale factor is assumed to be equal to the length scale factor Energy scale factor is derived as;

$$\lambda_e = \lambda_E \lambda_L^3 \quad (3.26)$$

Table 3.4. Summary of Dimensional Analysis Results for Strcutural Properties.

TERM	FORMULA	GENERAL SCALE FACTOR	SIMPLIFIED SCALE FACTOR
Period	$T = 2\pi \sqrt{\frac{m}{k}}$	$\lambda_T = \sqrt{\frac{\lambda_m}{\lambda_k}}$	$\lambda_T^2 = \frac{\lambda_m}{\lambda_E \lambda_L}$
Moment of Inertia	$I = \frac{b \times h^3}{12}$	$\lambda_I = \lambda_b \times \lambda_h^3$	$\lambda_I = \lambda_L^4$
Stiffness	$k = \frac{3EI}{L^3}$	$\lambda_k = \frac{\lambda_E \lambda_I}{\lambda_L^3}$	$\lambda_k = \frac{\lambda_E \lambda_L^4}{\lambda_L^3} = \lambda_E \lambda_L$
Mass	$m = \frac{T^2 \times k}{4 \times \pi^2}$	$\lambda_m = \frac{\lambda_E \times \lambda_I}{\lambda_L^3} \times \lambda_T^2$	$\lambda_m = \lambda_T^2 \lambda_E \lambda_L$
Energy	$E = m \times a \times d$	$\lambda_e = \lambda_m \lambda_a \lambda_L$	$\lambda_e = \lambda_E \lambda_L^3$

Table 3.4 summarizes the dimensional analysis formulations for general and simplified scale factors includes λ_I as λ_L^4 . The scale factor formula for structural properties were derived by using general formula of them. In this study, in analytical part, there is a special case. This case includes specimens' length ratio is determined as cross-section dimensional ratio. The forth column of the table represents the simplified version of the general scale factor formula. Simplified general scale factor formula of the moment of inertia term λ_I is equal to λ_L^4 . This case simplifies the stiffness and mass scale factor formula of the specimens.

Because of this dimensional analysis expression, energy scale factor between similar systems requires the information about geometric scale factor, λ_L , and material type scale factor, λ_E . By numerical analysis and experimental studies, the dimensional analysis result for the energy scale factor in Equation 3.26 is going to be compared. Numerical analysis and experimental analysis results will be evaluated at different period and at same period between specimens. The required energy scale factor is going to be recommended.

3.3. Material Behavior Model

There may be six different constitutive models to define the behavior of a structural system. These constitutive models are in group as flexural behavior model and flexure with slip models. Flexural behavior model consists of elastic-perfectly plastic, bilinear with strength hardening, Takeda and Clough. The other one consists of Takeda with slip and Clough with slip. The schematic representation of these models are shown in Figure 3.1.

System and material behavior models are defined in terms of elastic-perfectly plastic model this model is generally used for steel specimens to define hysteretic behavior. Elastic-perfectly plastic model is convenient to employ for the sake of predicting the energy components for the models representing steel structures (Dindar, 2009). That is, for the energy-based design method, hysteric behavior could be defined realistically by the elastic-perfectly plastic model as shown in Figure 3.2. In this research, steel and aluminum are used as material in numerical analysis and experimental part of this research. Two steel specimens and two aluminum specimens with different dimensions were used. Table 3.5 summarize the dimensions of the specimens.

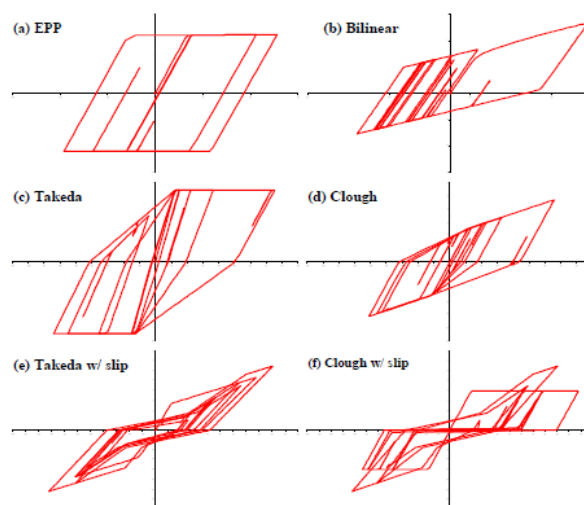


Figure 3.1. Type of Constitutive Behavior Models (Dander, 2009).

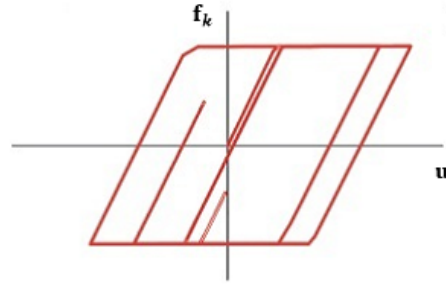


Figure 3.2. Elastic Perfectly Plastic Model (Dindar, 2009).

Table 3.5. Dimensions of Used Specimens.

Specimen	B(mm) (width)	H(mm) (depth)	T(mm) (thickness)	L(m) (Length)
ST80/40/2	40	80	2	1.50
AL80/40/2	40	80	2	1.50
ST40/20/1	20	40	1	0.75
AL40/20/1	20	40	1	0.75

Yield stress and ultimate stress of these materials were calculated by experimental study of small steel and aluminum specimens.

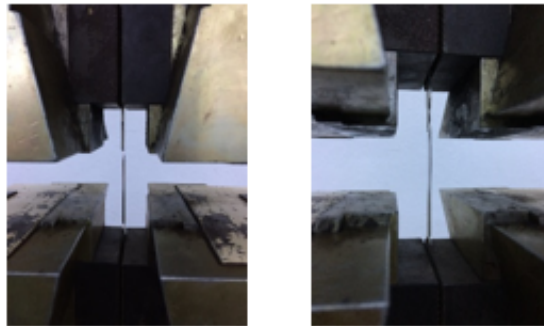


Figure 3.3. Experimental study for rupture of specimens to determine yield and ultimate stress value.

f_u is the ultimate stress f_y is the yield stress and E is modulus of elasticity of material.

Table 3.6. Material Ultimate and Yield Stress.

Specimen	f_u (Mpa)	f_y (Mpa)
AL80/40/2	237.52	198.53
ST80/40/2	413.56	351.47
AL40/20/1	237.52	198.53
ST40/20/1	413.56	351.47

These materials are used as input parameters in SAP2000 numerical model and also in MATLAB code. Therefore, steel and aluminum columns were modelled as cantilever hollow section columns with above-defined properties.

3.4. Numerical Model and Analysis

For numerical analysis, materials that were selected as steel (ST) and aluminum (AL), their properties were defined in numerical model. Length scale factor λ_L is determined as 2.0 and 1.0. Based on the selected material, λ_E represents modulus of elasticity scale factor between specimens. AL80/40/2, ST40/20/1 and AL40/20/1 hollow section column specimens were used for the analyses. Specimens were modelled as structural hollow section cantilever column. Figure 3.4 shows ST80/40/2 and AL80/40/2 specimens' dimensions. Figure 3.5 shows ST40/20/1 and AL40/20/1 specimens' dimensions.

Figure 3.5 explains ST80/40/2 and AL80/40/2 specimens' dimensions. Figure 3.6 explains ST40/20/1 and AL40/20/1 specimens' dimension.

Numerical model analysis steps are defined as;

- (i) Materials properties of selected steel (ST) and aluminum (AL) specimens were defined in each model based on the length scale factor selected as 2. Table 3.8 gives information about physical properties of specimens. Table 3.9 defines cross sections of the specimens' ultimate stress value as f_u and yield stress value as f_y .

Modulus of elasticity of the steel selected as 200000 MPa. Modulus of elasticity of aluminum selected as 69000 MPa since T6 aluminum material was selected for the study.

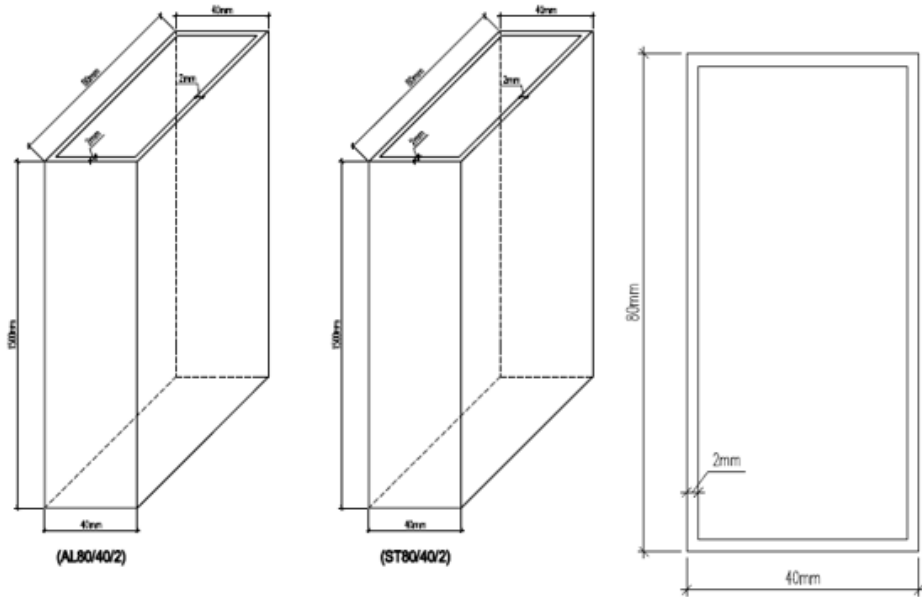


Figure 3.4. Cross Section of the 80/40/2 specimens.

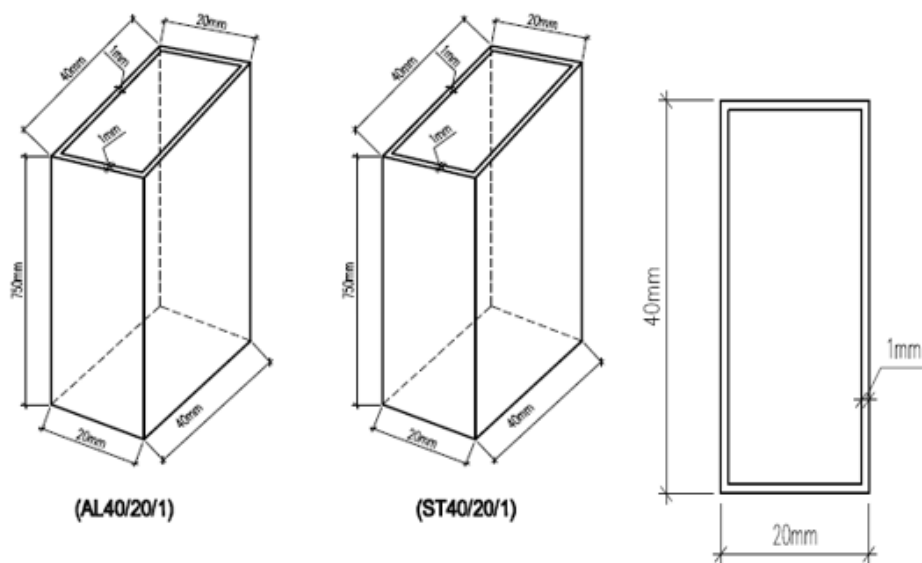


Figure 3.5. Cross Section of the 40/20/1 Specimens.

Table 3.7. Specimen Dimensional Properties.

	AL80/40/2	AL40/20/1	ST80/40/2	ST40/20/1
B(m)	0.08	0.04	0.08	0.04
H(m)	0.04	0.02	0.04	0.02
Thick(m)	0.002	0.001	0.002	0.001
I(m⁴)	1.31E-07	8.19E-09	1.31E-07	8.19E-09
E(N/mm²)	69000	69000	200000	200000
L(m)	1.50	0.75	1.50	0.75

Table 3.8. Specimens with Defined Material Properties.

Specimen	Width (mm)	Height (mm)	Thickness (mm)	Length (m)	f_u (Mpa)	f_y (Mpa)	E (Mpa)
AL80/40/2	40	80	2	1.50	237.52	198.53	69000
ST80/40/2	40	80	2	1.50	413.56	351.47	200000
AL40/20/1	40	20	1	0.75	237.52	198.53	69000
ST40/20/1	40	20	1	0.75	413.56	351.47	200000

- (ii) Numerical analysis was performed with ten different periods, and based on the selected ten different periods of the system, masses of the specimens were calculated using Equation 3.1 and the results are shown in Table 3.9.

Table 3.9. Applied Mass of Each Specimen at Defined Period of Numerical Model.

T(s)		Mass (Kg)	AL80/40/2	AL40/20/1	ST80/40/2	ST40/20/1
T1	0.159	M1	3.603	1.801	10.442	5.221
T2	0.277	M2	10.934	5.467	31.692	15.846
T3	0.333	M3	14.859	7.430	43.070	21.535
T4	0.385	M4	19.862	9.931	57.572	28.786
T5	0.455	M5	25.463	12.731	73.804	36.902
T6	0.500	M6	29.485	14.742	85.463	42.731
T7	0.667	M7	52.909	26.455	153.360	76.680
T8	1.000	M8	94.204	47.102	273.055	136.527
T9	1.250	M9	147.194	73.597	426.648	213.324
T10	1.670	M10	256.724	128.362	744.128	372.064

- (iii) Earthquake ground motion records were selected based on the records' soil type. Loma Prieta, San Salvador and Erzincan ground motion records were selected as Soil A, Soil B and Soil C type, respectively. This research was carried out in elastic range only. Thus, ground motion records were multiplied by a factor of

0.20 remains in elastic range so that the behavior of the specimens. Therefore, the input energy spectral values of each specimen was calculated using above calculated earthquake records Information on used ground motion records are shown in Table 3.10. In elastic range of the motion, energy imparted into the structure, or input energy, is evaluated. For each period, 0.20 San Slavador, 0.20 Loma Prieta and 0.20 Erzincan record data were carried out in numerical modelling and time history analysis cases were defined for each period of each specimens.

Table 3.10. Ground Motion Record Properties.

Ground Motion	Used Coefficient	PGA(g)	Record Soil Type	Duration(s)
Loma Prieta	0.20	0.096	A	39.990
San Salvador	0.20	0.148	B	9.020
Erzincan	0.20	0.099	C	20.785

The defined 0.20 Erzincan, 0.20 Loma Prieta and 0.20 San Salvador ground motion acceleration records are shown in Figure 3.6-Figure 3.8.

- (iv) Throughout the experimental study the damping ratio was determined as 0.003 by means of free vibration tests. Thus, damping ratio was defined as 0.003 in this study for each specimen.
- (v) Each defined model was evaluated for each defined period and the all energy components were found. In elastic case, input energy data were determined. These energy data also were evaluated with energy spectra that was developed. Dindar (2015) as shown in Figure 3.9 in Section 3.5. Based on the numerical modelling analysis results, input energy of each specimen under 3 ground motion records with 10 different periods were determined.

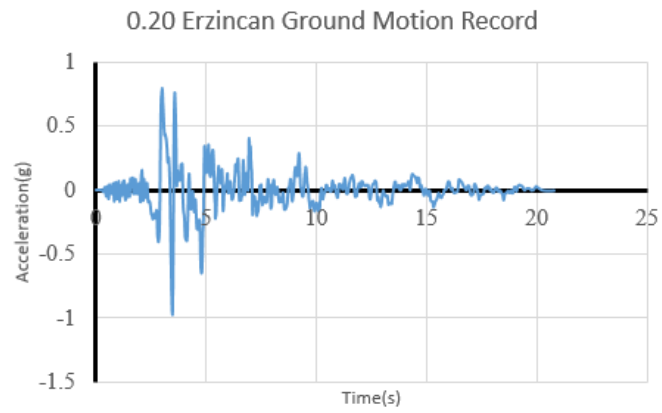


Figure 3.6. 0.20 Erzincan Ground Motion Record.

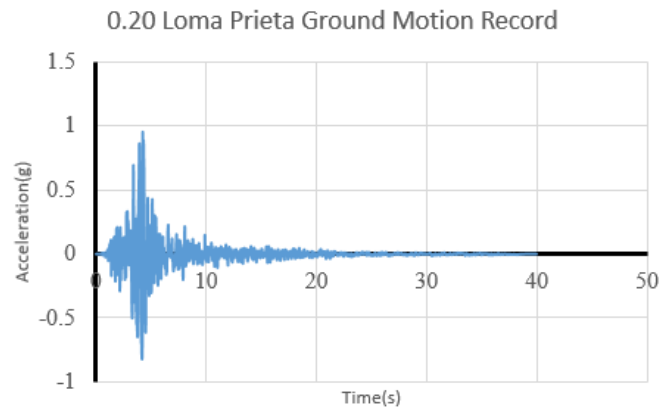


Figure 3.7. 0.20 Loma Prieta Ground Motion Record.

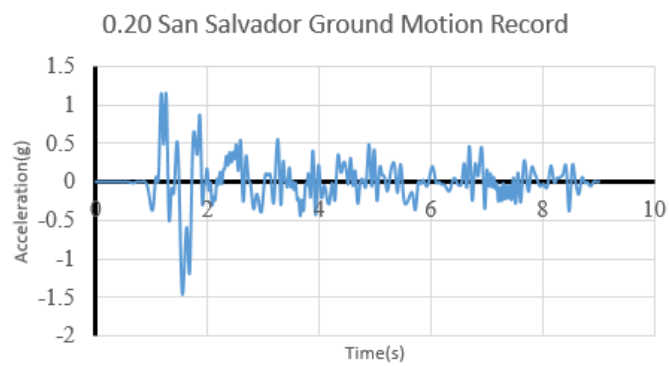


Figure 3.8. 0.20 San Salvador Ground Motion Record.

3.4.1. Numerical Analysis of ST80/40/2 Specimen

Table 3.11-Table 3.13 show the numerical analysis results for spectral input energy value and mass normalized spectral input energy value of ST80/40/2 specimen under defined ground motion records. T is period of the specimen, E_i is spectral input energy value, m is mass, E_i/m is mass normalized input energy value and L is the length of the specimen.

Table 3.11. ST80/40/2 Specimen 0.20 Loma Prieta Spectral Input Energy Results.

ST80/40/2-020 LOMA PRIETA				
T(sec)	E_i (kN.m)	m(kN.s²/m)	E_i/m(m²/s²)	L(m)
0.159	3.92E-05	1.04E-02	3.76E-03	1.690
0.277	7.42E-04	3.17E-02	2.34E-02	1.690
0.333	2.06E-03	4.31E-02	4.78E-02	1.725
0.385	5.40E-03	5.76E-02	9.38E-02	1.725
0.455	4.55E-03	7.38E-02	6.16E-02	1.775
0.500	3.34E-03	8.55E-02	3.91E-02	1.800
0.667	7.76E-04	1.53E-01	5.06E-03	1.795
1.000	6.87E-04	2.73E-01	2.51E-03	1.940
1.250	7.53E-03	4.27E-01	1.76E-02	1.940
1.670	8.59E-03	7.44E-01	1.15E-02	1.955

Table 3.12. ST80/40/2 Specimen 0.20 San Salvador Spectral Input Energy Results

ST80/40/2-020 SAN SALVADOR				
T(sec)	E_i (kN.m)	m(kN.s²/m)	E_i/m(m²/s²)	L(m)
0.159	9.98E-05	1.04E-02	9.56E-03	1.690
0.277	6.91E-04	3.17E-02	2.18E-02	1.690
0.333	1.18E-03	4.31E-02	2.74E-02	1.725
0.385	6.02E-04	5.76E-02	1.05E-02	1.725
0.455	1.93E-03	7.38E-02	2.62E-02	1.775
0.500	3.96E-03	8.55E-02	4.63E-02	1.800
0.667	2.09E-02	1.53E-01	1.36E-01	1.795
1.000	1.09E-02	2.73E-01	4.00E-02	1.940
1.250	1.90E-02	4.27E-01	4.45E-02	1.940
1.670	1.62E-02	7.44E-01	2.18E-02	1.955

Table 3.13. ST80/40/2 ST80/40/2 Specimen 0.20 Erzincan Spectral Input Energy Results.

ST80/40/2-020 ERZINCAN				
T(sec)	E_i (kN.m)	m (kN.s ² /m)	E_i/m (m ² /s ²)	L(m)
0.159	3.92E-05	1.04E-02	3.80E-03	1.690
0.277	7.42E-04	3.17E-02	2.30E-02	1.690
0.333	2.06E-03	4.31E-02	4.80E-02	1.725
0.385	3.10E-04	5.76E-02	5.40E-03	1.725
0.455	5.86E-04	7.38E-02	7.90E-03	1.775
0.500	2.03E-03	8.55E-02	2.40E-02	1.800
0.667	1.84E-02	1.53E-01	1.20E-01	1.795
1.000	1.65E-02	2.73E-01	6.00E-02	1.940
1.250	2.14E-02	4.27E-01	5.00E-02	1.940
1.670	3.19E-02	7.44E-01	4.30E-02	1.955

3.4.2. Numerical Analysis of ST40/20/1 Specimen

Table 3.14-Table 3.16 show the numerical analysis results for spectral input energy value and mass normalized spectral input energy value of ST40/20/1 specimen under defined ground motion records. T is period of the specimen, E_i is spectral input energy value, m is mass, E_i/m is mass normalized input energy value and L is the length of the specimen.

Table 3.14. ST40/20/1 Specimen 0.20 Loma Prieta Spectral Input Energy Results.

ST40/20/1-020 LOMA PRIETA				
T(sec)	E_i (kN.m)	m (kN.s ² /m)	E_i/m (m ² /s ²)	L(m)
0.159	1.66E-05	5.22E-03	3.18E-03	0.845
0.277	1.35E-04	1.58E-02	8.51E-03	0.845
0.333	4.80E-04	2.15E-02	2.23E-02	0.863
0.385	2.70E-03	2.88E-02	9.38E-02	0.863
0.455	2.27E-03	3.69E-02	6.15E-02	0.888
0.500	1.67E-03	4.27E-02	3.91E-02	0.900
0.667	3.88E-04	7.67E-02	5.06E-03	0.898
1.000	1.37E-03	1.37E-01	1.00E-02	0.970
1.250	3.77E-03	2.13E-01	1.77E-02	0.970
1.670	4.30E-03	3.72E-01	1.16E-02	0.978

Table 3.15. ST40/20/1 Specimen 0.20 San Salvador Spectral Input Energy Results.

ST40/20/1-020 SAN SALVADOR				
T(sec)	E_i(kN.m)	m(kN.s²/m)	E_i/m(m²/s²)	L(m)
0.159	4.99E-05	5.22E-03	9.56E-03	0.845
0.277	3.45E-04	1.58E-02	2.18E-02	0.845
0.333	5.89E-04	2.15E-02	2.73E-02	0.863
0.385	3.01E-04	2.88E-02	1.05E-02	0.863
0.455	9.66E-04	3.69E-02	2.62E-02	0.888
0.500	1.98E-03	4.27E-02	4.63E-02	0.900
0.667	1.05E-02	7.67E-02	1.36E-01	0.898
1.000	5.48E-03	1.37E-01	4.01E-02	0.970
1.250	9.48E-03	2.13E-01	4.44E-02	0.970

Table 3.16. ST40/20/1 Specimen 0.20 Erzincan Spectral Input Energy Results.

ST40/20/1-020 ERZINCAN				
T(sec)	E_i(kN.m)	m(kN.s²/m)	E_i/m(m²/s²)	L(m)
0.159	1.96E-05	5.22E-03	3.76E-03	0.845
0.277	3.71E-04	1.58E-02	2.34E-02	0.845
0.333	1.03E-03	2.15E-02	4.78E-02	0.863
0.385	1.55E-04	2.88E-02	5.39E-03	0.863
0.455	2.93E-04	3.69E-02	7.95E-03	0.888
0.500	1.02E-03	4.27E-02	2.39E-02	0.900
0.667	9.18E-03	7.67E-02	1.20E-01	0.898
1.000	8.27E-03	1.37E-01	6.06E-02	0.970
1.250	1.07E-02	2.13E-01	5.00E-02	0.970
1.670	1.57E-02	3.72E-01	4.23E-02	0.978

3.4.3. Numerical Analysis of AL80/40/2 Specimen

Table 3.17-Table 3.18 show the numerical analysis results for spectral input energy value and mass-normalized spectral input energy value of AL80/40/2 specimen under defined ground motion records. T is period of the specimen, E_i is spectral input energy value, m is mass, E_i/m is mass normalized input energy value and L is the length of the specimen.

Table 3.17. AL80/40/2 Specimen 0.20 Loma Prieta Spectral Input Energy Results.

AL80/40/2-0.20 LOMA PRIETA				
T(sec)	E_i(kN.m)	m(kN.s²/m)	E_i/m(m²/s²)	L(m)
0.159	1.36E-05	3.60E-03	3.76E-03	1.690
0.277	2.56E-04	1.09E-02	2.34E-02	1.690
0.333	3.34E-04	1.49E-02	2.25E-02	1.725
0.385	1.83E-03	1.99E-02	9.21E-02	1.725
0.455	1.54E-03	2.55E-02	6.05E-02	1.775
0.500	1.15E-03	2.95E-02	3.90E-02	1.800
0.667	2.68E-04	5.29E-02	5.06E-03	1.795
1.000	9.43E-04	9.42E-02	1.00E-02	1.940
1.250	2.60E-03	1.47E-01	1.77E-02	1.940
1.670	2.97E-03	2.57E-01	1.16E-02	1.955

Table 3.18. AL80/40/2 Specimen 0.20 San Salvador Spectral Input Energy Results.

AL80/40/2-0.20 SAN SALVADOR				
T(sec)	E_i(kN.m)	m(kN.s²/m)	E_i/m(m²/s²)	L(m)
0.159	3.45E-05	3.60E-03	9.58E-03	1.690
0.277	2.38E-04	1.09E-02	2.18E-02	1.690
0.333	4.00E-04	1.49E-02	2.69E-02	1.725
0.385	2.02E-04	1.99E-02	1.02E-02	1.725
0.455	6.40E-04	2.55E-02	2.51E-02	1.775
0.500	1.37E-03	2.95E-02	4.65E-02	1.800
0.667	7.22E-03	5.29E-02	1.36E-01	1.795
1.000	3.75E-03	9.42E-02	3.98E-02	1.940
1.250	6.54E-03	1.47E-01	4.44E-02	1.940
1.670	5.60E-03	2.57E-01	2.18E-02	1.955

Table 3.19. AL80/40/2 Specimen 0.20 Erzincan Spectral Input Energy Results.

AL80/40/2-0.20 ERZINCAN				
T(sec)	E_i(kN.m)	m(kN.s²/m)	E_i/m(m²/s²)	L(m)
0.159	1.36E-05	3.60E-03	3.76E-03	1.690
0.277	2.56E-04	1.09E-02	2.34E-02	1.690
0.333	6.89E-04	1.49E-02	4.63E-02	1.725
0.385	1.07E-04	1.99E-02	5.39E-03	1.725
0.455	2.00E-04	2.55E-02	7.85E-03	1.775
0.500	7.02E-04	2.95E-02	2.38E-02	1.800
0.667	6.34E-03	5.29E-02	1.20E-01	1.795
1.000	5.66E-03	9.42E-02	6.01E-02	1.940
1.250	7.36E-03	1.47E-01	5.00E-02	1.940
1.670	1.10E-02	2.57E-01	4.29E-02	1.955

3.4.4. AL40/20/1 Specimen Numerical Analysis Results for Input Energy Spectral Value

Table 3.20-Table 3.22 show the numerical analysis results for spectral input energy value and mass-normalized spectral input energy value of AL40/20/1 specimen under defined ground motion records. T is period of the specimen, E_i is spectral input energy value, m is mass, E_i/m is mass normalized input energy value and L is the length of the specimen.

Table 3.20. AL40/20/1 Specimen 0.20 Loma Prieta Spectral Input Energy Results.

AL40/20/1-020 LOMA PRIETA				
T(sec)	E_i(kN.m)	m(kN.s²/m)	E_i/m(m²/s²)	L(m)
0.159	5.73E-06	1.80E-03	3.18E-03	0.845
0.277	4.65E-05	5.47E-03	8.51E-03	0.845
0.333	1.66E-04	7.43E-03	2.23E-02	0.863
0.385	9.32E-04	9.93E-03	9.38E-02	0.863
0.455	7.85E-04	1.27E-02	6.16E-02	0.888
0.500	5.76E-04	1.47E-02	3.91E-02	0.900
0.667	1.34E-04	2.65E-02	5.06E-03	0.898
1.000	4.73E-04	4.71E-02	1.00E-02	0.970
1.250	1.27E-03	7.36E-02	1.73E-02	0.970
1.670	1.47E-03	1.28E-01	1.15E-02	0.978

Table 3.21. AL40/20/1 Specimen 0.20 San Salvador Spectral Input Energy Results.

AL40/20/1-020 SAN SALVADOR				
T(sec)	E_i(kN.m)	m(kN.s²/m)	E_i/m(m²/s²)	L(m)
0.159	1.72E-05	1.80E-03	9.54E-03	0.845
0.277	1.19E-04	5.47E-03	2.18E-02	0.845
0.333	2.03E-04	7.43E-03	2.73E-02	0.863
0.385	1.04E-04	9.93E-03	1.05E-02	0.863
0.455	3.33E-04	1.27E-02	2.62E-02	0.888
0.500	6.83E-04	1.47E-02	4.63E-02	0.900
0.667	3.61E-03	2.65E-02	1.36E-01	0.898
1.000	1.86E-03	4.71E-02	3.95E-02	0.970
1.250	3.23E-03	7.36E-02	4.39E-02	0.970
1.670	2.81E-03	1.28E-01	2.19E-02	0.9775

Table 3.22. AL40/20/1 Specimen 0.20 Erzincan Spectral Input Energy Results.

AL40/20/1-020 ERZINCAN				
T(sec)	E_i(kN.m)	m(kN.s²/m)	E_i/m(m²/s²)	L(m)
0.159	6.75E-06	1.80E-03	3.75E-03	0.845
0.277	1.28E-04	5.47E-03	2.34E-02	0.845
0.333	3.56E-04	7.43E-03	4.79E-02	0.863
0.385	5.35E-05	9.93E-03	5.39E-03	0.863
0.455	1.01E-04	1.27E-02	7.94E-03	0.888
0.500	3.51E-04	1.47E-02	2.38E-02	0.900
0.667	3.17E-03	2.65E-02	1.20E-01	0.898
1.000	2.79E-03	4.71E-02	5.92E-02	0.970
1.250	3.59E-03	7.36E-02	4.88E-02	0.970
1.670	5.39E-03	1.28E-01	4.20E-02	0.978

3.5. Dindar (2009) Input Energy Spectra

Dynamic response analysis of structures is a basic step for the energy based design method. There are many researches to develop energy response spectra. One of the Input and Plastic Energy demand spectra are proposed by Dindar (2015). This spectrum was developed with respect to different soil type and different ductility level in plastic and elastic range of ground motion record. The energy spectra for different soil types are depicted in Figure 3.9.

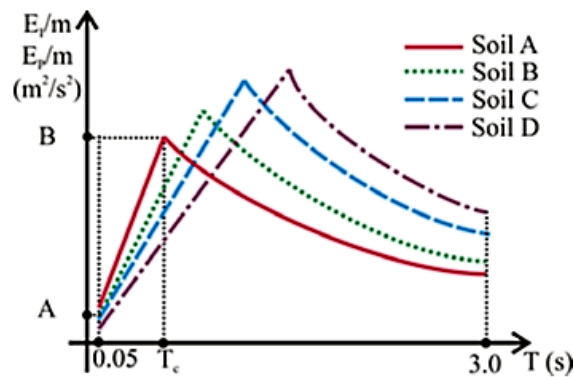


Figure 3.9. Proposed input and plastic energy spectra for different soil types considering 5% viscous damping ratio and EPP constitutive model with 84.1% confidence level(Dindar, 2015).

This energy spectra depend on the period of structure, soil type and PGA of the ground motion record. Specimens that are exposed to same ground motion data under same soil type between same period range, have same mass normalized input energy spectra in elastic range according to Dindar (2015) input energy spectra. Thus, these derived energy spectra verifies that there is an enrgy spectrum for energy based design.

The general formulation of the input and plastic energy demand spectra is defined as follows;

$$E_1^{PGA} = \left(\frac{PGA}{0, 1g} \right)^2 \times E_1 \times m \quad (3.27)$$

where, PGA is the peak ground acceleration of the seismic intensity, E_1 is the mass normalized input energy for the base seismic intensity in Equation 3.28 and Equation 3.29;

$$E_1 = A + (B - A)(T - 0.05)/(T_c - 0.05) \quad for \quad 0.05 \leq T \leq T_c \quad (3.28)$$

$$E_1 = B(T_c/T)^k \quad for \quad 0.05 \leq T \leq T_c \quad (3.29)$$

The parameters A , B , T_c and k used in Equation 3.28 and Equation 3.29 for input energies of Soil A, Soil B and Soil C are given in Table 3.23 and Table 3.25 respectively (Dindar, 2015). In this study, Soil A, Soil B and Soil C were selected with Loma Prieta, San Salvador and Erzincan ground motion record, respectively. The input energy values under defined ground motion records were calculated using the mass-normalized energy function.

Table 3.23. Input Energy Parameters for Soil A (Dindar, 2015).

Ductility	A(m ² /s ²)	B(m ² /s ²)	Tc(s)	k
1	0.0059	0.0650	0.50	0.910
2	0.0051	0.0551	0.45	0.848
4	0.0044	0.0444	0.40	0.889
6	0.0040	0.0350	0.35	0.861

Table 3.24. Input Energy Parameters for Soil B (Dindar, 2015).

Ductility	A(m ² /s ²)	B(m ² /s ²)	Tc(s)	k
1	0.0050	0.0705	0.50	1.905
2	0.0046	0.0624	0.45	1.071
4	0.0042	0.05	0.40	1.107
6	0.0035	0.041	0.35	1.110

Table 3.25. Input Energy Parameters for Soil C (Dindar, 2015).

Ductility	A(m ² /s ²)	B(m ² /s ²)	Tc(s)	k
1	0.0040	0.077	0.90	1.456
2	0.0038	0.065	0.80	1.320
4	0.0037	0.053	0.70	1.260
6	0.0036	0.044	0.65	1.272

In this research, numerical results were obtained from SAP2000 structural analysis software and input energy spectra was found for each earthquake record. Dindar (2015) energy spectrum was then compared with numerical modelling analysis results. The proposed mass-normalized energy spectrum only depends on the period range, PGA of the ground motion record and soil type. For these four specimens, in elastic range for defined period range, the mass-normalized input energy spectra are calculated. These specimens are different in terms of materials and dimensions. Under the same ground motion data, having same soil type and period range, mass normalized input energy spectra in elastic range is same. The mass normalized input energy spectra for the 0.20 Loma Prieta, 0.20 San Salvador and 0.20 Erzincan earthquakes are shown in Figure 3.10-Figure 3.12 respectively.

Elastic case analysis was completed with ductility value of 1 and 0.20 Loma Prieta, 0.20 San Salvador and 0.20 Erzincan earthquake records. The comparison of numerical analysis results for spectral input energy value generally fall inside the input energy soil spectra that were proposed produced by Dindar (2015). Comparison between soil type mass-normalized input energy spectrum with defined ground motion data and numerical modelling analysis results for input energy spectral value in elastic range are plotted in Figure 3.13-Figure 3.15 respectively. Only San Salvador earthquake record comparisons agree more than other records.

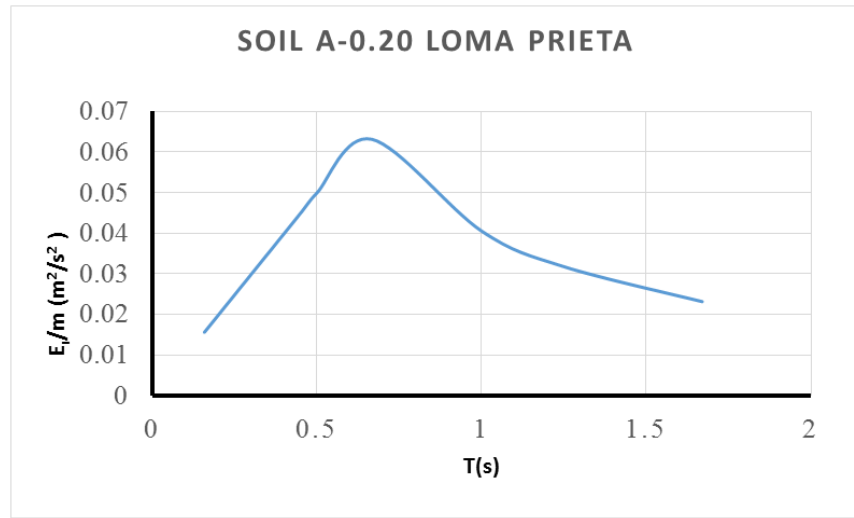


Figure 3.10. Soil A 0.20 Loma Prieta Earthquake Mass Normalized Input Energy Spectrum.

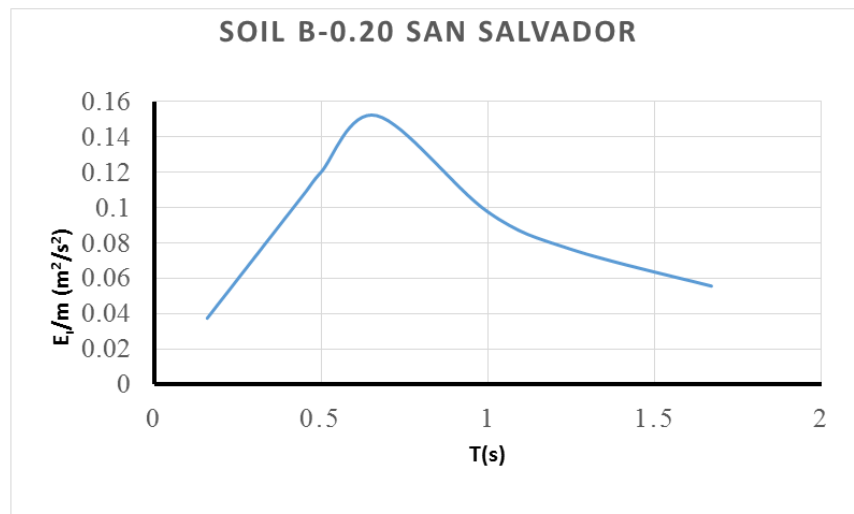


Figure 3.11. Soil B 0.20 San Salvador Earthquake Mass Normalized Input Energy Spectrum.

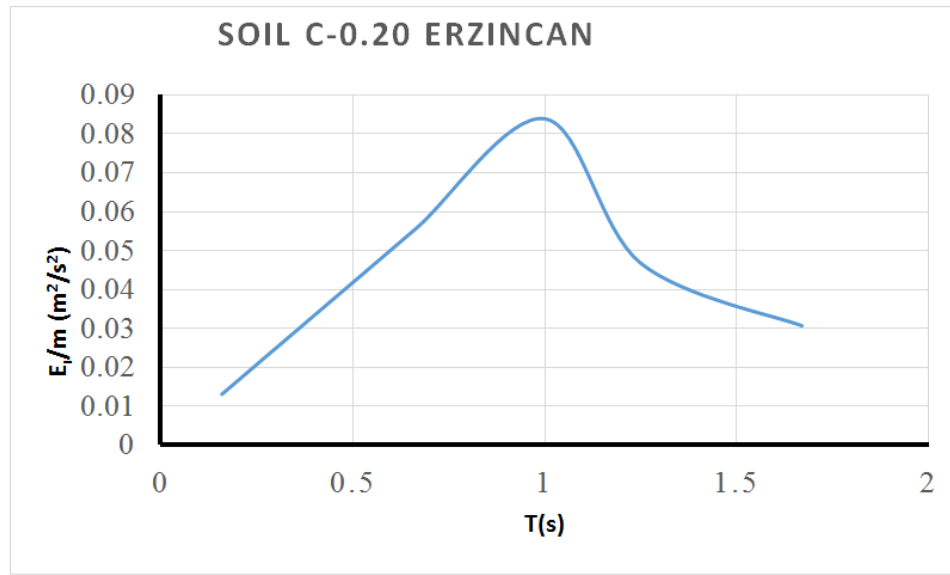


Figure 3.12. Soil C 0.20 Erzincan Earthquake Mass Normalized Input Energy Spectrum.

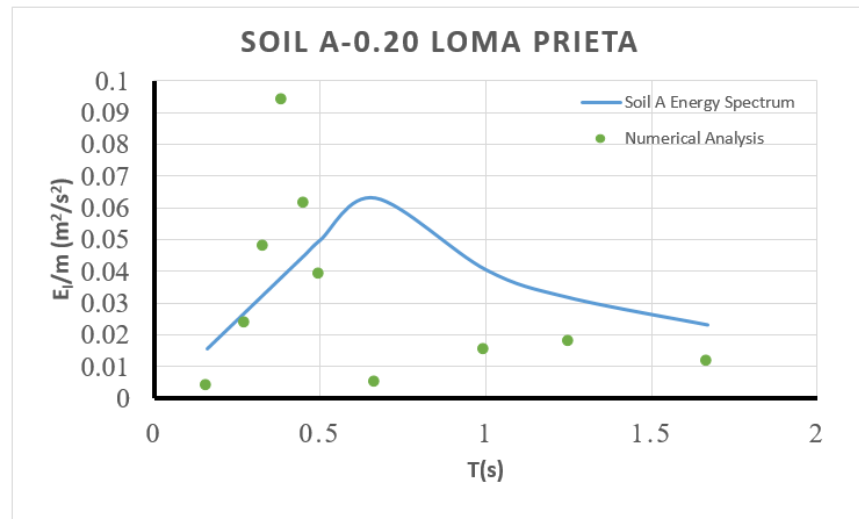


Figure 3.13. Input Energy Spectra of Soil A -Energy Spectrum of 0.20 Loma Prieta.

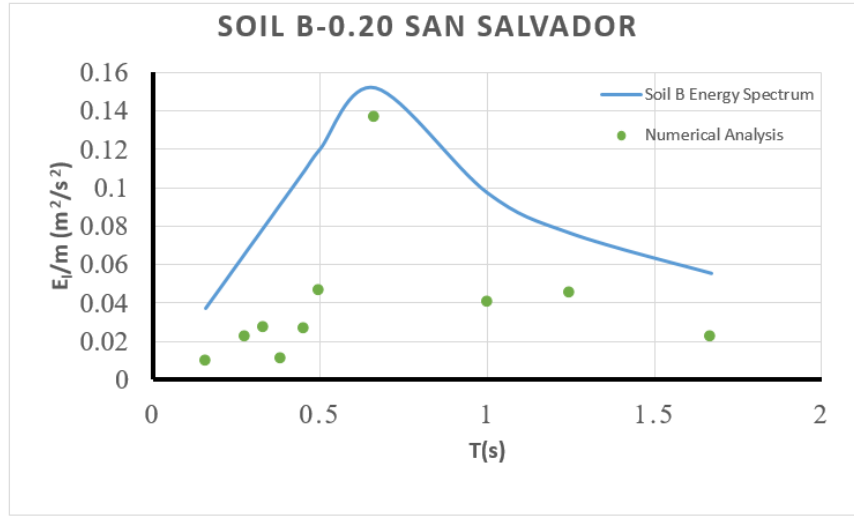


Figure 3.14. Input Energy Spectra of Soil B -Energy Spectrum of 0.20 San Salvador.

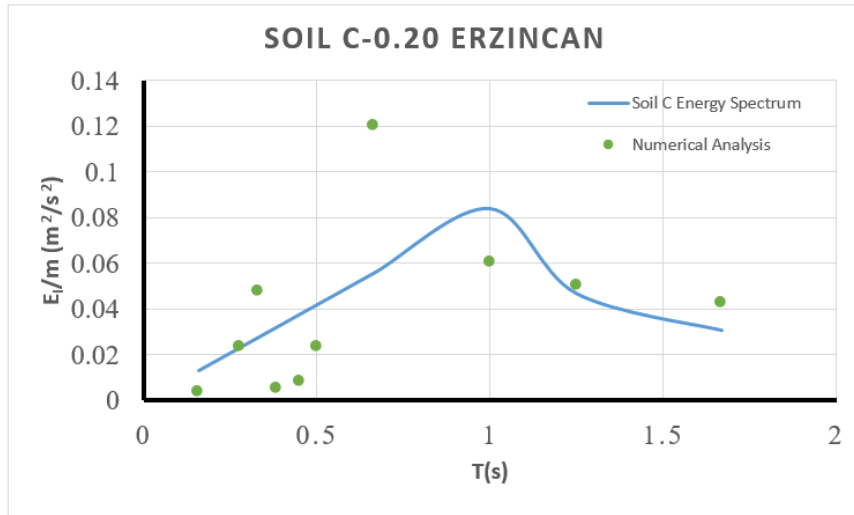


Figure 3.15. Input Energy Spectra of Soil C -Energy Spectrum of 0.20 Erzincan.

3.6. Dimensional Analysis for Elastic Case Results of Input Energy Spectra

Length scale factor is determined in Equation 3.30,

$$\lambda_L = \frac{L_{Specimen1}}{L_{Specimen2}} \quad (3.30)$$

Material scale factor is determined in Equation 3.31

$$\lambda_E = \frac{E_{Specimen1}}{E_{Specimen2}} \quad (3.31)$$

Mass ratio between specimens is determined as follows;

$$Mass \ Ratio = \frac{m_{Specimen1}}{m_{Specimen2}} = \lambda_m \quad (3.32)$$

Moment of inertia ratio between specimens is derived from ratio between cross section dimensions that are defined as λ_b and λ_h scale factors. By using these scale factors with dimensional analysis, moment of inertia scale factor is derived as in Equation

After numerical model analysis results for spectral input energy of specimens, dimensional analysis and scale analysis are applied for defined seven cases with binary state. These cases are defined in Table 3.26.

Table 3.26. Seven Cases for Scale Analysis of The Input Energy with Length Ratio and Modulus of Elasticity Ratio Between Specimens.

CASES FOR RATIO ANALYSIS			λ_b	λ_h	λ_L	λ_E	λ_e	λ_I
Case 1	ST80/40/2	AL80/40/2	1.00	1.00	1.00	2.89	2.89	1.00
Case 2	ST40/20/1	AL40/20/1	1.00	1.00	1.00	2.89	2.89	1.00
Case 3	ST80/40/2	ST40/20/1	2.00	2.00	2.00	1.00	2.00	16.00
Case 4	AL80/40/2	AL40/20/1	2.00	2.00	2.00	1.00	2.00	16.00
Case 5	ST80/40/2	AL40/20/1	2.00	2.00	2.00	2.89	5.78	16.00
Case 6	AL80/40/2	ST80/40/2	1.00	1.00	1.00	0.35	0.345	1.00
Case 7	AL80/40/2	ST40/20/1	2.00	2.00	2.00	0.35	0.69	16.00

Between developed seven cases with binary state, theoretical spectral input energy value ratios were calculated. In terms of the dimensional analysis steps defined in Section 3.2, input energy ratio between specimens should be correlated with Equation 3.26.

By using numerical model analysis, it shall be determined that whether the Equation 3.26 represents the correct relationship of the energy ratio between specimens or not.

The following tables show the energy ratio results of numerical study for defined binary states between specimens. E_i is spectral input energy value, m is the mass. E_i/m is the mass normalized input energy and L is the length of the specimen. Table 3.27 show the case 1 results, Table 3.29 show the case 2 results, Table 3.30 shows case 3 results, Table 3.31 show the case 4 results, Table 3.32 show the case 5 results, Table 3.33 shows case 6 results and Table 3.34 shows case 7 results for each defined ground motion record.

$$\lambda_e = \lambda_E \lambda_L^3 \quad (3.33)$$

λ_E is the modulus of elasticity ratio between specimens, λ_L is the length ratio between specimens, λ_e is the energy ratio between specimens. By using numerical model analysis, it was analyzed whether Equation 3.33 represents or not the energy ratio between specimens.

Based on the numerical modelling analysis of the input energy spectral value ratio between each specimen is given for each defined case with binary state under same period with same ground motion record in following tables. E_i is spectral input energy value, M is the mass of the specimen. E_i/m is the mass normalized input energy of the specimen.

Table 3.27. ST80/40/2-AL80/40/2 0.20 Loma Prieta, Erzincan and San Salvador Input Energy Spectral Value and Their Ratio.

ST80/40/2-020LOMA PRIETA					AL80/40/2-020LOMA PRIETA					ST80/40/2-AL80/40/2-020LOMA PRIETA				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	3.92E-05	1.04E-02	3.76E-03	1.690	0.159	1.36E-05	3.60E-03	3.76E-03	1.690	1.00	2.89	2.90	1.00	1.00
0.277	7.42E-04	3.17E-02	2.34E-02	1.690	0.277	2.56E-04	1.09E-02	2.34E-02	1.690	1.00	2.90	2.90	1.00	1.00
0.333	2.06E-03	4.31E-02	4.78E-02	1.725	0.333	3.34E-04	1.49E-02	2.25E-02	1.725	1.00	2.90	2.90	1.00	1.00
0.385	5.40E-03	5.76E-02	9.38E-02	1.725	0.385	1.83E-03	1.99E-02	9.21E-02	1.725	1.00	2.95	2.90	1.02	1.00
0.455	4.55E-03	7.38E-02	6.16E-02	1.775	0.455	1.54E-03	2.55E-02	6.05E-02	1.775	1.00	2.95	2.90	1.02	1.00
0.500	3.34E-03	8.55E-02	3.91E-02	1.800	0.500	1.15E-03	2.95E-02	3.90E-02	1.800	1.00	2.90	2.90	1.00	1.00
0.667	7.76E-04	1.53E-01	5.06E-03	1.795	0.667	2.68E-04	5.29E-02	5.06E-03	1.795	1.00	2.90	2.90	1.00	1.00
1.000	6.87E-04	2.73E-01	2.51E-03	1.940	1.000	9.43E-04	9.42E-02	1.00E-02	1.940	1.00	2.90	2.90	1.00	1.00
1.250	7.53E-03	4.27E-01	1.76E-02	1.940	1.250	2.60E-03	1.47E-01	1.77E-02	1.940	1.00	2.90	2.90	1.00	1.00
1.670	8.59E-03	7.44E-01	1.15E-02	1.955	1.670	2.97E-03	2.57E-01	1.16E-02	1.955	1.00	2.89	2.90	1.00	1.00
ST80/40/2-020ERZINCAN					AL80/40/2-020ERZINCAN					ST80/40/2-AL80/40/2 020ERZINCAN				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	3.9E-05	1.0E-02	3.8E-03	1.690	0.159	1.36E-05	3.60E-03	3.76E-03	1.690	1.00	2.89	2.90	1.00	1.00
0.277	7.4E-04	3.2E-02	2.3E-02	1.690	0.277	2.56E-04	1.09E-02	2.34E-02	1.690	1.00	2.90	2.90	1.00	1.00
0.333	2.1E-03	4.3E-02	4.8E-02	1.725	0.333	6.89E-04	1.49E-02	4.63E-02	1.725	1.00	2.99	2.90	1.03	1.00
0.385	3.1E-04	5.8E-02	5.4E-03	1.725	0.385	1.07E-04	1.99E-02	5.39E-03	1.725	1.00	2.90	2.90	1.00	1.00
0.455	5.9E-04	7.4E-02	7.9E-03	1.775	0.455	2.00E-04	2.55E-02	7.85E-03	1.775	1.00	2.93	2.90	1.01	1.00
0.500	2.0E-03	8.5E-02	2.4E-02	1.800	0.500	7.02E-04	2.95E-02	2.38E-02	1.800	1.00	2.89	2.90	1.00	1.00
0.667	1.8E-02	1.5E-01	1.2E-01	1.795	0.667	6.34E-03	5.29E-02	1.20E-01	1.795	1.00	2.90	2.90	1.00	1.00
1.000	1.6E-02	2.7E-01	6.0E-02	1.940	1.000	5.66E-03	9.42E-02	6.01E-02	1.940	1.00	2.91	2.90	1.00	1.00
1.250	2.1E-02	4.3E-01	5.0E-02	1.940	1.250	7.36E-03	1.47E-01	5.00E-02	1.940	1.00	2.90	2.90	1.00	1.00
1.670	3.2E-02	7.4E-01	4.3E-02	1.955	1.670	1.10E-02	2.57E-01	4.29E-02	1.955	1.00	2.90	2.90	1.00	1.00
ST80/40/2-020SAN SALVADOR					AL80/40/2-020SAN SALVADOR					ST80/40/2-AL80/40/2 020SAN SALVADOR				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	9.98E-05	1.04E-02	9.56E-03	1.690	0.159	3.45E-05	3.60E-03	9.58E-03	1.690	1.00	2.89	2.90	1.00	1.00
0.277	6.91E-04	3.17E-02	2.18E-02	1.690	0.277	2.38E-04	1.09E-02	2.18E-02	1.690	1.00	2.90	2.90	1.00	1.00
0.333	1.18E-03	4.31E-02	2.74E-02	1.725	0.333	4.00E-04	1.49E-02	2.69E-02	1.725	1.00	2.95	2.90	1.02	1.00
0.385	6.02E-04	5.76E-02	1.05E-02	1.725	0.385	2.02E-04	1.99E-02	1.02E-02	1.725	1.00	2.98	2.90	1.03	1.00
0.455	1.93E-03	7.38E-02	2.62E-02	1.775	0.455	6.40E-04	2.55E-02	2.51E-02	1.775	1.00	3.02	2.90	1.04	1.00
0.500	3.96E-03	8.55E-02	4.63E-02	1.800	0.500	1.37E-03	2.95E-02	4.65E-02	1.800	1.00	2.89	2.90	1.00	1.00
0.667	2.09E-02	1.53E-01	1.36E-01	1.795	0.667	7.22E-03	5.29E-02	1.36E-01	1.795	1.00	2.90	2.90	1.00	1.00
1.000	1.09E-02	2.73E-01	4.00E-02	1.940	1.000	3.75E-03	9.42E-02	3.98E-02	1.940	1.00	2.91	2.90	1.00	1.00
1.250	1.90E-02	4.27E-01	4.45E-02	1.940	1.250	6.54E-03	1.47E-01	4.44E-02	1.940	1.00	2.90	2.90	1.00	1.00
1.670	1.62E-02	7.44E-01	2.18E-02	1.955	1.670	5.60E-03	2.57E-01	2.18E-02	1.955	1.00	2.90	2.90	1.00	1.00

Table 3.28. ST40/20/1-AL40/20/1 0.20 Loma Prieta, Erzincan and San Salvador Input Energy Spectral Value and Their Ratio.

ST40/20/1-020LOMA PRIETA					AL40/20/1-020LOMA PRIETA					ST40/20/1-AL40/20/1-020LOMA PRIETA				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	1.66E-05	5.22E-03	3.18E-03	0.845	0.159	5.73E-06	1.80E-03	3.18E-03	0.845	1.00	2.90	2.90	1.00	1.00
0.277	1.35E-04	1.58E-02	8.51E-03	0.845	0.277	4.65E-05	5.47E-03	8.51E-03	0.845	1.00	2.90	2.90	1.00	1.00
0.333	4.80E-04	2.15E-02	2.23E-02	0.863	0.333	1.66E-04	7.43E-03	2.23E-02	0.863	1.00	2.90	2.90	1.00	1.00
0.385	2.70E-03	2.88E-02	9.38E-02	0.863	0.385	9.32E-04	9.93E-03	9.38E-02	0.863	1.00	2.90	2.90	1.00	1.00
0.455	2.27E-03	3.69E-02	6.15E-02	0.888	0.455	7.85E-04	1.27E-02	6.16E-02	0.888	1.00	2.89	2.90	1.00	1.00
0.500	1.67E-03	4.27E-02	3.91E-02	0.900	0.500	5.76E-04	1.47E-02	3.91E-02	0.900	1.00	2.90	2.90	1.00	1.00
0.667	3.88E-04	7.67E-02	5.06E-03	0.898	0.667	1.34E-04	2.65E-02	5.06E-03	0.898	1.00	2.90	2.90	1.00	1.00
1.000	1.37E-03	1.37E-01	1.00E-02	0.970	1.000	4.73E-04	4.71E-02	1.00E-02	0.970	1.00	2.90	2.90	1.00	1.00
1.250	3.77E-03	2.13E-01	1.77E-02	0.970	1.250	1.27E-03	7.36E-02	1.73E-02	0.970	1.00	2.97	2.90	1.02	1.00
1.670	4.30E-03	3.72E-01	1.16E-02	0.978	1.670	1.47E-03	1.28E-01	1.15E-02	0.978	1.00	2.93	2.90	1.01	1.00
ST40/20/1-020ERZINCAN					AL40/20/1-020ERZINCAN					ST40/20/1-AL40/20/1-020ERZINCAN				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	1.96E-05	5.22E-03	3.76E-03	0.845	0.159	6.75E-06	1.80E-03	3.75E-03	0.845	1.00	2.91	2.90	1.00	1.00
0.277	3.71E-04	1.58E-02	2.34E-02	0.845	0.277	1.28E-04	5.47E-03	2.34E-02	0.845	1.00	2.90	2.90	1.00	1.00
0.333	1.03E-03	2.15E-02	4.78E-02	0.863	0.333	3.56E-04	7.43E-03	4.79E-02	0.863	1.00	2.90	2.90	1.00	1.00
0.385	1.55E-04	2.88E-02	5.39E-03	0.863	0.385	5.35E-05	9.93E-03	5.39E-03	0.863	1.00	2.90	2.90	1.00	1.00
0.455	2.93E-04	3.69E-02	7.95E-03	0.888	0.455	1.01E-04	1.27E-02	7.94E-03	0.888	1.00	2.90	2.90	1.00	1.00
0.500	1.02E-03	4.27E-02	2.39E-02	0.900	0.500	3.51E-04	1.47E-02	2.38E-02	0.900	1.00	2.91	2.90	1.00	1.00
0.667	9.18E-03	7.67E-02	1.20E-01	0.898	0.667	3.17E-03	2.65E-02	1.20E-01	0.898	1.00	2.90	2.90	1.00	1.00
1.000	8.27E-03	1.37E-01	6.06E-02	0.970	1.000	2.79E-03	4.71E-02	5.92E-02	0.970	1.00	2.96	2.90	1.02	1.00
1.250	1.07E-02	2.13E-01	5.00E-02	0.970	1.250	3.59E-03	7.36E-02	4.88E-02	0.970	1.00	2.97	2.90	1.02	1.00
1.670	1.57E-02	3.72E-01	4.23E-02	0.978	1.670	5.39E-03	1.28E-01	4.20E-02	0.978	1.00	2.92	2.90	1.01	1.00
ST40/20/1-020SAN SALVADOR					AL40/20/1-020SAN SALVADOR					ST40/20/1-AL40/20/1-020SAN SALVADOR				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	4.99E-05	5.22E-03	9.56E-03	0.845	0.159	1.72E-05	1.80E-03	9.54E-03	0.845	1.00	2.90	2.90	1.00	1.00
0.277	3.45E-04	1.58E-02	2.18E-02	0.845	0.277	1.19E-04	5.47E-03	2.18E-02	0.845	1.00	2.90	2.90	1.00	1.00
0.333	5.89E-04	2.15E-02	2.73E-02	0.863	0.333	2.03E-04	7.43E-03	2.73E-02	0.863	1.00	2.90	2.90	1.00	1.00
0.385	3.01E-04	2.88E-02	1.05E-02	0.863	0.385	1.04E-04	9.93E-03	1.05E-02	0.863	1.00	2.90	2.90	1.00	1.00
0.455	9.66E-04	3.69E-02	2.62E-02	0.888	0.455	3.33E-04	1.27E-02	2.62E-02	0.888	1.00	2.90	2.90	1.00	1.00
0.500	1.98E-03	4.27E-02	4.63E-02	0.900	0.500	6.83E-04	1.47E-02	4.63E-02	0.900	1.00	2.90	2.90	1.00	1.00
0.667	1.05E-02	7.67E-02	1.36E-01	0.898	0.667	3.61E-03	2.65E-02	1.36E-01	0.898	1.00	2.90	2.90	1.00	1.00
1.000	5.48E-03	1.37E-01	4.01E-02	0.970	1.000	1.86E-03	4.71E-02	3.95E-02	0.970	1.00	2.95	2.90	1.02	1.00
1.250	9.48E-03	2.13E-01	4.44E-02	0.970	1.250	3.23E-03	7.36E-02	4.39E-02	0.970	1.00	2.93	2.90	1.01	1.00
1.670	8.12E-03	3.72E-01	2.18E-02	0.978	1.670	2.81E-03	1.28E-01	2.19E-02	0.978	1.00	2.89	2.90	1.00	1.00

Table 3.29. AL80/40/2-AL40/20/1 0.20 Loma Prieta, Erzincan and San Salvador Input Energy Spectral Value and Their Ratio.

AL80/40/2-020LOMA PRIETA					AL40/20/1-020LOMA PRIETA					AL80/40/2-AL40/20/1-020 LOMA PRIETA				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	1.36E-05	3.60E-03	3.76E-03	1.690	0.159	5.73E-06	1.80E-03	3.18E-03	0.845	1.00	2.37	2.00	1.18	2.00
0.277	2.56E-04	1.09E-02	2.34E-02	1.690	0.277	4.67E-05	5.47E-03	8.54E-03	0.845	1.00	1.99	2.00	1.00	2.00
0.333	3.34E-04	1.49E-02	2.25E-02	1.725	0.333	1.66E-04	7.43E-03	2.23E-02	0.863	1.00	2.02	2.00	1.01	2.00
0.385	1.83E-03	1.99E-02	9.21E-02	1.725	0.385	9.32E-04	9.93E-03	9.38E-02	0.863	1.00	1.96	2.00	0.98	2.00
0.455	1.54E-03	2.55E-02	6.05E-02	1.775	0.455	7.85E-04	1.27E-02	6.16E-02	0.888	1.00	1.96	2.00	0.98	2.00
0.500	1.15E-03	2.95E-02	3.90E-02	1.800	0.500	5.76E-04	1.47E-02	3.91E-02	0.900	1.00	2.00	2.00	1.00	2.00
0.667	2.68E-04	5.29E-02	5.06E-03	1.795	0.667	1.34E-04	2.65E-02	5.06E-03	0.898	1.00	2.00	2.00	1.00	2.00
1.000	9.43E-04	9.42E-02	1.00E-02	1.940	1.000	4.73E-04	4.71E-02	1.00E-02	0.970	1.00	1.99	2.00	1.00	2.00
1.250	2.60E-03	1.47E-01	1.77E-02	1.940	1.250	1.27E-03	7.36E-02	1.73E-02	0.970	1.00	2.05	2.00	1.02	2.00
1.670	2.97E-03	2.57E-01	1.16E-02	1.955	1.670	1.47E-03	1.28E-01	1.15E-02	0.978	1.00	2.02	2.00	1.01	2.00
AL80/40/2-020ERZINCAN					AL40/20/1-020ERZINCAN					AL80/40/2-AL40/20/1 020 ERZINCAN				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	1.36E-05	3.60E-03	3.76E-03	1.690	0.159	6.75E-06	1.80E-03	3.75E-03	0.845	1.00	2.01	2.00	1.00	2.00
0.277	2.56E-04	1.09E-02	2.34E-02	1.690	0.277	1.28E-04	5.47E-03	2.34E-02	0.845	1.00	2.00	2.00	1.00	2.00
0.333	6.89E-04	1.49E-02	4.63E-02	1.725	0.333	3.56E-04	7.43E-03	4.79E-02	0.863	1.00	1.94	2.00	0.97	2.00
0.385	1.07E-04	1.99E-02	5.39E-03	1.725	0.385	5.35E-05	9.93E-03	5.39E-03	0.863	1.00	2.00	2.00	1.00	2.00
0.455	2.00E-04	2.55E-02	7.85E-03	1.775	0.455	1.01E-04	1.27E-02	7.94E-03	0.888	1.00	1.98	2.00	0.99	2.00
0.500	7.02E-04	2.95E-02	2.38E-02	1.800	0.500	3.51E-04	1.47E-02	2.38E-02	0.900	1.00	2.00	2.00	1.00	2.00
0.667	6.34E-03	5.29E-02	1.20E-01	1.795	0.667	3.17E-03	2.65E-02	1.20E-01	0.898	1.00	2.00	2.00	1.00	2.00
1.000	5.66E-03	9.42E-02	6.01E-02	1.940	1.000	2.79E-03	4.71E-02	5.92E-02	0.970	1.00	2.03	2.00	1.01	2.00
1.250	7.36E-03	1.47E-01	5.00E-02	1.940	1.250	3.59E-03	7.36E-02	4.88E-02	0.970	1.00	2.05	2.00	1.03	2.00
1.670	1.10E-02	2.57E-01	4.29E-02	1.955	1.670	5.39E-03	1.28E-01	4.20E-02	0.978	1.00	2.04	2.00	1.02	2.00
AL80/40/2-020SAN SALVADOR					AL40/20/1-020SAN SALVADOR					AL80/40/2-AL40/20/1 020SAN SALVADOR				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	3.45E-05	3.60E-03	9.58E-03	1.690	0.159	1.72E-05	1.80E-03	9.54E-03	0.845	1.00	2.01	2.00	1.00	2.00
0.277	2.38E-04	1.09E-02	2.18E-02	1.690	0.277	1.19E-04	5.47E-03	2.18E-02	0.845	1.00	2.00	2.00	1.00	2.00
0.333	4.00E-04	1.49E-02	2.69E-02	1.725	0.333	2.03E-04	7.43E-03	2.73E-02	0.863	1.00	1.97	2.00	0.98	2.00
0.385	2.02E-04	1.99E-02	1.02E-02	1.725	0.385	1.04E-04	9.93E-03	1.05E-02	0.863	1.00	1.95	2.00	0.97	2.00
0.455	6.40E-04	2.55E-02	2.51E-02	1.775	0.455	3.33E-04	1.27E-02	2.62E-02	0.888	1.00	1.92	2.00	0.96	2.00
0.500	1.37E-03	2.95E-02	4.65E-02	1.800	0.500	6.83E-04	1.47E-02	4.63E-02	0.900	1.00	2.01	2.00	1.00	2.00
0.667	7.22E-03	5.29E-02	1.36E-01	1.795	0.667	3.61E-03	2.65E-02	1.36E-01	0.898	1.00	2.00	2.00	1.00	2.00
1.000	3.75E-03	9.42E-02	3.98E-02	1.940	1.000	1.86E-03	4.71E-02	3.95E-02	0.970	1.00	2.02	2.00	1.01	2.00
1.250	6.54E-03	1.47E-01	4.44E-02	1.940	1.250	3.23E-03	7.36E-02	4.39E-02	0.970	1.00	2.02	2.00	1.01	2.00
1.670	5.60E-03	2.57E-01	2.18E-02	1.955	1.670	2.81E-03	1.28E-01	2.19E-02	0.978	1.00	1.99	2.00	1.00	2.00

Table 3.30. ST80/40/2-ST40/20/1 0.20 Loma Prieta, Erzincan and San Salvador Input Energy Spectral Value and Their Ratio.

ST80/40/2-020LOMA PRIETA					ST40/20/1-020LOMA PRIETA					ST80/40/2-ST40/20/1-020 LOMA PRIETA				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	3.92E-05	1.04E-02	3.76E-03	1.690	0.159	1.66E-05	5.22E-03	3.18E-03	0.845	1.00	2.36	2.00	1.18	2.00
0.277	7.42E-04	3.17E-02	2.34E-02	1.690	0.277	1.35E-04	1.58E-02	8.51E-03	0.845	1.00	1.99	2.00	1.00	2.00
0.333	2.06E-03	4.31E-02	4.78E-02	1.725	0.333	4.78E-04	2.15E-02	2.23E-02	0.863	1.00	1.99	2.00	1.00	2.00
0.385	5.40E-03	5.76E-02	9.38E-02	1.725	0.385	2.70E-03	2.88E-02	9.38E-02	0.863	1.00	2.00	2.00	1.00	2.00
0.455	4.55E-03	7.38E-02	6.16E-02	1.775	0.455	2.27E-03	3.69E-02	6.15E-02	0.888	1.00	2.00	2.00	1.00	2.00
0.500	3.34E-03	8.55E-02	3.91E-02	1.800	0.500	1.67E-03	4.27E-02	3.91E-02	0.900	1.00	2.00	2.00	1.00	2.00
0.667	7.76E-04	1.53E-01	5.06E-03	1.795	0.667	3.88E-04	7.67E-02	5.06E-03	0.898	1.00	2.00	2.00	1.00	2.00
1.000	6.87E-04	2.73E-01	2.51E-03	1.940	1.000	1.37E-03	1.37E-01	1.00E-02	0.970	1.00	0.50	2.00	0.25	2.00
1.250	7.53E-03	4.27E-01	1.76E-02	1.940	1.250	3.77E-03	2.13E-01	1.77E-02	0.970	1.00	2.00	2.00	1.00	2.00
1.670	8.59E-03	7.44E-01	1.15E-02	1.955	1.670	4.30E-03	3.72E-01	1.16E-02	0.978	1.00	2.00	2.00	1.00	2.00
ST80/40/2-020ERZINCAN					ST40/20/1-020ERZINCAN					ST80/40/2-ST40/20/1 020ERZINCAN				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	3.92E-05	1.04E-02	3.76E-03	1.690	0.159	1.96E-05	5.22E-03	3.76E-03	0.845	1.00	2.00	2.00	1.00	2.00
0.277	7.42E-04	3.17E-02	2.34E-02	1.690	0.277	3.71E-04	1.58E-02	2.34E-02	0.845	1.00	2.00	2.00	1.00	2.00
0.333	2.06E-03	4.31E-02	4.78E-02	1.725	0.333	1.03E-03	2.15E-02	4.78E-02	0.863	1.00	2.00	2.00	1.00	2.00
0.385	3.10E-04	5.76E-02	5.39E-03	1.725	0.385	1.55E-04	2.88E-02	5.39E-03	0.863	1.00	2.00	2.00	1.00	2.00
0.455	5.86E-04	7.38E-02	7.94E-03	1.775	0.455	2.93E-04	3.69E-02	7.95E-03	0.888	1.00	2.00	2.00	1.00	2.00
0.500	2.03E-03	8.55E-02	2.38E-02	1.800	0.500	1.02E-03	4.27E-02	2.39E-02	0.900	1.00	1.99	2.00	1.00	2.00
0.667	1.84E-02	1.53E-01	1.20E-01	1.795	0.667	9.18E-03	7.67E-02	1.20E-01	0.898	1.00	2.00	2.00	1.00	2.00
1.000	1.65E-02	2.73E-01	6.02E-02	1.940	1.000	8.27E-03	1.37E-01	6.06E-02	0.970	1.00	1.99	2.00	0.99	2.00
1.250	2.14E-02	4.27E-01	5.01E-02	1.940	1.250	1.07E-02	2.13E-01	5.00E-02	0.970	1.00	2.01	2.00	1.00	2.00
1.670	3.19E-02	7.44E-01	4.29E-02	1.955	1.670	1.57E-02	3.72E-01	4.23E-02	0.978	1.00	2.03	2.00	1.01	2.00
ST80/40/2-020SAN SALVADOR					ST40/20/1-020SAN SALVADOR					ST80/40/2-ST40/20/1 020SAN SALVADOR				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	9.98E-05	1.04E-02	9.56E-03	1.690	0.159	4.99E-05	5.22E-03	9.56E-03	0.845	1.00	2.00	2.00	1.00	2.00
0.277	6.91E-04	3.17E-02	2.18E-02	1.690	0.277	3.45E-04	1.58E-02	2.18E-02	0.845	1.00	2.00	2.00	1.00	2.00
0.333	1.18E-03	4.31E-02	2.74E-02	1.725	0.333	5.89E-04	2.15E-02	2.73E-02	0.863	1.00	2.00	2.00	1.00	2.00
0.385	6.02E-04	5.76E-02	1.05E-02	1.725	0.385	3.01E-04	2.88E-02	1.05E-02	0.863	1.00	2.00	2.00	1.00	2.00
0.455	1.93E-03	7.38E-02	2.62E-02	1.775	0.455	9.66E-04	3.69E-02	2.62E-02	0.888	1.00	2.00	2.00	1.00	2.00
0.500	3.96E-03	8.55E-02	4.63E-02	1.800	0.500	1.98E-03	4.27E-02	4.63E-02	0.900	1.00	2.00	2.00	1.00	2.00
0.667	2.09E-02	1.53E-01	1.36E-01	1.795	0.667	1.05E-02	7.67E-02	1.36E-01	0.898	1.00	2.00	2.00	1.00	2.00
1.000	1.09E-02	2.73E-01	4.00E-02	1.940	1.000	5.48E-03	1.37E-01	4.01E-02	0.970	1.00	1.99	2.00	1.00	2.00
1.250	1.90E-02	4.27E-01	4.45E-02	1.940	1.250	9.48E-03	2.13E-01	4.44E-02	0.970	1.00	2.00	2.00	1.00	2.00
1.670	1.62E-02	7.44E-01	2.18E-02	1.955	1.670	8.12E-03	3.72E-01	2.18E-02	0.978	1.00	2.00	2.00	1.00	2.00

Table 3.31. ST80/40/2-AL40/20/1 0.20 Loma Prieta, Erzincan and San Salvador Input Energy Spectral Value and Their Ratio.

ST80/40/2-020LOMA PRIETA					AL40/20/1-020LOMA PRIETA					ST80/40/2-AL40/20/1-020 LOMA PRIETA				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	3.92E-05	1.04E-02	3.76E-03	1.690	0.159	5.73E-06	1.80E-03	3.18E-03	0.845	1.00	6.84	5.80	1.18	2.00
0.277	7.42E-04	3.17E-02	2.34E-02	1.690	0.277	4.67E-05	5.47E-03	8.54E-03	0.845	1.00	15.89	5.80	2.74	2.00
0.333	2.06E-03	4.31E-02	4.78E-02	1.725	0.333	1.66E-04	7.43E-03	2.23E-02	0.863	1.00	12.45	5.80	2.15	2.00
0.385	5.40E-03	5.76E-02	9.38E-02	1.725	0.385	9.32E-04	9.93E-03	9.38E-02	0.863	1.00	5.79	5.80	1.00	2.00
0.455	4.55E-03	7.38E-02	6.16E-02	1.775	0.455	7.85E-04	1.27E-02	6.16E-02	0.888	1.00	5.80	5.80	1.00	2.00
0.500	3.34E-03	8.55E-02	3.91E-02	1.800	0.500	5.76E-04	1.47E-02	3.91E-02	0.900	1.00	5.79	5.80	1.00	2.00
0.667	7.76E-04	1.53E-01	5.06E-03	1.795	0.667	1.34E-04	2.65E-02	5.06E-03	0.898	1.00	5.80	5.80	1.00	2.00
1.000	6.87E-04	2.73E-01	2.51E-03	1.940	1.000	4.73E-04	4.71E-02	1.00E-02	0.970	1.00	1.45	5.80	0.25	2.00
1.250	7.53E-03	4.27E-01	1.76E-02	1.940	1.250	1.27E-03	7.36E-02	1.73E-02	0.970	1.00	5.93	5.80	1.02	2.00
1.670	8.59E-03	7.44E-01	1.15E-02	1.955	1.670	1.47E-03	1.28E-01	1.15E-02	0.978	1.00	5.84	5.80	1.01	2.00
ST80/40/2-020ERZINCAN					AL40/20/1-020ERZINCAN					ST80/40/2-AL40/20/1-0.20 ERZINCAN				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	3.92E-05	1.04E-02	3.76E-03	1.690	0.159	6.75E-06	1.80E-03	3.75E-03	0.845	1.00	5.81	5.80	1.00	2.00
0.277	7.42E-04	3.17E-02	2.34E-02	1.690	0.277	1.28E-04	5.47E-03	2.34E-02	0.845	1.00	5.80	5.80	1.00	2.00
0.333	2.06E-03	4.31E-02	4.78E-02	1.725	0.333	3.56E-04	7.43E-03	4.79E-02	0.863	1.00	5.79	5.80	1.00	2.00
0.385	3.10E-04	5.76E-02	5.39E-03	1.725	0.385	5.35E-05	9.93E-03	5.39E-03	0.863	1.00	5.80	5.80	1.00	2.00
0.455	5.86E-04	7.38E-02	7.94E-03	1.775	0.455	1.01E-04	1.27E-02	7.94E-03	0.888	1.00	5.80	5.80	1.00	2.00
0.500	2.03E-03	8.55E-02	2.38E-02	1.800	0.500	3.51E-04	1.47E-02	2.38E-02	0.900	1.00	5.78	5.80	1.00	2.00
0.667	1.84E-02	1.53E-01	1.20E-01	1.795	0.667	3.17E-03	2.65E-02	1.20E-01	0.898	1.00	5.79	5.80	1.00	2.00
1.000	1.65E-02	2.73E-01	6.02E-02	1.940	1.000	2.79E-03	4.71E-02	5.92E-02	0.970	1.00	5.90	5.80	1.02	2.00
1.250	2.14E-02	4.27E-01	5.01E-02	1.940	1.250	3.59E-03	7.36E-02	4.88E-02	0.970	1.00	5.96	5.80	1.03	2.00
1.670	3.19E-02	7.44E-01	4.29E-02	1.955	1.670	5.39E-03	1.28E-01	4.20E-02	0.978	1.00	5.92	5.80	1.02	2.00
ST80/40/2-020SAN SALVADOR					AL40/20/1-020SAN SALVADOR					ST80/40/2-AL40/20/1 020SAN SALVADOR				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	9.98E-05	1.04E-02	9.56E-03	1.690	0.159	1.72E-05	1.80E-03	9.54E-03	0.845	1.00	5.81	5.80	1.00	2.00
0.277	6.91E-04	3.17E-02	2.18E-02	1.690	0.277	1.19E-04	5.47E-03	2.18E-02	0.845	1.00	5.80	5.80	1.00	2.00
0.333	1.18E-03	4.31E-02	2.74E-02	1.725	0.333	2.03E-04	7.43E-03	2.73E-02	0.863	1.00	5.81	5.80	1.00	2.00
0.385	6.02E-04	5.76E-02	1.05E-02	1.725	0.385	1.04E-04	9.93E-03	1.05E-02	0.863	1.00	5.80	5.80	1.00	2.00
0.455	1.93E-03	7.38E-02	2.62E-02	1.775	0.455	3.33E-04	1.27E-02	2.62E-02	0.888	1.00	5.79	5.80	1.00	2.00
0.500	3.96E-03	8.55E-02	4.63E-02	1.800	0.500	6.83E-04	1.47E-02	4.63E-02	0.900	1.00	5.80	5.80	1.00	2.00
0.667	2.09E-02	1.53E-01	1.36E-01	1.795	0.667	3.61E-03	2.65E-02	1.36E-01	0.898	1.00	5.80	5.80	1.00	2.00
1.000	1.09E-02	2.73E-01	4.00E-02	1.940	1.000	1.86E-03	4.71E-02	3.95E-02	0.970	1.00	5.87	5.80	1.01	2.00
1.250	1.90E-02	4.27E-01	4.45E-02	1.940	1.250	3.23E-03	7.36E-02	4.39E-02	0.970	1.00	5.87	5.80	1.01	2.00
1.670	1.62E-02	7.44E-01	2.18E-02	1.955	1.670	2.81E-03	1.28E-01	2.19E-02	0.978	1.00	5.78	5.80	1.00	2.00

Table 3.32. AL80/40/2-ST40/20/1- 0.20 Loma Prieta, Erzincan and San Salvador Input Energy Spectral Value and Their Ratio.

AL80/40/2-020LOMA PRIETA					ST40/20/1-020LOMA PRIETA					AL80/40/2-ST40/20/1-020 LOMA PRIETA				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	1.36E-05	3.60E-03	3.76E-03	1.690	0.159	1.66E-05	5.22E-03	3.18E-03	0.845	1.00	0.82	0.69	1.18	2.00
0.277	2.56E-04	1.09E-02	2.34E-02	1.690	0.277	1.35E-04	1.58E-02	8.51E-03	0.845	1.00	1.90	0.69	2.75	2.00
0.333	3.34E-04	1.49E-02	2.25E-02	1.725	0.333	4.80E-04	2.15E-02	2.23E-02	0.863	1.00	0.70	0.69	1.01	2.00
0.385	1.83E-03	1.99E-02	9.21E-02	1.725	0.385	2.70E-03	2.88E-02	9.38E-02	0.863	1.00	0.68	0.69	0.98	2.00
0.455	1.54E-03	2.55E-02	6.03E-02	1.775	0.455	2.27E-03	3.69E-02	6.15E-02	0.888	1.00	0.68	0.69	0.98	2.00
0.500	1.15E-03	2.95E-02	3.90E-02	1.800	0.500	1.67E-03	4.27E-02	3.91E-02	0.900	1.00	0.69	0.69	1.00	2.00
0.667	2.68E-04	5.29E-02	5.06E-03	1.795	0.667	3.88E-04	7.67E-02	5.06E-03	0.898	1.00	0.69	0.69	1.00	2.00
1.000	9.43E-04	9.42E-02	1.00E-02	1.940	1.000	1.37E-03	1.37E-01	1.00E-02	0.970	1.00	0.69	0.69	1.00	2.00
1.250	2.60E-03	1.47E-01	1.77E-02	1.940	1.250	3.77E-03	2.13E-01	1.77E-02	0.970	1.00	0.69	0.69	1.00	2.00
1.670	2.97E-03	2.57E-01	1.16E-02	1.955	1.670	4.30E-03	3.72E-01	1.16E-02	0.978	1.00	0.69	0.69	1.00	2.00
AL80/40/2-020ERZINCAN					ST40/20/1-020ERZINCAN					AL80/40/2-ST40/20/1 020ERZINCAN				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	1.36E-05	3.60E-03	3.76E-03	1.690	0.159	1.96E-05	5.22E-03	3.76E-03	0.845	1.00	0.69	0.69	1.00	2.00
0.277	2.56E-04	1.09E-02	2.34E-02	1.690	0.277	3.71E-04	1.58E-02	2.34E-02	0.845	1.00	0.69	0.69	1.00	2.00
0.333	6.89E-04	1.49E-02	4.63E-02	1.725	0.333	1.03E-03	2.15E-02	4.78E-02	0.863	1.00	0.67	0.69	0.97	2.00
0.385	1.07E-04	1.99E-02	5.39E-03	1.725	0.385	1.55E-04	2.88E-02	5.39E-03	0.863	1.00	0.69	0.69	1.00	2.00
0.455	2.00E-04	2.55E-02	7.85E-03	1.775	0.455	2.93E-04	3.69E-02	7.95E-03	0.888	1.00	0.68	0.69	0.99	2.00
0.500	7.02E-04	2.95E-02	2.38E-02	1.800	0.500	1.02E-03	4.27E-02	2.39E-02	0.900	1.00	0.69	0.69	1.00	2.00
0.667	6.34E-03	5.29E-02	1.20E-01	1.795	0.667	9.18E-03	7.67E-02	1.20E-01	0.898	1.00	0.69	0.69	1.00	2.00
1.000	5.66E-03	9.42E-02	6.01E-02	1.940	1.000	8.27E-03	1.37E-01	6.06E-02	0.970	1.00	0.68	0.69	0.99	2.00
1.250	7.36E-03	1.47E-01	5.00E-02	1.940	1.250	1.07E-02	2.13E-01	5.00E-02	0.970	1.00	0.69	0.69	1.00	2.00
1.670	1.10E-02	2.57E-01	4.29E-02	1.955	1.670	1.57E-02	3.72E-01	4.23E-02	0.978	1.00	0.70	0.69	1.01	2.00
AL80/40/2-020SAN SALVADOR					ST40/20/1-020SAN SALVADOR					AL80/40/2-ST40/20/1 020SAN SALVADOR				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	3.45E-05	3.60E-03	9.58E-03	1.690	0.159	4.99E-05	5.22E-03	9.56E-03	0.845	1.00	0.69	0.69	1.00	2.00
0.277	2.38E-04	1.09E-02	2.18E-02	1.690	0.277	3.45E-04	1.58E-02	2.18E-02	0.845	1.00	0.69	0.69	1.00	2.00
0.333	4.00E-04	1.49E-02	2.69E-02	1.725	0.333	5.89E-04	2.15E-02	2.73E-02	0.863	1.00	0.68	0.69	0.98	2.00
0.385	2.02E-04	1.99E-02	1.02E-02	1.725	0.385	3.01E-04	2.88E-02	1.05E-02	0.863	1.00	0.67	0.69	0.97	2.00
0.455	6.40E-04	2.55E-02	2.51E-02	1.775	0.455	9.66E-04	3.69E-02	2.62E-02	0.888	1.00	0.66	0.69	0.96	2.00
0.500	1.37E-03	2.95E-02	4.65E-02	1.800	0.500	1.98E-03	4.27E-02	4.63E-02	0.900	1.00	0.69	0.69	1.00	2.00
0.667	7.22E-03	5.29E-02	1.36E-01	1.795	0.667	1.05E-02	7.67E-02	1.36E-01	0.898	1.00	0.69	0.69	1.00	2.00
1.000	3.75E-03	9.42E-02	3.98E-02	1.940	1.000	5.48E-03	1.37E-01	4.01E-02	0.970	1.00	0.68	0.69	0.99	2.00
1.250	6.54E-03	1.47E-01	4.44E-02	1.940	1.250	9.48E-03	2.13E-01	4.44E-02	0.970	1.00	0.69	0.69	1.00	2.00
1.670	5.60E-03	2.57E-01	2.18E-02	1.955	1.670	8.12E-03	3.72E-01	2.18E-02	0.978	1.00	0.69	0.69	1.00	2.00

Table 3.33. AL80/40/2-ST80/40/2 0.20 Loma Prieta, Erzincan and San Salvador Input Energy Spectral Value and Their Ratio.

AL80/40/2-020LOMA PRIETA					ST80/40/2-020LOMA PRIETA					AL80/40/2-ST80/40/2-020 LOMA PRIETA				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	1.36E-05	3.60E-03	3.76E-03	1.690	0.159	3.92E-05	1.04E-02	3.76E-03	1.690	1.00	0.35	0.35	1.00	1.00
0.277	2.56E-04	1.09E-02	2.34E-02	1.690	0.277	7.42E-04	3.17E-02	2.34E-02	1.690	1.00	0.35	0.35	1.00	1.00
0.333	3.34E-04	1.49E-02	2.25E-02	1.725	0.333	2.06E-03	4.31E-02	4.78E-02	1.725	1.00	0.16	0.35	0.47	1.00
0.385	1.83E-03	1.99E-02	9.21E-02	1.725	0.385	5.40E-03	5.76E-02	9.38E-02	1.725	1.00	0.34	0.35	0.98	1.00
0.455	1.54E-03	2.55E-02	6.05E-02	1.775	0.455	4.55E-03	7.38E-02	6.16E-02	1.775	1.00	0.34	0.35	0.98	1.00
0.500	1.15E-03	2.95E-02	3.90E-02	1.800	0.500	3.34E-03	8.55E-02	3.91E-02	1.800	1.00	0.34	0.35	1.00	1.00
0.667	2.68E-04	5.29E-02	5.06E-03	1.795	0.667	7.76E-04	1.53E-01	5.06E-03	1.795	1.00	0.35	0.35	1.00	1.00
1.000	9.43E-04	9.42E-02	1.00E-02	1.940	1.000	6.87E-04	2.73E-01	2.51E-03	1.940	1.00	0.35	0.35	1.00	1.00
1.250	2.60E-03	1.47E-01	1.77E-02	1.940	1.250	7.53E-03	4.27E-01	1.76E-02	1.940	1.00	0.35	0.35	1.00	1.00
1.670	2.97E-03	2.57E-01	1.16E-02	1.955	1.670	8.59E-03	7.44E-01	1.15E-02	1.955	1.00	0.35	0.35	1.00	1.00
AL80/40/2-020ERZINCAN					ST80/40/2-020ERZINCAN					AL80/40/2-ST80/40/2 020ERZINCAN				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	1.36E-05	3.60E-03	3.76E-03	1.690	0.159	3.92E-05	1.04E-02	3.76E-03	1.690	1.00	0.35	0.35	1.00	1.00
0.277	2.56E-04	1.09E-02	2.34E-02	1.690	0.277	7.42E-04	3.17E-02	2.34E-02	1.690	1.00	0.35	0.35	1.00	1.00
0.333	6.89E-04	1.49E-02	4.63E-02	1.725	0.333	2.06E-03	4.31E-02	4.78E-02	1.725	1.00	0.33	0.35	0.97	1.00
0.385	1.07E-04	1.99E-02	5.39E-03	1.725	0.385	3.10E-04	5.76E-02	5.39E-03	1.725	1.00	0.34	0.35	1.00	1.00
0.455	2.00E-04	2.55E-02	7.85E-03	1.775	0.455	5.86E-04	7.38E-02	7.94E-03	1.775	1.00	0.34	0.35	0.99	1.00
0.500	7.02E-04	2.95E-02	2.38E-02	1.800	0.500	2.03E-03	8.55E-02	2.38E-02	1.800	1.00	0.35	0.35	1.00	1.00
0.667	6.34E-03	5.29E-02	1.20E-01	1.795	0.667	1.84E-02	1.53E-01	1.20E-01	1.795	1.00	0.35	0.35	1.00	1.00
1.000	5.66E-03	9.42E-02	6.01E-02	1.940	1.000	1.65E-02	2.73E-01	6.02E-02	1.940	1.00	0.34	0.35	1.00	1.00
1.250	7.36E-03	1.47E-01	5.00E-02	1.940	1.250	2.14E-02	4.27E-01	5.01E-02	1.940	1.00	0.34	0.35	1.00	1.00
1.670	1.10E-02	2.57E-01	4.29E-02	1.955	1.670	3.19E-02	7.44E-01	4.29E-02	1.955	1.00	0.35	0.35	1.00	1.00
AL80/40/2-020SAN SALVADOR					ST80/40/2-020SAN SALVADOR					AL80/40/2-ST80/40/2 020SAN SALVADOR				
T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	E _i /m(m ² /s ²)	L(m)	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
0.159	3.45E-05	3.60E-03	9.58E-03	1.690	0.159	9.98E-05	1.04E-02	9.56E-03	1.690	1.00	0.35	0.35	1.00	1.00
0.277	2.38E-04	1.09E-02	2.18E-02	1.690	0.277	6.91E-04	3.17E-02	2.18E-02	1.690	1.00	0.35	0.35	1.00	1.00
0.333	4.00E-04	1.49E-02	2.69E-02	1.725	0.333	1.18E-03	4.31E-02	2.74E-02	1.725	1.00	0.34	0.35	0.98	1.00
0.385	2.02E-04	1.99E-02	1.02E-02	1.725	0.385	6.02E-04	5.76E-02	1.05E-02	1.725	1.00	0.34	0.35	0.97	1.00
0.455	6.40E-04	2.55E-02	2.51E-02	1.775	0.455	1.93E-03	7.38E-02	2.62E-02	1.775	1.00	0.33	0.35	0.96	1.00
0.500	1.37E-03	2.95E-02	4.65E-02	1.800	0.500	3.96E-03	8.55E-02	4.63E-02	1.800	1.00	0.35	0.35	1.00	1.00
0.667	7.22E-03	5.29E-02	1.36E-01	1.795	0.667	2.09E-02	1.53E-01	1.36E-01	1.795	1.00	0.35	0.35	1.00	1.00
1.000	3.75E-03	9.42E-02	3.98E-02	1.940	1.000	1.09E-02	2.73E-01	4.00E-02	1.940	1.00	0.34	0.35	1.00	1.00
1.250	6.54E-03	1.47E-01	4.44E-02	1.940	1.250	1.90E-02	4.27E-01	4.45E-02	1.940	1.00	0.34	0.35	1.00	1.00
1.670	5.60E-03	2.57E-01	2.18E-02	1.955	1.670	1.62E-02	7.44E-01	2.18E-02	1.955	1.00	0.34	0.35	1.00	1.00

3.6.1. Dimensional Analysis Results for Input Energy Spectral Value of Numerical Modelling

The results of each defined cases for input energy ratio show that input energy ratio is equal to the mass ratio between specimens for same period under same ground motion record. Based on the dimensional analysis steps, spectral energy ratio between specimens is shown in Equation 3.34. In numerical analysis steps, since cross-sectional dimension ratio is equal to the length ratio between specimens (ie., $\lambda_b = \lambda_h = \lambda_L$) for between defined binary cases, moment of inertia scale factor was defined in Equation 3.8. The numerical analysis results show that mass ratio is equal to the calculated mass scale factor. Also, at the same period under the same ground motion record, spectral input energy ratio is equal to the mass ratio between specimens at defined each binary case. These results were plotted for each earthquake ground motion record in Figure 3.16-Figure 3.18 below. The Equation 3.34 can be written as;

$$\lambda_e = \lambda_m = \frac{\lambda_E \lambda_I}{\lambda_L^3} \lambda_T^2 \quad (3.34)$$

$$\lambda_e = \lambda_m = \lambda_E \lambda_L \lambda_T^2 \quad (3.35)$$

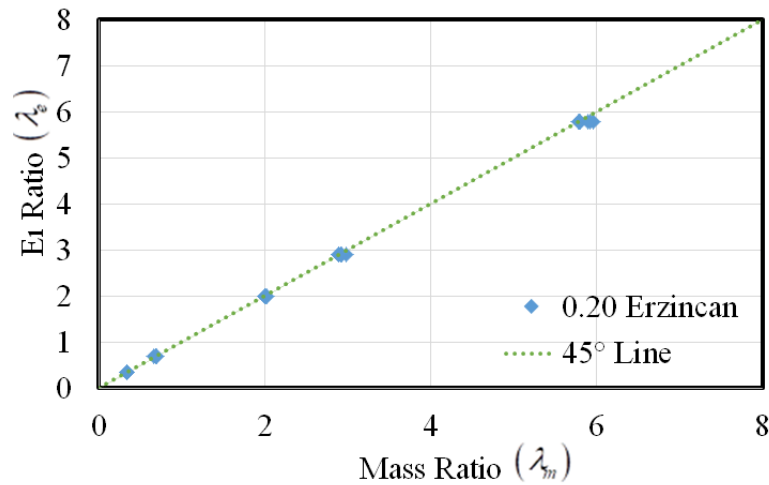


Figure 3.16. E₁ Ratio-Mass Ratio Relationship of the Specimens under 0.20 Erzincan Ground Motion Record in Elastic Range.

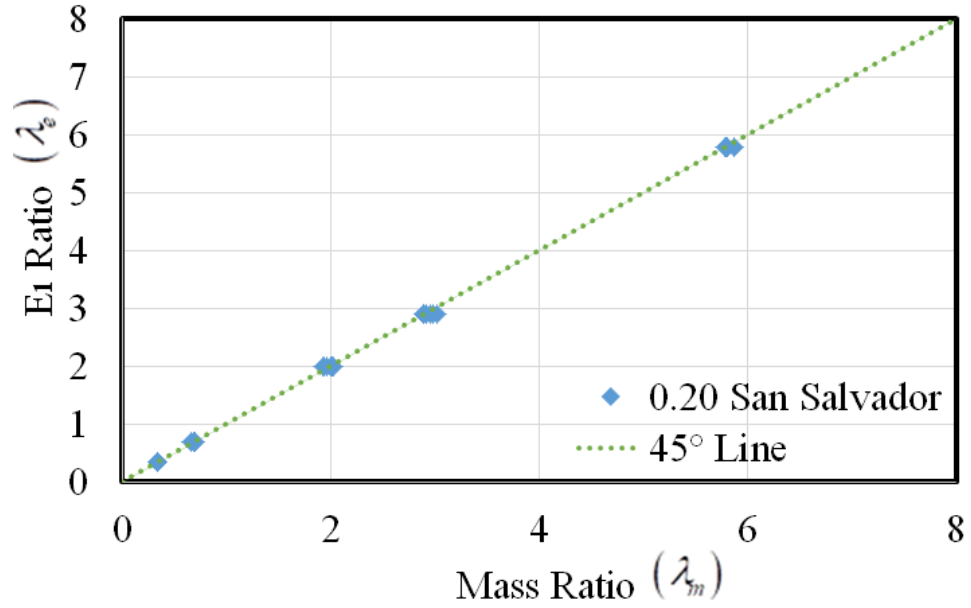


Figure 3.17. E_1 Ratio-Mass Ratio Relationship of the Specimens under 0.20 San Salvador Ground Motion Record in Elastic Range.

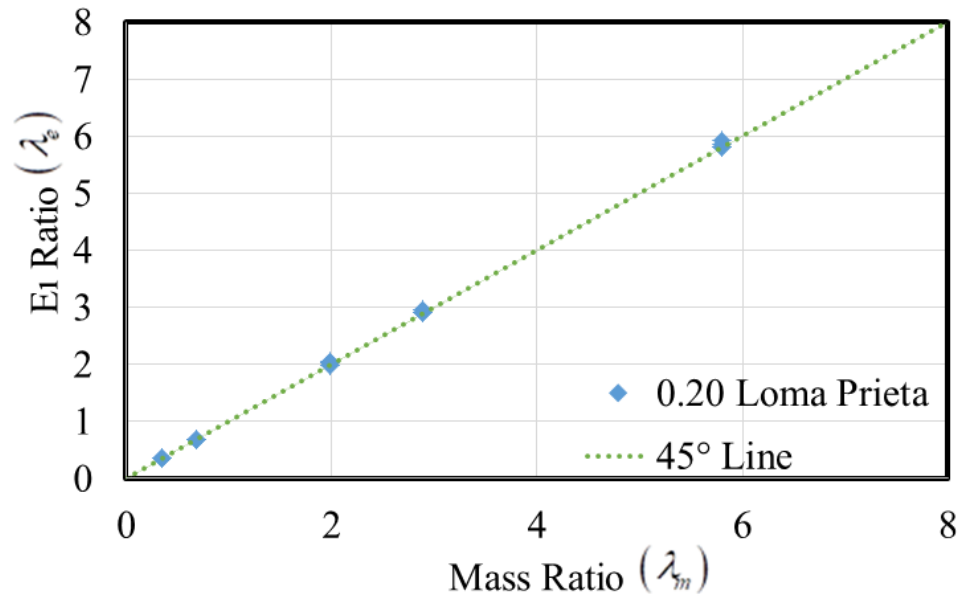


Figure 3.18. E_1 Ratio-Mass Ratio Relationship of the Specimens under 0.20 Loma Prieta Ground Motion Record in Elastic Range.

Figure 3.19-Figure 3.21 show the relationship between mass ratio-mass scale factor derived from dimensional analysis at the same period under same ground motion record.

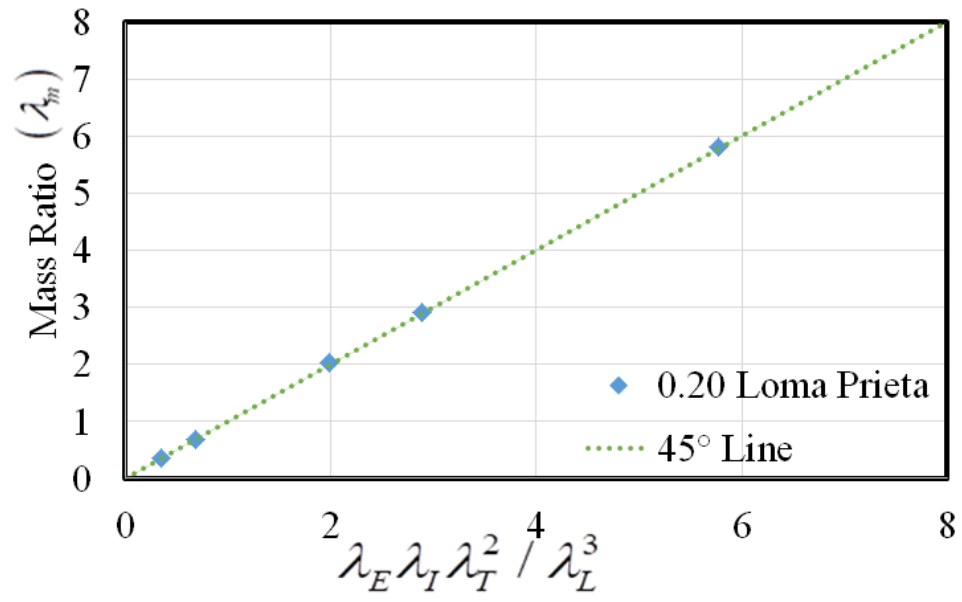


Figure 3.19. Mass Ratio-Mass Scale Relationship for 0.20 Loma Prieta Earthquake.

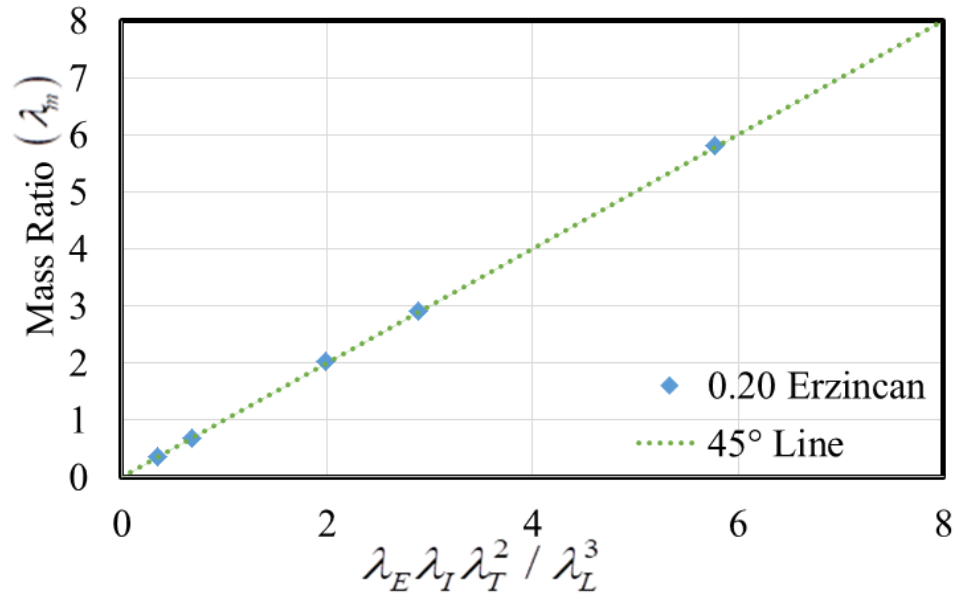


Figure 3.20. Mass Ratio-Mass Scale Relationship for 0.20 Erzincan Earthquake.

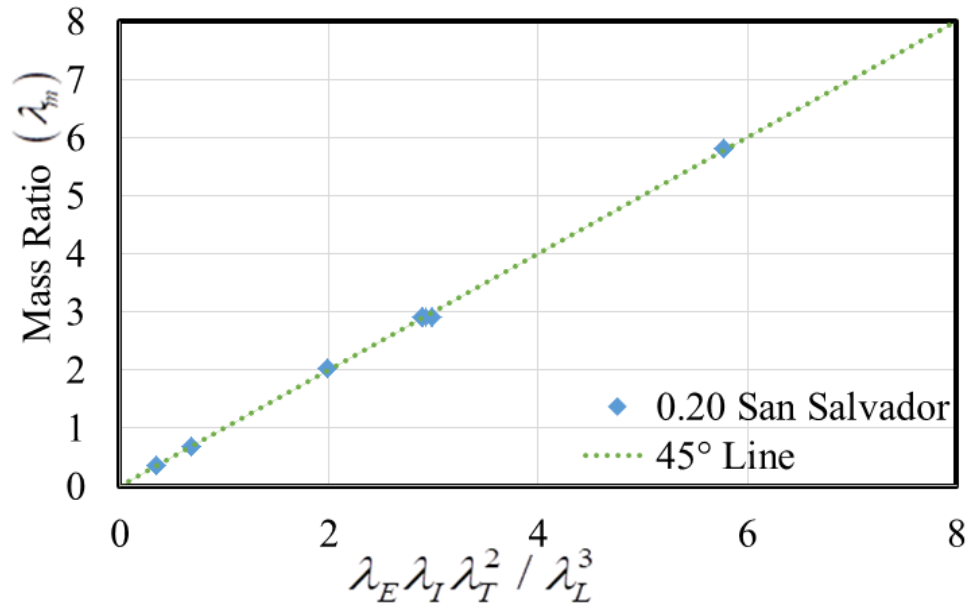


Figure 3.21. Mass Ratio-Mass Scale Relationship for 0.20 San Salvador Earthquake.

Energy ratios were calculated between specimens at different periods. Thus, in general, the energy scale formula should be as follows;

$$\lambda_e = \frac{\lambda_E \lambda_I}{\lambda_L^3} \lambda_T^N = \frac{\lambda_E \lambda_L^4}{\lambda_L^3} \lambda_T^N = \lambda_E \lambda_L \lambda_T^N \quad (3.36)$$

For each different earthquake ground motion record, different N value was calculated. Numerical model analysis results for the N value were shown in Table 3.34 for each earthquake.

Table 3.34. N Value for Recommended Formula for Each Earthquake.

Ground Motion Data	N value
0.20 Loma Prieta	0.50
0.20 r San Salvador	2.00
0.20 Erzincan Erzincan	0.47

Input Energy ratio for ach defined cases were plotted with recommended formula with calculated N values. Figures 29-31 show the relationship between input energy ratio and recommended formula.

These results show that there is no certain formula for energy scale factor between specimens for different periods. This analysis results were compared with energy spectra results in Section 3.6.2.

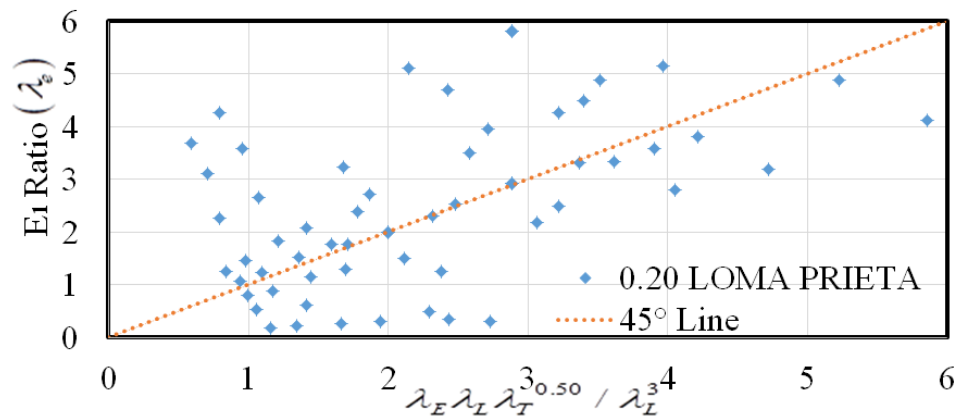


Figure 3.22. 0.20 Loma Prieta Energy Spectrum Analysis for Input Energy Ratio with Energy Scale Factor.

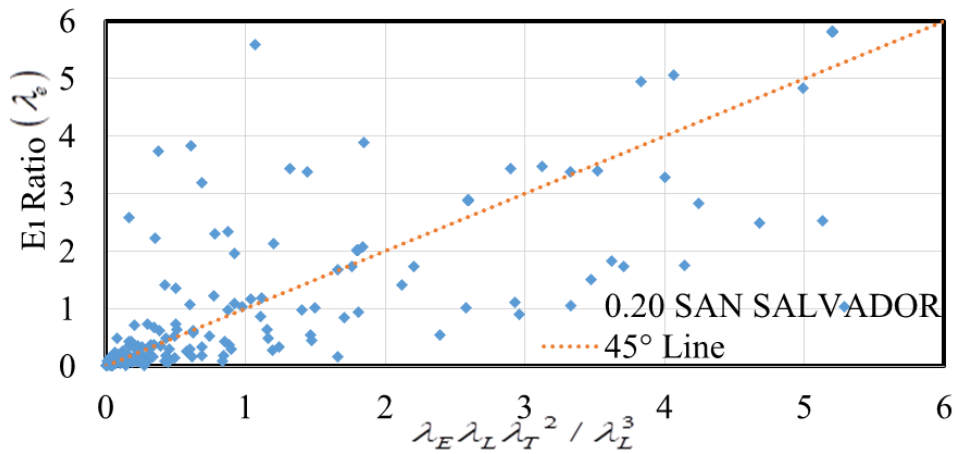


Figure 3.23. 0.20 San Salvador Energy Spectrum Analysis for Input Energy Ratio with Energy Scale Factor.

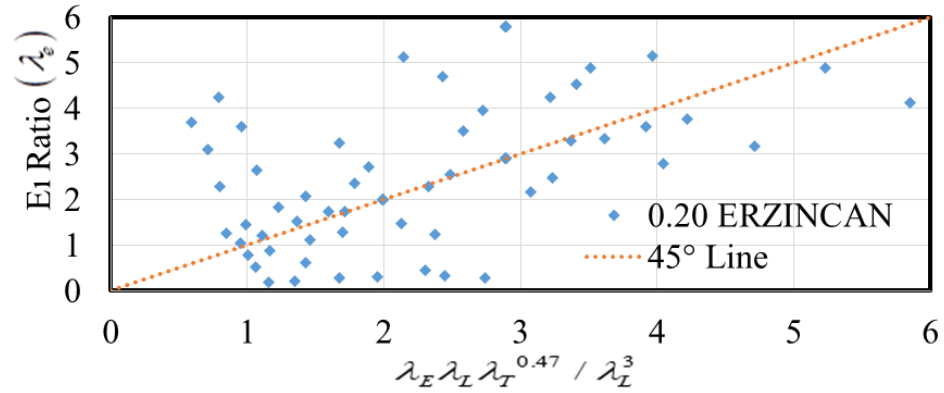


Figure 3.24. 0.20 Erzincan Energy Spectrum Analysis for Input Energy Ratio with Energy Scale Factor.

3.6.2. Dimensional Analysis Results for Input Energy Spectral Value of Input Energy Spectra Analysis

Spectral input energy ratio of each defined binary case was compared with mass ratio for the results of Dindar (2015) spectrum analysis in Figure 3.25-Figure 3.27.

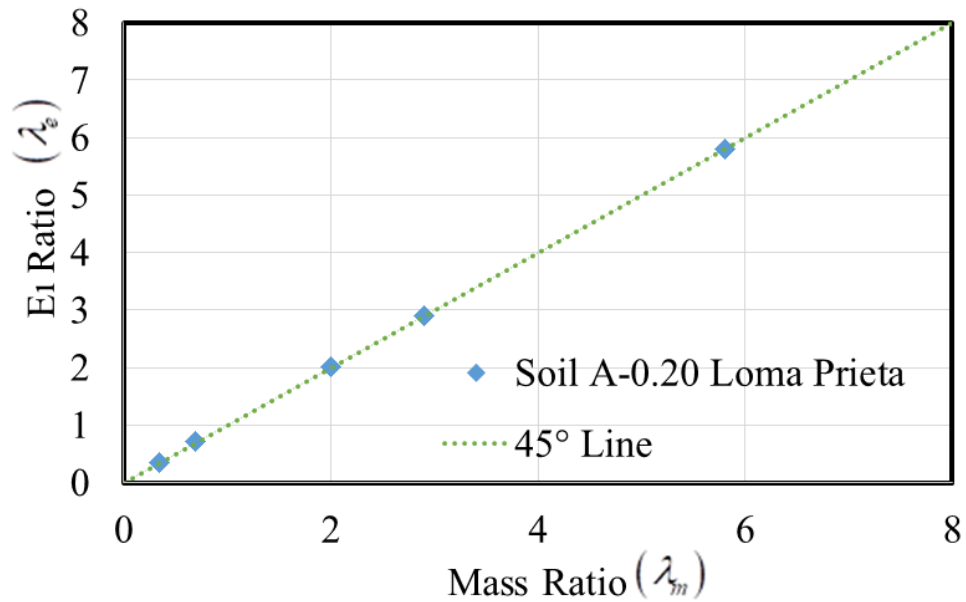


Figure 3.25. E_1 Ratio-Mass Ratio Relationship of the Specimens under 0.20 Loma Prieta Ground Motion Record in Elastic Range (Soil A Spectra Analysis).

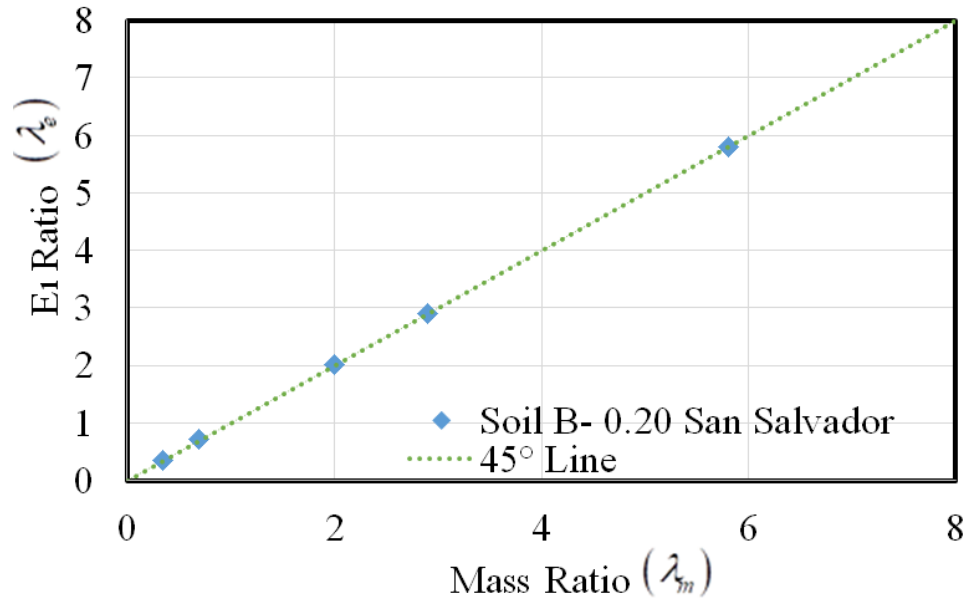


Figure 3.26. E_1 Ratio-Mass Ratio Relationship of the Specimens under 0.20 San Salvador Ground Motion Record in Elastic Range (Soil B Spectra Analysis).

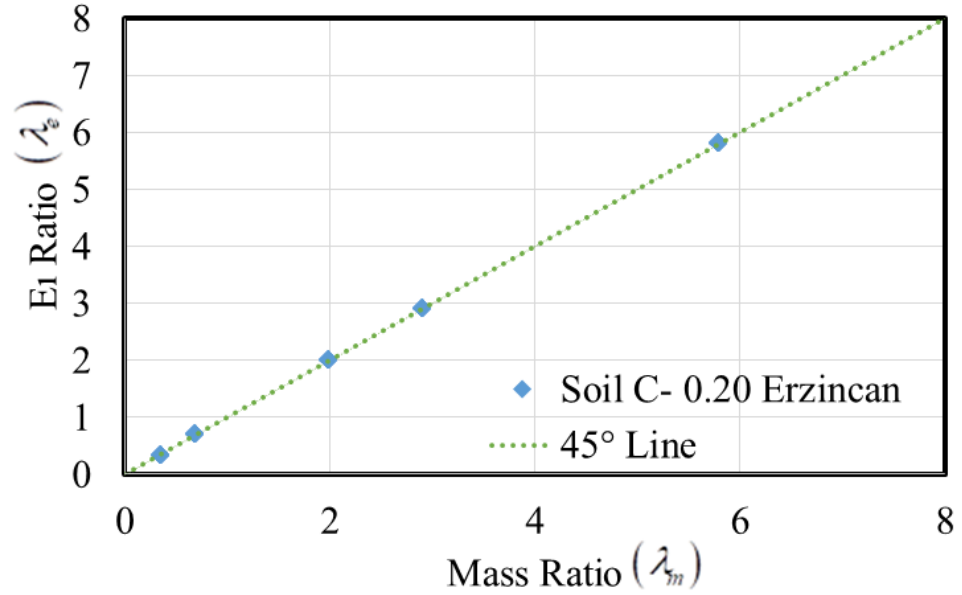


Figure 3.27. E_1 Ratio-Mass Ratio Relationship of the Specimens under 0.20 Erzincan Ground Motion Record in Elastic Range (Soil C Spectra Analysis).

These Figures show that input energy ratio is equal to the mass ratio between specimens for same period under same ground motion data. This case is defined in

Equation 3.37.

$$\frac{\lambda_e}{\lambda_m} = 1 \quad (3.37)$$

Equation 3.37 is correlated with only for the same period with same ground motion record. In other words, the mass ratio is a scale factor for the input energy for elastic case analysis with same period and same ground motion record.

Also, Equation 3.37 describes that mass normalized input energy ratio between each specimen at the same period with same ground motion record is equal to one. E_i/m is calculated from Equation 3.1 depends on the damping of the system, natural period of the structure, mass of the structure and equivalent velocity spectrum (Kuawamura, 1989).

Specimens at same period were analyzed with the same earthquake ground motion for all seven binary cases. So, the equivalent velocity was same at the same period. That is, mass-normalized input energy ratio is equal to one. That means spectral input energy ratio is equal to mass ratio between specimens at the same period for the same ground motion data in elastic range.

Spectral energy ratio analysis was performed between different periods of the specimens under same ground motion record. Analysis results shows that for each different period under same ground motion record, energy ratio scale formula can be represented as in Equation 3.36 derived from dimensional analysis steps.

For each earthquake ground motion record, different N value reached. Energy spectra model analysis results and numerical model results for N value are explained in Table 3.35 as;

Table 3.35. N Value for Recommended Formula.

Ground Motion Data	N value (Energy Spectrum)	N value (SAP2000 Model)
0.20 Loma Prieta (Soil A)	1.93	0.50
0.20 San Salvador (Soil B)	1.87	2.00
0.20 Erzincan (Soil C)	2.14	0.47

Figure 3.28-Figure 3.30 show the relationship between spectrain input energy ratio and energy scale facror formula with defined N values. These N values were varified with experimental study.

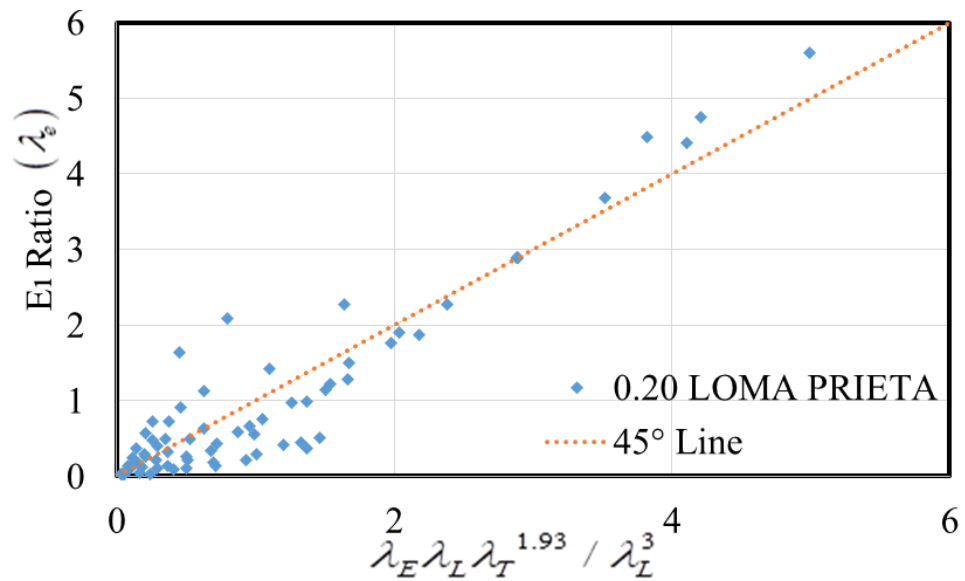


Figure 3.28. 0.20 Loma Prieta Energy Spectrum Analysis for Input Energy Ratio with Energy Scale Factor.

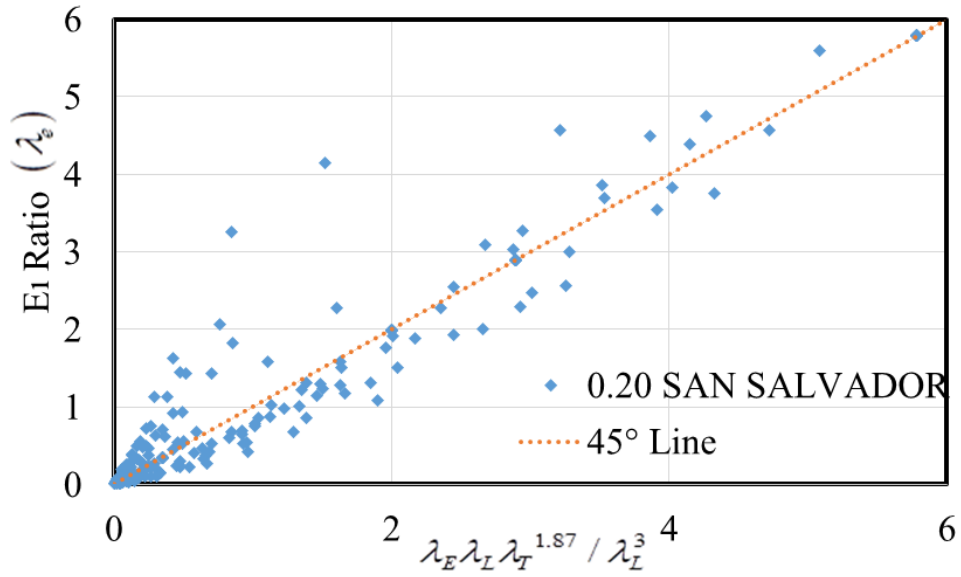


Figure 3.29. 0.20 San Salvador Energy Spectrum Analysis for Input Energy Ratio with Energy Scale Factor.

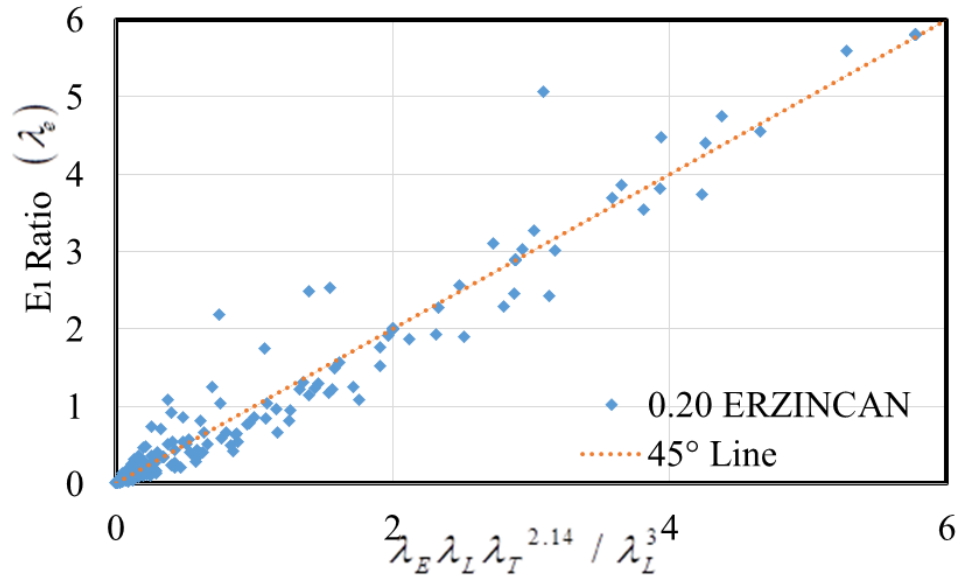


Figure 3.30. 0.20 Erzincan Energy Spectrum Analysis for Input Energy Ratio with Energy Scale Factor.

Spectral input energy ratio was plotted with derived energy scale factor from dimensional analysis case shown Equation 3.37. Since this energy scale factor contains displacement scale factor same as geometric scale factor, numerical analysis results for energy ratio do not correlate with the dimensional analysis formula for energy term.

Figure 3.31-Figure 3.33 show that there is no any the relationship between energy ratio and derived energy scale factor from dimensional analysis.

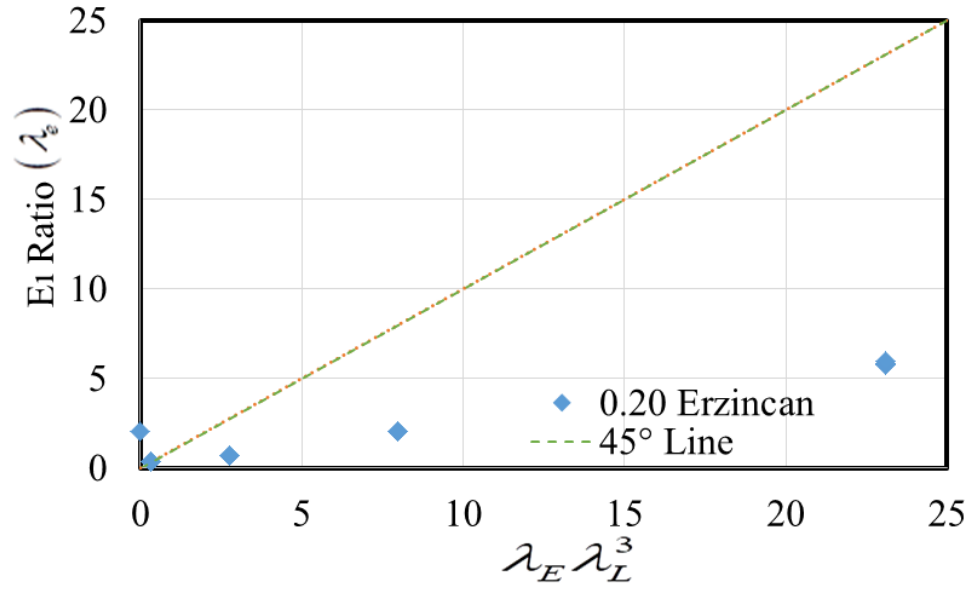


Figure 3.31. 0.20 Erzincan Input Energy Ratio-Derived Energy Scale Factor Analysis.

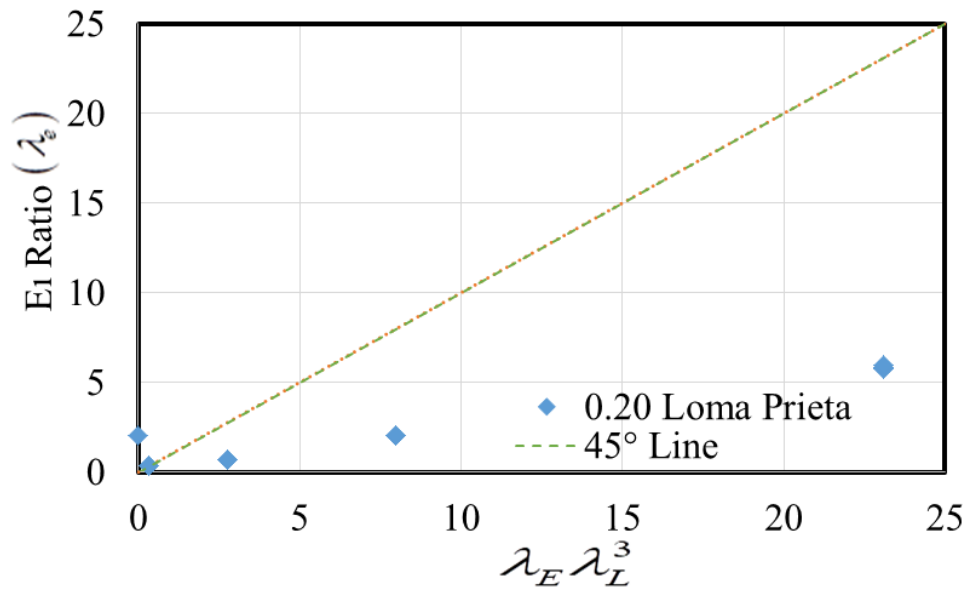


Figure 3.32. 0.20 Loma Prieta Input Energy Ratio-Derived Energy Scale Factor Analysis.

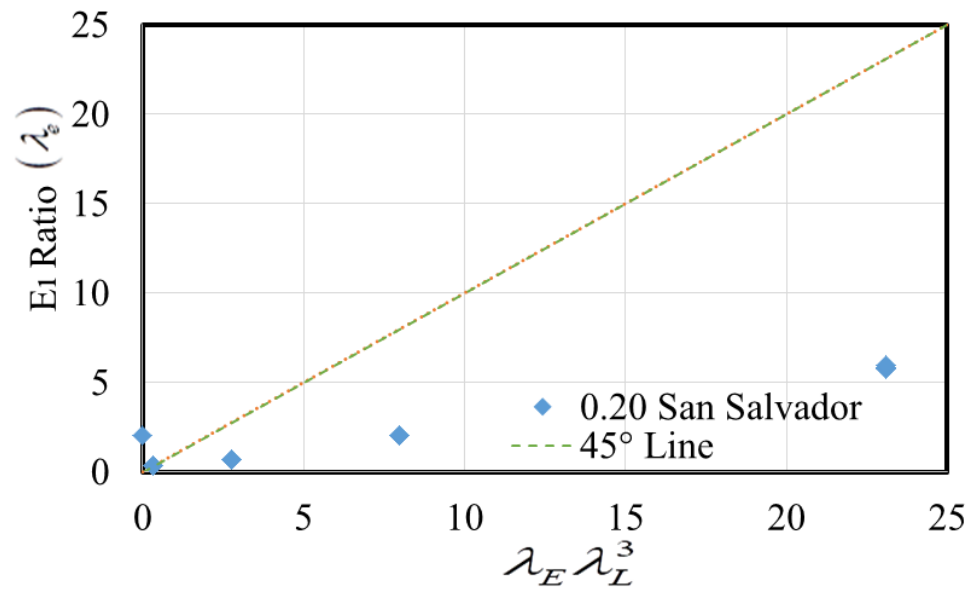


Figure 3.33. 0.20 San Salvador Input Energy Ratio-Derived Energy Scale Factor Analysis.

4. EXPERIMENTAL TEST

This part of thesis incorporates experimental study of the thesis. Thirty-six experiments were completed using San Salvador, Erzincan and Loma Prieta ground motion data with four different specimens as steel and aluminum cantilever hollow section columns. All experiments were fulfilled with three different periods. For each specimen at each experiment, analytical and experimental value of energy responses and dynamic responses were compared to find the result for energy scale factor successfully.

4.1. Experimental Study Set Up

Experimental study aims to verify the asserted energy scale factor by numerical results. Energy scale factor was analyzed between different size and different material specimen. Spectral input energy scale factor was calculated based on the period ratio, modulus of elasticity ratio and length ratio between used specimens. Test set up sketch is shown with Figure 4.1.

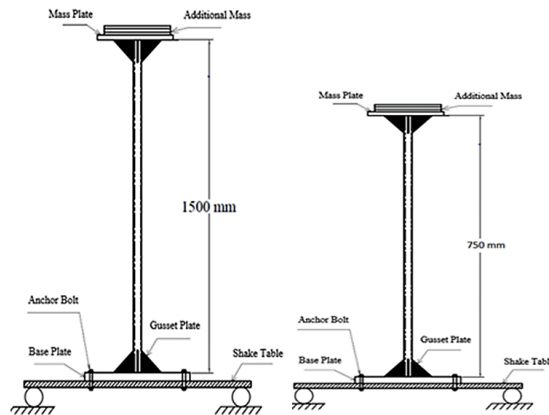


Figure 4.1. Test Set Up Sketch for Long and Short Specimen.

Four specimens were used during experimental study. Two of them 1,5 m height with 80/40/2 mm structural hollow section steel and aluminum column and two of them 0,75 m height with 40/20/1 mm structural hollow section steel and aluminum column.

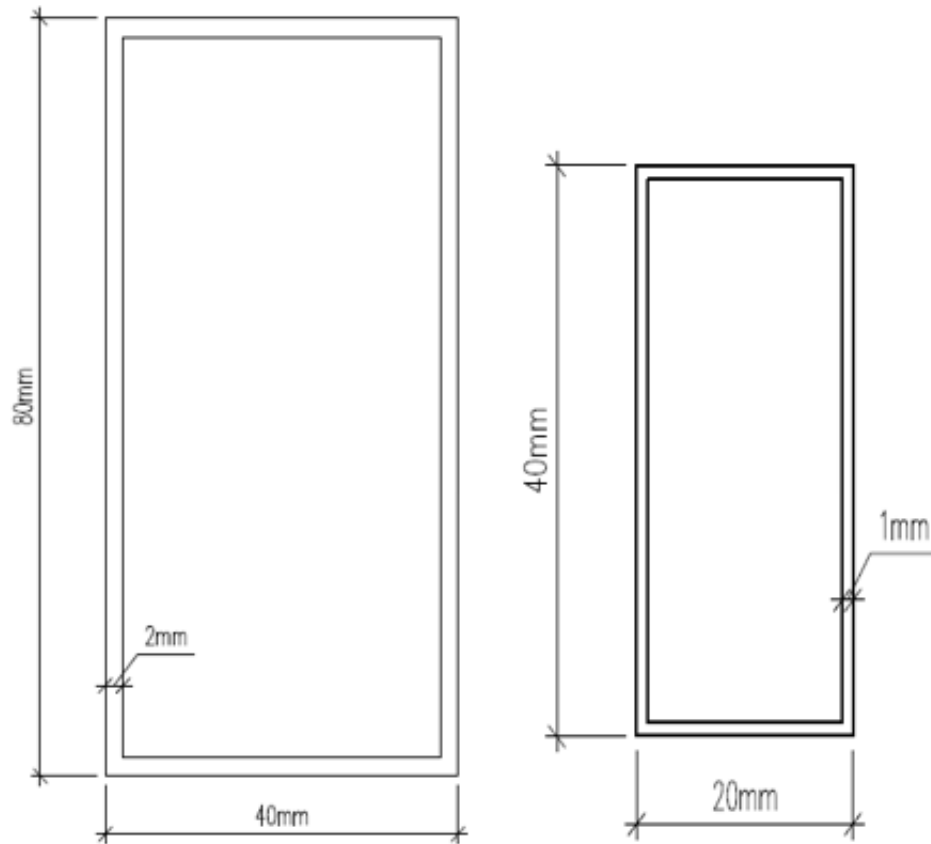


Figure 4.2. Strcutural Hollow Section 80/40/2 mm and 40/20/1 mm.

Used specimen material properties are listed in Table 4.1, E is the modulus of elasticity of the material, L is the length of the material, b is the width of the cross section of the specimen, h is the height of the cross section of the specimen and t is the thickness of the cross section of the specimen.

Table 4.1. Properties of the Specimens Material Properties.

Specimen	Material	$E(N/mm^2)$	$L(m)$	$b(m)$	$h(m)$	$t(m)$	Weight(kg)
AL80/40/2	Aluminum	69000	1.50	0.04	0.08	0.002	3.1
ST80/40/2	Steel	200000	1.50	0.04	0.08	0.002	9.0
AL40/20/1	Aluminum	69000	0.75	0.02	0.04	0.001	1.5
ST40/20/1	Steel	200000	0.75	0.02	0.04	0.001	4.5

Experimental study was performed with three different earthquake records. For each period, cantilever column specimen stiffness and inertia value calculated and shown in Table 4.2, Table 4.3 and Table 4.4 for each period.

Table 4.2. $T_1=0.500$ sec Specimen Properties.

$T_1=0.500$ SEC	Elasticity Modulus $E(N/mm^2)$	Height $L(m)$	Moment of Inertia $I (m^4)$	Initial Stiffness $k(N/m)$
ST80/40/2	200000	1.813	1.311E-07	13495
AL80/40/2	69000	1.751	1.311E-07	5058
ST40/20/1	200000	0.940	8.199E-09	5923

Table 4.3. $T_2=0.667$ sec Specimen Properties.

$T_2=0.667$ SEC	Elasticity Modulus $E(N/mm^2)$	Height $L(m)$	Moment of Inertia $I (m^4)$	Initial Stiffness $k(N/m)$
ST80/40/2	200000	1.795	1.311E-07	13609
AL80/40/2	69000	1.880	1.311E-07	4086
ST40/20/1	200000	0.990	8.199E-09	5062
AL40/20/1	69000	1.100	8.199E-09	1275

Table 4.4. $T_3=1.00$ sec Specimen Properties.

$T_3=1.00$ SEC	Elasticity Modulus $E(N/mm^2)$	Height $L(m)$	Moment of Inertia $I (m^4)$	Initial Stiffness $k(N/m)$
ST80/40/2	200000	1.970	1.311E-07	10295
AL80/40/2	69000	2.060	1.31E-07	3106
ST40/20/1	200000	1.125	8.199E-09	3455
AL40/20/1	69000	1.137	8.199E-09	1155

Due to laboratory limitations, AL40/20/1 specimen could not be tested at $T=0.500$ sec. Experiments were conducted in elastic range. Thus, earthquake ground motion records coefficient was taken as 0.20. Therefore, 0.20 San Salvador earthquake ground motion record, 0.20 Erzincan earthquake ground motion record and 0.20 Loma Prieta ground motion records were used in elastic range. Ground motion record properties used in experimental study are shown in Table 4.8.

Two accelerometers were used as sensors. One of them was placed on the top of the specimen, one of them was placed on the shake table. Specimen with sensor sketch is shown in Figure 4.3.

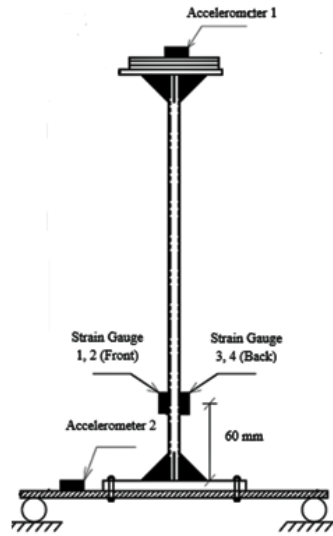


Figure 4.3. Specimen with Sensors.

Four strain gauges were used to measure the strain values. Two of them were placed at front face and two of them were placed at back face of each specimen as shown in Figure 44. By using strain value, displacement of the specimens were calculated using moment-curvature relationship including $P-\Delta$ effect. First derivative of the displacement gives the velocity response of the specimen and the second derivative of the displacement gives the acceleration response of the specimen. By using dynamic responses in the energy balance equation, energy terms of each specimen were calculated.



Figure 4.4. Strain gauges placement on the specimen.

This experimental study was performed on the shake table in Structural Laboratory of Istanbul Technical University. This shake table limitations are listed below as;

- Displacement capacity is 32.5 cm from the resting point.
- Velocity capacity is 100 cm/sec.
- Acceleration capacity is 2g.

4.2. Experimental Study Process

Before the experiments began, by generating free vibration with initial displacement on the specimen, accelerometer operation and strain gages measurements were controlled. With generated free vibration on specimens, period and frequency of the specimens were calculated. Frequency domain for each specimen was found as shown in Figure 4.5.

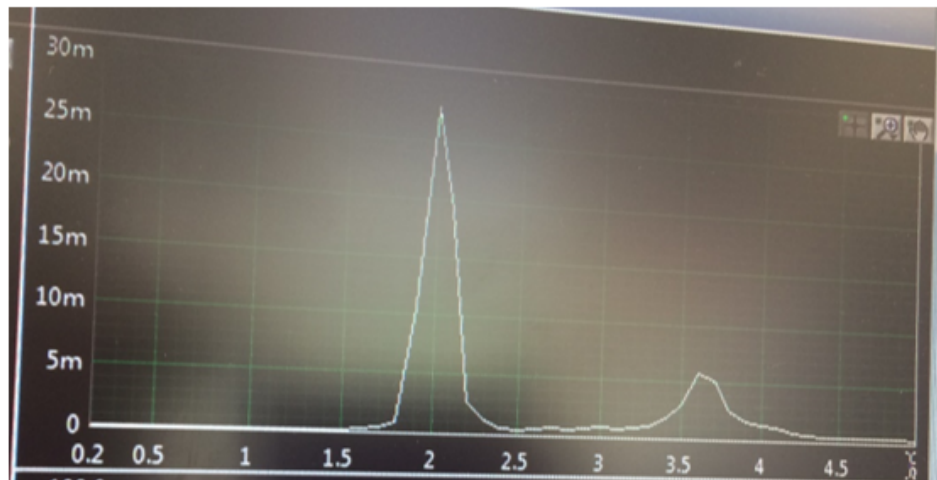


Figure 4.5. Frequency Control Mechanism.

The experimentally-obtained frequency values were used to determine the damping ratio of the specimens. Damping is calculated from logarithmic decrement relationship, as shown in Figure 4.6.

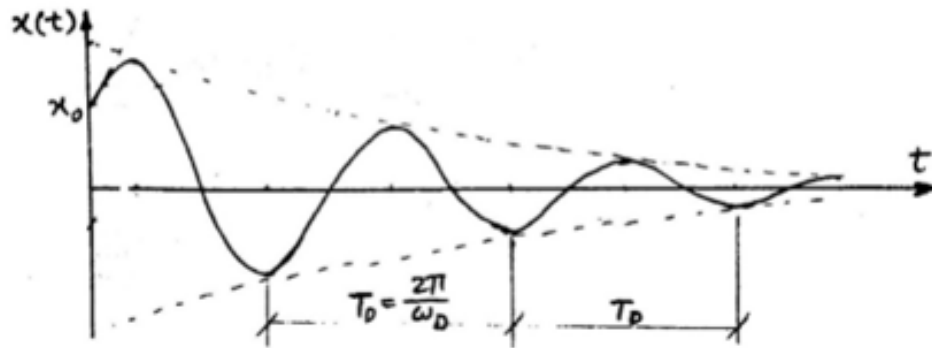


Figure 4.6. Calculation of the Damping Ratio from Logarithmic Curve (Terenzi, 1999).

$$\varepsilon = \frac{1}{2\pi n} \ln \left(\frac{x(t)}{x(t + nT_D)} \right) \quad (4.1)$$

Here, T_D is the period of damped system and n is the number of cycles. Steel and aluminum specimens' damping ratios were calculated accordingly. Figure 4.5-Figure 4.8 show the damping of the specimens for each period. After completion of control of the sensors and definition properties of the specimen, ground motion records were applied on each specimen.

Table 4.5. ST80/40/2 Damping Ratio for Each Period.

ST80/40/2 Experimental Damping Ratio			
	T1=0.500 sec	T2=0.667 sec	T3=1.000 sec
0.20 Loma Prieta	0.004	0.001	0.001
0.20 San Salvador	0.004	0.006	0.045
0.20 Erzincan	0.001	0.006	0.045

Table 4.6. ST40/20/1 Damping Ratio for Each Period.

ST40/20/1 Experimental Damping Ratio			
	T1=0.500 sec	T2=0.667 sec	T3=1.000 sec
0.20 Loma Prieta	0.004	0.001	0.003
0.20 San Salvador	0.004	0.006	0.003
0.20 Erzincan	0.006	0.006	0.045

Table 4.7. AL80/40/2 Damping Ratio for Each Period.

AL80/40/2 Experimental Damping Ratio			
	T1=0.500 sec	T2=0.667 sec	T3=1.000 sec
0.20 Loma Prieta	0.001	0.001	0.006
0.20 San Salvador	0.003	0.005	0.01
0.20 Erzincan	0.003	0.005	0.005

Table 4.8. AL40/20/1 Damping Ratio for Each Period.

AL40/20/1 Experimental Damping Ratio			
	T1=0.500 sec	T2=0.667 sec	T3=1.000 sec
0.20 Loma Prieta	NA	0.001	0.001
0.20 San Salvador	NA	0.006	0.005
0.20 Erzincan	NA	0.01	0.01

Experiments began with tall steel specimen having 80/40/2 mm structural hollow section, which is named as ST80/40/2. This specimen location was determined on the shake table and this specimen was assembled with bolts on the shake table. For the selected each period, mass was calculated and mass was placed on top of the specimen.

Experiments were performed for three different periods. To obtain the right period value of the specimen, masses were added to specimens. Period of the specimens were adjusted on the specimen by these additional masses. Height of these masses

changes the effective length of the specimen. Cantilever length of the specimen was evaluated from middle of the strain gauges to middle of the additional mass. Thus, experimental length of each specimen is different than analytical part of the study. Also, small dimension of the specimens are sensitive and PDelta effect is important to calculate the responses of the specimen.

Thus, P-Delta effect was included to the energy response during numerical analyses. Experimental study diagram was shown in Figure 4.7.

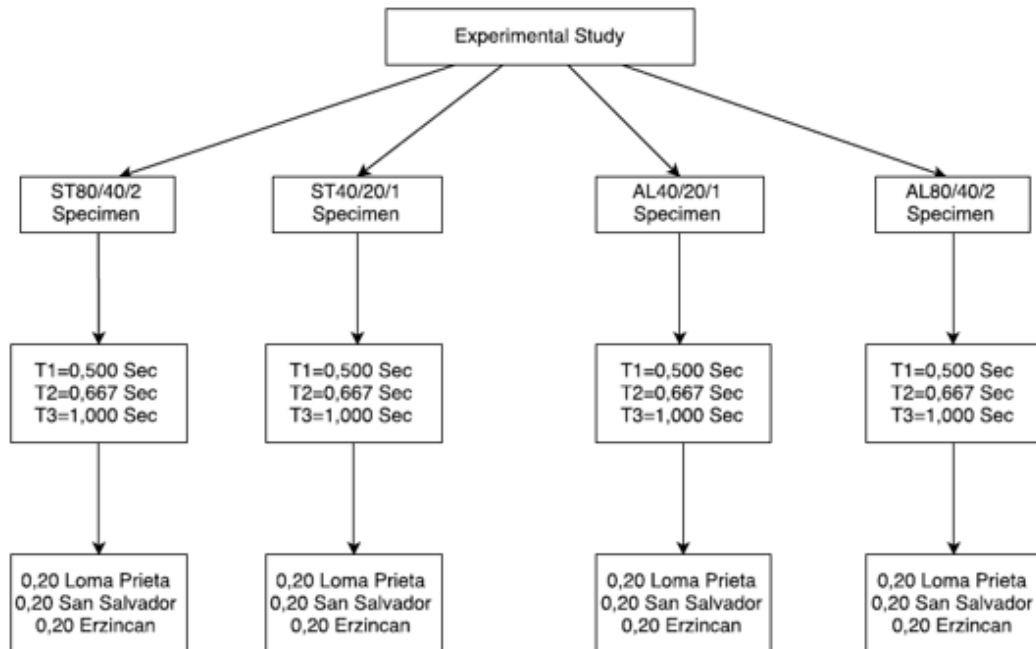


Figure 4.7. Experimental Study Concept Diagram.

After the responses of the specimens, strain gauges values, input energy, kinetic energy, damping energy and strain energy data were calculated. Experimental set ups and frequency checks for each specimen are shown in Figure 4.8-Figure 4.11.

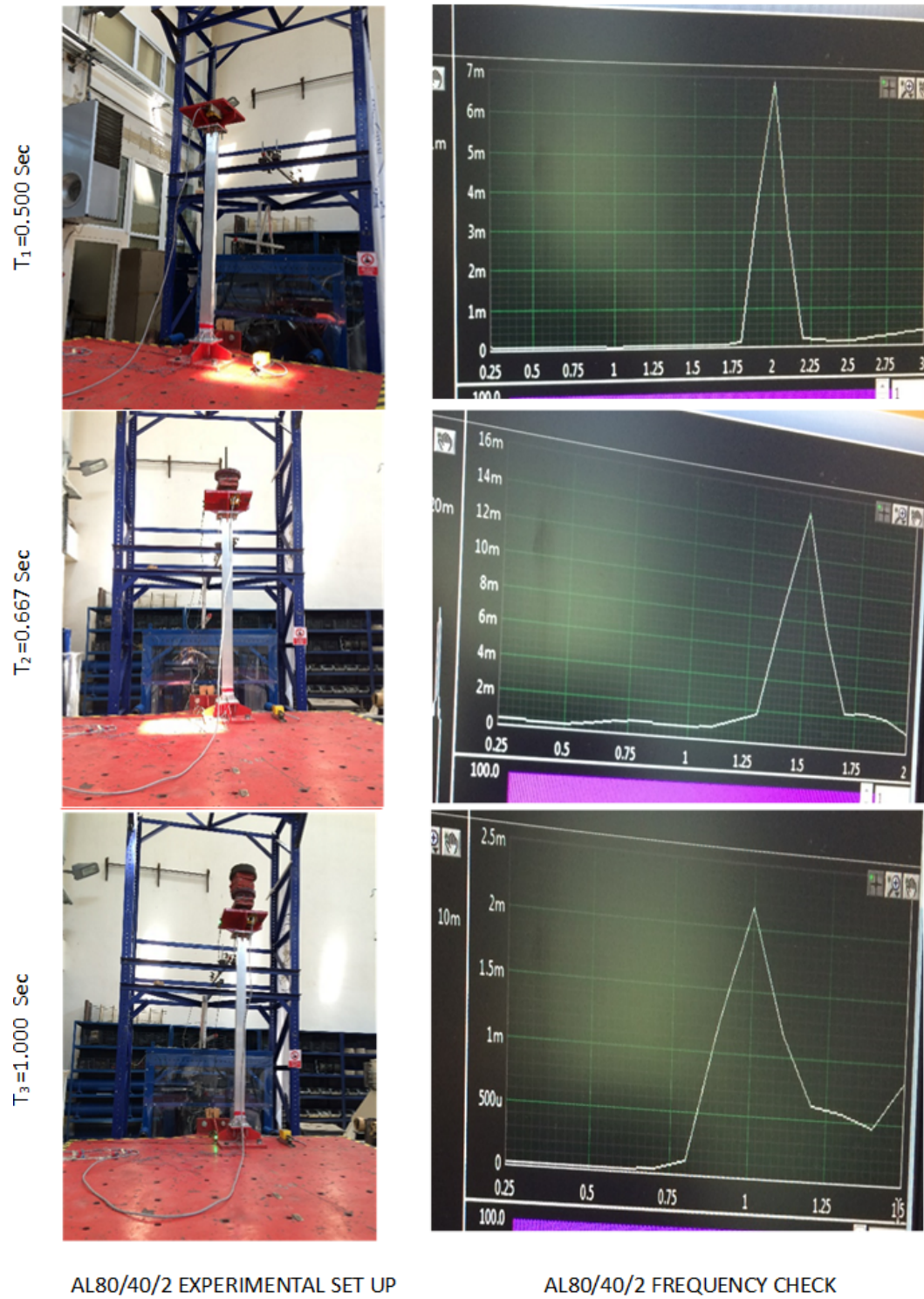


Figure 4.8. Experimental Study Concept AL80/40/2.

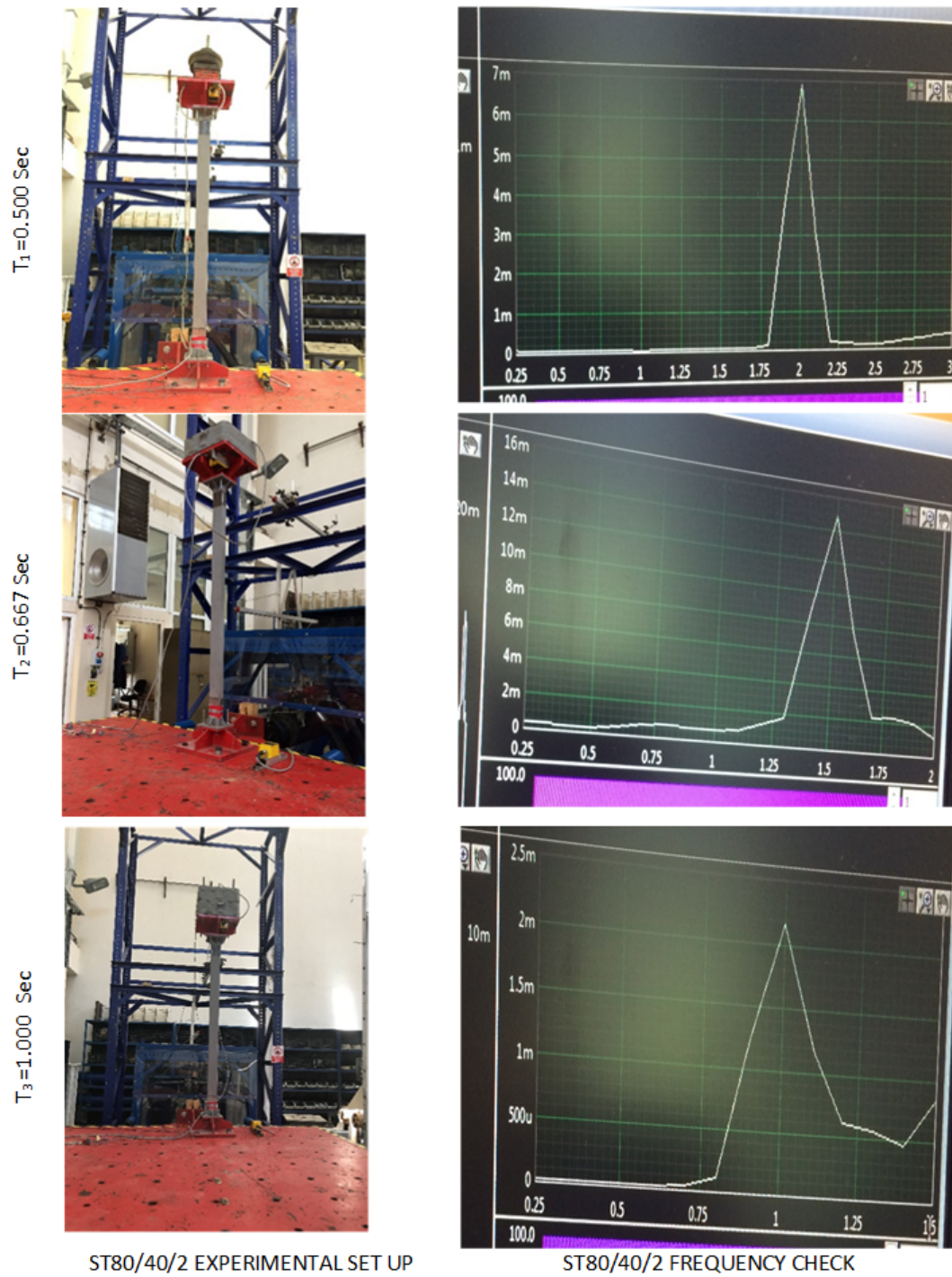


Figure 4.9. Experimental Study ST80/40/2.

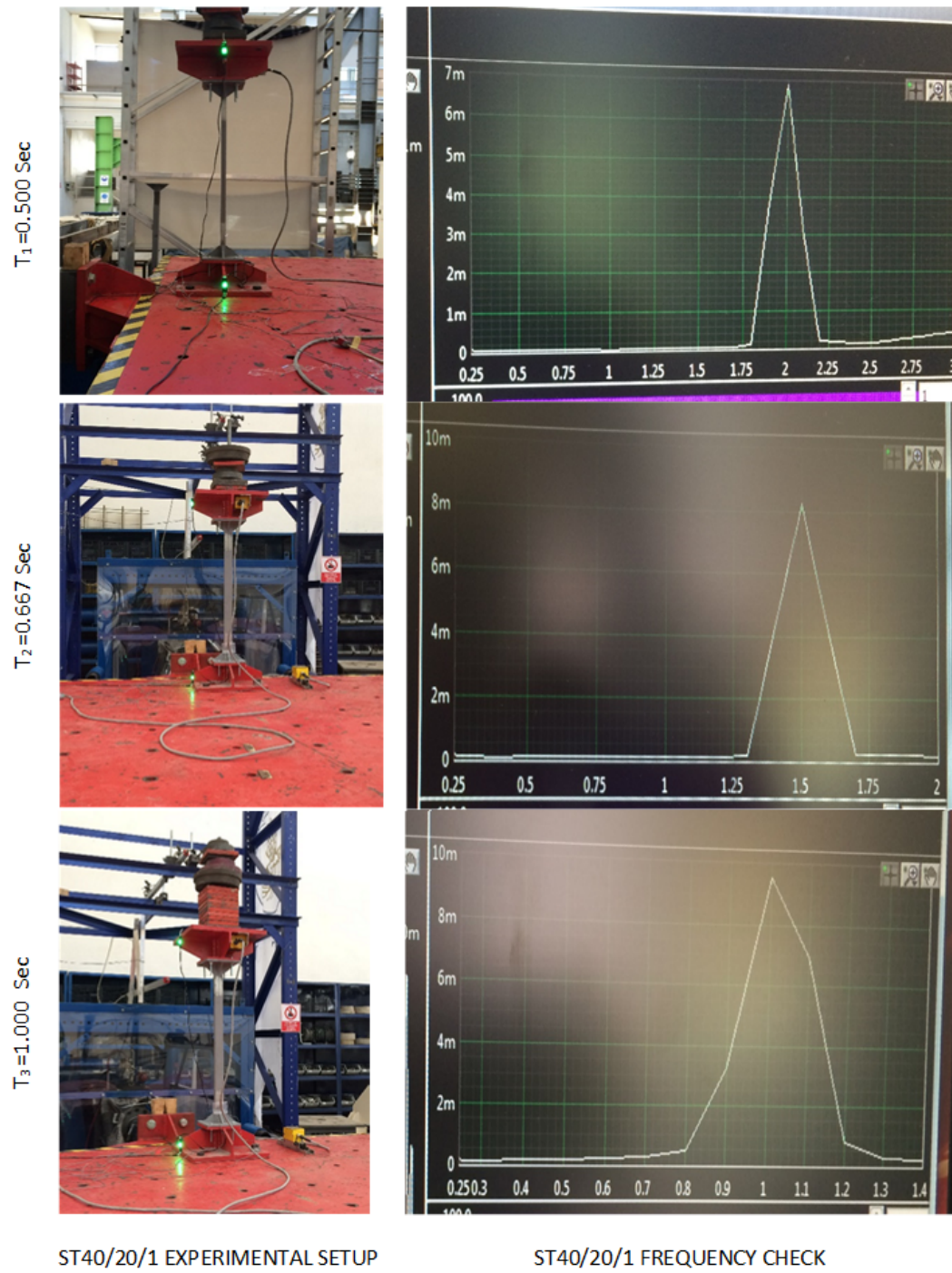


Figure 4.10. Experimental Study ST40/20/1.

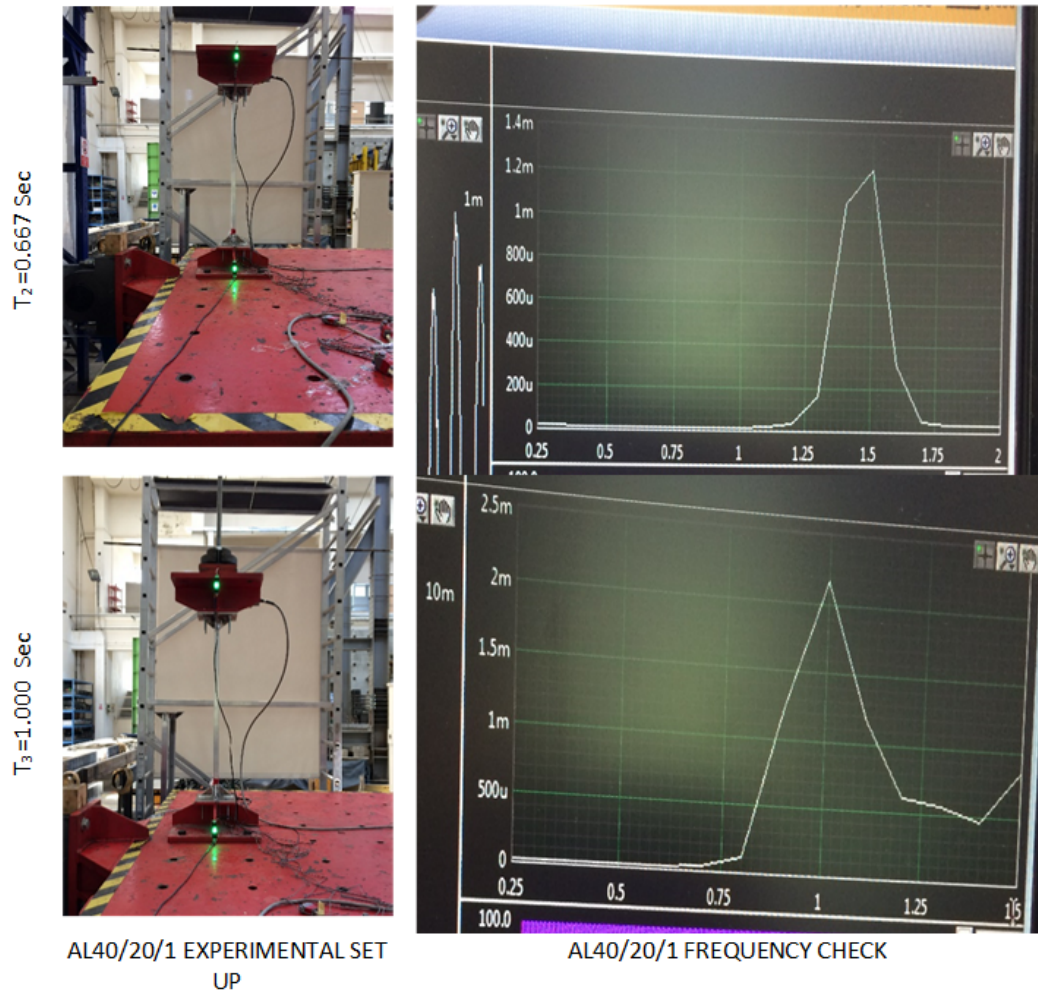


Figure 4.11. Experimental Study AL40/20/1.

4.3. Data Obtained from Each Experiment

For the data acquisition from experimental study, low pass filter was used. Experimental data was filtered with frequency lower than 15 Hz. Experimental data processing steps were shown in Figure 4.12. After experiments were completed, strain gauges data from front and back sensors were collected. Average of the front strain gauges data were used as front strain value, average of the back-strain gauges data was used as back strain value of each specimen. By using these strain data, moment curvature analysis was performed and displacement of the specimen was obtained. The first derivative of the displacement gives the velocity of the specimen. The second derivative of the displacement gives acceleration of the specimen. By using these responses,

energy terms of the specimen in Equation 2.9 were calculated.

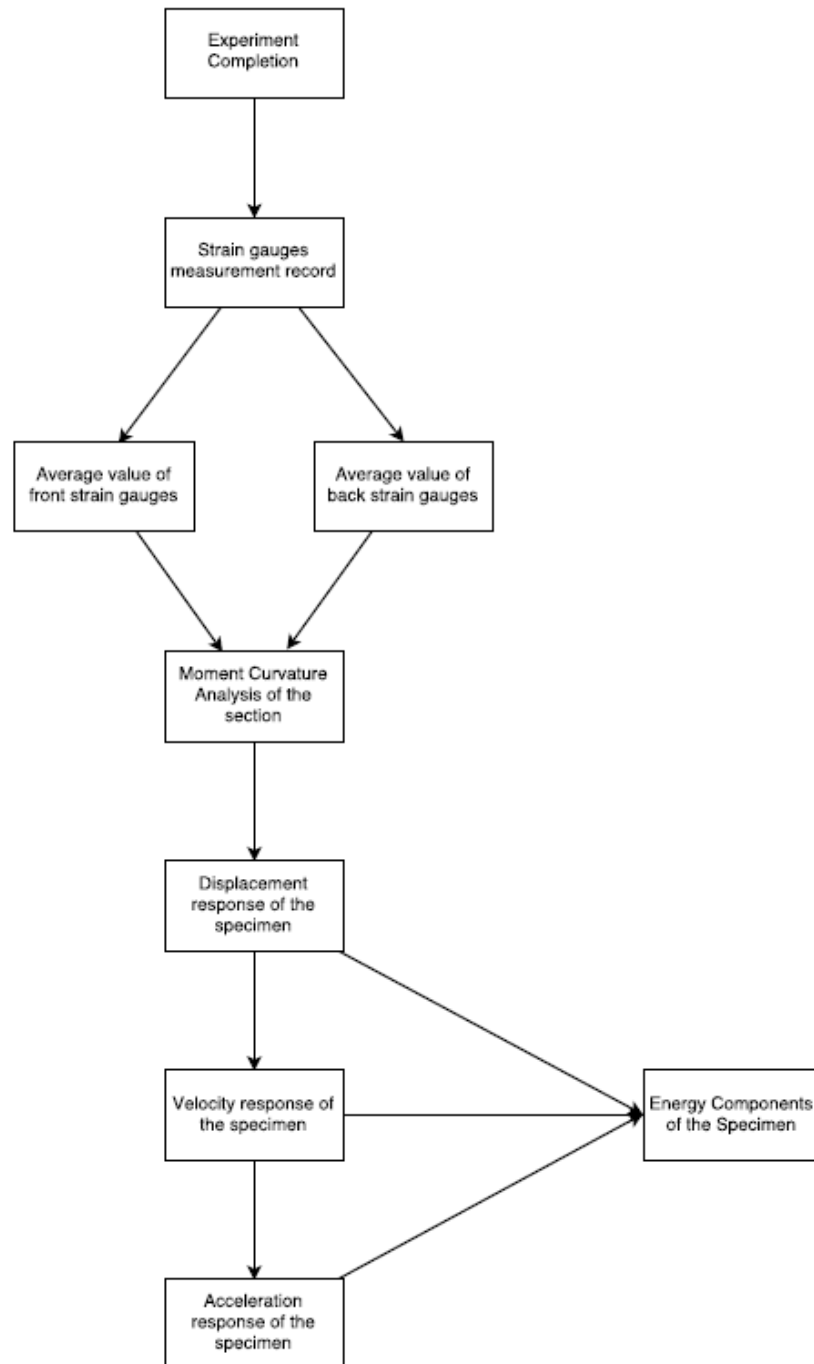


Figure 4.12. Experimental Data Processing to Calculate Energy Terms.

4.3.1. ST80/40/2 Experimental Results for Responses

Relative acceleration, relative velocity and relative displacement values in time for 1.50 m height with 80/40/2 mm structural hollow section steel were plotted in Figure 4.13-Figure 4.15 respectively.

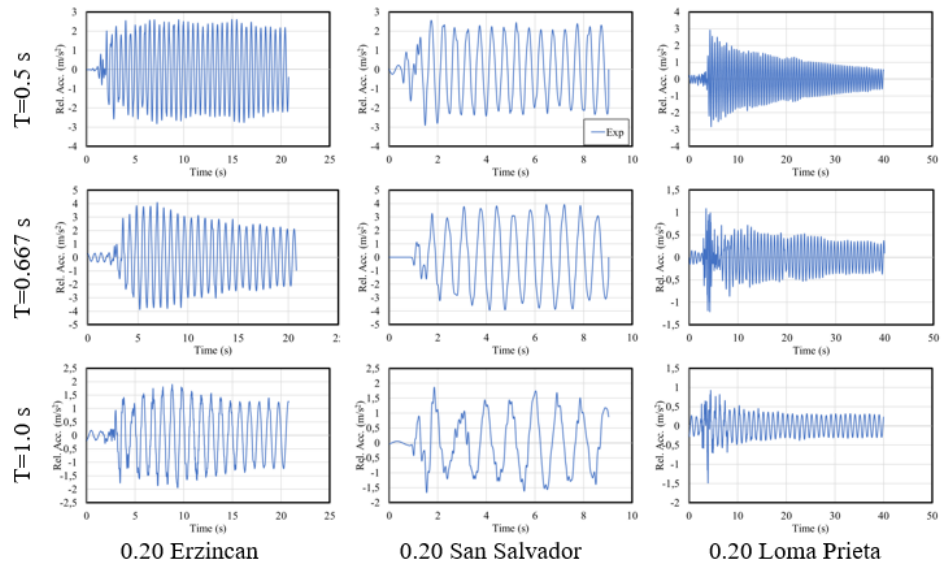


Figure 4.13. ST 80/40/2 Rectangular hollow section Relative Acceleration-Time Figure.

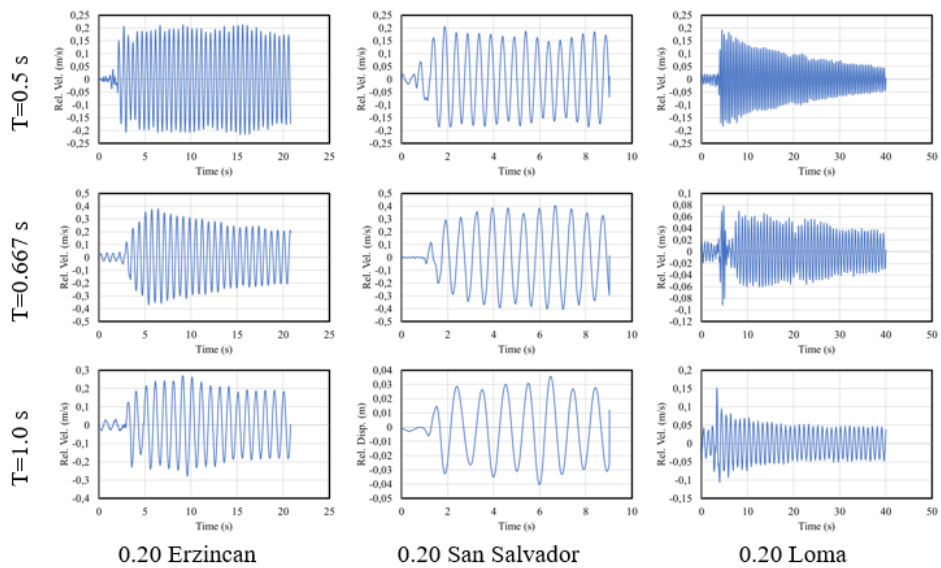


Figure 4.14. ST 80/40/2 Rectangular hollow section Relative Velocity-Time Figure.

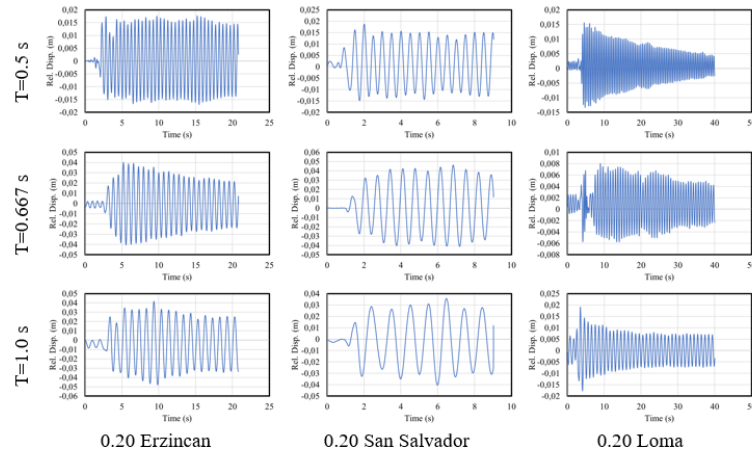


Figure 4.15. ST 80/40/2 Rectangular hollow section Relative Displacement -Time Figure.

4.3.2. ST40/20/1 Experimental Results for Responses

Relative acceleration, relative velocity and relative displacement values in time for 0.75 m height with 40/20/1 mm structural hollow section steel were plotted in Figure 4.16-Figure 4.18 respectively.

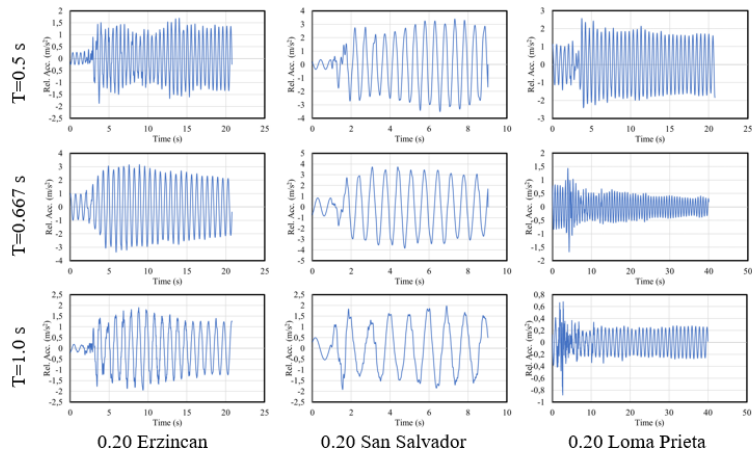


Figure 4.16. ST 40/20/1 Rectangular hollow section Relative Acceleration -Time Figure.

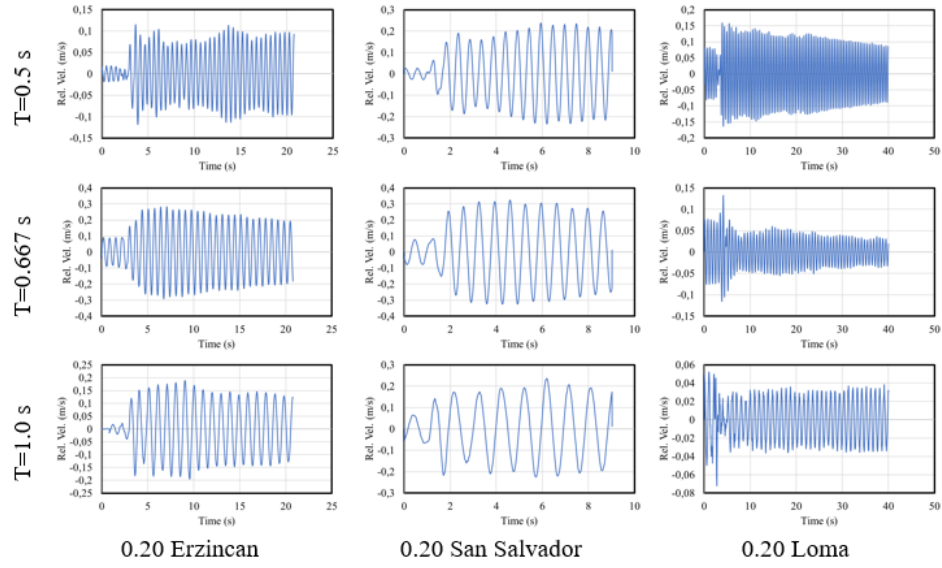


Figure 4.17. ST40/20/1 Rectangular hollow section Relative Velocity-Time Figure.

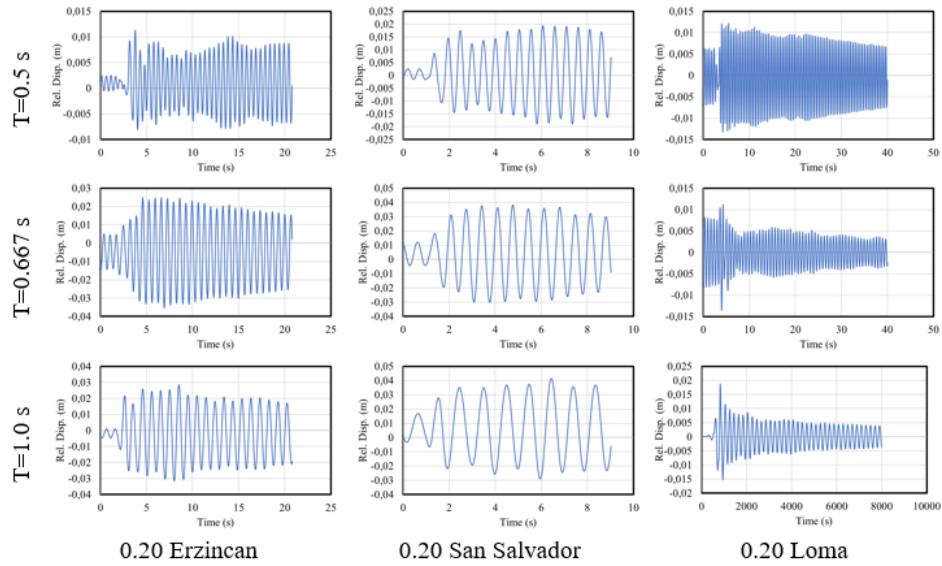


Figure 4.18. ST40/20/1 Rectangular hollow section Relative Displacement-Time Figure.

4.3.3. AL80/40/2 Experimental Results for Responses

Relative acceleration, relative velocity and relative displacement values in time for 1.50 m height with 80/40/2 mm structural hollow section aluminum specimen were plotted in Figure 4.19-Figure 4.21 respectively.

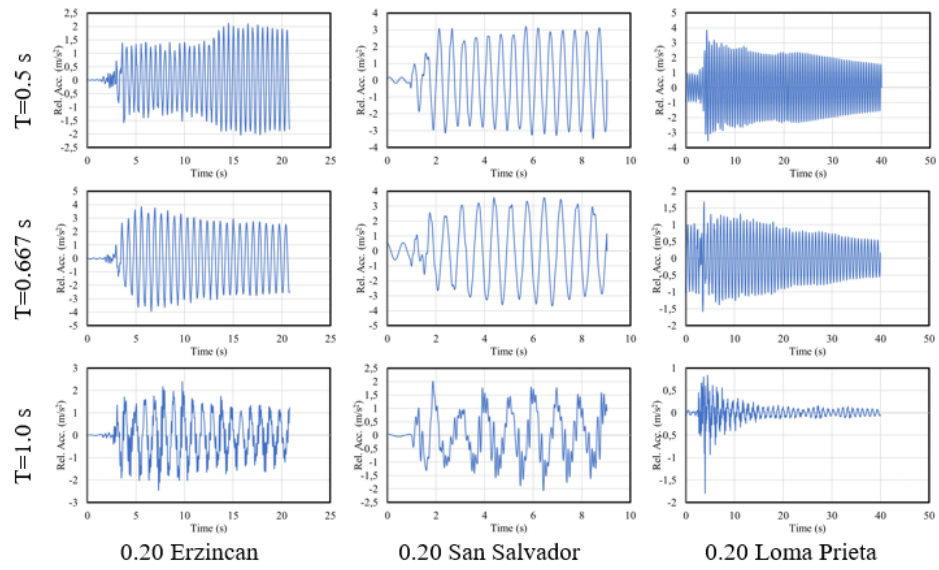


Figure 4.19. AL80/40/2 Rectangular hollow section Relative Acceleration-Time Figure.

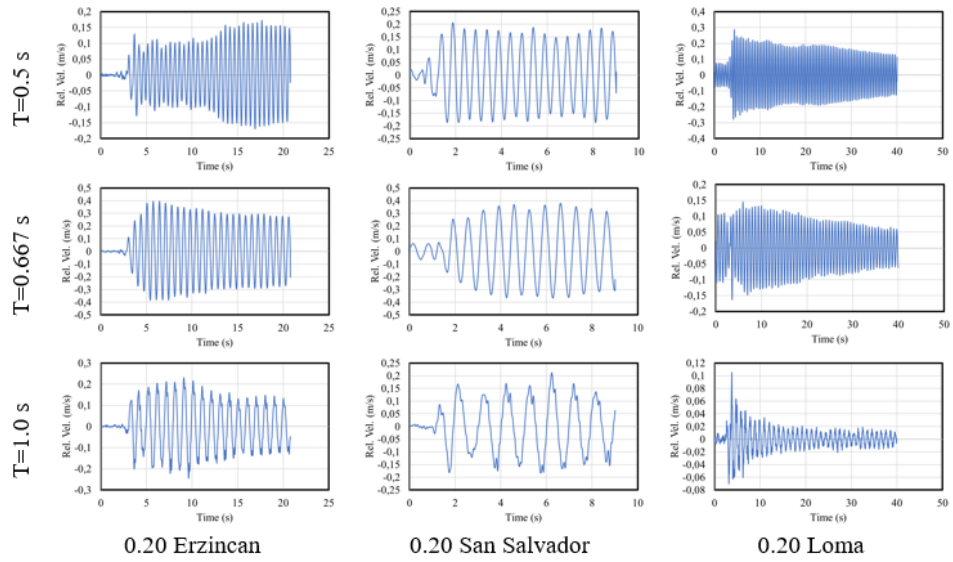


Figure 4.20. AL80/40/2 Rectangular hollow section Relative Velocity-Time Figure.

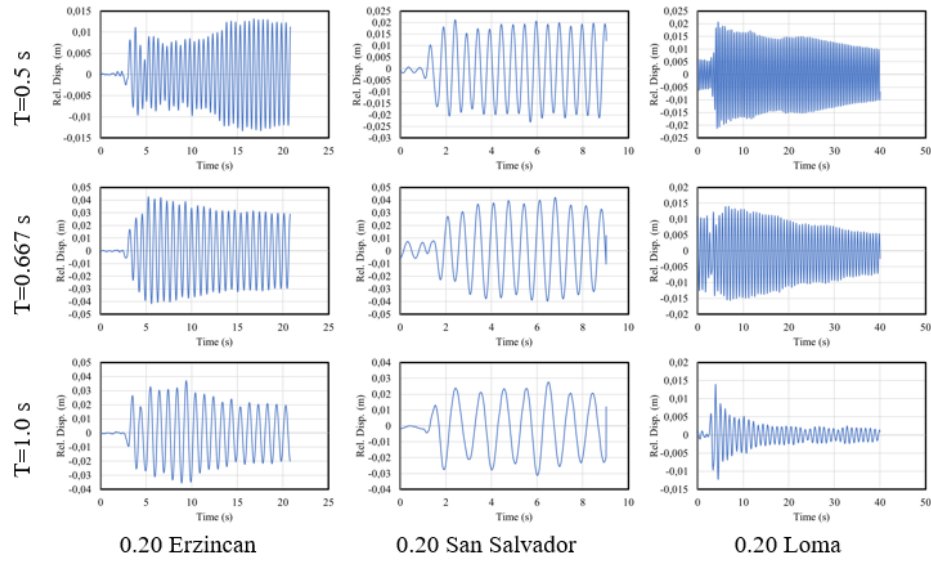


Figure 4.21. AL80/40/2 Rectangular hollow section Relative Displacement-Time Figure.

4.3.4. AL40/20/1 Experimental Results for Responses

Relative acceleration, relative velocity and relative displacement values in time for 0.75 m height with 40/20/1 mm structural hollow section aluminum specimen were plotted in Figure 4.22-Figure 4.24 respectively.

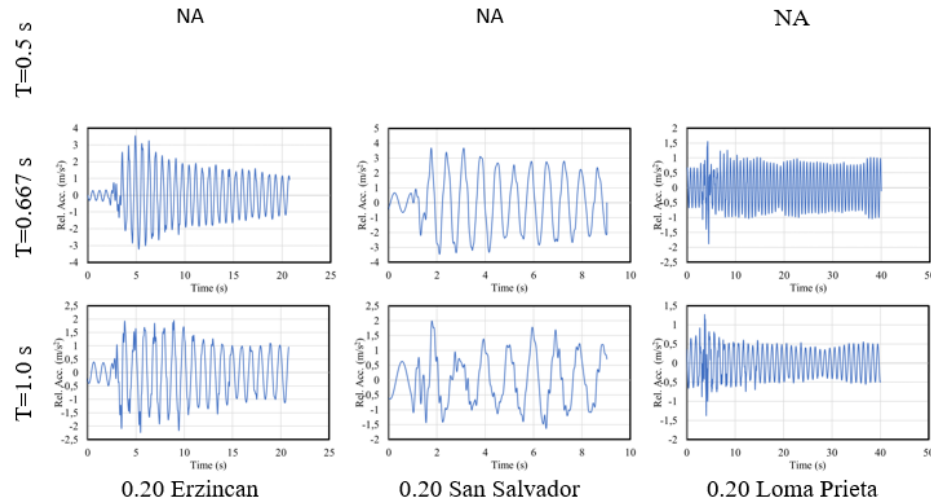


Figure 4.22. AL40/20/1 Rectangular hollow section Relative Acceleration-Time Figure.

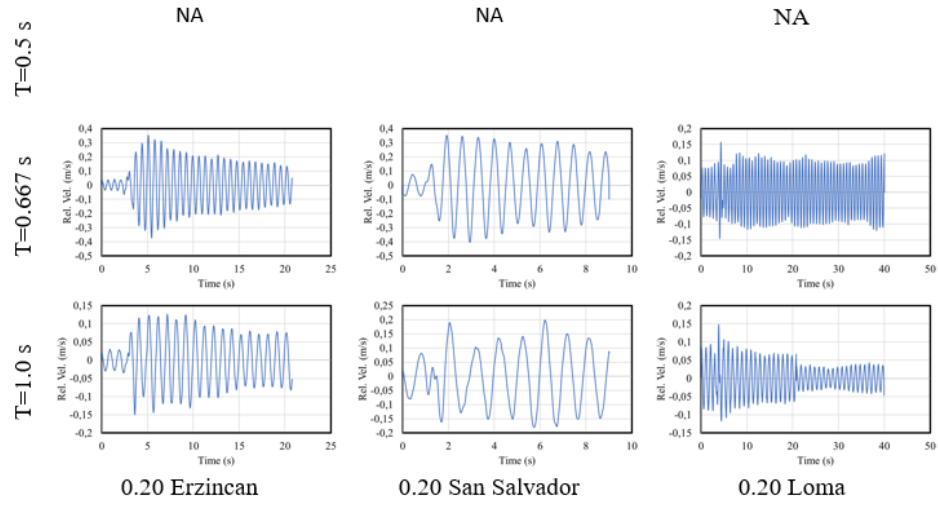


Figure 4.23. AL40/20/1 Rectangular hollow section Relative Velocity-Time Figure.

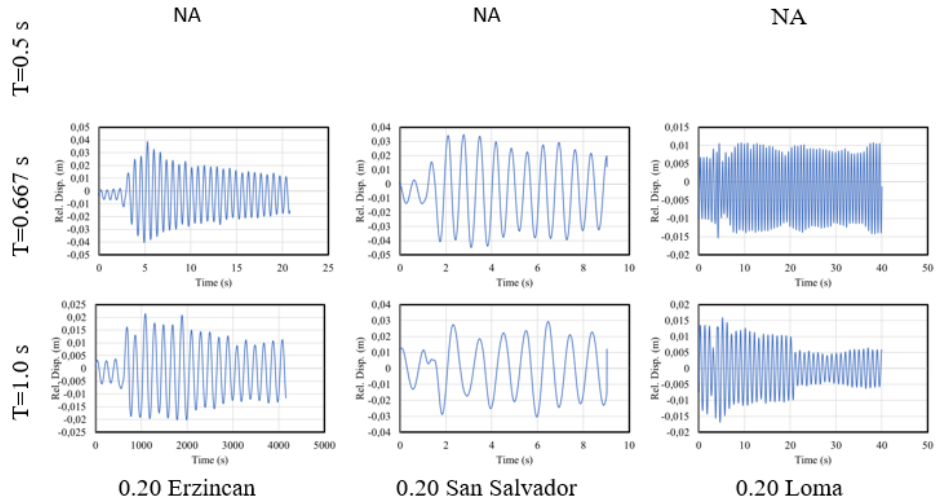


Figure 4.24. AL40/20/1 Rectangular hollow section Relative Displacement-Time Figure.

4.3.5. ST80/40/2 T=0.500 sec Energy Components

Figure 4.25-Figure 4.27 show the energy terms results of ST80/40/2 specimen for T=0.500 sec for each ground motion record.

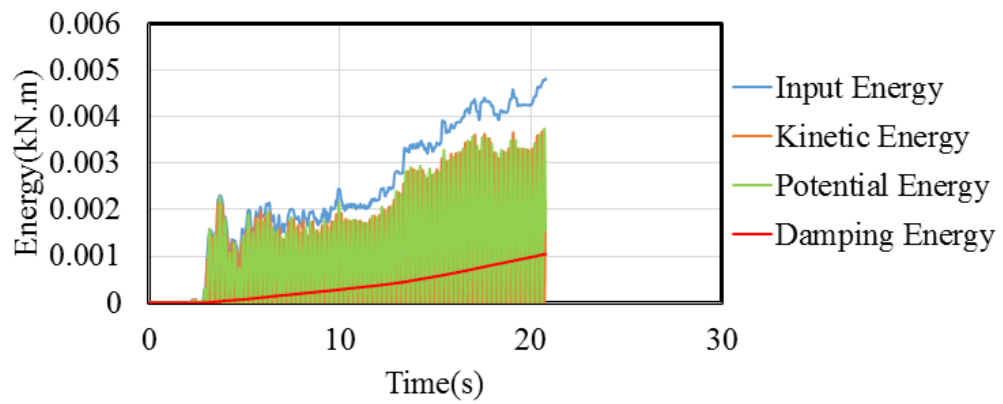


Figure 4.25. ST80/40/2 T=0.500 Sec 0.20 Erzincan Energy Components.

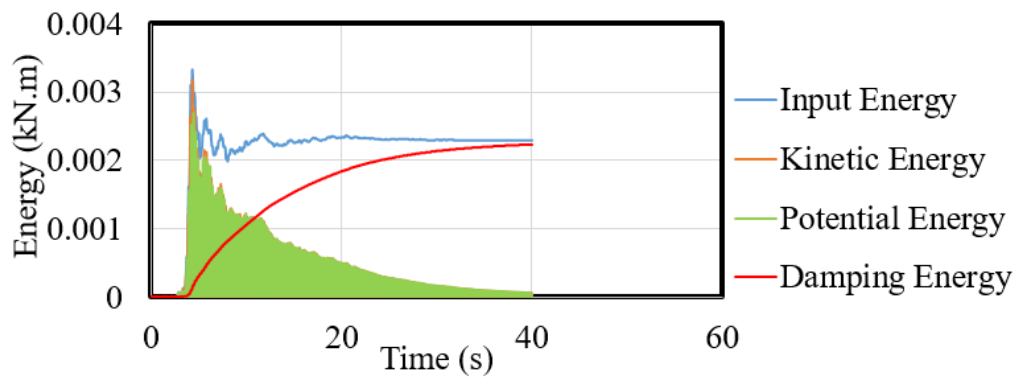


Figure 4.26. ST80/40/2 T=0.500 Sec 0.20 Loma Prieta Energy Components.

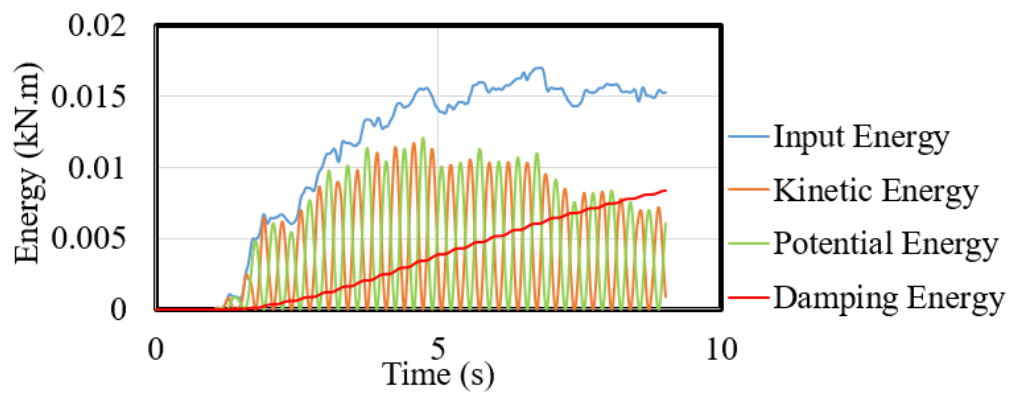


Figure 4.27. T=0.500 Sec 0.20 San Salvador Energy Components.

4.3.6. ST80/40/2 $T=0.667$ sec Energy Components

Figure 4.28-Figure 4.30 show the energy terms results of ST80/40/2 specimen for $T=0.667$ sec for each ground motion record.

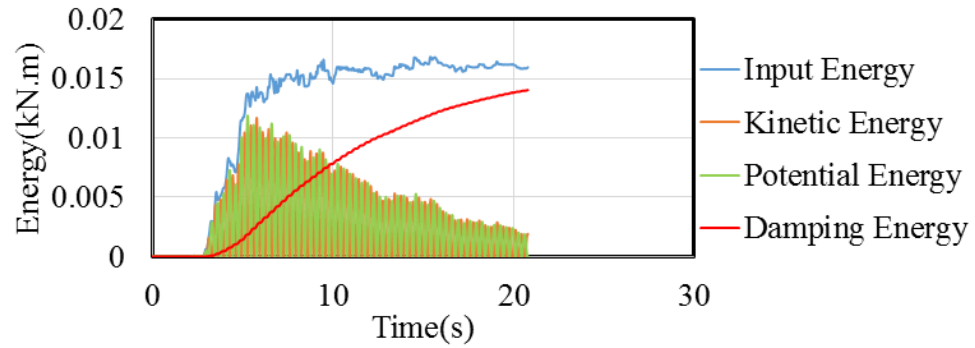


Figure 4.28. ST80/40/2 $T=0.667$ Sec 0.20 Erzincan Energy Components.

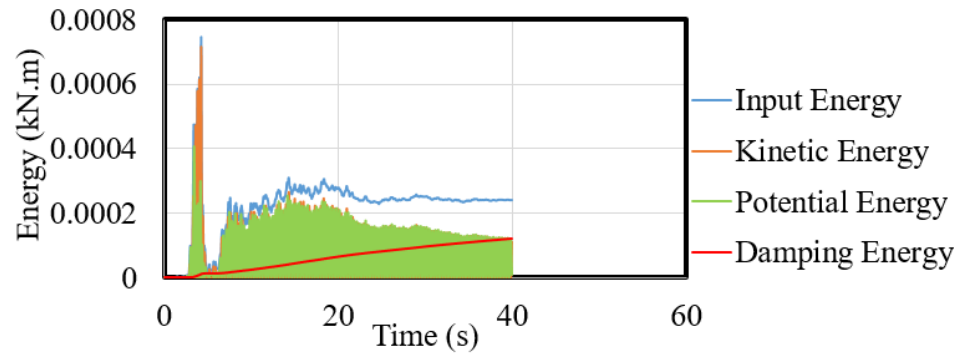


Figure 4.29. ST80/40/2 $T=0.667$ Sec 0.20 Loma Prieta Energy Components.

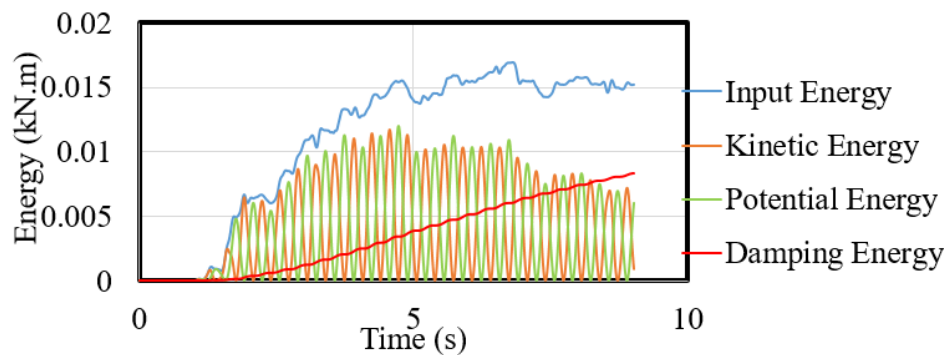


Figure 4.30. ST80/40/2 $T=0.667$ Sec 0.20 San Salvador Energy Components.

4.3.7. ST80/40/2 T=1.000 sec Energy Components

Figure 4.31-Figure 4.33 show the energy terms results of ST80/40/2 specimen for T=1.000 sec for each ground motion record.

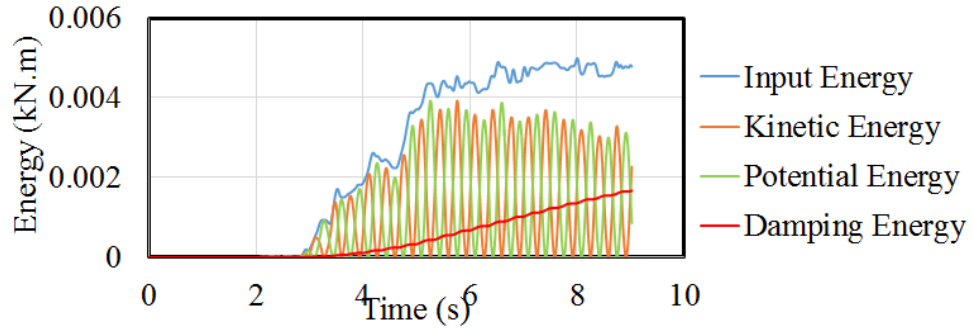


Figure 4.31. ST80/40/2 T=1.000 Sec 0.20 Erzincan Energy Components.

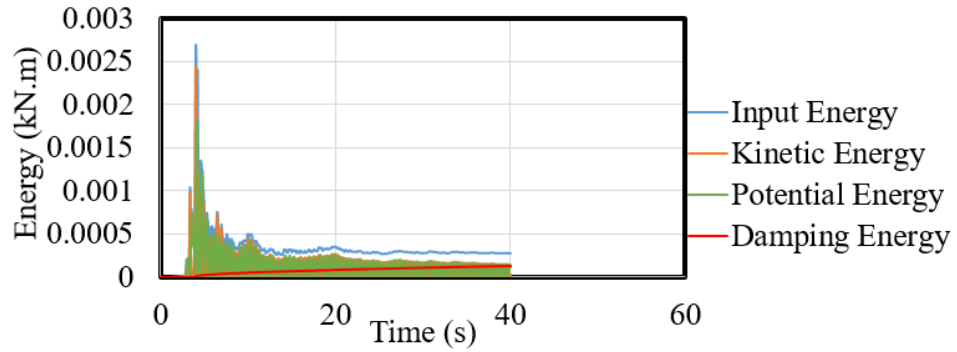


Figure 4.32. ST80/40/2 T=1.000 Sec 0.20 Loma Prieta Energy Components.

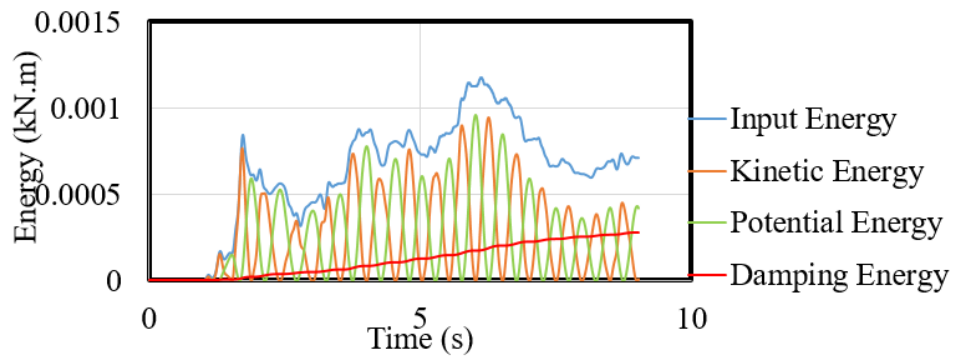


Figure 4.33. ST80/40/2 T=1.000 Sec 0.20 San Salvador Energy Components.

4.3.8. ST40/20/1 T=0.500 sec Energy Components

Figure 4.34-Figure 4.36 show the energy terms results of ST40/20/1 specimen for T=0.500 sec for each ground motion record.

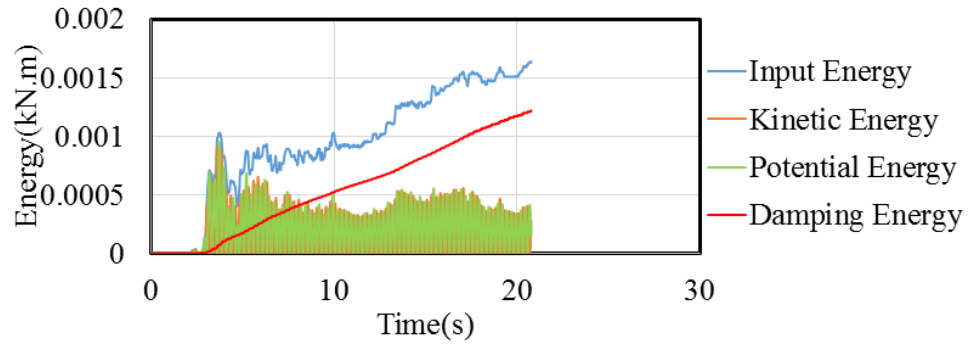


Figure 4.34. ST40/20/1 T=0.500 Sec 0.20 Erzincan Energy Components.

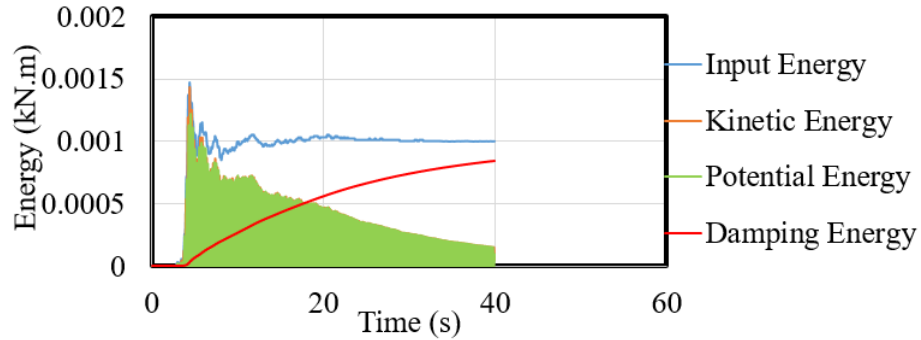


Figure 4.35. ST40/20/1 T=0.500 Sec 0.20 Loma Prieta Energy Components(Exp).

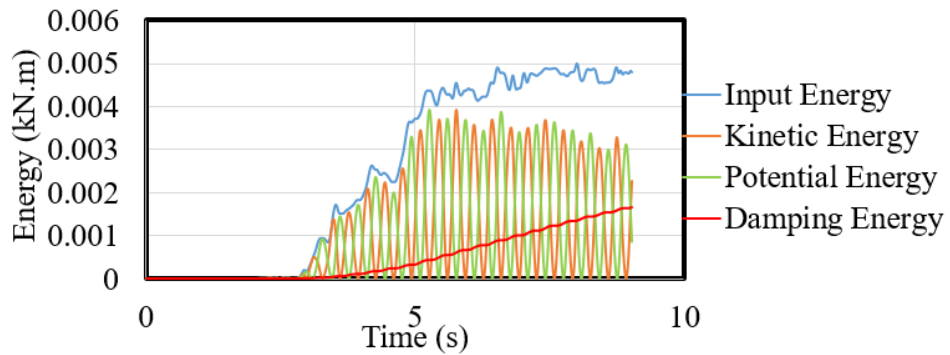


Figure 4.36. ST40/20/1 T=0.500 Sec 0.20 San Salvador Energy Components.

4.3.9. ST40/20/1 T=0.667 sec Energy Components

Figure 4.37-Figure 4.39 show the energy terms results of ST40/20/1 specimen for T=0.667 sec for each ground motion record.

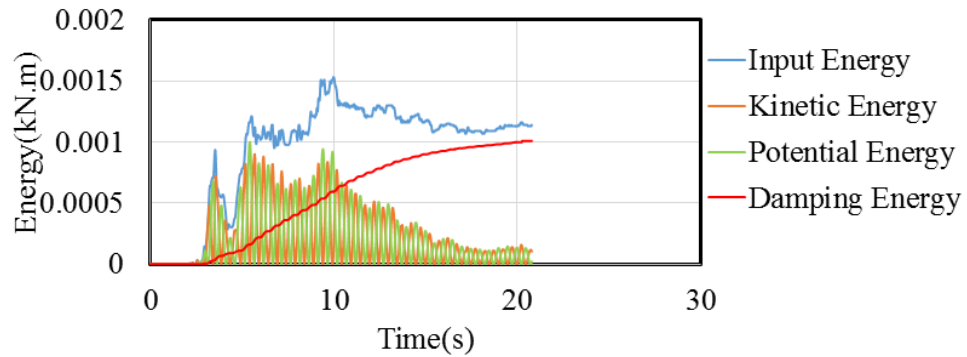


Figure 4.37. ST40/20/1 T=0.667 Sec 0.20 Erzincan Energy Components.

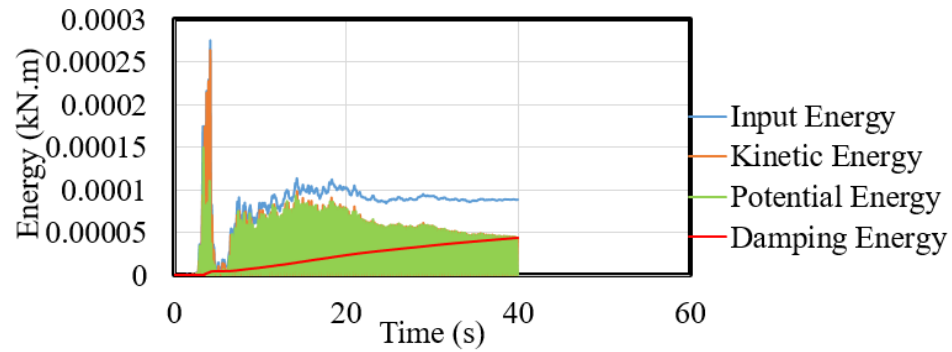


Figure 4.38. ST40/20/1 T=0.667 Sec 0.20 Loma Prieta Energy Components.

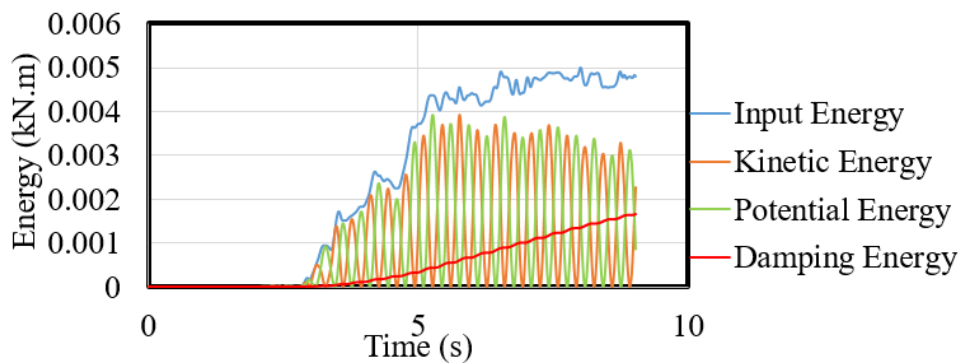


Figure 4.39. ST40/20/1 T=0.667 Sec 0.20 San Salvador Energy Components.

4.3.10. ST40/20/1 T=1.000 sec Energy Components

Figure 4.40-Figure 4.42 show the energy terms results of ST40/20/1 specimen for T=1.000 sec for each ground motion record.

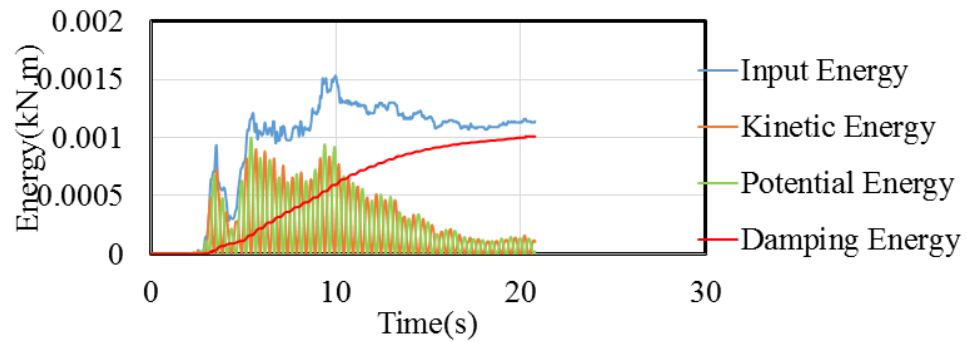


Figure 4.40. ST40/20/1 T=1.000 Sec 0.20 Erzincan Energy Components.

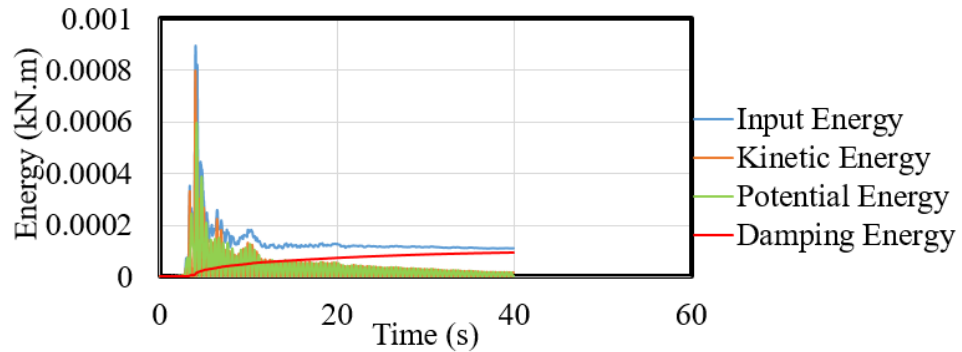


Figure 4.41. ST40/20/1 T=1.000 Sec 0.20 Loma Prieta Energy Components.

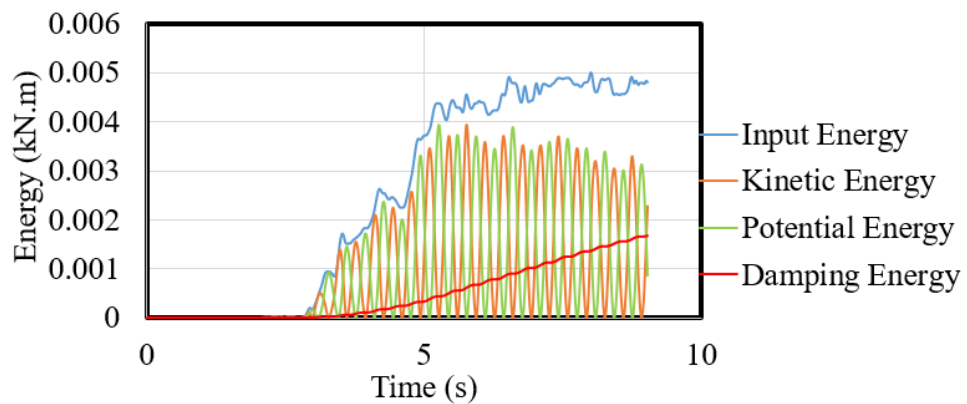


Figure 4.42. ST40/20/1 T=1.000 Sec 0.20 San Salvador Energy Components.

4.3.11. AL80/4/2 T=0.500 Sec Energy Components

Figure 4.43-Figure 4.45 show the energy terms results of AL80/40/2 specimen for T=0.500 sec for each ground motion record.

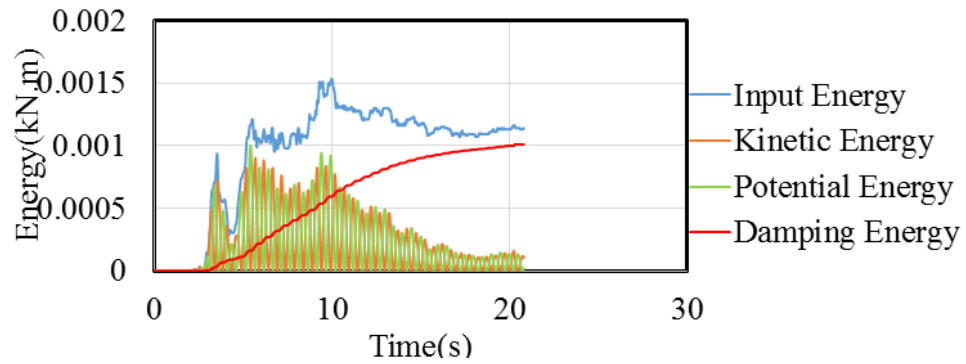


Figure 4.43. AL80/40/2 T=0.500 Sec 0.20 Erzincan Energy Components.

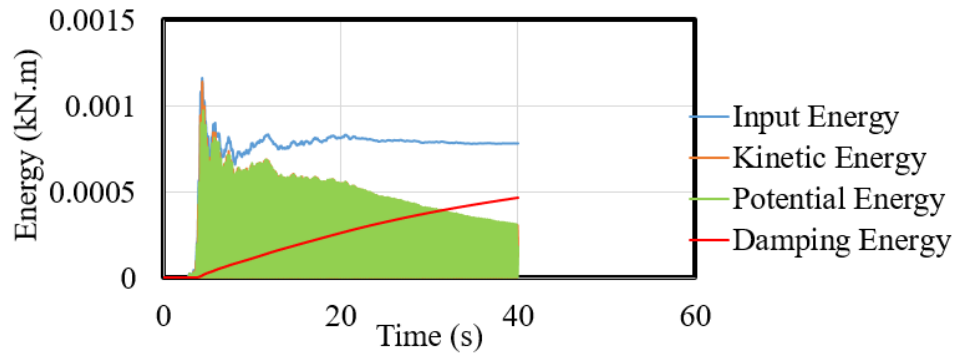


Figure 4.44. AL80/40/2 T=0.500 Sec 0.20 Loma Prieta Energy Components.

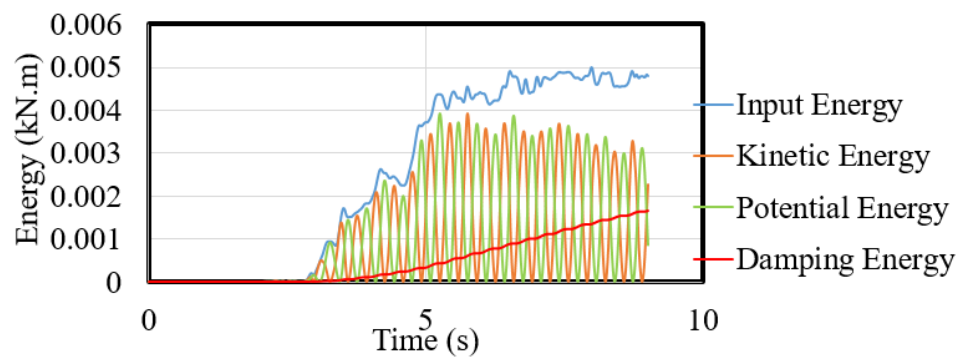


Figure 4.45. AL80/40/2 T=0.500 Sec 0.20 San Salvador Energy Components.

4.3.12. AL80/4/2 T=0.667 Sec Energy Components

Figure 4.46-Figure 4.48 show the energy terms results of AL80/40/2 specimen for T=0.667 sec for each ground motion record.

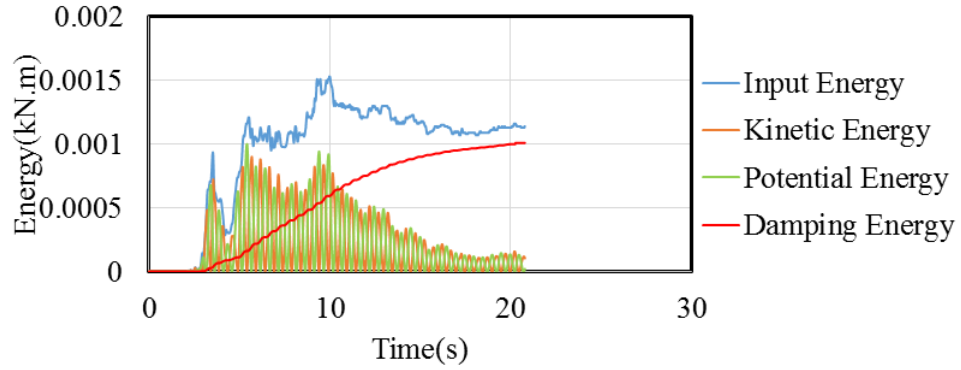


Figure 4.46. AL80/40/2 T=0.667 Sec 0.20 Erzincan Energy Components.

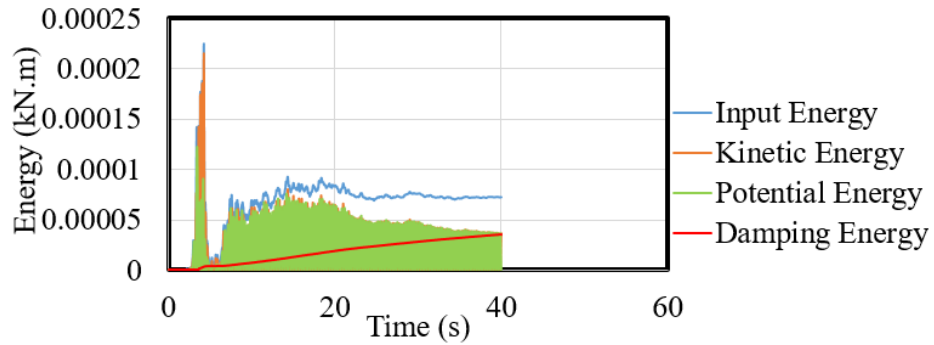


Figure 4.47. AL80/40/2 T=0.667 Sec 0.20 Loma Prieta Energy Components.

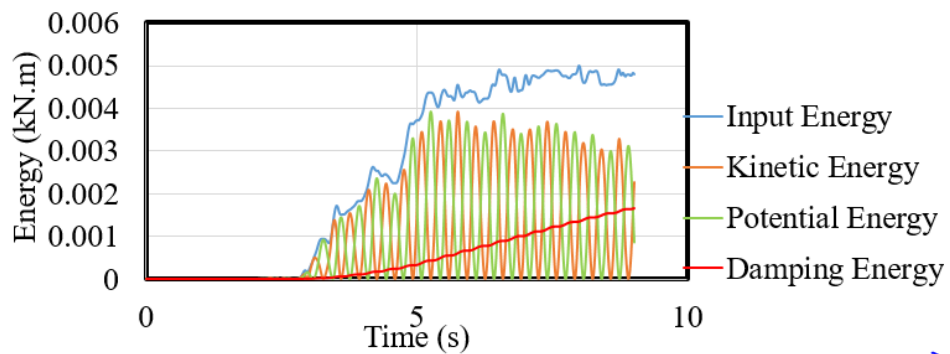


Figure 4.48. AL80/40/2 T=0.667 Sec 0.20 San Salvador Energy Components.

4.3.13. AL80/40/2 T=1.000 Sec Energy Components

Figure 4.49-Figure 4.51 show the energy terms results of AL40/20/1 specimen for T=1.000 sec for each ground motion record.

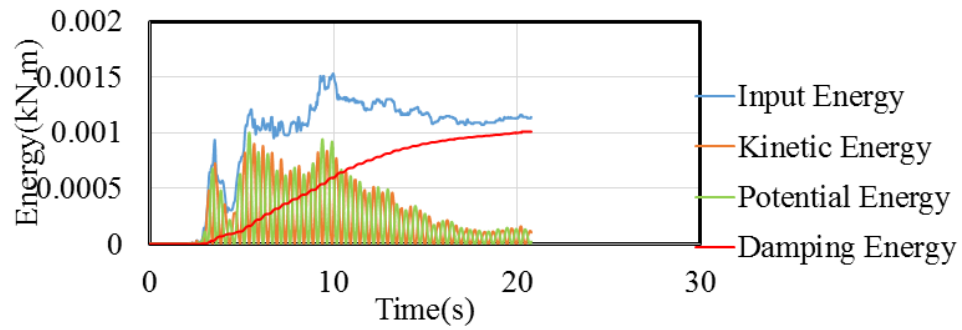


Figure 4.49. AL80/40/2 T=1.000 Sec 0.20 Erzincan Energy Components.

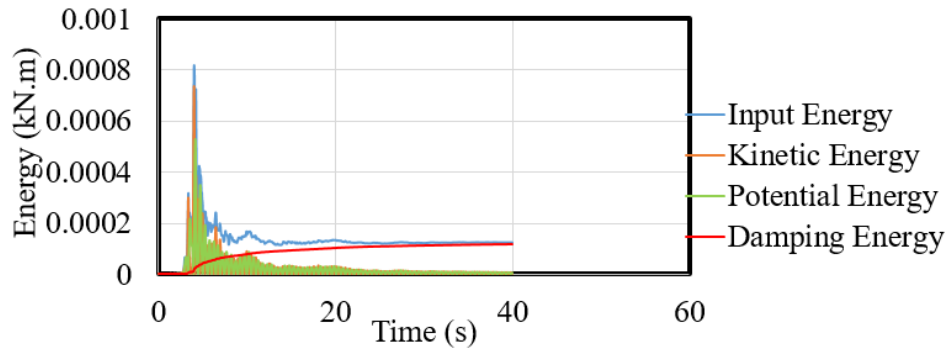


Figure 4.50. AL80/40/2 T=1.000 Sec 0.20 Loma Prieta Energy Components.

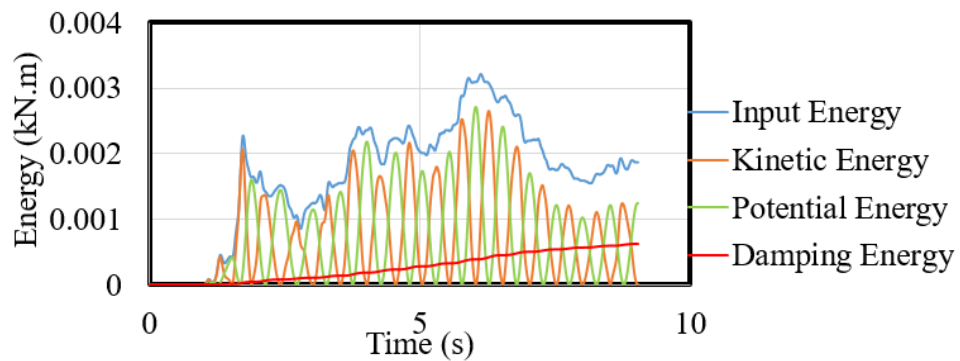


Figure 4.51. AL80/40/2 T=1.000 Sec 0.20 San Salvador Energy Components.

4.3.14. AL40/20/1 T=0.667 sec Energy Components

Figure 4.52-Figure 4.54 show the energy terms results of AL80/40/2 specimen for T=0.667 sec for each ground motion record.

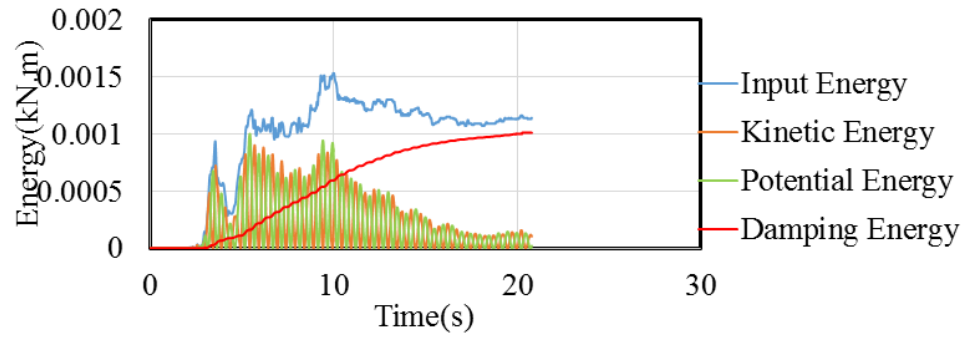


Figure 4.52. AL40/20/1 T=0.667 Sec 0.20 Erzincan Energy Components.

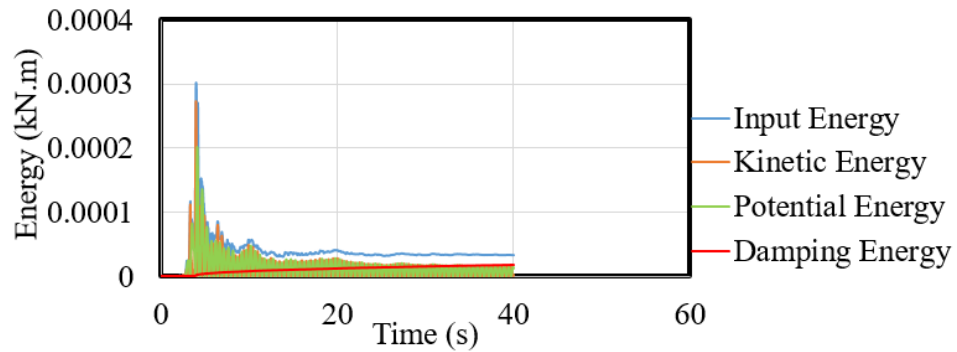


Figure 4.53. AL40/20/1 T=0.667 Sec 0.20 Loma Prieta Energy Components.

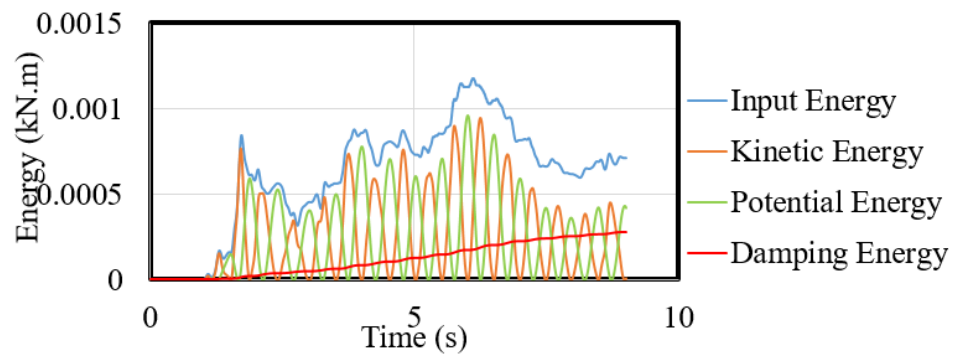


Figure 4.54. AL40/20/1 T=0.667 Sec 0.20 San Salvador Energy Components.

4.3.15. AL40/20/1 T=1.000 sec Energy Components

Figure 4.55-Figure 4.57 show the energy terms results of AL80/40/2 specimen for T=1.000 sec for each ground motion record.

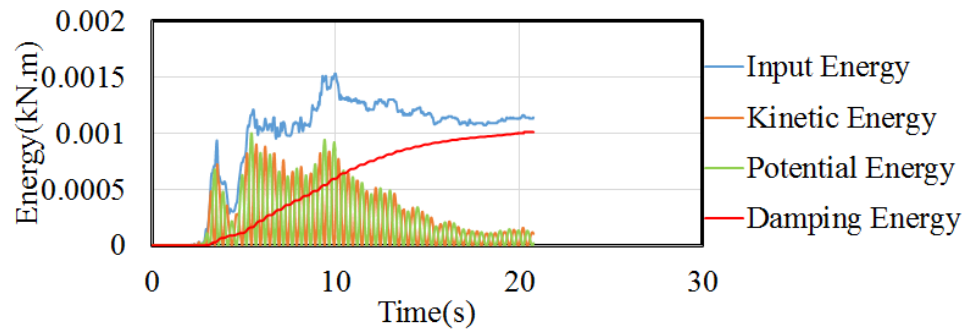


Figure 4.55. AL40/20/1 T=1.000 Sec 0.20 Erzincan Energy Components.

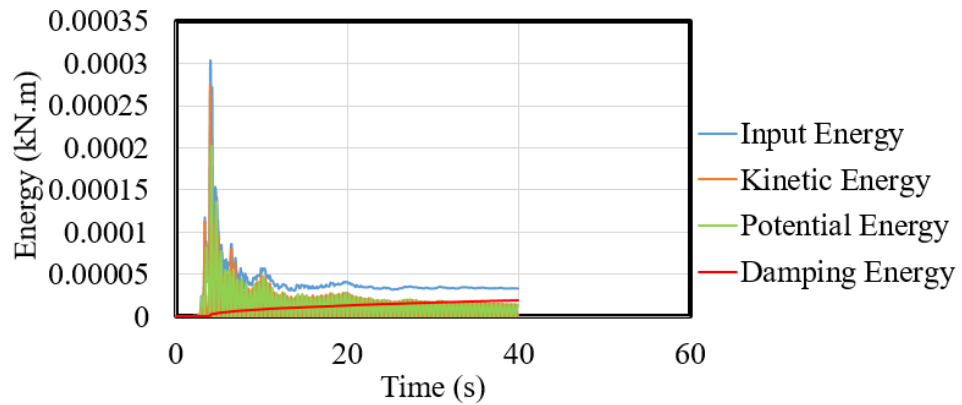


Figure 4.56. AL40/20/1 T=1.000 Sec 0.20 Loma Prieta Energy Components.

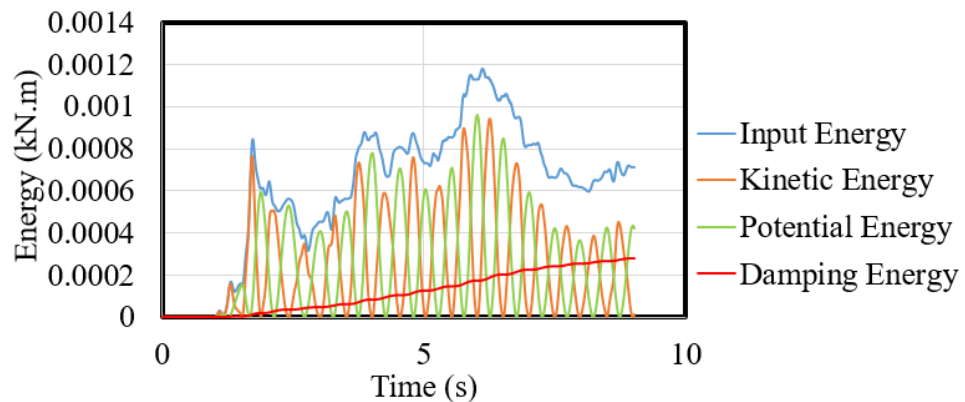


Figure 4.57. AL40/20/1 T=1.000 Sec 0.20 San Salvador Energy Components.

4.3.16. Spectral Input Energy Value Results

Spectral input energy value of each specimen for each period under defined ground motion records were calculated. Table 4.9-Table 4.20 summarize spectral input energy value (E_i), mass (m), length(L) and mass normalized input energy value (E_i/m) of each specimen under defined ground motion records for three different periods.

Table 4.9. ST80/40/2 Spectral Input Energy Value under 0.20 Erzincan.

ST80/40/2-020ERZINCAN				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	0.0049	0.085	1.813	0.0578
0.667	0.0178	0.147	1.819	0.1212
1.000	0.0145	0.262	1.973	0.0555

Table 4.10. ST80/40/2 Spectral Input Energy Value under 0.20 San Salvador.

ST80/40/2-020SAN SALVADOR				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	0.0034	0.085	1.813	0.040
0.667	0.0178	0.147	1.819	0.121
1.000	0.0108	0.262	1.973	0.041

Table 4.11. ST80/40/2 Spectral Input Energy Value under 0.20 Loma Prieta.

ST80/40/2-020LOMA PRIETA				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	0.0033	0.085	1.800	0.039
0.667	0.0007	0.147	1.795	0.005
1.000	0.0035	0.262	1.970	0.013

Table 4.12. ST40/20/1 Spectral Input Energy Value under 0.20 Erzincan.

ST40/20/1-020ERZINCAN				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	0.0017	0.038	0.940	0.045
0.667	0.0063	0.057	0.990	0.111
1.000	0.0048	0.088	1.125	0.055

Table 4.13. ST40/20/1 Spectral Input Energy Value under 0.20 San Salvador.

ST40/20/1-020SAN SALVADOR				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	0.0016	0.038	0.940	0.043
0.667	0.0068	0.057	0.990	0.120
1.000	0.0036	0.088	1.125	0.041

Table 4.14. ST40/20/1 Spectral Input Energy Value under 0.20 Loma Prieta.

ST40/20/1-020LOMA PRIETA				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	0.0014	0.038	0.936	0.038
0.667	0.0002	0.057	0.990	0.005
1.000	0.0008	0.088	1.125	0.013

Table 4.15. AL80/40/2 Spectral Input Energy Value under 0.20 Erzincan.

AL80/40/2-020 ERZINCAN				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	0.0017	0.032	1.751	0.055
0.667	0.0056	0.046	1.880	0.123
1.000	0.00437	0.080	2.060	0.055

Table 4.16. AL80/40/2 Spectral Input Energy Value under 0.20 San Salvador.

AL80/40/2-020 SAN SALVADOR				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	0.0013	0.032	1.751	0.042
0.667	0.0051	0.046	1.880	0.113
1.000	0.0031	0.080	2.060	0.039

Table 4.17. AL80/40/2 Spectral Input Energy Value under 0.20 Loma Prieta.

AL80/40/2-020 LOMA PRIETA				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	0.0012	0.032	1.751	0.039
0.667	0.0002	0.046	1.880	0.005
1.000	0.0008	0.080	2.060	0.01

Table 4.18. AL40/20/1 Spectral Input Energy Value under 0.20 Erzincan.

AL40/20/1-020 ERZINCAN				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	NA	NA	NA	NA
0.667	0.0015	0.014	1.100	0.111
1.000	0.0016	0.029	1.137	0.054

Table 4.19. AL40/20/1 Spectral Input Energy Value under 0.20 San Salvador.

AL40/20/1-020 SAN SALVADOR				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	NA	NA	NA	NA
0.667	0.0016	0.014	1.100	0.115
1.000	0.0012	0.030	1.137	0.041

Table 4.20. AL40/20/1 Spectral Input Energy Value under 0.20 Loma Prieta.

AL40/20/1-020LOMA PRIETA				
T(sec)	E_i(kN.m)	m(kN.s²/m)	L(m)	E_i/m(m²/s²)
0.500	NA	NA	NA	NA
0.667	6.72E-05	0.014	1.100	0.005
1.000	0.0003	0.030	1.137	0.012

Mass normalized input energy values of each specimen for three different ground motion records were plotted into the input energy spectra obtained in Section 3.5, as shown in Figure 4.58-Figure 4.60.

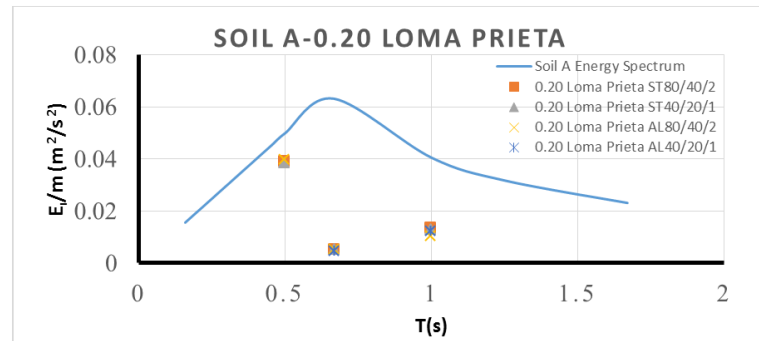


Figure 4.58. Soil A Input Energy Spectrum and Experimental Spectral Input Energy Result.

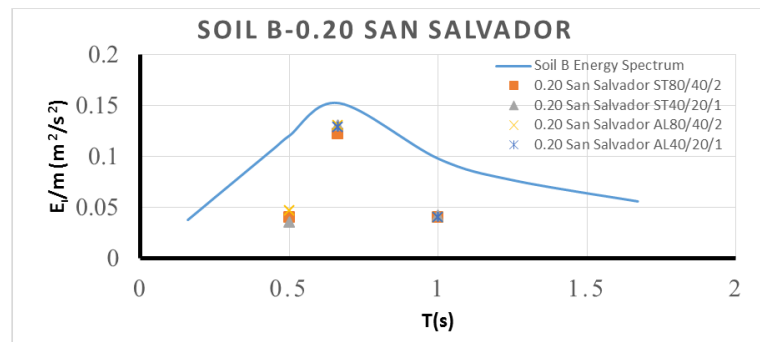


Figure 4.59. Soil B Input Energy Spectrum and Experimental Spectral Input Energy Results.

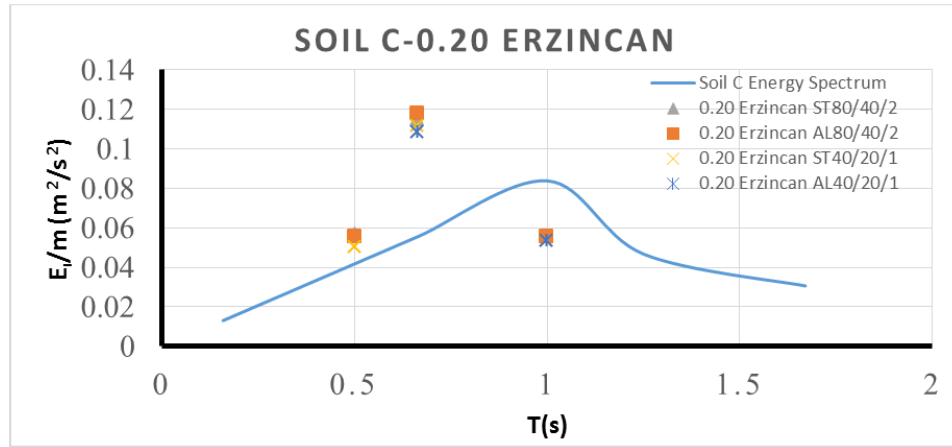


Figure 4.60. Soil C spectrum and Experimental Input Energy Results.

4.3.17. Scale Analysis of Spectral Input Energy

After calculation of spectral input energy value of the specimens under three earthquake ground motion records for three different periods, spectral input energy ratio between specimens at the same period were evaluated. Seven cases between specimens were used to evaluate the E_i ratio. The length of each specimen is changed by additional mass height. Thus, each binary case has different length ratio from numerical results. The cross-sectional dimension of specimens in binary cases are same with numerical analysis thus moment of inertia scale between specimens are same with numerical analysis results. Table 4.21 defines binary states.

Table 4.21. Cross Section Scale Analysis of Seven Binary Cases.

CASES FOR RATIO ANALYSIS			λ_b	λ_h	λ_l
Case 1	ST80/40/2	AL80/40/2	1	1	1
Case 2	ST40/20/1	AL40/20/1	1	1	1
Case 3	ST80/40/2	ST40/20/1	2	2	16
Case 4	AL80/40/2	AL40/20/1	2	2	16
Case 5	ST80/40/2	AL40/20/1	2	2	16
Case 6	AL80/40/2	ST80/40/2	1	1	1
Case 7	AL80/40/2	ST40/20/1	2	2	16

Based on each case analysis, results for the spectral input energy ratio, mass ratio, mass normalized input energy ratio and length ratio between specimens were shown in Table 4.23-Table 4.29. Table 4.21 shows Case 1 results, Table 4.23 shows Case 2 results. Table 4.24 shows Case 3 results. Table 4.25 shows Case 4 results. Table 4.26 shows Case 5 results. Table 4.27 shows Case 6 results. Table 4.28 shows Case 7 results. For each earthquake record, relationship between E_1 ratio and Mass ratio results were plotted in Figure 4.61-Figure 4.63;

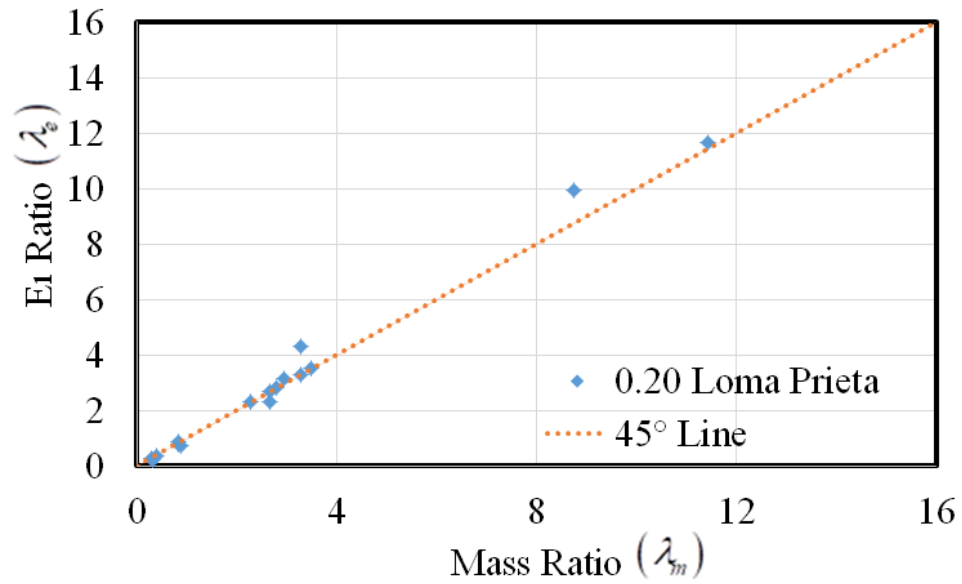


Figure 4.61. 0.20 Loma Prieta E_1 Ratio-Mass Ratio.

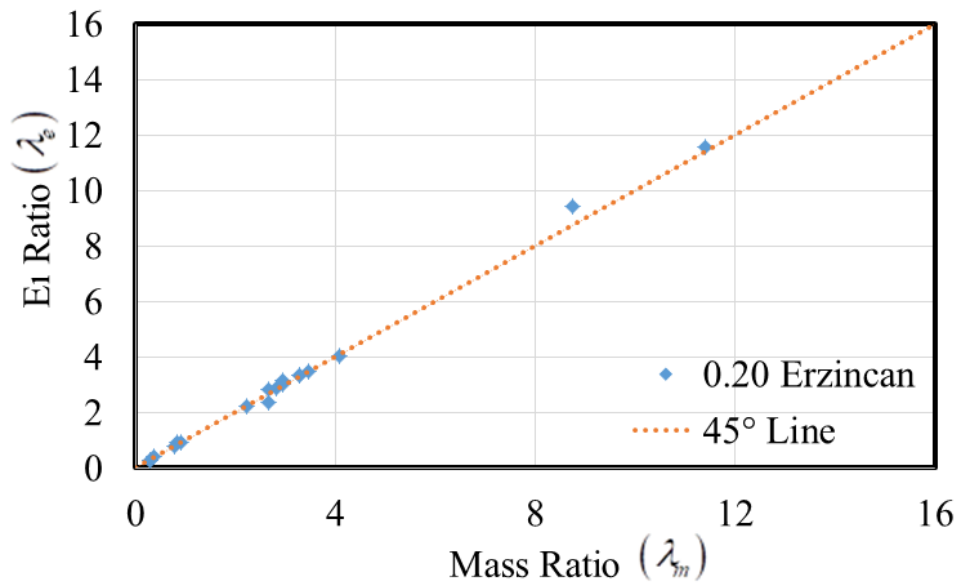


Figure 4.62. 0.20 Erzincan E_1 ratio-Mass Ratio.

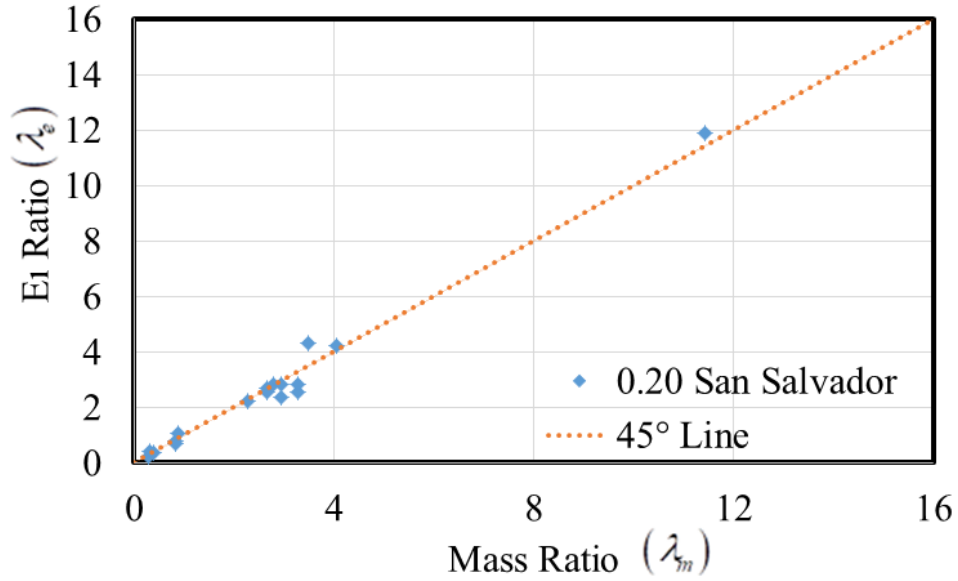


Figure 4.63. 0.20 San Salvador E_1 Ratio-Mass Ratio.

Results show that in elastic range, at the same period under same ground motion record, input energy ratios are approximately equal to the mass ratio for each defined case. That means, mass ratio could be a scale factor for spectral input energy between specimens at the same period under same ground motion record.

Spectral input energy ratio is also evaluated at different period under same ground motion record between defined each binary case. While specimens are evaluated at different periods, their spectral energy ratio is related to the recommended formula in analytical part in Equation 3.36. The experimental study results for N value are shown in Table 4.22.

Input energy ratio for each ground motion record were plotted with recommended formula which is Equation 3.36, as shown in Figure 4.61-Figure 4.63.

Table 4.22. N Value Derived From Experimental Study.

Ground Motion Data	N value(Experimental Study)
0.20 Loma Prieta (Soil A)	0.40
0.20 San Salvador (Soil B)	1.90
0.20 Erzincan (Soil C)	0.35

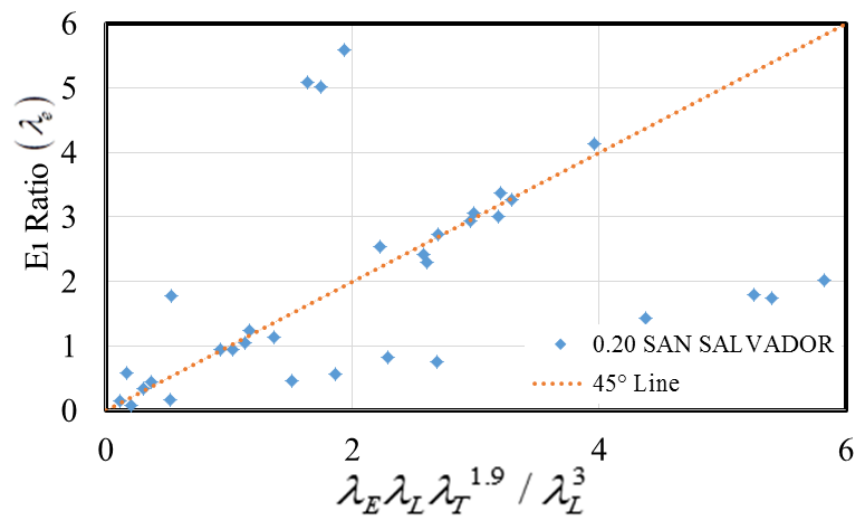


Figure 4.64. 0.20 San Salvador Experimental Result for Input Energy Ratio Energy Scale Factor Analysis.

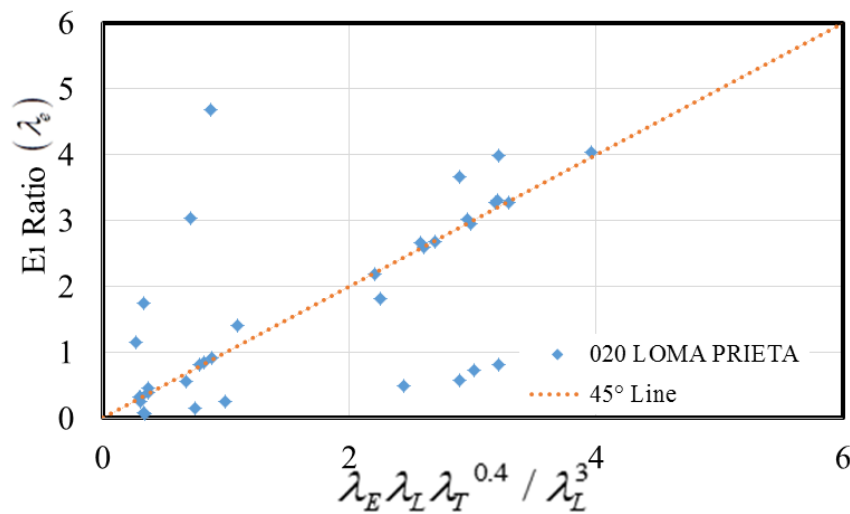


Figure 4.65. 0.20 Loma Prieta Experimental Result for Different Period Input Energy Ratio Energy Scale Factor Analysis.

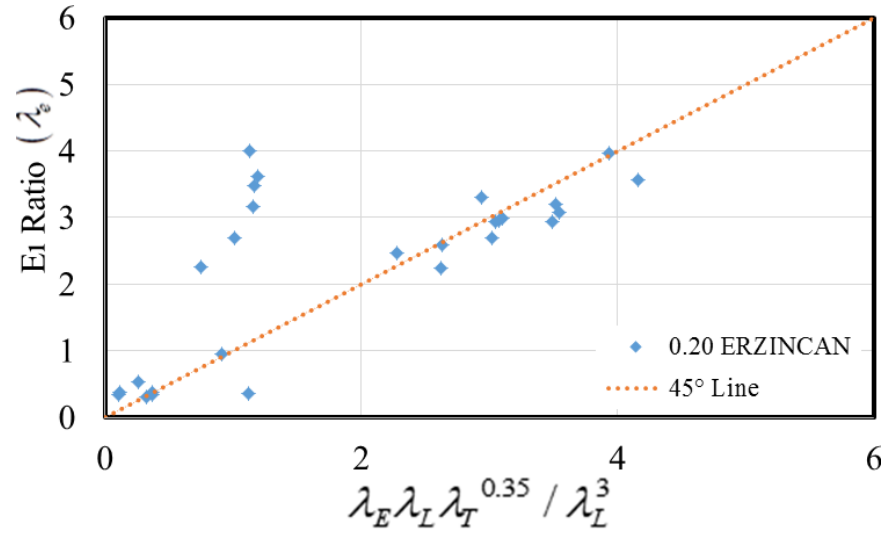


Figure 4.66. 0.20 Erzincan Experimental Result for Different Period Input Energy Ratio Energy Scale Factor Analysis.

Table 4.23. ST80/40/2-AL80/40/2 0.20 Loma Prieta, Erzincan and San Salvador Spectral Input Energy Ratio Results.

ST80/40/2-AL80/40/2 0.20 Loma Prieta Spectral Input Energy Ratio Results											
ST80/40/2-020LOMA PRIETA						AL80/40/2-020LOMA PRIETA					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	Mass Ratio
0.500	0.0033	0.0836	1.813	0.0390	0.500	0.0013	0.0320	1.751	0.0394	1.00	2.61
0.667	0.0007	0.1470	1.819	0.0049	0.667	0.0002	0.0460	1.880	0.0048	1.00	3.20
1.000	0.0027	0.2624	1.973	0.0102	1.000	0.0008	0.0800	2.060	0.0102	1.00	3.28
ST80/40/2-AL80/40/2 0.20 San Salvador Spectral Input Energy Ratio Results											
ST80/40/2-020SAN SALVADOR						AL80/40/2-020SAN SALVADOR					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	Mass Ratio
0.500	0.003	0.085	1.813	0.040	0.500	0.001	0.032	1.751	0.046	1.00	2.66
0.667	0.018	0.147	1.819	0.122	0.667	0.006	0.046	1.880	0.130	1.00	3.20
1.000	0.011	0.262	1.973	0.040	1.000	0.003	0.080	2.060	0.040	1.00	3.28
ST80/40/2-AL80/40/2 0.20 Erzincan Spectral Input Energy Ratio Results											
ST80/40/2-020ERZINCAN						AL80/40/2-020ERZINCAN					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	Mass Ratio
0.500	0.005	0.085	1.813	0.057	0.500	0.002	0.032	1.751	0.055	1.00	2.66
0.667	0.017	0.147	1.819	0.114	0.667	0.005	0.046	1.880	0.117	1.00	3.20
1.000	0.015	0.262	1.973	0.056	1.000	0.004	0.080	2.060	0.055	1.00	3.28

ST80/40/2-AL80/40/2-020LOMA PRIETA

AL80/40/2-AL80/40/2-020ERZINCAN

ST80/40/2-AL80/40/2-020ERZINCAN

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

E_i/m Ratio

Mass Ratio

T ratio

E_i Ratio

E_i/m(m² /s²)

m(kN.s² /m)

E_i (kN.m)

T(sec)

E_i/m(m² /s²)

L(m)

m(kN.s² /m)

E_i (kN.m)

T(sec)

L Ratio

Table 4.24. ST40/20/1-AL40/20/1 0.20 Loma Prieta, Erzincan and San Salvador Spectral Input Energy Ratio Results.

ST40/20/1-AL40/20/1 0.20 Loma Prieta Spectral Input Energy Ratio Results											
ST40/20/1-020LOMA PRIETA						AL40/20/1-020LOMA PRIETA					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio
0.500	0.0015	0.0380	0.937	0.0393	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.0003	0.0570	0.991	0.0047	0.667	0.0001	0.0140	1.100	0.0048	1.00	4.03
1.000	0.0009	0.0888	1.125	0.0101	1.000	0.0003	0.0300	1.137	0.0101	1.00	2.94
ST40/20/1-AL40/20/1 0.20 San Salvador Spectral Input Energy Ratio Results											
ST40/20/1-020SAN SALVADOR						AL40/20/1-020SAN SALVADOR					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio
0.500	0.001	0.038	0.940	0.035	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.007	0.057	0.991	0.130	0.667	0.002	0.014	1.100	0.128	1.00	4.13
1.000	0.004	0.089	1.125	0.040	1.000	0.001	0.030	1.137	0.039	1.00	3.04
ST40/20/1-AL40/20/1 0.20 Erzincan Spectral Input Energy Ratio Results											
ST40/20/1-020ERZINCAN						AL40/20/1-020ERZINCAN					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio
0.500	0.002	0.038	0.940	0.048	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.006	0.057	0.991	0.112	0.667	0.002	0.014	1.100	0.116	1.00	3.94
1.000	0.005	0.089	1.125	0.053	1.000	0.002	0.029	1.137	0.053	1.00	3.10
ST40/20/1-AL40/20/1-020LOMA PRIETA											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio
0.500	0.0015	0.0380	0.937	0.0393	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.0003	0.0570	0.991	0.0047	0.667	0.0001	0.0140	1.100	0.0048	1.00	4.03
1.000	0.0009	0.0888	1.125	0.0101	1.000	0.0003	0.0300	1.137	0.0101	1.00	2.94
ST40/20/1-AL40/20/1-020SAN SALVADOR											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio
0.500	0.001	0.038	0.940	0.035	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.007	0.057	0.991	0.130	0.667	0.002	0.014	1.100	0.128	1.00	4.13
1.000	0.004	0.089	1.125	0.040	1.000	0.001	0.030	1.137	0.039	1.00	3.04
ST40/20/1-AL40/20/1-020ERZINCAN											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio
0.500	0.002	0.038	0.940	0.048	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.006	0.057	0.991	0.112	0.667	0.002	0.014	1.100	0.116	1.00	3.94
1.000	0.005	0.089	1.125	0.053	1.000	0.002	0.029	1.137	0.053	1.00	3.10

Table 4.25. ST80/40/2-ST40/20/1 0.20 Loma Prieta, Erzincan and San Salvador Spectral Input Energy Ratio Results.

ST80/40/2-ST40/20/1 0.20 Loma Prieta Spectral Input Energy Ratio Results												
ST80/40/2-020LOMA PRIETA						ST40/20/1-020LOMA PRIETA						
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.0033	0.0836	1.813	0.0390	0.500	0.0015	0.0380	0.937	0.0393	1.00	2.18	2.20
0.667	0.0007	0.1470	1.819	0.0049	0.667	0.0003	0.0570	0.991	0.0047	1.00	2.67	2.58
1.000	0.0027	0.2624	1.973	0.0102	1.000	0.0009	0.0888	1.125	0.0101	1.00	3.00	2.95
ST80/40/2-ST40/20/1 0.20 San Salvador Spectral Input Energy Ratio Results												
ST80/40/2-020SAN SALVADOR						ST40/20/1-020SAN SALVADOR						
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.003	0.085	1.813	0.040	0.500	0.001	0.038	0.940	0.035	1.00	2.53	2.24
0.667	0.018	0.147	1.819	0.122	0.667	0.007	0.057	0.991	0.130	1.00	2.43	2.58
1.000	0.011	0.262	1.973	0.040	1.000	0.004	0.089	1.125	0.040	1.00	2.93	2.95
ST80/40/2-ST40/20/1 0.20 Erzincan Spectral Input Energy Ratio Results												
ST80/40/2-020ERZINCAN						ST40/20/1-020ERZINCAN						
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.005	0.085	1.813	0.057	0.500	0.002	0.038	0.940	0.048	1.00	2.62	2.24
0.667	0.017	0.147	1.819	0.114	0.667	0.006	0.057	0.991	0.112	1.00	2.64	2.58
1.000	0.015	0.262	1.973	0.056	1.000	0.005	0.089	1.125	0.053	1.00	3.07	2.95
ST80/40/2-ST40/20/1 0.20 LOMA PRIETA												
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.0033	0.0836	1.813	0.0390	0.500	0.0015	0.0380	0.937	0.0393	1.00	2.18	2.20
0.667	0.0007	0.1470	1.819	0.0049	0.667	0.0003	0.0570	0.991	0.0047	1.00	2.67	2.58
1.000	0.0027	0.2624	1.973	0.0102	1.000	0.0009	0.0888	1.125	0.0101	1.00	3.00	2.95
ST80/40/2-ST40/20/1 0.20 SAN SALVADOR												
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.003	0.085	1.813	0.040	0.500	0.001	0.038	0.940	0.035	1.00	2.53	2.24
0.667	0.018	0.147	1.819	0.122	0.667	0.007	0.057	0.991	0.130	1.00	2.43	2.58
1.000	0.011	0.262	1.973	0.040	1.000	0.004	0.089	1.125	0.040	1.00	2.93	2.95
ST80/40/2-ST40/20/1 0.20 ERZINCAN												
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.005	0.085	1.813	0.057	0.500	0.002	0.038	0.940	0.048	1.00	2.62	2.24
0.667	0.017	0.147	1.819	0.114	0.667	0.006	0.057	0.991	0.112	1.00	2.64	2.58
1.000	0.015	0.262	1.973	0.056	1.000	0.005	0.089	1.125	0.053	1.00	3.07	2.95

Table 4.26. AL80/40/2-AL40/20/1 0.20 Loma Prieta, Erzincan and San Salvador Spectral Input Energy Ratio Results.

AL80/40/2-AL40/20/1 0.20 Loma Prieta Spectral Input Energy Ratio Results											
AL80/40/2-020LOMA PRIETA						AL40/20/1-020LOMA PRIETA					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	Mass Ratio
0.500	0.0013	0.0320	1.751	0.0394	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.0002	0.0460	1.880	0.0048	0.667	0.0001	0.0140	1.100	0.0048	1.00	3.29
1.000	0.0008	0.0800	2.060	0.0102	1.000	0.0003	0.0300	1.137	0.0101	1.00	2.67
AL80/40/2-AL40/20/1 0.20 San Salvador Spectral Input Energy Ratio Results											
AL80/40/2-020SAN SALVADOR						AL40/20/1-020SAN SALVADOR					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	Mass Ratio
0.500	0.001	0.032	1.751	0.046	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.006	0.046	1.880	0.130	0.667	0.002	0.014	1.100	0.128	1.00	3.35
1.000	0.003	0.080	2.060	0.040	1.000	0.001	0.030	1.137	0.039	1.00	2.73
AL80/40/2-AL40/20/1 0.20 Erzincan Spectral Input Energy Ratio Results											
AL80/40/2-020ERZINCAN						AL40/20/1-020ERZINCAN					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	Mass Ratio
0.500	0.002	0.032	1.751	0.055	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.005	0.046	1.880	0.117	0.667	0.002	0.014	1.100	0.109	1.00	3.55
1.000	0.004	0.080	2.060	0.055	1.000	0.002	0.029	1.137	0.053	1.00	2.89
AL80/40/2-AL40/20/1-020LOMA PRIETA											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	Mass Ratio
0.500	0.0013	0.0320	1.751	0.0394	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.0002	0.0460	1.880	0.0048	0.667	0.0001	0.0140	1.100	0.0048	1.00	3.29
1.000	0.0008	0.0800	2.060	0.0102	1.000	0.0003	0.0300	1.137	0.0101	1.00	2.67
AL80/40/2-AL40/20/1-020SAN SALVADOR											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	Mass Ratio
0.500	0.001	0.032	1.751	0.046	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.006	0.046	1.880	0.130	0.667	0.002	0.014	1.100	0.128	1.00	3.35
1.000	0.003	0.080	2.060	0.040	1.000	0.001	0.030	1.137	0.039	1.00	2.73
AL80/40/2-AL40/20/1-020ERZINCAN											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	Mass Ratio
0.500	0.002	0.032	1.751	0.055	0.500	NA	NA	NA	NA	1.00	NA
0.667	0.005	0.046	1.880	0.117	0.667	0.002	0.014	1.100	0.109	1.00	3.55
1.000	0.004	0.080	2.060	0.055	1.000	0.002	0.029	1.137	0.053	1.00	2.89

Table 4.27. ST80/40/2-AL40/20/1 0.20 Loma Prieta, Erzincan and San Salvador Spectral Input Energy Ratio Results.

ST80/40/2-AL40/20/1 0.20 Loma Prieta Spectral Input Energy Ratio Results												
ST80/40/2-020LOMA PRIETA						5 AL40/20/1-020LOMA PRIETA						
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.0033	0.0836	1.813	0.0390	0.500	NA	NA	NA	NA	1.00	NA	NA
0.667	0.0007	0.1470	1.819	0.0049	0.667	6.7E-05	0.014	1.100	0.0048	1.00	10.76	10.50
1.000	0.0027	0.2624	1.973	0.0102	1.000	0.0003	0.03	1.137	0.0101	1.00	8.84	8.75
ST80/40/2-AL40/20/1 0.20 San Salvador Spectral Input Energy Ratio Results												
ST80/40/2-020SAN SALVADOR						5 AL40/20/1-020SAN SALVADOR						
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.003	0.085	1.813	0.040	0.500	NA	NA	NA	NA	1.00	NA	NA
0.667	0.018	0.147	1.819	0.122	0.667	0.002	0.014	1.100	0.128	1.00	10.04	10.50
1.000	0.011	0.262	1.973	0.040	1.000	0.001	0.030	1.137	0.039	1.00	8.91	8.75
ST80/40/2-AL40/20/1 0.20 Erzincan Spectral Input Energy Ratio Results												
ST80/40/2-020ERZINCAN						5 ST80/40/2-AL40/20/1-020ERZINCAN						
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.005	0.085	1.813	0.057	0.500	NA	NA	NA	NA	1.00	NA	NA
0.667	0.017	0.147	1.819	0.114	0.667	0.002	0.014	1.100	0.116	1.00	10.39	10.50
1.000	0.015	0.262	1.973	0.056	1.000	0.002	0.029	1.137	0.053	1.00	9.51	9.05
ST80/40/2-AL40/20/1 0.20 LOMA PRIETA												
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.0033	0.0836	1.813	0.0390	0.500	NA	NA	NA	NA	1.00	NA	NA
0.667	0.0007	0.1470	1.819	0.0049	0.667	6.7E-05	0.014	1.100	0.0048	1.00	10.76	10.50
1.000	0.0027	0.2624	1.973	0.0102	1.000	0.0003	0.03	1.137	0.0101	1.00	8.84	8.75
ST80/40/2-020SAN SALVADOR												
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.003	0.085	1.813	0.040	0.500	NA	NA	NA	NA	1.00	NA	NA
0.667	0.018	0.147	1.819	0.122	0.667	0.002	0.014	1.100	0.128	1.00	10.04	10.50
1.000	0.011	0.262	1.973	0.040	1.000	0.001	0.030	1.137	0.039	1.00	8.91	8.75
ST80/40/2-020ERZINCAN												
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i Ratio	Mass Ratio
0.500	0.005	0.085	1.813	0.057	0.500	NA	NA	NA	NA	1.00	NA	NA
0.667	0.017	0.147	1.819	0.114	0.667	0.002	0.014	1.100	0.116	1.00	10.39	10.50
1.000	0.015	0.262	1.973	0.056	1.000	0.002	0.029	1.137	0.053	1.00	9.51	9.05

Table 4.28. AL80/40/2-ST80/40/2 0.20 Loma Prieta, Erzincan and San Salvador Spectral Input Energy Ratio Results.

AL80/40/2-ST80/40/2 0.20 Loma Prieta Spectral Input Energy Ratio Results											
AL80/40/2-020LOMA PRIETA						ST80/40/2-020LOMA PRIETA					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.0013	0.0320	1.751	0.0394	0.500	0.0033	0.0836	1.813	0.0390	1.00	0.386
0.667	0.0002	0.0460	1.880	0.0048	0.667	0.0007	0.1470	1.819	0.0049	1.00	0.306
1.000	0.0008	0.0800	2.060	0.0102	1.000	0.0027	0.2624	1.973	0.0102	1.00	0.305
AL80/40/2-ST80/40/2 0.20 San Salvador Spectral Input Energy Ratio Results											
AL80/40/2-020SAN SALVADOR						ST80/40/2-020SAN SALVADOR					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.001	0.032	1.751	0.046	0.500	0.003	0.085	1.813	0.040	1.00	0.43
0.667	0.006	0.046	1.880	0.130	0.667	0.018	0.147	1.819	0.122	1.00	0.33
1.000	0.003	0.080	2.060	0.040	1.000	0.011	0.262	1.973	0.040	1.00	0.31
AL80/40/2-ST80/40/2 0.20 Erzincan Spectral Input Energy Ratio Results											
AL80/40/2-020ERZINCAN						ST80/40/2-020ERZINCAN					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.001	0.032	1.751	0.046	0.500	0.001	0.038	0.940	0.036	1.00	1.07
0.667	0.006	0.046	1.880	0.130	0.667	0.007	0.057	0.991	0.130	1.00	0.81
1.000	0.003	0.080	2.060	0.040	1.000	0.004	0.089	1.125	0.040	1.00	0.90
AL80/40/2-ST80/40/2-020LOMA PRIETA											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.0013	0.0320	1.751	0.0394	0.500	0.0033	0.0836	1.813	0.0390	1.00	0.386
0.667	0.0002	0.0460	1.880	0.0048	0.667	0.0007	0.1470	1.819	0.0049	1.00	0.306
1.000	0.0008	0.0800	2.060	0.0102	1.000	0.0027	0.2624	1.973	0.0102	1.00	0.305
AL80/40/2-ST80/40/2-020SAN SALVADOR											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.001	0.032	1.751	0.046	0.500	0.003	0.085	1.813	0.040	1.00	0.43
0.667	0.006	0.046	1.880	0.130	0.667	0.018	0.147	1.819	0.122	1.00	0.33
1.000	0.003	0.080	2.060	0.040	1.000	0.011	0.262	1.973	0.040	1.00	0.31
AL80/40/2-ST80/40/2-020ERZINCAN											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.001	0.032	1.751	0.046	0.500	0.001	0.038	0.940	0.036	1.00	1.27
0.667	0.006	0.046	1.880	0.130	0.667	0.007	0.057	0.991	0.130	1.00	0.81
1.000	0.003	0.080	2.060	0.040	1.000	0.004	0.089	1.125	0.040	1.00	0.90

Table 4.29. AL80/40/2-ST40/20/1 0.20 Loma Prieta, Erzincan and San Salvador Spectral Input Energy Ratio Results.

AL80/40/2-ST40/20/1 0.20 Loma Prieta Spectral Input Energy Ratio Results											
AL80/40/2-020LOMA PRIETA						ST40/20/1-020LOMA PRIETA					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.0013	0.0320	1.751	0.0394	0.500	0.0015	0.0380	0.937	0.0393	1.00	0.84
0.667	0.0002	0.0460	1.880	0.0048	0.667	0.0003	0.0570	0.991	0.0047	1.00	0.82
1.000	0.0008	0.0800	2.060	0.0102	1.000	0.0009	0.0888	1.125	0.0101	1.00	0.92
AL80/40/2-ST40/20/1 0.20 San Salvador Spectral Input Energy Ratio Results											
AL80/40/2-020SAN SALVADOR						ST40/20/1-020SAN SALVADOR					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.001	0.032	1.751	0.046	0.500	0.001	0.038	0.940	0.036	1.00	1.07
0.667	0.006	0.046	1.880	0.130	0.667	0.007	0.057	0.991	0.130	1.00	0.81
1.000	0.003	0.080	2.060	0.040	1.000	0.004	0.089	1.125	0.040	1.00	0.90
AL80/40/2-ST40/20/1 0.20 Erzincan Spectral Input Energy Ratio Results											
AL80/40/2-020ERZINCAN						ST40/20/1-020ERZINCAN					
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.002	0.032	1.751	0.055	0.500	0.002	0.038	0.940	0.048	1.00	0.97
0.667	0.005	0.046	1.880	0.117	0.667	0.006	0.057	0.991	0.112	1.00	0.85
1.000	0.004	0.080	2.060	0.055	1.000	0.005	0.089	1.125	0.053	1.00	0.93
AL80/40/2-ST40/20/1-020LOMA PRIETA											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.0013	0.0320	1.751	0.0394	0.500	0.0015	0.0380	0.937	0.0393	1.00	0.84
0.667	0.0002	0.0460	1.880	0.0048	0.667	0.0003	0.0570	0.991	0.0047	1.00	0.82
1.000	0.0008	0.0800	2.060	0.0102	1.000	0.0009	0.0888	1.125	0.0101	1.00	0.92
AL80/40/2-ST40/20/1-020SAN SALVADOR											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.001	0.032	1.751	0.046	0.500	0.001	0.038	0.940	0.036	1.00	1.07
0.667	0.006	0.046	1.880	0.130	0.667	0.007	0.057	0.991	0.130	1.00	0.81
1.000	0.003	0.080	2.060	0.040	1.000	0.004	0.089	1.125	0.040	1.00	0.90
AL80/40/2-ST40/20/1-020ERZINCAN											
T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T(sec)	E _i (kN.m)	m(kN.s ² /m)	L(m)	E _i /m(m ² /s ²)	T ratio	E _i /m Ratio
0.500	0.002	0.032	1.751	0.055	0.500	0.002	0.038	0.940	0.048	1.00	0.97
0.667	0.005	0.046	1.880	0.117	0.667	0.006	0.057	0.991	0.112	1.00	0.85
1.000	0.004	0.080	2.060	0.055	1.000	0.005	0.089	1.125	0.053	1.00	0.93

5. ANALYSIS AND COMPARISON OF THE ANALYTICAL AND EXPERIMENTAL RESULTS

In this chapter, experimental and analytical results for input energy scale factor between SDOF systems were compared.

5.1. Scale Analysis Results of Spectral Input Energy Between SDOF Systems

Based on each defined case analysis in Table 3.24, experimental and numerical analysis results for the spectral input energy ratio between specimens were compared. Table 5.1-Table 5.3 show experimental and numerical analysis results for the same period, spectral input energy ratio, mass ratio, length ratio and mass normalized input energy ratio of specimens under 0.20 Erzincan, 0.20 San Salvador and 0.20 Loma Prieta ground motion record, respectively. Mass normalized input energy value of each specimen for each ground motion record obtained from experimental study and numerical study were plotted with the input energy spectrum. These results were shown in Figure 5.1-Figure 5.3 for 0.20 Loma Prieta, 0.20 San Salvador and 0.20 Erzincan earthquake, respectively.

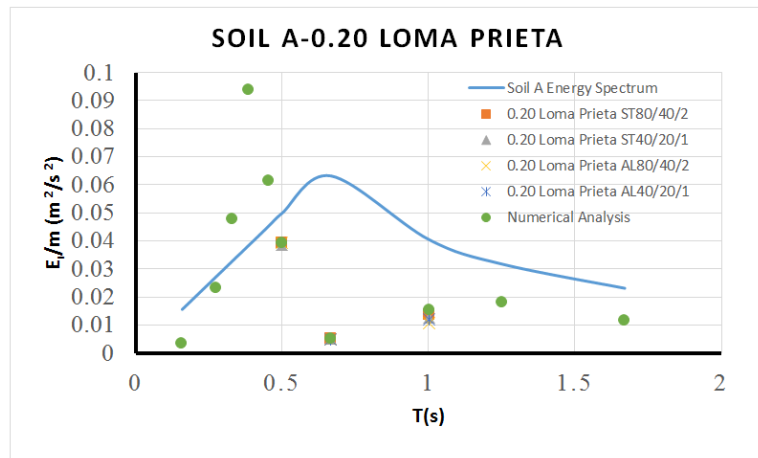


Figure 5.1. Soil A 0.20 Loma Prieta Input Energy Spectrum.

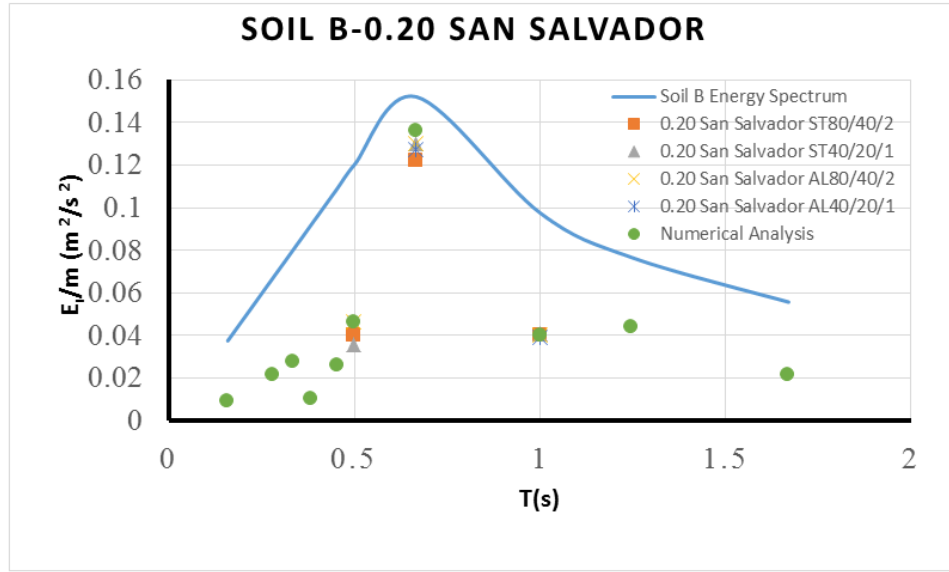


Figure 5.2. Soil B 0.20 San Salvador Input Energy Spectrum.

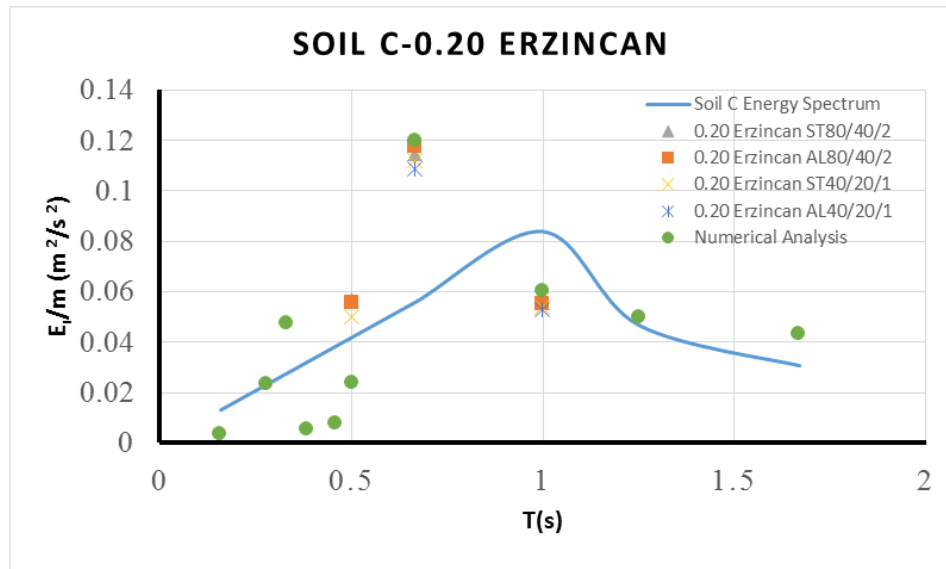


Figure 5.3. Soil C 0.20 Erzincan Input Energy Spectrum.

For each earthquake record, relationship between E_1 ratio and Mass ratio between specimens obtained from experimental and numerical study results, were plotted in Figure 5.4.

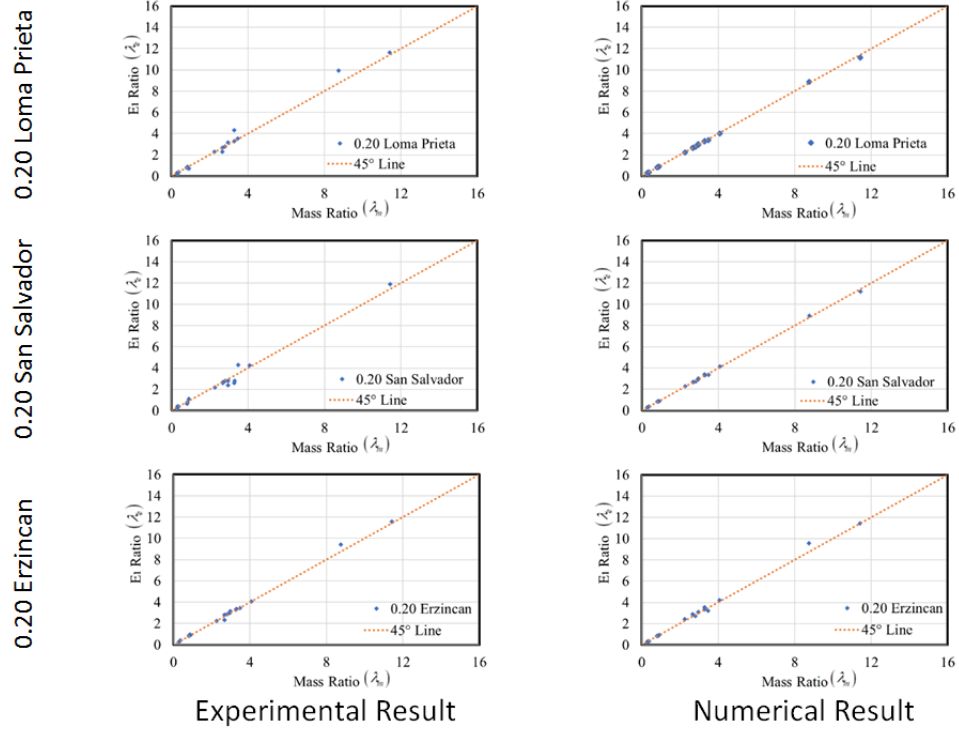


Figure 5.4. E_i ratio-Mass Ratio Comparision Between Experimental and Numerical Analysis Results.

Spectral input energy ratio evaluation gives result as spectral input energy ratio is proportional to the mass ratio between specimen at same period. Figure 5.5- Figure 5.6 show the numerical and experimental results, respectively, to show relationship between mass ratio and mass scale factor, and also relationship between input energy ratio and mass scale factor. Figure 5.5- Figure 5.6 shows that mass ratio is proportional to the mass scale formula derived from dimensional analysis. Also, mass ratio is proportional to the spectral input energy ratio for each defined binary case.

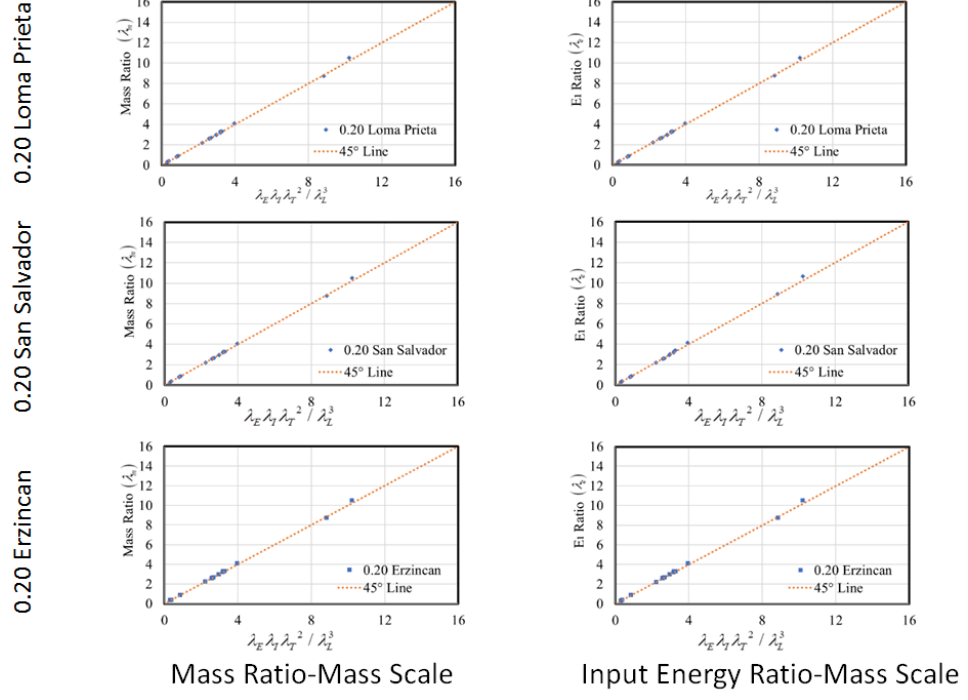


Figure 5.5. Numerical Results for Mass Ratio-Mass Scale Analysis and Input Energy Ratio-Mass Scale Analysis.

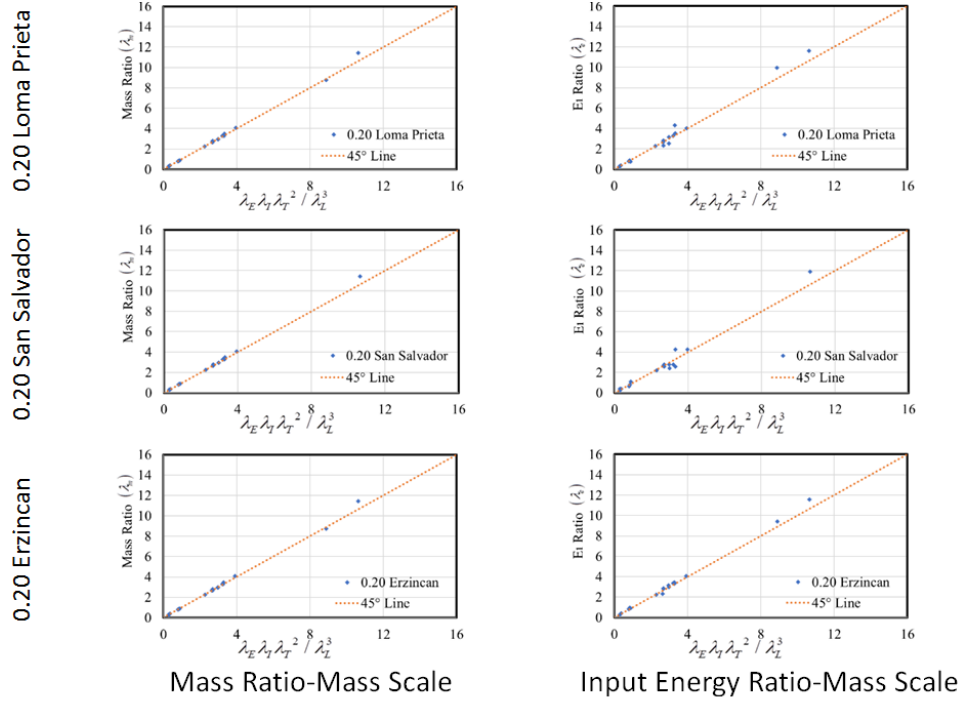


Figure 5.6. Experimental Results for Mass Ratio-Mass Scale Analysis and Input Energy Ratio-Mass Scale Analysis.

Results show that in elastic range, at the same period under same ground motion record, specimens' input energy ratio is approximately equal to the specimens' mass scale factor. That means, mass scale could be a scale factor for energy between specimens. Thus, mass scale factor formula is equal to spectral input energy scale formula between specimens. This case is shown in Figure 5.7 based on both experimental and analytical results.

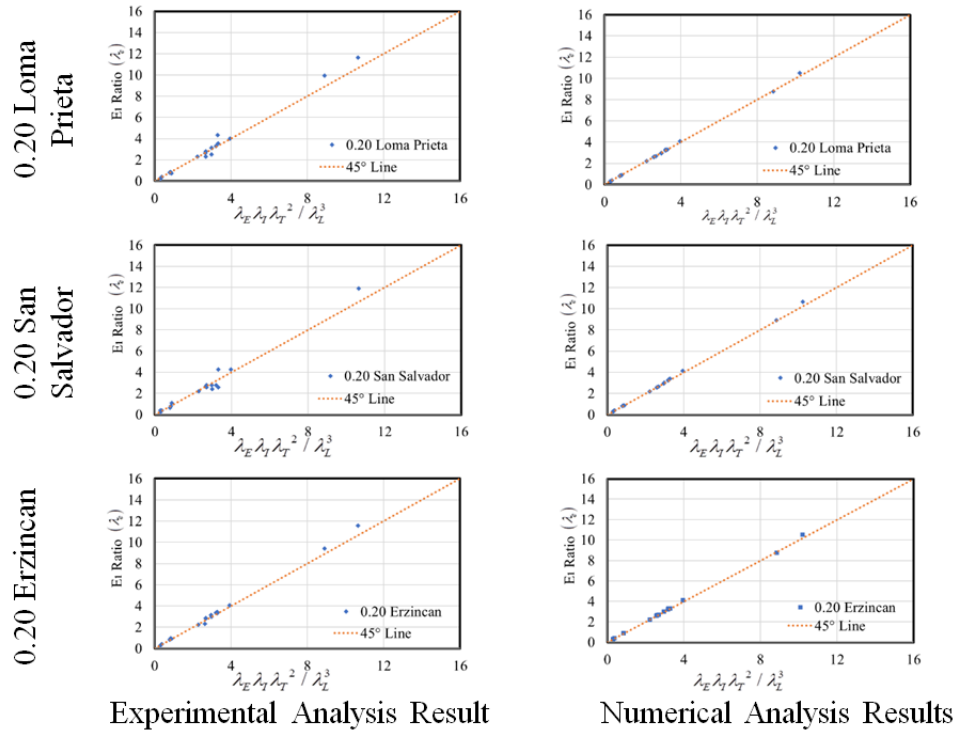


Figure 5.7. Input Energy Ratio- Mass Scale Formula Relationship.

Spectral energy ratio analysis was also performed between different periods under same ground motion record in analytical part and experimental part of this study. Analysis results show that for different period under same ground motion record, energy scale formula could be represented as in Equation 3.37. For each earthquake ground motion record, different N value calculated. Energy spectra model analysis results, numerical model analysis results and experimental study results for N value are explained in Table 5.4.

5.2. Comparison of Ratio Analysis for 0.20 Erzincan Ground Motion Record

Table 5.1. 0.20 Erzincan Ratio Analysis Results of Experimental Study and Numerical Study at Same Period.

ST80/40/2-AL80/40/2-020ERZINCAN					ST80/40/2-AL80/40/2-020ERZINCAN				
T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio	T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio
1	2.72	2.66	1.02	0.97	1.00	2.77	2.66	1.04	0.97
1	3.12	3.20	0.98	1.03	1.00	3.15	3.20	0.99	1.03
1	3.29	3.28	1.00	1.04	1.00	3.33	3.28	1.02	1.04
ST40/20/1-AL40/20/1-020ERZINCAN					ST40/20/1-AL40/20/1-020ERZINCAN				
T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio	T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio
1	NA	NA	NA	NA	1.00	NA	NA	NA	NA
1	3.94	4.07	0.97	1.11	1.00	4.08	4.07	1.00	1.11
1	3.10	3.06	1.01	1.01	1.00	3.09	3.06	1.01	1.01
ST80/40/2-ST40/20/1-020ERZINCAN					ST80/40/2-ST40/20/1-020ERZINCAN				
T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio	T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio
1	2.62	2.24	1.17	0.52	1.00	2.56	2.24	1.14	0.52
1	2.64	2.58	1.02	0.54	1.00	2.82	2.58	1.09	0.54
1	3.07	2.95	1.04	0.57	1.00	3.01	2.95	1.02	0.57
AL80/40/2-AL40/20/1-020ERZINCAN					AL80/40/2-AL40/20/1-020ERZINCAN				
T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio	T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio
1	NA	NA	NA	NA	1.00	NA	NA	NA	NA
1	3.55	3.29	1.08	0.59	1.00	3.64	3.29	1.11	0.59
1	2.89	2.76	1.05	0.55	1.00	2.78	2.76	1.01	0.55
ST80/40/2-AL40/20/1-020ERZINCAN					ST80/40/2-AL40/20/1-020ERZINCAN				
T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio	T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio
1	NA	NA	NA	NA	1.00	NA	NA	NA	NA
1	10.39	10.50	0.99	0.60	1.00	11.48	10.50	1.09	0.60
1	9.51	9.05	1.05	0.58	1.00	9.29	9.05	1.03	0.58
AL80/40/2-ST80/40/2-020ERZINCAN					AL80/40/2-ST80/40/2-020ERZINCAN				
T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio	T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio
1	0.37	0.38	0.98	1.04	1.00	0.36	0.38	0.96	1.04
1	0.32	0.31	1.03	0.97	1.00	0.32	0.31	1.01	0.97
1	0.30	0.30	1.00	0.96	1.00	0.30	0.30	0.98	0.96
AL80/40/2-ST40/20/1-020ERZINCAN					AL80/40/2-ST40/20/1-020ERZINCAN				
T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio	T ratio	E ₁ Ratio	Mass Ratio	E ₁ /m Ratio	L Ratio
1	0.97	0.84	1.15	0.54	1.00	0.92	0.84	1.09	0.54
1	0.85	0.81	1.05	0.53	1.00	0.89	0.81	1.11	0.53
1	0.93	0.90	1.04	0.55	1.00	0.90	0.90	1.00	0.55
Numerical Analysis Result					Experimental Analysis Result				

5.3. Comparison of Ratio Analysis For 0.20 San Salvador Ground Motion Record

Table 5.2. 0.20 San Salvador Ratio Analysis Results of Experimental Study and Numerical Study.

ST80/40/2-AL80/40/2-020SAN SALVADOR					ST80/40/2-AL80/40/2-020SAN SALVADOR				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	2.30	2.66	0.87	0.97	1.00	2.55	2.66	0.96	0.97
1	3.00	3.20	0.94	1.03	1.00	3.43	3.20	1.07	1.03
1	3.27	3.28	1.00	1.04	1.00	3.44	3.28	1.05	1.04
ST40/20/1-AL40/20/1-020SAN SALVADOR					ST40/20/1-AL40/20/1-020SAN SALVADOR				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	NA	NA	NA	NA	1.00	NA	NA	NA	NA
1	4.13	4.07	1.02	1.11	1.00	4.25	4.07	1.04	1.11
1	3.04	2.96	1.03	1.01	1.00	2.96	2.96	1.00	1.01
ST80/40/2-ST40/20/1-020SAN SALVADOR					ST80/40/2-ST40/20/1-020SAN SALVADOR				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	2.53	2.24	1.13	0.52	1.00	2.08	2.24	0.93	0.52
1	2.43	2.58	0.94	0.54	1.00	2.60	2.58	1.01	0.54
1	2.93	2.95	0.99	0.57	1.00	2.95	2.95	1.00	0.57
AL80/40/2-AL40/20/1-020SAN SALVADOR					AL80/40/2-AL40/20/1-020SAN SALVADOR				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	NA	NA	NA	NA	1.00	NA	NA	NA	NA
1	3.35	3.29	1.02	0.59	1.00	3.22	3.29	0.98	0.59
1	2.73	2.67	1.02	0.55	1.00	2.54	2.67	0.95	0.55
ST80/40/2-AL40/20/1-020SAN SALVADOR					ST80/40/2-AL40/20/1-020SAN SALVADOR				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	NA	NA	NA	NA	1.00	NA	NA	NA	NA
1	10.04	10.50	0.96	0.60	1.00	11.04	10.50	1.05	0.60
1	8.91	8.75	1.02	0.58	1.00	8.74	8.75	1.00	0.58
AL80/40/2-ST80/40/2-020SAN SALVADOR					AL80/40/2-ST80/40/2-020SAN SALVADOR				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	0.43	0.38	1.15	1.04	1.00	0.39	0.38	1.04	1.04
1	0.33	0.31	1.07	0.97	1.00	0.29	0.31	0.93	0.97
1	0.31	0.30	1.00	0.96	1.00	0.29	0.30	0.95	0.96
AL80/40/2-ST40/20/1-020SAN SALVADOR					AL80/40/2-ST40/20/1-020SAN SALVADOR				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	1.07	0.84	1.27	0.54	1.00	0.82	0.84	0.97	0.54
1	0.81	0.81	1.00	0.53	1.00	0.76	0.81	0.94	0.53
1	0.90	0.90	1.00	0.55	1.00	0.86	0.90	0.95	0.55
Numerical Analysis Result					Experimental Analysis Result				

5.4. Comparison of Ratio Analysis For 0.20 Loma Prieta Ground Motion Record

Table 5.3. 0.20 Loma Prieta Ratio Analysis Results of Experimental Study and Numerical Study.

ST80/40/2-AL80/40/2-020 LOMA PRIETA					ST80/40/2-AL80/40/2-020 LOMA PRIETA				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	2.59	2.61	0.99	0.97	1.00	2.65	2.67	0.99	0.97
1	3.27	3.20	1.02	1.03	1.00	3.53	3.48	1.02	1.03
1	3.28	3.28	1.00	1.04	1.00	4.31	3.28	1.32	1.04
ST40/20/1-AL40/20/1-020 LOMA PRIETA					ST40/20/1-AL40/20/1-020 LOMA PRIETA				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	NA	NA	NA	NA	1.00	NA	NA	NA	NA
1	4.03	4.07	0.99	1.11	1.00	4.02	4.07	1.02	1.11
1	2.94	2.96	0.99	1.01	1.00	2.51	2.96	1.07	1.01
ST80/40/2-ST40/20/1-020 LOMA PRIETA					ST80/40/2-ST40/20/1-020 LOMA PRIETA				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	2.18	2.20	0.99	0.52	1.00	2.28	2.25	1.02	0.52
1	2.67	2.58	1.04	0.54	1.00	2.80	2.81	1.00	0.54
1	3.00	2.95	1.02	0.57	1.00	3.15	2.95	1.07	0.57
AL80/40/2-AL40/20/1-020 LOMA PRIETA					AL80/40/2-AL40/20/1-020 LOMA PRIETA				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	NA	NA	NA	NA	1.00	NA	NA	NA	NA
1	3.29	3.29	1.00	0.59	1.00	3.29	3.29	1.00	0.59
1	2.70	2.67	1.01	0.55	1.00	2.30	2.67	0.86	0.55
ST80/40/2-AL40/20/1-020 LOMA PRIETA					ST80/40/2-AL40/20/1-020 LOMA PRIETA				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	NA	NA	NA	NA	1.00	NA	NA	NA	NA
1	10.76	10.50	1.02	0.60	1.00	11.63	11.43	1.02	0.60
1	8.84	8.75	1.01	0.58	1.00	9.94	8.75	1.14	0.58
AL80/40/2-ST80/40/2-020 LOMA PRIETA					AL80/40/2-ST80/40/2-020 LOMA PRIETA				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	0.386	0.383	1.009	1.035	1.00	0.38	0.37	1.01	1.04
1	0.306	0.313	0.977	0.968	1.00	0.28	0.29	0.98	0.97
1	0.305	0.305	1.000	0.958	1.00	0.23	0.30	0.76	0.96
AL80/40/2-ST40/20/1-020 LOMA PRIETA					AL80/40/2-ST40/20/1-020 LOMA PRIETA				
T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio	T ratio	E _i Ratio	Mass Ratio	E _i /m Ratio	L Ratio
1	0.84	0.84	1.00	0.53	1.00	0.86	0.84	1.02	0.54
1	0.82	0.81	1.01	0.53	1.00	0.79	0.81	0.98	0.53
1	0.92	0.90	1.02	0.55	1.00	0.73	0.90	0.81	0.55
Numerical Analysis Result					Experimental Analysis Result				

Table 5.4. N Value for Recommended Formula.

Ground Motion Data	N value (Energy Spectrum)	N value (SAP2000 Model)	N value (Experimental Study)
0.20 Loma Prieta (Soil A)	1.93	0.50	0.40
0.20 San Salvador (Soil B)	1.87	2.00	1.90
0.20 Erzincan (Soil C)	2.14	0.47	0.35

Experimental results and numerical results for mass normalized input energy are correlated with each other that are shown in Figure 5.1-Figure 5.3. Mass normalized energies obtained from experimental study and numerical study are covered by Dindar (2015) input energy spectrum curve as shown in Figure 5.1-Figure 5.3. Thus, N value derived from energy spectrum analysis gives more reliable information about energy scale factor between specimens at different periods. It can be said that N value approximately is equal to 2. That means, energy scale factor formula at the same period and different period case could be expressed as in Equation 5.1.

$$\lambda_e = \frac{\lambda_E \lambda_I}{\lambda_L^3} \lambda_T^N = \frac{\lambda_E \lambda_I}{\lambda_L^3} \lambda_T^2 \quad (5.1)$$

6. SUMMARY AND CONCLUSION

Earthquake resistant design of structures with energy-based design method requires that energy dissipation capacity of the system must be greater than energy imparted into the structure. Thus, information about input energy should be provided in design methodologies. Energy imparted into the structure is dissipated by energy dissipation mechanism of the structure. Plastic deformations and ductility determine energy dissipation and also the damage level of earthquake.

In this study, dimensional analysis was incorporated with the energy based design method. Dimensional analysis was applied to find the scale factor of spectral input energy between SDOF systems. Variables for SDOF systems such as length of column, moment of inertia of cross section, modulus elasticity of the material and period of the structure are combined to scale prototype to actual structures' input energies.

Analytical studies and experimental studies were performed to get a scale factor for spectral input energy between SDOF systems. The results of the analytical studies for input energy scale factor were verified with thirty-six experimental studies. Each analysis was done at same period and at different periods for each defined binary case in Table 3.24. As a result of these studies, input energy scale factor between SDOF systems under same earthquake ground motion record was found as mass scale factor derived from dimensional analysis as shown in Equation 3.23.

Results of the all studies can be expressed as;

- In elastic range, input energy is dissipated by damping of the system and restored by the kinetic and potential energy of the system.
- Dimensional analysis of the energy gives an energy scale factor as $\lambda_E \lambda_L^3$, but analysis results show that dimensional analysis result for energy cannot be used as energy scale factor. Because, based on dimensional analysis principle, displacement term in energy equation has same dimension with length of the specimen

as L . It means that displacement ratio is equal to the length scale factor between specimens. Displacement scale factor cannot be equal to the length scale factor always although they have same dimensional term as meter (L). Thus, $\lambda_E \lambda_L^3$, equation does not valid for scale factor of input energy between SDOF systems.

- Although specimens are different in terms of material properties and length, spectral input energy ratio between them is proportional to their mass ratio. Also, mass ratio is equal to the mass scale factor formula derived from dimensional analysis. Thus, mass scale factor formula is valid to calculate the spectral input energy ratio between different specimens at same period under same ground motion record in elastic range.
- λ_m is the mass scale between specimens and λ_e is the energy scale between specimens, Experimental study and analytical study verify that mass scale is equal to the energy scale. Thus, mass normalized input energy ratios of specimens are equal at same period under same ground motion record follows Equation 3.23. This result verifies that there should be an energy spectrum for SDOF systems.
- Also, at different periods under same ground motion record between SDOF systems, spectral input energy ratio is equal to the mass scale as shown as Equation 3.23. This result shows that mass scale factor could be used to get input energy ratio between SDOF systems under same ground motion record for different period also.

As a result of the complete study for SDOF systems, input energy could be calculated from its prototype input energy value by using mass scale factor between them. Thus, recommended formula for input energy scale is the mass scale derived from dimensional analysis as follow Equation 3.23. This makes design process easier and time saving during design process. The formula for input energy ratio between SDOF systems is shown as Equation 3.34.

This research was done only for SDOF structure in elastic range. However, this study needs to be extended to inelastic range and multi degree of freedom systems. Similar experiment should be done for MDOF structures in elastic and inelastic range.

REFERENCES

- Benavent C., A., Francisco, L. Almansa and A.B.G. Diego, “Design Energy Input Spectra for Moderate - to - High Seismicity Regions Based on Colombian Earthquakes”, *Soil Dynamics and Earthquake Engineering*, Vol. 30, No. 11, pp 1129-1148, 2010.
- Calvi, G.M., M.J.N. Priestley, M.J. Kowalsky, “Displacement-based seismic design of structures”, *3rd National Conference on Earthquake Engineering and Engineering Seismology*, 2008.
- Chopra, A.K. “Dynamics of Structures: Theory and Applications to Earthquake Engineering”, *Prentice-Hall*, 2001.
- D’Ambrisi, A. and M. Marco, “An Energy-Based Approach for Nonlinear Static Analysis of Structures.” *Bulletin Of Earthquake Engineering*, Vol. 13, No. 5, pp. 1513-1530, 2015.
- D’Ambrisi, A., M. Marco, “An Energy-Based Approach for Nonlinear Static Analysis of Structures”, *Bulletin of Earthquake Engineering*, Vol. 13, No. 5, pp. 1513-1530, 2015.
- Decanini, L.D., and M. Fabrizio, “An Energy-Based Methodology for the Assessment of Seismic Demand”, *Soil Dynamics and Earthquake Engineering*, Vol. 21, No. 2, pp. 113-137, 2001.
- Decanini, L.D., and M. Fabrizio, “Formulation of Elastic Earthquake Input Energy Spectra”, *Earthquake Engineering and Structural Dynamics*, Vol. 27, No. 12, pp. 1503-1522, 1998.
- Dindar, A.A. *et al.*, “Development of Earthquake Energy Demand Spectra”, *Earthquake Spectra*, Vol. 31, No. 3, pp. 1667-1689, 2015.

- Fajfar, P., “Capacity Spectrum Method Based On Inelastic Demand Spectra”, *Earthquake Engineering and Structural Dynamics*, Vol. 28, No. 9, pp. 979-994, 1999.
- Gioncu, V. and M. Federico, “Earthquake Engineering For Structural Design”, *CRC Press*, 2010.
- Hibbeler, R.C., “Structural Analysis”, *Simon and Schuster Books for Young Readers*, 1995.
- Kuwamura, H. and V. Theodore, “Earthquake Load for Structural Reliability”, *Journal of Structural Engineering*, Vol. 115, No. 6, pp. 1446-1462, 1998.
- Leelataviwat, S., C.G. Subhash and S. Bozidar, “Energy-Based Seismic Design Of Structures Using Yield Mechanism And Target Drift”, *Journal of Structural Engineering*, Vol. 128, No. 8, pp. 1046-1054, 2002.
- Léger, P. and D. Serge, “Seismic-Energy Dissipation in MDOF Structures”, *Journal of Structural Engineering*, Vol. 118, No .5, pp. 1251-1269, 1992.
- Medhekar, M.S., D.J.L. Kennedy, “Displacement - Based Seismic Design of Buildings-Theory”, *Engineering Structures*, Vol. 22, No. 3, pp. 201-209, 2000.
- Moehle, J.P., “Displacement - Based Design of RC Structures Subjected to Earthquakes”, *Earthquake Spectra*, Vol. 8, No. 3, pp. 403-428, 1992.
- Newmark, N.M., and J.H. William, “Earthquake Spectra and Design”, *Earth System Dynamics*, 1982.
- Priestley, M.J.N., “Performance Based Seismic Design”, *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 33, No. 3, pp. 325-346, 2002.
- Priestley, M.J.N., G.M. Calvi, and M.J. Kowalsky, “Direct Displacement - Based Seismic Design of Structures”, 2007 NZSEE Conference. 2007.

- Riddell, R. and E.G. Jaime, "Hysteretic Energy Spectrum and Damage Control", *Earthquake Engineering and Structural Dynamics*, Vol. 30, No.12, pp. 1791-1816, 2011.
- Takewaki, I., "Earthquake Input Energy to Two Buildings Connected By Viscous Dampers", *Journal of Structural Engineering*, Vol.133, No. 5, pp 620-628, 2007.
- Terenzi, G. "Dynamics of SDOF Systems with Nonlinear Viscous Damping", *Journal of Engineering Mechanics*, Vol. 125, No. 8, pp. 956-963, 1999.
- Uang, C.M., and V.B. Vitelmo, "Evaluation of Seismic Energy in Structures", *Earthquake Engineering and Structural Dynamics*, Vol. 19, No.1, pp. 77-90, 1990.
- Uang, C.M., and V.B. Vitelmo, "Earthquake Simulation Tests and Associated Studies of a 0.3 - Scale Model of a Six - Story Concentrically", *Braced Steel Structure*, Vol. 86. No. 10. 1986.
- Vidic, T., F. Peter and F. Matej, "Consistent Inelastic Design Spectra: Strength and Displacement", *Earthquake Engineering and Structural Dynamics*, Vol. 23, No. 5, pp. 507-521, 1994.
- Ye, L. *et al.*, "Study on Energy-Based Seismic Design Method and Application on Steel Braced Frame Structures", *Jianzhu Jiegou Xuebao Journal of Building Structures*, Vol. 33, No. 11, pp. 36-45, 2012.
- Zahrah, T.F. and J.H. William, "Earthquake Energy Absorption in SDOF Structures", *Journal of Structural Engineering*, Vol. 110, No. 8, pp. 1757-1772, 1984.