Numerical Study and Optimization of Post-Tensioning Energy Dissipating Connections with Inerters

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NUMERICAL STUDY AND OPTIMIZATION OF POST-TENSIONING ENERGY DISSIPATING CONNECTIONS WITH INERTERS

by

HECTOR BLANCO GAVILLAN
B.S. College of Engineering and Computer Science 2022

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Sciences in the Department of Civil, Environmental and Construction Engineering in the College of Engineering and Computer Science at the University of Central Florida

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ABSTRACT

Posttensioned connections for steel moment resisting frames (MRF) can reduce residual deformations through self-centering capabilities. Devices are added to improve the connections energy dissipating capability and includes energy dissipating (ED) bars, friction dampers, and steel angles located at the top and bottom of the beam-to-column connections. The Post-Tensioned Energy dissipating (PTED) connection reduces inelastic deformation to the beams and columns, is installed with minimum welding, displays self-centering thus reducing residual deformations, and allows for easy replacement of the ED devices.

An inerter is a two-terminal mechanical device that generates a force proportional to the relative acceleration between its nodes. The inerter dampens structural responses, inter-story drift, and vibration by simulating a mass element; the mass of an inerter is very small. The inertance is a constant of proportionality that illustrates the simulated mass of the device.

This Thesis aims to reduce residual drift by comparing the different PTED connections and the inerter. Three PTED models utilizing either ED bars, friction dampers, or steel angles as ED devices are created using the finite element software OpenSees. Each model is subjected to eleven different earthquakes and the structure responses are compared to a typical welded moment resisting frame (WMRF). Results indicate that the seismic performance of PTED connections exceed that of the WMRF.

Each PTED model is re-subjected to the eleven earthquakes with the addition of the inerter. The responses are compared to the WMRF and the PTED models that do not include the inerter. Models
utilizing the inerter exhibited better seismic performance than the WMRF and PTED models that did not have the inerter.

Optimization of the PTED connections with and without the inerter is conducted by using a genetic algorithm that focuses on parameters of the ED devices and posttensioned strands. Furthermore, the genetic algorithm revealed that uniform parameters, that is the external and internal calculations having the same parameters, on a given story is the optimal design in all but one connection. The optimal solution is the PTED connection utilizing friction dampers and inerter which displayed the lowest residual drift.
ACKNOWLEDGEMENTS

I would like to express my thanks and gratitude to all my professors here at the University of Central Florida, both as an undergraduate and graduate student. You have all made my goal possible, achievable, and a reality.

I would like to highlight my thanks and gratitude to Professor Georgios Apostolakis. Without his patience, passion, and knowledge, this Thesis would have gone nowhere. I am sure there are times where it felt as if we were making no progress, but you were correct, this entire process has taught me much more than a typical course would have.

The greatest thanks and gratitude are reserved for my family, blood and non-blood. Their thoughtfulness and concern have made this stage of my life all the more easier. To all my siblings: Melysa, Maklin, Ava, Mateo, Santiago, and Carolina. To my fiancé, Kelly Perez, your sacrifice knows no bounds. Finally, to my parents, Hector, and Iris, for their support and encouragement; we did it!
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CHAPTER 1: INTRODUCTION

The mention of earthquakes can be found in a multitude of antiquated records and alongside, the mention of a great loss of life. Comparing natural disasters, earthquakes rank as one of the most destructive, capable of great loss of life and livelihood. Each year, around 100,000 earthquakes are felt by people worldwide and on average 10,000 people die each year. Loss of life is certainly the worst outcome from the destruction of earthquakes, but economic losses can devastate the livelihoods of survivors and the economy of an unfortunate country; one severe consequence is not necessarily the loss of structures, but the cost of recovery. Table 1.1 below displays the financial losses from important earthquakes.

Not to mention, other natural disasters have the potential of spawning after an earthquake such as fires and tsunamis, which can lead to further losses. Monetary losses are in the billions and with more and more developing countries continuing to urbanize, the damaging effects of earthquakes have the potential to increase. Psychological effects can also be a consequence as survivors have to deal with recovery, loss of loved ones, fear, helplessness, PTSD, and depression.
Table 1.1: Financial losses of important earthquakes that occurred from 1970 to 2011.

<table>
<thead>
<tr>
<th>Country</th>
<th>Earthquake Location</th>
<th>Year</th>
<th>Loss ($ billion)</th>
<th>Loss (% GNP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nicaragua</td>
<td>Managua</td>
<td>1972</td>
<td>2.0</td>
<td>40.0</td>
</tr>
<tr>
<td>Guatemala</td>
<td>Guatemala City</td>
<td>1976</td>
<td>1.1</td>
<td>18.0</td>
</tr>
<tr>
<td>Romania</td>
<td>Bucharest</td>
<td>1977</td>
<td>0.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Yugoslavia</td>
<td>Montenegro</td>
<td>1979</td>
<td>2.2</td>
<td>10.0</td>
</tr>
<tr>
<td>Italy</td>
<td>Campania</td>
<td>1980</td>
<td>45.0</td>
<td>6.8</td>
</tr>
<tr>
<td>Mexico</td>
<td>Mexico City</td>
<td>1985</td>
<td>5.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Greece</td>
<td>Kalamata</td>
<td>1986</td>
<td>0.8</td>
<td>2.0</td>
</tr>
<tr>
<td>El Salvador</td>
<td>San Salvador</td>
<td>1986</td>
<td>1.5</td>
<td>31.0</td>
</tr>
<tr>
<td>USSR</td>
<td>Armenia</td>
<td>1988</td>
<td>17.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Iran</td>
<td>Manjil</td>
<td>1990</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Japan</td>
<td>Kobe</td>
<td>1995</td>
<td>100</td>
<td>~2.0</td>
</tr>
<tr>
<td>China</td>
<td>Wenchuan</td>
<td>2008</td>
<td>60</td>
<td>1.8</td>
</tr>
<tr>
<td>New Zealand</td>
<td>Canterbury</td>
<td>2010</td>
<td>6</td>
<td>5.3</td>
</tr>
<tr>
<td>Haiti</td>
<td>Port-au-Prince</td>
<td>2010</td>
<td>8</td>
<td>12.1</td>
</tr>
<tr>
<td>Chile</td>
<td>Santiago</td>
<td>2010</td>
<td>30</td>
<td>19</td>
</tr>
<tr>
<td>New Zealand</td>
<td>Christchurch</td>
<td>2011</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Japan</td>
<td>Sendai</td>
<td>2011</td>
<td>210-300</td>
<td>3.8-5.4</td>
</tr>
</tbody>
</table>

As a response, earthquake engineering came to life, and for all intent and purposes, is a relatively new and young discipline. In the beginning, the consensus on earthquake engineering was to use an equivalent static procedure and over time dynamic considerations were introduced. Some early buildings centuries ago have proven resistant to earthquakes and remain intact and standing but that is more the exception rather than the rule; seismic analysis was not yet developed. Seismic analysis is a tool for engineers to estimate the structural responses in the design of structures subjected to earthquakes. In theory it can be difficult because the responses can be nonlinear, dynamic, and random. Earthquake engineering is considered interdisciplinary and encompasses seismologists, civil engineers, architects, data technologists, and social scientists. The numerous different disciplines are essential to one another to help learn, communicate, and grow the field of earthquake engineering.

Specifically in the United States, earthquake engineering commenced after the 1906 earthquake in San Francisco. This resulted in more stringent building standards for the city of San Francisco but unfortunately were lowered due to the slow rebuilding of the city. Some engineers began to integrate allowances for the effect of earthquakes felt by buildings by using an equivalent wind-speed approach. Harry Fielding Reid, a professor at John Hopkins University devised his elastic rebound theory in 1910 and it remains the basis of the principal model of an earthquake cycle. Essentially his theory states that the Earth’s crust stores elastic stress that is suddenly released during an earthquake. It is akin to a stretched rubber band that is suddenly cut or broken; and releases the stored elastic energy.

The first edition of the Uniform Building Code (UBC) published after the 1925 Santa Barbara earthquake mentions the effects of earthquakes but falls short by not mentioning any specific
design requirements. The 1930 edition of the UBC was the first time a design equation was mentioned. The lateral static seismic force at any given story of a building was formulated as:

$$F = CW$$

(1.1)

where $W$ is the total dead load plus the design live load above that story and $C$ is a seismic coefficient that is dependent on the design strength of the foundation material. The 1930 edition also sets forth strict standards for mortar and construction of masonry buildings. Following the 1933 Long Beach earthquake, the state of California legislated the Field and Riley acts that required seismic design for almost all public buildings and schools. The 1949 edition of the UBC introduced the concept of seismic zoning which defined values for the seismic coefficient ($C$), which was introduced in the 1930 edition. Three seismic zones were considered, and the maximum value of $C$ (0.100) was given for Zone 3.

The Structural Engineering Association of California (SEAOC) published the first version of the Recommended Lateral Requirements and Commentary (commonly known as the Blue Book) in 1959. The first edition stated that the base shear equation as:

$$V = KCW$$

(1.2)

where $K$ is the horizontal force factor which depends on the structural system used to resist seismic forces. This factor evolves into the strength reduction factor that is used in current codes and practice. In this edition, the seismic coefficient ($C$) is now dependent on the fundamental period of the building. In 1961, the American Association of State Highway and Transportation Officials (AASHTO) adopts the 1943 California Department of Transportation provisions for the seismic design of bridges in all the United States. In 1977, the United States Congress passed the Earthquake Hazards Reduction Act which established the National Earthquake Hazard Reduction
Program (NEHRP); the NEHRP is now the source of innovation, code development, and code writing in the practice of earthquake engineering.

The 1990’s experienced an increase in the science of earthquake engineering primarily because of the Internet and advances in computer technologies. The National Science Foundation (NSF) funded three earthquake engineering research centers in 1997. Also occurring in the 1990’s was the implementation of performance-based earthquake engineering in codes. The International Building Code (IBC) published in 2000 reflects the desire to design structures to reach and surpass specific performance levels while under increased levels of seismic activity. This was led by expectations of structure owners, local municipalities, and insurance owners, who, to mitigate potential losses, now expect not only prevention of structural collapse but also limited damage in the structure. Too much damage will require the structure to be demolished adding to the financial cost/loss.

This discipline is concerned with the estimation of earthquake consequences and the mitigation of said consequences. More importantly, efforts are geared towards (1) The protection of human lives, (2) Prevention of structure collapse, and (3) Limiting structural damage. It has evolved into life-safety design performance level under a design level earthquake and a collapse prevention performance level under a maximum earthquake. Structural engineers aim to meet these objectives by controlling building responses during and after an earthquake. It can be considered as a balance between supply and demand; demand being imposed actions, forces, and deformations, and supply being the capacity to withstand the demand. One important factor to consider is a trade-off between safety and cost; it is not economically feasible to construct a structure capable of withstanding a strong earthquake without suffering any damage. This type of system is an elastic system which is
designing the structure stiff/strong enough to remain elastic during a seismic event. Additionally, due to the random nature of earthquakes it is also unsafe to design a structure as strictly elastic; the structure would not have sufficient ductility and could collapse during a maximum seismic event.

In response, a yielding system (inelastic system) is more favorable which controls forces and accelerations by using nonlinear fuses; these fuses are plastic hinges. As shown in Figure 1.1, compared to an elastic system, the yielding system controls the maximum seismic force while having a maximum displacement similar to, or larger than the elastic system and dissipates energy through hysteretic yielding. It is most beneficial to design energy dissipation into components that are not part of the gravity or lateral resisting system.

Figure 1.1: Yielding system and the corresponding elastic system (Apostolakis 2006)
Numerous earthquake resistant systems exist to protect and reduce damage in structures during and after a seismic event. Primarily this is achieved by way of supplemental damping or base isolation systems. Supplemental damping dissipates energy by introducing additional damping into a structure; these can be either active, semi-active, or passive damping. Supplemental damping could affect the natural period of the structure. Passive supplemental damping work without external power sources and are activated by the movement of the structure. They are unable to adapt to changes in either structural properties or to the random nature of external excitations and/or earthquakes. Examples of passive supplemental damping include friction and viscoelastic dampers. In contrast, active supplemental damping works by use of external power sources. Active dampers can adapt to a wide range of operating conditions and structures. Examples include tuned mass dampers and rheological dampers. Meanwhile, semi-active supplemental damping combines both by displaying the reliability of passive supplemental damping and the adaptability of active supplemental damping. Base isolation systems protect the structure by using a support that isolates the structure from the ground shaking. It works by introducing a low lateral stiffness between the structure and foundation which lengthens the period. Examples include lead rubber bearing and friction pendulum sliding bearing. As mentioned before, both systems aim to protect and reduce damage in structures from seismic events by altering the response and behavior of the structure and thus these systems should be implemented with care.

With an inelastic system, energy dissipation is done by way of hysteretic yielding. The area under the hysteretic curve is a measure of how much energy is dissipated, therefore, a larger area relates to more energy dissipated per cycle and thus smaller peak structure responses are anticipated.
Different hysteretic curves are possible depending on the energy dissipation method chosen as shown in Figure 1.2.

Figure 1.2: Examples of Hysteric Loops (Apostolakis 2006)
The hysteretic curves shown in Figure 1.2 could also predict the residual drift of a system. As stated above, the shape of the hysteresis loop is a direct measure of the energy dissipation capacity of a given system which is signified by the area under the curve. The force-loading relationship, more specifically the loading and unloading path of the force, dictates the amount of residual drift a system could experience. Once the loading reaches zero, if the displacement is not at zero, that would imply some value of residual drift.

Although an elastoplastic hysteretic curve is larger in theory, Priestley and Tao (1993), Brewer (1993), and Christopoulos et al. (2002) demonstrated that the flag-shaped hysteretic curve results in similar or even smaller displacements when subjected to an earthquake. Furthermore, a flag-shaped hysteretic curve makes it more difficult for a structure to reach resonance and due to the posttensioning, it has self-centering capability resulting in little to no residual drifts compared to a typical elastoplastic hysteretic curve. A posttensioning energy dissipating connection exhibits a flag-shaped hysteretic curve while typically a steel moment resisting frame exhibits an elastoplastic hysteretic curve.

The flag-shaped hysteretic curve demonstrates more desirable characteristics, such as self-centering and energy dissipation, when compared to a typical moment resisting frame and therefore is the optimal system. This paper will compare three different posttensioning energy dissipating (PTED) connections to a traditional welded moment resisting frame (WMRF) in an effort to reduce building responses (drift, residual drift, and acceleration) felt during and after an earthquake. Additionally, the three PTED connections will then include an inerter device and will again be compared to each other and the WMRF. Finally, a genetic algorithm is applied to optimize the design of the PTED connections.
CHAPTER 2: LITERATURE REVIEW

This chapter aims to introduce and summarize the relevant topics that are discussed and studied in this Thesis. Previous studies on each topic were investigated and reviewed to understand the history and to recognize any gaps that could be covered by the current study. The chapter begins by first introducing self-centering connections, followed by PTED connections and the different devices used in the connections, next is the discussion on the inerter damper, and ends on genetic algorithms.

2.1 Self-Centering Systems

Self-centering systems have the characteristics of controlling damage and reducing or even eliminating residual drift in a structure following a seismic event.

The National Institute of Standards and Technology (NIST) initiated a multi-phase study. The first study by Cheok and Lew (1991) first introduced and tested the seismic performance of a self-centering connection on a precast concrete beam-column connection. Four monolithic connections were compared to two precast, posttensioned connections. Results conclude that the posttensioned precast concrete beam-to-column connection is as strong and ductile as the monolithic connection however, this type of connection could use improvement on energy dissipation.

Priestley and Tao (1993) explored a self-centering connection with a partially debonded posttensioned tendon. Preliminary results indicate that the ductility demands of a partially debonded posttensioned tendon was no different than one of a fully bonded posttensioned strand.
Cheok and Lew (1993) investigated the location of posttensioned steel, posttensioning vs prestressed steel strands, and the use of bonded vs unbonded steel strands. Results showed that all precast concrete specimens displayed similar failure modes indicated by yielding of the posttensioned steel, beam crushing, and opening at the connection. The opening at the connection increased when the posttensioned strands were placed closer to the centroid of the beam. All specimens had lower story drift values at failure when compared to the monolithic specimens. The results also indicate that the precast concrete specimens still need improvement on energy dissipation.

Cheok and Stone (1994) and Cheok et al. (1998) studied the use of hybrid precast connections. The term hybrid refers to the use of mild strength steel and high strength steel in the connection. The idea is that the mild strength steel will serve as an energy dissipator. Results from this study reveal that the hybrid connection can be designed to replicate a monolithic connection in terms of connection strength, drift capacity, energy dissipation, residual drift, and damage to the concrete.

Macrae and Priestley (1994) investigated interior and exterior ungrouted posttensioned precast concrete joint subassemblies to determine the seismic performance of ungrouted prestressed precast frames. Results indicate that the subassembly achieved drifts up to 4% but with no major strength degradation nor damage.

El-Sheikh et al. (1998) created two models for an unbonded posttensioned precast concrete frame and subjected them to nonlinear push over static and dynamic time history analyses. The study demonstrates that the posttensioned precast frame experiences higher drift but smaller residual drift when compared to a typical cast-in-place reinforced concrete frame due to the posttensioned
strands. Results indicate that the frame has poor energy dissipation but smaller residual deformations when compared to similar cast-in-place concrete frames.

Priestley et al. (1999) conducted an experimental study where a five-story precast concrete building was constructed and subjected to simulated seismic events. The model building included four different ductile structural frame systems. These consisted of the hybrid posttensioned connection, the Tension/Compression/Yielding (TCY) gap connection, the TCY connection and a pretensioned connection. Results indicate that each of the systems performed well despite experiencing seismic intensities 50% above the design level. Damage to the wall building was indicated by minor spalling and cracking at the wall base, floor slabs, column bases. In the frame direction, the damage was much smaller than what would be expected from an equivalent reinforced concrete structure. The TCY gap connection displayed more damage than the other connections in the early stages but can be corrected by minor changes in the design criteria. For more detailed results and information, refer to the study.

Rosenboom and Kowalsky (2004) expanded posttensioning systems by investigating their use into clay brick masonry walls. Their study constructed five walls that utilized posttensioning strands. Variables for the walls included bonded versus unbonded posttensioning steel, grouted versus ungrouted masonry, confined versus unconfined masonry, and application of mild steel as energy dissipators. Results from the study indicate that the best configuration was the unbonded and confined wall. Unbonded posttensioning walls have little to no residual deformation but also have low energy dissipation. Kurama et al. (1999a and 1999b) established methods for the design and analysis of this system.
Kurama and Shen (2004) investigated concrete walls coupled with steel beams that include posttensioning. The steel beam is not embedded into the concrete walls. The concrete walls were either precast or cast-in-place while the steel beam was a W-section. The coupled beams included four posttensioned tendons, while steel angles were also included at the top and bottom of the connection between the steel beam and concrete wall. Results indicate that the posttensioned steel beams behave like the embedded steel beams while producing minor damage and minor residual drifts. A drawback to the unembedded steel couple beams is the energy dissipation capability when compared to the embedded steel beam even with the steel angle connections.

Arguably the overarching theme from the self-centering connections utilizing posttensioning tendons is the poor energy dissipation of the tendons during a seismic event. This can be seen in Figure 2.1 which presents the idealized bilinear elastic hysteretic curve of a posttensioned connection where little to no energy is dissipated. This eventually led to studies incorporating devices strictly aimed at energy dissipation while the posttensioning tendons recenter the structure and significantly reducing residual drift.

![Figure 2.1: Idealized hysteretic curve for posttensioned connections (Priestley & Tao 1993)](image)
2.2 Posttensioning Energy Dissipation (PTED) Connections

A PTED connection employs posttensioning tendons to provide self-centering capabilities and a device aimed at improving energy dissipation. Currently, no real structures exist that use a PTED connection as a seismic resistant system, but previous studies conducted full scale modeling to fully test the connection. A PTED connection is more economical than a WMRF due to minimal welding requirements and the easy replacement of ED devices instead of the replacement of a beam-column connections or structure after a seismic event.

Section 2.2 introduces three different devices and begins with a discussion on energy dissipation bars, continued with friction dampers, and ends with steel angles. These three devices are modeled and tested in this study.

2.2.1 Energy Dissipating (ED) Bars

Christopoulos et al. (2002) presented a posttensioned connection that includes energy dissipating bars based on a concept from Stanton et al. (1997). This connection utilizes the posttensioning strands that run along the length of the beam and are anchored at the exterior columns. The energy dissipation device is a steel bar that is capable of axial yielding in tension and compression. They are located at the top and bottom of the beam on either side of the web. During this study, this connection was investigated analytically and experimentally. The monotonic moment-rotation relationship was determined analytically. The experimental portion reveals that the PTED connection can experience large deformations with energy dissipation characteristics but without damage or residual drift.
Christopoulos (2004) investigated the behavior of single degree of freedom systems that exhibit the flag-shaped hysteresis loop; shown in Figure 2.2. The study concludes that when properly designed, systems with the flag-shaped hysteresis loop will experience maximum deformation demands while only dissipating about half of the energy dissipation capability of an equivalent elastoplastic system, with the exception that flag-shaped system will eliminate residual drift. The study also states caution that flag-shaped systems can reach resonance under certain loading. Subsequent studies by Collins (2002), Chou et al. (2009), Apostolakis (2006), and Apostolakis et al. (2014) demonstrated numerical and experimental studies on the PTED connection. Chou et al. (2009) experimentally investigated a full-scale subassembly consisting of PTED connections. The subassemblies demonstrate that the PTED connection has durability in terms of strength and energy dissipation.

Figure 2.2: Hysteretic curve for a PTED connection (Apostolakis 2006)
Different styles and uses for ED bars are investigated in the following studies. Wang et al. (2019) reviewed bamboo shaped ED bars inside a PTED connection used on a precast concrete frame. Different values of the connection parameters were also evaluated. Results from experimental tests revealed that the connection displayed a stable hysteretic behavior without strength degradation and demonstrated self-centering capabilities. Sarti et al. (2016) performed an experimental and numerical evaluation on a milled down steel bar that is filled with either grout or epoxy. The objective of the study was to collect data that can be used for the dissipator design and to calibrate a hysteretic rule. Similarly, Aragon et al. (2019) also studied the use of ED bars that are now surrounded by grout as opposed to being filled with grout. Rahmzadeh et al. (2018) investigated the use of ED bars with steel bridge piers that are subject to rocking. The steel bridge piers also utilize posttensioning strands to provide self-centering capabilities. Similarly, Shen et al. (2021) performed cyclic tests on posttensioned precast concrete columns with ED bars.

2.2.2 Friction Dampers as ED devices

Morgen and Kurama (2004) introduced the use of friction dampers with a PTED connection for use on a precast concrete frame. The study tested full scale frames with and without friction dampers under cyclic loading. Study results demonstrate that the dampers can provide sufficient energy dissipation.

Rojas et al. (2005) extended the use of friction dampers to steel moment resisting frames. The friction dampers are located on the beam flanges and requires no welding. Inelastic analyses were performed on six-story, four-bay steel moment resisting frame. Results indicate that the combination of the posttensioned tendons with the friction dampers creates an initial stiffness
similar to a typical welded moment resisting frame. Additionally, analytical models demonstrate that the PTED connection performs better than a typical welded moment resisting frame while reducing residual drift.

Kim and Christopoulos (2008, 2009) further investigated the use of friction dampers with PTED connections. Their studies concluded that the frictional behavior is stable, repeatable, and predictable although it has a relatively low friction coefficient. The PTED connection can produce similar stiffness and strength to that of a welded frame and undergoing large deformations with good energy dissipation without inducing inelastic deformations or residual drift. They also outlined a design procedure of the PTED connection; a model was created using the proposed solution and tested. Results support that the friction damper connection produces similar drifts and accelerations but almost zero residual drift when compared to a welded moment resisting frame.

Further studies investigated the use of friction dampers located in the bottom flange of the beam. Iyama et al. (2009) studied the connection considering static and dynamic loading and concluded that the asymmetric nature of the connection leads to increased inelastic strain in the top beam flange which could lead to the flange buckling. Despite the increased inelastic strain, Wolski et al. (2009) demonstrated that the bottom flange friction damper is can still provide reliable energy dissipation without experiencing damage.

Tsai et al. (2008) presented the force-deformation relationship of a web bolted friction damper with the posttensioned tendons and conducted full scale testing. Results conclude that the force-deformation relationship yielded reasonable experimental results and that the hysteretic behavior is very stable. Additional studies conducted by Lin et al. (2008, 2013, and 2013), Zhang et al.
(2016), and Song et al. (2014 and 2015) support the idea of placing a friction damper on the beam web.

2.2.3 Steel Angles as ED devices

Shen and Astaneh-Asl (1999 and 2000) presented an experimental investigation into the behavior of bolted steel angles. They focused on the inelastic behavior under large cyclic deformation, failure modes under cyclic loading, and the energy dissipation of capacity of the steel angles. Their results established a foundation for the development of a behavioral hysteresis model of bolted steel angles. Their subsequent model then presented a hysteresis model for bolted angle connections.

Ricles et al. (2001) proposed the use of steel angles as energy dissipation devices for a PTED connection on a steel frame. Advantages include no field welding required, the stiffness is similar to a welded moment resisting frame, self-centering capability, and significant damage is isolated to the steel angles. The study also presented an analytical model calibrated by experimental testing. Subsequent experimental and analytical studies investigated the seismic performance of the bolted angles (Ricles et al., 2001 and 2002, Garlock et al., 2005, Guan et al., 2018) and the effect of the angle and bolt geometry on the stiffness, strength, and energy dissipation of the connection (Garlock et al. 2003). Results from these studies indicate that this connection holds good seismic performance and provides satisfactory elastic stiffness, strength, and ductility under cyclic loading. Due to the self-centering capability, these connections residual drift is reduced. Damage is concentrated the steel angles which allow the beams and columns to remain elastic.
Further studies utilizing steel angles were also conducted on posttensioned precast concrete frames. Cai et al. (2021 and 2021) conducted experimental and numerical studies and results reflect the same conclusions gathered from the use of steel angles on steel frames. Lu et al. (2015) investigated self-centering reinforced concrete frames. Posttensioned strands were inputted along the beam connected at the ends to the columns. In addition, they were added to the columns and anchored to the ground. Steel angles were also included at the beam-to-column connections for energy dissipation. A ½ scale model was created and tested using a shake table. In addition, a numerical model was created using OpenSees. Results indicate that the self-centering reinforced concrete frame displays satisfactory seismic performance. Base column uplift was observed but no structural damage was observed, and the model returned to its initial position and displayed negligible residual deformation. Cui et al. (2017) investigated a tri-axial self-centering concrete frame through shake table tests. Posttensioned strands were included in the beams and columns. This allows the beam-to-column joints to recenter in the X and Y direction while the base column will recenter via gravity and the PT tendons in the Z direction. Steel angles were also included at the base columns for energy dissipation. A ½ scale three story model was created and tested. The study demonstrates that the tri-axial self-centering reinforced concrete frame performed satisfactorily to seismic events. No major damage was observed throughout the testing. The natural frequency of the structure decreased by 24%. Gap openings were observed but the model self-centered and little to no residual drift was observed.

Jiang et al. (2020) presented and tested, numerically and experimentally, a similar connection. A steel arc plate was used instead of a steel angle in the PTED connection. The connection was first theoretically analyzed in detail and validated by experimental testing; a parametric analysis is
simulated. Results from the study conclude that the new joint exhibits a bilinear elastoplastic moment-rotation relationship. The joint exhibits flag-shaped hysteresis curves while the steel arc plate provides energy dissipation.

In general, the hysteretic curve of an ED device demonstrates significant energy dissipation capability measured by the area under the curve. Due to it being a pure yielding device, residual drift and damage are expected since the displacement is not zero when the force reaches zero; as shown in Figure 2.3. Coupled with a posttensioned connection, the sought-after characteristic of energy dissipation and reduced displacement is reached; as shown in Figure 2.2.

2.3 Inerter Damper

Smith (2002) first introduced the inerter as the device equivalent to the electrical capacitor. The inerter is a mechanical device that generates a force that is proportional to the relative acceleration between its nodes as shown in Figure 2.4. Equation 2.1 below displays the relationship between the force and relative acceleration. A constant of proportionality (denoted by the letter b) called
the inertance with units of kilograms is introduced and is effectively a mass equivalent; in other words, an inerter with an inertance of 300 kg exhibits the same force as a 300 kg mass. This is beneficial given that an inerter as a device should have a small mass. This constant characterizes the behavior of the inerter. Inerter devices were first applied in vehicle suspension systems, more specifically inside Formula 1 race cars, but given the benefit inerter have, to reduce vibrations and displacements, it quickly moved to more civil applications.

\[ F = b(\dot{v}_2 - \dot{v}_1) \]  \hspace{1cm} (2.1)

![Figure 2.4: Schematic of a two-terminal inerter (Wagg 2019)](image)

Pradono et al. (2018) and Domenico and Ricciardi (2018, 2018, 2018) investigated the use of an inerter alongside a base isolated structure. Their studies conclude that the inerter can further reduce the responses of an already dampened building. Hwang et al. (2007) numerically investigated the use of the inerter with toggle bracing and concluded that the use of the inerter alongside other energy dissipation mechanisms can reduce structural vibration.

Smith’s initial study introduced a rack and pinion inerter. Papageorgiou and Smith (2005) built on Smith’s initial study by introducing a ball and screw inerter which alongside the rack and pinion inerter, works by the rotation of a flywheel. Papageorgiou et al. (2009) experimentally tested these
devices and found that the model inerter does not behave like the ideal inerter due to friction. Figure 2.5 below is a picture of both iners.

![Image of inerters](image)

Figure 2.5: Rack and Pinion Inerter (left) and Ball-and-Screw Inerter (right) (Smith 2005)

Unfortunately, the rotating flywheels inside the inerter store energy that has the possibility of transferring it back into the structure which may add to the displacement of the structure. Makris and Kampas (2016) and Makris and Moghimi (2018) proposed the use of two parallel rotational inertia systems that only resist the motion without adding to it. This concept works by using a clutch so that the pinion of each gearwheel of the two parallel systems are unable to drive the rack and instead only the motion of the translating rack can drive the pinion-gearwheel. This is considered the cluthcing inerter damper (CID). Further studies were conducted involving the analysis and use of CID (Wang and Sun 2018, Li et al. 2019, Chuquitaype et al. 2019, Liang and Li 2020 and 2020).
Ikago et al. (2012) and Garrido et al. (2013) studied and introduced a new type of viscous damper consisting of a ball and screw inerter connected to a viscous damper. Essentially it is a ball and screw inerter that still utilizes a rotating flywheel, but the screw also extends further and is connected to a cylinder that rotates through a viscous fluid. The results conclude that the viscous inerter damper is more effective at reducing responses when compared to more traditional damper systems. Swift et al. (2013) proposed the fluid inerter: an inerter that utilizes a mass of fluid flowing through helical channels to provide the inertance. This type of inerter can also be considered as a viscous damper since the fluid through the helical channels behaves better with a viscous fluid. The device inertance can be increased by reducing the area of the channel or increasing the area of the piston. More recently, Javidialesaadi and Wierschem (2019) introduced the one directional rotational inertia viscous damper (ODRIVD) which behaves like a CID by not allowing energy to transfer back into the structure.

Nakamura et al. (2014) introduced the electromagnetic inerter mass damper (EIMD) which consists of a ball and screw inerter and an electric generator. The combination of the rotating flywheel and rotating generator produces an inertial force. The generator also produces damping forces by the dissipation of electromagnetic energy. Shaking table tests indicate that the EIMD can reduce story drifts and accelerations and performs better when compared to conventional dampers. Luo et al. (2017) proposed the electromagnetic resonant shunt tuned mass damper inerter (ERS-TMDI). Zhu et al. (2019) built on Nakamura’s 2014 study by being able to suppress vibrations and harvest energy from the EIMD.

Several studies investigated the use of inerter in specific layouts. Lazar et al. (2013) proposed the use of an inerter in place of a tuned mass damper (TMD). While a TMD behaves on a single story,
a tuned inerter damper (TID) behaves in between stories and is in series with a spring and damper. Essentially the inerter replaces the TMD; refer to Figure 2.6. Numerical results indicate a reduction in structure vibration. Later studies investigate the analysis and design of TID.

Similarly, Marian and Giaralis (2013) proposed the use of inerters alongside traditional TMD; to work in tandem; also known as a tuned-mass damper inerter (TMDI). Figure 2.7 demonstrates the layout. Results from this study demonstrate that the combination of the inerter and TMD reduced peak average top floor displacement compared to an optimally designed TMD. Numerous subsequent studies arose investigating the analysis and optimal design of the TMD and inerter.

![Figure 2.6: Schematic representation of a TID (Lazar et al. 2013)](image)

![Figure 2.7: Schematic representation of a TMDI (Marian & Giaralis 2013)](image)
2.4 Genetic Algorithm

Genetic algorithms belong to the non-classical method of solving problems or optimizing solutions. Non-classical methods are based on heuristic concepts and rely on computing power to conduct an extensive and thorough search. The fitness of trial parameters is analyzed, and the next set of parameters are chosen either by neural or evolutionary means.

Evolutionary algorithms are a search algorithm that are based on the heuristic concept of natural selection, adaptation, and genetic operators and work by mimicking these concepts. Genetic algorithms are under the evolutionary algorithms umbrella.

Holland (1975) first introduced the idea of genetic algorithms (GA) by studying adaptation in nature and fostered an artificial version for use in computer systems. The GA imitates evolution in nature by natural selection. The genetic algorithm consists of chromosomes which represent a population member within a generation. It works by evolution of populations into the next generation by means of genetic operators, such as crossover and mutation. The genetic operators work on probability which also dictates which genes of a population individual will move onto the next generation; this is done by calculating the fitness of the individual. Advantages of the GA include the higher chance of global optimization due to the algorithm searching from population to population and genetic operators, easier to understand and implement, probabilistic in nature, requires only one objective function to calculate the fitness of a population, and has a self-start capability which does not require an initial guess.

Previous studies investigated the use of genetic algorithms for civil applications. Levin and Lieven (1998) compared the genetic algorithm to another optimization algorithm, the simulated annealing
(SA). Their study presented the theory of each algorithm and then applied each to a FE model updating problem. It was concluded that the SA outperformed the GA, but the GA could have been improved by increasing the discretization level at the expense of a longer computing time. Cunha et al. (1999), Chou and Ghaboussi (2001), and Koh et al. (2003) also tested the GA by means of structural identification applications.

Other studies include, Camp et al. (1998) using a genetic algorithm to optimize the design of two-dimensional structures, Furuta et al. (1998) and Dogaki et al. (2001) using a genetic algorithm to optimize the painting schedule of a bridge and to optimize the maintenance planning of reinforced concrete decks respectively, Sato et al. (2000) determining the optimal arrangement of base-isolators by means of genetic algorithms, and similarly, Movaffaghi and Friberg (2002) optimizing the location of visco-elastic dampers by genetic algorithms.

structures with passive devices. Finally, Blanco and Apostolakis (2022) proposed an evolutionary aseismic control of steel frames with self-centering systems.

2.5 Summary

This chapter presented the relevant topics included in this thesis and will be investigated further. Self-centering connections can control damage and reducing residual drift in posttensioned connections, but with the drawback of a limited ability of dissipating energy. The hysteretic curve of a posttensioned connection is an idealized bilinear elastic line. Devices aimed specifically at energy dissipating through hysteretic yielding are presented alongside the posttensioned connections. Devices include an ED bar, friction damper, and steel angle. This new connection labeled as a posttensioned energy dissipating (PTED) connection displays self-centering capabilities and satisfactory energy dissipation. A pure yielding system like the ED devices display a hysteretic curve that will result in result drift but with great energy dissipation capacity. Adding both the posttensioned strands with an ED device results in a hysteretic curve shaped like a flagpole. The flagpole hysteretic curve as mentioned in the first chapter can produce similar or smaller displacements compared to an elastoplastic hysteretic curve and is considered ideal. Although no current structure uses a PTED connection, previous studies conducted full scaled modeling and testing. No real dollar amount exists when comparing a WMRF to a PTED connection, but arguably the PTED connection is more economical than the WMRF due to minimal welding requirements and the cost of replacing an ED device is less compared to replacing an entire beam-column connection or structure. The addition of the inerter device was included since it is a novel seismic resistant system and previous studies have not investigated the use of
inerters with PTED connections. The flagpole hysteretic curve and PTED connections with the addition of inerters are investigated further while being optimized by way of genetic algorithms.
CHAPTER 3: METHODOLOGY

The previous chapter discussed and summarized the relevant literature review on the topics that this paper includes. Foremost, a structure can exhibit self-centering capabilities with the inclusion of post tensioned (PT) strands. Previous studies concluded the use of PT strands as a viable connection in high seismic regions and helps with the reduction of residual drift after an earthquake event. The downside is the energy dissipation capabilities of a PT connection. The inclusion of energy dissipating devices alongside post tensioned strands creates a posttensioned energy dissipating connection (PTED) which dissipates energy through hysteretic yielding. There exists different ED devices and previous studies investigated steel bars, steel angles, and friction dampers. In addition, an inerter is a device introduced by Malcom Smith that reduces vibrations and displacements. Numerous different inerter devices exist that ranges from rotational inerter dampers, electromagnetic inerter dampers, viscous inerter dampers, and can be used alongside traditional tuned mass dampers or in substitute of one. Finally, genetic algorithms are a computational framework that imitates natures evolution by natural selection. Previous studies demonstrated the use of genetic algorithms to optimize the design of different civil applications.

This chapter will discuss and summarize the methods performed to first, create the moment resisting frame, the three PTED connections, and the three PTED connections with the inerter using OpenSees, second, create MATLAB scripts for the iterative testing of the structures and for the use of genetic algorithms for the optimal design of the PTED connections, and finally, the post-processing of the results using MATLAB.
The general overview of the methodology applied in this thesis is presented below:

- Perform literature review of topics.
- Take previous DRAIN-2DX WMRF and PTED models and convert them into OpenSees.
- Create new PTED models inside OpenSees utilizing friction dampers and steel angles as ED devices.
- Use the genetic algorithm inside MATLAB and OpenSees to perform dynamic analysis of several generations of different PTED models using different seismic events. Each model represents a structure with different parameters.
- Use MATLAB to perform post-processing of results taken from OpenSees.
- Determine which PTED model and which parameters yield the best results.

This thesis paper builds upon the work of Apostolakis (2006) and Apostolakis et. al (2014) in which a computational framework is used to optimize the design of a PTED connection. In those two papers, Drain-2DX software was used for the modeling of the structures. For this paper, OpenSees is used as the finite element analysis program. OpenSees is an open-source software from the Pacific Earthquake Engineering Research (PEER) center. Due to past limitations of available computational procedures, the goal of OpenSees development is to improve the modeling and computational simulation in earthquake engineering. The following sections go into more detail of how each step was created and performed.
3.1 **Welded Moment Resisting Frame (WMRF)**

Due to the different syntax of the two software, the first step taken was to take the previous Drain-2DX models and alter them into OpenSees compatible models. The first model transferred from Drain-2DX to OpenSees was the traditional welded moment resisting frame. The floor dimensions of the building are 120 ft x 90 ft and has four bays in the east to west direction and three bays in the other direction; each bay is 30 ft wide. There are three floors with the first floor being 14 ft high while the second and third floor are both 11.5 ft high. The building columns differ depending on which floor it is located on and whether it is an exterior or interior column. Meanwhile, the first and second floors have the same beam size while the third floor has a different, smaller beam. The design of the beams includes a reduced section for all three floors. Figure 3.1 and 3.2 below displays the plan view and the east to west elevation view of the model. Member sizes and properties for the beams and columns are presented in Table 3.1: the section area $A$, the second moment of inertia about the strong axis $I_x$, the section plastic moment $M_p$, the reduced RBS section plastic moment $M_p^{RBS}$, and the axial yielding force $C$.

<table>
<thead>
<tr>
<th>Section</th>
<th>Beam</th>
<th>Area, $in^2$</th>
<th>$I_x, in^4$</th>
<th>$M_p, kip - in$</th>
<th>$M_p^{RBS}, kip - in$</th>
<th>$C_Y, kips$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W18X40</td>
<td>11.8</td>
<td>612</td>
<td>3920</td>
<td>3136</td>
<td>590</td>
<td></td>
</tr>
<tr>
<td>W21x57</td>
<td>16.7</td>
<td>1170</td>
<td>6450</td>
<td>5160</td>
<td>835</td>
<td></td>
</tr>
<tr>
<td>W14x43</td>
<td>12.6</td>
<td>428</td>
<td>3480</td>
<td>N/A</td>
<td>630</td>
<td></td>
</tr>
<tr>
<td>W14x90</td>
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<td>999</td>
<td>7850</td>
<td>N/A</td>
<td>1325</td>
<td></td>
</tr>
<tr>
<td>W14x82</td>
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<td>881</td>
<td>6950</td>
<td>N/A</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>W14X176</td>
<td>51.8</td>
<td>2140</td>
<td>16000</td>
<td>N/A</td>
<td>2590</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.1: Plan view of WMRF (Apostolakis 2006)

Figure 3.2 Elevation view of WMRF Modeling of the WMRF (Apostolakis 2006)
Like the Drain-2DX model, the OpenSees model is considered as a two-dimensional assemblage of columns and beams, therefore, the centerline properties are used, and the beams and columns are connected at intersecting joints. The gravity and seismic masses are lumped at the intersection of the beam and column joints.

The beams are modeled using the OpenSees element ‘elasticBeamColumn’ and are designed and modeled to consider reduced beam sections (RBS). The plastic hinges are assumed to be located a length equal to the beam depth away from the column face. The RBS sections have a plastic moment that is reduced by 80% ($0.8 M_p$). The stiffness of the plastic hinges was modeled into OpenSees by calculating the modified rotational stiffness and assigned to the nodes and elements that were placed at the location of the plastic hinges; a special OpenSees command ‘rotSpring_STEEL01’ was used to model the hinges. The strain hardening ratio and damping were also modified by a similar procedure and assigned to the modified elements.

The columns were also modeled using the OpenSees element ‘elasticBeamColumn’. P-delta effects are considered and modeled inside the software. An additional column line is modeled adjacent to the building as ‘elasticBeamColumn’. These columns have a large moment of inertia and area values to combine the aggregate effect of all gravity columns. OpenSees truss elements are used to connect and transfer the P-delta effects to the main frame. P-M interaction curves per AISC-LRFD 2001 for symmetric members under bending and axial compression is defined by the following equations:

$$\frac{c}{C_y} + \frac{8}{9} \frac{M}{M_p} = 1, \text{ for } \frac{c}{C_y} \geq 0.2 \quad (3.1)$$

$$\frac{c}{2C_y} + \frac{M}{M_p} = 1, \text{ for } \frac{c}{C_y} \leq 0.2 \quad (3.2)$$
where \( C \) is the axial compression force at the section, \( C_y \) is the axial yielding force of the section, \( M \) is the moment of the section, and \( M_p \) is the plastic moment of the section.

For axial tension the interaction curve is defined by the following equation:

\[
\frac{T}{T_y} + \frac{M}{M_p} = 1
\]  

(3.3)

where \( T \) is the axial tension in the section and \( T_y \) is the axial yielding force of the section. Figure 3.3 represents a graphical representation of the interaction curves.

The yielding stress of the steel is assumed to be 50 MPa while the tension yield force is assumed to be the same as the compression yield force since the sections used in the model are compact. The column connections at the ground were modeled as fixed connections while the additional P-delta columns are pinned.

![Figure 3.3: Column P-M Interaction Curve (Apostolakis 2006)]
To account for uniform damping energy for elastic and inelastic response, a damping coefficient of 2% of the critical damping is used for the model. Rayleigh damping is used and calculated using the following equation:

\[ C = \alpha M + \beta K \]  

(3.4)

where \( C \) is the damping matrix, \( M \) is the mass matrix, and \( K \) is the elastic stiffness matrix.

The coefficients \( \alpha \) & \( \beta \) are calculated using the following equations:

\[ \alpha = \zeta \frac{2\omega_i \omega_j}{\omega_i + \omega_j} \]  

(3.5)

\[ \beta = \zeta \frac{2}{\omega_i + \omega_j} \]  

(3.6)

where \( \zeta \) is the damping ratio, and \( \omega_i \) & \( \omega_j \) are the cyclic frequency of the \( i^{th} \) and \( j^{th} \) mode respectively.

For the analysis of this building, the first and third modes are used to calculate the coefficients above. This results in a good distribution of damping at all the significant modes. Due to the floor slab in-plane rigidity the exterior nodes at every floor are restrained in the horizontal direction. The columns are modeled as fixed connections at the base of the building.

3.2 Description of the Genetic Algorithm (GA)

As mentioned earlier, one purpose of this paper is to optimize the design of the PTED connection; that is to determine which combination of parameters yield the best results when subjected to a seismic event. Optimization is done using the genetic algorithm and MATLAB software. The genetic algorithm works by considering the evolution of generations. Each generation has a set number of population which for the purpose of this study represents a different combination of PT
and ED parameters. For example, the genetic algorithm could start with one generation that has a population of 2. Each member of the population will be subjected to an earthquake and thus will have different drift, residual drift, and acceleration results. These results will be compared to one another to determine which population member yielded the best results. The member with the best results will then have its combination of PT and ED parameters weighed more favorably. This gives it a better chance that the parameters in that population member will be replicated in the next generation. The process then repeats itself by moving onto the next generation where the population will have members with randomly selected parameters, parameters from the previous generation that yielded the best results, or a combination of both random and best parameters. This is achieved by replicating genetics. Like genetics in nature, genes can be selected, cross overed, or mutated; this is mimicked inside the genetic algorithm. This process continues for a set number of generations and population size. This process ensures the best PT and ED parameters are selected by comparing it to the other parameters in a role of “survival of the fittest”; only the best parameters can move onto the next generation.

There are a total of two MATLAB scripts that work in tandem for the GA. At the beginning of the GA certain input parameters must be specified. Four different parameters, each with eight different values, are considered for the PTED connection and investigated in four different scenarios using the genetic algorithm. Each of the six different PTED models includes eight GA scripts (two for each scenario). Scenario 1 represents the exterior and interior PTED beam-to-column connections having different parameters. This means both exterior connections on a single floor will have the same parameters while the interior connections will have different parameters. Scenario 2 is the same as Scenario 1 with the exception that a wider range of parameters are considered. A total of
eight values are still used but the range between the minimum and maximum values of a given parameter is increased. Scenario 3 considers all connections on a given floor use the same parameter values, while scenario 4 considers uniform parameters with a wider range of options.

The GA works by means of binary chromosomes and therefore, each of the eight values of parameters from each scenario for a given PTED model is converted into binary. This makes it easier for evaluating and choosing the parameters that will move onto the next generation. A single chromosome represents one story of one population member inside a generation. Like in nature, a chromosome is made up of genes; a single parameter is the equivalent to a gene. An allele represents every different possible of a gene. Since binary only has two digits (ones and zeros), for it to represent a single parameter/gene, three bits are needed; \(2^3 = 8\), where 2 is the binary digits, 8 is the number of parameter values; solving this will give you three bits per parameter/gene. In later sections, the eight values of the four parameters and their equivalent binary gene of each PTED model are presented. Figure 3.4 below displays a visual representation of a sample binary chromosome.

After the inputs, the GA is ready to begin; there is a capability to randomize the initial population parameters or input a chromosome and essentially choose the initial parameters. The random option is chosen to start each PTED model. The GA begins by taking the randomly chosen parameters and converts them into an equivalent chromosome. To correctly model certain elements, OpenSees software calls those certain parameters be in the form they call for. An example is inputting the yielding force instead of yielding stress. This portion is explained in more detail in the later sections.
Once the correct parameters from the initial generation are chosen randomly, correctly converted in a binary chromosome, and exported into text files, the dynamic analysis part of the GA is ready to begin. MATLAB calls the OpenSees software to model the population member using the input parameters. OpenSees then subjects the population member to the first earthquake and saves the results in separate text files. These results are post processed internally in MATLAB. The results are inputted into the relative performance index (RPI). The RPI was introduced to evaluate the performance of each population member within a generation. The RPI is calculated as follows:

$$RPI = \alpha \frac{\text{Drift Results}}{\text{Drift Target}} + \beta \frac{\text{Res.Drift Results}}{\text{Res.Drift Target}} + \gamma \frac{\text{Vel.Results}}{\text{Vel.Target}} + \delta \frac{\text{Acc.Results}}{\text{Acc.Target}}$$  \hspace{1cm} (3.7)$$

where the Greek coefficients denote weights that add up to unity.
The drift, residual drift, velocity, and acceleration targets are values that the PTED models aim to meet for it to be considered as a feasible alternative to the traditional WMRF model. The drift, velocity, and acceleration results represent the absolute maximum value for each story for a given seismic event. The residual drift is calculated by taking the absolute average of the tail end drift values experienced by the model during a seismic event. The number of values taken into consideration is a function of the model natural period and time step of the seismic event. A fitness value is calculated by taking the inverse of the computed RPI for a given earthquake. A member fitness is also calculated by taking the average of all 11 fitness values. This member fitness is what is taken into consideration when comparing the entire population of a given generation and to determine which parameters yield the best results and thus should move onto the subsequent generation. The target values and their weights (Greek coefficients) used to calculate the RPI are presented in Table 3.2.

<table>
<thead>
<tr>
<th>Value</th>
<th>Target Value</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>1.5 %</td>
<td>0.4</td>
</tr>
<tr>
<td>Residual Drift</td>
<td>0.5 %</td>
<td>0.4</td>
</tr>
<tr>
<td>Velocity</td>
<td>50.0 in/sec</td>
<td>0.0</td>
</tr>
<tr>
<td>Acceleration</td>
<td>1.0 g</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The weights presented in Table 3.2 were chosen and thus not taken from another study or code. A higher weight was given to the residual drift response to focus on a model’s residual drift since the objective of this study is to reduce that response. If the weights were equal or a higher weight was
given to another response, it could lead to systems with a high RPI value due to acceleration or drift values below the target values, but with a high residual drift. This is unfavored and thus a systems RPI value should be more influenced by its residual drift response.

Meanwhile, the target values for drift, residual drift, velocity, and acceleration were chosen from FEMA P58 and FEMA 356. These codes present a variety of limits that depend on a structures height, occupancy, lateral stiffness, lateral system type, lateral strength, and design ground motion.

Each PTED model in this paper is subjected to 101 generations; each generation has a population of five. Each population member inside a generation is subjected to all 11 earthquakes for the first generation and every five generations afterwards (Generation 1, 6, 11, 16, etc.). The generations in between (Generation 2-5, 7-10, etc.) are only subjected to the five worst earthquakes which were calculated and described during the generations that included all 11 earthquakes. Essentially, the first generation includes all 11 earthquakes and the five earthquakes that cause the models to exhibit poor results are branded as the worst-case scenario or strongest earthquakes. It is these five earthquakes that the next generations will be subjected to. At generation six, the population will once again be subjected to all 11 earthquakes and the process repeats itself. This is included inside the GA so that the population in a generation are being tested against the strongest earthquakes. Weaker earthquakes have the potential of skewing the results because a population member could receive a high RPI due to very good results from the weaker earthquakes.

At this point, the first population member has been modeled, subjected to the first earthquake, and given a RPI value. The GA then calls for the population member to be subjected to the next earthquake and the process repeats itself for all applicable earthquakes before moving onto the
next population member. All 11 of the earthquake time histories are saved in a text file that OpenSees references and are not used in the MATLAB script; however, MATLAB does ensure that the population is subjected and moves to all applicable earthquakes.

The GA then moves into creating the next generation after all population members are tested. The GA starts at population member number one and compares the RPI to different members. Depending on the RPIs of the other two members in question, the GA moves into three different scenarios. Scenario 1 is when the “left” member has a higher RPI than the “right” member. Scenario 2 is when the “right” member has a higher RPI than the “left” member, and Scenario 3 is when both “left” and “right” have the same RPI value. Once a scenario is chosen, there are 3 subsequent scenarios which now depend on the current member RPI. Only one is chosen and this determines what action is taken in terms of creating the next generation. Subsequent scenario 1 is when the current member is the most fit (highest RPI) and thus no crossover is warranted with the “left” and “right” and a mutation event is warranted. Subsequent scenario 2 is when the current member is the least fit (lowest RPI) and therefore the “left” and “right” members will crossover with each other, and the current member will mutate. The last subsequent scenario depends on the previous scenario level. Either the current member will crossover with “left” or “right” (dependent on which has the highest RPI) and will mutate, or the current member will only mutate while the “left” and “right” members crossover.

Crossover and mutation events are the process in which parameters are introduced into the next generation. The idea is to create new blocks of different chromosomes to consider every parameter and every combination of parameters in a model. Population members inside a generation with a
high RPI have a greater opportunity to send their well performing parameters into the subsequent generation. These events are controlled by inputted probabilities.

In a crossover event, either a single or double crossover event can ensue where bits of two “parent” chromosomes are exchanged to produce two “offspring” chromosomes; this essentially creates a new population member for the subsequent generation. During a crossover event, the probability of a single-point crossover is 80% and thus there is a lower probability that there will be double crossover event will occur. Recall that also inside the GA for a double crossover point to occur, the scenarios that are dependent on the RPIs must call for a double crossover event. Figure 3.5 illustrates a visual representation of a single point crossover event.

![Figure 3.5: Representation of crossover (left) and mutation (right) event (Apostolakis 2006)](image)

During a mutation event, every bit inside a chromosome has a chance to change its value (0 to 1 or 1 to 0), which also creates new chromosomes. There is a 5% probability that a mutation event
will occur. Based on the aforementioned scenarios, it is possible that a chromosome could be subjected to both a crossover and mutation event.

3.3 **PTED: ED, Friction, and Angles**

Three different PTED models were created using the OpenSees software. One model was created for each energy dissipating device this paper investigates: energy dissipating bars, friction dampers, and steel angles. The sections below describe how each model generally works, how they were modeled, and how the genetic algorithm was altered for each connection.

3.3.1 **PTED connection using ED bars**

Discussed in the previous chapter, during a seismic event the building starts to sway which creates gap openings at the top and bottom of the beam-to-column connections. This PTED connection uses posttensioned strands that run parallel to the beams and are anchored at the exterior columns. In addition, energy dissipating bars are located at the top and bottom of the beam on each side of the beam web. The PT strands allow the structure to self-center itself after a seismic event which closes the gaps, while the ED bars dissipate energy and can yield in both compression and tension. Once an ED bar yields, it is easily replaceable. This connection works by isolating inelastic action to the ED bars and keeps the beams and columns elastic.

Comparable to the WMRF model, the OpenSees PTED model is considered as a two-dimensional assemblage of columns and beams, therefore, the centerline properties are used. The gravity and seismic masses are lumped at the column joints.
Unlike the WMRF model, this model accounts for the beam depth. Three nodes are used to model the beam depth at the external and internal beam-to-column connection as shown in Figure 3.6 and 3.7. The central node of the column is slaved to the central node of the beam in the Y direction. It is assumed no deformation takes place in the column panel zone; therefore, the addition of rigid elements connects the top and bottom column node to the central node. This assumption is based on Christopoulos et al. (2002). The study conducted a large-scale connection test that reinforced the column web with a doubler plate and stiffeners. Testing results revealed no noticeable damage at the PTED connection, no deformation in the column panel zone or column flanges. Thus, in the present thesis panel zone is not explicitly modeled.

The contact between the beam and column is modeled with two parallel contact elements connecting the top and bottom of beam to the column. For modeling, TwoNodeLink elements are used inside OpenSees to model the contact elements. This element behaves like the contact element and experiences gap opening in tension and high initial stiffness in compression. A stiffness value of 150000 kips/inch is used for the first and second story contact elements, while a stiffness value of 130000 kips/inch is used for the third story contact elements. Figure 3.8 displays the hysteretic curve of the contact element model.

The energy dissipating bars are modeled inside OpenSees using the element TwoNodeLink. This element uses a pre-defined uniaxial material that asks for a yielding force, stiffness, and strain hardening ratio. Figure 3.9 illustrates the bilinear elasto-plastic rule used to model the ED bars. Since the two parameters that are being considered for the optimization of the ED bars are the ED bar area and ED bar length, the parameters that OpenSees uses are calculated inside MATLAB and exported.
Figure 3.6: External connection model accounting for beam depth (Apostolakis 2006)
Figure 3.7: Internal connection model accounting for beam depth (Apostolakis 2006)
These internal calculations are completed using the material properties of the ED bars which are as follows: yielding stress is 60 ksi, Young’s Modulus is 30 ksi, and strain hardening ratio is 0.02. Equation 3.8 and 3.9 are used to calculate the yielding force and stiffness respectively.

\[ F_{y,ED} = A_{ED} \times f_{y,ED} \quad (3.8) \]

\[ K_{ED} = \frac{A_{ED} \times E_{ED}}{L_{ED}} \quad (3.9) \]

where \( A_{ED} \) represents the area, \( f_{y,ED} \) represents the yield stress, \( E_{ED} \) represents the Young’s Modulus, and \( L_{ED} \) represents the length of the ED bars.

Figure 3.8: Hysteretic rule for the contact elements (Apostolakis 2006)
Like the ED bars, two PT strand parameters are being optimized: PT area and initial prestress level. To model the PT strands inside OpenSees, a uniaxial material is predefined that utilizes an initial strain. This initial strain value must be calculated internally inside MATLAB and exported to OpenSees. The material is then used with the truss element which also asks for an area. A Young’s Modulus of 28,000 ksi and ultimate stress of 270 ksi are used with the PT area and initial prestress level to calculate the initial strain. The posttensioned strands inside OpenSees connect the exterior nodes at each floor level. Figure 3.10 illustrates the hysteretic rule of the PT strands and Equation 3.10 is used to complete the calculations:

\[
\varepsilon_{PT} = \frac{\text{Prestress level of PT} \times f_{u,PT}}{E_{PT}} \quad (3.10)
\]

where \( f_{u,PT} \) represents the ultimate stress and \( E_{PT} \) represents the Young’s Modulus of the PT strands. The values of prestress level for the PT strands are presented in a later section.
Reinforced beam sections are modeled near the beam-to-column connections to ensure the beam remains elastic during the gap opening and closing. These are modeled as separate elasticBeamColumn elements inside OpenSees and have their own properties separate from the beams. These properties are given below in Table 3.3.

**Figure 3.10: Hysteretic rule of PT strands (Apostolakis 2006)**

<table>
<thead>
<tr>
<th>Reinforced Beam Sections</th>
<th>( A, \text{inches} )</th>
<th>( I_X, \text{in}^4 )</th>
<th>( M_P, \text{kip-in} )</th>
<th>( C_Y, \text{kips} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>W18X40</td>
<td>18.4</td>
<td>1175.7</td>
<td>6974.4</td>
<td>921.1</td>
</tr>
<tr>
<td>W21X57</td>
<td>23.9</td>
<td>2015.8</td>
<td>10355.7</td>
<td>1195.8</td>
</tr>
</tbody>
</table>
To account for uniform damping energy for elastic and inelastic response, a damping coefficient of 2% of the critical damping is used for the model. Rayleigh damping is used and calculated using the following equation:

\[ C = \alpha M + \beta K \]  

(3.11)

where \( C \) is the damping matrix, \( M \) is the mass matrix, and \( K \) is the elastic stiffness matrix.

The coefficients \( \alpha \) & \( \beta \) are calculated using the following equations:

\[ \alpha = \zeta * \frac{2 \omega_i \omega_j}{\omega_i + \omega_j} \]  

(3.12)

\[ \beta = \zeta * \frac{2}{\omega_i + \omega_j} \]  

(3.13)

where \( \zeta \) is the damping ratio, and \( \omega_i \) & \( \omega_j \) are the cyclic frequency of the \( i^{th} \) and \( j^{th} \) mode respectively.

For the analysis of this building, the first and third modes are used to calculate the coefficients above. This results in a good distribution of damping at all the significant modes. Due to the floor slab in-plane rigidity the exterior nodes at every floor are restrained in the horizontal direction. The columns are modeled as fixed connections at the base of the building.

P-delta effects are considered and modeled inside the software. An additional column line is modeled adjacent to the building as ‘elasticBeamColumn’. These columns have a large moment of inertia and area values to combine the aggregate effect of all gravity columns. OpenSees truss elements are used to connect and transfer the P-delta effects to the main frame. P-M interaction curves per AISC-LRFD 2001 for symmetric members under bending and axial compression is defined by the following equations:
\[
\frac{C}{C_y} + \frac{8}{9} \frac{M}{M_p} = 1, \text{ for } \frac{C}{C_y} \geq 0.2 \quad (3.14)
\]
\[
\frac{C}{2C_y} + \frac{M}{M_p} = 1, \text{ for } \frac{C}{C_y} \leq 0.2 \quad (3.15)
\]

where \(C\) is the axial compression force at the section, \(C_y\) is the axial yielding force of the section, \(M\) is the moment of the section, and \(M_p\) is the plastic moment of the section.

For axial tension the interaction curve is defined by the following equation:

\[
\frac{T}{T_y} + \frac{M}{M_p} = 1 \quad (3.16)
\]

where \(T\) is the axial tension in the section and \(T_y\) is the axial yielding force of the section.

The yielding stress of the steel is assumed to be 50 MPa while the tension yield force is assumed to be the same as the compression yield force since the sections used in the model are compact.

The P-delta columns are pinned at the ground.

In terms of the PTED connection utilizing the ED bars, four different parameters are considered for the PTED connection and investigated in four different scenarios using the genetic algorithm. As mentioned before, Scenario 1 represents the exterior and interior PTED beam-to-column connections having different parameters. This means both exterior connections on a single floor will have the same parameters while the interior connections will have different parameters. Scenario 2 is the same as scenario 1 with the exception that a wider range of parameters are considered. A total of eight values are still used but the range between the minimum and maximum values of a given parameter is increased. Scenario 3 considers all connections on a given floor use the same parameter values, while scenario 4 considers uniform parameters with a wider range of options. The four parameters optimized for this connection include the ED area, ED length, PT
area, and PT prestress level. Recall that previously in this chapter it was stated that OpenSees needs certain parameters to model the structure correctly. Because of this the GA takes the inputted parameters and internally calculates and exports them for OpenSees to use. In terms of chromosome bits, the ED area corresponds to the ED yielding force, the ED length corresponds to the ED stiffness, and the PT initial prestress level corresponds to the PT strain. Table 3.4 below shows the parameter values of each scenario.

**Table 3.4: Parameter values for the ED Bar connection**

<table>
<thead>
<tr>
<th>Scenario 1 &amp; 3</th>
<th>Parameter</th>
<th>Parameter Values</th>
<th>(allele)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ED Area</td>
<td>0.4 0.5 0.6 0.7 0.8 0.9 1 1.1</td>
<td>in²</td>
</tr>
<tr>
<td></td>
<td>ED Length</td>
<td>13 15 17 19 21 23 25 27</td>
<td>in</td>
</tr>
<tr>
<td></td>
<td>PT Area</td>
<td>1.085 1.302 1.519 1.736 1.953 2.17 2.387 2.604</td>
<td>in²</td>
</tr>
<tr>
<td></td>
<td>PT Prestress</td>
<td>26 28 30 32 34 36 38 40</td>
<td>%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario 2 &amp; 4</th>
<th>Parameter</th>
<th>Parameter Values</th>
<th>(allele)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ED Area</td>
<td>0.4 0.6 0.8 1 1.2 1.4 1.6 1.8</td>
<td>in²</td>
</tr>
<tr>
<td></td>
<td>ED Length</td>
<td>13 15 17 19 21 23 25 27</td>
<td>in</td>
</tr>
<tr>
<td></td>
<td>PT Area</td>
<td>0.868 1.302 1.736 2.17 2.604 3.038 3.472 3.906</td>
<td>in²</td>
</tr>
<tr>
<td></td>
<td>PT Prestress</td>
<td>26 28 30 32 34 36 38 40</td>
<td>%</td>
</tr>
</tbody>
</table>

For scenario 1 and 2, both PT and ED parameters are encoded in a binary chromosome to make it easier for selection, crossover, and mutation events. A single chromosome represents one story of one population member inside a generation. Like in nature, a chromosome is made up of genes. A single parameter is the equivalent to a gene. These two scenarios consider the external and internal connections to have different parameter values; this causes the chromosome to have more bits compared to scenario 3 and 4. Since binary only has two digits (ones and zeros), for it to represent a single parameter/gene, three bits are needed; $2^3 = 8$, where 2 is the binary digits, 8 is the number of parameter values; solving this will give you three bits per parameter/gene. With now six
different parameters to choose from for a single story (the external and internal connections will have different parameter values), 18 digits are needed. The building has three stories; a chromosome of 54 digits will represent an entire structure. The first three bits represent the external ED area values (yielding force), the second three bits represent the external ED length values (ED stiffness), the third three bits represent the internal ED area values, (yielding force) the fourth three bits represent the internal ED length values (ED stiffness), the fifth three bits represent the PT area, while the remaining three bits represent the PT prestress (PT strain). Figure 3.11 below gives a visual representation.

![18 Bit Length](image)

**Figure 3.11: Visual illustration of ED chromosome for one story (Scenario 1 & 2)**

For scenario 3 and 4, both PT and ED parameters are encoded in a binary chromosome to make it easier for selection, crossover, and mutation events. A single chromosome represents one story of one population member inside a generation. Like in nature, a chromosome is made up of genes. A single parameter is the equivalent to a gene. Since binary only has two digits (ones and zeros), for it to represent a single parameter/gene, three bits are needed; $2^X = 8$, where 2 is the binary digits, 8 is the number of parameter values; solving this will give you three bits per parameter/gene. With four different parameters to choose from for a single story, 12 digits are needed. Since the model
in question has three stories, a chromosome of 36 digits will represent an entire structure. The first three bits represent the ED area, the second three bits represent the ED length, the third three bits represent the PT area, while the remaining three bits represent the PT prestress. Figure 3.12 below gives a visual representation.

![12 Bit Length](image)

**Figure 3.12: Visual illustration of ED chromosome for one story (Scenario 3 & 4)**

All four scenarios have their own GA/MATLAB script. Once the input of parameters, creation of initial population, and conversion of parameters to binary chromosome are complete, the GA then subjects the population to the seismic events.

3.3.2 **PTED Connection using Friction Dampers**

Like the PTED connection with the ED bars, the structures begin to sway during a seismic event which creates gap openings at the top and bottom of the beam-to-column connection. This connection still uses posttensioned strands that run parallel to the beams and are anchored at the exterior columns. The PT strands allow the structure to self-center itself after a seismic event (closing the gaps), while the friction dampers replace the ED bars as the energy dissipation devices. In addition, friction dampers are located at the top and bottom of the beams. Once a friction damper
yields, it is easily replaceable since it is bolted to the beam and column. Friction dampers also have the option of being bolted to the web of the beam.

Modeling of the PTED connection that uses friction dampers inside OpenSees follows the same procedures and assumptions as the PTED connection that uses energy dissipating bars with only a small number of modifications. In fact, the same OpenSees script is employed for modeling the friction damper and only two parameters were changed. The first parameter changed is the stiffness of the friction dampers. The Young’s Modulus of the ED bars are 29,000 ksi, while a stiffness of 20,000 kip/in is used to model the friction dampers. Recall that OpenSees uses stiffness when defining the uniaxial material and thus the ED length does not need to be optimized in the GA (Equation 3.9 is not applicable). The second parameter changed is the strain hardening ratio. The ED bars are modeled using a strain hardening ratio of 0.02, while the friction dampers are given a value of 0.0001. Equation 3.8 is still used when calculating the yielding force of the ED. The parameters for the PT remain the same and thus Equation 3.10 is still applicable. All other modeling and assumptions for the PTED connection using friction dampers remain valid and is stated in Section 3.3.1.

The genetic algorithm used for the PTED connection now focuses on the optimization of three parameters: ED area, PT area, and PT prestress. Four different scenarios are still considered. Scenario 1 represents the exterior and interior PTED beam-to-column connections having different parameters. This means both exterior connections on a single floor will have the same parameters while the interior connections will have different parameters. Scenario 2 is the same as Scenario 1 with the exception that a wider range of parameters are considered. A total of eight values are still used but the range between the minimum and maximum values of a given parameter is increased.
Scenario 3 considers all connections on a given floor use the same parameter values, while Scenario 4 considers uniform parameters with a wider range of options.

Recall that previously in this chapter it was stated that OpenSees needs certain parameters to model the structure correctly. Because of this the GA takes the inputted parameters and internally calculates and exports them for OpenSees to use. In terms of chromosome bits, the ED area corresponds to the ED yielding force and the PT initial prestress level corresponds to the PT strain. Table 3.5 below shows the parameter values of each scenario.

### Table 3.5: Parameter values for the Friction Damper connection

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Parameter</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ED Area</td>
<td>0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 ( in^2 )</td>
</tr>
<tr>
<td></td>
<td>PT Area</td>
<td>1.085 1.302 1.519 1.736 1.953 2.17 2.387 2.604 ( in^2 )</td>
</tr>
<tr>
<td></td>
<td>PT Prestress</td>
<td>26 28 30 32 34 36 38 40 %</td>
</tr>
<tr>
<td>1 &amp; 3</td>
<td>ED Area</td>
<td>0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 ( in^2 )</td>
</tr>
<tr>
<td></td>
<td>PT Area</td>
<td>0.868 1.302 1.736 2.17 2.604 3.038 3.472 3.906 ( in^2 )</td>
</tr>
<tr>
<td></td>
<td>PT Prestress</td>
<td>26 28 30 32 34 36 38 40 %</td>
</tr>
</tbody>
</table>

For scenario 1 and 2, both PT and ED parameters are encoded in a binary chromosome. A single chromosome represents one story of one population member inside a generation. Like in nature, a chromosome is made up of genes. A single parameter is the equivalent to a gene. These two scenarios consider the external and internal connections to have different parameter values. Since binary only has two digits (ones and zeros), for it to represent a single parameter/gene, three bits are needed; \( 2^3 = 8 \), where 2 is the binary digits, 8 is the number of parameter values; solving this will give you 3 bits per parameter/gene. As previously mentioned, the ED length parameter is not
optimized for the friction cases since the stiffness of the friction dampers remains constant. With now four different parameters to choose from for a single story (the external and internal connections will have different parameter values and the ED length is not considered), 12 digits are needed. The building has three stories; a chromosome of 36 digits will represent an entire structure. The first three bits represent the external ED area values, the second three bits represent the internal ED area values, the third three bits represent the PT area, while the remaining three bits represent the PT prestress. Figure 3.13 below gives a visual representation.

Figure 3.13: Visual Illustration of Friction chromosome for one story (Scenario 1 & 2)

For scenario 3 and 4, both PT and ED parameters are encoded in a binary chromosome. Following the same logic and procedure, with three different parameters to choose from for a single story (the ED length value is not optimized, and the external and internal connections will not have different values), nine digits are needed. Since the model in question has three stories, a chromosome of 27 digits will represent an entire structure. The first three bits represent the ED area, the second three bits represent the PT area, while the remaining three bits represent the PT prestress. Figure 3.14 below gives a visual representation.
All four scenarios have their own GA/MATLAB script. Once the input of parameters, creation of initial population, and conversion of parameters to binary chromosome are complete, the GA then subjects the population to the seismic events.

### 3.3.3 PTED connection using Steel Angles

This PTED connection behaves like the other two PTED connections. The PT strands provide self-centering capabilities while steel angles provide energy dissipation through hysteretic yielding. The steel angles can be located at the top and bottom of the beam-to-column connection. Like the other two connections, the steel angles are easily replaceable since they are attached using bolts.

Modeling of the PTED connection that uses steel angles inside OpenSees follows the same procedures and assumptions as the PTED connection that uses energy dissipating bars with only a small number of modifications. The properties of the PT strands remain the same meaning Equation 3.10 is still applicable to calculate the PT strain. The difference comes from modeling the ED device. A bilinear approximation is used to properly model the steel angles into OpenSees as shown in Figure 3.15.
The GA for the previous two connections aimed to optimize the ED area and length. For the steel angles, the ED parameters depend on the angle size; once an angle size is chosen, the ED stiffness, yielding force, and strain hardening ratio are known and are extracted into OpenSees. These parameters are needed to properly model the steel angles and are in the proper format for OpenSees to read and thus no internal calculations were needed contrary to what was done for the other two PTED connections. Four different angle sizes were taken from Garlock et al. (2003); an experimental study in which several angle sizes are tested, and a mathematical method is outlined to create the force-deformation model and calculate several parameters including the stiffness, yielding force, and strain hardening ratio. Table 3.6 displays the sizes and their corresponding parameters used in the GA. Four more angle sizes are taken from Beland et al. (2020) and Table 3.6 displays the sizes and their corresponding parameters.

**Figure 3.15: Force-Deformation relationship of Steel Angles (Garlock et al. 2003)**
Table 3.6: Angle sizes and parameters used in the GA

<table>
<thead>
<tr>
<th>Source</th>
<th>Angle Size</th>
<th>Allele</th>
<th>$K_i$ (kips/in)</th>
<th>$V_m$ (kips)</th>
<th>$F_y$ (kips)</th>
<th>$K_{post}$ (kip/in)</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garland et al.</td>
<td>L8-58-7</td>
<td>000</td>
<td>211.85</td>
<td>14.61</td>
<td>17.99</td>
<td>17.44</td>
<td>0.0823</td>
</tr>
<tr>
<td></td>
<td>L8-34-6</td>
<td>001</td>
<td>312.92</td>
<td>20.68</td>
<td>25.37</td>
<td>24.69</td>
<td>0.0789</td>
</tr>
<tr>
<td></td>
<td>L8-58-4</td>
<td>010</td>
<td>472.80</td>
<td>24.73</td>
<td>29.80</td>
<td>29.52</td>
<td>0.0624</td>
</tr>
<tr>
<td></td>
<td>L8-34-4</td>
<td>011</td>
<td>561.88</td>
<td>30.35</td>
<td>36.66</td>
<td>36.23</td>
<td>0.0645</td>
</tr>
<tr>
<td>Beland et al.</td>
<td>L152x203x15.9 (T12)</td>
<td>100</td>
<td>1952.87</td>
<td>0.00</td>
<td>42.94</td>
<td>33.69</td>
<td>0.0173</td>
</tr>
<tr>
<td></td>
<td>L152x203x15.9 (T11)</td>
<td>101</td>
<td>2626.67</td>
<td>0.00</td>
<td>49.46</td>
<td>49.11</td>
<td>0.0187</td>
</tr>
<tr>
<td></td>
<td>L152x203x19.1 (TC14)</td>
<td>110</td>
<td>3277.62</td>
<td>0.00</td>
<td>56.88</td>
<td>54.25</td>
<td>0.0166</td>
</tr>
<tr>
<td></td>
<td>L152x203x19.1 (TC13)</td>
<td>111</td>
<td>4128.44</td>
<td>0.00</td>
<td>67.44</td>
<td>67.95</td>
<td>0.0165</td>
</tr>
</tbody>
</table>

Where $K_i$ represents the initial stiffness, $V_m$ represents the shear force where the angle yields, $K_{post}$ represents the post yield stiffness, $b$ represents the strain hardening ratio, and $F_y$ represents the force where the initial stiffness and post yield stiffness intersect.

The Beland et al. study presented all necessary parameters, and no internal calculations were needed. The Garlock et al. study presented most of all necessary parameters, but internal calculations were needed to find the necessary parameters. Equations 3.17, 3.18, and 3.19 were used for the internal calculations and taken from the mathematical model the Garlock et al. study presented.

$$F_y = \frac{1.13V_mK_i}{(K_i - K_{post})} \quad (3.17)$$

$$K_{post} = 0.047V_m \quad (3.18)$$

$$b = \frac{K_{post}}{K_i} \quad (3.19)$$
The same OpenSees script used for the ED bars and friction dampers is employed for modeling the steel angles. All other modeling and assumptions for the PTED connection using steel angles remain valid and is stated in the ED bar section.

In terms of the PTED connection utilizing the steel angles, the parameters optimized are essentially the steel angles size, the PT area, and the PT prestress. Recall that the angle size determines the ED parameters used in modeling. These parameters are investigated in the four scenarios previously mentioned. Scenario 1 represents the exterior and interior PTED beam-to-column connections having different parameters. This means both exterior connections on a single floor will have the same parameters while the interior connections will have different parameters. Scenario 2 is the same as scenario 1 with the exception that a wider range of parameters are considered for the PT strands; the same eight steel angle sizes are used in Scenario 2. A total of eight values are still used but the range between the minimum and maximum values of a given parameter is increased. Scenario 3 considers all connections on a given floor use the same parameter values, while scenario 4 considers uniform parameters with a wider range of options for the PT strands; the same eight steel angle sizes are used in Scenario 4. No internal calculations are needed for this PTED connection except for the PT strain. In terms of chromosome bits, the steel angle size corresponds to the ED yielding force, the ED strain hardening ratio, and the ED stiffness, while the PT initial prestress level corresponds to the PT strain. Refer to Table 3.6 for the steel angle parameters and sizes and Table 3.5 for the PT strand parameters.

For scenario 1 and 2, both PT and ED parameters are encoded in a binary chromosome to make it easier for selection, crossover, and mutation events. A single chromosome represents one story of one population member inside a generation. Like in nature, a chromosome is made up of genes. A
A single parameter is the equivalent to a gene. These two scenarios consider the external and internal connections to have different parameter values; this causes the chromosome to have more bits compared to scenario 3 and 4. Since binary only has two digits (ones and zeros), for it to represent a single parameter/gene, three bits are needed; \(2^3 = 8\), where 2 is the binary digits, 8 is the number of parameter values; solving this will give you three bits per parameter/gene. Both scenarios have four different parameters to optimize (the external and internal connections will have different parameter values), thus 12 digits are needed. The building has three stories; a chromosome of 36 digits will represent an entire structure. The first three bits represent the external angle size (yielding force, stiffness, strain hardening ratio), the second three bits represent the internal angle size (yielding force, stiffness, strain hardening ratio), the third three bits represent the PT area, and the last three bits represent the PT prestress (PT strain). Figure 3.16 below gives a visual representation.

![12 Bit Length](image)

**Figure 3.16: Visual Illustration of Angle chromosome for one story (Scenario 1 & 2)**

For scenario 3 and 4, both PT and ED parameters are encoded in a binary chromosome to make it easier for selection, crossover, and mutation events. A single chromosome represents one story of one population member inside a generation. Like in nature, a chromosome is made up of genes. A
single parameter is the equivalent to a gene. Since binary only has two digits (ones and zeros), for it to represent a single parameter/gene, three bits are needed; $2^3 = 8$, where 2 is the binary digits, 8 is the number of parameter values; solving this will give you three bits per parameter/gene. With three different parameters to choose from for a single story, nine digits are needed. Since the model in question has three stories, a chromosome of 27 digits will represent an entire structure. The first three bits represent the angle size (yield force, stiffness, strain hardening ratio), the second three bits represent the PT area, and the last three bits represent the PT prestress (PT strain). Figure 3.17 below gives a visual representation.

![9 Bit Length](image)

**Figure 3.17: Visual Illustration of Angle chromosome for one story (Scenario 3 & 4)**

All four scenarios have their own GA/MATLAB script. Once the input of parameters, creation of initial population, and conversion of parameters to binary chromosome are complete, the GA then subjects the population to the seismic events.

3.4 **PTED with Inerter**

In addition to the three PTED connections that employ ED bars, friction dampers, and steel angles as energy dissipating devices, three more PTED models were created but this time an inerter device
was added to the model. These additional models will be compared to the original three PTED connections and to the WMRF model. The GA is still used to model the structure inside OpenSees, to subject it to the seismic events, and to optimize the inerter parameters by subjecting it to several generations.

Ideally, an inerter would be implemented by way of chevron frames like the one proposed in Makris and Kampas (2016). This ensures that the inerter stays and acts horizontally since the device works by the relative acceleration between two nodes. If the building is moving horizontally due to seismic events, the inerter would have to be positioned to resist the motion. The chevron frame is considered very stiff and flexible so that its deformation is negligible to the translational displacement of the structure.

3.4.1 General Modeling of the Inerter

As previously discussed, there are several types of inerter devices that range from clutching inerter devices to viscous inerter. Due to the variety of devices and to the inertance values of each, the inerter was modeled inside OpenSees by suggesting an inertance-to-mass ratio. The ratio is a percentage of the total mass of the structure. The ratios considered in this study are: 0%, 5%, 10% and 15%. This range was considered due to practical reasons. The ratio is dependent on the mass of the structure and thus too high of a mass would require an unrealistic inertance to be reached.

The same OpenSees scripts that were utilized for the original three PTED connections are used again for the inerter cases since the only change needed was the addition of a couple lines of code in the script that model the inerter. The element ‘InerterElement’ is used in the script. This element calls for nodes, inerter type, inertance value, and orientation of the inerter. The inerter is placed on
the middle column from the ground floor to the bottom of the first floor. Double inerters engaged with a clutch (Makris and Kampas 2016) are used in the model while the inertance values vary. The inerter is modeled to act in the x-axis due to the earthquakes acting in the same axis. Inerter implementation in OpenSees was done by introducing a new element by Dr Apostolakis. Figure 3.18 displays the location of the inerter in the model. All other assumptions and modeling of the structure remain the same.

![Diagram of the structure with an inerter highlighted, showing locations labeled for each floor, with dimensions and a seismic event waveform.]  

**Figure 3.18: Location of the inerter for all PTED models (Apostolakis 2006)**

3.4.2 **Using the Genetic Algorithm with Inerters**

Recall that the binary chromosome represents all three stories in the PTED models. The inerter is only modeled on the first floor and thus only affects the binary chromosome in the area that represents the first floor; all other parts of the chromosome remain the same. Each PTED connection with inerter devices still considers the four different scenarios that were previously mentioned thus the GA used for the inerter models is the same GA except with the addition of the
inerter on the first floor. This addition results in the addition of more bits the overall length of the binary chromosome. With four different inertance-to-mass ratios values, the binary chromosome could only change by a length of two. Recall that binary has two digits (1 and 0); for it to represent a single gene or inerter value, two bits are needed since \(2^2 = 4\), where 2 is the binary digits, and 4 is the number of inerter values. Solving this will give you two bits per gene. Table 3.7 displays the inerter parameter values and their equivalent binary value.

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Parameter} & \text{Parameter Values} \\
\hline
\text{Inertance-to-mass ratio} & 0\% & 5\% & 10\% & 15\% \\
\hline
\end{array}
\]

For the ED model utilizing iners, each Scenario previously discussed for the ED bar models will have their total length increased by two bits. The same will occur for both the Friction and Angle models. The change originates from the addition of the first floor inerter. Refer to Table 3.8 below. Figure 3.19 below illustrates an example of the change in length of a binary chromosome with the addition of the inerter on the first floor. The number of bits for the second and third floor will not change and will still have the same number of bits as the original PTED models.
Figure 3.19: Visual Illustration of Friction + Inerter chromosome for 1st story (Scenario 3 & 4)

Table 3.8: Total change in length of binary chromosome due to the 1st floor Inerter

<table>
<thead>
<tr>
<th>Model</th>
<th>ED</th>
<th>Friction</th>
<th>Angle</th>
<th>ED + Inerter</th>
<th>Friction + Inerter</th>
<th>Angle + Inerter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>12</td>
<td>12</td>
<td>20</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>12</td>
<td>12</td>
<td>20</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>9</td>
<td>9</td>
<td>14</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>9</td>
<td>9</td>
<td>14</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

3.5 Seismic Environment

The seismic environments considered in this Thesis consist of several predefined earthquake time histories that were collected from the Pacific Earthquake Engineering Research (PEER) ground motion database. The database contains three different spectrums; for this study, the PEER NGA-West2 spectrum is chosen to subject the model to earthquakes that could potentially strike downtown Los Angeles. Each earthquake has their own properties that are used in the GA. These properties consist of the scale factor, timestep of the earthquake time history, number of time steps
in the time history, timestep of analysis, and the tolerance of the analysis. Table 3.9 below displays the properties for all 11 earthquakes.

Table 3.9: Earthquake Properties

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Scale Factor</th>
<th>Timestep of EQ time history</th>
<th>Time steps in time history</th>
<th>Timestep of analysis</th>
<th>Tolerance of analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.3061</td>
<td>0.005</td>
<td>8000</td>
<td>0.001</td>
<td>1e-6</td>
</tr>
<tr>
<td>2</td>
<td>4.7676</td>
<td>0.01</td>
<td>6380</td>
<td>0.002</td>
<td>1e-6</td>
</tr>
<tr>
<td>3</td>
<td>5.1252</td>
<td>0.0029</td>
<td>13190</td>
<td>0.001</td>
<td>1e-6</td>
</tr>
<tr>
<td>4</td>
<td>3.8203</td>
<td>0.01</td>
<td>4130</td>
<td>0.002</td>
<td>1e-6</td>
</tr>
<tr>
<td>5</td>
<td>7.3245</td>
<td>0.05</td>
<td>7810</td>
<td>0.001</td>
<td>1e-6</td>
</tr>
<tr>
<td>6</td>
<td>4.2387</td>
<td>0.02</td>
<td>2200</td>
<td>0.002</td>
<td>1e-6</td>
</tr>
<tr>
<td>7</td>
<td>3.1862</td>
<td>0.02</td>
<td>2200</td>
<td>0.001</td>
<td>1e-6</td>
</tr>
<tr>
<td>8</td>
<td>5.5378</td>
<td>0.01</td>
<td>2995</td>
<td>0.002</td>
<td>1e-6</td>
</tr>
<tr>
<td>9</td>
<td>7.0842</td>
<td>0.01</td>
<td>4230</td>
<td>0.002</td>
<td>1e-6</td>
</tr>
<tr>
<td>10</td>
<td>3.7577</td>
<td>0.01</td>
<td>6000</td>
<td>0.002</td>
<td>1e-6</td>
</tr>
<tr>
<td>11</td>
<td>2.0412</td>
<td>0.005</td>
<td>27730</td>
<td>0.001</td>
<td>1e-6</td>
</tr>
</tbody>
</table>

It should be noted that the model was not designed for seismic events in downtown Los Angeles and therefore each earthquake scale factor is 30% of what is given in Table 3.8 (multiplied by 0.7). The scale factors from the table above are too severe for the model and thus the target values for this model were unattainable. Scaling down the earthquake scale factors provides us reachable target values.
3.6 **Validation**

This study is based upon a study from Apostolakis (2006). That study also incorporated a genetic algorithm to optimize the design of a PTED connection that utilized ED bars. That study used Drain-2DX software to model the WMRF and PTED models. The results from that study are used to validate this paper’s OpenSees models and genetic algorithms.

Additionally, the 2006 paper is validated by comparing its results to previous studies conducted by Filiatrault and Christopoulos; both investigated PTED connections.
CHAPTER 4: FINDINGS

The previous chapter discussed the methods and processes used and conducted to complete the numerical study. The chapter first presented a general overview of the study. It then presented the WMRF model by discussing the dimensions, modeling assumptions, and modeling procedures used to model the WMRF inside OpenSees. Next, the genetic algorithm was presented with an introduction to the RPI function and chromosome modifiers. After, each PTED connection is presented alongside the modeling assumptions, modeling procedures, and GA used to model the PTED connections into OpenSees. This step is repeated for presenting the PTED connections that include the inerter.

This chapter’s focus is to present the results of the genetic algorithm for each PTED connection and for each PTED connection plus the inerter. The genetic algorithm presents us the optimized design of each PTED connection and each PTED connection plus inerter, which we can then compare these optimized models and their seismic results to the traditional WMRF model. The results presented include time histories, PTED properties distribution, and comparison of the drift, residual drift, and acceleration of the optimal designs to the WMRF.

4.1 Process and Results for WMRF

A batch file is used to take the OpenSees WMRF script that was discussed in the previous chapter, and subjects it to all 11 earthquakes considered in this study. No optimization is done on the WMRF and therefore it only needs to be subjected to each earthquake once. Recall that each of the 11 earthquakes is scaled down by 30%.
The WMRF results from OpenSees include results from each earthquake and include the time histories of the displacement, inter-story drift, and acceleration for each story in the model. The displacement and acceleration results from OpenSees were collected by using the ‘recorder node’ command inside OpenSees; the inter-story drift results were collected by using the ‘recorder drift’ command. The residual drift reflects the drift values at the end of an earthquake; any residual drift indicates the model or building is no longer at its initial location it was in prior to the seismic event.

MATLAB scripts were used to post process the drift and acceleration from each earthquake. First, the OpenSees drift values were collected and loaded into MATLAB. Second, the absolute value of each drift value was calculated since the drift of the building can go in either direction; we are concerned with the worst-case or largest drift value. The maximum of the absolute drift values was found for each story. This same process was done for the acceleration values. The residual drift for the WMRF was also calculated in MATLAB. As previously mentioned, to find the residual drift only the tail end of the drift values is considered. To find the appropriate number of values to calculate the residual drift, equation 4.1 is used:

\[ T = \text{end} - \frac{2T_n}{dt} \]  

(4.1)

where \text{end} corresponds to the final time value of the earthquake analysis, \( T_n \) is the natural period of the structure, \( dt \) corresponds to the time step of the earthquake analysis, and \( T \) is the first-time value considered for calculating the residual drift. The time values for the residual drift start at \( T \) and end at the last time value of the earthquake.

The residual drift is then calculated by finding the absolute value of the mean drift values inside the time range mentioned above. Again, as is the case for the drift and acceleration, this is done
for each story in the model and for each earthquake. The WMRF results collected and post-processed represent the standard that the PTED connections need to exceed to be considered a feasible alternative to the WMRF.

The maximum drift, residual drift, and acceleration values of all the floors were found for each earthquake. The average of these values was calculated. Essentially this represents the average maximum drift, residual drift, and acceleration of the WMRF model. Table 4.1 displays these values for the model with the 0.7 scale factor.

Table 4.1: Average Maximum of the WMRF Model

<table>
<thead>
<tr>
<th>EQ</th>
<th>SF x 0.7</th>
<th>Drift</th>
<th>Res Drift</th>
<th>Acc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.41</td>
<td>2.05</td>
<td>0.07</td>
<td>0.92</td>
</tr>
<tr>
<td>2</td>
<td>3.34</td>
<td>1.95</td>
<td>0.59</td>
<td>1.01</td>
</tr>
<tr>
<td>3</td>
<td>3.58</td>
<td>1.57</td>
<td>0.39</td>
<td>0.76</td>
</tr>
<tr>
<td>4</td>
<td>2.67</td>
<td>3.04</td>
<td>0.84</td>
<td>0.93</td>
</tr>
<tr>
<td>5</td>
<td>5.12</td>
<td>2.60</td>
<td>0.55</td>
<td>0.89</td>
</tr>
<tr>
<td>6</td>
<td>2.97</td>
<td>1.77</td>
<td>0.21</td>
<td>0.88</td>
</tr>
<tr>
<td>7</td>
<td>2.23</td>
<td>3.91</td>
<td>1.57</td>
<td>0.95</td>
</tr>
<tr>
<td>8</td>
<td>3.88</td>
<td>2.09</td>
<td>0.22</td>
<td>0.91</td>
</tr>
<tr>
<td>9</td>
<td>4.96</td>
<td>3.06</td>
<td>0.18</td>
<td>0.98</td>
</tr>
<tr>
<td>10</td>
<td>2.63</td>
<td>1.88</td>
<td>0.21</td>
<td>0.92</td>
</tr>
<tr>
<td>11</td>
<td>1.43</td>
<td>1.57</td>
<td>0.27</td>
<td>1.28</td>
</tr>
<tr>
<td>Mean</td>
<td>2.32</td>
<td>0.46</td>
<td>0.95</td>
<td></td>
</tr>
</tbody>
</table>

4.2 Process for PTED Connections

A total of two MATLAB scripts were used to successfully test the PTED connections to the genetic algorithm. One script displays the inputs needed for the GA and performs the process of forming the next generation. The second script transforms the parameters into chromosomes and references
OpenSees to perform the FEA dynamic analysis. Recall, the PTED connections is subjected to 101 generations of the genetic algorithm. Each generation has a population of five. Recall, that there are four scenarios to investigate: one where the external and internal connections have differing parameters, another with the same scenario but with an extended range of parameters to choose from, another where all connections on a given story have the same parameters, and finally the last scenario is where all the connections on a given story have the same parameters, but there is an extended range of parameters to choose from.

Random parameters are chosen for the ED devices (ED bars, friction dampers, and angles) and PT strands to begin a generation. These parameters are assigned an equivalent binary number and together represent a chromosome. The parameters are also exported into files that OpenSees references to build the model and perform dynamic analysis. Once the dynamic analysis is complete for the first earthquake, MATLAB imports the results and begins to post-process them to compare them to the target values. A fitness function number is assigned which depends on how they performed compared to the target values. This process repeats itself for all 11 earthquakes and finally an average fitness function is calculated considering all 11 fitness functions; this is called the member fitness. This repeats itself for all five population members in a generation. At this point, MATLAB begins to form the next generation and either performs a crossover or mutation event or even allows a gene to move to the next generation if it performed very well to the seismic events. Recall this occurs for all four scenarios.

At the end of all 101 generations, the top three chromosome strings with the highest fitness function from each scenario is found. The top three chromosome strings are post processed using MATLAB to determine which of the three is considered the optimal solution for that scenario. It
is not as simple as choosing the chromosome string with the highest fitness function and comparison of the drift, residual drift, and acceleration is needed. This paper focuses on reducing residual drifts and more attention is focused on those results. A certain population may have a higher fitness function but may have higher residual drifts compared to another population member and thus the population member with the lower residual drift may be chosen as the optimal solution.

Once a single chromosome is chosen for each scenario and is designated as the best and optimal solution, these four optimal solutions are once again compared to one another considering drift, residual drift, and acceleration to determine which of the four scenarios is the optimal solution for that PTED connection. The solution chosen for a given PTED connection is the one chosen to compare to the WMRF results.

4.3 Post-Processing of PTED Results

For each PTED connection, results from OpenSees include results from each earthquake and include the time histories of the displacement, inter-story drift, and acceleration for each story in the model. The PTED connections also include time histories of the contact elements, PT strands, and ED bars from OpenSees.

The displacement and acceleration results from OpenSees were collected by using the same process discussed in Section 4.1 for the WMRF model. Post processing of results: drift, residual drift, and acceleration, from each earthquake was also conducted using the same process as Section 4.1. The PTED results collected and post-processed are the results that will be compared to the WMRF model.
In the case of the PT strands, the element force during the seismic events is recorded and collected using the ‘recorder element’ command inside OpenSees. The same command is used to collect and record the displacement of the contact elements. The displacement of the contact elements indicates the opening and closing of the gap during the seismic events. Both force and displacement of the ED devices are recorded and collected using the same ‘recorder element’ command.

4.4 Optimal Solutions

This section will present the optimal solution of each PTED connection and display the corresponding chromosome. The following will also be presented: the distribution of the parameters per story, the RPI, the structure period, time histories if applicable, and the average maximum of the drift, residual drift, and acceleration of each story.

4.4.1 PTED Connection with ED Bars

The optimal design for the PTED connection consisting of the ED bars is from scenario three; the design of the PTED connection consists of the same parameters along the same story regardless of location (external vs internal).

The chromosome for the optimal design is as follows:

\[111\ 000\ 100\ 000\ \quad 111\ 000\ 101\ 001\ \quad 111\ 001\ 110\ 011.\]

The first set of bits correspond to the first story, while the second set corresponds to the second story, and finally the final set correspond to the third story. The bits correspond to optimal values for each parameter considered in this study. These are presented below per story for each parameter.
**First story: 111 000 100 000**

ED element area, \( A_{EDB} = 1.1 \text{ in}^2 \)

ED element length, \( L_{EDB} = 13 \text{ in} \)

PT element area, \( A_{PT} = 1.953 \text{ in}^2 \)

Initial PT force, \( F_{initial,PT} = 26\% \times F_{u,PT} \)

**Second Story: 111 000 101 001**

ED element area, \( A_{EDB} = 1.1 \text{ in}^2 \)

ED element length, \( L_{EDB} = 13 \text{ in} \)

PT element area, \( A_{PT} = 2.17 \text{ in}^2 \)

Initial PT force, \( F_{initial,PT} = 28\% \times F_{u,PT} \)

**Third Story: 111 001 110 011**

ED element area, \( A_{EDB} = 1.1 \text{ in}^2 \)

ED element length, \( L_{EDB} = 15 \text{ in} \)

PT element area, \( A_{PT} = 2.387 \text{ in}^2 \)

Initial PT force, \( F_{initial,PT} = 32\% \times F_{u,PT} \)
The fitness function or RPI for this optimal chromosome is 0.915; this is the average of the member fitness for all 11 earthquakes. Table 4.2 below summarizes the parameters that correspond to this optimal design chromosome and are labeled to easily identify them. The green box refers to the first story, the red box corresponds to the second story, while the yellow box refers to the third story. Figure 4.1 demonstrates the distribution of the PTED properties by level.

Table 4.2: Summary of the Optimal ED Bar Solution

<table>
<thead>
<tr>
<th>Scenario 3 RPI = 0.915</th>
<th>Parameter</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ED Area</td>
<td>0.4 0.5 0.6 0.7 0.8 0.9 1 in²</td>
</tr>
<tr>
<td></td>
<td>ED Length</td>
<td>13 15 17 19 21 23 25 in</td>
</tr>
<tr>
<td></td>
<td>PT Area</td>
<td>1.085 1.302 1.519 1.736 1.953 2.17 2.387 2.604 in²</td>
</tr>
<tr>
<td></td>
<td>PT Prestress</td>
<td>26 28 30 32 34 36 38 40 %</td>
</tr>
</tbody>
</table>

Figure 4.1: Property distribution by level for the PTED ED Bars Connection

The top and bottom contact element gap opening time history for a first-floor external connection during the median earthquake six is presented in Figure 4.2. When either the top or bottom gap has a value of zero, the other gap is opening; essentially, when gap is open, the other is closed.
The gap openings begin at 5 seconds and continue until the end of the time history. The maximum top gap opening is 0.44 inches while the maximum bottom gap opening is 0.32 inches.

![Graph showing gap openings](image)

**Figure 4.2: Gap Opening for 1st floor External Connection utilizing ED Bars**

The axial force time history of the PT strands is presented in Figure 4.3. The plot demonstrates that the PT strands were activated around 5 seconds and continued until the end of the time history. The maximum force is about 174 kips.
Table 4.3 below displays the average maximums for drift, residual drift, and acceleration. The table demonstrates the average maximum for each floor from all 11 earthquakes and compares it to the average maximum of the entire structure from all 11 earthquakes. Compared to the target values given in Table 3.2, the PTED connection utilizing the ED bars exceed the target values for both drift and acceleration but are well below the target value for residual drift.
4.4.2 PTED Connection with Friction Dampers

The optimal design for the PTED connection consisting of the friction dampers is from scenario four; the design of the PTED connection consists of the same parameters along the same story regardless of location (external vs internal) but with the range of extended parameters.

The chromosome for the optimal design is as follows:

101 010 111 110 110 100 110 111 100.

**First story: 101 010 111**

ED element area, $A_{EDF} = 1.4 \text{ in}^2$

PT element area, $A_{PT} = 1.736 \text{ in}^2$

Initial PT force, $F_{initial,PT} = 40\% \times F_{u,PT}$

**Second Story: 110 110 100**

ED element area, $A_{EDF} = 1.6 \text{ in}^2$

PT element area, $A_{PT} = 3.472 \text{ in}^2$

Initial PT force, $F_{initial,PT} = 34\% \times F_{u,PT}$
**Third Story: 110 111 100**

ED element area, $A_{EDF} = 1.6 \text{ in}^2$

PT element area, $A_{PT} = 3.906 \text{ in}^2$

Initial PT force, $F_{initial,PT} = 34\% \times F_{u,PT}$

The fitness function or RPI for this optimal chromosome is 1.066; this is the average of the member fitness for all 11 earthquakes. Table 4.4 below summarizes the parameters that correspond to this optimal design chromosome and are labeled to easily identify them. The green box refers to the first story, the red box corresponds to the second story, while the yellow box refers to the third story. Figure 4.4 demonstrates the distribution of the PTED properties by level.

**Table 4.4: Summary of the Optimal Friction Damper Solution**

<table>
<thead>
<tr>
<th>Scenario 4 RPI = 1.066</th>
<th>Parameter</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>000</td>
<td>001</td>
</tr>
<tr>
<td>ED Area</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>PT Area</td>
<td>0.868</td>
<td>1.302</td>
</tr>
<tr>
<td>PT Prestress</td>
<td>26.0</td>
<td>28.0</td>
</tr>
</tbody>
</table>

The top and bottom contact element gap opening time history for a first-floor external connection during the median earthquake six is presented in Figure 4.5. The gap openings begin at 5 seconds and end around 32 seconds. The maximum top gap opening is 0.34 inches while the maximum bottom gap opening is 0.30 inches.
Figure 4.4: Property distribution by level for the PTED Friction Damper Connection

Figure 4.5: Gap Opening for 1st floor External Connection utilizing Friction Dampers
The axial force time history of the PT strands is presented in Figure 4.6. The plot demonstrates that the PT strands were activated around 5 seconds and ended around 30 seconds. The maximum force is about 207 kips.

Table 4.5 displays the average maximums for drift, residual drift, and acceleration for the PTED connection utilizing the friction dampers. Compared to the target values given in Table 3.2, the PTED connection utilizing the friction dampers exceed the target values for both drift and acceleration but are well below the target value for residual drift.
Table 4.5: Average Maximum values for Friction Damper Connection

<table>
<thead>
<tr>
<th>Floors</th>
<th>Drift (%)</th>
<th>$\sigma$</th>
<th>Res. Drift (%)</th>
<th>$\sigma$</th>
<th>Acc. (g)</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story 1</td>
<td>1.755</td>
<td>0.519</td>
<td>0.076</td>
<td>0.056</td>
<td>1.313</td>
<td>0.437</td>
</tr>
<tr>
<td>Story 2</td>
<td>2.400</td>
<td>0.797</td>
<td>0.079</td>
<td>0.062</td>
<td>1.236</td>
<td>0.353</td>
</tr>
<tr>
<td>Story 3</td>
<td>2.170</td>
<td>0.779</td>
<td>0.063</td>
<td>0.049</td>
<td>1.270</td>
<td>0.462</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.473</td>
<td>0.090</td>
<td></td>
<td></td>
<td>1.421</td>
<td></td>
</tr>
</tbody>
</table>

4.4.3 PTED Connection with Steel Angles

The optimal design for the PTED connection consisting of steel angles is from scenario three; the design of the PTED connection consists of the same parameters along the same story regardless of location (external vs internal). The chromosome for the optimal design is as follows:

111 010 011 111 010 100 111 110 000.

**First story: 111 010 011**

ED element stiffness, $K_{EDA} = 4128.436 \text{ kip/in}$

ED element yielding force, $F_{y,EDA} = 67.443 \text{ kips}$

ED element strain hardening ratio, $b_{EDA} = 0.01646$

PT element area, $A_{PT} = 1.519 \text{ in}^2$

Initial PT force, $F_{\text{initial PT}} = 32\% \times F_{u,PT}$

**Second Story: 111 010 100**

ED element stiffness, $K_{EDA} = 4128.436 \text{ kip/in}$
ED element yielding force, $F_{y,EDA} = 67.443 \text{ kips}$

ED element strain hardening ratio, $b_{EDA} = 0.01646$

PT element area, $A_{PT} = 1.519 \text{ in}^2$

Initial PT force, $F_{initial,PT} = 34\% * F_{u,PT}$

**Third Story: 111 110 000**

ED element stiffness, $K_{EDA} = 4128.436 \text{ kip/in}$

ED element yielding force, $F_{y,EDA} = 67.443 \text{ kips}$

ED element strain hardening ratio, $b_{EDA} = 0.01646$

PT element area, $A_{PT} = 2.387 \text{ in}^2$

Initial PT force, $F_{initial,PT} = 26\% * F_{u,PT}$

The fitness function or RPI for this optimal chromosome is 0.95; this is the average of the member fitness for all 11 earthquakes. Table 4.6 below summarizes the parameters that correspond to this optimal design chromosome and are labeled to easily identify them. The green box refers to the first story, the red box corresponds to the second story, while the yellow box refers to the third story. Figure 4.7 demonstrates the distribution of the PTED properties by level.
Table 4.6: Summary of the Optimal Steel Angle Solution

<table>
<thead>
<tr>
<th>Scenario 3</th>
<th>RPI = 0.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Parameter Values</td>
</tr>
<tr>
<td></td>
<td>000</td>
</tr>
<tr>
<td>ED Yielding</td>
<td>17.9</td>
</tr>
<tr>
<td>ED Stiffness</td>
<td>211.8</td>
</tr>
<tr>
<td>ED Strain Hardening Ratio</td>
<td>0.08</td>
</tr>
<tr>
<td>PT Area</td>
<td>1.09</td>
</tr>
<tr>
<td>PT Prestress</td>
<td>26.0</td>
</tr>
</tbody>
</table>

Figure 4.7: Property distribution by level for the PTED Steel Angle Connection

The top and bottom contact element gap opening time history for a first-floor external connection during the median earthquake six is presented in Figure 4.8. The gap openings begin at 5 seconds and continues until the end of the time history. The maximum top gap opening is 0.44 inches while the maximum bottom gap opening is 0.28 inches.
The axial force time history of the PT strands is presented in Figure 4.9. The plot demonstrates that the PT strands were activated around 5 seconds and continues until the end of the time history. The maximum force is about 162 kips.

Table 4.7 displays the average maximums for drift, residual drift, and acceleration for the PTED connection utilizing the steel angles. Compared to the target values given in Table 3.2, the PTED connection utilizing the steel angles exceed the target values for both drift and acceleration but are well below the target value for residual drift.
Figure 4.9: Time History of PT Force for Steel Angles under EQ 6

Table 4.7: Average Maximum values for Steel Angle Connection

<table>
<thead>
<tr>
<th>Floors</th>
<th>Drift (%)</th>
<th>σ</th>
<th>Res. Drift (%)</th>
<th>σ</th>
<th>Acc. (g)</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story 1</td>
<td>1.790</td>
<td>0.529</td>
<td>0.071</td>
<td>0.066</td>
<td>1.201</td>
<td>0.256</td>
</tr>
<tr>
<td>Story 2</td>
<td>2.448</td>
<td>0.835</td>
<td>0.072</td>
<td>0.076</td>
<td>1.199</td>
<td>0.438</td>
</tr>
<tr>
<td>Story 3</td>
<td>2.548</td>
<td>0.873</td>
<td>0.058</td>
<td>0.059</td>
<td>1.658</td>
<td>0.555</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.664</td>
<td>0.083</td>
<td></td>
<td></td>
<td>1.696</td>
<td></td>
</tr>
</tbody>
</table>
4.4.4 PTED Connection with ED Bars and Inerter

The optimal design for the PTED connection consisting of ED bars and inerter is from scenario three; the design of the PTED connection consists of the same parameters along the same story regardless of location (external vs internal).

The chromosome for the optimal design is as follows:

\[
\begin{align*}
11 & 11 0 0 0 1 0 0 1 1 & 11 & 11 0 0 0 1 1 0 0 1 0 & 11 & 1 0 1 1 0 0 1 1 1 1 0 0 .
\end{align*}
\]

**First story:** 11 11 1 0 0 0 1 0 1 1

Inertance-to-mass ratio, \( b = 15\% \)

ED element area, \( A_{EDB} = 1.1 \text{ in}^2 \)

ED element length, \( L_{EDB} = 13 \text{ in} \)

PT element area, \( A_{PT} = 1.52 \text{ in}^2 \)

Initial PT force, \( F_{Initial,PT} = 32\% \times F_{u,PT} \)

**Second Story:** 11 11 1 0 0 0 1 1 0 0 1 0

ED element area, \( A_{EDB} = 1.1 \text{ in}^2 \)

ED element length, \( L_{EDB} = 15 \text{ in} \)

PT element area, \( A_{PT} = 1.953 \text{ in}^2 \)

Initial PT force, \( F_{Initial,PT} = 34\% \times F_{u,PT} \)
Third Story: 11 101 100 111 100

ED element area, $A_{EDB} = 0.9\, \text{in}^2$

ED element length, $L_{EDB} = 21\, \text{in}$

PT element area, $A_{PT} = 2.604\, \text{in}^2$

Initial PT force, $F_{\text{initial,PT}} = 34\% \times F_{u,PT}$

The fitness function or RPI for this optimal chromosome is 1.002; this is the average of the member fitness for all 11 earthquakes. Table 4.8 and Table 4.9 below summarize the parameters that correspond to this optimal design chromosome and are labeled to easily identify them. The green box refers to the first story, the red box corresponds to the second story, while the yellow box refers to the third story. Figure 4.10 demonstrates the distribution of the PTED properties by level.

### Table 4.8: Summary of the Optimal ED Bar with Inerter Solution

<table>
<thead>
<tr>
<th>Scenario 3 RPI = 1.002</th>
<th>Parameter</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>000</td>
</tr>
<tr>
<td>ED Area</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>ED Length</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>PT Area</td>
<td></td>
<td>1.085</td>
</tr>
<tr>
<td>PT Prestress</td>
<td></td>
<td>26</td>
</tr>
</tbody>
</table>
Table 4.9: Summary of the Inerter for the ED Bar with Inerter Solution

| Scenario 3  
<p>| RPI = 1.002 |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertance-to-mass ratio</td>
<td>0%</td>
</tr>
</tbody>
</table>

Figure 4.10: Property distribution by level for the PTED ED Bar with Inerter Connection

A time history of the top and bottom contact element gap openings is presented in Figure 4.11 for a first-floor external connection. The plot displays that the gap openings begin at 5 second and essentially end around 35 seconds, while some minor openings still occur until the end of the event. The maximum top gap opening is about 0.43 inches while the maximum bottom gap opening reached about 0.3 inches.
Additionally, the time history of the axial force for the PT strands is presented in Figure 4.12. The PT strands are activated at the 5 second mark and continue until about 35 seconds. The maximum force reaches about 159 kips.

Table 4.10 below displays the average maximums for drift, residual drift, and acceleration. The table demonstrates the average maximum for each floor from all 11 earthquakes and compares it to the average maximum of the entire structure from all 11 earthquakes. Compared to the target values given in Table 3.2, the PTED connection utilizing the ED bars with inerter exceed the target values for both drift and acceleration but are well below the target value for residual drift.
Figure 4.12: Time History of PT Force for ED Bars with Inerter

Table 4.10: Average Maximum values for ED with Inerter Connection

<table>
<thead>
<tr>
<th>Floors</th>
<th>Drift (%)</th>
<th>σ</th>
<th>Res. Drift (%)</th>
<th>σ</th>
<th>Acc. (g)</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story 1</td>
<td>1.794</td>
<td>0.541</td>
<td>0.074</td>
<td>0.068</td>
<td>1.299</td>
<td>0.272</td>
</tr>
<tr>
<td>Story 2</td>
<td>2.421</td>
<td>0.804</td>
<td>0.084</td>
<td>0.079</td>
<td>1.241</td>
<td>0.499</td>
</tr>
<tr>
<td>Story 3</td>
<td>2.489</td>
<td>0.842</td>
<td>0.084</td>
<td>0.059</td>
<td>1.328</td>
<td>0.480</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.580</td>
<td>0.095</td>
<td></td>
<td></td>
<td>1.489</td>
<td></td>
</tr>
</tbody>
</table>
4.4.5 PTED Connection with Friction Damper and Inerter

The optimal design for the PTED connection consisting of friction damper and inerter is from scenario two; the design of the PTED connection consists of different parameters but choosing from an extended range (external vs internal).

The chromosome for the optimal design is as follows:

\[11 \ 111 \ 100 \ 010 \ 110 \ 01 \ 100 \ 111 \ 100 \ 101 \ 10 \ 100 \ 111 \ 111 \ 010.\]

**First story: 11 111 100 010 110**

Inertance-to-mass ratio, \( b = 15\% \)

External ED element area, \( A_{EDF} = 1.8 \text{ in}^2 \)

Internal ED element area, \( A_{EDF} = 1.2 \text{ in}^2 \)

PT element area, \( A_{PT} = 1.736 \text{ in}^2 \)

Initial PT force, \( F_{Initial,PT} = 38\% \times F_{u,PT} \)

**Second Story: 01 100 111 100 101**

External ED element area, \( A_{EDF} = 1.2 \text{ in}^2 \)

Internal ED element area, \( A_{EDF} = 1.8 \text{ in}^2 \)

PT element area, \( A_{PT} = 2.604 \text{ in}^2 \)

Initial PT force, \( F_{Initial,PT} = 36\% \times F_{u,PT} \)
Third Story: 10 100 111 111 010

External ED element area, \( A_{EDF} = 1.2 \text{ in}^2 \)

Internal ED element area, \( A_{EDF} = 1.8 \text{ in}^2 \)

PT element area, \( A_{PT} = 3.906 \text{ in}^2 \)

Initial PT force, \( F_{\text{initial,PT}} = 30\% \times F_{u,PT} \)

The fitness function or RPI for this optimal chromosome is 1.202; this is the average of the member fitness for all 11 earthquakes. Table 4.11 and Table 4.12 below summarize the parameters that correspond to this optimal design chromosome and are labeled to easily identify them. The green box refers to the first story, the red box corresponds to the second story, while the yellow box refers to the third story. Figure 4.13 demonstrates the distribution of the PTED properties by level.

### Table 4.11: Summary of the Optimal Friction Damper with Inerter Solution

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>ED Area</td>
<td>0.4  0.6 0.8 1</td>
</tr>
<tr>
<td>ED Length</td>
<td>0.868 1.302 1.736 2.17</td>
</tr>
<tr>
<td>PT Area</td>
<td>26  28 30 32 34 36 38 40</td>
</tr>
</tbody>
</table>
Table 4.12: Summary of the Inerter for the Friction Damper with Inerter Solution

<table>
<thead>
<tr>
<th>Scenario 2 RPI = 1.202</th>
<th>Parameter</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inertance-to-mass ratio</td>
<td>0% 5% 10% 15%</td>
</tr>
</tbody>
</table>

Figure 4.13: Property distribution by level for the PTED Friction with Inerter Connection
A time history of the top and bottom contact element gap openings is presented in Figure 4.14 for a first-floor external connection. The plot displays that the gap openings begin at 5 seconds and continues until around 20 seconds, while some minor openings still occur until the end of the event. The maximum top gap opening is about 0.28 inches while the maximum bottom gap opening reached about 0.22 inches.

Figure 4.14: Gap Opening for 1st Floor External Connection Utilizing Friction with Inerter

Additionally, the time history of the axial force for the PT strands is presented in Figure 4.15. The PT strands are activated at the 5 second mark and continue until about 24 seconds. The maximum force reaches about 200 kips.
Table 4.13 below displays the average maximums for drift, residual drift, and acceleration. The table demonstrates the average maximum for each floor from all 11 earthquakes and compares it to the average maximum of the entire structure from all 11 earthquakes. Compared to the target values given in Table 3.2, the PTED connection utilizing the friction damper with inerter exceed the target values for both drift and acceleration but are well below the target value for residual drift.
<table>
<thead>
<tr>
<th>Floors</th>
<th>Drift (%)</th>
<th>$\sigma$</th>
<th>Res. Drift (%)</th>
<th>$\sigma$</th>
<th>Acc. (g)</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story 1</td>
<td>1.628</td>
<td>0.503</td>
<td>0.061</td>
<td>0.049</td>
<td>1.069</td>
<td>0.289</td>
</tr>
<tr>
<td>Story 2</td>
<td>2.230</td>
<td>0.745</td>
<td>0.058</td>
<td>0.030</td>
<td>1.018</td>
<td>0.326</td>
</tr>
<tr>
<td>Story 3</td>
<td>1.969</td>
<td>0.727</td>
<td>0.041</td>
<td>0.036</td>
<td>1.052</td>
<td>0.302</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.248</td>
<td>0.079</td>
<td></td>
<td></td>
<td>1.160</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.13: Average Maximum values for Friction with Inerter Connection**

4.4.6 PTED Connection with Steel Angles and Inerter

The optimal design for the PTED connection consisting of steel angles and inerter is from scenario three; the design of the PTED connection consists of different parameters depending on location (external vs internal).

The chromosome for the optimal design is as follows:

\[
1101010011011110010111100111100111100111100110
\]

**First story: 11 110 001 010**

Inertance-to-mass ratio, $b = 15\%$

ED element stiffness, $K_{EDA} = 3277.62 \text{ kip/in}$

ED element yielding force, $F_{y,EDA} = 56.88 \text{ kips}$

ED element strain hardening ratio, $b_{EDA} = .0166$

PT element area, $A_{PT} = 1.3 \text{ in}^2$

Initial PT force, $F_{initial,PT} = 30\% \times F_{u,PT}$
Second Story: 11 111 101 001

ED element stiffness, \( K_{EDA} = 4128.436 \text{ kip/in} \)

ED element yielding force, \( F_{y,EDA} = 67.44 \text{ kips} \)

ED element strain hardening ratio, \( b_{EDA} = .01646 \)

PT element area, \( A_{PT} = 2.17 \text{ in}^2 \)

Initial PT force, \( F_{initial,PT} = 28\% \ast F_{u,PT} \)

Third Story: 11 111 100 110

ED element stiffness, \( K_{EDA} = 4128.436 \text{ kip/in} \)

ED element yielding force, \( F_{y,EDA} = 67.443 \text{ kips} \)

ED element strain hardening ratio, \( b_{EDA} = .01646 \)

PT element area, \( A_{PT} = 1.95 \text{ in}^2 \)

Initial PT force, \( F_{initial,PT} = 38\% \ast F_{u,PT} \)

The fitness function or RPI for this optimal chromosome is 1.063; this is the average of the member fitness for all 11 earthquakes. Table 4.14 and Table 4.15 below summarize the parameters that correspond to this optimal design chromosome and are labeled to easily identify them. The green box refers to the first story, the red box corresponds to the second story, while the yellow box refers to the third story. Figure 4.16 demonstrates the distribution of the PTED properties by level.
Table 4.14: Summary of the Optimal Steel Angles with Inerter Solution

<table>
<thead>
<tr>
<th>Scenario 3</th>
<th>Parameter</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPI = 1.063</td>
<td>ED Yielding</td>
<td>17.99 25.37 29.81 36.66 42.94 49.46 56.88 67.44 kips</td>
</tr>
<tr>
<td>RPI = 1.063</td>
<td>ED Stiffness</td>
<td>211.85 312.92 472.80 561.88 1952.87 2626.67 3277.62 4128.44 kip/in</td>
</tr>
<tr>
<td>RPI = 1.063</td>
<td>ED Strain Hardening Ratio</td>
<td>0.08 0.08 0.06 0.06 0.02 0.02 0.02 in²</td>
</tr>
<tr>
<td>RPI = 1.063</td>
<td>PT Area</td>
<td>1.09 1.30 1.52 1.74 1.95 2.17 2.39 2.60 in²</td>
</tr>
<tr>
<td>RPI = 1.063</td>
<td>PT Prestress</td>
<td>26.00 28.00 30.00 32.00 34.00 36.00 38.00 40.00 %F₀</td>
</tr>
</tbody>
</table>

Table 4.15: Summary of the Inerter for the Steel Angles with Inerter Solution

<table>
<thead>
<tr>
<th>Scenario 3</th>
<th>Parameter</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPI = 1.063</td>
<td>Inertance-to-mass ratio</td>
<td>0% 5% 10% 15%</td>
</tr>
</tbody>
</table>

Figure 4.16: Property distribution by level for the PTED Angle with Inerter Connection
A time history of the top and bottom contact element gap openings is presented in Figure 4.17 for a first-floor external connection. The plot displays that the gap openings begin at 5 second and essentially end around 35 seconds. The maximum top gap opening is about 0.45 inches while the maximum bottom gap opening reached about 0.32 inches.

![Figure 4.17: Gap Opening or 1st Floor External Connection Utilizing Angles with Inerter](image)

Additionally, the time history of the axial force for the PT strands is presented in Figure 4.18. The PT strands are activated at the 5 second mark and continue until about 35 seconds. The maximum force reaches about 133 kips.
Figure 4.18: Time History of PT Force for Steel Angles with Inerter

Table 4.16 below displays the average maximums for drift, residual drift, and acceleration. The table demonstrates the average maximum for each floor from all 11 earthquakes and compares it to the average maximum of the entire structure from all 11 earthquakes. Compared to the target values given in Table 3.2, the PTED connection utilizing the steel angles with inerter exceed the target values for both drift and acceleration but are well below the target value for residual drift.
Table 4.16: Average Maximum values for Angles with Inerter Connection

<table>
<thead>
<tr>
<th>Floors</th>
<th>Drift (%)</th>
<th>σ</th>
<th>Res. Drift (%)</th>
<th>σ</th>
<th>Acc. (g)</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story 1</td>
<td>1.797</td>
<td>0.576</td>
<td>0.055</td>
<td>0.056</td>
<td>1.062</td>
<td>0.216</td>
</tr>
<tr>
<td>Story 2</td>
<td>2.390</td>
<td>0.813</td>
<td>0.071</td>
<td>0.072</td>
<td>1.121</td>
<td>0.395</td>
</tr>
<tr>
<td>Story 3</td>
<td>2.351</td>
<td>0.863</td>
<td>0.072</td>
<td>0.048</td>
<td>1.265</td>
<td>0.430</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.480</td>
<td>0.080</td>
<td></td>
<td></td>
<td>1.343</td>
<td></td>
</tr>
</tbody>
</table>

4.5 Comparison

Table 4.17 below displays the natural period of the first three modes for each structure. The natural periods of each model are expected to be the same due to the same member sizes, but the slight variations most likely arise from modeling assumptions such as the contact element stiffness and the fact that the PTED connection considers the beam depth.

Table 4.17: Natural Periods for each model

<table>
<thead>
<tr>
<th>Mode</th>
<th>WMRF</th>
<th>ED</th>
<th>Fric + Angle</th>
<th>ED + Inerter</th>
<th>Fric + Inerter</th>
<th>Ang + Inerter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period 1</td>
<td>0.970</td>
<td>0.942</td>
<td>0.942</td>
<td>0.942</td>
<td>0.942</td>
<td>0.942</td>
</tr>
<tr>
<td>Period 2</td>
<td>0.310</td>
<td>0.295</td>
<td>0.295</td>
<td>0.295</td>
<td>0.295</td>
<td>0.295</td>
</tr>
<tr>
<td>Period 3</td>
<td>0.142</td>
<td>0.139</td>
<td>0.139</td>
<td>0.139</td>
<td>0.139</td>
<td>0.139</td>
</tr>
</tbody>
</table>

The following plots compare the average drift, residual drift, and acceleration for each story to the WMRF average. The average response of each story considers all 11 earthquakes. Figure 4.19 through Figure 4.21 compares the first three PTED connections to the WMRF, while Figure 4.22 through Figure 4.24 compares the PTED + inerter connections to the WMRF.
Figure 4.19: Average Drift for PTED vs. WMRF

Figure 4.20: Average Residual Drift for PTED vs. WMRF
The PTED connections recorded higher drift and acceleration values for all floor levels when compared to the WMRF but have lower residual drift values. When comparing the PTED connections to one another the connection utilizing the ED bars consistently ranked last in all responses. The connection with the friction dampers displayed the lowest drift values and lowest acceleration value for the third-floor level. However, the connection with the steel angles outperformed the other PTED connections by displaying the lowest residual drift values. The connection with the friction damper was a close second in the residual drift category. When comparing the average maximum responses for the entire structure (Table 4.5 and Table 4.7), the friction damper connection had lower drift and acceleration values, but a slightly higher residual drift.
Figure 4.22: Average Drift for PTED + Inerter vs. WMRF

Figure 4.23: Average Residual Drift for PTED + Inerter vs. WMRF
Figure 4.24: Average Acceleration for PTED + Inerter vs. WMRF

The PTED connections with inerters recorded higher acceleration values for all floor levels and higher drift values excluding the first floor. Comparing the residual drifts shows the connections with the inerters outperformed the WMRF. When comparing the PTED connections to one another the connection utilizing the ED bars consistently ranked last in all responses. The connection with the friction dampers displayed the lowest drift values and lowest acceleration values. Generally, the connection with the steel angles ranked the second best out of the PTED connections with the inerter. Considering the average maximum tables presented earlier in the chapter, the friction damper with inerter connection exhibited lower drift, residual drift, and acceleration than the other PTED connections with inerters.
When comparing the drift time histories of all PTED connections to the WMRF side by side as shown in Figures 4.25 through Figures 4.27 we can determine which connection performed the best and which exhibited lower residual drifts. Figure 4.26 demonstrates that the connection utilizing the friction dampers exhibited less drift when compared to the WMRF. Figures 4.25 through Figures 4.27 also demonstrate that the PTED connections exhibit less drift towards the end of the time history signifying a reduction in residual drift. This trend is reflected in Figures 4.28 through Figures 4.30 for the PTED connections with inerters. This behavior is supported from the average maximum tables presented earlier in the chapter for each optimal solution.

Figure 4.25: Drift Time History comparison of ED Bar and WMRF
Figure 4.26: Drift Time History comparison of Friction Damper and WMRF

Figure 4.27: Drift Time History comparison of Steel Angles and WMRF
Figure 4.28: Drift Time History comparison of ED Bar + Inerter and WMRF

Figure 4.29: Drift Time History comparison of Friction + Inerter and WMRF
4.6 Summary of Results

Considering all the results presented in this chapter (gap openings, drift, residual drift, acceleration, etc.), the conclusion reached is that for all self-centering systems and study cases, the evolutionary framework identified optimal design solutions where the PTED exhibits no residual drift and comparable drifts and accelerations with the base WMRF.

Comparing the PTED models against the WMRF, the PTED models with and without ininers larger acceleration and drift values than the WMRF but along the same magnitude. However, the PTED models consistently eliminated residual drifts when compared to the WMRF. This is reflected in Figures 4.25 through 4.30. The natural period of the PTED models differed when
compared to the WMRF but were the same amongst each other; this is a consequence of modeling assumptions.

Comparing the PTED models amongst each other, overall, the PTED with friction dampers performed better than the other models as it displayed lower drift and acceleration values. The PTED model with steel angles displayed slightly better residual drift results but at the cost of higher drift and acceleration. The addition of the inerter to the PTED connections demonstrated that the inerter benefits the structure by further reducing the structure responses during and after a seismic event. Each PTED model exhibited even better results when the inerter was added to the model. The friction damper with inerter again outperformed the other models and resulted in lower residual drifts than the steel angles with inerters.

When considering the PTED models, the results exhibited by each model were very similar to one another. This is due to the fact that each model had the same choice of PT parameters, and the only difference came from the ED parameters. That is to say that each model essentially had the same self-centering capabilities and capacity, but different energy dissipation capacity. When comparing the ED properties, the PTED model with friction dampers has a higher initial stiffness and lower strain hardening ratio when compared to the other two PTED models. Due to the similar yielding capacities amongst each PTED model, the friction dampers dissipate more energy because of their larger hysteresis loop per cycle.

When comparing the optimal solutions of each PTED model with and without inerters, all solutions except one came from scenarios that represented uniform parameters across a given floor. Two out of the six solutions come from the extended parameter scenarios. This is an important observation
and points to the conclusion that optimal solutions and design should come from uniform parameters and original range of parameters. The extended range of parameters considers higher ED areas which signify higher yielding capacity. If the yielding capacity of an ED device is too high, it will not yield (thus no energy dissipation) and the gaps at the connections will not open. This will lead to more energy and damage at the beams and columns which is undesirable. Nonetheless, previously presented figures also conclude that a high yielding or slip force is favored since it represents higher energy dissipation; the key is that it cannot be too high or too low. No noticeable trend was discovered for the PT strand parameters. Optimal solutions for the models considering the inerter all used a 15% inerter-to-mass ratio signifying that higher inerterance is favored and leads to better results.

The best option among the different PTED systems is the PTED connection utilizing the friction dampers and inerter. The tables and figures presented earlier in the chapter corroborate this conclusion. The tables demonstrate that the friction damper with inerter connection displayed the lowest average maximum drift, residual drift, and acceleration values for the entire structure and for each floor level when compared to the other PTED connections. In addition, the friction dampers with and without inerter consistently displayed the least amount of gap openings and the smallest value of gap openings as displayed in Figures 4.5 and 4.14. Due to the friction dampers having a higher energy dissipation capacity per cycle, the beam-to-column connections will not exhibit a large gap opening and not as often when compared to the other PTED models.

When compared to the WMRF the friction damper with inerter exhibited higher acceleration values which is caused by the gap opening and closing. Comparing the gap opening time histories of each PTED connection shows that the friction damper with inerter connection also displayed
the least gap opening value. Furthermore, when looking at Figure 4.29, the drift time history of the friction damper with inerter consistently displayed lower drift during the seismic event (the blue plot is more visible than the red plot) and more importantly, the drift at the end of the time history for the friction damper with inerter is much smaller than the WMRF which signifies lower residual drift.

To summarize, the friction damper with inerter connection exhibited:

- Lowest average maximum drift, residual drift, and acceleration values compared to the other PTED connections
- Slightly higher average maximum acceleration when compared to the WMRF due to the gap opening and closings but had lower drift and residual drift values
- Lowest least gap opening when compared to the other PTED connections
CHAPTER 5: CONCLUSIONS

The objective of this thesis was to develop an evolutionary computational framework to provide with robust designs of various PTED self-centering systems. The primary goal was to design PTED frames that eliminate residual drifts in earthquake-stricken buildings. To achieve this goal, three PTED models and three PTED models incorporating inerter were compared to a typical WMRF. Another goal is to optimize the design of the PTED connections which was achieved using a genetic algorithm to identify optimal distribution of the self-centering connections along the height of the structures.

The introduction begins by discussing the effects and damage of earthquakes which led to the onset of earthquake engineering in building and design codes. Due to building cost and the stochastic nature of earthquakes, inelastic design is presented as the alternative and preferred method as it controls the maximum seismic force but experiences a maximum displacement similar to elastic systems. Specifically, a flag-shaped hysteretic curve is presented as the curve for a PTED connection. Next, literature review is conducted on the relevant topics that are covered and used in this thesis. Brief summaries of the histories of self-centering connections, PTED connections, inerter, and genetic algorithms are presented.

A description of the model structure and the process of creating the models in OpenSees is presented for the WMRF building, and three PTED connections with and without inerter. Additionally, a discussion on the description of how the genetic algorithm works for each PTED connection is given. Including details on chromosomes, fitness functions, and evolution into the next generation. Details of the earthquakes used on the models are also presented.
The genetic algorithm is engaged on each model for 101 generations and the results are collected and post-processed. An optimal solution for each PTED model is found and presented along with the pertinent results: drift, residual drift, acceleration, chromosome, RPI, etc. Each optimal solution was compared to the WMRF, to each other, and to the target values. Results indicate that the PTED models outperformed the WMRF. The optimal solution is the PTED connection utilizing the friction damper and inerter.

5.1 PTED Conclusions, Suggestions, and Future Research

The results collected and observed in this thesis with regards to the PTED connections lead to the following conclusions:

- The performances of the PTED connections exceed that of the WMRF.
- The PTED connections exhibit self-centering characteristics that lead to the elimination of residual drift after a seismic event.
- The PTED connection utilizing the friction device outperformed the other PTED connections, even though it exhibited the smallest connection gap openings.
- Typically, moderate to high values of ED yield/slip levels were favored, to maximize energy dissipation
- PT posttensioning/stiffness distribution trends vary drastically, and do not follow common uniform or linear distribution along the height of the structure
- PTED connections can be cost effective requiring the use of standard materials and skill sets.
• The cost of repairing PTED connections are low due to the isolation of yielding and damage to the ED devices.

• PTED connections utilizing the inerter exhibited better results and thus outperformed the PTED connections without ineters.

Practical uses of the thesis work:

• Framework for design of self-centering connections within PBEE

• Develop guidelines for self-centering connections property distribution design trends

• Design of resilient structures

• Reducing economic losses and downtime after earthquake events

• Framework can be extended to other alternative and novel seismic systems

Future Research

• Extend self-centering PT strands to base columns

• Investigate 3D model that considers PTED connections throughout the building

• Compute and compare concrete economical cost of WMRF and PTED connections
5.2 Genetic Algorithm Conclusions, Suggestions, and Future Research

Results and observations following the use of the evolutionary framework led to the following conclusions:

- The evolutionary framework was successful in finding the optimal solution and is an effective tool that can be used for other optimization problems.
- Framework is relatively easy to implement using a computer.
- It has no requirement of gradient information in contradiction to the classical methods and therefore is very attractive for optimization problems.
- It is suitable for distributed computing since it has a high level of concurrency.

This study further proves that PTED connections are a viable lateral seismic resistant force system capable of eliminating residual drift. These connections are arguably easier to implement and retrofit a building when compared to other seismic resistant systems (base isolation systems, tuned mass dampers, etc.) without large disruption to the natural period of the structure. This study also demonstrates the advantages and benefits of an inerter damper. Previous studies have proven the inerter can reduce structure responses and combined the use of inerters with other seismic resistant systems. This study is the first to combine the inerter with PTED connections and compare different energy dissipating devices and meets the objective of reducing residual drift.
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