SLOTTED-BOLTED FRICTION DAMPER AS A SEISMIC-ENERGY DISSIPATOR IN A BRACED TIMBER-FRAME

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A THESIS submitted to Oregon State University in partial fulfillment of the requirements for the degree of

Master of Science in Civil Engineering and Forest Products

Presented ...., 2001
Commencement ...., 2001
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1. Introduction

1.1 Background

In the 1994 Northridge Earthquake, about half of the $40 billion loss occurred in wood structures (NEHRP 1994). All but one of 25 fatalities caused by building damage occurred in woodframe construction (COES 1997). In the 1995 Kobe earthquake, thousands of timber structures collapsed. These examples of structural performance prove that woodframe building design for lateral force resistance has been overlooked and under-researched.

“Although 99% of the residences in California are of woodframe construction, there has been surprisingly little research focused on improving their earthquake resistance.” (Beck, 1998; quoted from CUREe Newsletter)

The seismic response of timber structures is controlled by the quality and the design of the connections. Significant stiffness and strength degradation and hysteresis pinching are observed in typical timber connections in strong cyclic loads (Fig. 1.1) (Dowrick, 1986; Foliente 1995). This behavior is caused by the yielding of steel components in connection, bolts and holes clearance, and the crushing of wood fibers. This behavior is very detrimental to the overall performance of timber structures. Hence, the quality of the materials
workmanship of the connection are critical to the seismic response of woodframe buildings (Seible, 1998).

Figure 1.1. Typical hysteresis loops for a wood joint with a yielding bolt (Dowrick, 1986)

Light industrial buildings and moderate-rise structures are often designed as moment resisting frames that are either braced or unbraced. Extensive research has gone into controlling and modifying the seismic response of steel and concrete structures in this size class and larger as well as predicting structural performance (Filiatrault and Cherry, 1989; Filiatrault and Cherry 1987; Soong and Dargush, 1997). Timber structures are sometimes not considered for use in seismic zones because damping systems have not been evaluated with timber. Recently, a four-story structure with almost one-million square feet was designed as a timber structure for a project in Southern California, but an energy dissipating system had not been evaluated for heavy timber.

It is common to model a plane frame that is subjected to lateral forces as a one-degree system. In a one degree system, the position of the system can be described in terms of a single coordinate. Figure 1.2 shows the frame and idealized-mass systems where the load function is a load-time relationship.
Figure 1.2. The structure and idealized mass subjected to 2 load function

In general, structural damping is considered to be viscous damping (Biggs, 1964), which implies that the damping force is opposite but proportional to velocity. The one degree of freedom model can be revised to incorporate the viscous damping as shown in Figure 1.3.
Figure 1.3. One-degree of freedom models with (a) viscous damping, (b) friction damping

The equation of motion for the single degree of freedom system is (Biggs, 1964):

\[ ky + M\ddot{y} + c\dot{y} = F(t) \]  \hspace{2cm} (1)

There are two ways to put a damper system in a building: external damper and internal damper. An example of this external damper is base isolation system, where the damper system is put on the foundation of a building to absorb energy from ground motion before it reaches the main structures. Examples of internal damper are metallic damper, fluid viscous damper, visco-elastic, friction damper. In the internal damper system, the building absorbs energy from ground motion or wind in their connections.
The main purpose of damper system is to dissipate energy or to absorb energy from ground motion or wind to prevent serious damage on primary members of a structure.

There is an increasing need for energy dissipating system that can increase the seismic related performance of timber structures connections. There are two types of energy dissipation system control: active and passive. An active energy dissipation system uses a computer or manual system to control the building structural response in case of unexpected lateral force because of ground motion or wind. A passive energy dissipation system is implemented with an energy dissipation device that operates without active interference of a computer or human.

Some experts suggest that passive energy dissipation system is more preferable than the active control, because in the event of an earthquake or other hazard situation, a computer or human is not reliable to handle such a big responsibility.

There are two types of passive energy-dissipation methods for building systems: viscoelastic and mechanical/hysteresis. Fluid dampers are a viscoelastic energy-dissipation method, while friction dampers, such as slotted bolted-connections, are mechanical/hysteresis energy-dissipation systems.

Studies with energy dissipators in wood structures have been reported by Filiatrault (1990), Young and Filiatrault (1990), Dinehart et al. (1999), Duff (1998), and Duff et al. (1998). The research by Filiatrault, Young and Filiatrault, and Dinehart et al. were conducted for shearwall applications in typical light-frame
wood systems. The studies by Duff and Duff et al. were proof of concept experiments for dissipating energy with a hidden connector system.

Friction dampers work by dissipating energy by friction between two known surfaces. The resistance to motion is provided by simple friction or coulomb friction (Soong and Dargush, 1999). The amplitude of the friction is constant and depends on the coefficient of friction between the contacting surfaces assuming a constant coefficient of friction. The SDOF model representing a friction damper is illustrated in figure 1.3b. For friction damper, Biggs (1964) wrote the equation of motion as:

$$m\ddot{y} + ky = \pm F_f$$

(2)

From equation 2, it can be seen that friction dampers can be effective mechanisms.

The energy dissipated in a friction damper system is equal to the product of the slip load and the slip distance. Setting the slip load too high or too low will result in energy dissipation becoming negligible. The intermediate slip load between these two values where the energy dissipated is as close as the input lateral-motion energy is defined by Filiatrault as “Optimum Slip Load” (1990).

The ease of implementation and reliable performance of slotted bolted-connection for steel frames suggests that it maybe possible to implement it in timber structures. There is no doubt that general characteristics of SBC in timber structure will have an excellent behavior as seen in steel systems. There are some specific questions that need to be addressed and studied such as:
1. The effect of the interaction of the steel and wood components on the performance of individual dampers and on the behavior of the overall system.

2. The effect of the brittle modes of the wood on ultimate system ductility.

3. The effect that the hysteretic behavior of un-damped connections in the frame has on global hysteretic behavior.

4. The member, location, and orientation of friction dampers in specific design situations.

This study will be the next step toward understanding the behavior of slotted bolted-connections in timber frames.

Slotted bolted-connection in steel frame tested for the first time in 1976 at San Jose University (Venuti, 1976). Similar tests were also conducted in some other countries. Friction joints for seismic control of large panelized concrete structures were tested in Canada (Paï et al., 1980). It also has been tested under pseudo-dynamic conditions in Germany in 1988 (Roik, et al., 1988) and truly dynamic conditions (Filitrault and Cherry, 1989; Tremblay and Steimer, 1993; Colajanni and Papia, 1995; Ciampi et al., 1995). Grigorian and Popov in 1994, greatly improved the behavior of slotted bolted connection with the inclusion of brass shims in the system.

A generic SBC has three parts: slider plate, side plate, and the bolting apparatus. Figure 1.4 illustrates the connection. It dissipates energy by friction between the slider plate and the cover plates. The slip force ($F_s$) is controlled by the tensile force in the bolts.
Friction dampers have been implemented successfully in steel and concrete structural systems (Soong and Dargush, 1997). In the commercial application friction dampers have been used in braced frames, some of which have been multistory structures. According to Soong and Dargush, the most common types of passive damper are a chevron and cross-braced structural system as shown in figure 1.4b and 1.4a. Another design might use a toggle brace (Constantinou et al., 2004) as in figure 1.4d. A diagonal brace (figure 1.4c) is an attractive design scenario for an SBC because the connection would be loaded and functioned purely in axial compression or tensile modes.
Figure 1.4. Alternative bracing strategies with passive energy dampers; (a) cross-brace; (b) chevron brace; (c) diagonal brace; (d) toggle brace

1.2 Objectives

Global objective is to evaluate the potential for passive energy dampers for use in heavy timber braced frames.

Specific objectives:

- Design a generic friction damper based on a slotted bolted-connection.
- Assess the merits of different cyclic test protocols for friction dampers in timber structures.
- Evaluate the performance attributes of the friction damper in terms of energy dissipation and equivalent viscous damping.
- Evaluate the friction damper performance when it is connected to a timber brace where the attachment connection was designed using the NDS.

2. Literature Review
2.1 Slotted-Bolted Connections

2.1.1 How to measure the bolt tension

There are ways to tighten the bolts and to measure the specific tension in the bolts is achieved.

Direct Tension Indicator washer is a steel washer with bumps around the washers forming a circle. These bumps will flatten under specific load. DTI washer is manufactured in different sizes of thickness, inside diameter, outside diameter, and also types of steel material. The manufacturer also usually provides the information of the maximum load it will endure before it become flat.

The purpose of using DTI washers is to provide assurance that the minimum specified bolt tension is achieved and it is currently the best method of controlling bolt tightening. The DTI washers that has been use are based on ASTM designation F959 (Grigorian and Popov 1994). Method 2 assembly of DTI washers is usually preferred by manufacturer and user, but for accuracy on predicted slip force and to avoid the full yielding of the bolts, method 1 assembly is more preferred by designer.

The usage of DTI washers, however, is not required and it will not effect the behavior of the slotted bolted connections as long as the specified bolts tension is achieved.

2.1.2 Belleville Washers

Belleville washer, figure 2.1, is a type of washer that acted as a spring. It is a regular washer with a curvature if it is viewed from cross section. The
Belleville washer is manufactured with different sizes of thickness, inside diameter, outside diameter, and maximum deflection before it become flatten. They were also available with different stiffness. Manufacturer usually provided the information such as how much load it will endure until it flatten.

![Diagram of Belleville washer](image)

**Figure 2.1. Typical Belleville washer**

In slotted-bolted connections for steel, the bolt pretension will decrease eventually because of the wears out of friction surfaces. There are some phenomena that can cause bolt loosening: embedment relaxation, gasket creep, bolt creep, vibration, elastic interactions, and differential thermal expansion. The Belleville washers can prevent or slow down the lost of tension in the bolt by storing some potential energy in the washer in the form of initial deflection. According to Grigorian and Popov (1994), using more than one Belleville washers in slotted-bolted connection System with brass shims will have a significant different in its performance to maintain relatively constant slip force.
Different numbers of Belleville washers and combinations can be used in a bolted connection (figure 2.2). The numbers and combinations of these washers should be carefully tested and studied. The load will not be the only consideration to pick the right number and combination. It will also necessary to make sure that the maximum bolt tension within the elastic region of the washers stiffness. In other words, using combination of washers in parallel and series might be necessary.

![Parallel Combination](image1.png) ![Series Combination](image2.png)

Figure 2.2. Basic combination of Belleville washers

2.1.3 Long slotted holes

Typical SBC connection has a 76.2 to 101.6 mm (3 to 4 inches) long slotted holes and the bolt diameter plus 1.5875 mm (1/16 inches) wide. Popov et al. (1993) proposed a 88.9 mm (3.5 inches) long slot and Grigorian and Pepov (1994) proposed a 101.6 mm (4 inches) long slot. The length of the bolt can be adjusted to accommodate the allowable movement of the structure member or
the story drift of the building. For the purpose of comparing the behavior of SBC in wood to those used in steel, we use 101.6 mm (4 inches) of long slotted holes, assuming the designed allowable lateral motion of the frame shall not exceed 101.6 mm (4 inches).

2.1.4 Bolts

The strength and the dimensions of the bolts are designed based on the steel ASD standard. This decision was made because the wood design part is based on Wood NDS (which is ASD standard).

Previous studies (Grigorian and Popov 1994, Duff 1998) use A325 bolts for the system. Since the objective of this study is to learn the behavior of SBC under cyclic loads, higher strength bolts were used to prevent any bolt yielding when tensioned to a specific load. The bolts are grade 8 bolts with 13 threads per inch and lubricated before the installment. The lubricant used is BOSTIK, anti-seize and lubricating compound (pipe compound with Teflon). The length of the bolts specified such that the shank part shall not be shorter than the total thickness of the plates.

2.1.5 Brass shims

Typical conventional friction dampers such as slotted bolted connections are only based on the friction of steel versus steel surfaces. Grigorian and Popov in 1994, added the usage of brass shims “sandwiched” between the steel plates.
(see figure 2.3). This was also implemented in the design by Dufl in 1998 for SBC in timber structures.

Figure 2.3. Typical Slotted Bolted-Connection by Grigorian and Popov (1994)

The addition of brass shims in between the outer plates and the slotted plate help reduce the wear out volume of the surfaces out of the SBC system. Brass is a softer metal compared to steel. When the brass and steel surfaces move to each other, the steel surface grooves the brass surface and causing it to wear fairly quick. In steel-steel friction, the metals have the same hardness, so both surfaces losing particles due to friction. Since steel does not have adhesive wear, total volume of the metals after friction period chance significantly due to the lost of particles out of the system and the bolts that clamped the system together losing significant amount of the pretension load.

Brass has a tendency of abrasive and adhesive wear, the wear out brass particles smear and stick on the steel surface due to friction. It is also called smearing adhesion. This phenomenon keeps the pretension bolts almost
constant before and after we applied the load, because there is no change in
total volume of brass and steel.

The experiment uses half-hard cartridge brass (UNS-260) with standard
holes. The bolt tolerance is about 1.5975 mm (1/16th inch) on 3.175 mm (1/8")
 thick brass shims. The brass shims are placed in between the side plates and the
slotted plate. The width of the brass shims is 101.6 mm (4 inches), which is the
same length as the slotted holes in the plate. The length of the shims is as long
as the width of the wood member.

2.2 The Role of Tribology

Tribology is the study of wear, friction and lubrication of materials. This is
the most important concept in the basics of designing slotted bolted connections.
These are some important definitions from tribology:

Friction is the resistance to relative motion of contacting bodies.

Wear is a process of removal of material from one or both of two solid
surfaces in solid-state contact (Bhushan and Gupta, 1991)

Adhesive wear, often called galling or scuffing, is the form of wear which
occurs when two smooth bodies are slid over each other, and fragments
are pulled off one surface to adhere to the other (Rabinowicz, 1966).
Abrasive wear is the form of wear which occurs when a rough hard surface, or a soft surface containing hard particles, slides on a softer surface, and poughs a series of grooves in it (Rabinowicz, 1966).

Coefficient of friction is more a random range of number rather than a specific value. Static friction is the maximum slip force that it has to achieve to make a system start to move. Kinetic friction, however, is the minimum slip force that a system need to maintain to keep it moving after it achieved static friction.

The nominal static slip force or static frictional force is the force needed to overcome frictional force of a system to keep it at rest. Friction coefficient between clean mill steel surface and brass shim (UNS-260) is in a range of 0-30-0.26 (Grigorian and Popov 1994). This value is obtained from the testing of SBCs with "virgin" surfaces, which means they never been used for any friction testing before.

According to David Tabor (Singer and Pollock, 1992), the friction energy dissipated in the form of vibrations, when the atoms in the shear plane are displaced from their equilibrium position until they reach unstable configuration and flick back to another equilibrium position (plastic deformation). The strain energy in turn degrades into heat.

Frictional force between various metals is not constant or continuous. It proceeds with discontinuities, which we called it "stick slip" behavior. The stick-slip behavior is expected during the test. This behavior can occur in friction where two surfaces were sheared. "Stick" is when the system is building up the
potential energy and trying to keep the system "static". After the specific amount of energy is reached, the two surfaces slide or "slip" and releasing the same amount of initial potential energy in the form of kinetic energy (velocity), heat, and potentially wears of material. The uniqueness of stick-slip behavior depends on several yet unknown factors. Bowden and Leben (1939) examined that for various metals on steel shows that the extent of the rapid slip is governed by the melting-point of the metal. The lower melting point has the larger slip. Certain long chain fatty acids, however, may prevent stick-slip and allow continuous sliding to take place.

2.3 Slotted-Bolt Connections for Timber Structures

Slotted-bolted connections originally designed for steel structures. (some references here). The system has been proven to be effective in terms of cost, construction, and energy dissipated. This type of friction damper attached to timber structures has been preliminary studied and tested aggressively by Duff since 1996. His preliminary studies showed that slotted bolted connections used in timber structures resulting excellent hysteretic behavior under cyclic loading, with negligible strength and stiffness degradation (Duff et al, 1998).

2.4 Testing Protocol

There are many types of test methods that can be used to analyze the performance of a structure. Some of these are:
Static Monotonic loading is where a slow static load is applied in increments in one direction only until failure or excessive deformation occurs.

Pseudo-dynamic test is a testing protocol that is a combination of quasi-static and dynamic shaking-table test. This testing is subjecting selected points in the structure and applying them with time-varying displacements based on the incremental dynamic analysis of the specimen response to a pre-selected input motion, using measured stiffness data from the preceding loading increment and prescribed data on specimen mass and damping with a relatively slow rate.

Quasi-static test is slowly reversed, loading test to avoid any inertia effect. In this method, the specimen is subjected to statically applied increments of deformation at discrete points and the magnitudes are calculated based on a predetermined earthquake input and the measured stiffness and estimated damping of the structure (predetermined amplitude).

Dynamic test is using shaking tables. This is the most realistic, expensive and complicated method.

For testing slotted bolt connections in wood structures, the testing protocol will play major role in producing the best-predicted behavior in the connection. It
is impossible to predict how a connection will fail in a real earthquake. So far, there is no standard testing protocol for mechanical friction damper. Most of the test protocols are designed specifically to address bolt yielding rather than slipping. This makes harder for us to pick and to use one that will give the best prediction of the structure.

In 1994, Grigorian and Popov tested slotted bolt connections in steel structures. They used sinusoidal imposed displacement with increasing amplitude and decreasing frequency then followed by decreasing amplitude and increasing frequency. Using the chosen testing protocol, Grigorian and Popov demonstrate that SBCs can be used as an effective means for energy dissipation in seismic events in steel structures.

In wood connection, the behavior of the SBC might not be the same as the SBCs used in steel structure. Because of this, there is a need to use a more effective testing protocol that will better describe the behavior of SBCs in wood structures.

In this study, we will use Grigorian and Popov's test protocol to validate our SBC design and then use a standard protocol to compare the hysteretic performance of SBC with and without timber specimen. There are three test protocols considered: Sequential Phased Displacement (SPD), International Standard Organization (ISO), or CUREe.

SPD proposed by Dolan in 1994 is used by Porter (1987) and completed by Polensek (1988). This method is used by TCCMAR (Joint Technical Coordinating Committee on Masonry Research) for the United States-Japan
Coordinated Earthquake Research Program. This test protocol is not a good method for testing bolt connections since it was used primarily for masonry testing and then later proposed for wood shear walls.

ISO’s testing protocol is designed specifically for mechanical fasteners in timber structures under seismic action. It is a quasi-static reversed-cyclic test and it is best to describe elastic and inelastic properties of a joint. It can also be used to develop envelope curves for joints. It is recommended to use a minimum number of 6 static and cyclic tests and frequency of 0.1-10 mm/sec.

CUREe’s testing protocol for wood frame structures is proposed in 2000. It is the only one with a statistical basis that used a non-linear analysis on about 10,000 earthquakes. It is a quasi-static cyclic test and can be used to determine cyclic behavior characteristics. It is tested in shear walls and is being proposed by a lot of people to be the standard of wood frame testing.

For SBC testing in wood frame, presently, ISO is probably the best available test standard that fit our objectives and situation to answer our questions. SPD was designed for masonry walls and CUREe was designed for shear walls. SBCs have different features from regular bolt connections and the decision to choose which protocol will give close approximation of real life building is tough but we decided that choosing ISO as the test protocol will give a good approximation and comparison we need to a traditional bolt connections.

2.5 Analysis of Hysteresis Data

2.5.1 Ideal Hysteresis Behavior
Hysteretic energy dissipation is one of the most effective ways to provide substantial level of energy dissipation. Friction is one of many methods of energy dissipation which is used to limit deflection. The weaknesses of this method are difficult to quantify and most frictional devices are not self-centering (may result in permanent offset).

There are four basic types of force-deflection relationships:

1. A linear is where a system has the same isolated period over all earthquake load level.
2. A hardening is where a system is soft initially and then stiffens as load increases.
3. A softening is where a system is stiff initially and then softens.
4. A sliding is where a system is governed by friction force of the isolation system.

There are three options that can be considered in hysteresis model:

1. The basic (non-degrading) bilinear model (unrealistic for wood).
2. The basic peak-oriented (Clough).
3. The basic pinching model (more realistic in wood).

An ideal hysteretic loop for friction system is where the system is perfectly elastic and plastic. The energy dissipated is the area inside the loop. Since the displacement can be in the positive and negative region, tension energy dissipation is the area of the loop where displacement is positive and the
compression energy dissipation is the area of the loop where displacement is negative.

Pinching in load-displacement hysteresis loop is due mainly to sliding shear. In wood structure, this pinching can be caused by the sliding of bolts in the holes of the wood beam. This hole usually is fairly small (about 1.5875 mm or 1/16 inch). The basic bilinear model and basic peak-oriented model are better than basic pinching model because in pinching model the energy that supposed to be dissipated in bilinear model or peak-oriented model is lost (not dissipated by the friction damping system) to the structure.


2.5.2 Equivalent Viscous Damping

Equivalent viscous damping is used to compare damping characteristics and for numerical modeling of the dynamic response of structures. The equivalent viscous damping, $\xi$, is calculated using the equation:

$$\xi = \frac{E_h}{2\pi E_p}$$

$E_h = $ Hysteretic Energy

$E_p = $ Potential Energy
Figure 2.4. Hysteresis Loop A-B-C-D

From figure 2.4, the hysteretic energy is the area enclosed by the hysteretic loop A-B-C-D and the potential energy is the area enclosed by the shaded triangles.

3. Design of SBCs in Timber Structure

3.1 Overview of the Building

Slotted bolted connections can be use in the bracing connection to the structure. An example of this design is a 20 ft high warehouse with 120 ft x 120 ft area, three frames and 60 ft apart located in Willamette Valley, OR. Assuming the frames have 6 bays and cross braced at one of the end bays. The SBCs are mounted at the upper end of the bracings. The detailed drawing of this building can be find in Appendix B.
3.2 Loadings

The loads assumed to be 20 psf dead load, 25 psf snow load. Willamette Valley in Oregon is in zone 4 and type A source of earthquake with unknown soil type. Using UBC equations for seismic base shear, the governing base shear is 42428.9 lbs.

Uniform load on the roof is calculated based on Allowable Stress Design specification and UBC.

3.3 Designs of the Primary Structural System

The design of the primary members of the frame based on National Design Specification for wood construction (NDS) and Allowable Stress Design for steel structures (ASD). We decided to use ASD design specification rather than LRFD because NDS is based on ASD.

Using McGuire's semi rigid connection analysis of 50% rigidity in the frame (1995). The design of the structural members is shown in Appendix B.

The slotted bolted-connection is mounted in the bracing member of the frame, so the main concern is to calculate what is the approximate maximum tension and compression force in it. Since this frame is an indeterminate structure of more than one degree of freedom, we use SAP2000 program to calculate the approximate axial force on the bracing. The input and output files of the program is shown in Appendix C. From the output file, the maximum axial
force of the bracing members of the structure under various ASD loading combination is 30,000 lbs.

The optimum slip load distribution can be determined by a series of time-step dynamic analyses using computer programs such as DRAIN-2D. Filiatrault and Cherry in 1988 generated a new, efficient numerical modeling for friction damped braced steel plane frames to estimate this optimum slip load distribution. This can be used to calculate the expected slip load of a known building structure, however, is not the objective of this paper.

3.4 Design of SBCs

The slot length of the SBCs can based on the UBC allowable story drift or the maximum drift allowed by the designer. This decision is open and should be based on the purpose of the building and factor safety set by the designers. Typically, the SBCs' slot length is 3.5 to 4 inch long. For tall structures, the SBCs can be attached to both ends of the bracing members to allow for more lateral drift.

Compression washers, such as Belleville washers, are essential to the behavior of the SBCs. Not only it minimizes the bolt loosening caused by vibration, but also the effect of temperature dependent material such as wood on bolt tension. These washers should be installed considering the moisture content of the wood at the time of construction and the typical range of equilibrium moisture content of buildings in the area to allow both shrinkage and
swelling of the wood member. Measuring the moisture content of the wood members is recommended before installing the compression washers.

In this test, the bolts pretension for steel-wood connections is designed such that the steel plates will not slide against the wood and also will not crush the wood surfaces.

Based on the information above, we decide what type, how many, and what combination of compression washers needed for the connection.

5. Conclusion

The dual slotted bolted-connection can be use in heavy timber braced frames with an excellent hysteresis behavior. The behavior of this type of friction damper is comparable to those used in steel structures. The effect of temperature and embedment strength of the wood appeared to be negligible with the addition of Belleville washers in the steel-wood connection design.

Basic parameters of typical hysteresis loop are calculated and recorded. This method is modified from Filiatrault and Cherry (1987) and explained in Appendix F.

The most important trait of SBC is that the friction lateral force resistance can be controlled. Commercially, it is the cheapest to build and maintain. Any damage or defect can be detected visually most of the time.

The equivalent viscous damping of the slotted bolted-connection from the tests showing a value of up to 0.55 compared to 0.64 to the perfect hysteresis
behavior (rigid-perfectly plastic hysteresis loop). This result agrees with Duff’s preliminary tests in 1998.

5.1 Recommendation for Further Study

- The effect of high frequency on the slotted bolted-connection needs to be more studied and researched.

- The level of coarseness of the surface condition of the steel plates varied and possibly changed before and after the test. To reuse the steel plates after the cyclic event, we need to find a good way to recondition the surfaces to get repeatable results, such that the only thing that we need to change after an earthquake event is the brass shims.

- In the event of long cycles, the load spikes occur in the hysteresis loops because of the non-uniform wear and adhesion of brass particles on the steel surfaces especially at the end strokes of high amplitudes. The expected number of cycles where the load spikes begin to occur and how to avoid it need to be studied more.