

**T.C. İSTANBUL KÜLTÜR UNIVERSITY
INSTITUTE OF GRADUATE STUDIES**

**THE EFFECT OF SURFACE FRICTION ON THE SEISMIC RESPONSE OF
ISOLATED STRUCTURES WITH TRIPLE FRICTION PENDULUM
BEARINGS**

Masters of Applied Science Thesis

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Department: Civil Engineering

Programme: Structural Engineering

Supervisor: Assist. Prof Dr. Gökhan YAZICI

SEPTEMBER 2022

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ABSTRACT

THE EFFECT OF SURFACE FRICTION ON THE SEISMIC RESPONSE OF ISOLATED STRUCTURES WITH TRIPLE FRICTION PENDULUM BEARINGS

Rawan Rabia ALJALAB

Since the 1970s, the aseismic design of structures has greatly benefited from the application of seismic control systems. Seismic isolation is used to protect the structural and non-structural components as well as the contents of structures. The triple friction pendulum bearings (TFPBs) have attracted the attention of engineers and researchers due to their adaptive performance. Triple Friction Pendulum Bearings (TFB) are seismic isolators which have four concave sliding surfaces. Radius of curvature and friction coefficients of these surfaces are adjusted to meet the performance objectives of the seismic isolation system. This study aims to investigate the effect of contact surface friction on the seismic response of structures on Triple Friction Pendulum Bearings under near-fault and far-fault earthquakes through a parametric study. Generally, the results of the analysis have shown that increasing the value of the coefficient of friction mostly decreases the bearing displacements and increases the story accelerations. It has also been found that the effect of increasing the friction coefficient had a more profound influence on the seismic response parameters for the isolated structure subjected to near-fault earthquake ground motions.

Keywords: Seismic Isolation, Triple friction pendulum system, OpenSEES, Seismic Response, Earthquake Resistant Design, Ground Motion Records

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KISA ÖZET

YÜZEY SÜRTÜNMESİNİN ÜÇLÜ SÜRTÜNMELİ SARKAÇ MESNETLİ YAPILARIN DEPREM YÜKLERİ ALTINDA DAVRANIŞINA ETKİSİ

Rawan Rabia ALJALAB

1970'lerden bu yana, yapıların sismik tasarımı, sismik kontrol sistemlerinin uygulanmasından büyük ölçüde faydalanmıştır. Sismik izolasyon, yapısal ve yapısal olmayan bileşenlerin yanı sıra yapıların içeriklerini korumak için Üçlü sürtünmeli sarkaç mesnetleri, uyarlanabilir performansları nedeniyle mühendislerin ve araştırmacıların dikkatini çekmiştir. Üçlü Sürtünmeli Sarkaçlı Mesnetler, dört içbükey kayma yüzeyine sahip sismik izolatörlerdir. Bu yüzeylerin eğrilik yarıçapları ve sürtünme katsayıları, sismik izolasyon sisteminin performans hedeflerini karşılayacak şekilde ayarlanmaktadır. Bu çalışma, yakın fay ve uzak fay depremleri altında Üçlü Sürtünmeli Sarkaç Mesnetler üzerinde temas yüzeyi sürtünmesinin yapıların sismik davranışı üzerindeki etkisini parametrik bir çalışma ile araştırmayı amaçlamaktadır. Genel olarak, analiz sonuçları, sürtünme katsayısı değerini artırmanın çoğunlukla mesnet yer değiştirmelerini azalttığını ve kat ivmelerini artırdığını göstermiştir. Ayrıca, yakın fay deprem yer hareketlerine maruz kalan izolasyonlu yapılar için sürtünme katsayısını artırmanın etkisinin sismik tepki parametreleri üzerinde daha önemli bir etkiye sahip olduğu bulunmuştur.

Anahtar Kelimeler: Sismik İzolasyon, Üçlü Sürtünmeli Sarkaç Sistemi, OpenSEES, Deprem Yükleri Altında Davranış, Depreme Dayanıklı Tasarım, yer hareketi kayıtları.

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LIST OF ABBREVIATIONS

ASCE: American Society of Civil Engineers
PGA: Peak Ground Acceleration
PGV: Peak ground velocity
DBE: Design Based Earthquake
MCE: Maximum Considered Earthquake
FEMA: Federal Emergency Management Agency
NHERP: National Earthquake Hazards Reduction Program
OPENSEES: Open System for Earthquake Engineering Simulation
TFP: Triple Friction Pendulum
PEER: Pacific Earthquake Engineering Research Centre
PTFE: Polytetrafluoroethylene
SFP: Single Friction Pendulum
TCL: Tool Command Language
THA: Time History Analysis

LIST OF SYMBOLS

a_1, a_2, a_3, a_4 : Bearing rate parameter (sec/m)
 A_b : Bonded rubber area (m²)
 b : Shortest plan dimension (m)
 β : Damping ratio
 β_s, β_b : Superstructure and base damping ratio
 B_D, B_M : Design and maximum damping correction factor
 c_s, c_b : Coefficients of damping for Superstructure and base
 C : Coefficient of Damping
 d : Longest plan dimension (m)
 d : the displacement capacities of Friction pendulum (m)
 d_1, d_2, d_3, d_4 : Friction pendulum displacement capacities 1, 2, 3 and 4 (m)
 D_D, D_M : Design and maximum displacement (m)
 D_{TD}, D_{TM} : Total design and total maximum displacement (m)
 D : the Bearing displacement (m)
 e : Eccentricity (m)
 ε : separation parameter
 E_c : Bearing compressive modulus (MPa)
 E_c : Concrete elastic modulus (MPa)
 E_s : Steel elastic modulus (MPa)
 E_s : Structure energy (kN.m)
 E_d : Dissipated energy (kN.m)
 E_k : Kinetic energy (kN.m)
 E_e : Elastic strain energy (kN.m)
 E_v : Viscous damping energy (kN.m)
 E_h : Hysteretic damping energy (kN.m)
EDC: Energy dissipation circle (kN.m)
 g : Acceleration due to gravity m/s²
 F : Lateral force (kN)
 F_f : Frictional force (kN)
 F_s : Story force (kN)
 F_a, F_v : Site coefficients for short and 1s period spectral acceleration
 G : Shear modulus (MPa)
 h_x : Story height (m)
 h_1, h_2, h_3, h_4 : Friction pendulum height 1, 2, 3 and 4 (m)
 h : Friction pendulum height (m)
 k_s, k_b : Superstructure and base stiffness (kN/m)
 k : Lateral force distribution correction coefficient
 K : Stiffness (kN/m)

K_d : Bearing stiffness (kN/m)
 K_{eff} : Effective bearing stiffness (kN/m)
 K_D, K_D : Design and maximum stiffness (kN/m)
 K_H, K_v : Bearing horizontal and vertical stiffness (kN/m)
 m_s, m_b : Superstructure and base mass (kg)
 M : Mass of structure (kg)
 η_D, η_M : Design and maximum damping correction factor
 φ : Mode shape
 θ : Sliding bearing angle (rad)
 P_T : The effective translational period (s)
 ρ_c : Mass per unit volume concrete (kg/m)
 ρ_c : Mass per unit volume steel (kg/m)
 σ_{yb} : Bearing yield strength (MPa)
 σ_y : Yield strength (MPa)
 σ_c : Compressive strength (MPa)
 Q : Bearing characteristic force strength (kN)
 R : Friction pendulum radius (m)
 R_{eff} : Effective pendulum bearing (m)
 R_1, R_2, R_3, R_4 : Friction pendulum radius 1, 2, 3 and 4 (m)
 $R_{eff1}, R_{eff2}, R_{eff3}, R_{eff4}$: Friction pendulum radius 1, 2, 3 and 4 (m)
 R : Modification Factor
 R_I : Modification factor
 S_{ae} : Spectral acceleration (m/s²)
 S_D, S_M : Design and maximum spectral acceleration (g)
 S_s : Spectral acceleration at short period (s)
 S_1 : Spectral acceleration at 1s (s)
 S_{D1}, S_{M1} : Design and maximum spectral acceleration at 1s (m/s²)
 S_1, S_2, S_3, S_4 : Sliding plate surface 1, 2, 3 and 4
 S : Shape factor
 t_r : The total thickness of rubber (m)
 T : Period (s)
 T_d : Bearing period (s)
 T_{eff} : Effective bearing period (s)
 T_D, T_M : Design and maximum structural period (s)
 $\mu_1, \mu_2, \mu_3, \mu_4$: Friction coefficient 1, 2, 3 and 4 (m)
 μ : Friction coefficient
 V_D, V_M : Design and maximum base shear (kN)
 V_{st} : Total unreduced shear-force of structure above the base level (kN)
 V_s : Total reduced shear force on elements above the base level (kN)
 ω : Natural frequency (rad/s)

ω_s, ω_b : Superstructure and base mass (rad/s)
 w : the Effective weight of the structure above the isolation (kN)
 w_x : Story weight (kN)
 W_s : the Effective weight of the structure above the isolation excluding base level (kN)
 x : Level (m)
 y : the Distance between centre of rigidity to plan corner (m)
 γ : Mass ratio



CHAPTER 1

INTRODUCTION

1.1 General introduction

Base isolation aims to decouple the structure from the harming impacts of earthquake ground motions. If the superstructure is isolated from the ground during an earthquake, the ground will move, but the structure will only experience a small movement [1]. Therefore, the most important reason for using base isolation is to limit the transfer of earthquake forces to the superstructure [2].

Since the 1970s, the aseismic design of structures has greatly benefited from the application of seismic control systems. Seismic isolation provides one of the few means to reduce seismic deformation while mitigating high acceleration requirements for non-structural parts and contents [1]. With the development of performance-based designs in recent years, the focus has been on the overall seismic performance of structures, which has emerged in both research and practice [2]. Base isolation is a mature that has been used to protect structures from earthquakes for decades [2]. Extensive work has been done using reliability-based methods to optimize the isolator parameters and study the effects of the parameters on the seismic response of the structure. However, these studies mainly focus on isolation systems with simple bilinear hysteresis. The triple friction pendulum bearings (TFPBs) have attracted the attention of engineers and researchers due to their multi-level operation and can be used in multi-level performance-based designs [3]. This newly-evolved isolator includes 4 concave surfaces and 3 pendulum mechanisms with 3 exclusive friction coefficients. The goal in the design of seismic isolation structures is to select the frictional properties of the bearings to achieve optimum performance across

various excitation and performance metrics [3]. The challenge in designing isolation systems is that bearings are often very large, stiff, and strong, with few isolations that can withstand very large or near-fault movements during moderate seismic events. Thus, without selecting the optimal parameters the best performance of triple friction pendulum bearing is not fully achieved [3] [4].

Triple friction pendulum bearings offer various combinations of stiffness and damping during their course of motion. The adaptive nature of TFPB allows the isolation system to perform well under different levels of earthquakes [3].

Determination of the TFPB's design variables (curvature radii, friction coefficient and displacement) is a complex process [4] [5]. While the search for the optimized combination of these variables depends on the input properties of the ground motion and the seismic performance objectives of the superstructure [3] [4] [5].

1.2 Objectives of this study

Base isolation reduces the earthquake response of the structure by changing the effective main frequency of the system out of the range wherein seismic movement would cause the biggest inertia forces [6]. In this case, resonance is reduced, and the earthquake acceleration response is minimized since the period has been increased well past the period limit of the seismically induced ground movement [2].

The target main period of the isolated structure can be achieved by altering the lateral stiffness of the isolation system [6]. Base isolation bearings with hysteric force-displacement properties have been shown to provide the required high lateral flexibility and damping while also having sufficient lateral stiffness to stand up to wind-induced horizontal forces [7].

1.3 Literature Review

Rezael S. Amiri G. and Namiranian P : In this study [8] two three dimensional RC buildings upheld by twenty isolators are idealized, different triple friction pendulum bearing setups are chosen for the isolation system, nonlinear time history analyses had been done by utilizing OPENSEES program to look at the effect of isolation system on basic reactions which incorporates isolator displacements, ground acceleration, inter-story drifts and base shear, beneath seven near-fault ground motions records, the results appear a critical lessening in confined basic reaction as compared to fixed base structures, in addition, although the periodic area is increased or the attenuation factor of the isolation system is reduced, the basic shear force of the acceleration, the inter-story drift and the superstructure is reduced, but the isolation displacement becomes large [8].

Weber F. Distl H. and Braun C: This study [9] optimizes a triple-friction pendulum bearing in terms of absolute structural acceleration using different coefficients of friction 1 and 4, assuming that the coefficients of friction of the sliding surfaces 2 and 3 of the rod assembly hinged slide is equal and small (1.75%) and the effective radius is given, the optimization, performed for PGAs equal to 2.5 m/s², 5 m/s² and 7.5 m/s², indicates that the coefficients of friction 1 and 4 of the triple friction pendulum must be chosen respectively, similar to the optimal coefficients of friction 1 and 2 in the double friction pendulum, this means that the optimal triple friction pendulum works very similar to the optimal double friction pendulum. Evaluation of triple and double friction pendulum is optimized according to the absolute structural acceleration for different PGA earthquakes to confirm the discovery that triple and double friction pendulum optimization behave similarly [9].

Amiri Namiranian, and Amiri : In this study [10] seismic response of rigid single-story buildings and flexible multi-layer buildings isolated by triple-friction pendulum under pulsed (near fault) and (far-fault) ground motion, bearing behavior adjusted by changing its geometric parameters such as the effective spherical radius or by specifying a different coefficient of friction for each surface, as a result, system stiffness and damping ratios can be optimized for multiple performance goals at multiple threat levels, seismic

response is evaluated under various isolation parameters of the system isolation displacement and superstructure demand function, including base shear, maximum inter-story drift, and absolute acceleration of the top floor isolated structure [10].

Chen Z. Jia P. Fan Y. and Liu Z: This study [11] analyzed the effects of the coefficient of friction and the equivalent radius on the damping effect of friction pendulum bearings at subway stations on distant and near earthquakes of different magnitudes, it was found that the parameters of the friction pendulum bearing clearly affect the seismic reduction efficiency, by combining the genetic algorithm with the finite element method, the parameters of the pendulum friction bearing in the station can be optimized, this study uses this method to determine the optimal parameter range, which serves as a reference for the parameter design of pendulum friction bearings in underground stations [11].

Tsipianitis A. and Tsompanakis Y: This work [12] focuses on optimizing the main parameter of triple friction bearing, for this reason, the efficient swarm intelligence optimization algorithm used to obtain an optimal coefficient of friction and radius of curvature and improves the dynamic performance of the base-isolated liquid storage tank, the main purpose of this study is to propose a formulation for minimizing the acceleration transmitted to the upper structure, is imposed by the attenuation and vibration period limitations OpenSees [12].

Papanikolaou, Kartalis-Kaounis, Protopapadakis, and Papadopoulos: This research [13] invented the latest graphical user interface for OpenSees, connect the OpenSees solver to the preprocessor and postprocessor GIDs, this graphical user interface gives advanced user dialogs and devices for making modular geometry and allotting materials, components, and constraints, users can also select analysis options and use the OpenSees solver to perform the analysis, after analysis, GID automatically transforms the results from the number line into a more comprehensible format, thanks to GID post-processing, the results could be explained as a deformed shape viewer with animation options, the main purpose of this GUI was to allow researchers and users using the OpenSees platform to analyze their work and save time in creating their own models [13].

Fenz and Constantinou: This study [5] proposed a series models collected of nonlinear elements since they can be instantly analysed using computer software, in any case, the behaviour of triple friction pendulum bearing is not precisely that of an arrangement course of action of a single friction pendulum bearing-though its comparable as studied in [14]. This research [5] showed and explained the modifications of the input parameters of the series model to achieve the true force-displacement behaviour exhibited by this device [5]. Modelling done by SAP2000 and explained using the analysis of a simple isolated structure, results are approved by (a) confirming the force-displacement behaviour by comparing it with exploratory information and (b) confirming the analysis by comparing it to the results that has been obtained by numerical integration of the ground motion equation [5].

Moeindarbari and Taghikhany: In this work [3] extensive nonlinear dynamic analysis is carried out to determine the effect of design variables on the superstructure response (roof acceleration and displacement of the isolated level), a particular numerical optimization technique based on genetic algorithms (GA) is utilized to establish the optimal values of the design variables that minimize the requirements of the superstructure, during this process a near-fault ground motion with extents of pulse periods and danger levels are used as input actions according to the GA outputs, the optimal design variables derived from TFPB have considerably separate target response such as story drift and TFPB displacement, as a result the response goals (single objective characteristic) are combined to create a new suitable function, the suggested optimization procedure for determining the design variables and design ranges can be used to study many other types of superstructure with similar behavior [3].

Quaglini, Gandelli, and Dubini: Due to the increasing of sliding bearing usages as seismic isolators, improvements of analytical models were applied to improve predictive capability of nonlinear time story analysis [1]. So this study by Quaglini, Gandelli and Dubini [15] proposed a mathematical formulation aims to handle the variation of friction coefficient established on experimental data that can be reclaimed from original tests on slider with curved surface, this formulation takes into account changing the coefficient of friction due to the temporary changes in axial load and shear rate at the contact interface,

as well as heat build-up due to periodic motion, it also includes new features such as static friction that happen then transitioning from the pre-sliding stage to the dynamic sliding stage [3]. OpenSees used for encoding the proposed model by altering the standard element single FB simple 3D which describe the force-displacement relationship of bearing consisting of sliding surface and spherical joint [15]. The main assumption in the development of the friction models and the validation of the newly developed element are validated by comparison with the available data, where case studies helped demonstrating that the new bearing element is predictive that their standard corresponding element when applied in real-world situation, for example high intensity earthquakes increase isolation displacement, superstructure drift, and base shear demand by 50% and low intensity or medium intensity earthquakes can deactivate sliding isolation [15].

Keikha and Amiri: In this study [16], a simplified technique was developed by merging the equivalent lateral force method with the energy spectrum method and assessed based on maximum isolator displacements and base shear for structures isolated by newly invented quintuple pendulum friction isolators. It uses two different sets of near-field bidirectional ground motions with different geometric and frictional properties and under two different response spectra, corresponding to the site classes of hard and soft soils, to evaluate the accuracy of the simplified method, we compare the results provided by the ELF method with the results of a nonlinear response history analysis by modeling the 3D elements of the OpenSees quintuple pendulum friction isolator. Finally, we comment on the accuracy of the simplified method for making the application more suitable for the actual design of the basic insulation system [16].

Giammona, Ryan, and Dao: In this paper [17] the SAP2000 commercial software program was used to design a ground isolated building supported by a triple friction pendulum bearing isolator, however, there is a limited comprehensive test data available to verify software usage in this application, furthermore previous work has shown that some hazards should be avoided when modeling these types of structures in SAP2000, where SAP2000 ability to predict key engineering require parameter used in the design of isolated building will be explored using the methods assumptions used in this paper

design method, the results of the SAP2000 analysis are compared to data from a complete fully isolated building vibration test and the corresponding prediction from a more complex OpenSees analysis model for the same building, this study [17] suggest that SAP2000 can predict responses with sufficient accuracy for design using methods and assumptions commonly used in engineering practice [17].

Xu, Becke and Guo: Triple friction pendulum bearing isolators are generally designed with taking into consideration earthquakes forces only or with a primary friction coefficient adequate to limit displacement under wind loads.[18]. Though, Xu, Becke and Guo [19] did a study in capacity high-rise applications, wind demand is a greater concern and increased structural flexibility can cause ground acceleration when the wind exceeds the [serviceability](#) limit state. This study focuses on the optimization technique (fast elite non-dominant genetic algorithm) to decide ideal parameters for triple friction pendulum bearing isolator that minimize structural response under wind and seismic loads in high-rise buildings [19]. The genetic algorithm (GA) is applied to find the optimal parameters for bearings designed individually for wind and seismic excitation, in any case triple friction pendulum bearing (TFPB) ideally designed for seismic excitation provide problematic wind resistance and vice versa, finally using multi objective optimization will allows a compromise between seismic isolation and wind resistance. TFPB design parameters can then be selected to achieve the best seismic isolation performance while ensuring that the wind load performance meets your requirements [19].

Yu, Li, Wei, Jiang, and Mao: This study [20] investigate the impact of friction pendulum bearing (FPB) on the response of single bearing bridge on high speed railway to longitudinal earthquakes, the OpenSees program was used to create a space-integrated railway bridge model using the CRTSII sheet meatal track and FPB, seismic response to different ground movements were calculated and compared with conventional steel ball joints, the comparison results show that the combination of FPB and CRTSII sheet metal track makes more sense, briefly the FPB can be used to efficiently preserve bridges and railway structures, in addition the multi-layer isolation mechanism through the FPB and sliding layers allows full protection of the rails, fasteners, CA layers and support in the

event of a strong earthquake [20]. Finally, 0.05 is identified as the best value for the coefficient of friction of FPB in longitudinal earthquakes [20].

Deringöl and Güneyisi: This study [21] examines the impact of the friction pendulum bearing isolator (FPB) properties on the non-linear response of buildings subjected to different seismic excitations, to cover a wide range of evaluations, this study examined three-story, six-story, and nine-story steel buildings with 27 different FPB isolator designs to distinguish between local and global deformations, three important parameters such as the isolation period T (such as 2, 2.5 and 3 s), the effective damping ratio β (such as 0.05, 0.15, 0.25) and the yield strength ratio F_y / W_s (such as 0.025, 0.05 and 0.10) were applied in the modelling of FPB, a two-dimensional model of a steel frame isolated from the ground was constructed and a non-linear time history analysis was performed through the movement of the ground due to a series of earthquakes. The behaviour of the isolated frames was measured based on isolation displacement, roof drift ratio, relative displacement, inter-story drift ratio, absolute acceleration, base shear, base moment, curve of hysteresis and varieties in dissipated energy, In this study, it was found that the seismic response of the seismic isolation frame can be accurately evaluated by changing the appropriate seismic isolation period, yield intensity ratio, and actual damping ratio of the structure [21].

Nassani and Abdulmajeed: In this work [22], two different structures (symmetrical and non-symmetrical school buildings) are presented, in which the seismic responses of the "fixed base" and "isolated base" situation were compared in order to verify the effect of the insulation system of the base using SAP2000 (a well-known computer program), base isolation system devices consist of a high damping rubber was used and installed at the foundation level, a time history analysis was carried out on three different earthquakes: El Centro, Loma, and Coyote, comparing the base isolation results with the fixed base results, the base isolation system proved its capability for reducing the base shear force and story-drift, while increasing the displacement [22].

Tsai, Chiang, and Chen: The test done in this study [23] consist of advanced Teflon composite, prototype multi friction pendulum isolator (MFPs), and the shaking table test of a full-scale structure, the test results showed that this new component provide a low

friction coefficient and perfect durability under high compressive strength, and over 2400 cyclic loading with no sign for deterioration, the MFPs implemented at the bottom of each column in the 3-story structure, the results that obtained from the shaking table test for the earthquakes: El Centro, Kobe, Chi-Chi, and Hua-Lien show that the introduced MFPs isolator provide a reduction in the unwanted seismic responses of the structure by increasing the structure period during earthquake, and illustrate how the MFPs give and excellent isolation for the structure under near-fault and far-fault excitations, from these observations, MFPs proved its capability for strengthening the seismic- resistibility of structure [23].

This study aims to assess the impact of various values of friction coefficients under near-fault and far-fault earthquakes and then select the optimal ones by conducting a parametric study.

1.4 Outline of the thesis

As mentioned previously, this study is intended to investigate the influence of changing the coefficient of friction in triple friction pendulum bearings on the performance of base-isolated structures. This is planned to be conducted by a numerical study to investigate the impact of each of the variables. The outline of this report is defined as follows: an introduction to the topic is provided in Chapter 1, where Chapter 2 will give a detailed description of the base isolation system, a discussion regarding triple friction pendulum bearings will be discussed in Chapter 3, in Chapter 4 an illustration of the selected ground motion with the criteria will be provided, and details of the numerical example with case studies will be reported in Chapter 5, then, the results and discussion will be highlighted in Chapter 6 and finally, the conclusion of the study is provided in Chapter 7.

CHAPTER 2

SEISMIC ISOLATION

2.1 Introduction

Seismic performance of structures is one of the most important issues in seismically active regions. Researchers have long looked for ways to precisely evaluate the response of buildings under earthquake ground motions [2]. When the seismic isolation system points to assess the seismic execution of a structure and assess the execution of a building to characterize shortcomings utilizing a comparable shear stack strategy examination strategy and nonlinear time history analysis [7] [24]. The suitable procedure for applying and overseeing different seismic isolation devices is at that point arranged, (Lead-core rubber bearings, flat bearings, friction pendulum bearings, and other types) on a structure to verify the improved capability of seismic isolation systems, against earthquake records and to verify how isolators can reduce story acceleration on upper floors, helping to reduce damage to non-structural elements [25].

Seismic isolation is a technology that aims to shift the fundamental natural period of a structure to a period range of 2 to 4 seconds by placing a horizontally flexible isolation interface at the base of the structure and physically separating the structure from the ground, in seismic excitation. This period shift reduces the story accelerations of the superstructure (the structure above the isolation system) and reduces the inter-story drift [24] [25]. The reduced demands allow the superstructure to remain elastic or nearly elastic during a design-level earthquake. In addition, the reduced demands minimize the potential for damage to displacement-sensitive and acceleration-sensitive devices, non-structural components, and contents. However, period shifts increase the displacement demands at the seismic isolation interface and seismic isolation devices must be designed to withstand these displacement demands. Simultaneous reduction of acceleration and drift demands

may be achieved by seismic isolation has become one of the most effective strategies for achieving operational or fully operational performance after large and rare earthquake events [24] [25].

2.2 Early History of Seismic Isolation

In 1876, British geologist and mining engineer John Milne was appointed professor of mining and geology at the University of Tokyo and remained there until 1895. During this time, Milne created an example of a seismic isolation structure based on a spherical sphere cast on an iron plate with a saucer-like edge on the pile heads [26] [27]. The building was instrumented and was exposed to seismic movements. In 1885 Milne reported his experiment to the British Science Association [26] [27].

A systematic study of seismic isolation was conducted at the University of Tokyo in the early 1980s. While, various Japanese construction companies were conducting experimental tests on isolation systems using natural rubber bearings [28].

The first work on the mechanism of rubber bearing for vibration isolation of buildings was done by the Malaysian Rubber Producers Research Association (MRPRA) in the United Kingdom in the 1960s under the guidance of a D.A.G. Thomas, A.N. Ghent, and Dr. Peter Lindley, first applied rubber bearings to bridge bearings and then to vibration isolation of hospitals, residences, and hotels in the United Kingdom [29] [30]. The first building to be isolated from low frequency ground noise with natural rubber was an apartment block built in 1966 just above London Underground Station [26]. Many of these projects have been completed in the UK using natural rubber isolation, such as low-cost public housing estates adjacent to two 24-hour, eight-track rail lines. Several hotels were completed using this technology and many hospitals were built using this approach [29].

By the early 1990s, seismic isolation had evolved into a viable and reliable seismic protection strategy, with large buildings and bridges supported by lead rubber bearings,

natural rubber bearings or single concave sliding bearings [26] [27]. After the earthquakes of Northridge, California 1994, and Kobe, Japan, 1995, seismic isolation was accepted worldwide for earthquake protection of civil structures [26].

2.3 Application of Seismic Isolation (Case Study):

2.3.1 Road Bridges [25] [31].

In New Zealand, by far the most common use of seismic isolation is in moderate two-span road bridges, where construction economics alone makes sense. The most common form of bridge insulation system uses lead rubber bearings that usually installed between the bridge superstructure and the supports [31]. When the bearing distorts beneath horizontal load, the cylindrical lead core experiences shear plastic deformation and dissipates energy through hysteresis. Lead-core elastomeric bearings combine the capacities of seismic isolation and energy dissipation in a single compact unit [25] [31].

2.4 Seismic Isolation Bearings

Various seismic isolation devices for seismic structural protection were designed and are used around the world. This section describes the basic features, mechanical behaviour, and analytical modelling of these devices.

2.4.1 Laminated Rubber Bearings (Elastomeric Bearings).

Elastomeric bearings consist of layers of steel plates and rubber layers [32]. Elastomeric bearings can be used in two ways without the use of lead cores. Steel plates provide vertical stiffness. Lead plugs are used for energy dissipation; and rubber layers provide horizontal flexibility [33]. Rubber layers can be made of low damping or high damping rubber compounds [32].

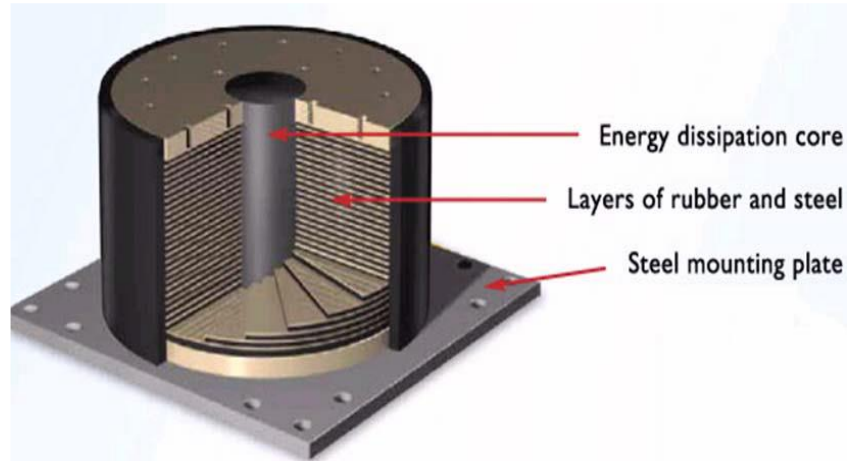


Figure 2.1: Lead Rubber Bearing Isolator [32].

2.4.2 Friction System (Flat Sliding Bearings).

Friction is a natural and compelling tool for dissipating energy. Flat sliders are usually with other elastomeric bearings, since they do not have a re-centering mechanism.

2.4.3 Friction Pendulum System.

This system has similar characteristics as a flat sliding isolator. However, Friction Pendulum Bearings, as shown in Figure 2.2, consist of an articulated slider on a concave steel surface which makes it [35] [36] [37] possible to adjust the target isolation period. The Triple Friction Pendulum System is discussed in detail in Chapter 3.

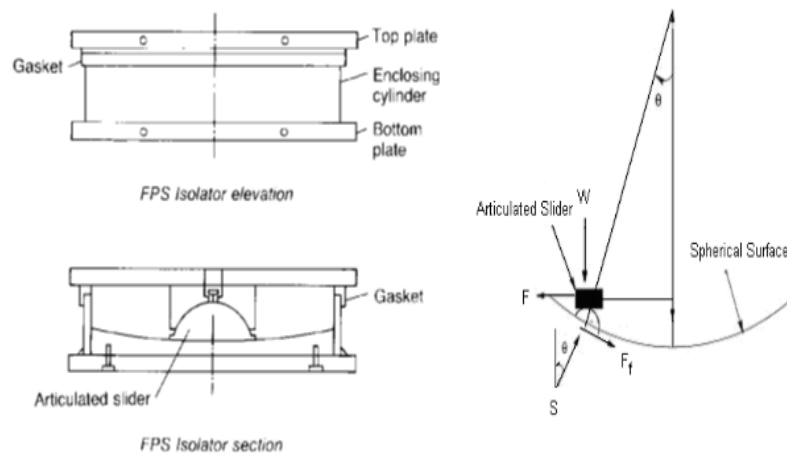


Figure 2. 2: Friction Pendulum Bearings [34].

2.5 OpenSees Modelling of Seismic Isolation Bearings

As discussed previously, this study adopts the OpenSees finite element modelling environment for conducting the nonlinear time history analysis. The OpenSees is code-based analysis software. Therefore, material properties, geometry of the building, geometry of the isolators, surfaces properties, column and beam properties, node locations, mass and weights have to be defined manually. In this section, the process that was followed to model the selected structure will be discussed in detail. The following need to be defined in the TCL file for analysis [43] [44] [45]:

1. Degree of freedom (3 or 6 degrees of freedom).
2. Model geometry.
3. Boundary conditions (i.e., fix support).
4. Rigid diaphragm constraints.
5. Story weights and masses.
6. Material properties for the isolators and structural members.
7. Earthquake input motion parameters.
8. Bearing parameters such as the effective length, friction model (Coulomb or Bouc-Wen), slow and fast friction coefficients, rate parameters, pendulum displacement limit, and yielding displacement.
9. Gravity loads and static analysis parameters.
10. Modal analysis parameters.
11. Time-history analysis parameters.
12. Recorders for obtaining analysis outputs.

2.5.1 Command Manual

2.5.1.1. Flat slider bearing element

This command is used to establish a flat slider bearing isolator which is defined by two nodes, the I-Node that represent the sliding surface and the J-Node that represent the slider. The bearing has unidirectional 2D or 3D friction properties for the shear deformation, and the force deformation behaviour defined with uniaxial material. To capture the uplift behaviour of the bearing, the user specifies uniaxial material in the axial direction for no tension behaviour [40]. P-Delta moments are entirely transferred to the flat sliding surface (I-Node). It is important to note that rotations at the I-Node affect the shear behaviour of the bearing. To avoid the damping leakage in the isolation system, the bearing element does not contribute to the Rayleigh damping by default. If the element has non-zero length, the local x-axis is determined from the nodal geometry unless the optional x-axis vector is specified in which case the nodal geometry is ignored and the user-defined orientation is utilized [5] [38] [39] [40].

For a two-dimensional problem:

```
element flatSliderBearing $eleTag $iNode $jNode $frnMdlTag $kInit -P $matTag -Mz  
$matTag <-orient $x1 $x2 $x3 $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-  
mass $m> <-iter $maxIter $tol>
```

For a three-dimensional problem:

```
element flatSliderBearing $eleTag $iNode $jNode $frnMdlTag $kInit -P $matTag -T  
$matTag -My $matTag -Mz $matTag <-orient <$x1 $x2 $x3> $y1 $y2 $y3> <-  
shearDist $sDratio> <-doRayleigh> <-mass $m> <-iter $maxIter $tol>
```

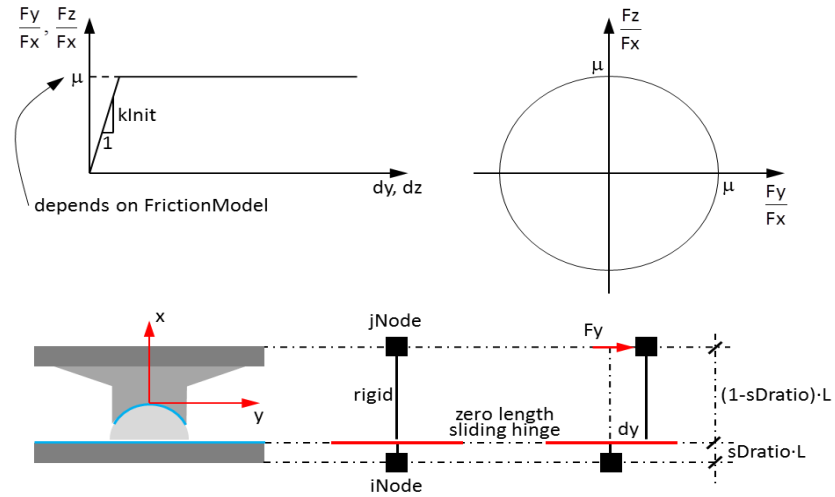


Figure 2. 3: Section view of flat slider bearing element [40].

2.5.1.2. Single friction pendulum bearing element

This command is used to construct a single friction pendulum bearing isolator, which is defined by two nodes. The I-Node represents the concave sliding surface and the J-Node represents the articulated slider. The element can have zero length or the appropriate bearing height. The bearing has unidirectional (2D) or coupled (3D) friction properties for the shear deformations, and force-deformation behaviours defined by uniaxial materials. To capture the uplift behaviour of the bearing, the user-specified uniaxial materials in the axial direction for no-tension behaviour [40]. P-Delta moments are entirely transferred to the I-Node. It is important to note that rotations at the I-Node affect the shear behaviour of the bearing. To avoid damping leakage in the isolation system, the bearing element does not contribute to the Rayleigh damping by default. If the element has non-zero length, the local x-axis is determined from the nodal geometry unless the optional x-axis vector is specified in which case the nodal geometry is ignored and the user-defined orientation is utilized [5] [38] [39] [40].

For a two-dimensional problem:

```

element singleFPBearing $eleTag $iNode $jNode $frnMdlTag $Reff $kInit -P
$matTag -Mz $matTag <-orient $x1 $x2 $x3 $y1 $y2 $y3> <-shearDist $sDratio> <-
doRayleigh> <-mass $m> <-iter $maxIter $tol>

```

For a three-dimensional problem:

```

element singleFPBearing $eleTag $iNode $jNode $frnMdlTag $Reff $kInit -P
$matTag -T $matTag -My $matTag -Mz $matTag <-orient <$x1 $x2 $x3> $y1 $y2
$y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m> <-iter $maxIter $tol>

```

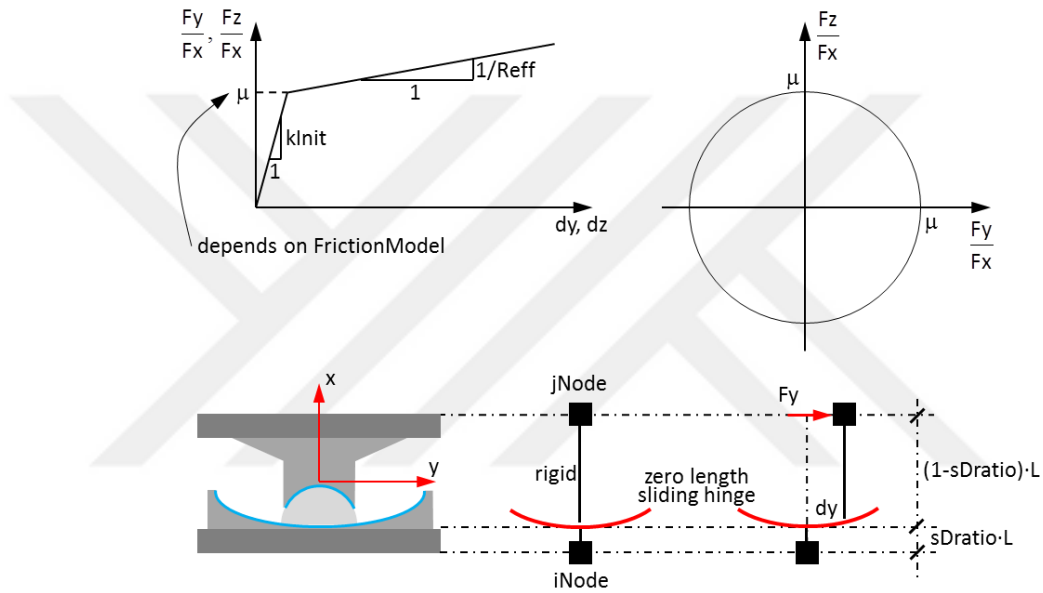


Figure 2. 4: Section view of a single friction pendulum bearing element [40].

2.5.1.3. Triple Friction Pendulum bearing element

This command is used to construct a Triple Friction Pendulum Bearing isolator (TPB) shown in Figure 2.5. This is a 3-dimensional element with variable friction coefficient models [38] [39]. The element accounts for the vertical-horizontal coupling and the bidirectional coupling in horizontal behaviour. The friction coefficient model is a general model that accounts for the variation of friction coefficient on velocity and vertical force. The element can also be used for modelling single friction pendulum bearings or double friction pendulum bearings by simplifying the general backbone curve of the TPB. Other simplified friction coefficient models such as vertical-force-independent friction

coefficient, velocity-independent friction coefficient and constant friction coefficient can also be defined. The horizontal normalized behaviour of the element is an extension of the unidirectional behaviour proposed by Fenz and Constantinou [5] and Morgan and Mahin [40]. Displacements and normalized forces are evaluated according to [39], [5] or [40]. Overturning moment and torsion due to the eccentricity of internal forces are equally distributed to the 2 nodes of the element. In the vertical direction, the element is multi-linear elastic with different stiffnesses.

Element TripleFrictionPendulum \$eleTag \$iNode \$jNode \$frnTag1 \$frnTag2 \$frnTag3 \$vertMatTag \$rotZMatTag \$rotXMatTag \$rotYMatTag \$L1 \$L2 \$L3 \$d1 \$d2 \$d3 \$W \$uy \$skvt \$minFv \$tol

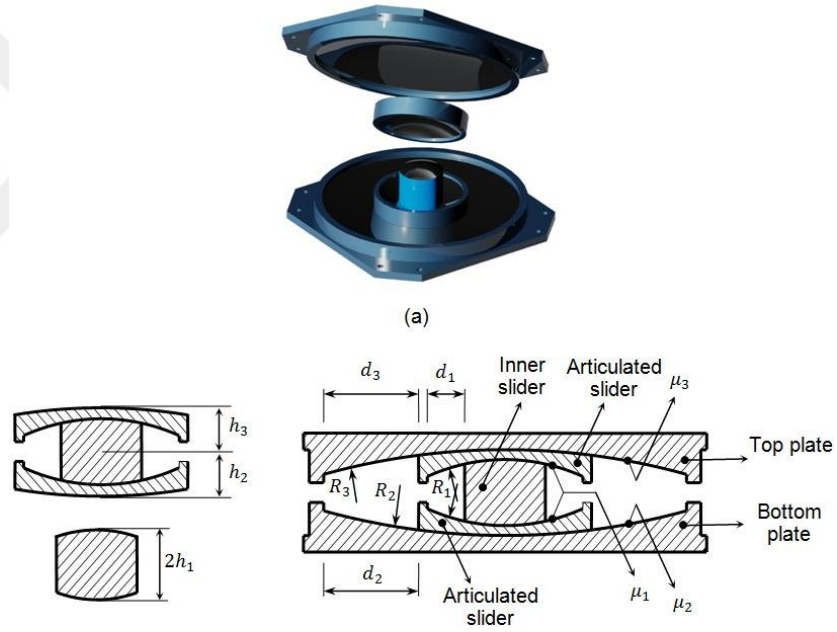


Figure 2. 5: Triple friction pendulum bearing (a) Three dimensional view (b) Section view and basic parameters [40].

CHAPTER 3

TRIPLE FRICTION PENDULUM BEARING

3.1 Introduction

A base isolated structure can be designed to be adaptive in order to adjust its rigidity during its movement. In order to achieve this, active or partially active control systems can be used along with traditional isolation bearings [1] [2]. However, information on the seismic performance of active and partially active structures is still very limited [3] [5] [7].

Current design codes focus on designing the structure to resist ground shear transferred from the design basis earthquake (DBE) and to design the isolation system to be capable of handling the maximum considered earthquake (MCE) displacements [3] [5]. The performance of the structure under smaller scale service level earthquake performance is usually not taken into consideration in the seismic design of structures [41]. In terms of strength and displacement capabilities small scale vibrations are not considered a design problem, however it can be considered a performance problem [3] [5] [12].

Triple Friction Pendulum bearings due to their adaptive nature, allow the isolated structure to be designed for low, mid and high intensity earthquake ground motions [42] [43].

3.2 Triple Friction Pendulum Bearing isolator

The Friction Pendulum System (TFPS) can provide various combinations of stiffness and damping in earthquakes. Its versatile operation is one of the most viable seismic isolation systems for structures subjected to near-field earthquake ground motions. The procedure for selecting its design parameters is complicated and depends on the input motion

characteristics [1] [3]. The Triple Friction Pendulum Bearings' behavior is named as adaptive since they continuously show a diverse hysteretic property at diverse stages of displacement [3].

A section of a TFPS bearing is shown in Figure 3.1. where R_i is the radius of curvature of surface i , h_i is the distance between the point of rotation and surface i , and μ_i is the coefficient of friction on the sliding surface [3] [4].

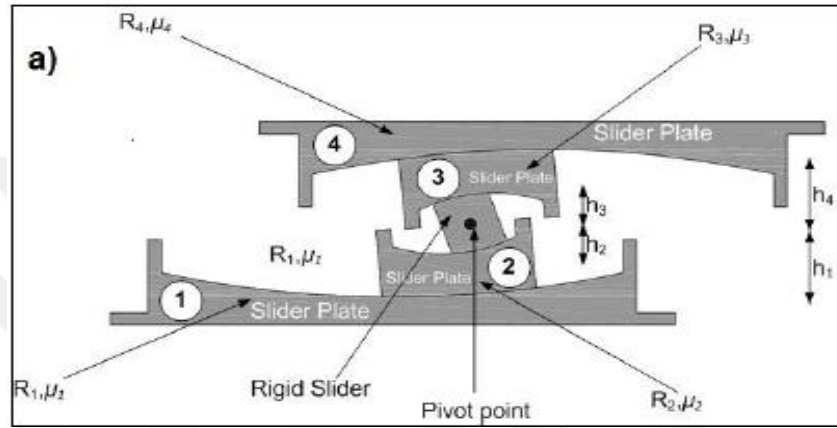


Figure 3. 1: Components of Triple Friction Pendulum Isolator [3]

The internal development of these bearings allows the slide of various surface combinations throughout the movement, resulting in varying stiffness and damping. The different stages of the slide associated with the versatile triple friction pendulum bearing isolator at different excitation levels are characterized as follows [5].

Stage 1: This stage slides only on surfaces 2 and 3 to form a one pendulum component, characterizing the isolation system at low excitation (service level earthquakes) [3] [4] [5].

Stage 2: Movement will halt on surface 2, whereas sliding will continue on surfaces 1 and 3. [3] [4] [5].

Stage 3: Movement will halt on surfaces 2 and 3, whereas sliding will continue on surfaces 1 and 4. [3] [4] [5].

Stage 4: Slider contacts restrainer on surface 1, movement still halted on surface 3, on

surfaces 2 and 4 sliding will occur. This process indicates isolation bearing properties past Maximum Credible Earthquake [3] [4] [5].

Stage 5: The slider bears are on the retainers of surfaces 1 and 4, and slides on surfaces 2 and 3 (last stage) [3] [4] [5].

3.3 Description of Friction in Sliding Interface

In order to use sliding bearings in seismic isolation applications, it is necessary to collect data on the friction properties of the sliding interface under both conditions of use and seismic load conditions, namely low-speed motion and high-speed motion. In addition, to properly interpret the results, it is necessary to understand the causes of friction at these interfaces [4] [5].

3.3.1 Basic Mechanisms of Friction

In recent years, various friction mechanisms have been proposed. All of these mechanisms are thought to contribute to the forming of the friction to varying levels regarding the situations. These mechanisms are explained in detail in the following resources [44] [45] [46].

3.3.2 Friction in PTFE

The PTFE-stainless steel is the most commonly used interface in sliding bearings PTFE comes in the form of a large sheet with small thickness and a larger size rigid highly polished stainless-steel plate, which compared to steel is very soft. Friction in this interface is mainly the result of adhesion, with the contribution of plowing being trivial. [47]. This section will brief details about the properties of macroscopic friction of PTFE-stainless steel interface, in addition for providing a physical interpretation of these properties [46].

3.3.2.1 Dependency on Velocity of Sliding and Pressure

Figure 3.2 shows the coefficient of friction's dependence on sliding velocity and normal

loads [46]. In general, increasing the normal load decreases the coefficient of friction. After the break away friction is overcome, the coefficient of friction varies between $f_{\min}$ and $f_{\max}$. $f_{\min}$ and $f_{\max}$ represent the coefficient of friction at low velocity and high velocity, respectively [4] [5] [46].

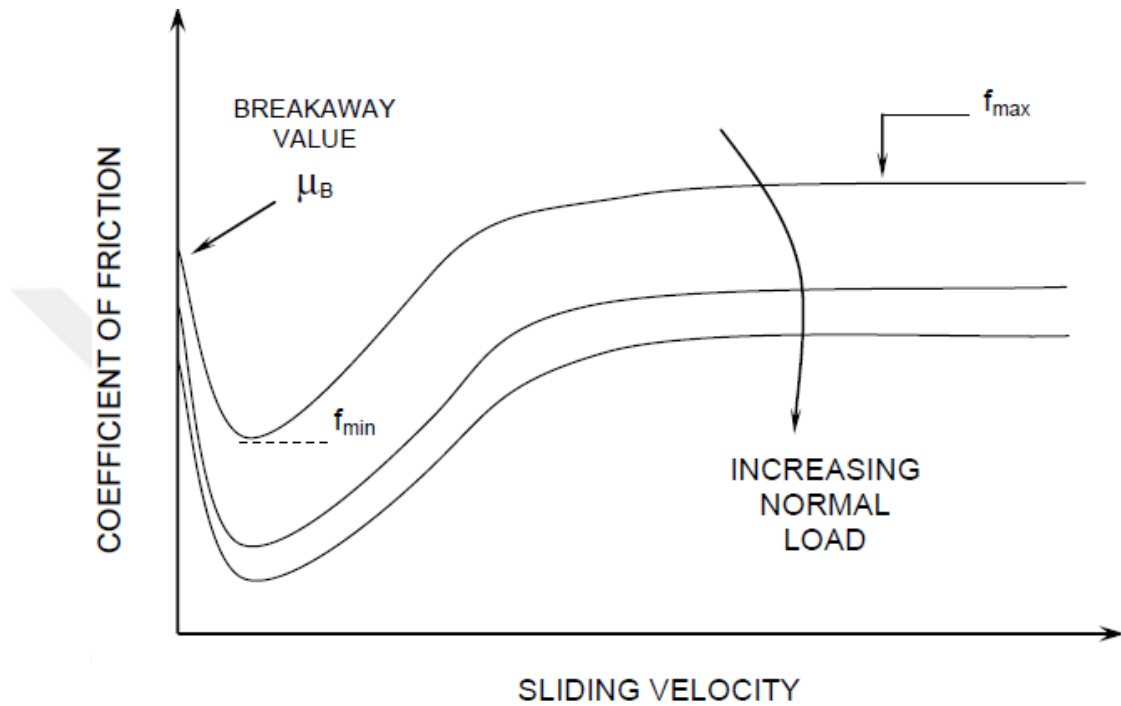


Figure 3. 2: Dependency of Coefficient of Friction for PTFE-Polished Stainless Steel [46].

3.3.2.2 Effect of Temperature

Campbell in 1991 [48] [49], shows that temperature has a significant effect on the coefficient of friction. With unfilled PTFE, the inactive friction and velocity values increase between (50 ° C) and (40 ° C) temperatures. This significant increase is due to changes in the viscous-elastic properties of PTFE with temperature. The thermal current generated by friction corresponds to the coefficient of friction, normal weight, and slip speed. The intense frictional heating of the slip surface occurs at high velocity, essentially eliminating the effects of low temperatures on the viscous-elastic properties of PTFE. As a result, when the temperature drops from 40 ° C to 20 ° C, the estimated coefficient of friction increases at high velocity around 50% [4] [5] [46] [48] [49].

3.4 Modelling and Construction of Triple Friction Pendulum Isolator Bearing

Curved sliding isolators are available in numerous arrangements and work with distinctive combinations of surfaces. The detailing and approval of the multi-ball sliding isolators are portrayed in Fenz and Constantinou [5]. Double and triple contact pendulum arrangements offer numerous advantages over single contact pendulum isolator setups [14]. Triple friction pendulum bearings can slide on multiple concave surfaces at the same time, this allows it to be way smaller than a basic pendulum friction isolator [4] [5] [14]. The triple friction pendulum in Figure 3.3 has two opposing concave stainless steel surfaces connected by an internal slider assembly. In figure 3.4 the effective radii of the concave plates are $R_{eff1} = R_1 - h_1$ and $R_{eff4} = R_4 - h_4$ where R_i is the radius of curvature of the i^{th} spherical and h_i is the radial distance between the i^{th} spherical and articulated slider pivot point. The articulated slide assembly has two concave slide plates. The innermost slider is rigid, but the entire assembly can rotate to supports different rotations of the upper slide plate and the lower slide plate. The surface of the sliding plate that contacts with the outer concave plate is coated with a non-metallic sliding material. The coefficients of friction of these interfaces are μ_1 and μ_4 . The inner surface of the two sliding plates has a spherical concave surface with effective radii of $R_{eff2} = R_2 - h_2$ and $R_{eff3} = R_3 - h_3$. The outer surfaces of the inner sliders are coated with PTFE to obtain the coefficients of friction of μ_2 and μ_3 [4] [5] [14]. The adaptive response triple friction pendulum bearings rely on the various sliders that provide full horizontal displacement capability. Therefore, displacement capacities d_1 to d_4 should be considered as an important design parameter that affects global behaviour as well as overall capacity limits [4].

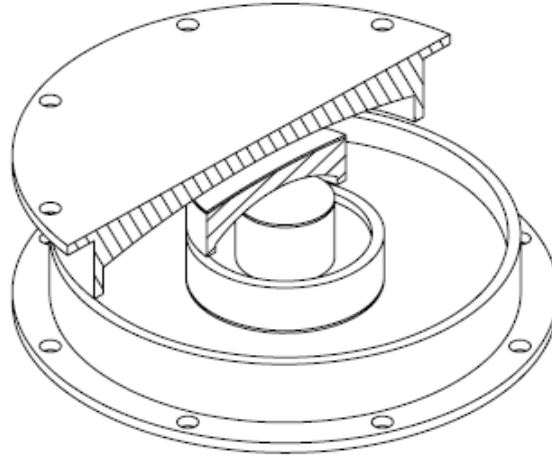


Figure 3. 3: Cutaway View of the Triple FP Bearing [5].

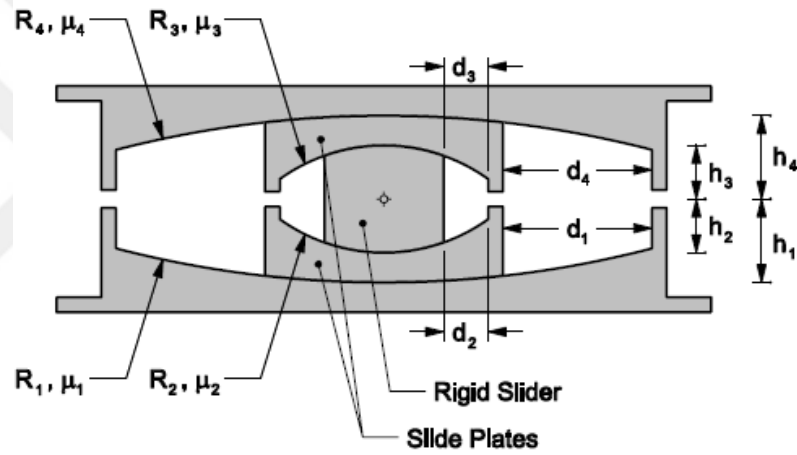


Figure 3. 4: Cross Section of the Triple friction pendulum Bearing [5].

The bilinear model shown in figure 3.5 is a simple model that can be used in the preliminary design of single and double friction pendulum isolators. The performance of the isolators governed by two parameters which is the characteristic strength at zero displacement Q_d and the post-elastic stiffness K_d . Q_d is a function of the coefficient of friction μ and the weight W , K_d on the other hand, is a function of the effective radius of curvature R_{eff} of the concave plate and the weight W . This is an accurate representation of single Friction pendulum isolators and double Friction pendulum isolators.

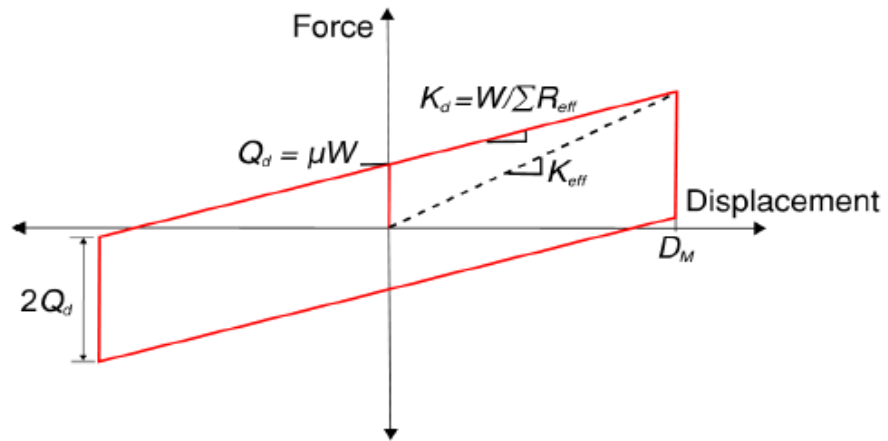


Figure 3. 5: Rigid-Linear Force-Displacement Behavior of friction pendulum Isolator [5].

Rigid linear or bilinear models provide reasonable estimates of the overall structural response. If structural acceleration and the remaining displacement is exceptionally critical than it is reasonable to use the trilinear model for triple FP isolators shown in Figure 3.6 [4].

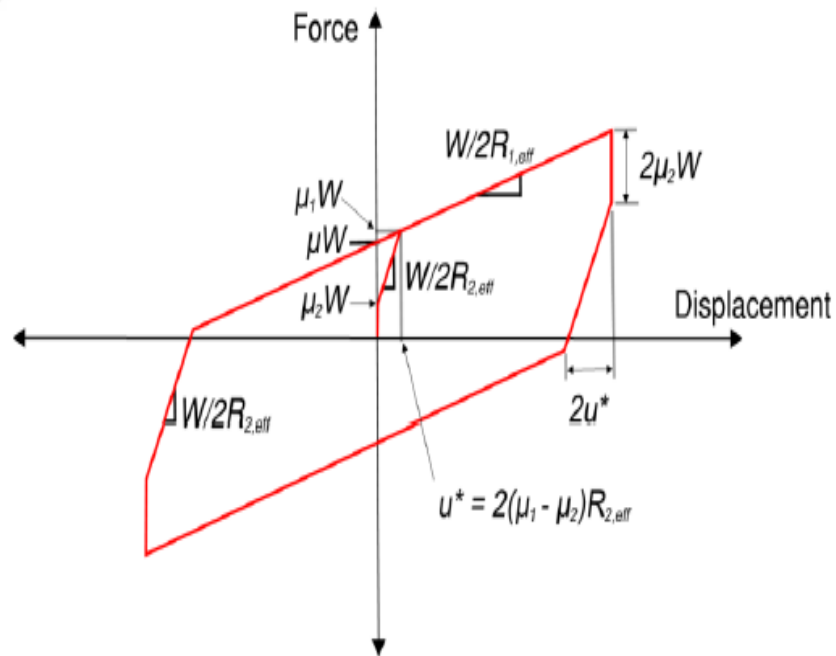


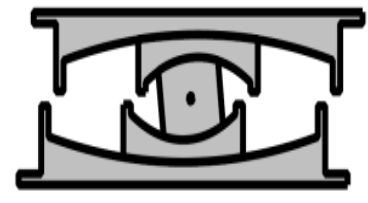
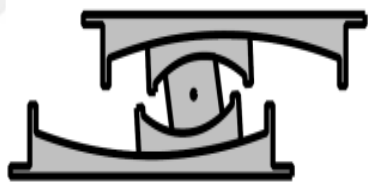
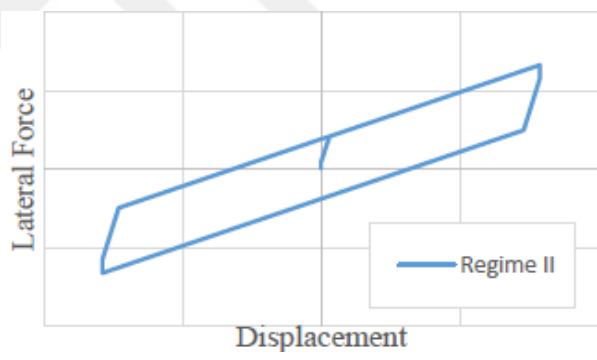
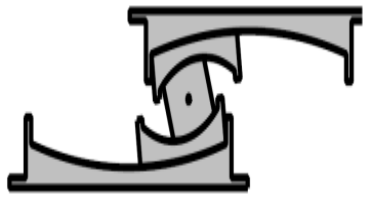
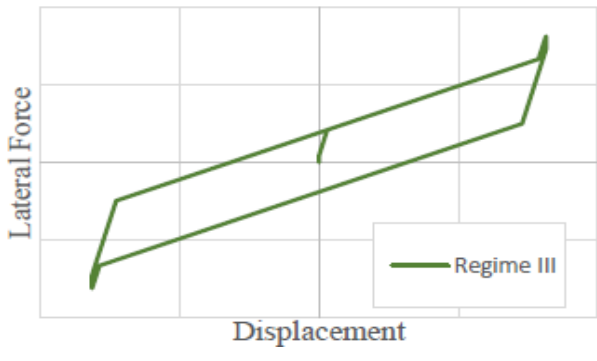
Figure 3. 6: Tri-linear Force-Displacement Behavior of Special Triple friction pendulum [4].

Triple friction pendulum isolators perform complex operations in a variety of displacement regimes. As the displacement increases, there will be changes in stiffness. As mentioned earlier, the shape and friction parameters characterize the constrained displacement behavior of the triple friction. To reduce the number of geometric and friction variables parameters the behavior of the displacement is reduced to three regimes, which are listed in table 1 and table 2 below [4].

Table A.1: Force-Displacement Behavior for a “Special” Triple Friction Pendulum Isolator [4].

Regime	Description	Force-Displacement relationship
1	Sliding occurs in only surfaces 2 and 3	$F = \frac{W}{2R_{eff2}} \times d + (\mu_2 \times W)$ $0 \leq d \leq d^*$ $d^* = 2(\mu_1 - \mu_2) \times 2R_{eff2}$
2	Movements will stop on surfaces 2 and 3; Sliding occurs in only surfaces 1 and 4	$F = \frac{W}{2R_{eff1}} \times (d - d^*) + (\mu_1 \times W)$ $d^* \leq d \leq d^*$ $d^{**} = d^* + 2d_1^*$
3	The slider is on the retainers on surfaces 1 and 4. Sliding occurs only on surfaces 2 and 3	$F = \frac{W}{2R_{eff2}} (d - d^{**}) + \frac{W}{2R_{eff1}} (d^{**} - d^*) + (\mu_1 \times W)$ $d^{**} \leq d \leq d_{cap}$ $d_{cap} = 2d_1^* + 2d_2^*$

Table A.2: Schematics of Force-Displacement Behavior for “Special” Triple Friction Pendulum Isolator [4].

Regime	Schematic of Isolator	Force-Displacement relationship
1		
2		
3		

3.5 Principle of Operation

Two spherical stainless-steel sides divided by a slider put in the internal assembly make up the triple FP bearing as showed in Figure 3.4, the external spherical plates have the effective radii R_{eff1} and R_{eff2} ,

$$R_{eff1} = R_1 - h_1 \quad \dots (3.1)$$

$$R_{eff4} = R_4 - h_4 \quad \dots (3.2)$$

Where the radius of curvature of the i^{th} spherical surface is R_i and the radial distance between the i^{th} spherical surface and the pivot point of the articulated slider is called h_i [4] [5].

Two spherical slide surfaces divided by a stiff slider make up the design slider assembly. A nonmetallic lubricant material covers the exterior part of the slider where they contact the outer spherical plates. The coefficient of friction of these spherical are μ_1 and μ_4 , the effective radii of the inner surfaces are,

$$R_{eff2} = R_2 - h_2 \quad \dots (3.3)$$

$$R_{eff3} = R_3 - h_3 \quad \dots (3.4)$$

d_1 - d_4 are the displacement capabilities of the slider surfaces 1-4 because of the effects of slider length and rotational characteristics, the actual displacement capabilities show small differences [4] [5]. The rigidity of the bearing is inversely related to the sum of radius of curvature of the surfaces on which sliding occurs. [4] [5].

Beginning from idle, sliding initiates on the i^{th} surface when the horizontal force transferred through the bearing F_{fi} , exceeds the surface's friction force, where W is the normal load on the bearing [4].

$$F_{fi} = \mu_i W \quad \dots (3.5)$$

Sliding is stopped by the displacement restrainer on the i^{th} surface when the relative displacement of the slider on this surface becomes equal to the displacement capability, d_i . The horizontal force at the moment the slider begins to bear upon this surface's displacement restrainer is

$$F_{dri} = \frac{W}{R_{eff}} d_i + F_{fi} \quad \dots (3.6)$$

After comparing the values of F_{fi} and F_{dri} the following series of activation and deactivation of sliding on multiple surfaces are determined [4] [5].

The standard structure of triple friction bearing is given by the following expression [4].

$$R_{eff1} = R_{eff4} \gg R_{eff2} = R_{eff3}.$$

The coefficients of frictions are chosen so that the bearing exerts high stiffness and low friction at first and afterwards decreases in stiffness and increases in stiffness as the magnitude of displacement goes over the design displacement. This is achieved by using friction values given by, [4] [5].

$$\mu_2 = \mu_3 < \mu_1 < \mu_4.$$

The displacement capabilities of each surface are selected so that there is incremental stiffening at large displacement. The slider should touch the displacement restrainers on surfaces 1 and 4 before surfaces 2 and 3. This is achieved as long as $F_{f1} < F_{dr2}$ and $F_{f4} < F_{dr3}$. In terms of displacement this condition is $d_2 > (\mu_1 - \mu_2) R_{eff2}$ and $d_3 > (\mu_4 - \mu_3) R_{eff3}$. [4] [5].

CHAPTER 4

NUMERICAL STUDY

4.1 Description of The Building Model

Single-story experimental construction model Figure 4.1 with a fundamental period of 0.2s, mentioned in Fenz and Constantinou (2008), was used as the numerical model for the parametric study. The characteristics of the triple friction pendulum system isolators are depicted in the following tables. Superstructure damping is 0.25%, the base weight is $W_b=66.67\text{ kN}$, and the weight of the first floor $W_s=133.33\text{ kN}$ and the overall weight acting on each isolator is 50 kN [5].

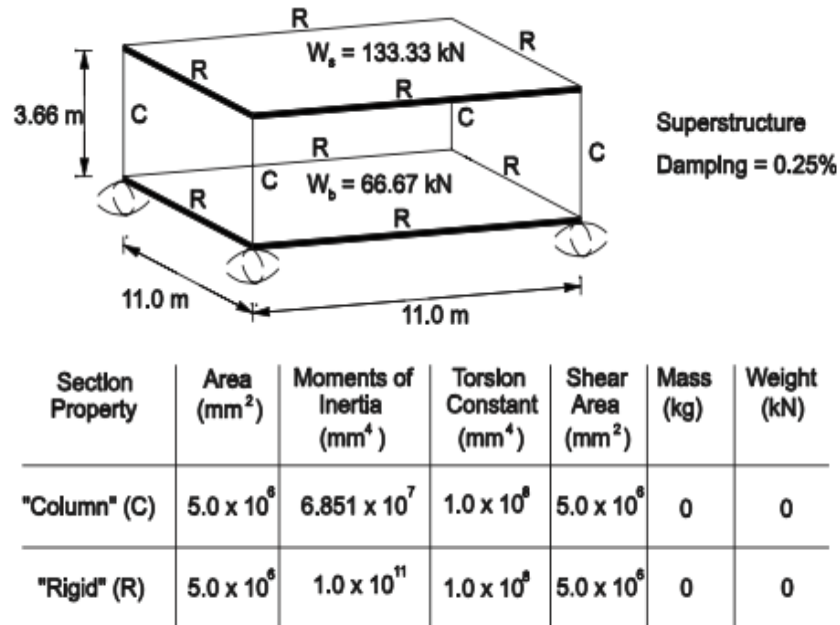


Figure 4. 1: Isolated structure model [5]

Modelling of the response of the TFPS isolators was conducted with SAP2000 [5] and OpenSees. The results of the triple friction pendulum verification analysis are shown in Figures 4.2 and 4.3. The 180 component of the 1940 El Centro record of (PGA 0.31 g)

was used as the earthquake ground motion. Record is available in the PEERNGA database [5].

Figures 4.4 and 4.5 show the verification of the OpenSees results [4] [5].

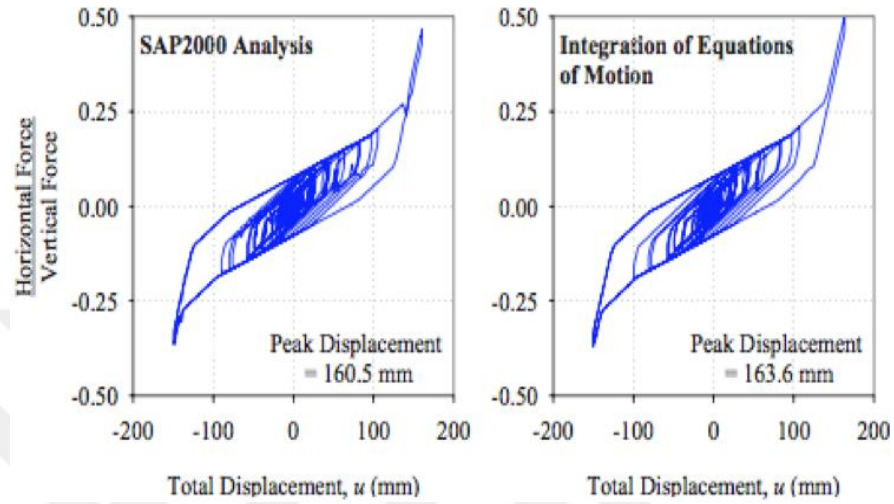


Figure 4. 2: Force-Displacement Curves [5]

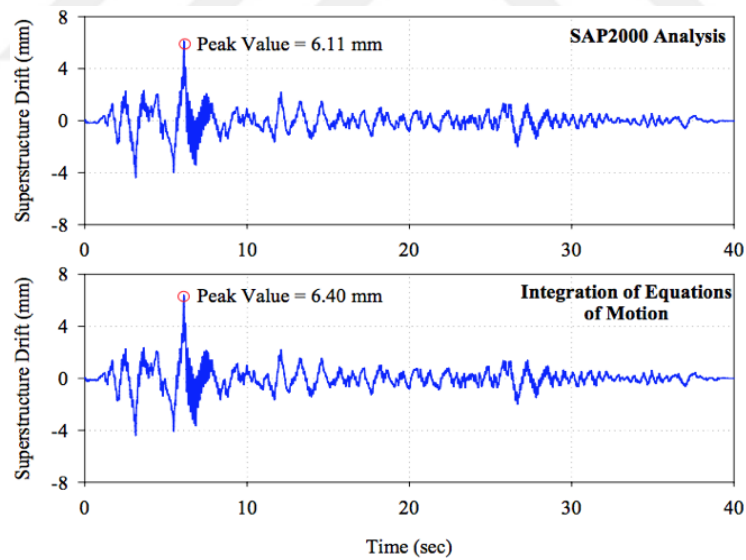


Figure 4. 3: Structure Drift [5]

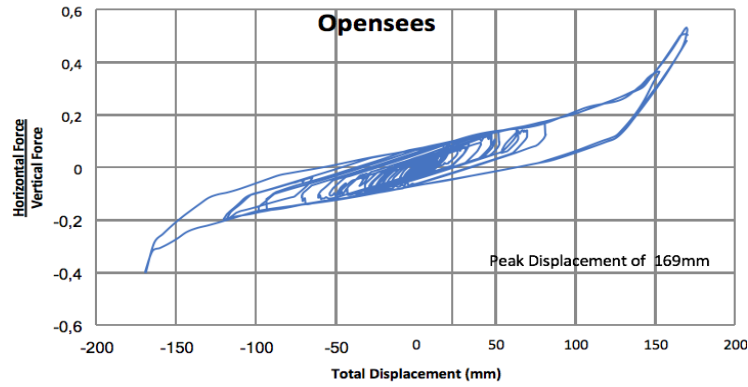


Figure 4. 4: Force-Displacement Curve using OpesSees [4] [5]

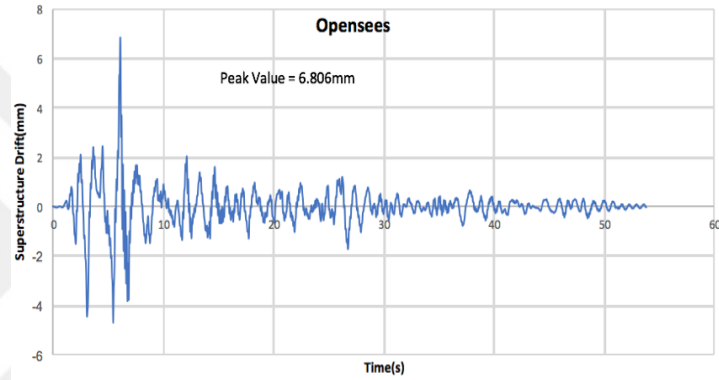


Figure 4. 5: Story Drift [4] [5]

4.2 Contact Surfaces Used in the Analysis (Curved Sliding Surface)

As described before, the triple friction pendulum behavior is influenced by the surface parameters namely, the radii of curvature, the height of the surfaces, the displacement limits of each surface, and the friction coefficients. The friction model for the triple friction pendulums is usually defined as velocity dependent due to its strong correlation with the rate of the loading. In this study, three different materials of triple friction pendulum bearing surfaces were used. These materials are named as A, B, and C as shown in Table 3, Table 4, and Table 5 respectively [55].

Table A.3: Properties of coefficient of frictions used for the case of material A [55].

<i>Material</i>		A	
$\mu 1$ SLOW	0.02	$\mu 1$ FAST	0.05
$\mu 2$ SLOW	0.01	$\mu 2$ FAST	0.01
$\mu 3$ SLOW	0.05	$\mu 3$ FAST	0.1

Table A.4: Properties of coefficient of frictions used for the case of material B [55].

<i>Material</i>		B	
$\mu 1$ SLOW	0.02	$\mu 1$ FAST	0.05
$\mu 2$ SLOW	0.01	$\mu 2$ FAST	0.01
$\mu 3$ SLOW	0.07	$\mu 3$ FAST	0.15

Table A.5: Properties of coefficient of frictions used for the case of material C [55].

<i>Material</i>		C	
$\mu 1$ SLOW	0.04	$\mu 1$ FAST	0.08
$\mu 2$ SLOW	0.01	$\mu 2$ FAST	0.02
$\mu 3$ SLOW	0.1	$\mu 3$ FAST	0.2

4.3 Ground Motion Selection

Non-linear response history analysis is increasingly being used in seismic engineering practices to demonstrate the performance of structures. This analysis method requires the selection and scaling of earthquake ground motions to be used in the analysis and design. Instructions for selecting and scaling seismic ground motion records for site-specific hazards can be found in the building codes [e.g., IBC 2006 (ICBO 2006) and CBC 2007 (ICBO 2007)] and have been the subject of extensive research in recent years [50].

Current performance-based design and evaluation methods prioritize intensity-based seismic scaling methods over spectrum matching techniques that change the phase of frequency content or records to match their response spectrum to the target spectrum [51]. In contrast, intensity-based scaling methods retain the original non-stationary content and change only its amplitude. The main goal of the intensity-based scaling methods is to provide scaling factors for a small number of seismic records so that the non-linear response history of the structure is accurate for these scaled [51] [52]. Scaling the ground

motion to match the target's peak ground acceleration (PGA) value is the fastest approach to the problem but produces inaccurate estimates with large spreads of EDP values [51] [52] [53]. Other scalar intensity measurements (IM) such as valid peak acceleration, Arias intensity, and peak velocity have also been shown to be inaccurate and inefficient [54]. None of the above IMs take into account the properties of the structure being analyzed. Including a vibration property of the structure led to improved methods to scale ground motions, e.g., scaling records to a target value of the elastic spectral acceleration [54].

In this study to two sets of earthquakes near-field and far-field were selected. In the first set, 23 near field and 22 far field ground motions were selected from [56]. Details of the selected ground motions are shown in Table A.6 and Table A.7. Moreover, the acceleration spectrums for the selected earthquake sets are given in Figure A-115 and Figure A-116 (Appendix A).

Table A.6: Properties of the near-field earthquake records selected for the analysis

Record Sequence Number	Earthquake Name	Year	Station Name	Magnitude	Distance to fault (km)	Soil shear wave velocity (m/s)
126	"Gazli_ USSR"	1976	"Karakyr"	6.8	3.92	259.59
165	"Imperial Valley-06"	1979	"Chihuahua"	6.53	7.29	242.05
182	"Imperial Valley-06"	1979	"El Centro Array #7"	6.53	0.56	210.51
741	"San Fernando"	1971	"Maricopa Array #1"	6.61	193.25	303.79
821	"Erzican_ Turkey"	1992	"Erzincan"	6.69	0	352.05
825	"Cape Mendocino"	1992	"Cape Mendocino"	7.01	0	567.78
838	"Landers"	1992	"Barstow"	7.28	34.86	370.08
879	"Landers"	1992	"Lucerne"	7.28	2.19	1369
1161	"Kocaeli_ Turkey"	1999	"Gebze"	7.51	7.57	792
1165	"Kocaeli_ Turkey"	1999	"Izmit"	7.51	3.62	811
1176	"Kocaeli_ Turkey"	1999	"Yarimca"	7.51	1.38	297
1529	"Chi-Chi_ Taiwan"	1999	"TCU102"	7.62	1.49	714.27
6897	"Darfield_ New Zealand"	2010	"DSLCL"	7	5.28	295.74
6927	"Darfield_ New Zealand"	2010	"LINC"	7	5.07	263.2
6928	"Darfield_ New Zealand"	2010	"LPCC"	7	25.21	649.67
6942	"Darfield_ New Zealand"	2010	"NNBS North New Brighton School "	7	26.76	211
6962	"Darfield_ New Zealand"	2010	"ROLCL"	7	0	295.74
6966	"Darfield_ New Zealand"	2010	"Shirley Library"	7	22.33	207
6969	"Darfield_ New Zealand"	2010	"Styx Mill Transfer Station "	7	20.86	247.5
6975	"Darfield_ New Zealand"	2010	"TPLCL"	7	6.11	249.28
8161	"El Mayor-Cucapah_ Mexico"	2010	"El Centro Array #12"	7.2	9.98	196.88
8164	"Duzce_ Turkey"	1999	"IRIGM 487"	7.14	2.65	690
8606	"El Mayor-Cucapah_ Mexico"	2010	"Westside Elementary School"	7.2	10.31	242

Table A.7: Properties of the far-field earthquake records selected for the analysis

Record Sequence Number	Earthquake Name	Year	Station Name	Magnitude	Distance to fault (km)	Soil shear wave velocity (m/s)
68	"San Fernando"	1971	"LA - Hollywood Stor FF"	6.61	22.77	316.46
125	"Friuli_ Italy-01"	1976	"Tolmezzo"	6.5	14.97	505.23
169	"Imperial Valley-06"	1979	"Delta"	6.53	22.03	242.05
174	"Imperial Valley-06"	1979	"El Centro Array #11"	6.53	12.56	196.25
721	"Superstition Hills-02"	1987	"El Centro Imp. Co. Cent"	6.54	18.2	192.05
725	"Superstition Hills-02"	1987	"Poe Road (temp)"	6.54	11.16	316.64
752	"Loma Prieta"	1989	"Capitola"	6.93	8.65	288.62
767	"Loma Prieta"	1989	"Gilroy Array #3"	6.93	12.23	349.85
848	"Landers"	1992	"Coolwater"	7.28	19.74	352.98
960	"Northridge-01"	1994	"Canyon Country - W Lost Cany"	6.69	11.39	325.6
1116	"Kobe_ Japan"	1995	"Shin-Osaka"	6.9	19.14	256
1148	"Kocaeli_ Turkey"	1999	"Arcelik"	7.51	10.56	523
1244	"Chi-Chi_ Taiwan"	1999	"CHY101"	7.62	9.94	258.89
1485	"Chi-Chi_ Taiwan"	1999	"TCU045"	7.62	26	704.64
1602	"Duzce_ Turkey"	1999	"Bolu"	7.14	12.02	293.57
1633	"Manjil_ Iran"	1990	"Abbar"	7.37	12.55	723.95
1787	"Hector Mine"	1999	"Hector"	7.13	10.35	726
3753	"Landers"	1992	"Fun Valley"	7.28	25.02	388.63
5837	"El Mayor-Cucapah_ Mexico"	2010	"El Centro - Imperial & Ross"	7.2	19.39	229.25
5985	"El Mayor-Cucapah_ Mexico"	2010	"El Centro Differential Array"	7.2	22.83	202.26
5991	"El Mayor-Cucapah_ Mexico"	2010	"El Centro Array #10"	7.2	19.36	202.85
6915	"Darfield_ New Zealand"	2010	"Heathcote Valley Primary School "	7	24.36	422

CHAPTER 5

Results and Discussions

As stated before, seismic isolation is an effective approach for securing structures and their contents from earthquake strong ground motion. In this approach, seismic isolation bearings are placed beneath the base of the structure to shift the fundamental period of the isolated structure to the region of low spectral acceleration. Furthermore, energy dissipation through hysteresis reduces the displacement demands of the seismic isolation system. In this section, the results of the time history analyses for the base-isolated structure considering different friction coefficients will be discussed.

5.1 Force–Displacement Hysteresis Curves under Near-Field Ground Motion Records

The coefficient of friction is a critical parameter that influences force-displacement response of the bearings. The coefficient of friction of the surface is preserved as ($\mu_2 = \mu_3 < \mu_1 < \mu_4$) according to the common design strategy of TFPS bearings. Hysteresis loops of TFPS bearings can be utilized to calculate cycle-by-cycle energy dissipation and bearing damping. The results of the time history analysis for the investigated near-field earthquakes and the selected isolators are provided in Figures 5.1 to 5.12. Most motion records show displacements of less than 300 mm, and initiate motion only on the inner slip surface. Figure 5.1 shows the seismic record using the coefficient of friction of Material A. The results for Material B are shown in Figure 5.2. These indicate that generally the average base shear increases as the friction value increases. In addition, Material C in Figure 5.3 shows that the base shear increases further as the coefficient of friction increases.

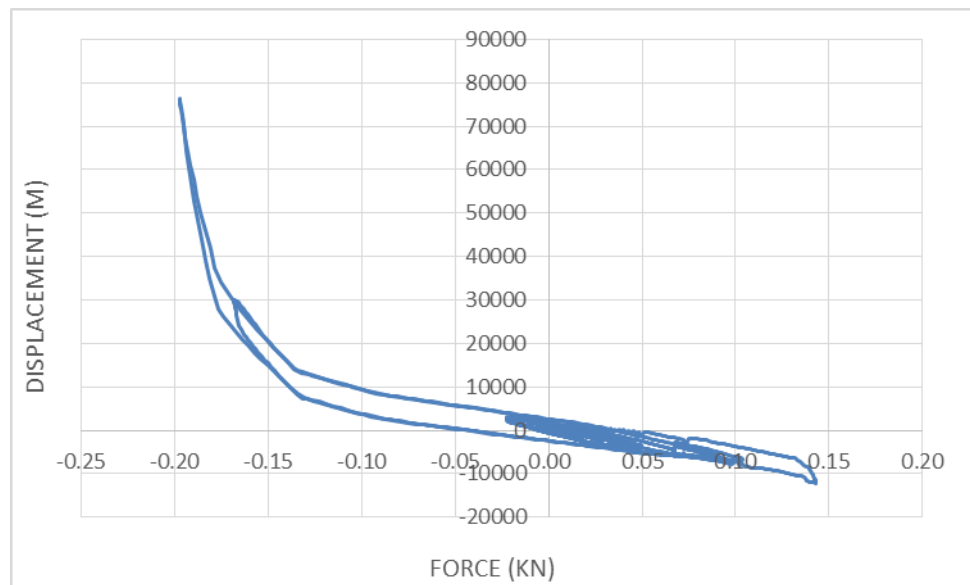


Figure 5. 1: Hysteresis loop of material A TFPB under RSN 182

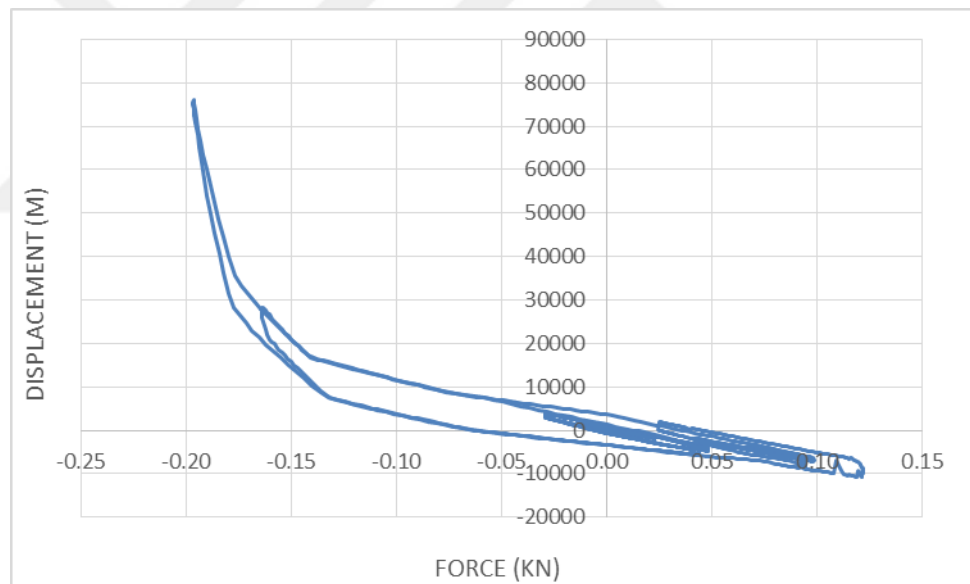


Figure 5. 2: Hysteresis loop of material B TFPB under RSN 182

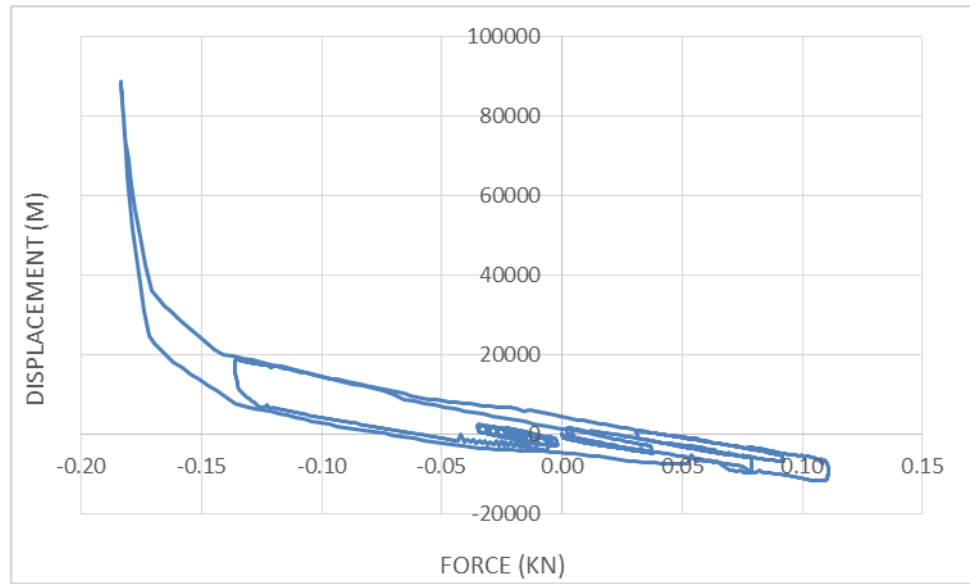


Figure 5. 3: Hysteresis loop of material C TFPB under RSN 182

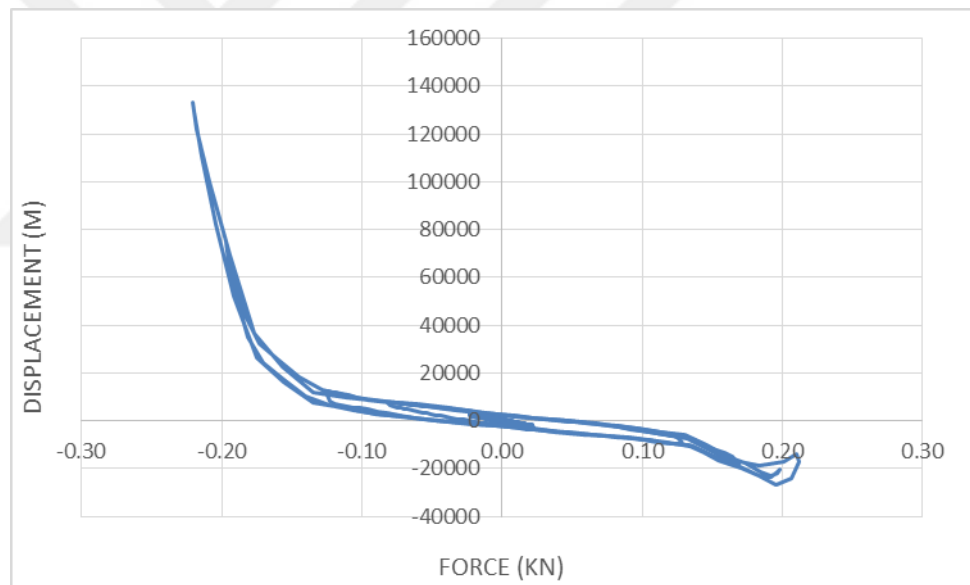


Figure 5. 4: Hysteresis loop of material A TFPB under RSN 825

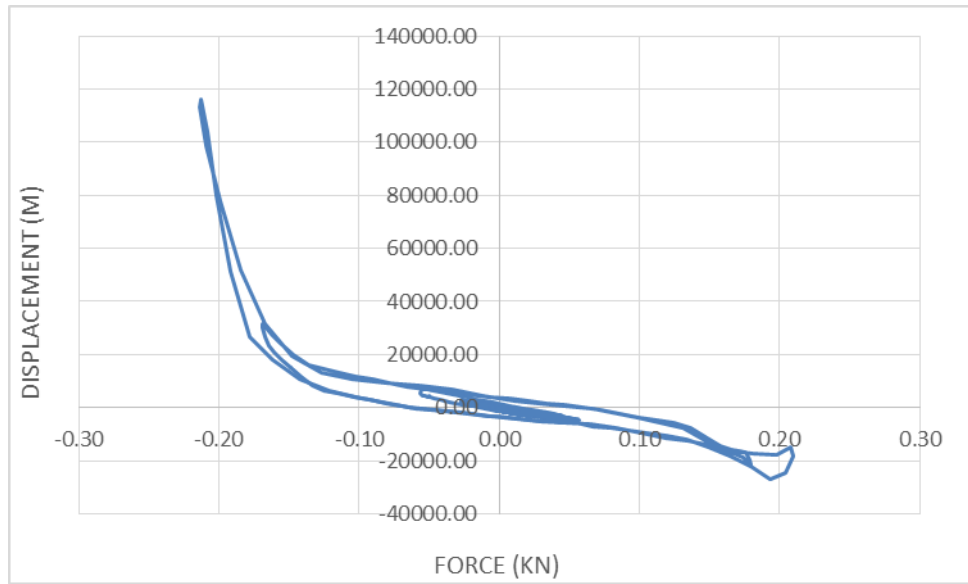


Figure 5. 5: Hysteresis loop of material B TFPB under RSN 825

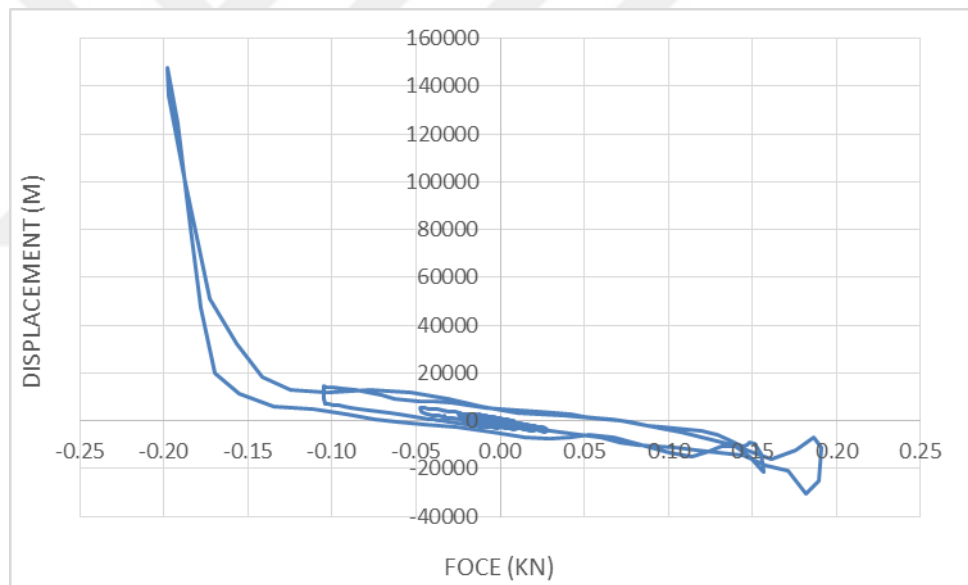


Figure 5. 6: Hysteresis loop of material C TFPB under RSN 825

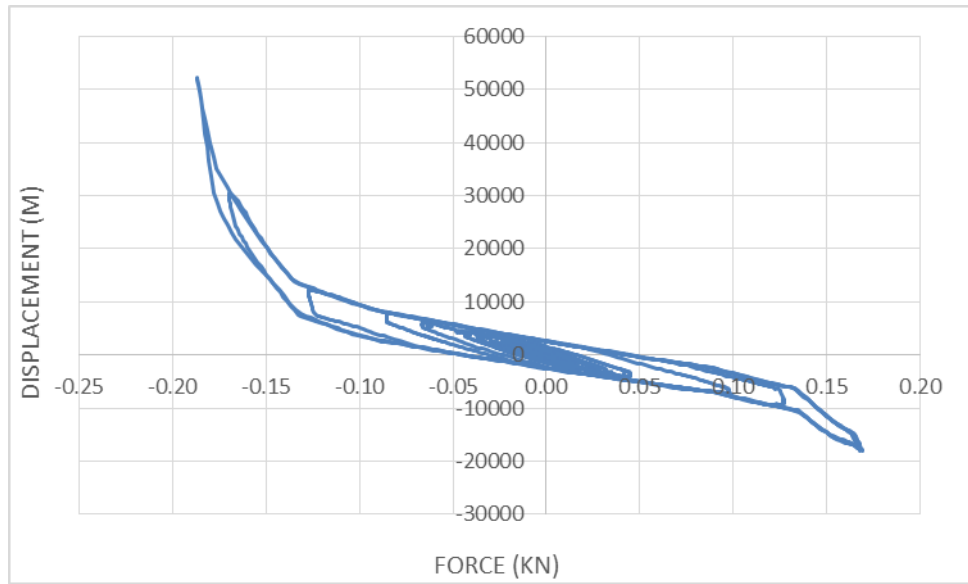


Figure 5. 7: Hysteresis loop of material A TFPB under RSN 1176

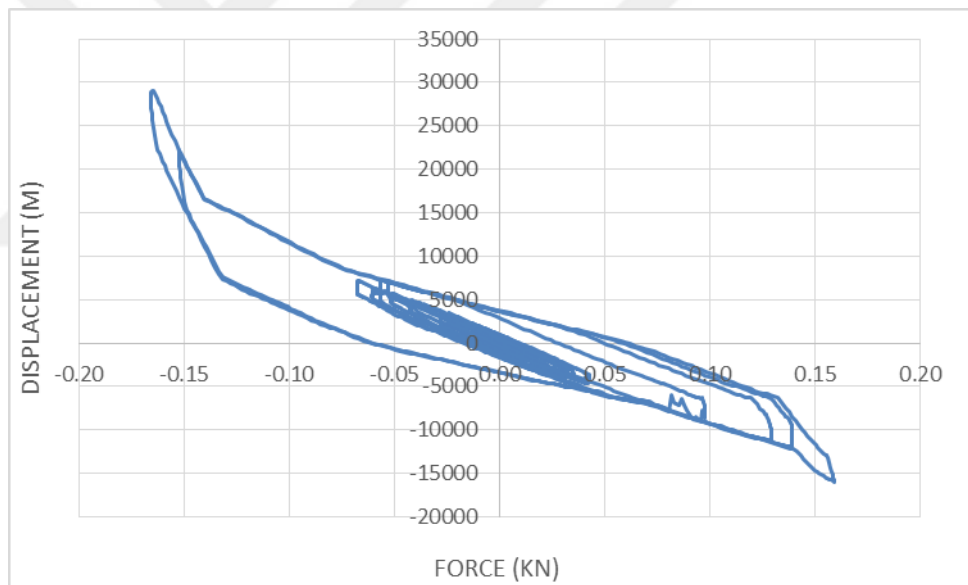


Figure 5. 8: Hysteresis loop of material B TFPB under RSN 1176

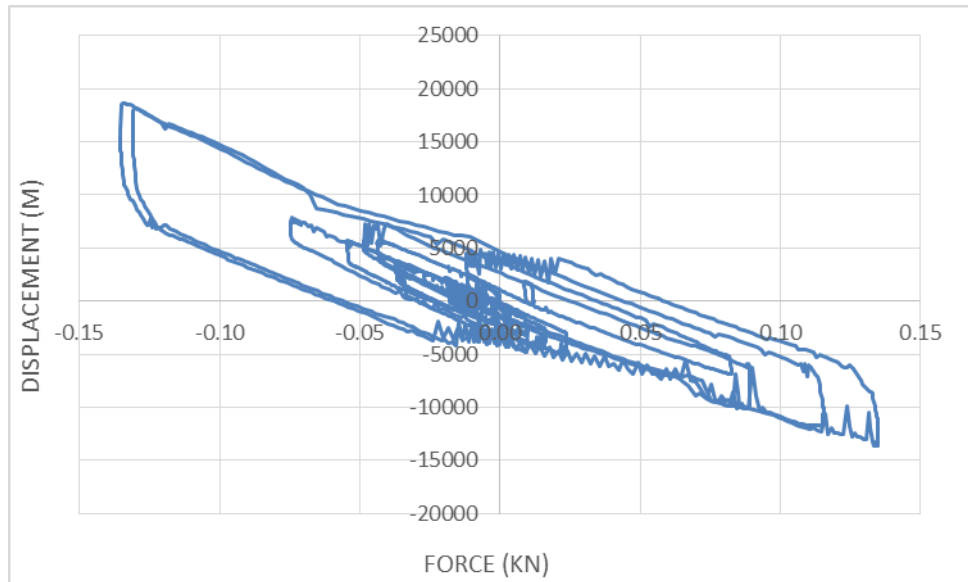


Figure 5. 9: Hysteresis loop of material C TFPB under RSN 1176

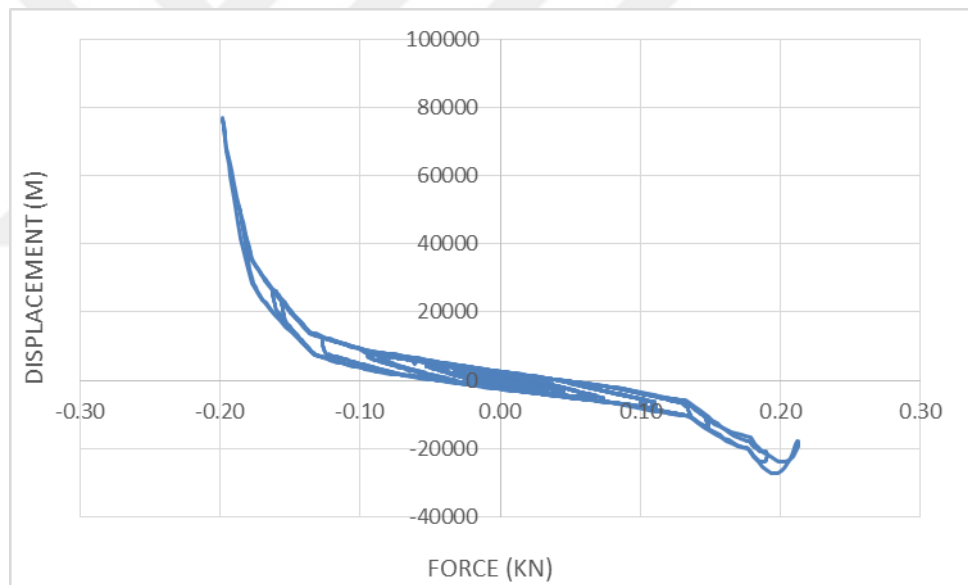


Figure 5. 10: Hysteresis loop of material A TFPB under RSN 1529

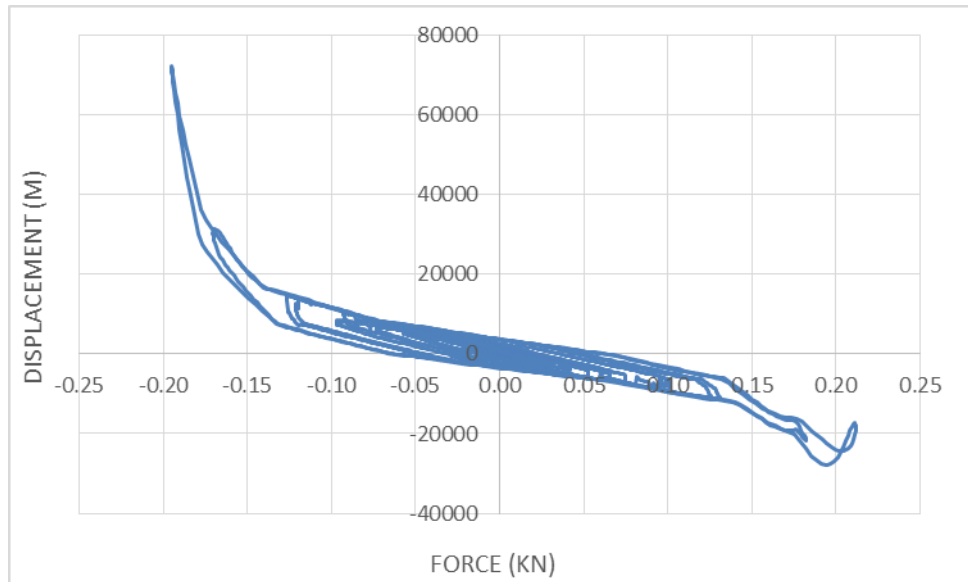


Figure 5.11: Hysteresis loop of material B TFPB under RSN 1529

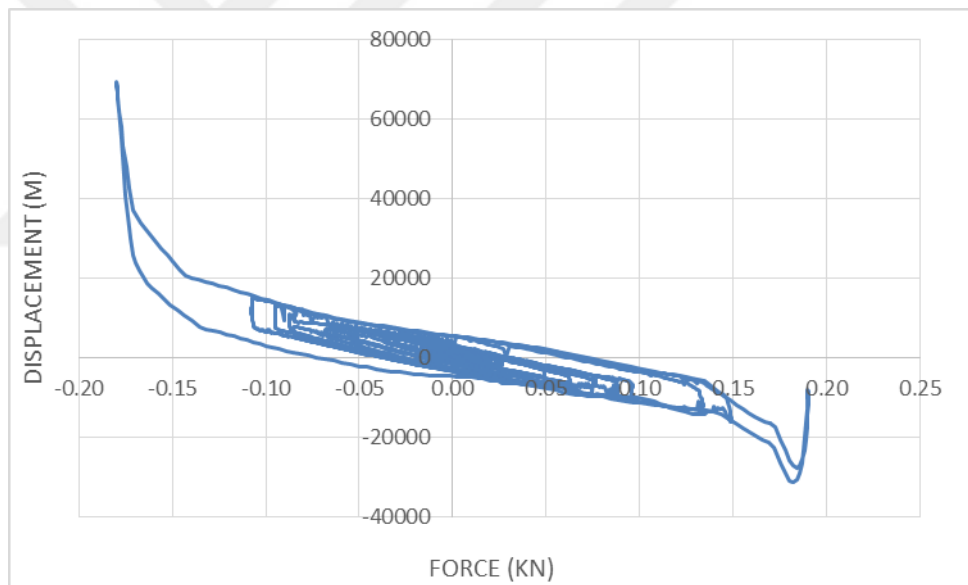


Figure 5.12: Hysteresis loop of material C TFPB under RSN 1529

The analysis results of the remaining near-field earthquakes are presented in Appendix A.

5.2 Variation of Time History Story Displacement with Friction Coefficient under Near-Field Ground Motion Records

The results of the study herein aim to investigate the impact of changing the friction coefficients on the bearing displacements of the building in each material case. Figures 5.13 shows seismic records using the coefficient of friction of Material A. The results for Material B are shown in Figures 5.14, showing that the displacement of the bearing increases as the friction value decreases. In addition, Material C in Figures 5.15 shows that the displacement of the bearing decreases further as the coefficient of friction decreases.

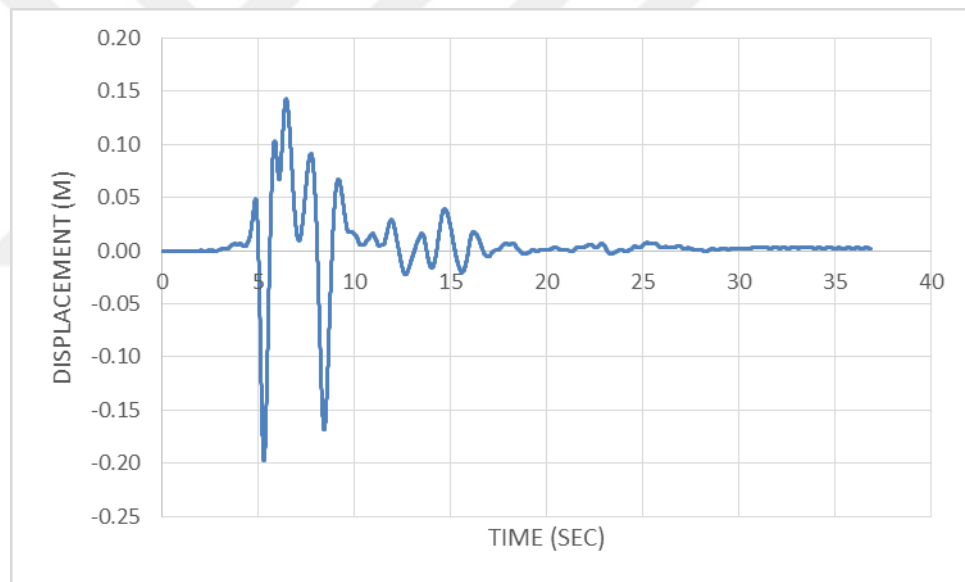


Figure 5. 133: Bearing displacement time history of material A TFPB under RSN 182

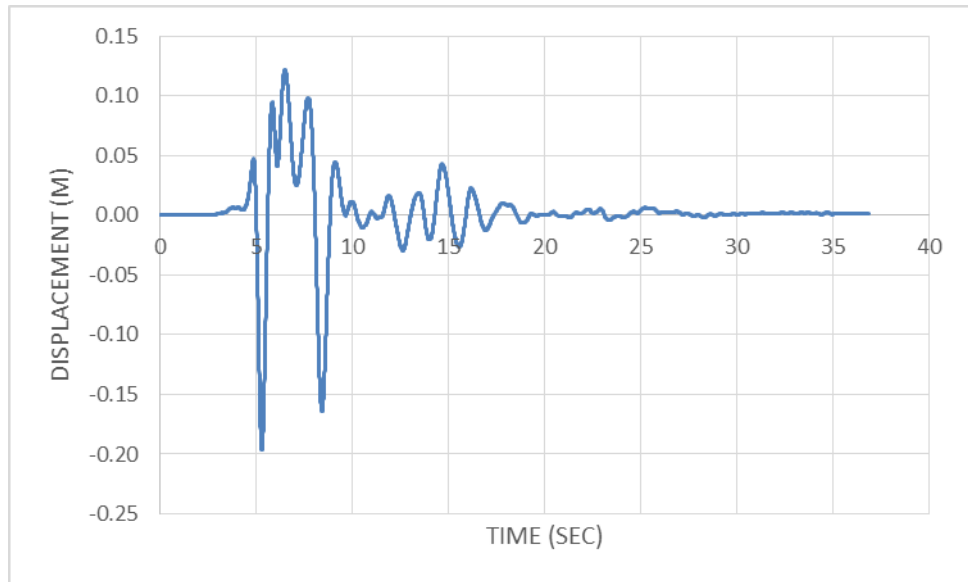


Figure 5. 14: Bearing displacement time history of material B TFPB under RSN 182

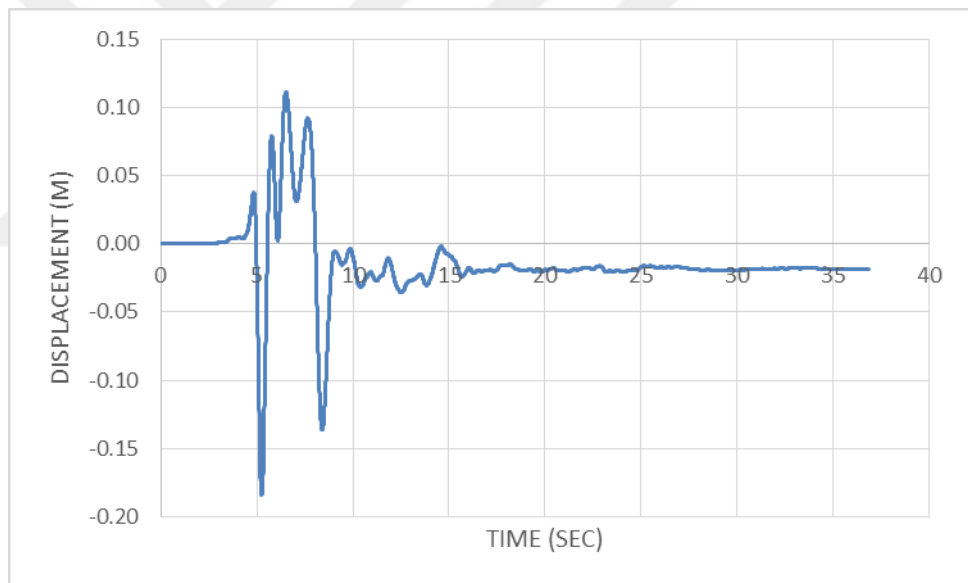


Figure 5. 15: Bearing displacement time history of material C TFPB under RSN 182

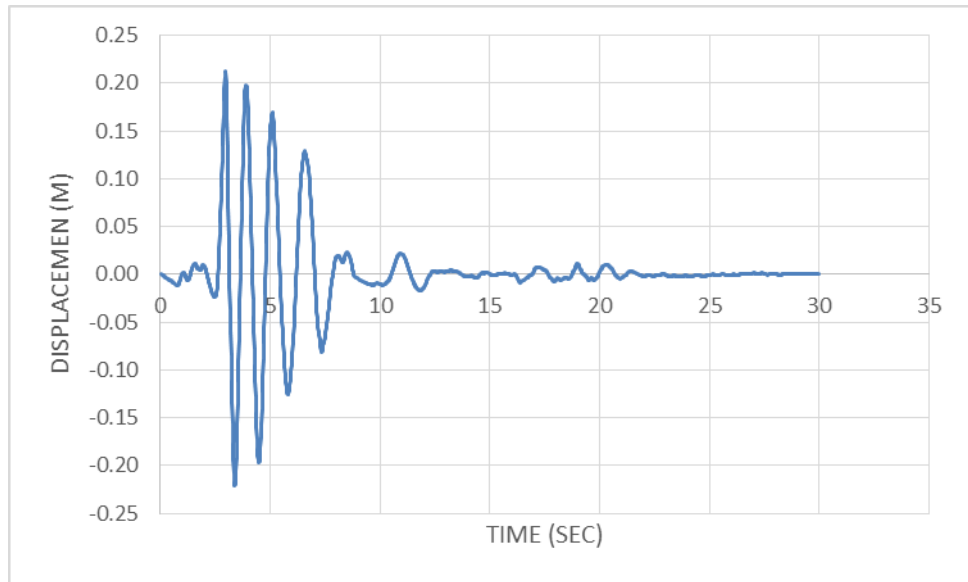


Figure 5. 16: Bearing displacement time history of material A TFPB under RSN 825

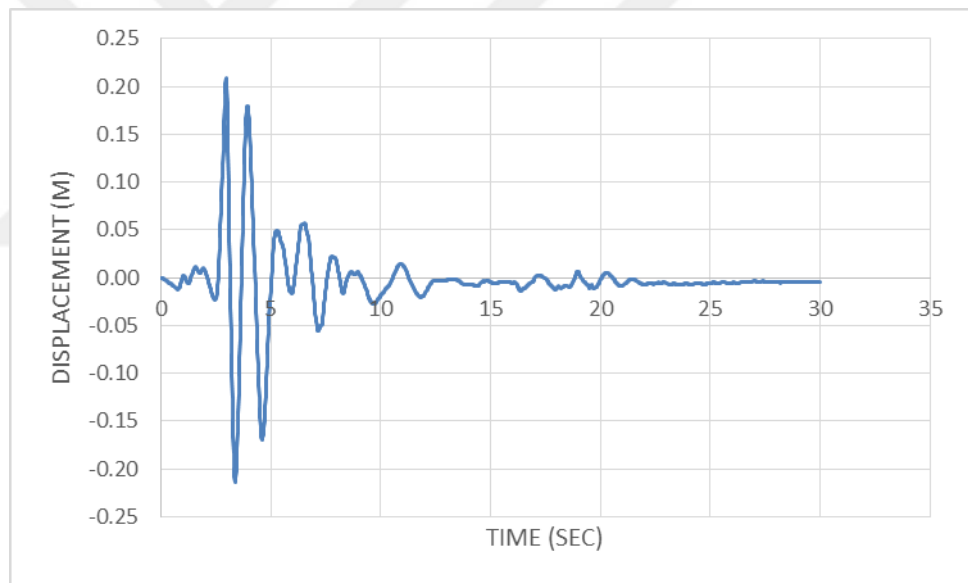


Figure 5. 17: Bearing displacement time history of material B TFPB under RSN 825

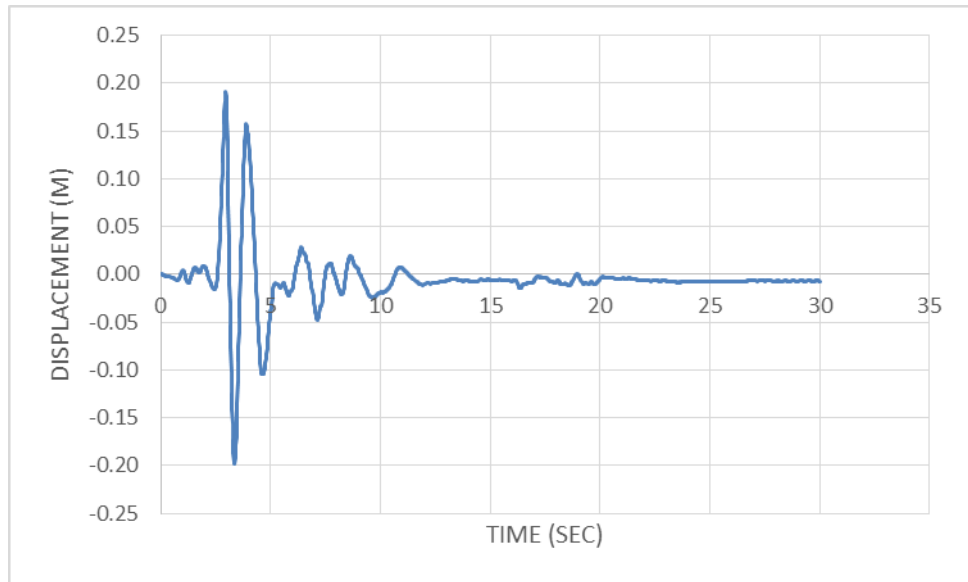


Figure 5. 18: Bearing displacement time history of material C TFPB under RSN 825

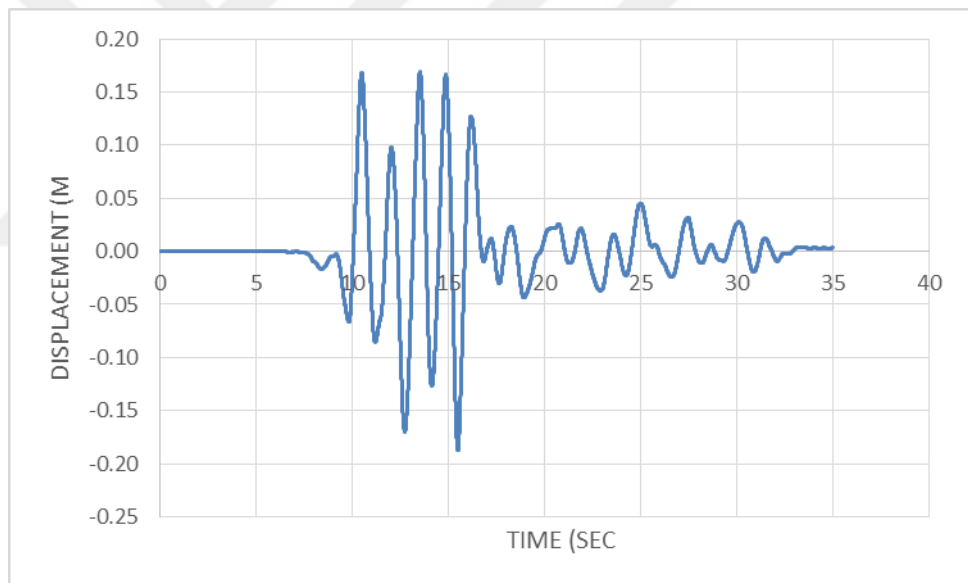


Figure 5. 19: Bearing displacement time history of material A TFPB under RSN 1176

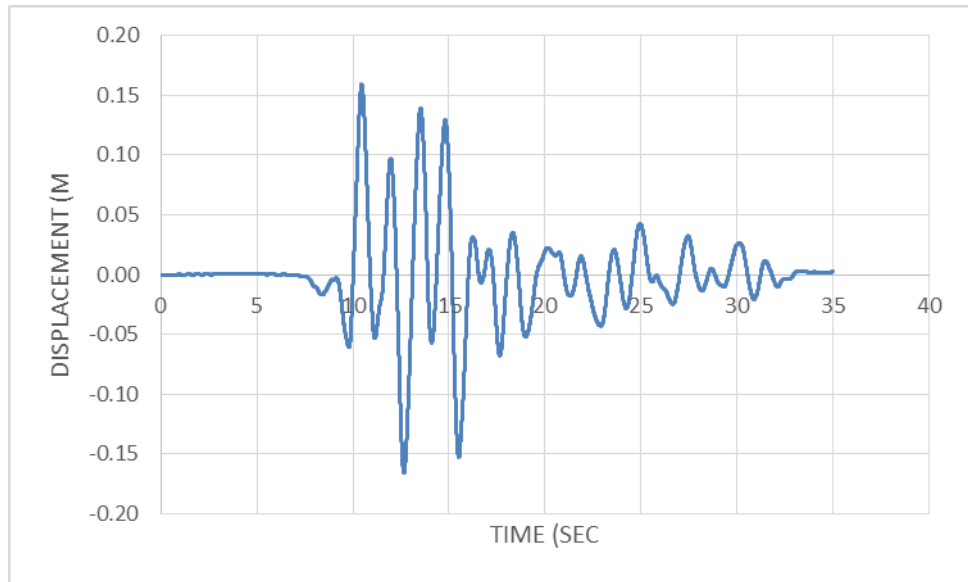


Figure 5. 20: Bearing displacement time history of material B TFPB under RSN 1176

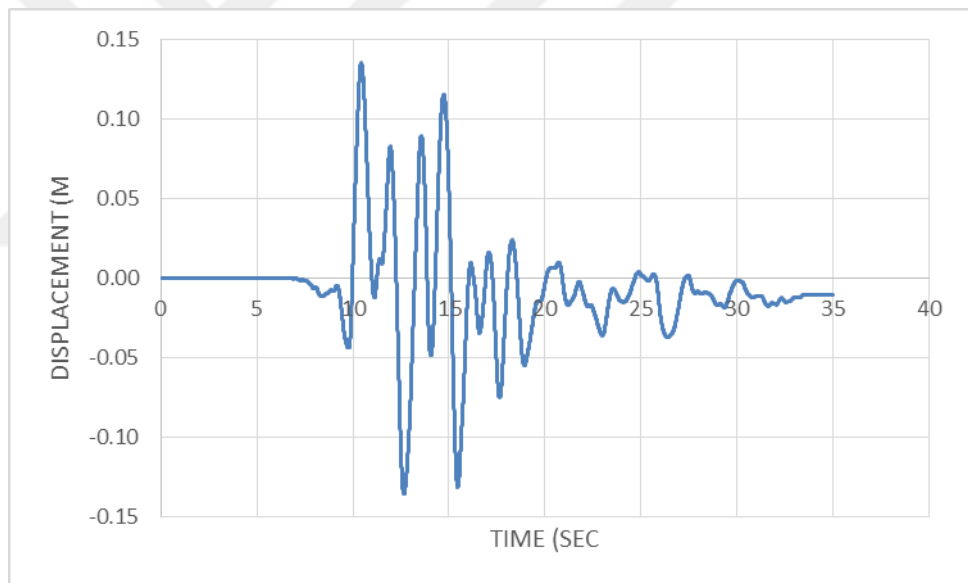


Figure 5. 21: Bearing displacement time history of material C TFPB under RSN 1176

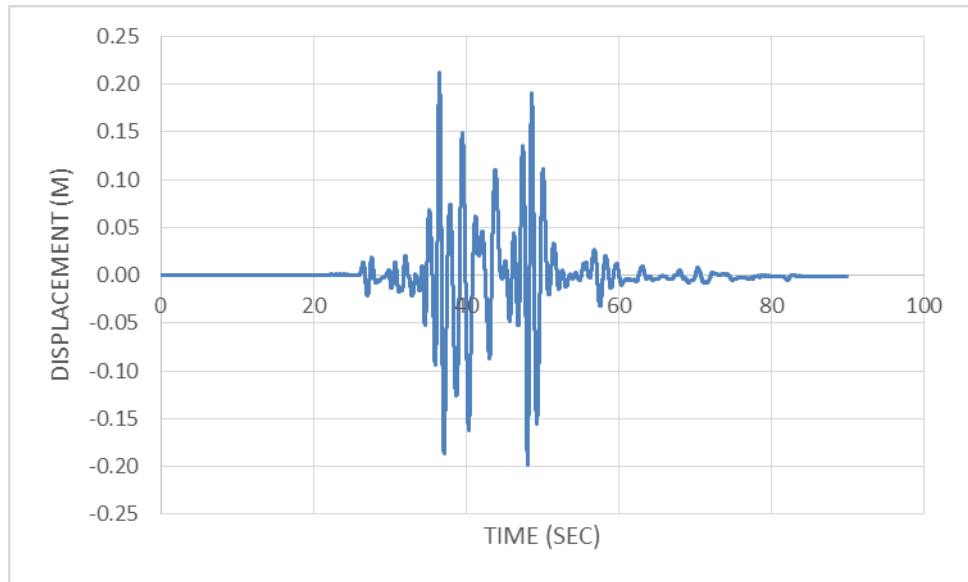


Figure 5. 22: Bearing displacement time history of material A TFPB under RSN 1529

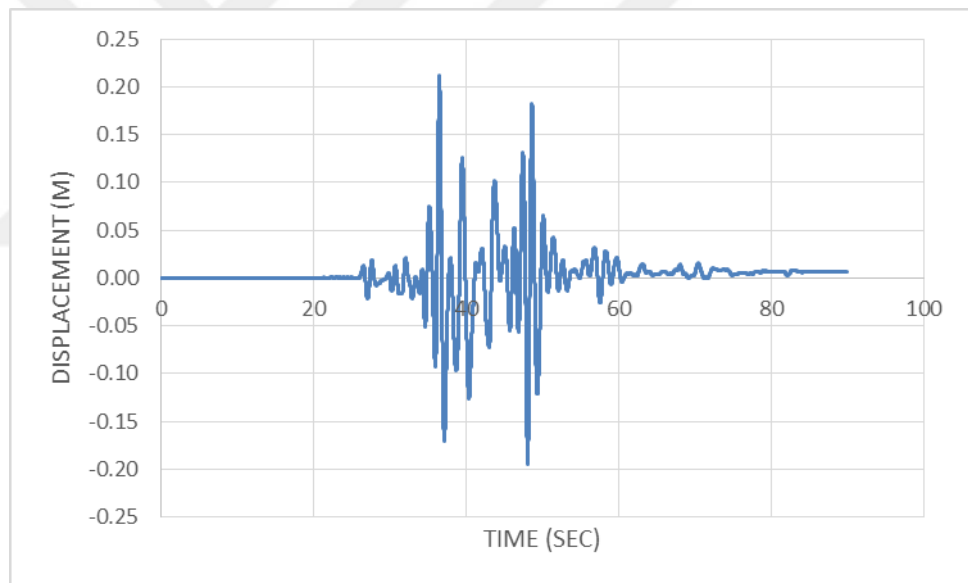


Figure 5. 143: Bearing displacement time history of material B TFPB under RSN 1529

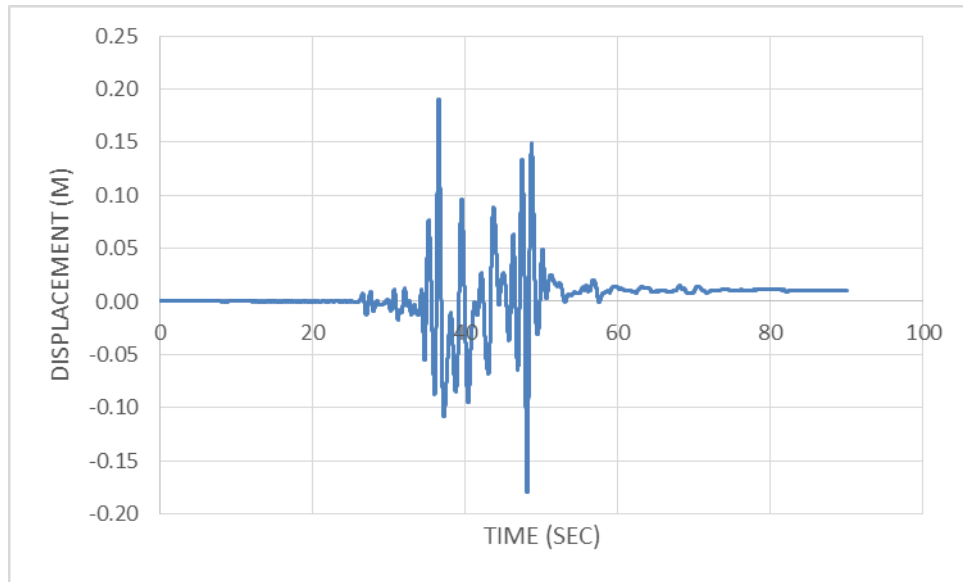


Figure 5. 24: Bearing displacement time history of material C TFPB under RSN 1529

The analysis results of the remaining near- field earthquakes are presented in Appendix A.

5.3 Force–Displacement Hysteresis Curves under Far-Field Ground Motion Records

The coefficient of friction is a significant parameter that impacts auxiliary movement and bearing displacement. The friction coefficient of the surface is kept up as ($\mu_2 = \mu_3 < \mu_1 < \mu_4$) throughout the investigation. Hysteresis loops show the constrained displacement reaction of triple friction self-pendulum bearing. The results of the time history analysis for the investigated far-field earthquakes and the selected isolators are provided in Figure 5.25 to Figure 5.36. Figure 5.25 shows the seismic record using the coefficient of friction of Material A. The results for Material B are shown in Figure 5.26. This indicates that the average base shear decreases as the friction value increases. In addition, Material C in Figure 5.27 shows that the base shear increases further as the coefficient of friction increases.

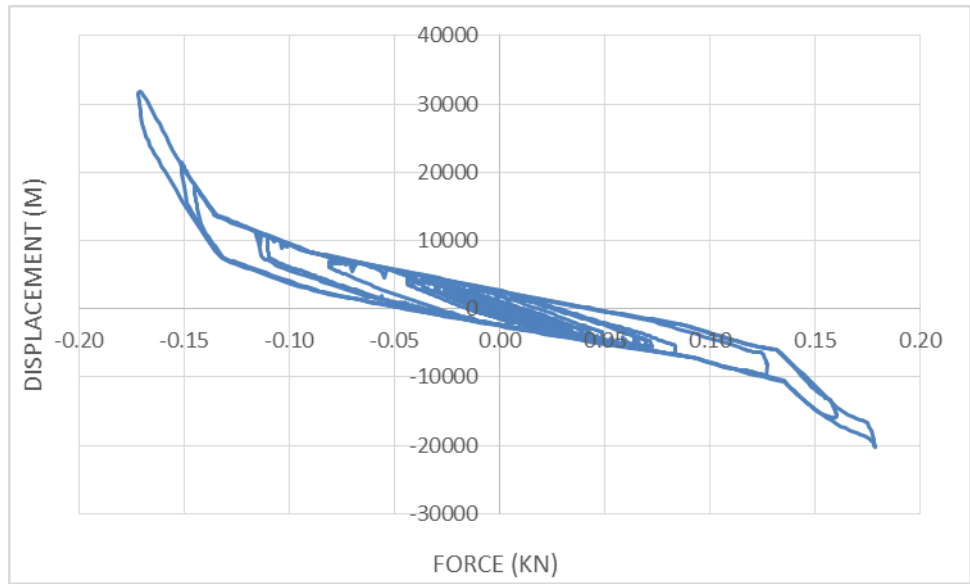


Figure 5. 25: Hysteresis loop of material A TFPB under RSN 752

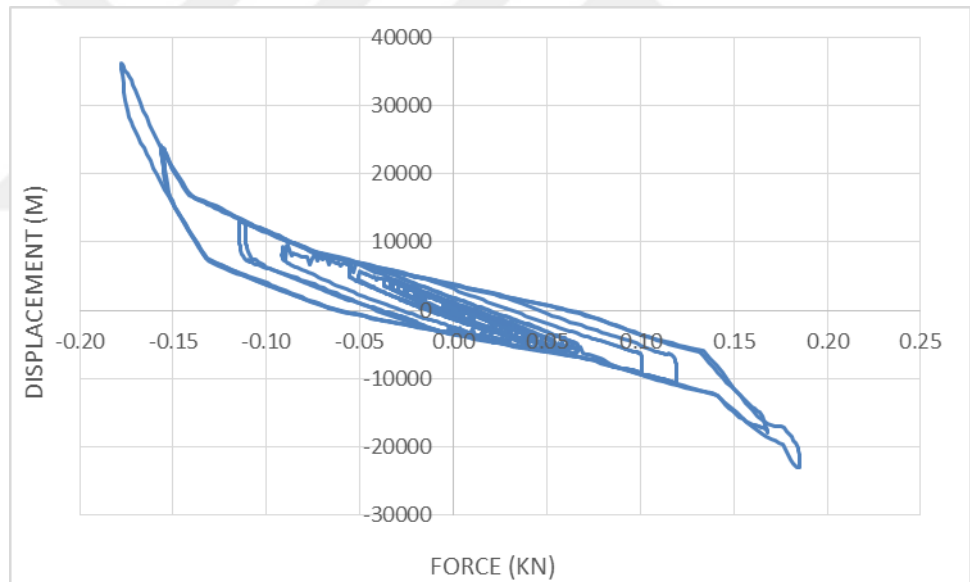


Figure 5. 26: Hysteresis loop of material B TFPB under RSN 752

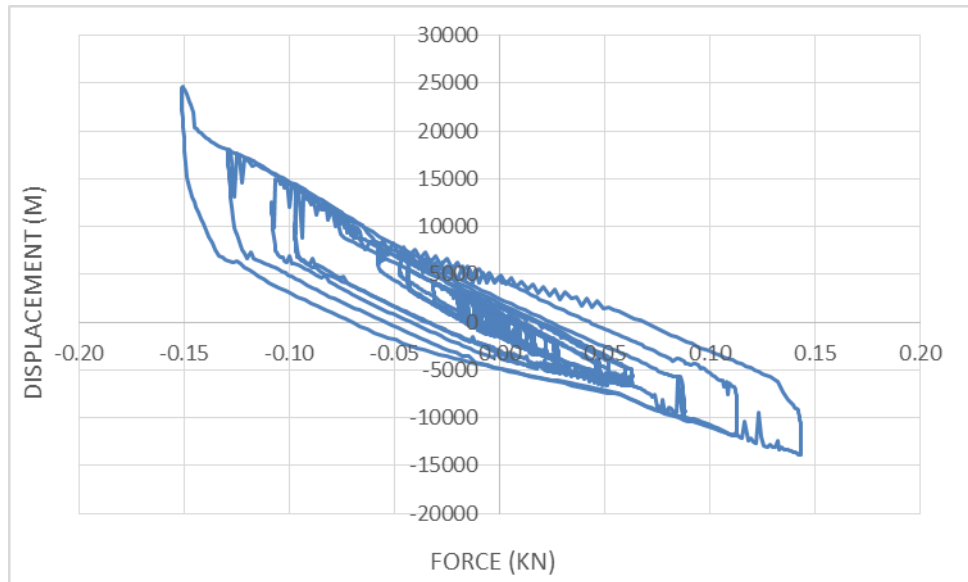


Figure 5. 27: Hysteresis loop of material C TFPB under RSN 752

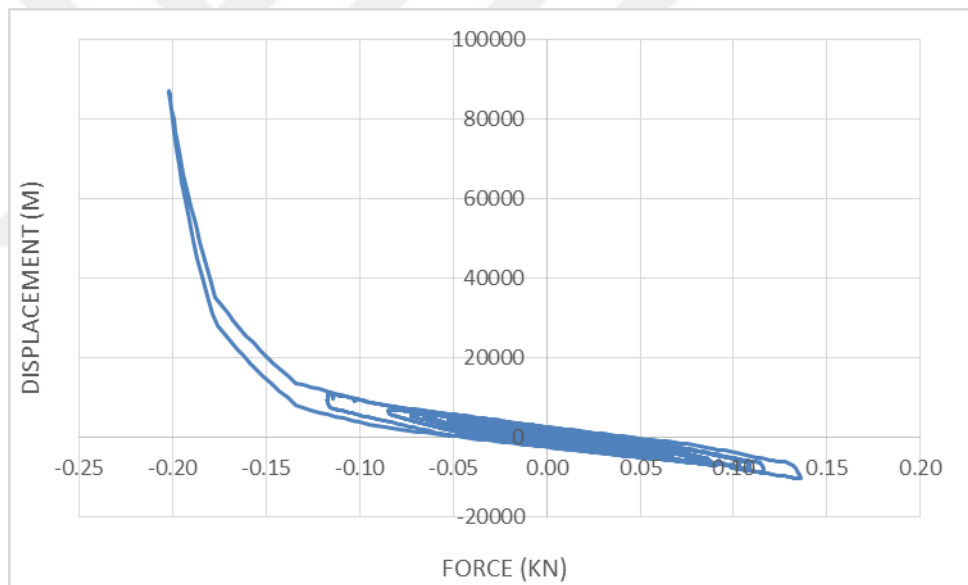


Figure 5. 28: Hysteresis loop of material A TFPB under RSN 1244

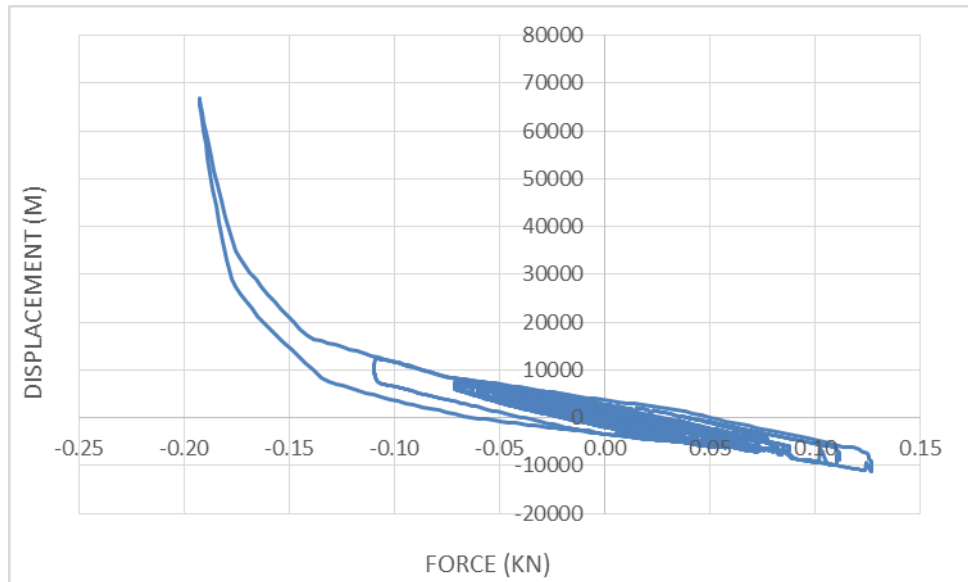


Figure 5. 29: Hysteresis loop of material B TFPB under RSN 1244

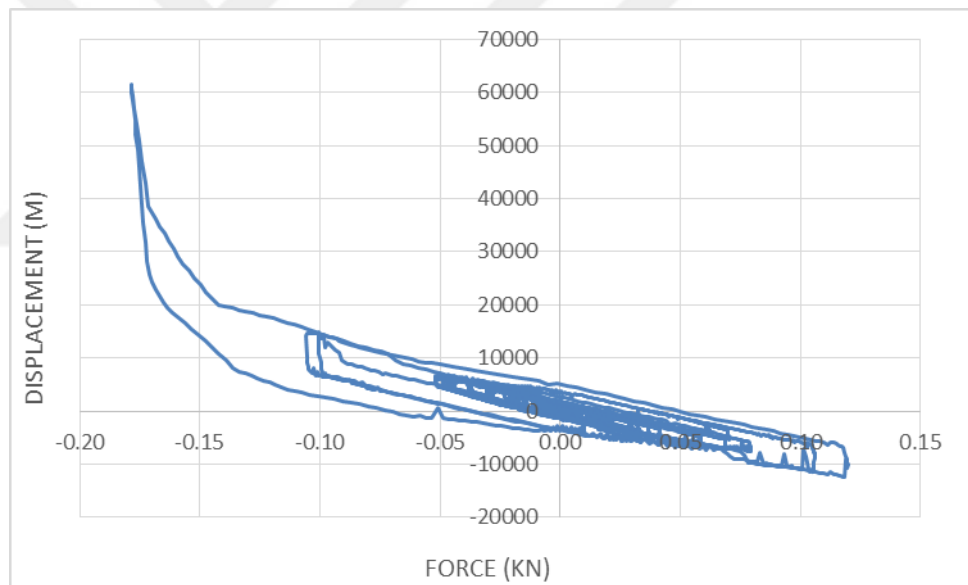


Figure 5. 30: Hysteresis loop of material C TFPB under RSN 1244

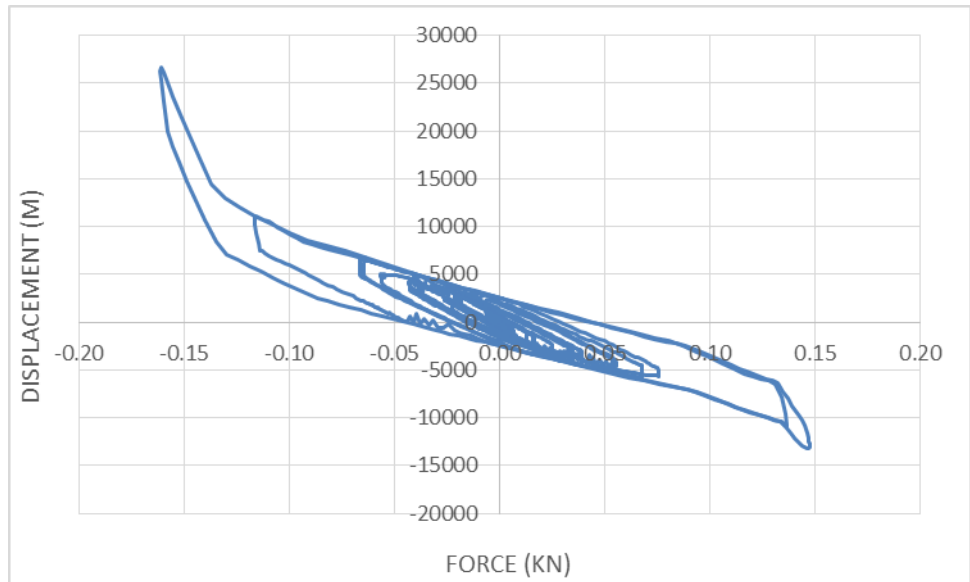


Figure 5. 31: Hysteresis loop of material A TFPB under RSN 1602

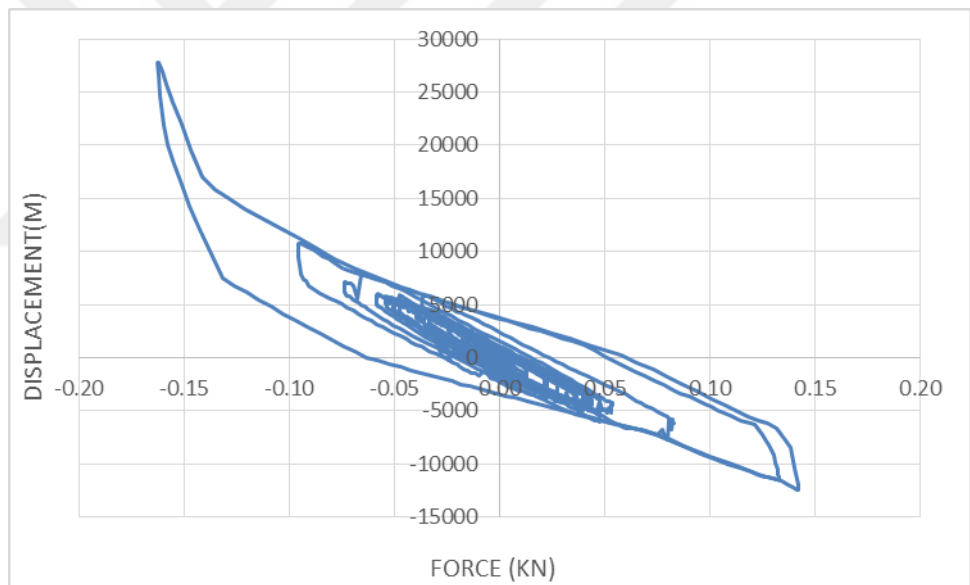


Figure 5. 32: Hysteresis loop of material B TFPB under RSN 1602

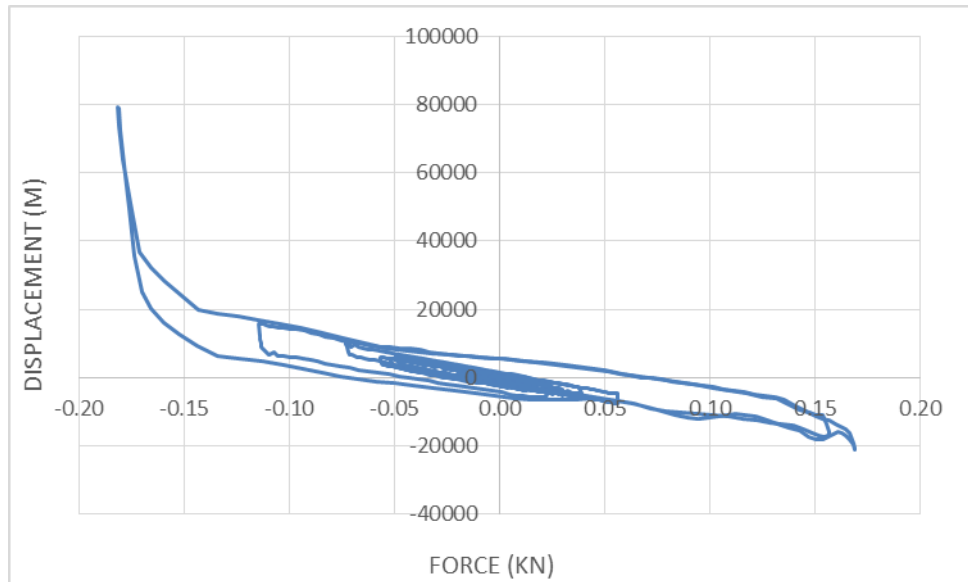


Figure 5. 33: The Hysteresis loop of material C TFPB under RSN 1602

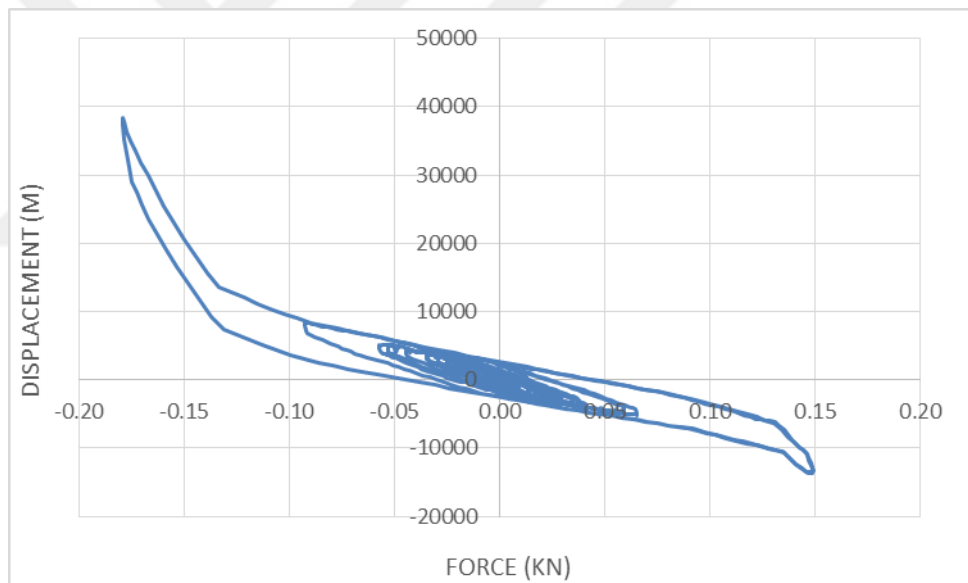


Figure 5. 34: The Hysteresis loop of material A TFPB under RSN 1787

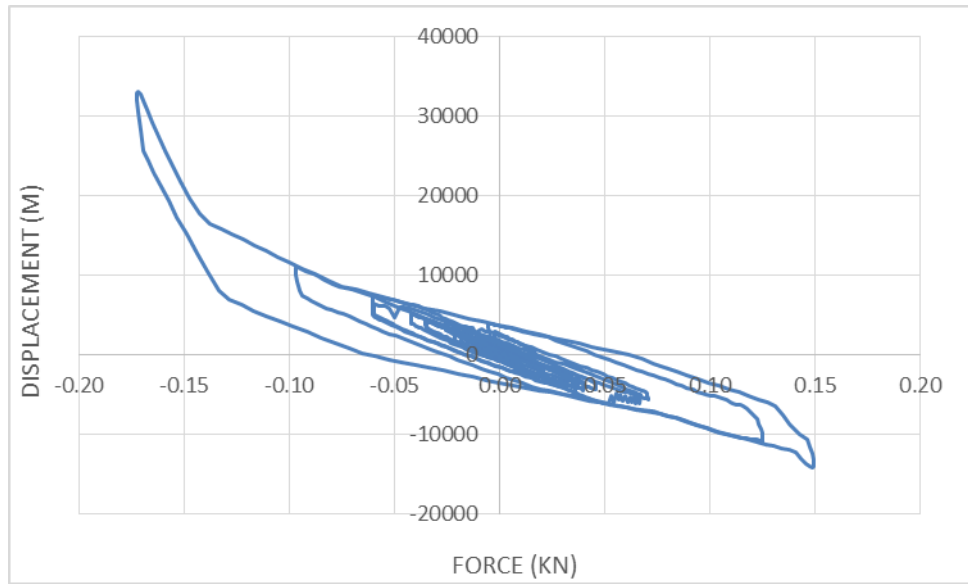


Figure 5. 35: Hysteresis loop of material B TFPB under RSN 1787

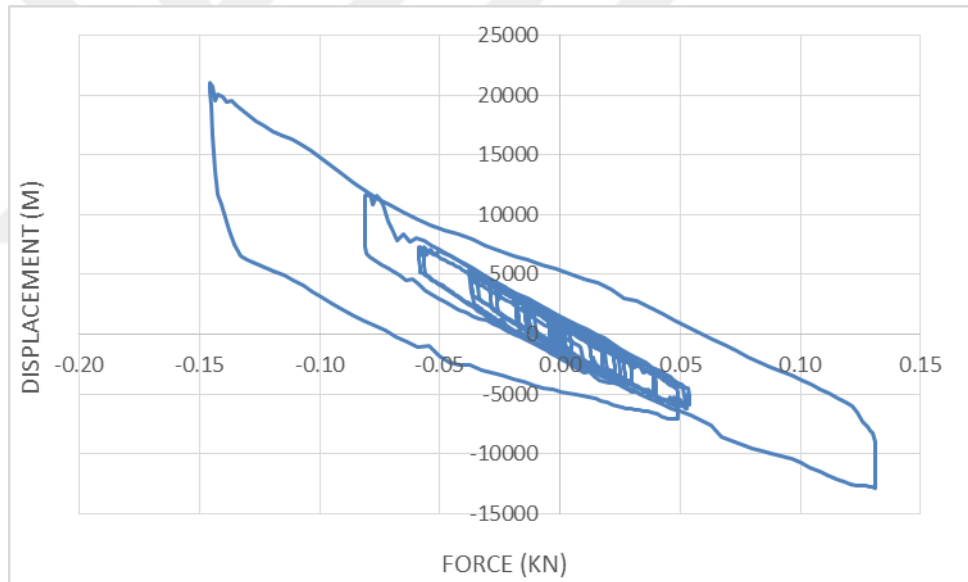


Figure 5. 36: Hysteresis loop of material C TFPB under RSN 1787

The analysis results of the remaining near- field earthquakes are presented in Appendix B.

5.4 Variation of Time History Story Displacement with Friction Coefficient under Far-Field Ground Motion Records

In The results of the study herein aim to investigate the impact of changing the friction coefficients on the performance of the buildings under far-field earthquakes for each material case. Figures 5.37 shows seismic records using the coefficient of friction of Material A. The results for Material B are shown in Figures 5.38, showing that the displacement of the bearings increases as the friction value decreases. In addition, Material C in Figures 5.39 shows that the displacement of the bearing decreases further as the coefficient of friction decreases.

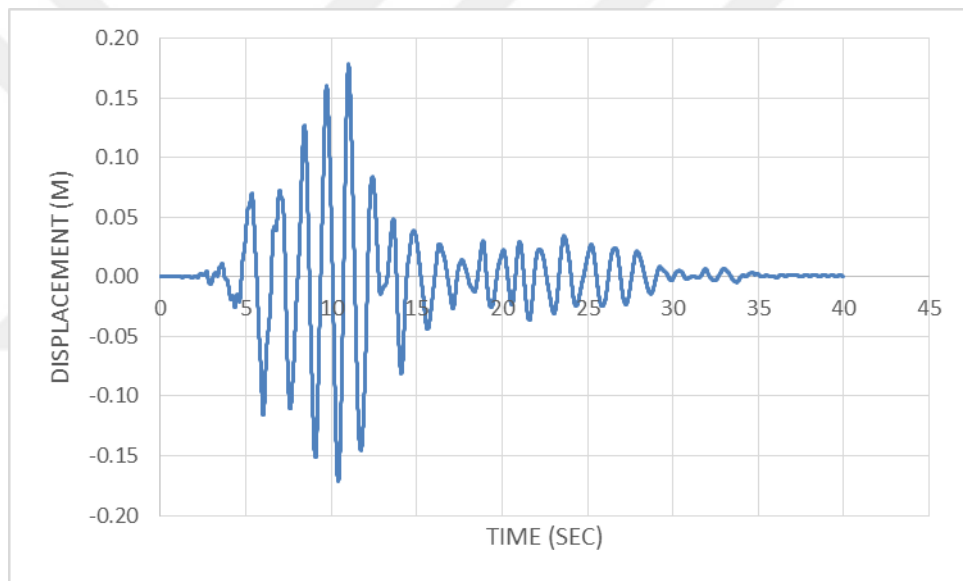


Figure 5. 37: Bearing displacement time history of material A TFPB under RSN 752

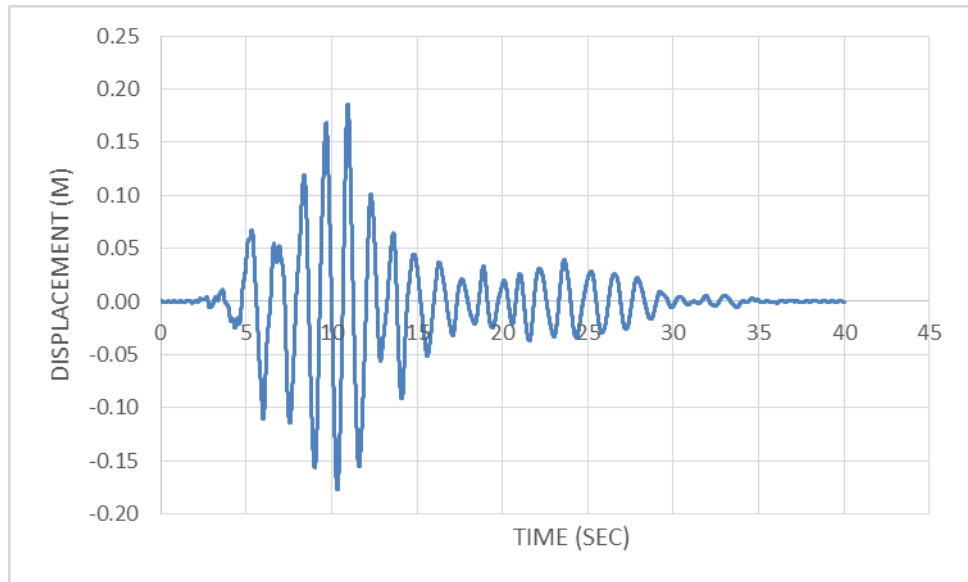


Figure 5. 38: Bearing displacement time history of material B TFPB under RSN 752

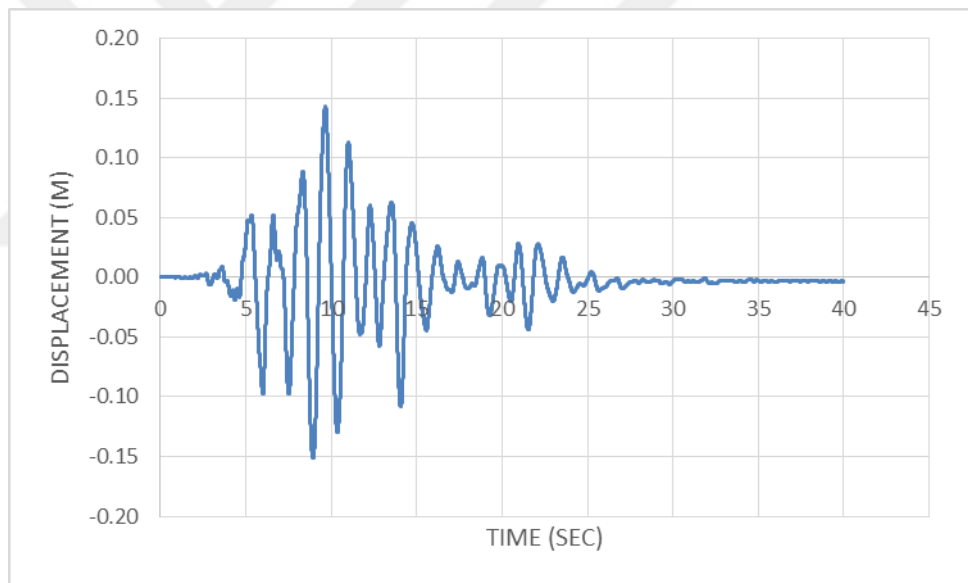


Figure 5. 39: Bearing displacement time history of material C TFPB under RSN 752

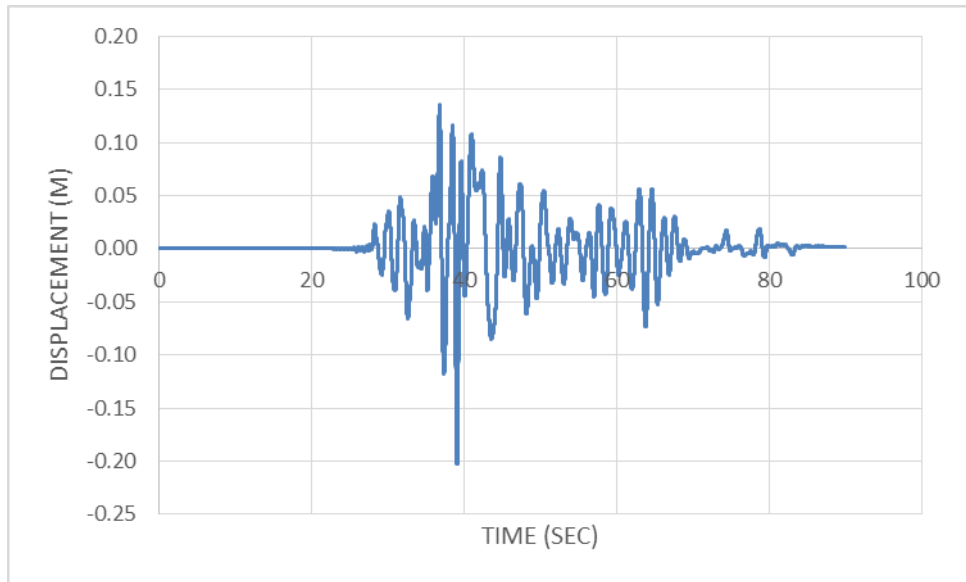


Figure 5. 40: Bearing displacement time history of material A TFPB under RSN 1244

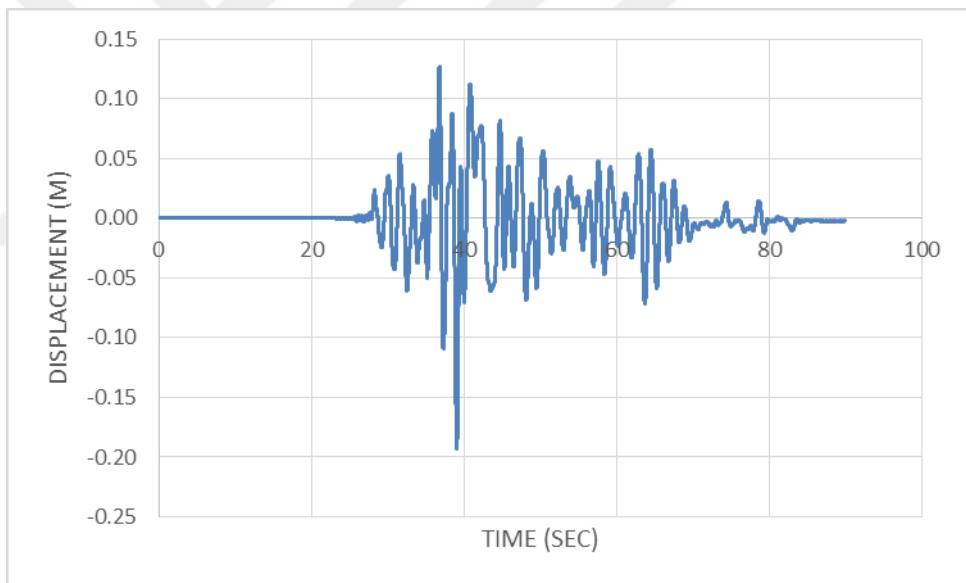


Figure 5. 41: Bearing displacement time history of material B TFPB under RSN 1244

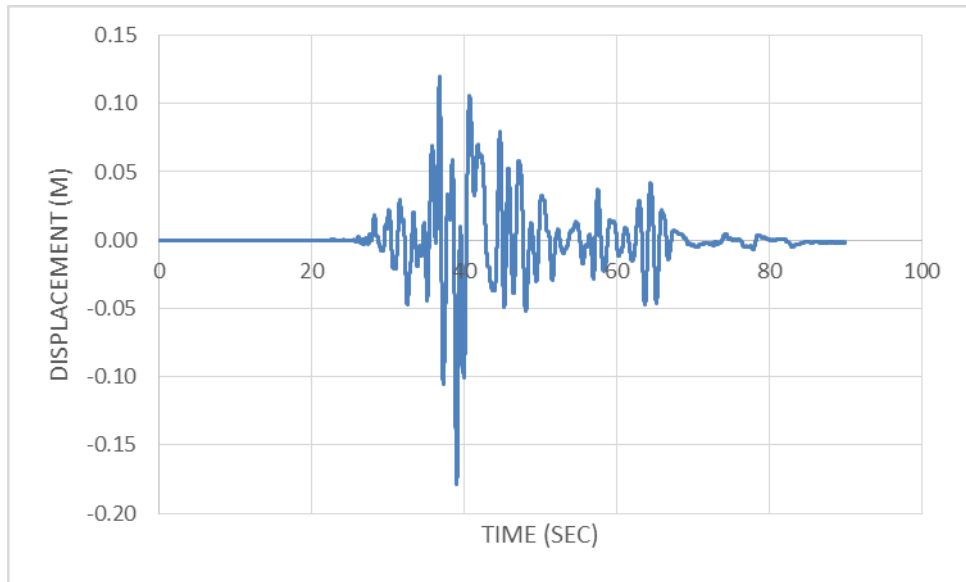


Figure 5. 42: Bearing displacement time history of material C TFPB under RSN 1244

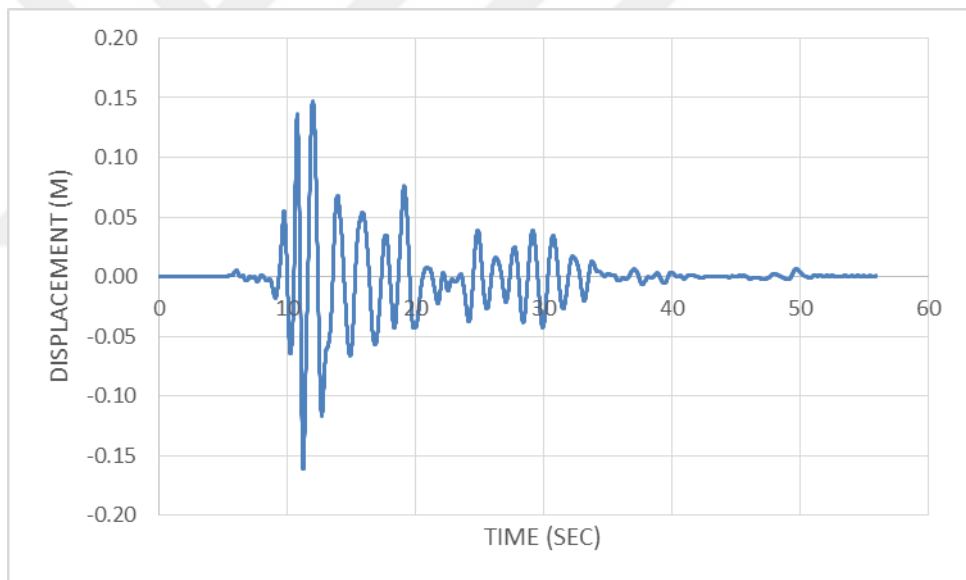


Figure 5. 43: Bearing displacement time history of material A TFPB under RSN 1602

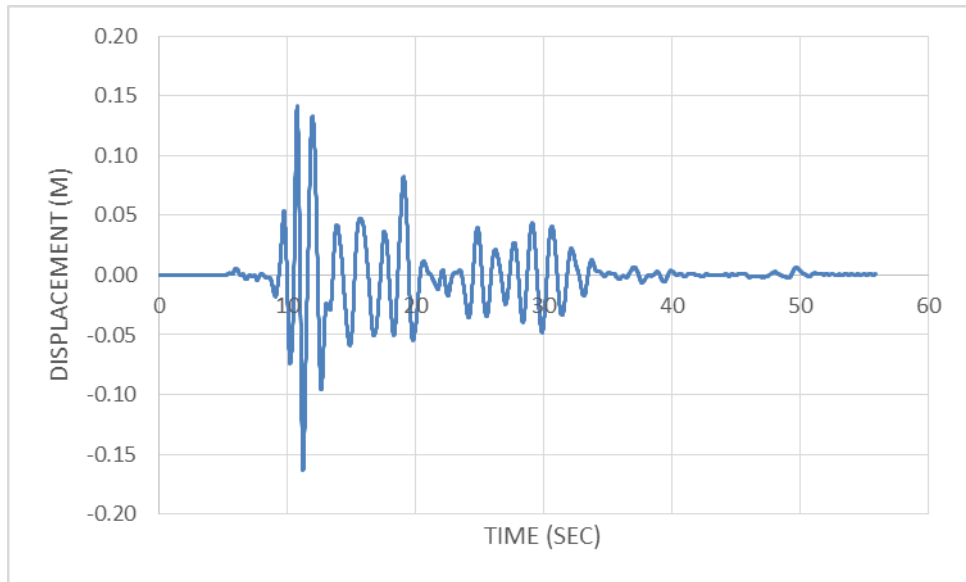


Figure 5. 44: Bearing displacement time history of material B TFPB under RSN 1602

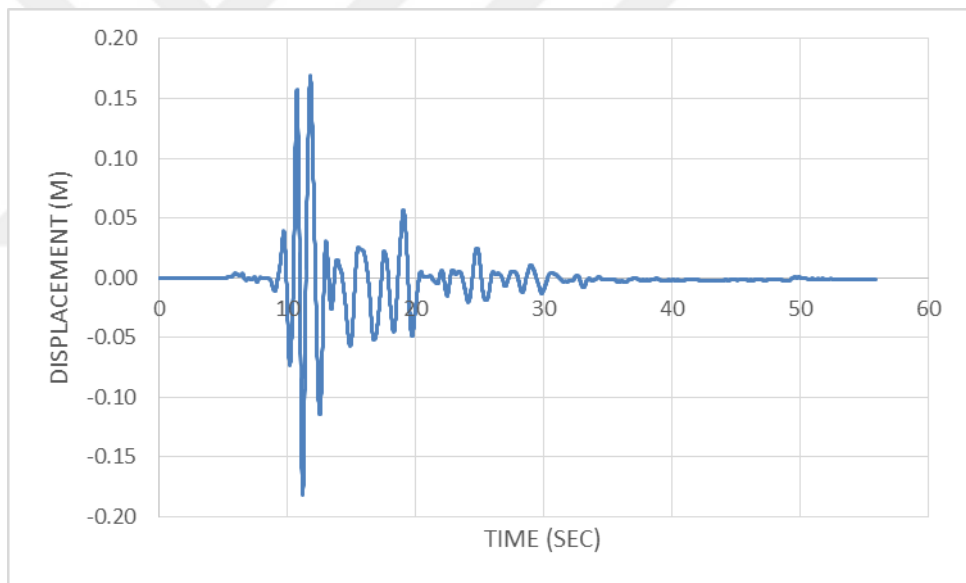


Figure 5. 45: Bearing displacement time history of material C TFPB under RSN 1602

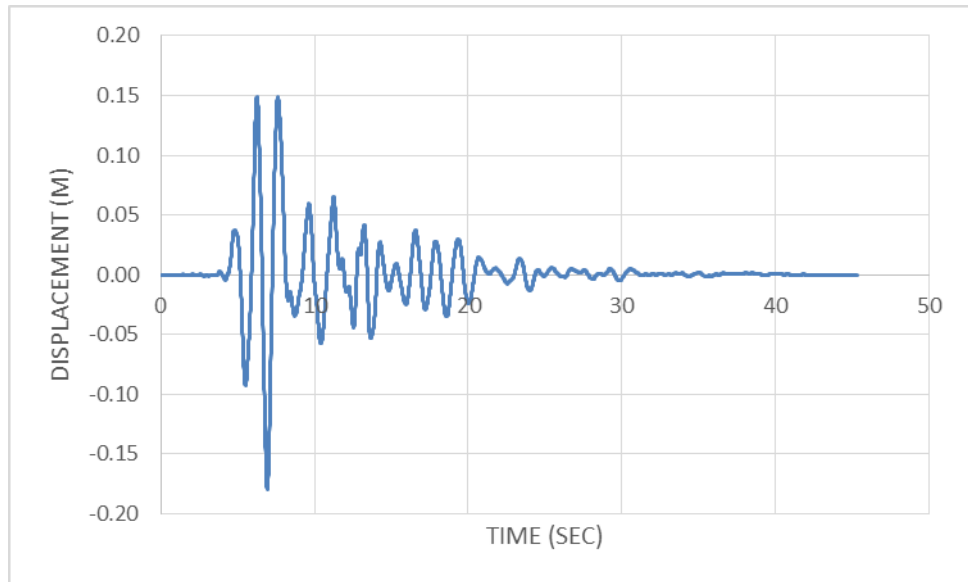


Figure 5. 46: Bearing displacement time history of material A TFPB under RSN 1787

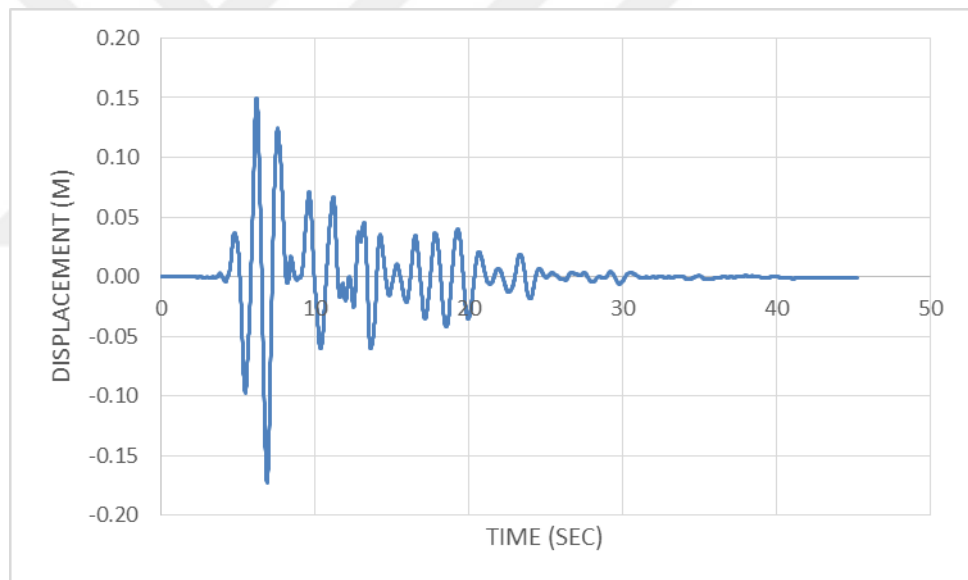


Figure 5. 47: Bearing displacement time history of material B TFPB under RSN 1787

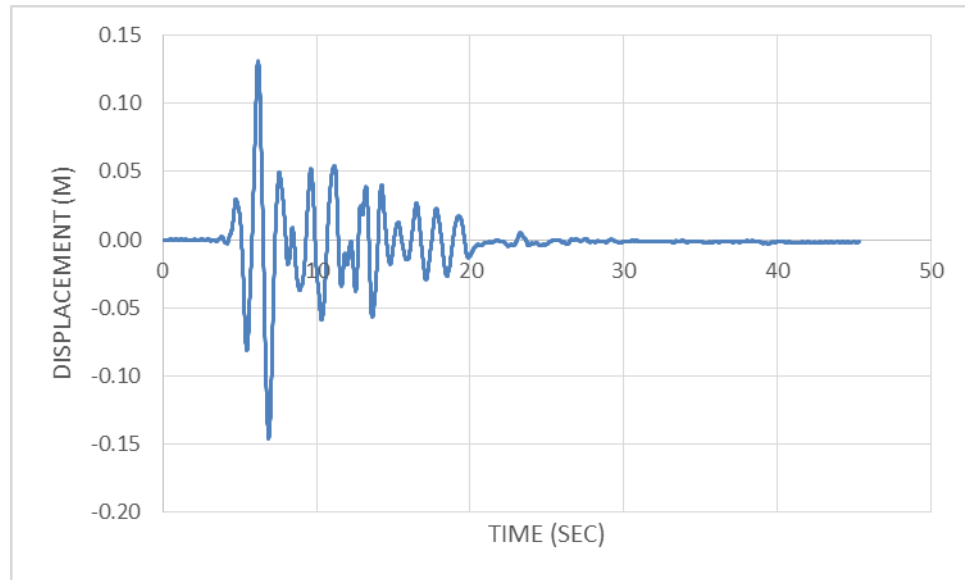


Figure 5. 48: Bearing displacement time history of material C TFPB under RSN 1787

The analysis results of the remaining near- field earthquakes are presented in Appendix B.

5.5 The Maximum and Average Bearing Displacement with Different Friction Coefficients under (Near and Far) Field Ground Motion Records

The maximum bearing displacements using the coefficient of friction of Material A, B and C are presented in Figure 5.49 for near-field records and Figure 5.50 for far-field records. These figures show that the displacement of the bearing decreases as the friction value increases. In addition, the variation of average bearing displacement under (near and far) field earthquakes with the friction coefficient of material A B and C in Figures 5.51 show that the displacement of the bearing further decreases with increasing coefficient of friction.

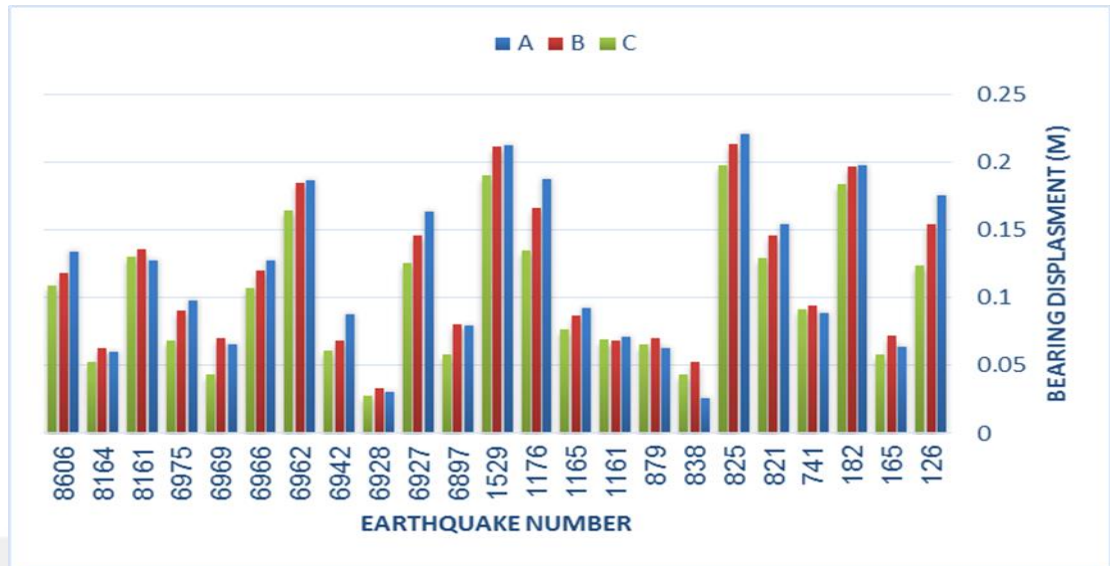


Figure 5. 49: Variation of maximum bearing displacement with materials A B and C for near-field earthquakes

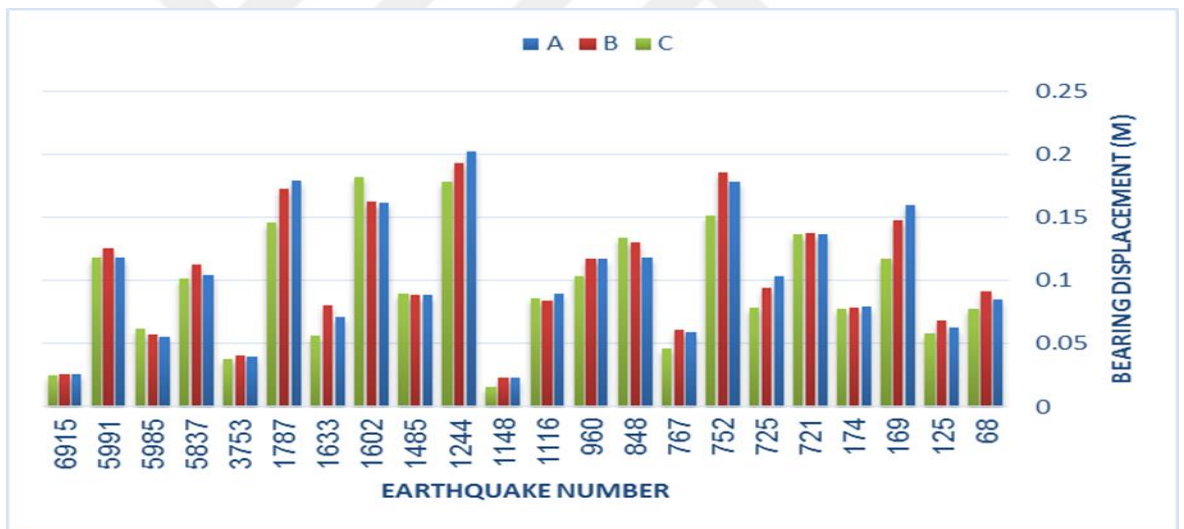


Figure 5. 50: Variation of maximum bearing displacement with materials A B and C for far-field earthquakes

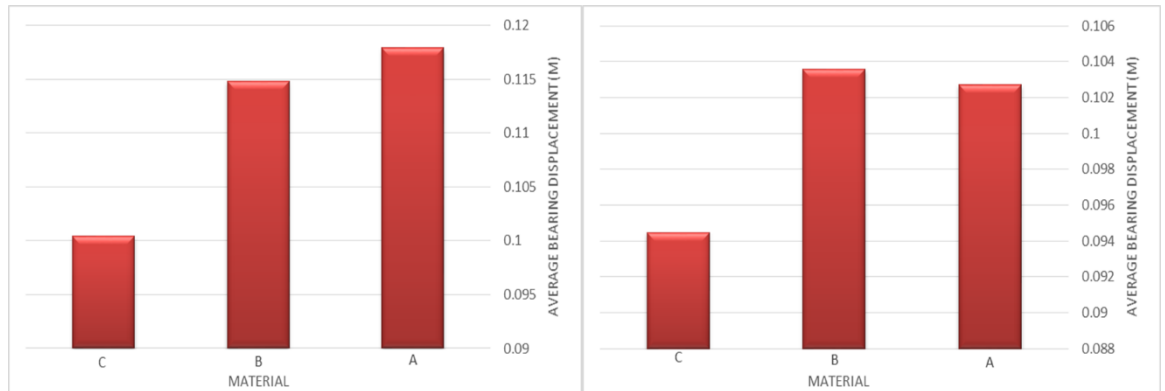


Figure 5. 51: Variation of average bearing displacement under (near and far) field earthquakes with Materials A B and C

5.6 The Drift Ratio with Different Friction Coefficients under (Near and Far) Field Ground Motion Records

Drift ratio is an important factor that is correlated to the damage to structural elements. The results of this section investigate the impact of changing the friction coefficients on the inter-story displacements. Figures 5.52 presents the drift ratios for the seismic (Near and Far) Field excitations using Materials A, B and C. The analyses indicate that drift ratios decrease as the friction value increases.

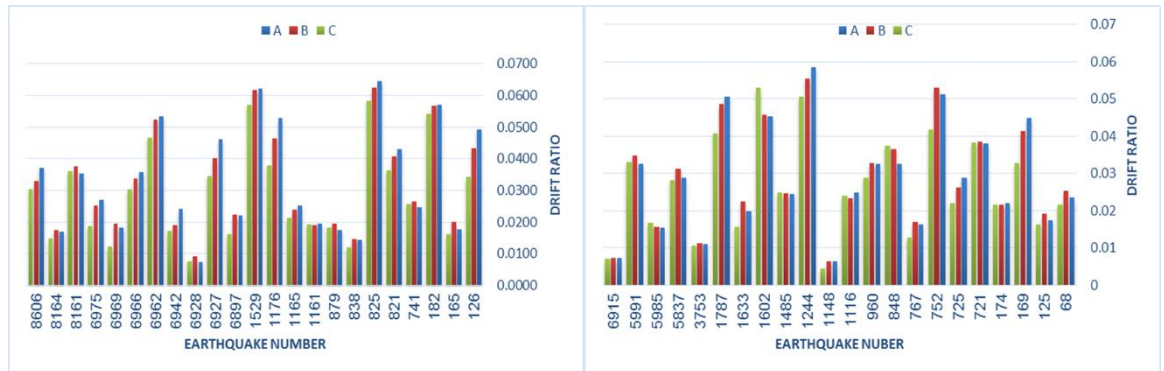


Figure 5. 52: Variation of drift ratio for (near and far) field earthquakes using materials A B and C

5.7 The Maximum and Average Floor Acceleration with Different Friction Coefficients under (Near and Far) Field Ground Motion Records

Floor acceleration is an important factor that correlates with the damage to non-structural elements. This section investigates the impact of sliding surface materials on floor accelerations. Figures 5.53 presents the analysis results for Near-Field whereas Figure 5.54 presents the results for Far-Field earthquakes. It is observed that story accelerations decrease as the friction increases under near field but the story acceleration increases as the friction value increases under far field excitations. In addition, the variation of average acceleration under (near and far) field earthquakes using materials A B and C is shown in Figures 5.55.

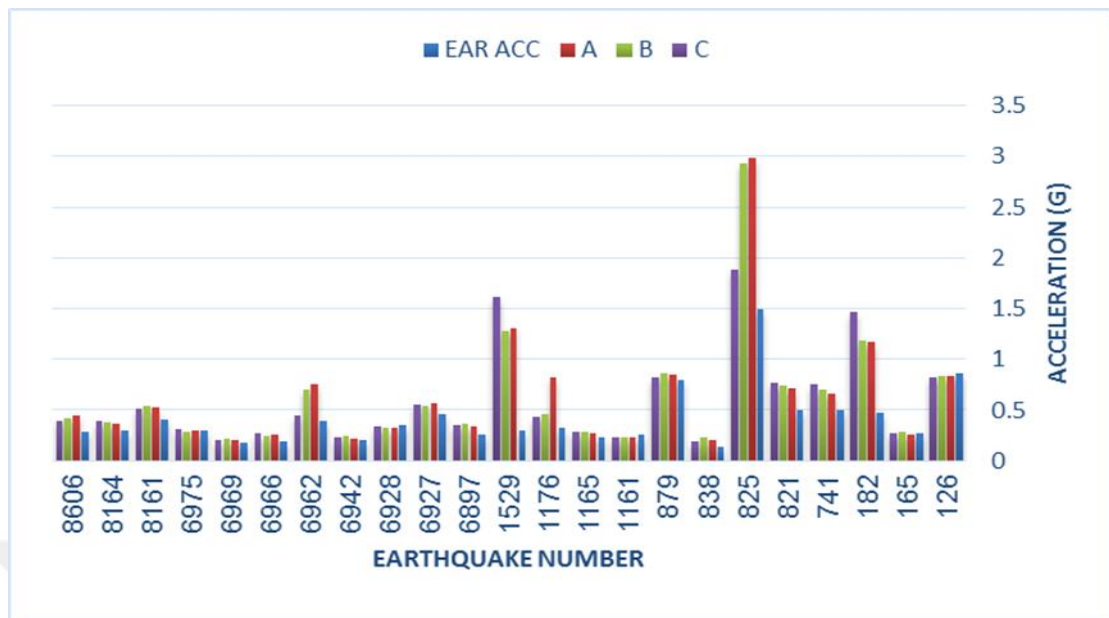


Figure 5. 53: Variation of maximum story acceleration for near field earthquakes with materials A B and C

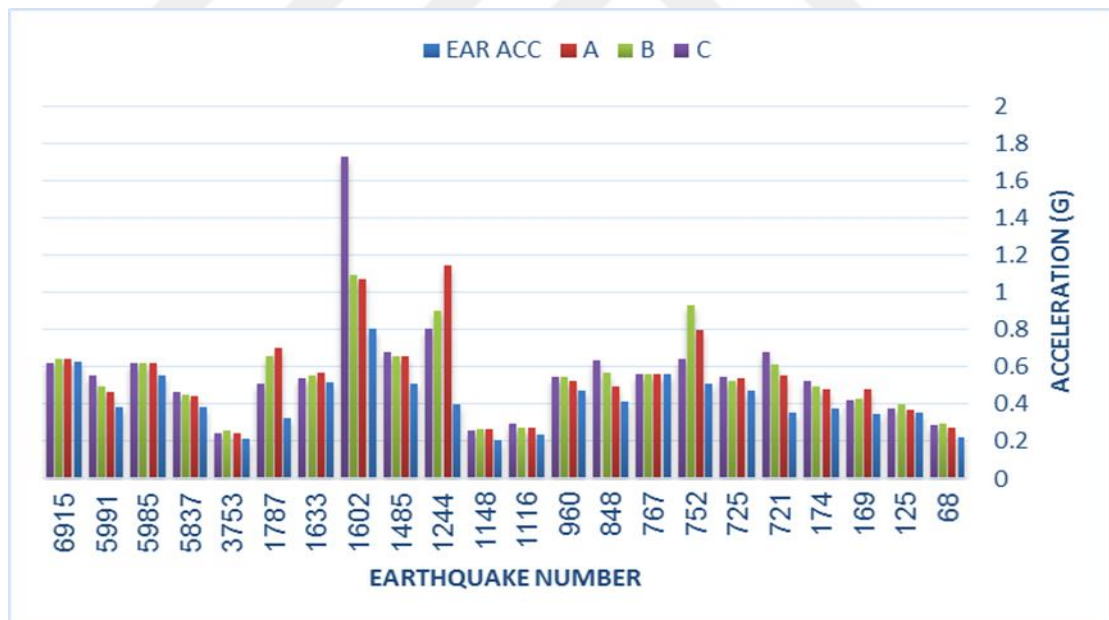


Figure 5. 54: Variation of maximum story acceleration for far field earthquakes with materials A B and C

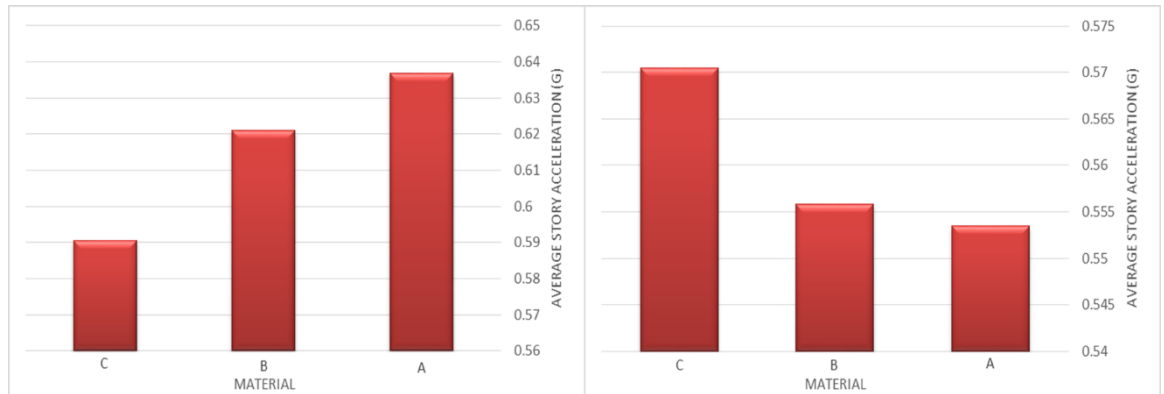
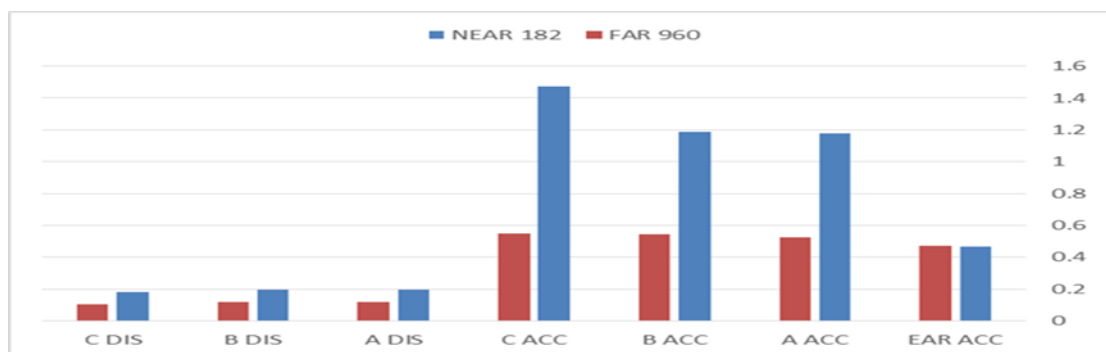


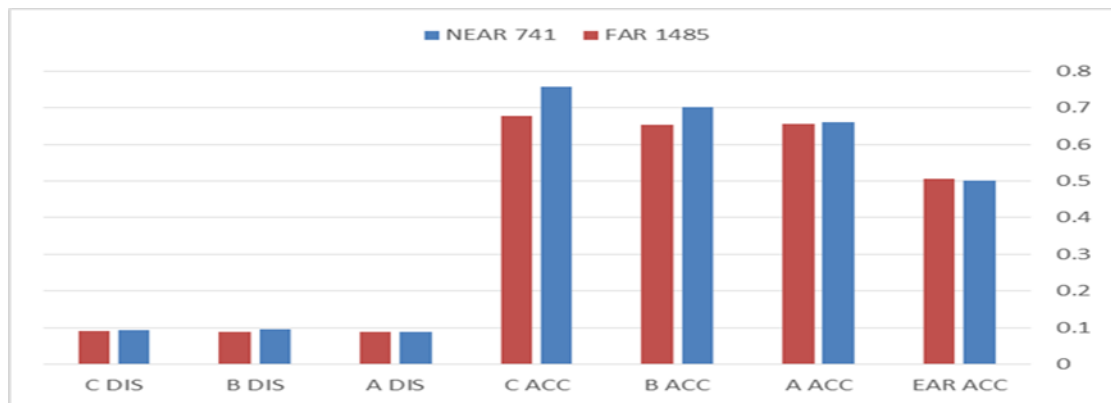
Figure 5. 55: Variation of average story acceleration under (near and far) field earthquakes with the materials A B and C

5.8 Comparing Near-field vs Far-field earthquake records have roughly the same Acceleration

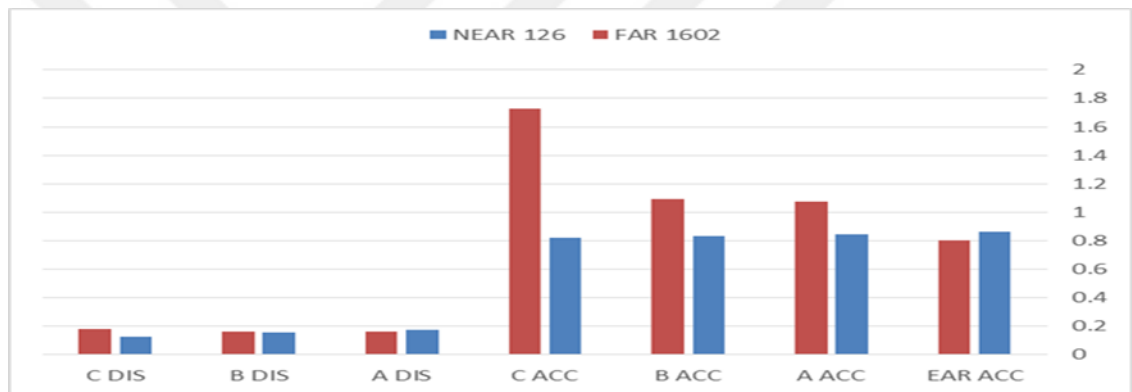
The Figures 5.56, 5.57 and 5.58 show the story acceleration and bearing displacement of (Near and Far) Field earthquake records that have approximately the same peak ground acceleration (PGA). These figures show that the story acceleration and bearing displacement values differ according to the type of earthquake excitations and friction coefficients of the material used in the isolators.



Figures 5 .56: Variation of average story acceleration and bearing displacement under (near 182 and far 960) field earthquakes with the friction coefficient of material A B and C that have roughly the same acceleration (revise)



Figures 5 .57: Variation of average story acceleration and bearing displacement under (near 741 and far 1485) field earthquakes with the friction coefficient of material A B and C that have roughly the same acceleration (revise)



Figures 5 .58: Variation of average story acceleration and bearing displacement under (near 126 and far 1602) field earthquakes with the friction coefficient of material A B and C that have roughly the same acceleration (revise)

CHAPTER 6

SUMMARY AND CONCLUSION

Summary and Conclusion.

In recent years, base isolation has been recognized by engineers as a successful strategy for the seismic retrofitting of structures. In this study, the influence of the friction properties of the sliding surface material of triple friction pendulum isolators on the performance of base-isolated structures subjected to near-field and far-field earthquakes was investigated through a parametric study. Based on the numerical simulations conducted in this study the following conclusions can be drawn:

- Seismic isolation is an effective strategy for reducing seismic actions on structures.
- The peak bearing displacement values vary with respect to the selected coefficient of friction and the type of earthquake applied.
- Increasing the value of the coefficient of friction in general decreases the maximum bearing displacement of isolated buildings.
- Increasing the value of the coefficient of friction is more effective at reducing the story acceleration of buildings subjected to near-field earthquake ground motions in comparison to far-field earthquake ground motions.

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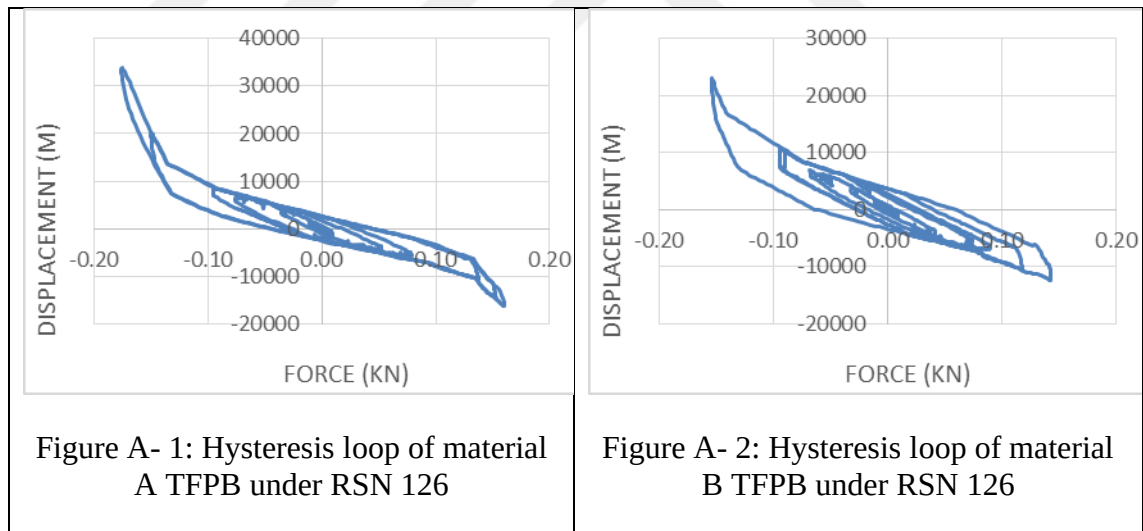
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APPENDIX A

Force–Displacement Hysteresis Curves under Near-Field Ground Motion Records:

The coefficient of friction is a critical parameter that influences force-displacement response of the bearings. The coefficient of friction of the surface is preserved as ($\mu_2 = \mu_3 < \mu_1 < \mu_4$) according to the common design strategy of TFPS bearings. Hysteresis loops of TFPS bearings can be utilized to calculate cycle-by-cycle energy dissipation and bearing damping. The results of the time history analysis for the investigated near-field earthquakes and the selected isolators are provided in Figures A- 1 to A- 57. Most motion records show displacements of less than 300 mm, and initiate motion only on the inner slip surface. Figure A- 1 shows the seismic record using the coefficient of friction of Material A. The results for Material B are shown in Figure A- 2. These indicate that generally the average base shear increases as the friction value increases.



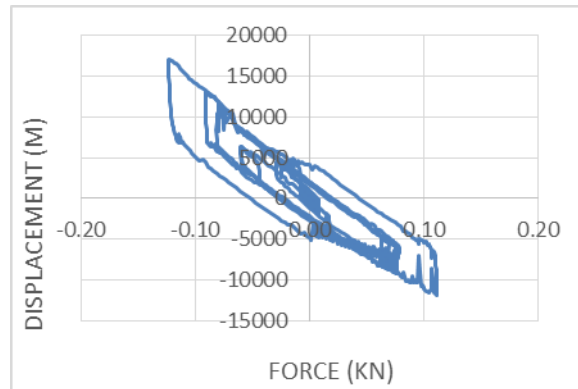


Figure A- 1: Hysteresis loop of material C TFPB under RSN 126

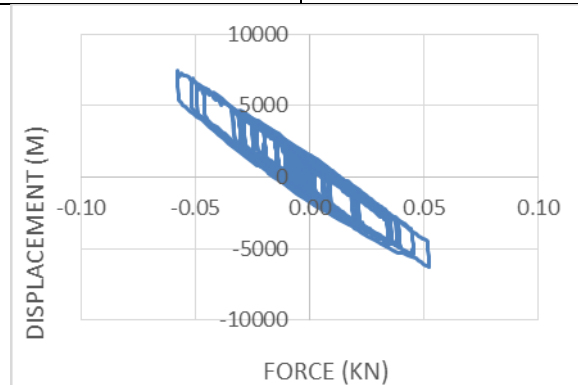
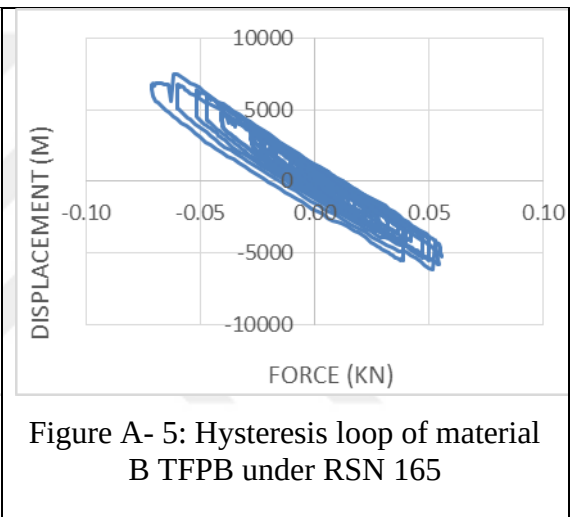
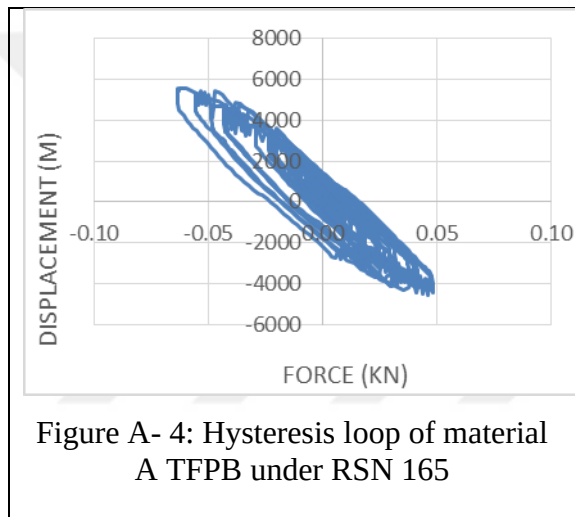


Figure A- 2: Hysteresis loop of material C TFPB under RSN 165

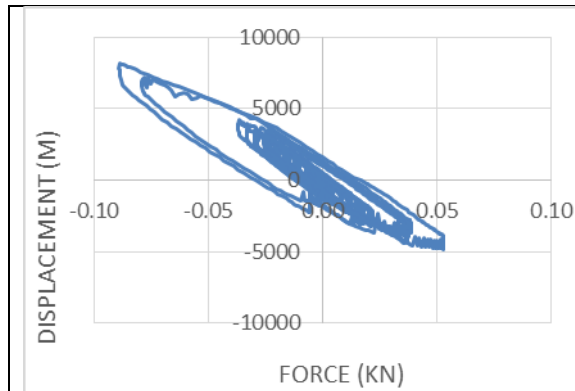


Figure A- 7: Hysteresis loop of material A TFPB under RSN 741

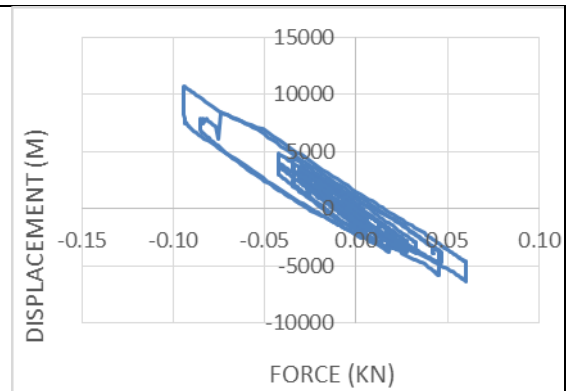


Figure A- 8: Hysteresis loop of material B TFPB under RSN 741

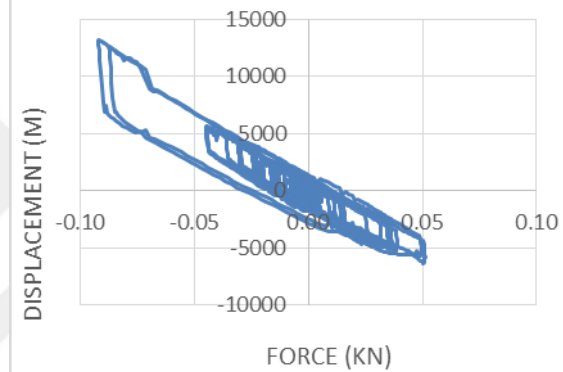


Figure A- 3: Hysteresis loop of material C TFPB under RSN 741

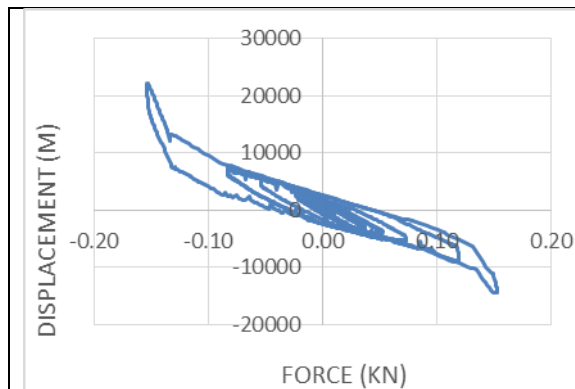


Figure A- 10: Hysteresis loop of material A TFPB under RSN 821

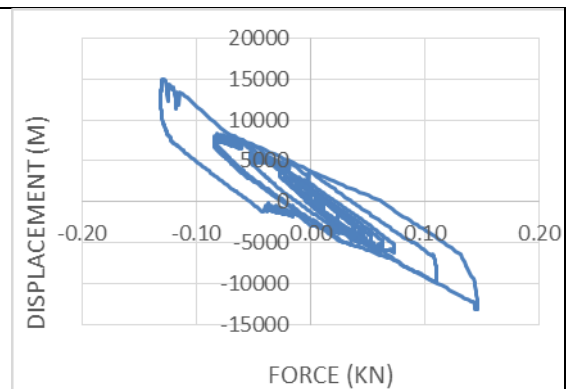


Figure A- 11: Hysteresis loop of material B TFPB under RSN 821

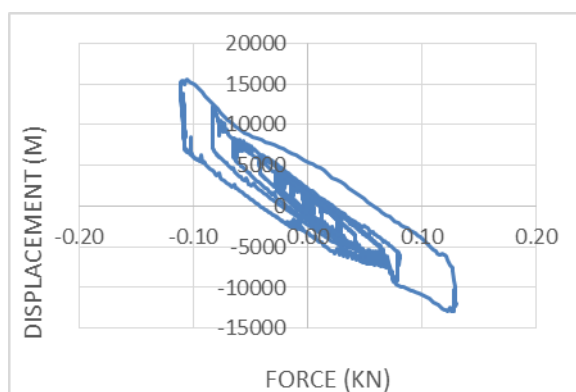


Figure A- 4: Hysteresis loop of material C TFPB under RSN 821

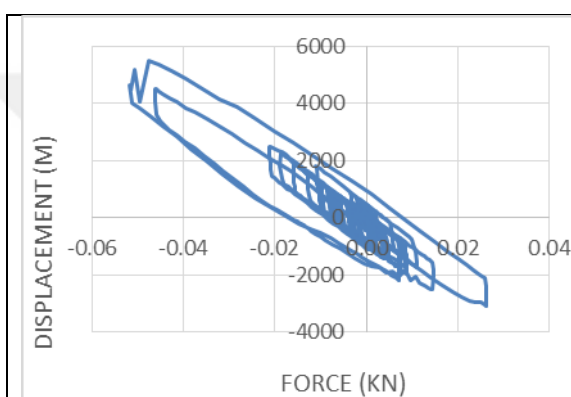


Figure A- 13: Hysteresis loop of material A TFPB under RSN 838

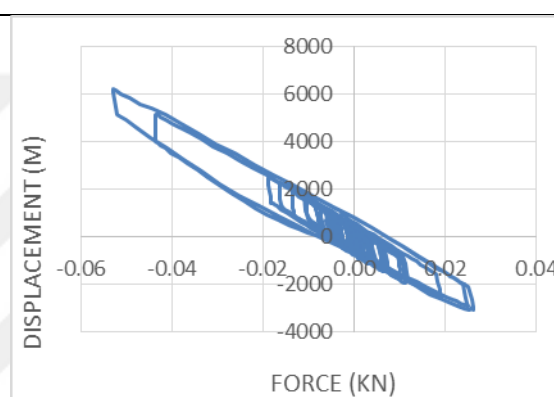


Figure A- 14: Hysteresis loop of material B TFPB under RSN 838

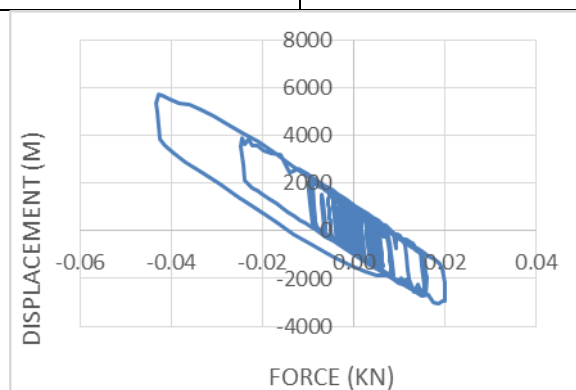


Figure A- 5: Hysteresis loop of material C TFPB under RSN 838

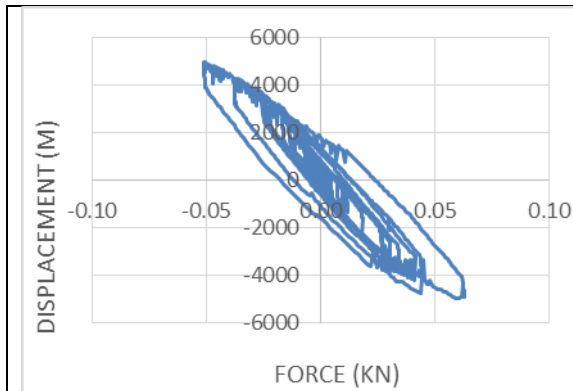


Figure A- 16: Hysteresis loop of material A TFPB under RSN 879

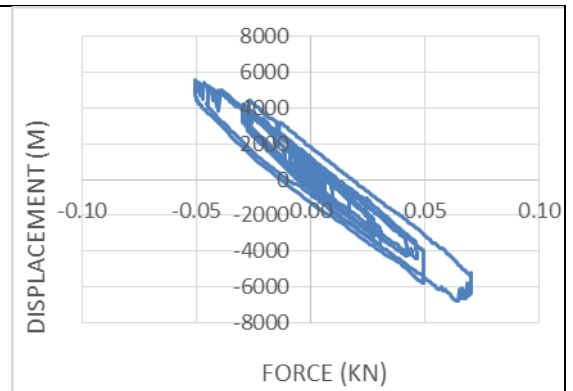


Figure A- 17: Hysteresis loop of material B TFPB under RSN 879

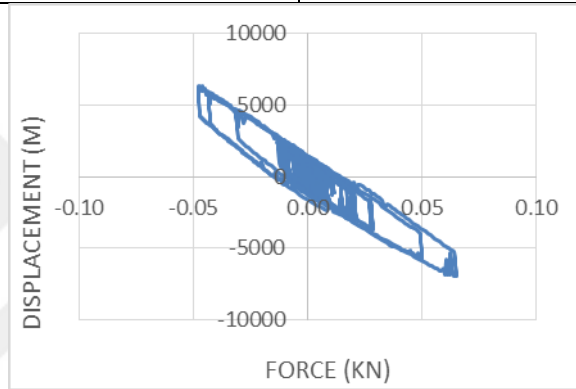


Figure A- 6: Hysteresis loop of material C TFPB under RSN 879

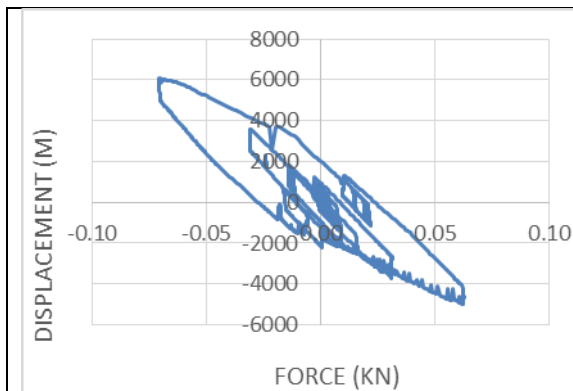


Figure A- 19: Hysteresis loop of material A TFPB under RSN 1161

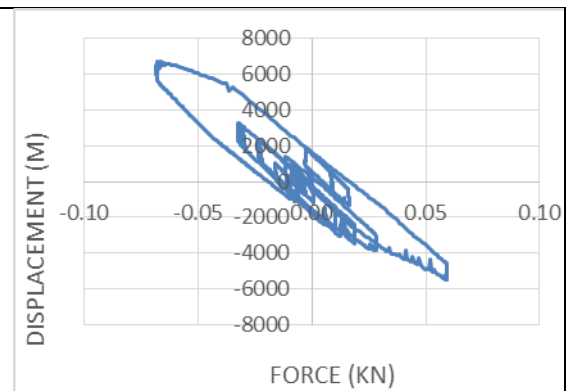


Figure A- 20: Hysteresis loop of material B TFPB under RSN 1161

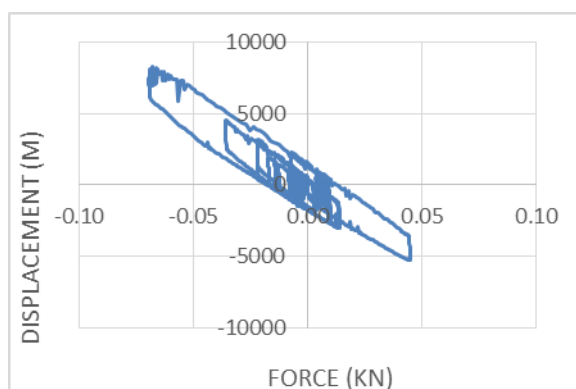


Figure A- 7: Hysteresis loop of material C TFPB under RSN 1161

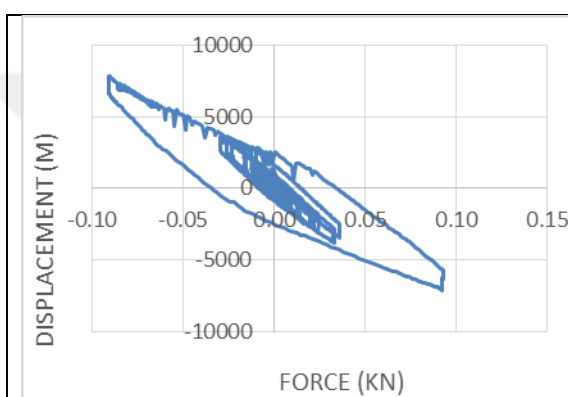


Figure A- 22: Hysteresis loop of material A TFPB under RSN 1165

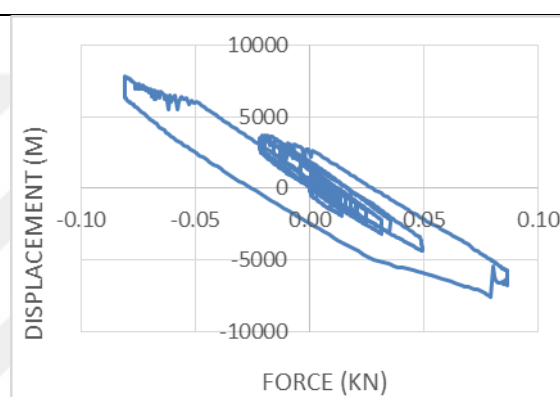


Figure A- 23: Hysteresis loop of material B TFPB under RSN 1165

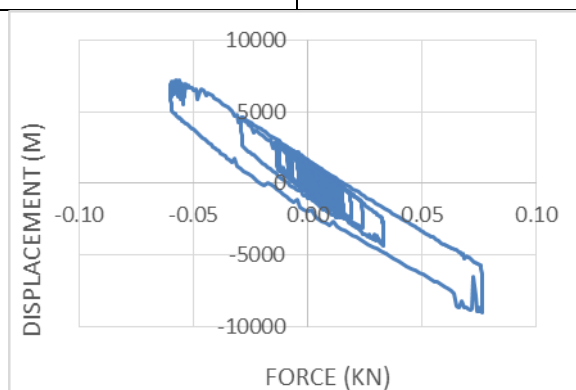


Figure A- 8: Hysteresis loop of material C TFPB under RSN 1165

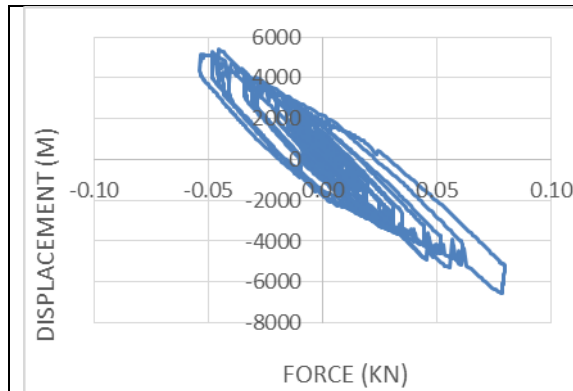


Figure A- 25: Hysteresis loop of material A TFPB under RSN 6897

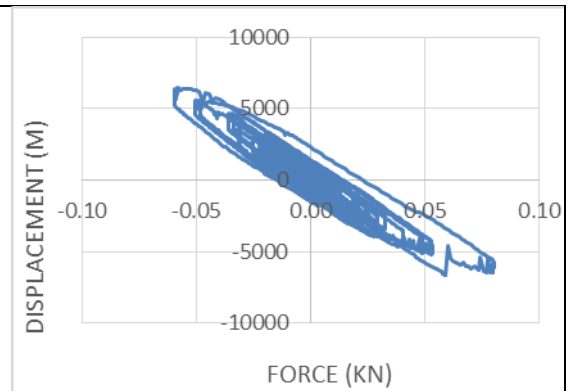


Figure A- 26: Hysteresis loop of material B TFPB under RSN 6897

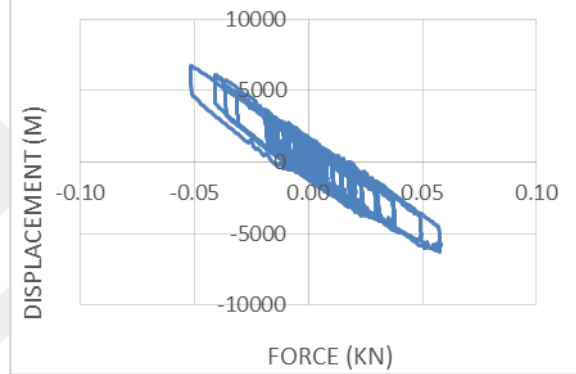


Figure A- 27: Hysteresis loop of material C TFPB under RSN 6897

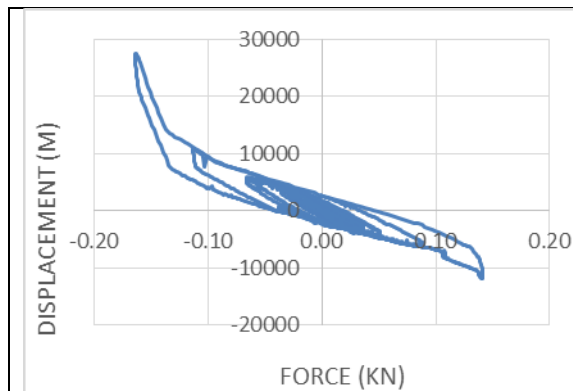


Figure A- 28: Hysteresis loop of material A TFPB under RSN 6927

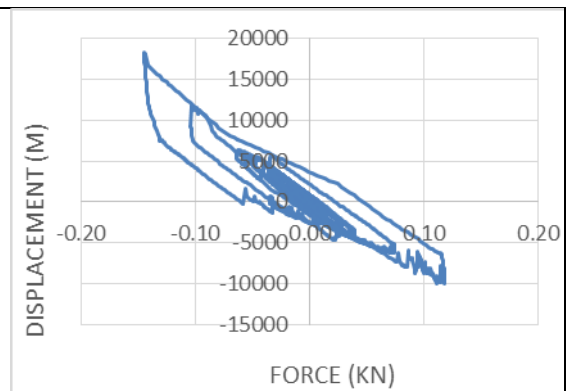


Figure A- 29: Hysteresis loop of material B TFPB under RSN 6927

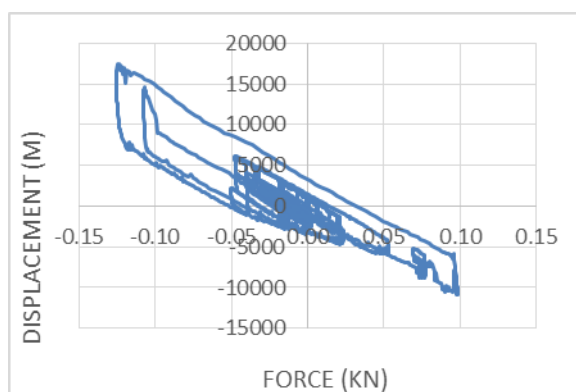


Figure A- 30: Hysteresis loop of material C TFPB under RSN 6927

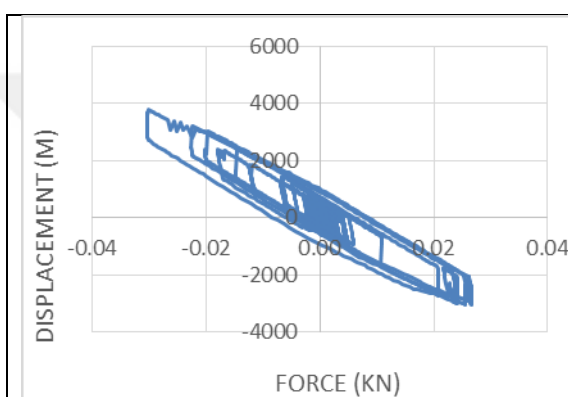


Figure A- 31: Hysteresis loop of material A TFPB under RSN 6928

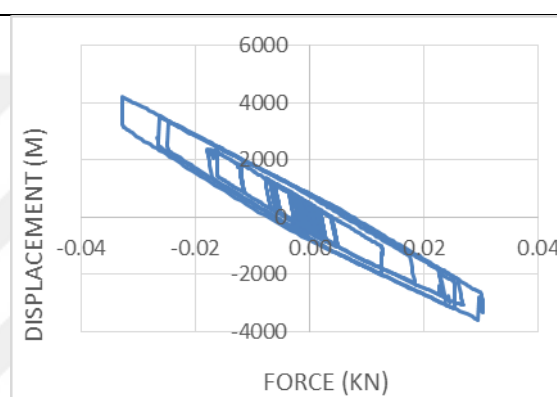


Figure A- 32: Hysteresis loop of material B TFPB under RSN 6928

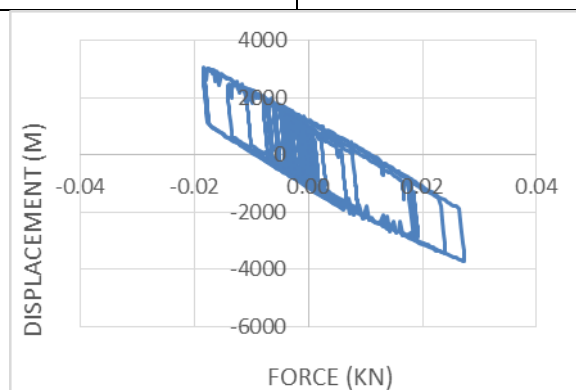


Figure A- 93: Hysteresis loop of material C TFPB under RSN 6928

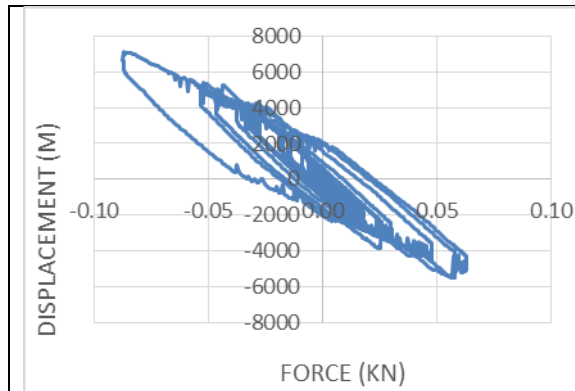


Figure A- 34: Hysteresis loop of material A TFPB under RSN 6942

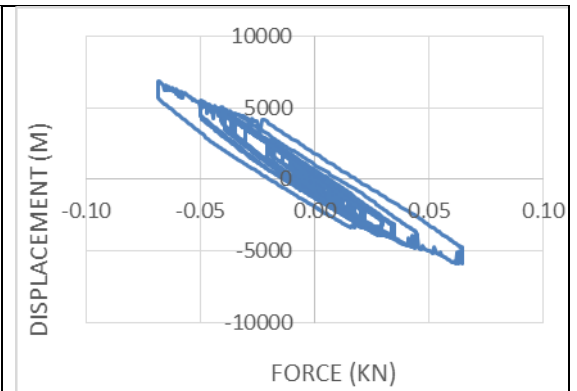


Figure A- 35: Hysteresis loop of material B TFPB under RSN 6942

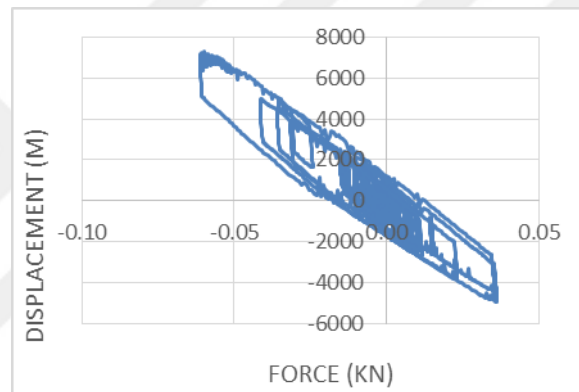


Figure A- 106: Hysteresis loop of material C TFPB under RSN 6942

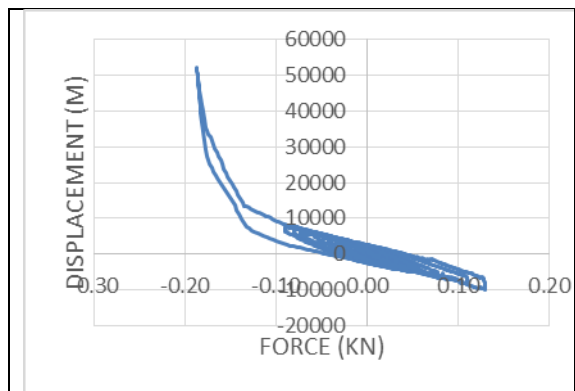


Figure A- 37: Hysteresis loop of material A TFPB under RSN 6962

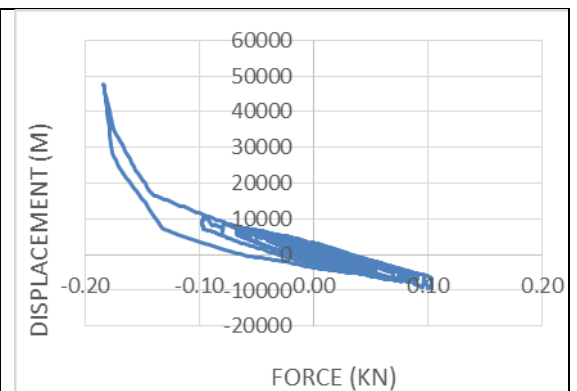


Figure A- 38: Hysteresis loop of material B TFPB under RSN 6962

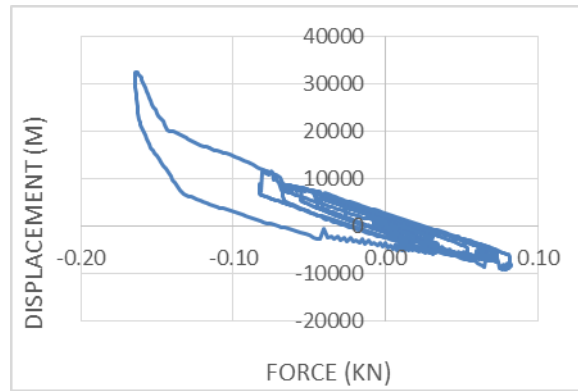


Figure A- 39: Hysteresis loop of material C TFPB under RSN 6962

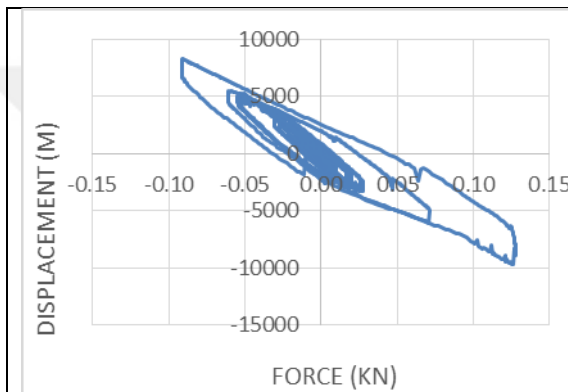


Figure A- 40: Hysteresis loop of material A TFPB under RSN 6966

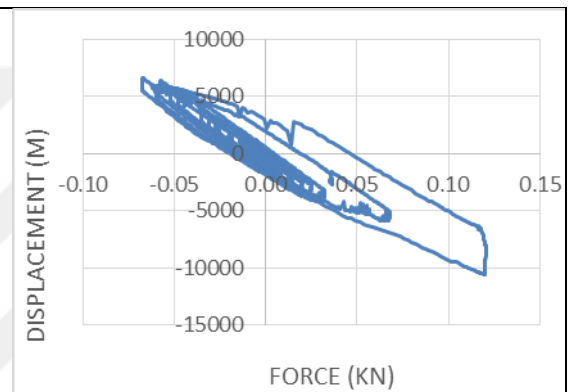


Figure A- 41: Hysteresis loop of material B TFPB under RSN 6966

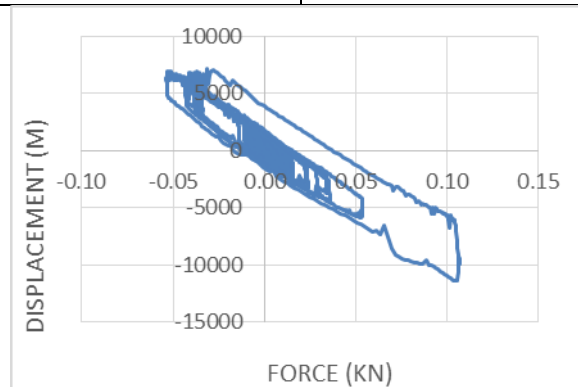


Figure A- 42: Hysteresis loop of material C TFPB under RSN 6966

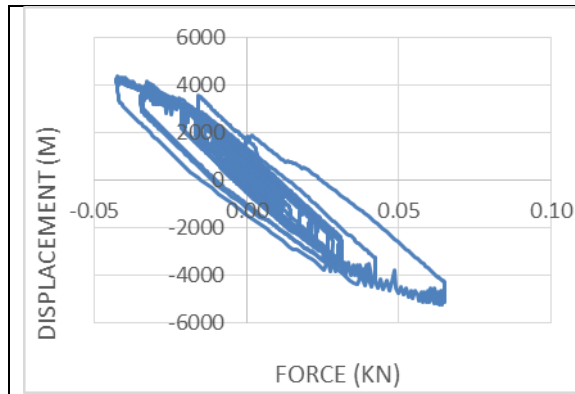


Figure A- 43: Hysteresis loop of material A TFPB under RSN 6969

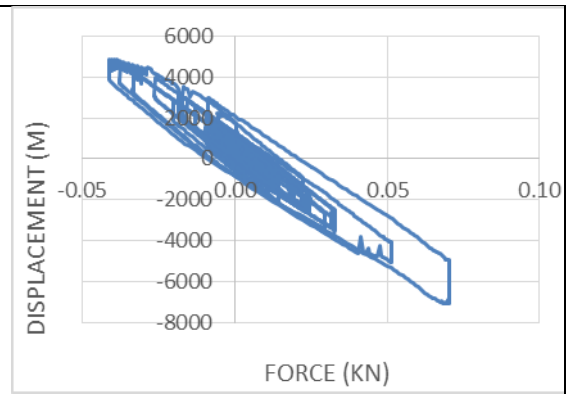


Figure A- 44: Hysteresis loop of material B TFPB under RSN 6969

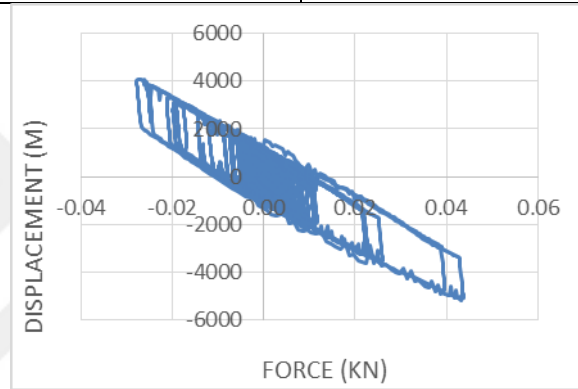


Figure A- 45: Hysteresis loop of material C TFPB under RSN 6969

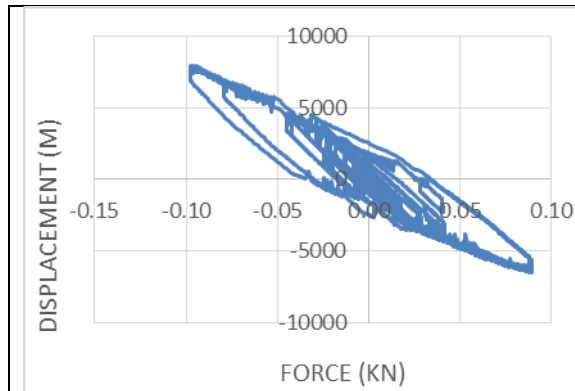


Figure A- 46: Hysteresis loop of material A TFPB under RSN 6975

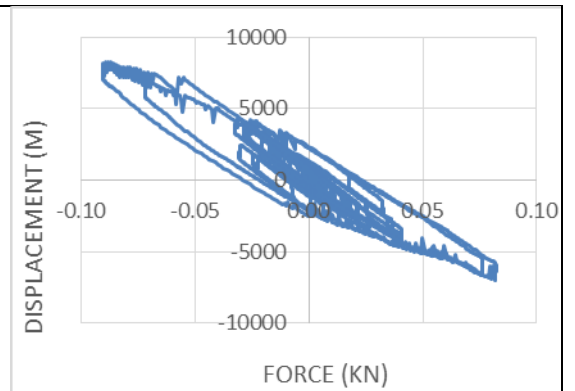


Figure A- 47: Hysteresis loop of material B TFPB under RSN 6975

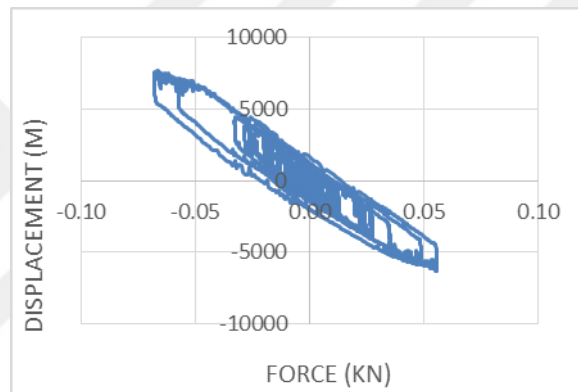


Figure A- 118: Hysteresis loop of material C TFPB under RSN 6975

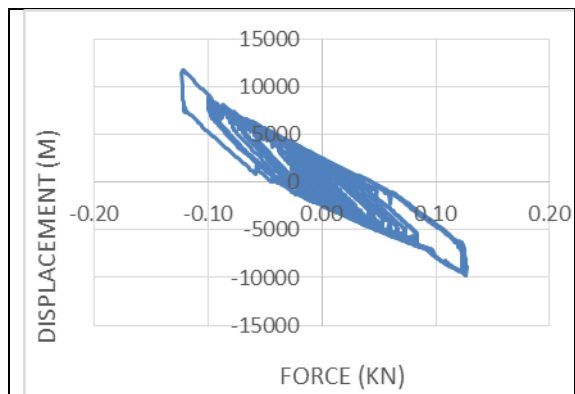


Figure A- 49: Hysteresis loop of material A TFPB under RSN 8161

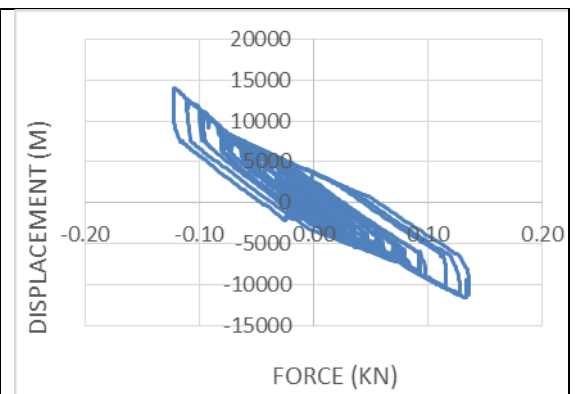


Figure A- 50: Hysteresis loop of material B TFPB under RSN 8161

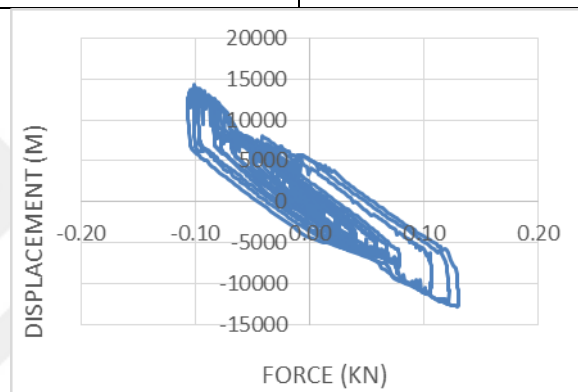


Figure A- 51: Hysteresis loop of material C TFPB under RSN 8161

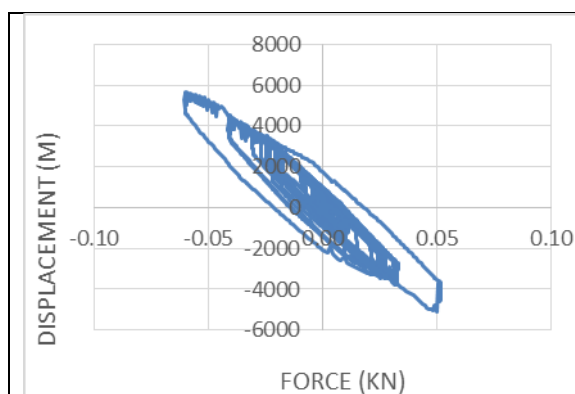


Figure A- 52: Hysteresis loop of material A TFPB under RSN 8164

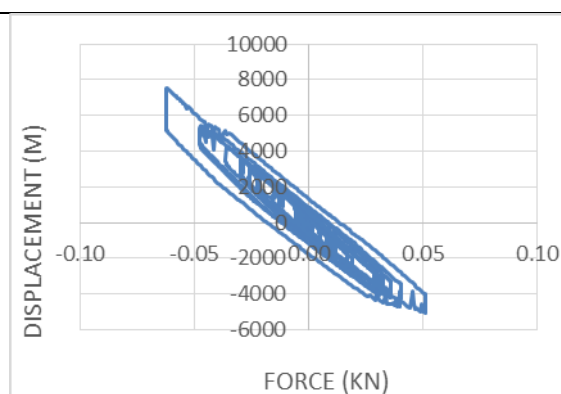


Figure A- 53: Hysteresis loop of material B TFPB under RSN 8164

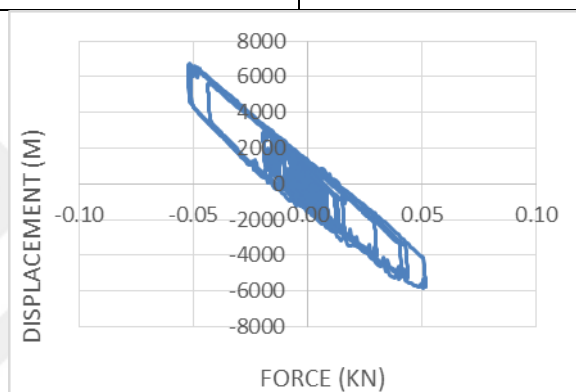


Figure A- 54: Hysteresis loop of material C TFPB under RSN 8164

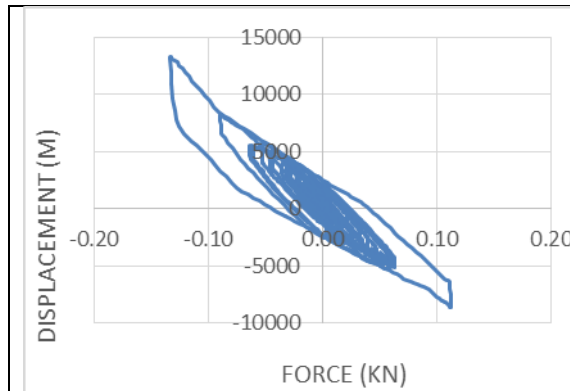


Figure A- 55: Hysteresis loop of material A TFPB under RSN 8606

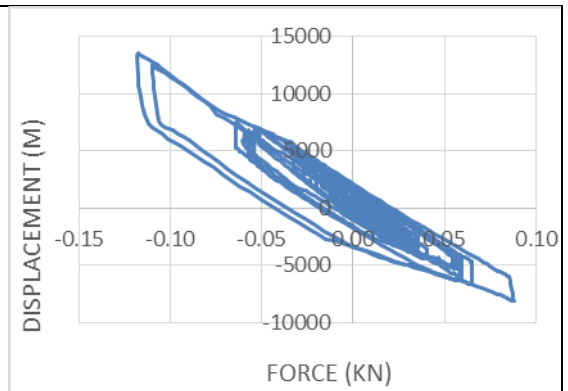


Figure A- 56: Hysteresis loop of material B TFPB under RSN 8606

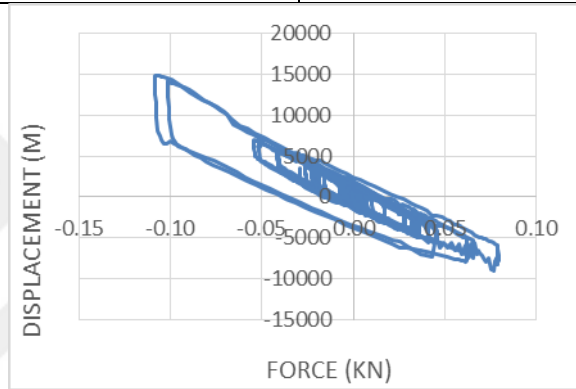


Figure A- 127: Hysteresis loop of material C TFPB under RSN 8606

Variation of Time History Story Displacement with Friction Coefficient under Near-Field Ground Motion Records:

The results of the study herein aim to investigate the impact of changing the friction coefficients on the bearing displacements of the building in each material case. Figures A- 58 shows seismic records using the coefficient of friction of Material A. The results for Material B are shown in Figures A- 59, showing that the displacement of the bearing increases as the friction value decreases. In addition, Material C in Figures A- 60 shows that the displacement of the bearing decreases further as the coefficient of friction decreases.

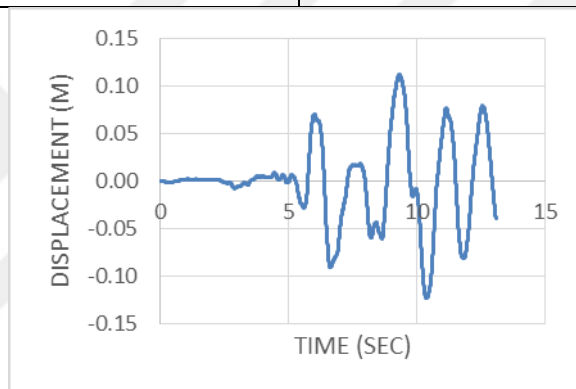
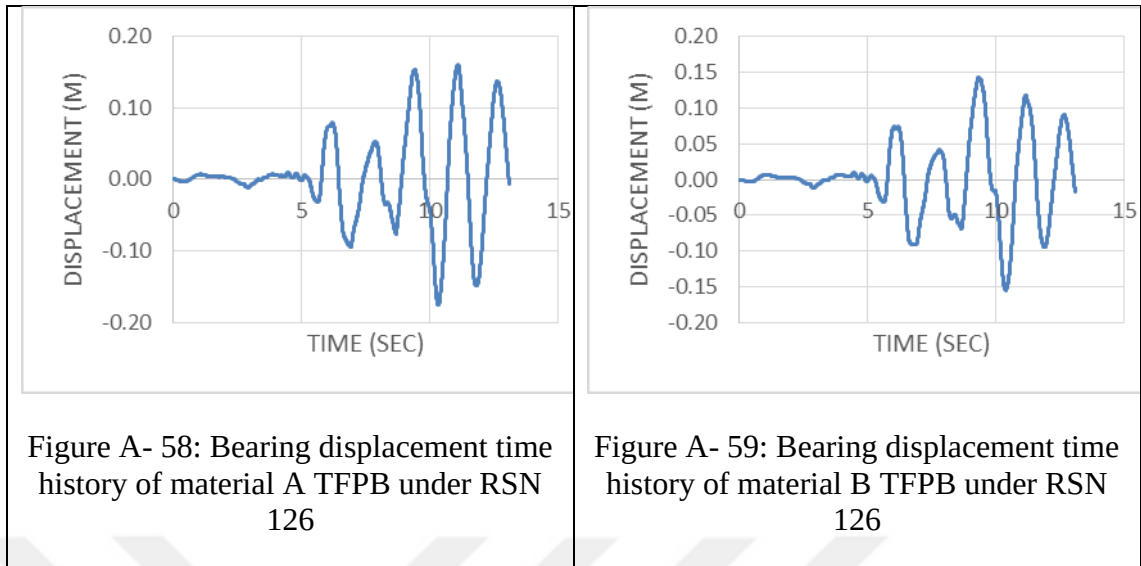
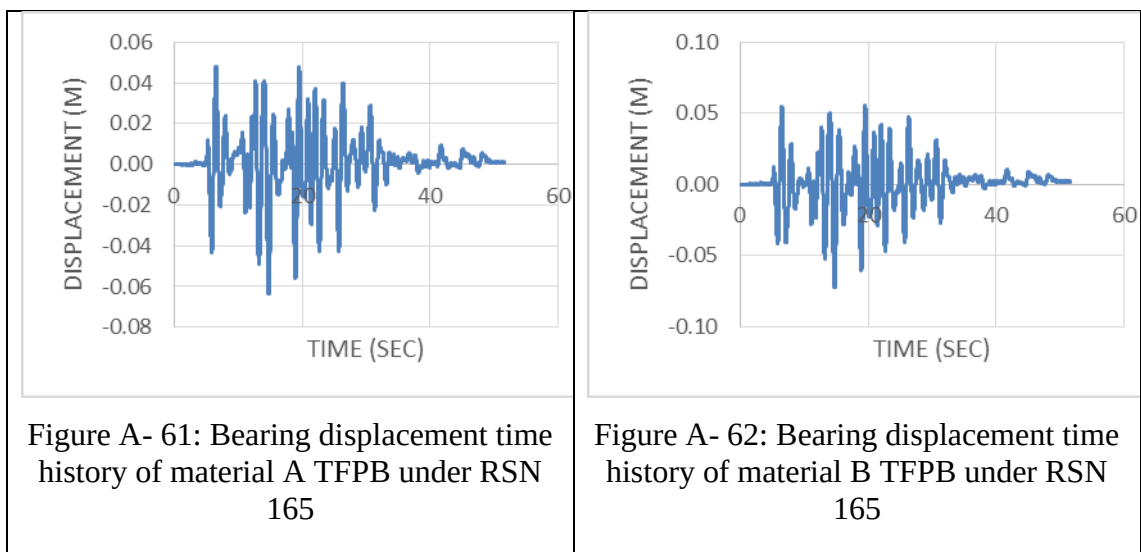


Figure A- 60: Bearing displacement time history of material C TFPB under RSN 126



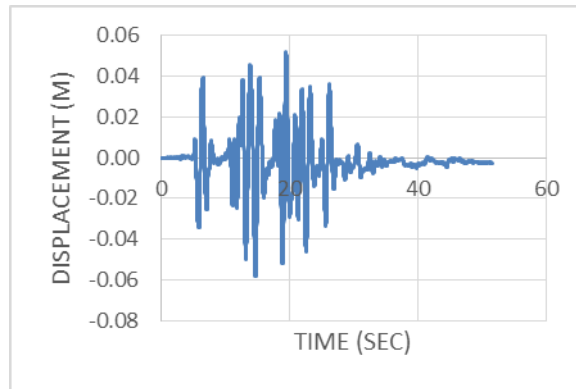


Figure A- 63: Bearing displacement time history of material C TFPB under RSN 165

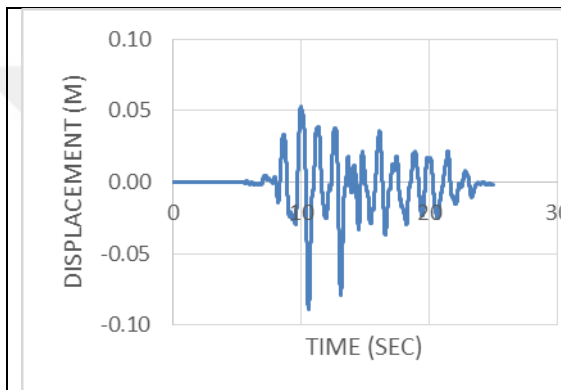


Figure A- 64: Bearing displacement time history of material A TFPB under RSN 741

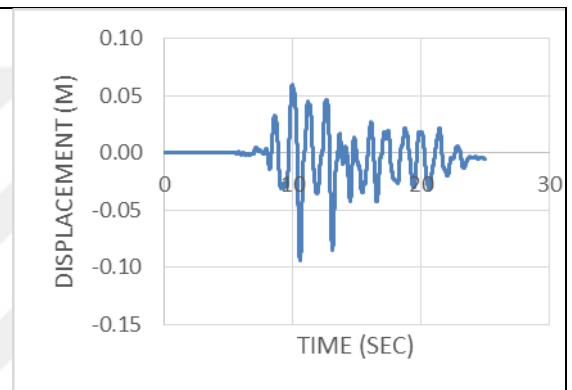


Figure A- 65: Bearing displacement time history of material B TFPB under RSN 741

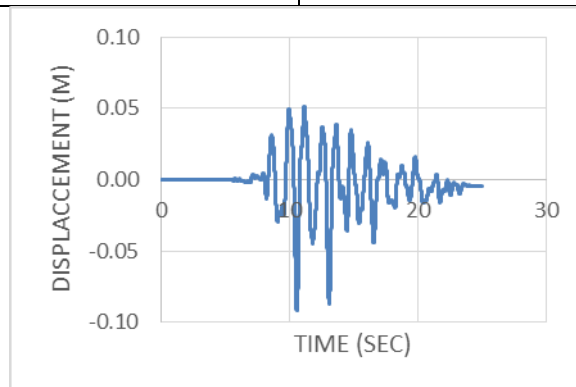


Figure A- 136: Bearing displacement time history of material C TFPB under RSN 741

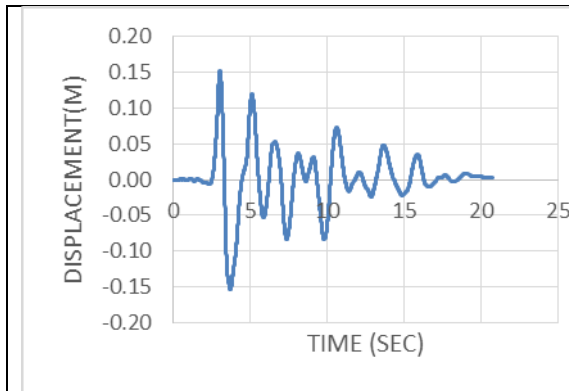


Figure A- 67: Bearing displacement time history of material A TFPB under RSN 821

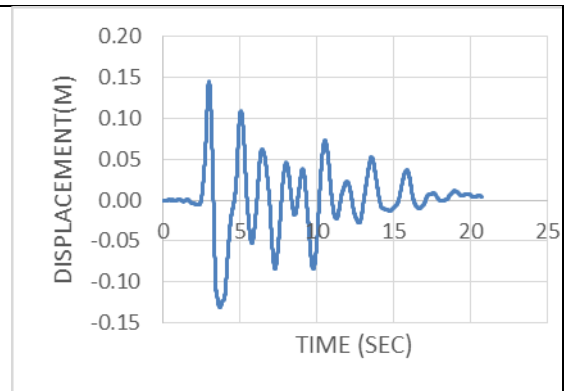


Figure A- 68: Bearing displacement time history of material B TFPB under RSN 821

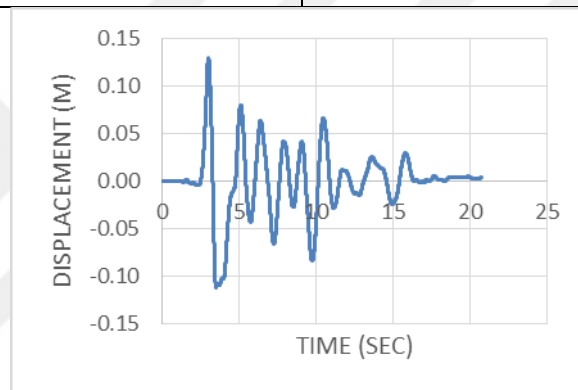


Figure A- 69: Bearing displacement time history of material C TFPB under RSN 821

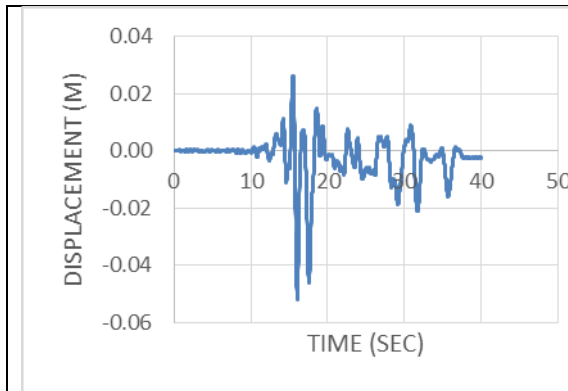


Figure A- 70: Bearing displacement time history of material A TFPB under RSN 838

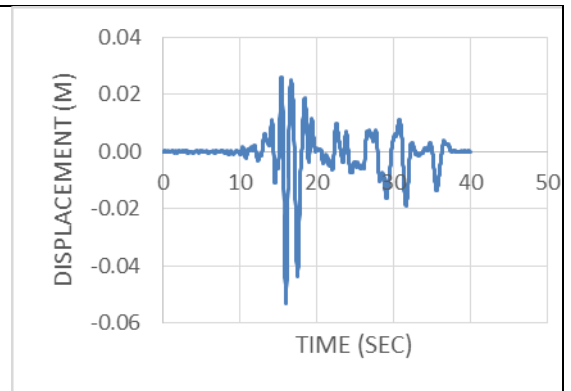


Figure A- 71: Bearing displacement time history of material B TFPB under RSN 838

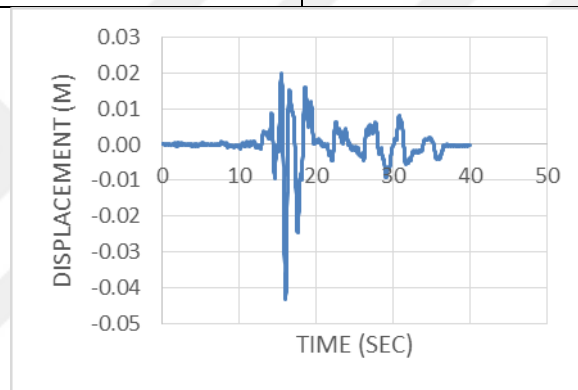


Figure A- 72: Bearing displacement time history of material C TFPB under RSN 838

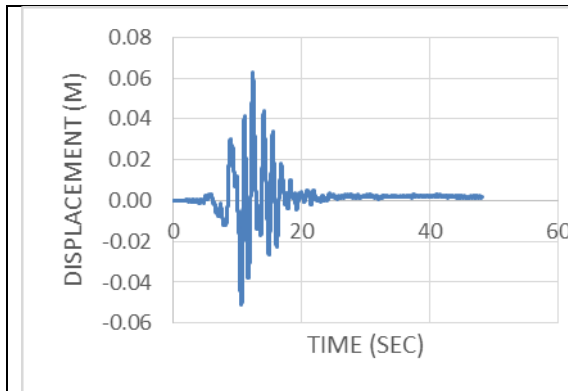


Figure A- 73: Bearing displacement time history of material A TFPB under RSN 879

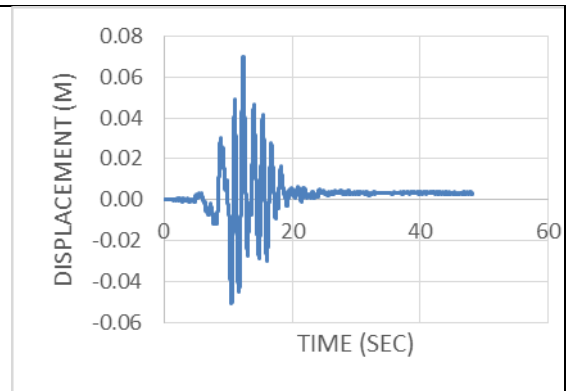


Figure A- 74: Bearing displacement time history of material B TFPB under RSN 879

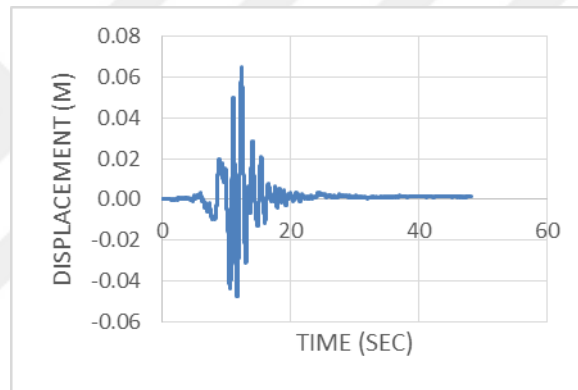


Figure A- 75: Bearing displacement time history of material C TFPB under RSN 879

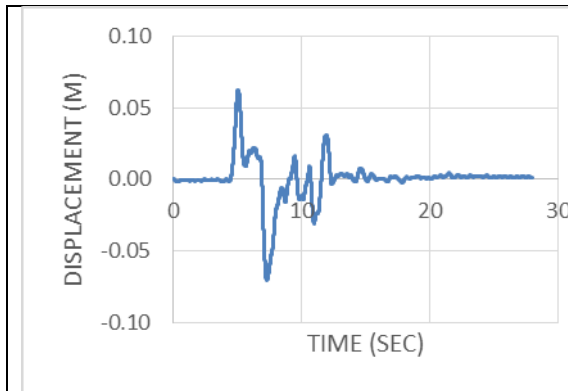


Figure A- 76: Bearing displacement time history of material A TFPB under RSN 1161

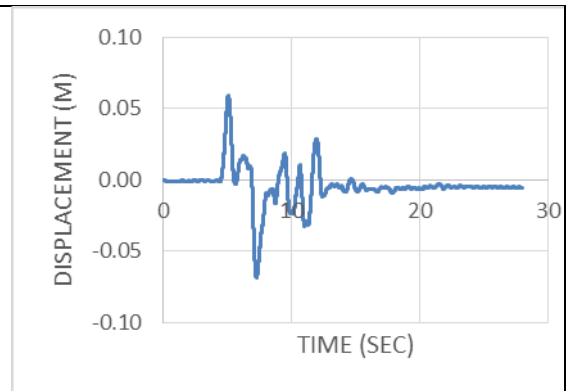


Figure A- 77: Bearing displacement time history of material B TFPB under RSN 1161

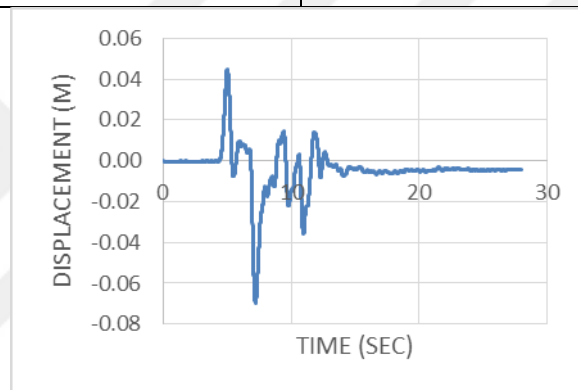


Figure A- 78: Bearing displacement time history of material C TFPB under RSN 1161

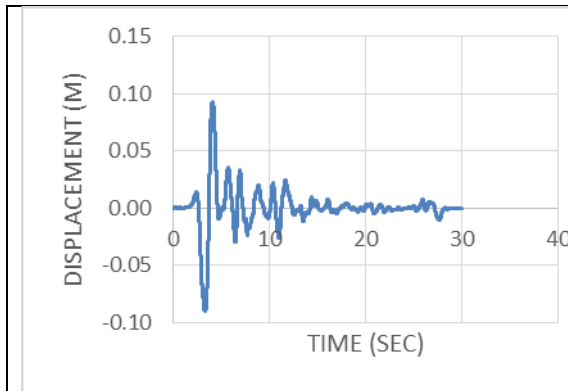


Figure A- 79: Bearing displacement time history of material A TFPB under RSN 1165

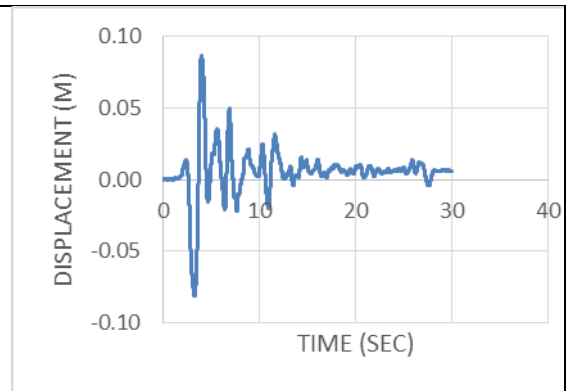


Figure A- 80: Bearing displacement time history of material B TFPB under RSN 1165

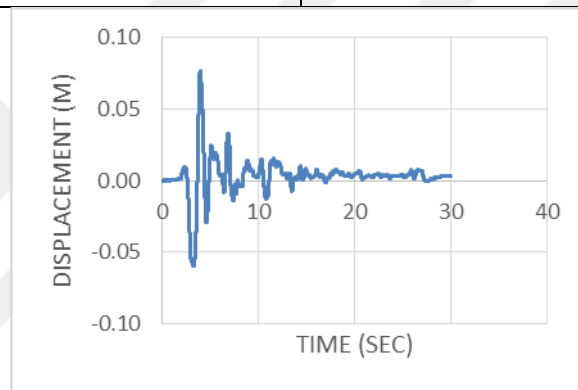


Figure A- 81: Bearing displacement time history of material C TFPB under RSN 1165

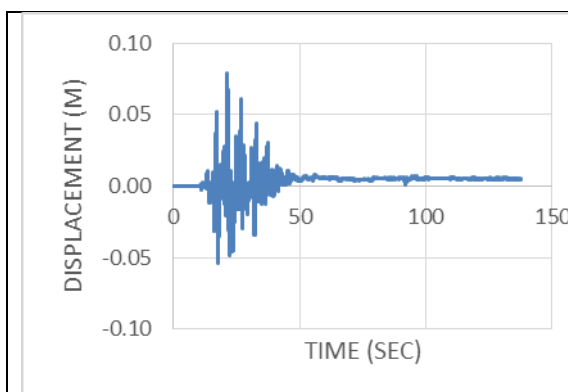


Figure A- 82: Bearing displacement time history of material A TFPB under RSN 6897

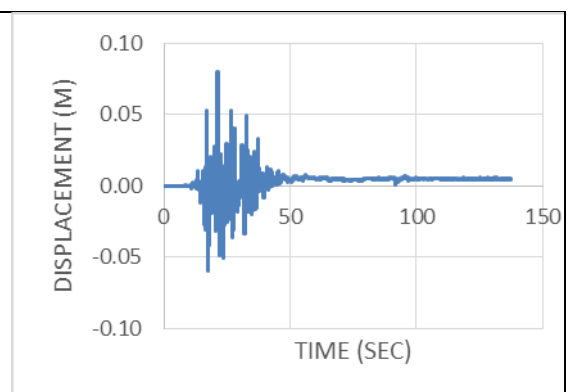


Figure A- 83: Bearing displacement time history of material B TFPB under RSN 6897

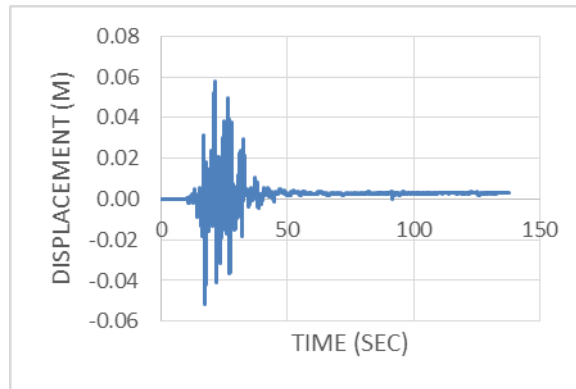


Figure A- 84: Bearing displacement time history of material C TFPB under RSN 6897

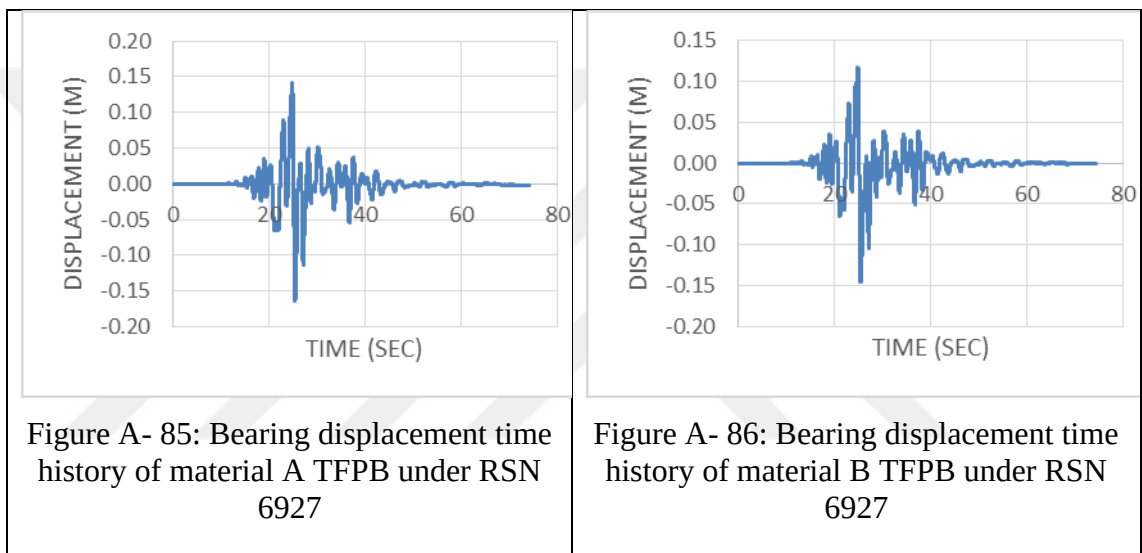


Figure A- 85: Bearing displacement time history of material A TFPB under RSN 6927

Figure A- 86: Bearing displacement time history of material B TFPB under RSN 6927

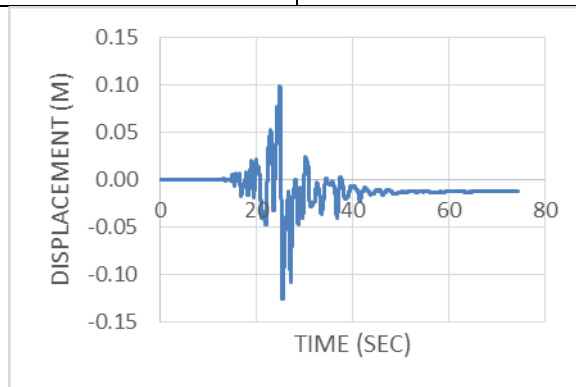


Figure A- 87: Bearing displacement time history of material C TFPB under RSN 6927

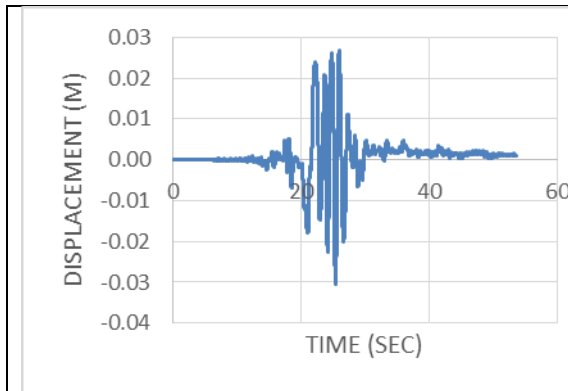


Figure A- 88: Bearing displacement time history of material A TFPB under RSN 6928

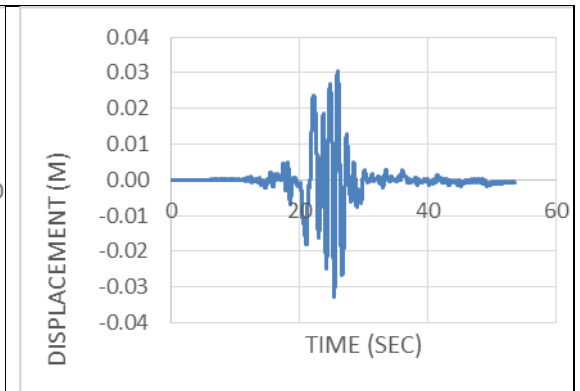


Figure A- 89: Bearing displacement time history of material B TFPB under RSN 6928

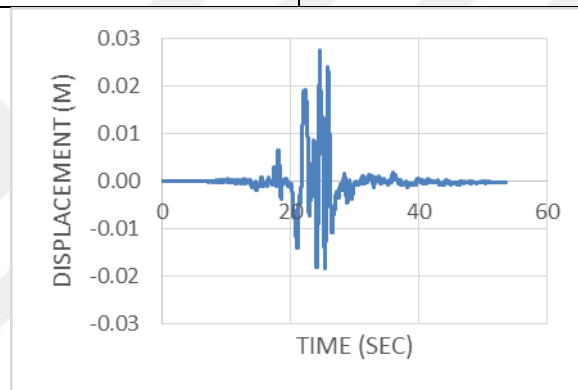


Figure A- 90: Bearing displacement time history of material C TFPB under RSN 6928

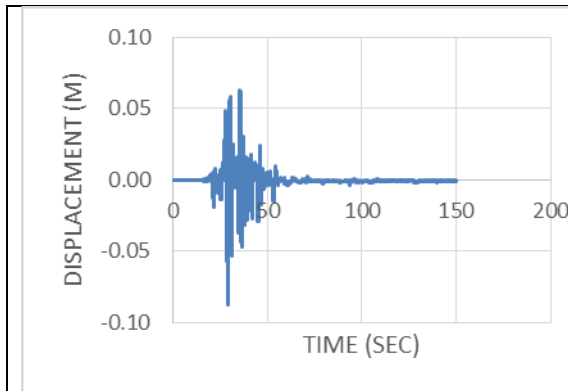


Figure A- 91: Bearing displacement time history of material A TFPB under RSN 6942

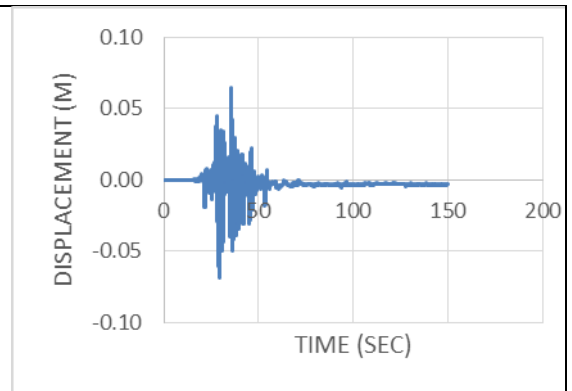


Figure A- 92: Bearing displacement time history of material B TFPB under RSN 6942

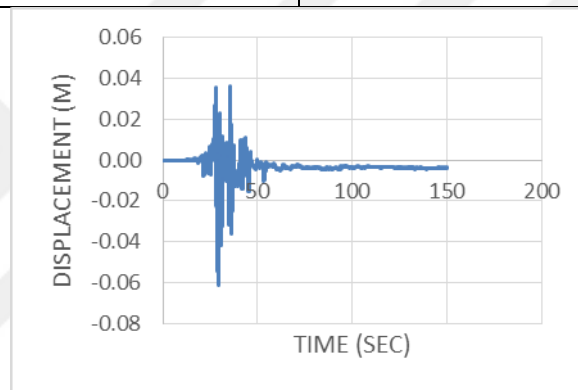


Figure A- 93: Bearing displacement time history of material C TFPB under RSN 6942

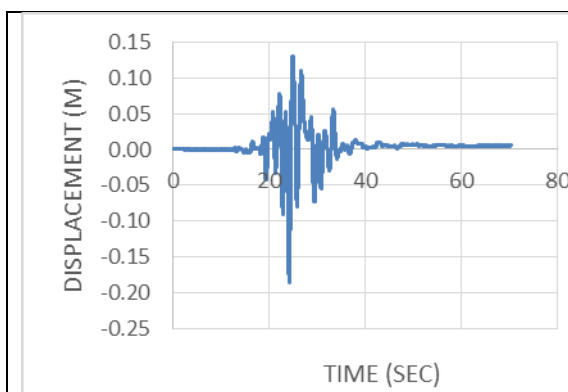


Figure A- 94: Bearing displacement time history of material A TFPB under RSN 6962

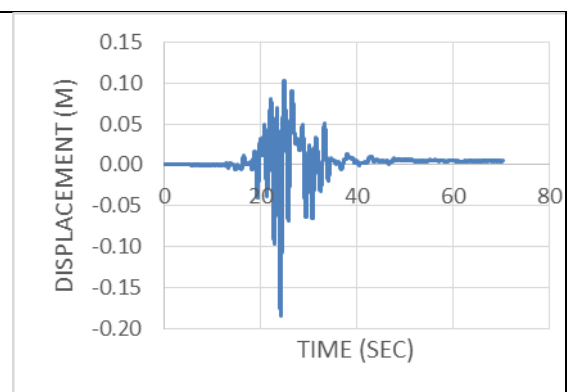


Figure A- 95: Bearing displacement time history of material B TFPB under RSN 6962

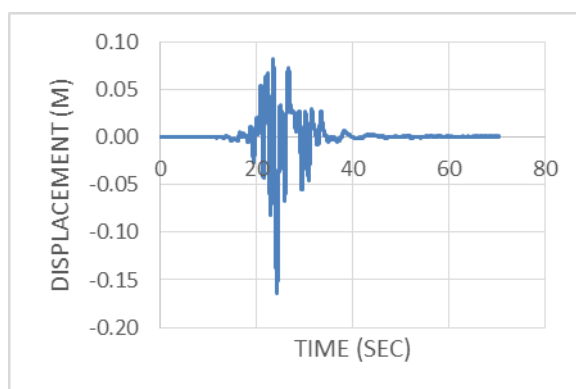


Figure A- 96: Bearing displacement time history of material C TFPB under RSN 6962

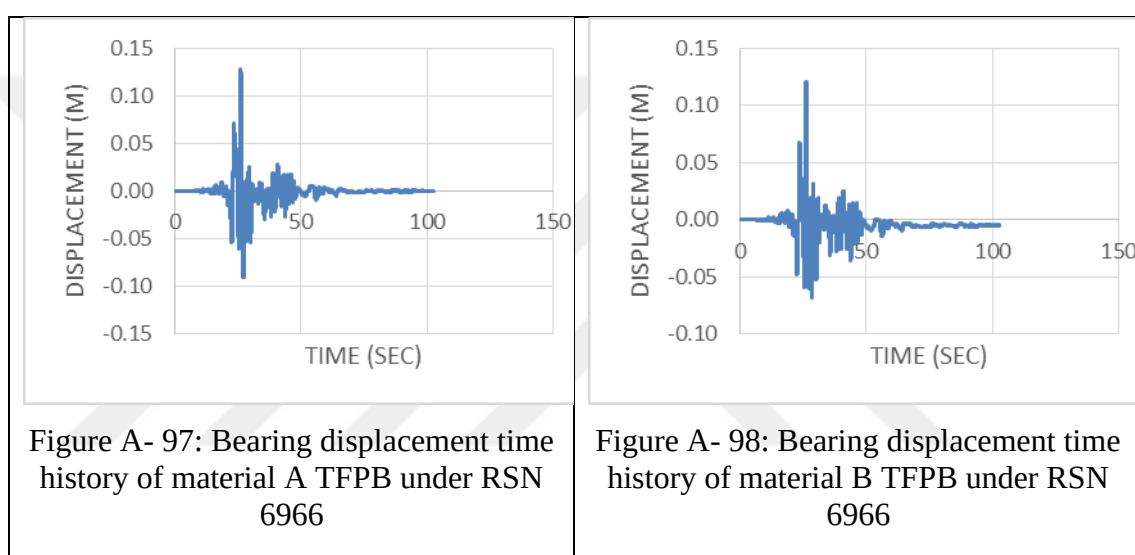


Figure A- 97: Bearing displacement time history of material A TFPB under RSN 6966

Figure A- 98: Bearing displacement time history of material B TFPB under RSN 6966

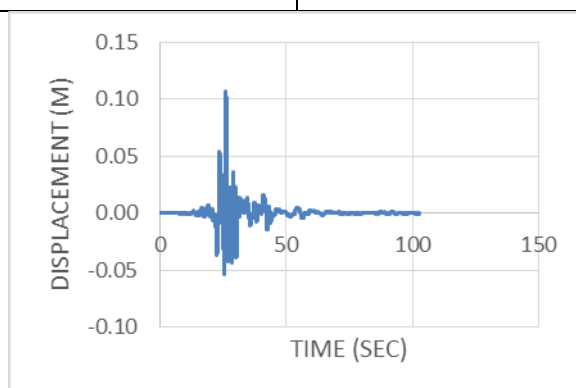
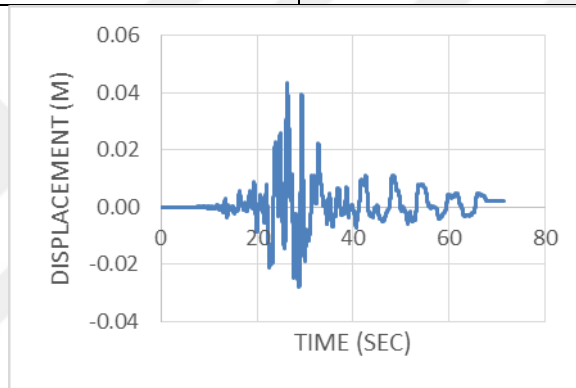
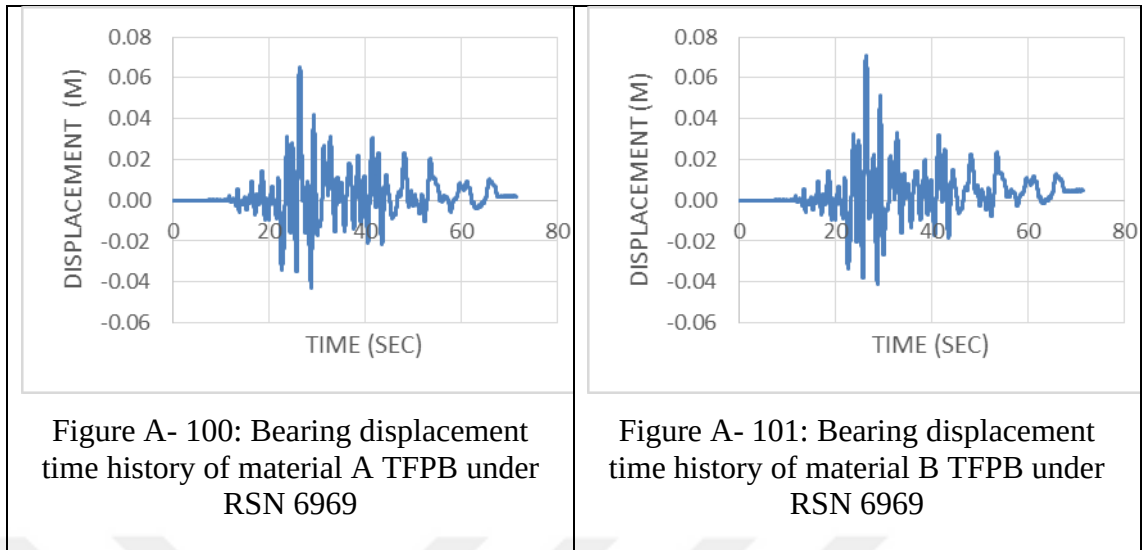


Figure A- 99: Bearing displacement time history of material C TFPB under RSN 6966



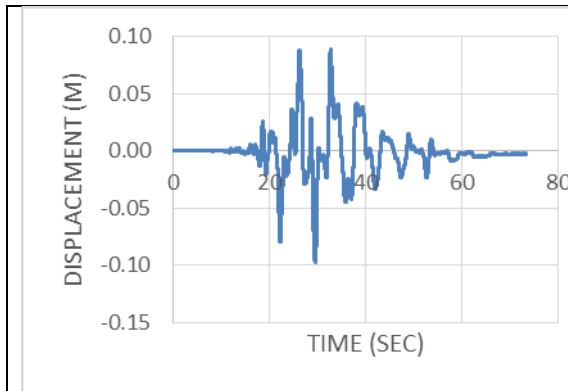


Figure A- 103: Bearing displacement time history of material A TFPB under RSN 6975

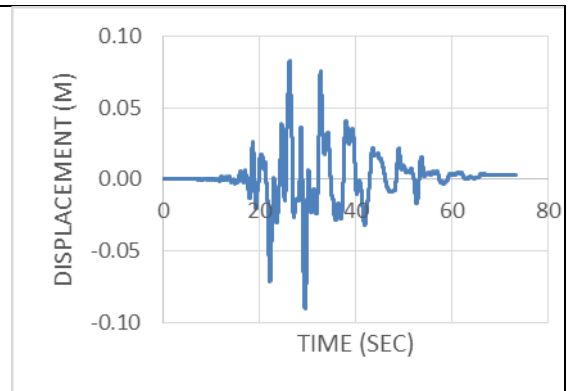


Figure A- 104: Bearing displacement time history of material B TFPB under RSN 6975

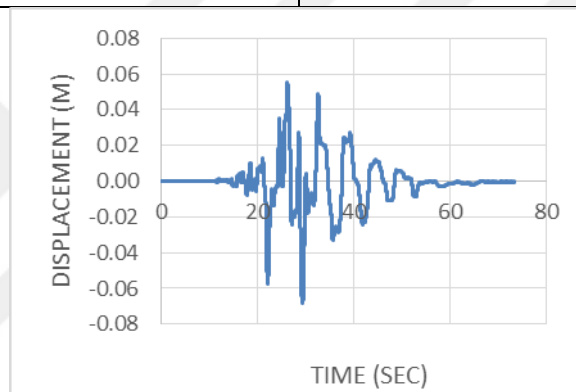


Figure A- 105: Bearing displacement time history of material C TFPB under RSN 6975

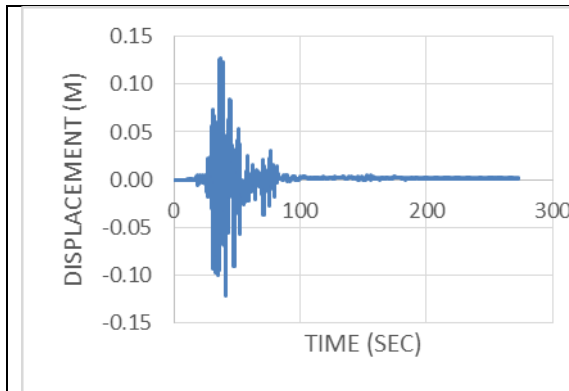


Figure A- 106: Bearing displacement time history of material A TFPB under RSN 8161

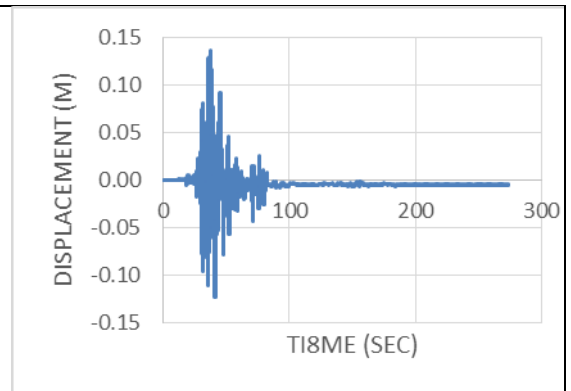


Figure A- 107: Bearing displacement time history of material B TFPB under RSN 8161

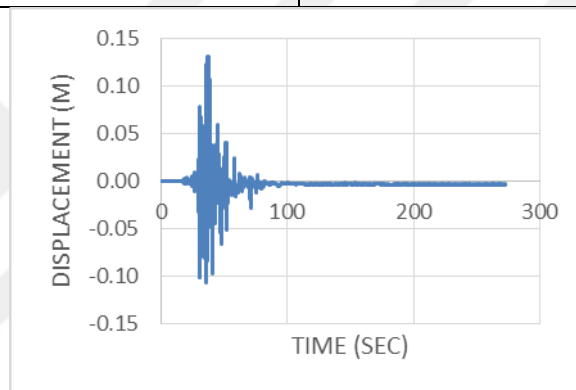


Figure A-108: Bearing displacement time history of material C TFPB under RSN 8161

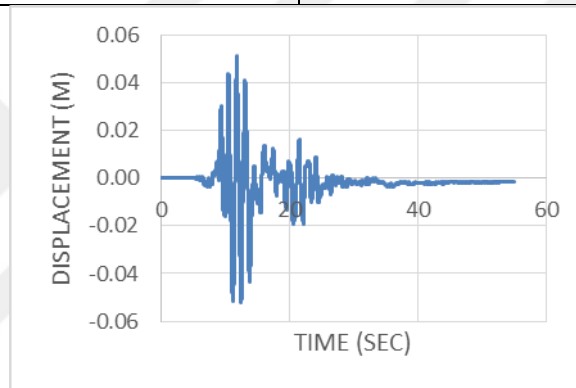
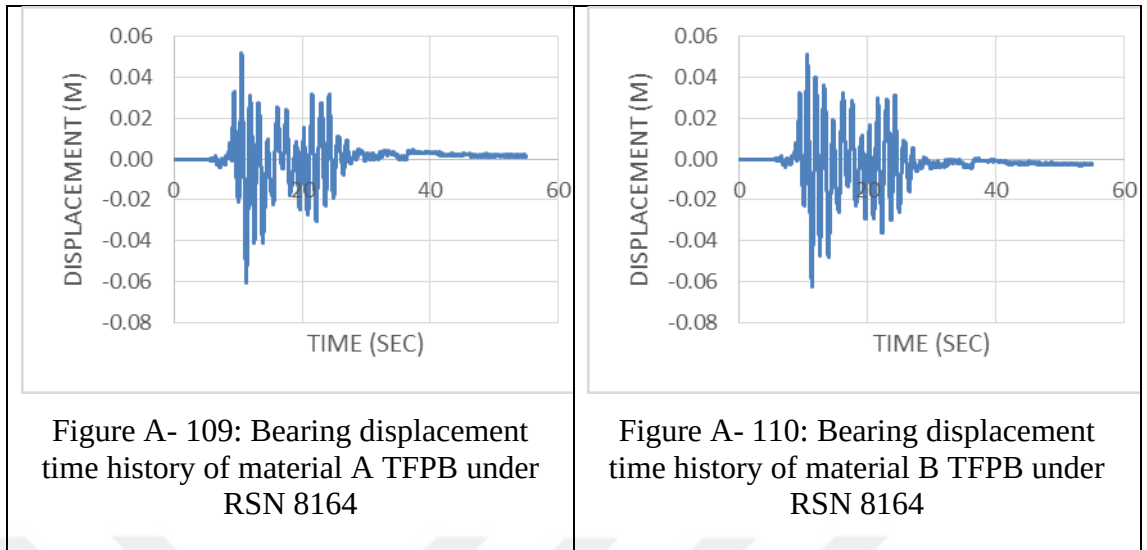


Figure A- 111: Bearing displacement time history of material C TFPB under RSN 8164

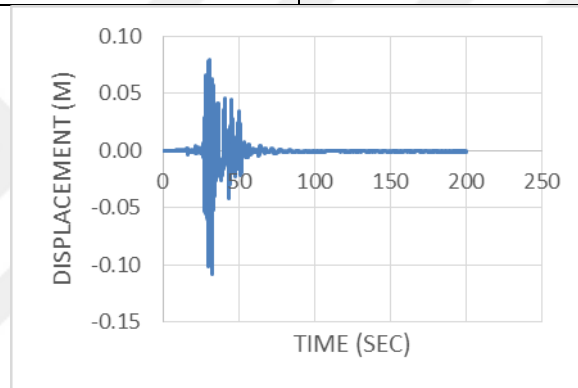
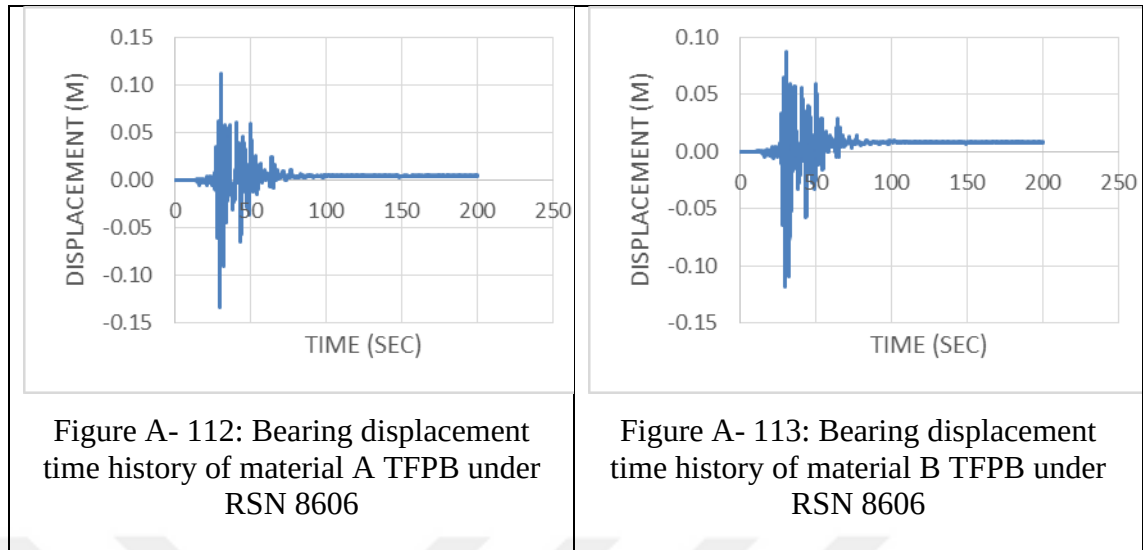


Figure A- 114: Bearing displacement time history of material C TFPB under RSN 8606

The acceleration spectrums for the selected earthquake sets:

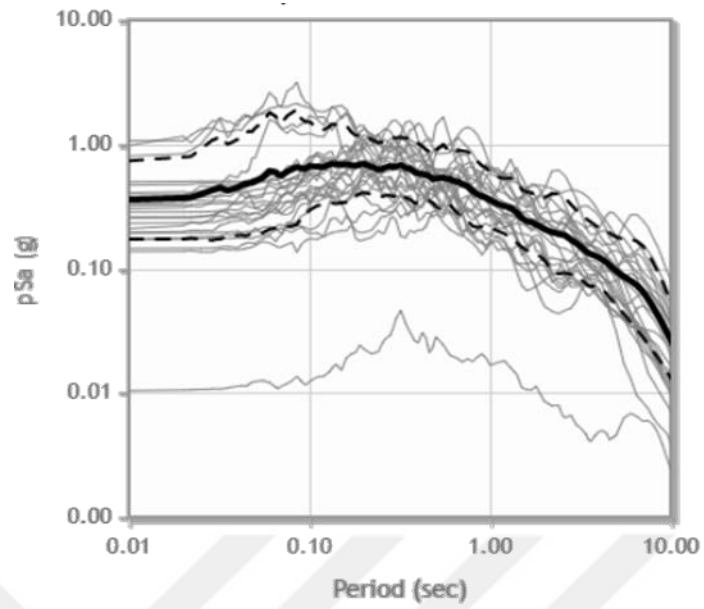


Figure A -115: Acceleration spectra for the selected near-field earthquakes

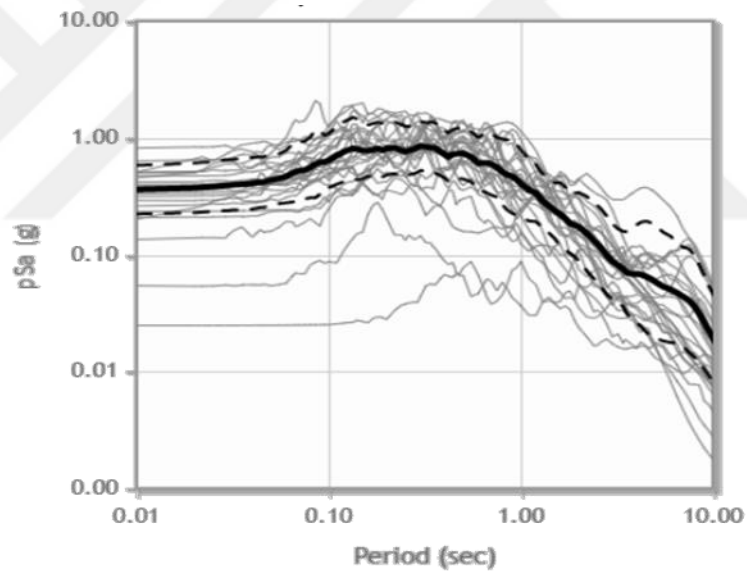


Figure A -116: Acceleration spectra for the selected far-field earthquakes

APPENDIX B

Force–Displacement Hysteresis Curves under Far-Field Ground Motion Records:

The coefficient of friction is a significant parameter that impacts auxiliary movement and bearing displacement. The friction coefficient of the surface is kept up as ($\mu_2 = \mu_3 < \mu_1 < \mu_4$) throughout the investigation. Hysteresis loops show the constrained displacement reaction of triple friction self-pendulum bearing. The results of the time history analysis for the investigated far-field earthquakes and the selected isolators are provided in Figure B- 14 to Figure B- 54. Figure B- 15 shows the seismic record using the coefficient of friction of Material A. The results for Material B are shown in Figure B-2. This indicates that the average base shear decreases as the friction value increases. In addition, Material C in Figure B- 3 shows that the base shear increases further as the coefficient of friction increases.

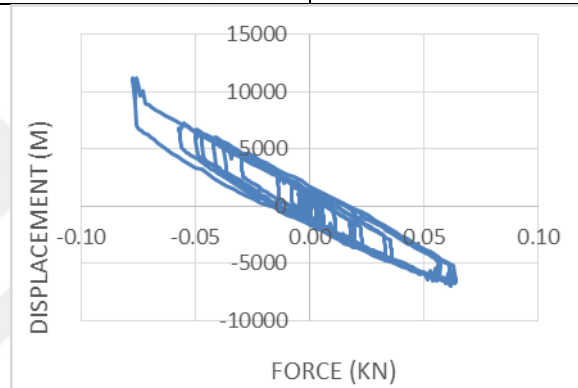
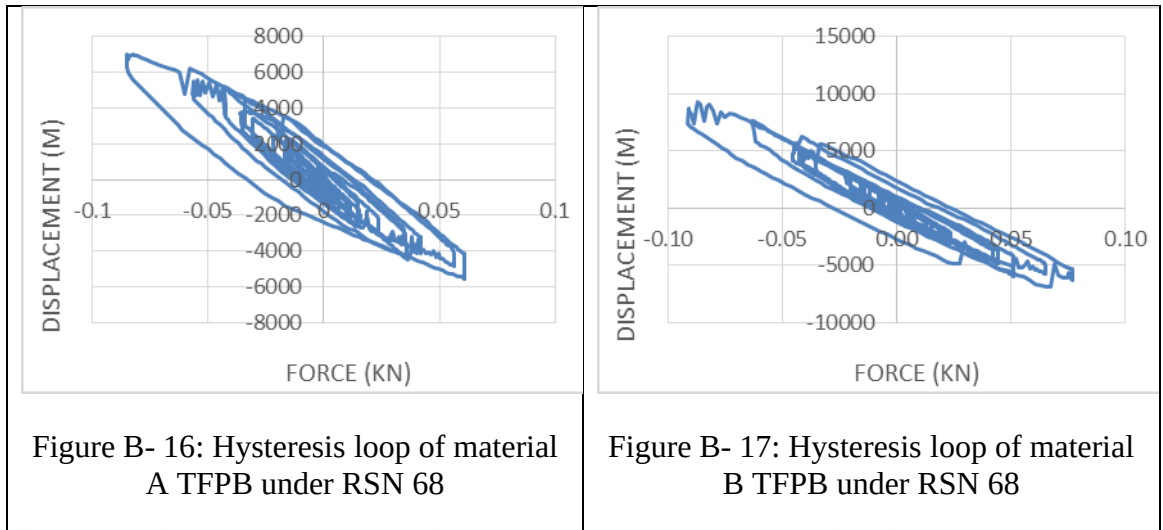


Figure B- 3: Hysteresis loop of material C TFPB under RSN 68

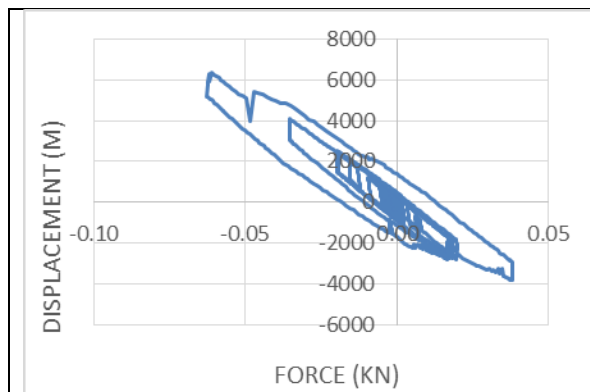


Figure B- 18: Hysteresis loop of material A TFPB under RSN 125

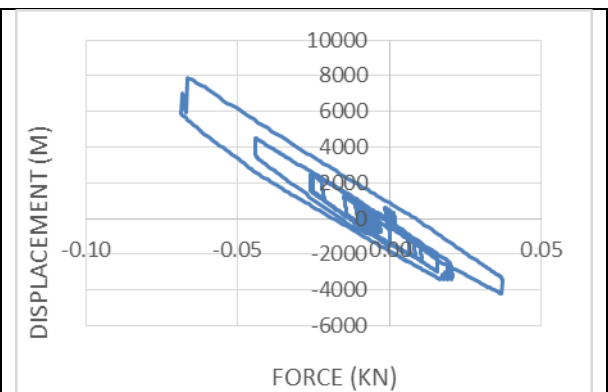


Figure B- 19: Hysteresis loop of material B TFPB under RSN 125

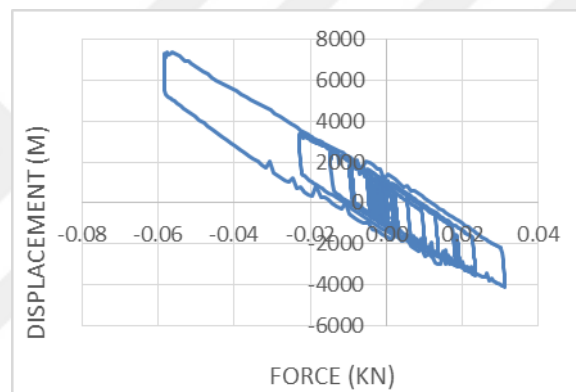


Figure B- 20: Hysteresis loop of material C TFPB under RSN 125

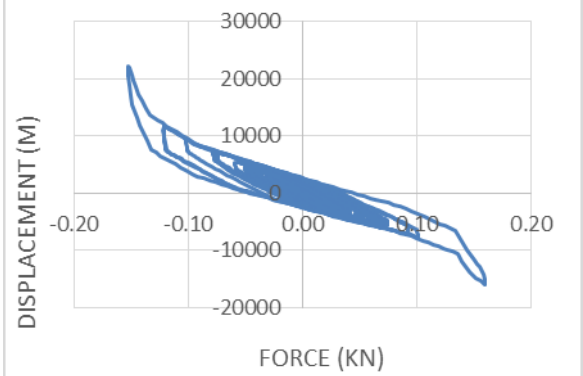


Figure B- 7: Hysteresis loop of material A TFPB under RSN 169

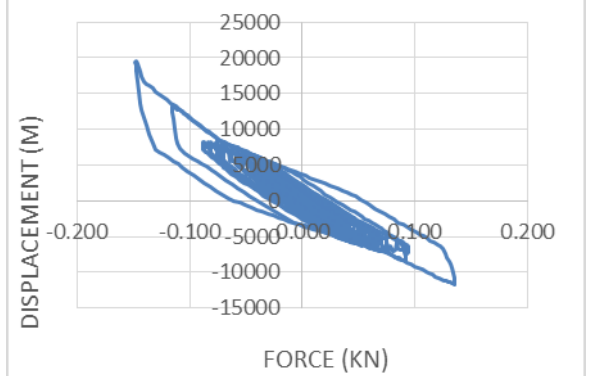


Figure B- 8: Hysteresis loop of material B TFPB under RSN 169

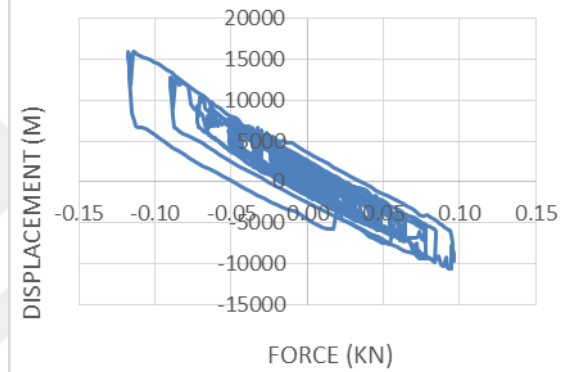


Figure B- 21: Hysteresis loop of material C TFPB under RSN 169

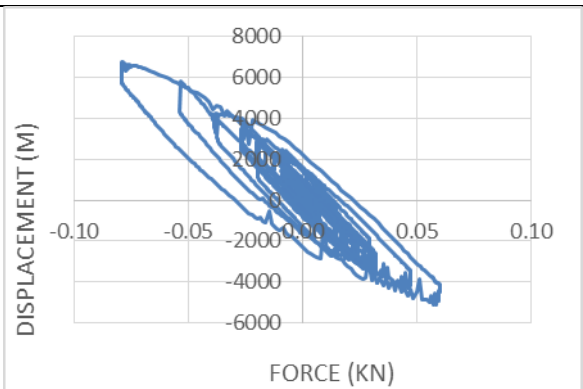


Figure B- 10: Hysteresis loop of material A TFPB under RSN 174

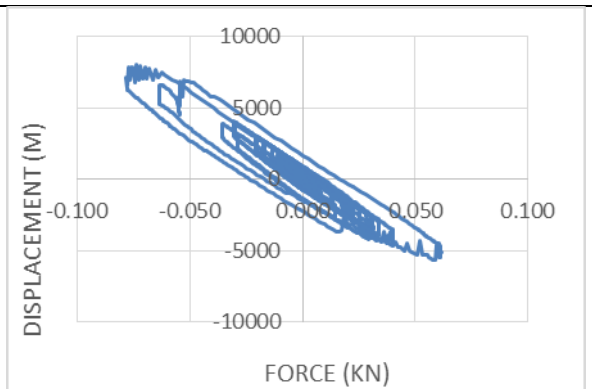


Figure B- 11: Hysteresis loop of material B TFPB under RSN 174

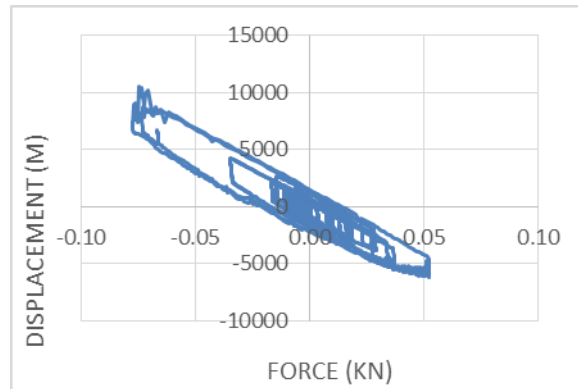


Figure B- 22: Hysteresis loop of material C TFPB under RSN 174

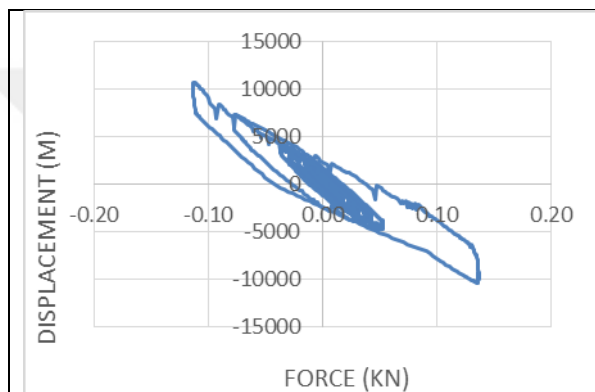


Figure B- 13: Hysteresis loop of material A TFPB under RSN 721

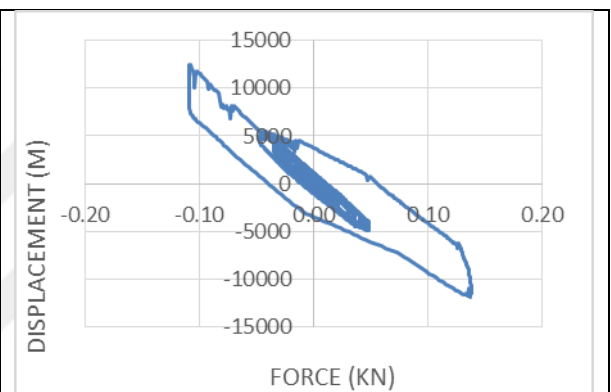


Figure B- 14: Hysteresis loop of material B TFPB under RSN 721

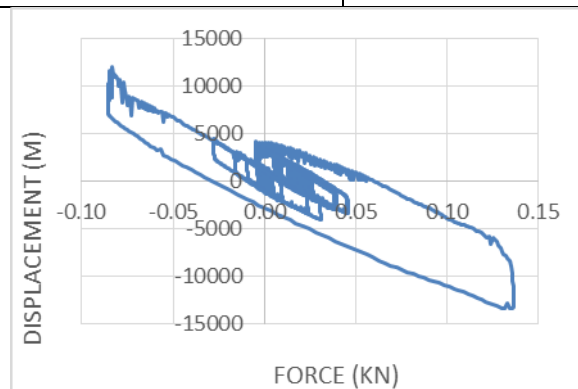


Figure B- 23: Hysteresis loop of material C TFPB under RSN 721

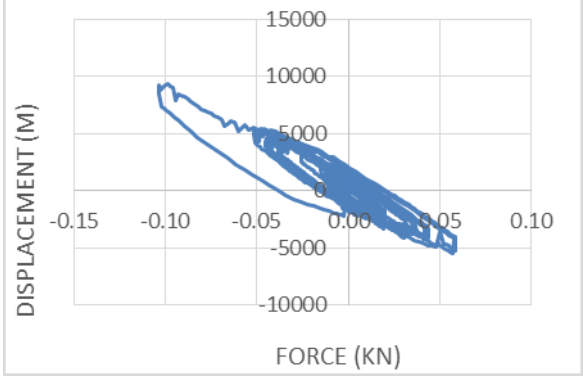


Figure B- 16: Hysteresis loop of material A TFPB under RSN 725

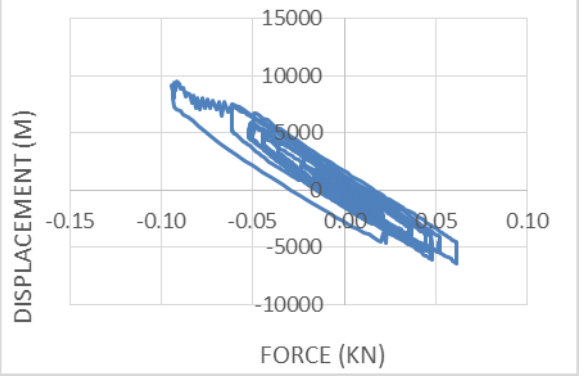


Figure B- 17: Hysteresis loop of material B TFPB under RSN 725

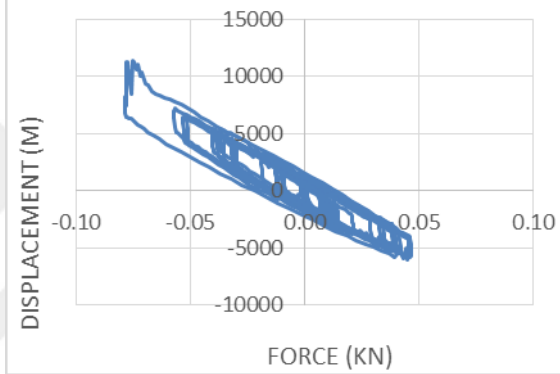


Figure B- 18: Hysteresis loop of material C TFPB under RSN 725

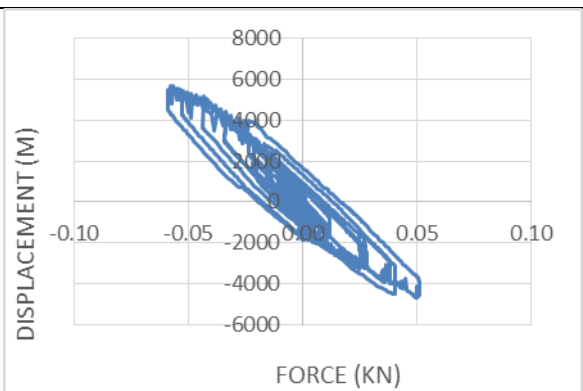


Figure B- 19: Hysteresis loop of material A TFPB under RSN 767

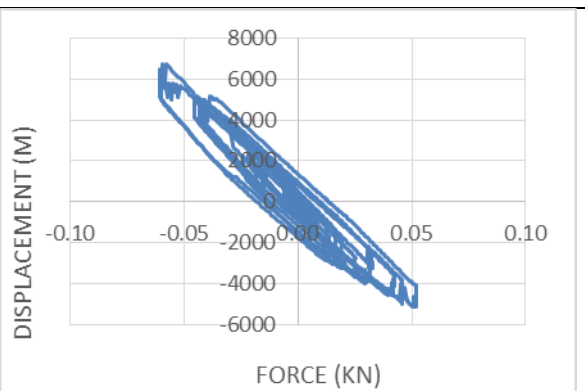


Figure B- 20: Hysteresis loop of material B TFPB under RSN 767

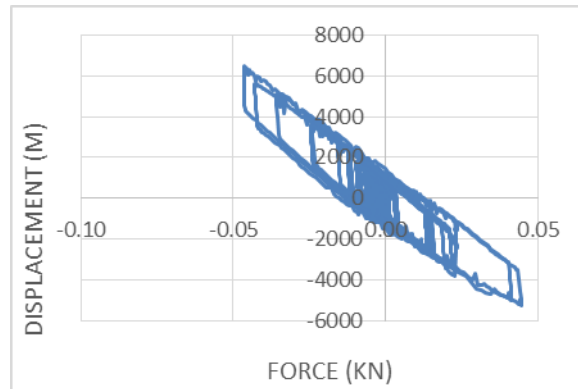


Figure B- 21: Hysteresis loop of material C TFPB under RSN 767

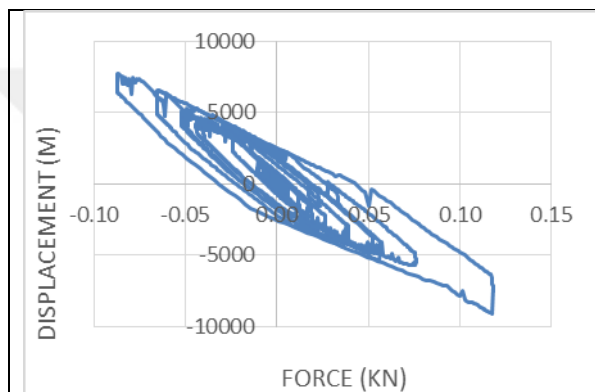


Figure B- 22: Hysteresis loop of material A TFPB under RSN 848

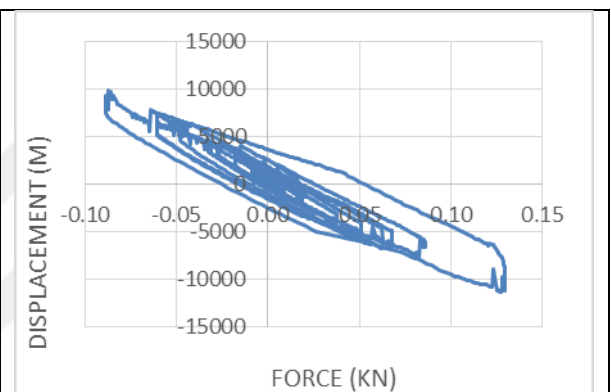


Figure B- 23: Hysteresis loop of material B TFPB under RSN 848

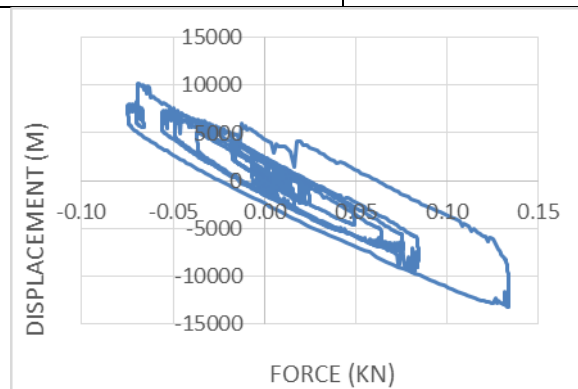


Figure B- 24: Hysteresis loop of material C TFPB under RSN 848

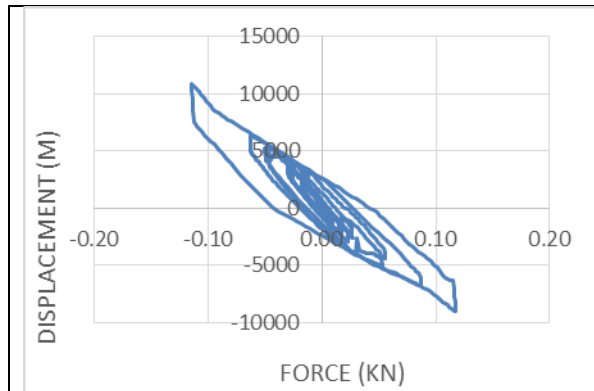


Figure B- 25: Hysteresis loop of material A TFPB under RSN 960

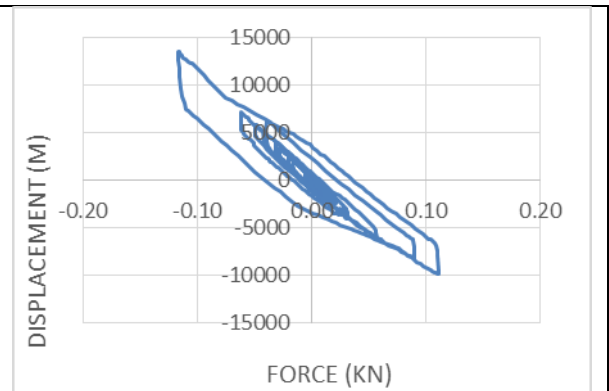


Figure B- 26: Hysteresis loop of material B TFPB under RSN 960

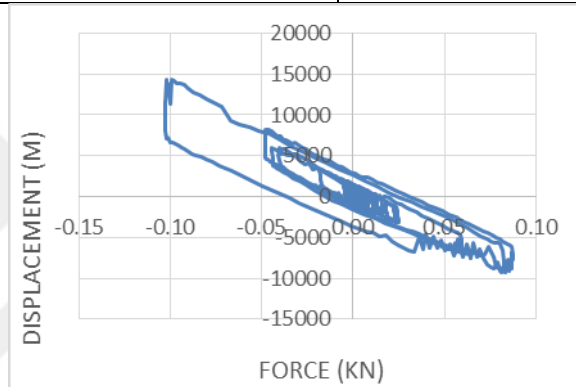


Figure B- 27: Hysteresis loop of material C TFPB under RSN 960

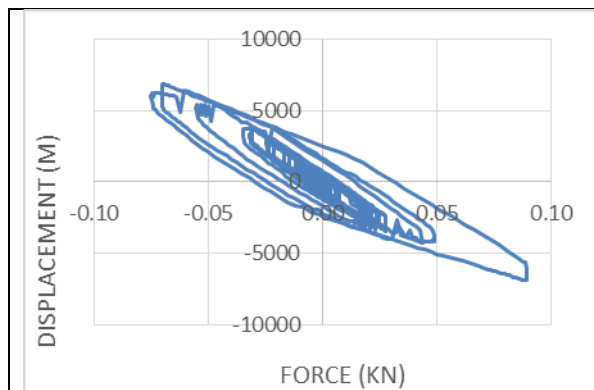


Figure B- 28: Hysteresis loop of material A TFPB under RSN 1116

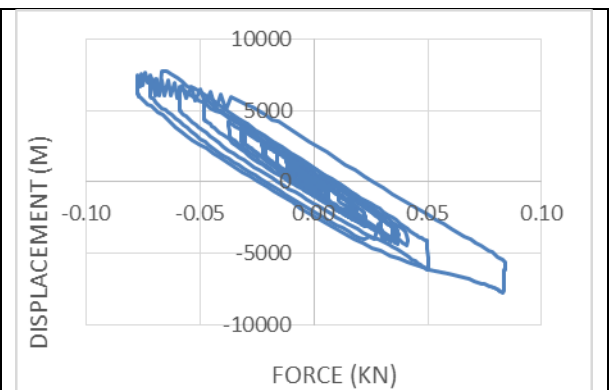


Figure B- 29: Hysteresis loop of material B TFPB under RSN 1116

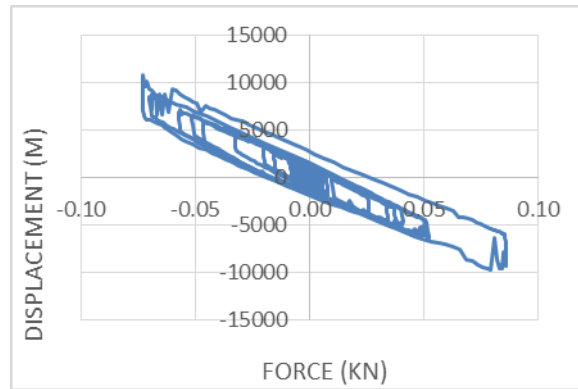


Figure B- 30: Hysteresis loop of material C TFPB under RSN 1116

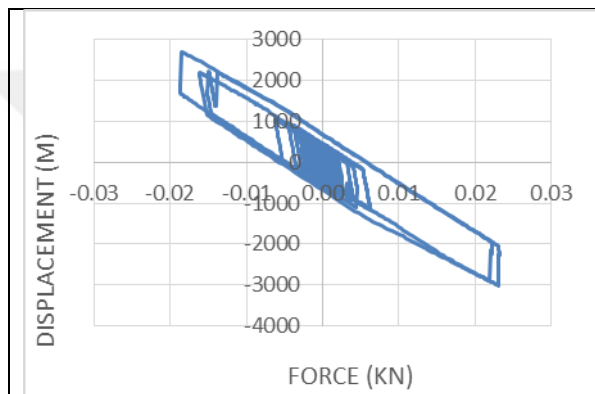


Figure B- 31: Hysteresis loop of material A TFPB under RSN 1148

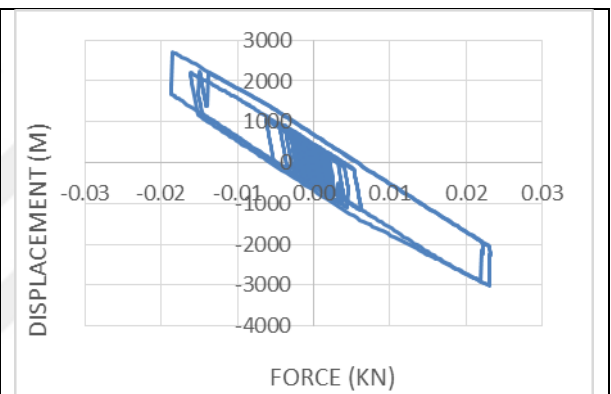


Figure B- 32: Hysteresis loop of material B TFPB under RSN 1148

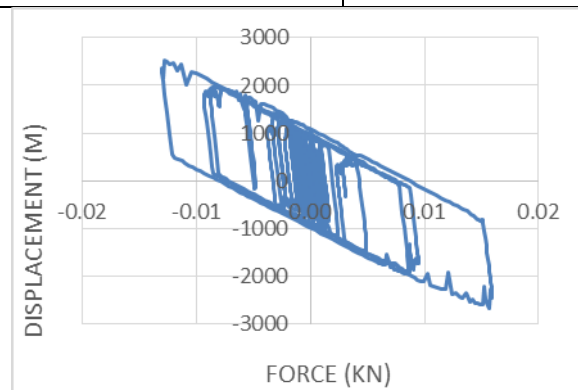


Figure B- 33: Hysteresis loop of material C TFPB under RSN 1148

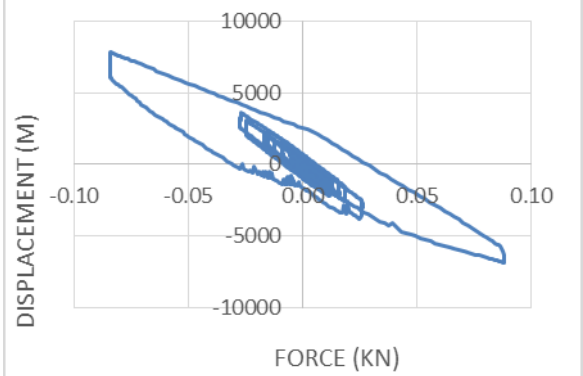


Figure B- 34: Hysteresis loop of material A TFPB under RSN 1485

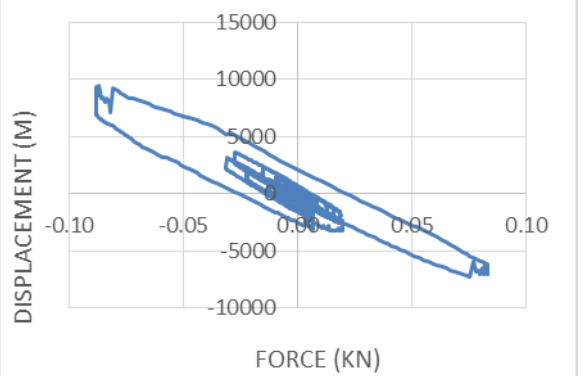


Figure B- 35: Hysteresis loop of material B TFPB under RSN 1485

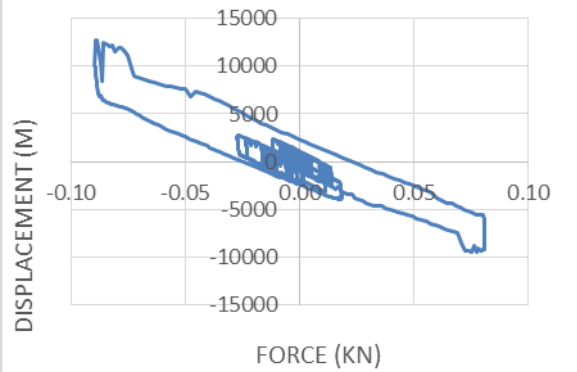


Figure B- 36: Hysteresis loop of material C TFPB under RSN 1485

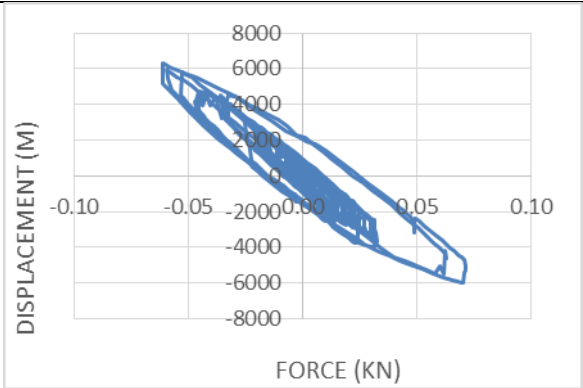


Figure B- 37: Hysteresis loop of material A TFPB under RSN 1633

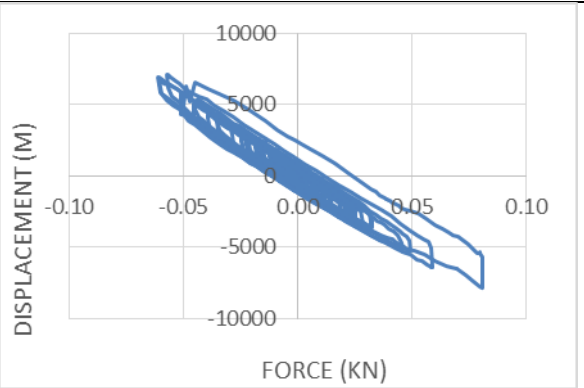


Figure B- 38: Hysteresis loop of material B TFPB under RSN 1633

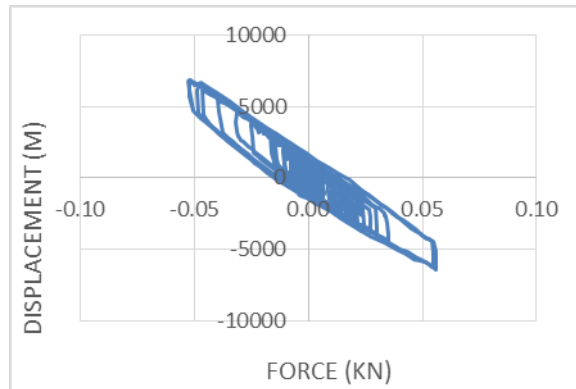


Figure B- 39: Hysteresis loop of material C TFPB under RSN 1633

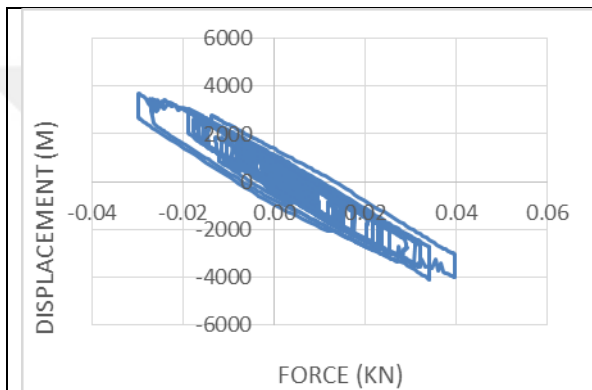


Figure B- 40: Hysteresis loop of material A TFPB under RSN 3753

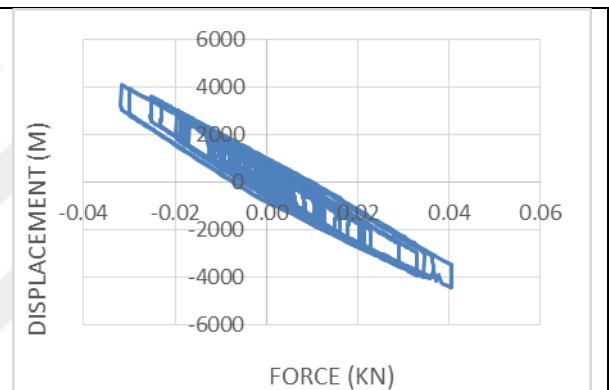


Figure B- 41: Hysteresis loop of material B TFPB under RSN 3753

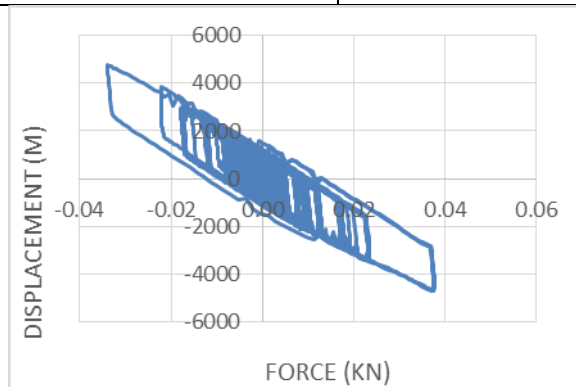


Figure B- 42: Hysteresis loop of material C TFPB under RSN 3753

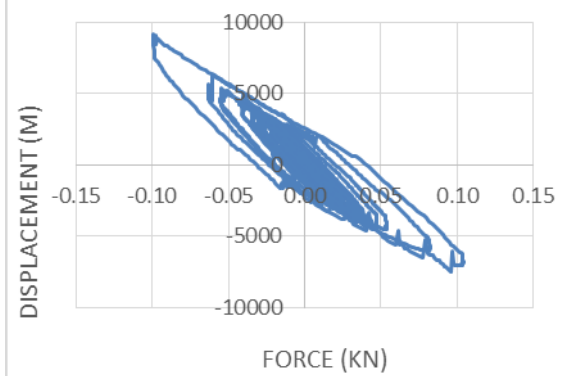


Figure B- 43: Hysteresis loop of material A TFPB under RSN 5837

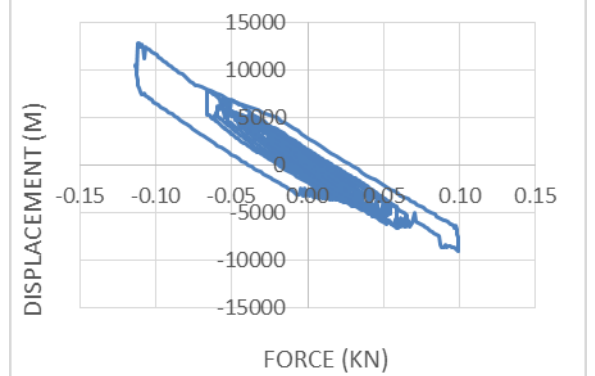


Figure B- 44: Hysteresis loop of material B TFPB under RSN 5837

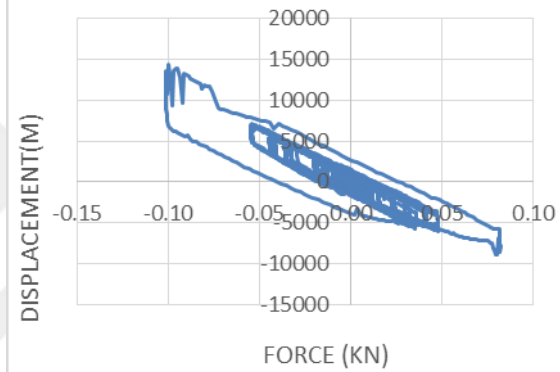


Figure B- 45: Hysteresis loop of material C TFPB under RSN 5837

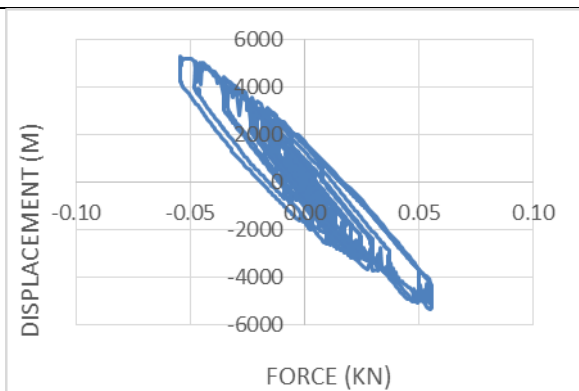


Figure B- 46: Hysteresis loop of material A TFPB under RSN 5985

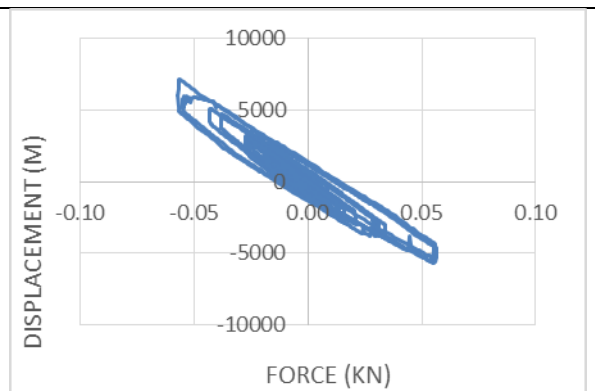


Figure B- 47: Hysteresis loop of material B TFPB under RSN 5985

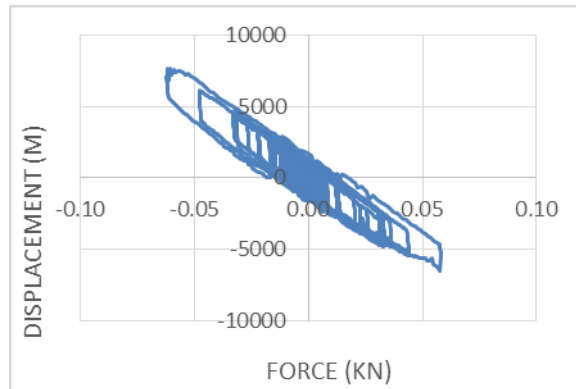


Figure B- 48: Hysteresis loop of material C TFPB under RSN 5985

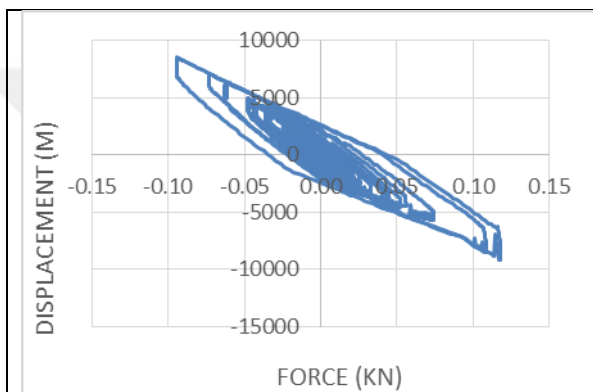


Figure B- 49: Hysteresis loop of material A TFPB under RSN 5991

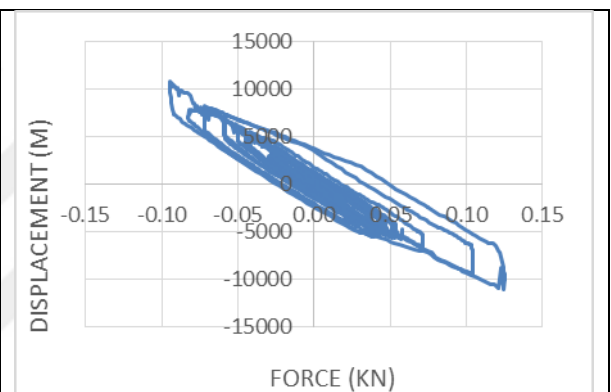


Figure B- 50: Hysteresis loop of material B TFPB under RSN 5991

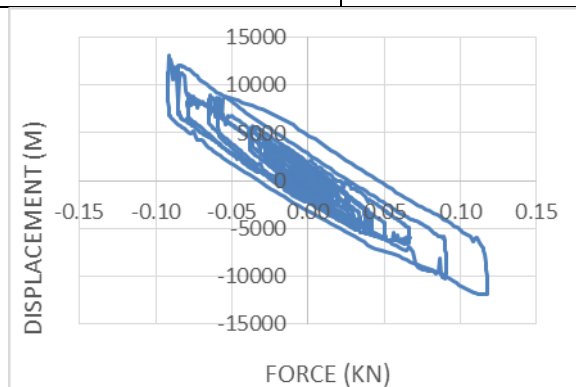


Figure B- 51: Hysteresis loop of material C TFPB under RSN 5991

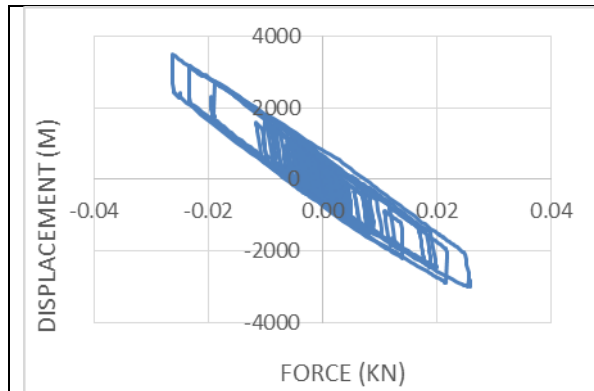


Figure B- 52: Hysteresis loop of material A TFPB under RSN 6915

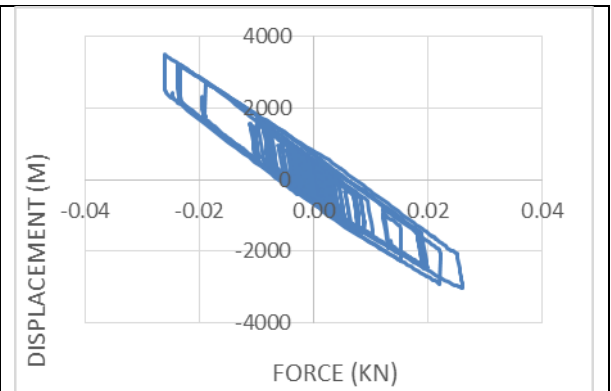


Figure B- 53: Hysteresis loop of material B TFPB under RSN 6915

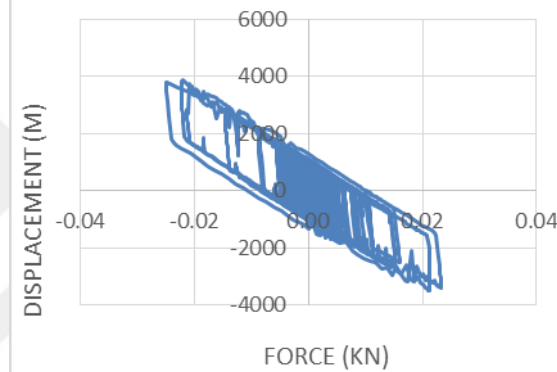


Figure B- 54: Hysteresis loop of material C TFPB under RSN 6915

Variation of Time History Story Displacement with Friction Coefficient under Far-Field Ground Motion Records:

The results of the study herein aim to investigate the impact of changing the friction coefficients on the performance of the buildings under far-field earthquakes for each material case. Figures B- 55 shows seismic records using the coefficient of friction of Material A. The results for Material B are shown in Figures B- 56, showing that the displacement of the bearings increases as the friction value decreases. In addition, Material C in Figures B- 57 shows that the displacement of the bearing decreases further as the coefficient of friction decreases.

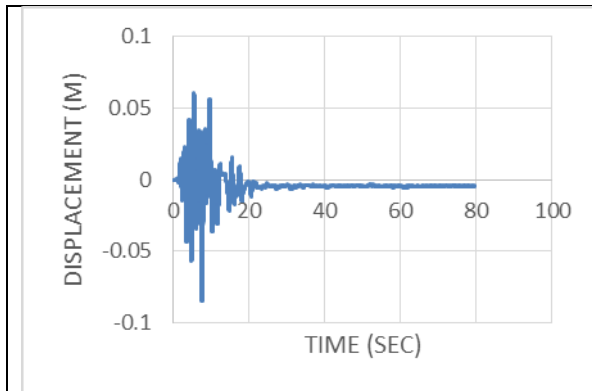


Figure B- 55: Bearing displacement time history of material A TFPB under RSN 68

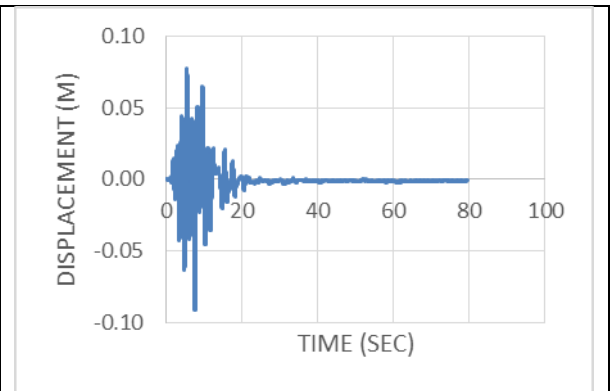


Figure B- 56: Bearing displacement time history of material B TFPB under RSN 68

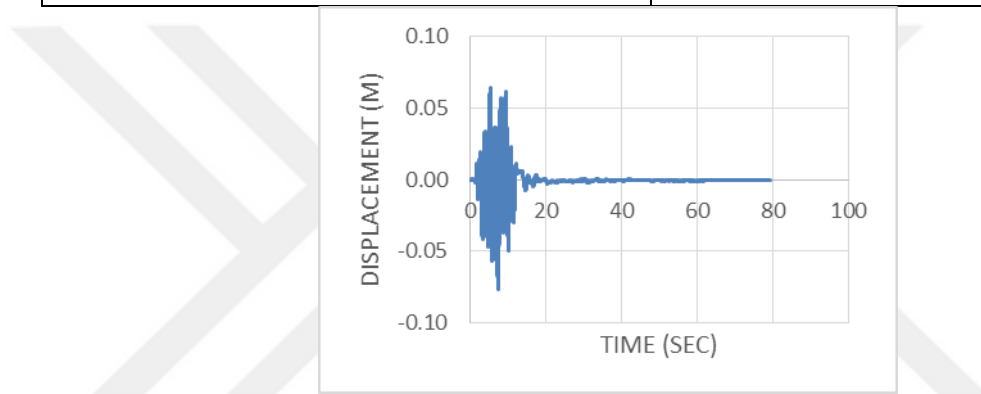


Figure B- 247: Bearing displacement time history of material C TFPB under RSN 68

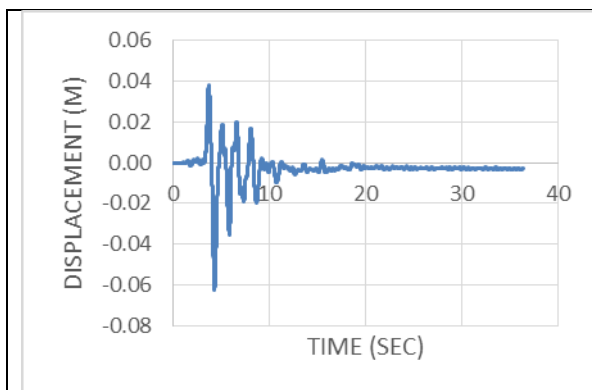


Figure B- 258: Bearing displacement time history of material A TFPB under RSN 125

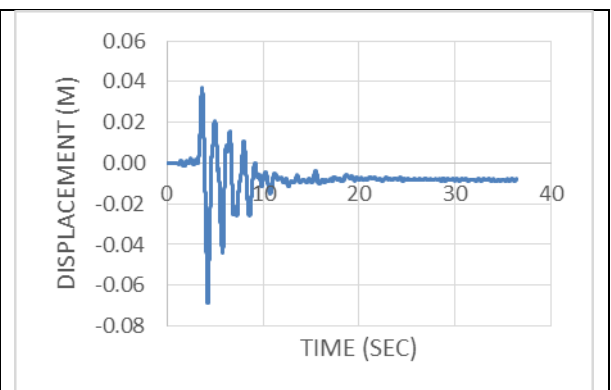


Figure B- 59: Bearing displacement time history of material B TFPB under RSN 125

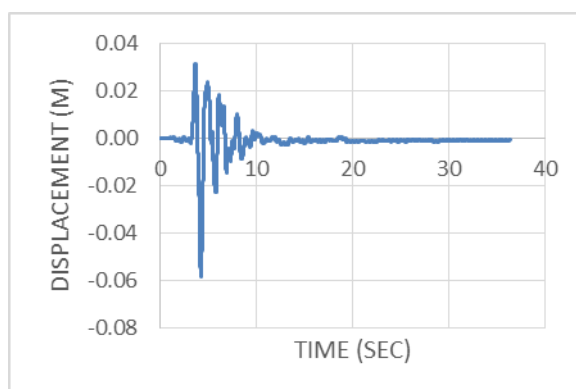


Figure B- 60: Bearing displacement time history of material C TFPB under RSN 125

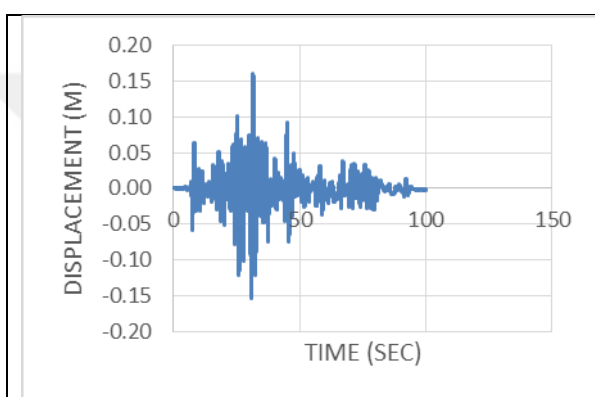


Figure B- 61: Bearing displacement time history of material A TFPB under RSN 169

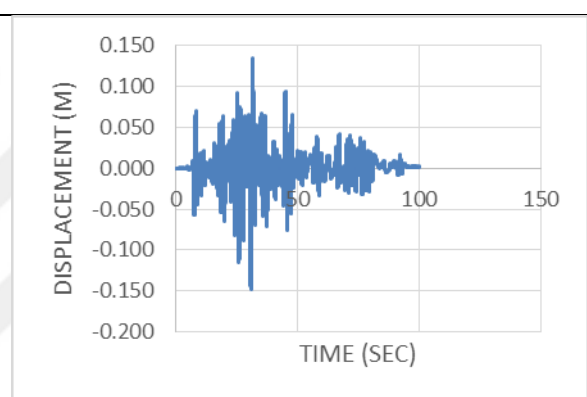


Figure B- 62: Bearing displacement time history of material B TFPB under RSN 169

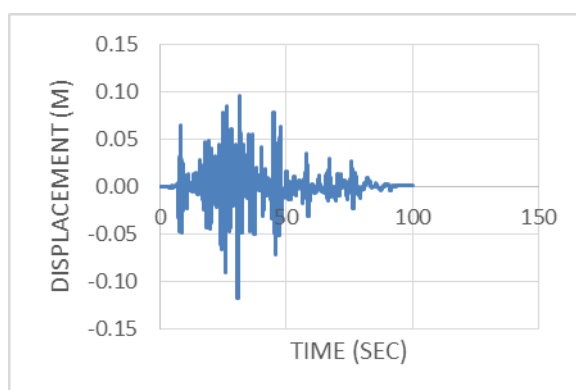


Figure B- 263: Bearing displacement time history of material C TFPB under RSN 169

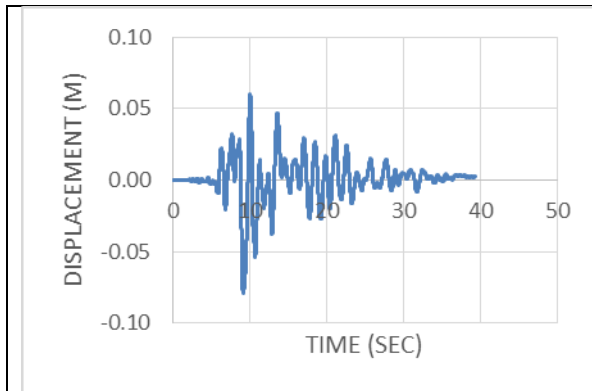


Figure B- 64: Bearing displacement time history of material A TFPB under RSN 174

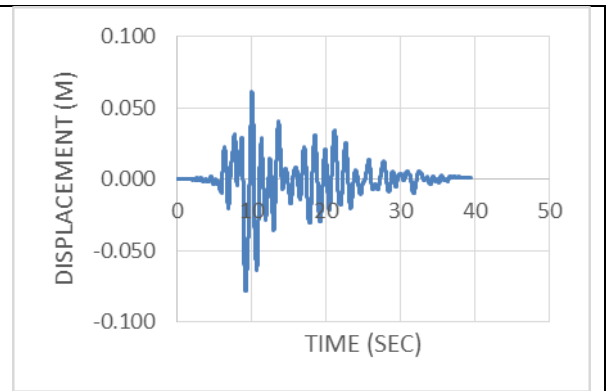


Figure B- 65: Bearing displacement time history of material B TFPB under RSN 174

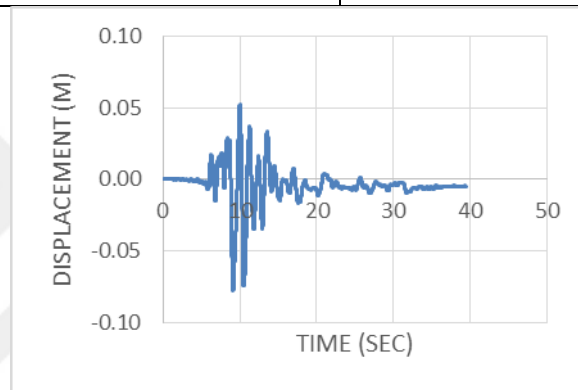


Figure B- 276: Bearing displacement time history of material C TFPB under RSN 174

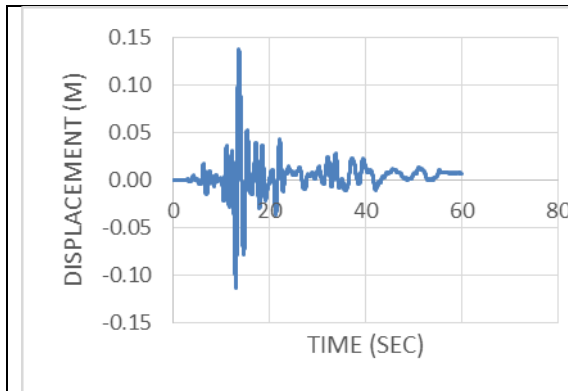


Figure B- 67: Bearing displacement time history of material A TFPB under RSN 721

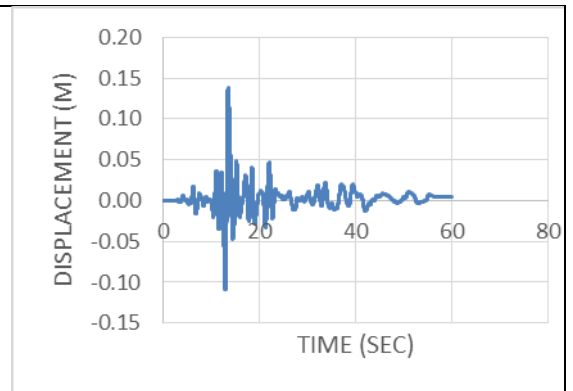


Figure B- 68: Bearing displacement time history of material B TFPB under RSN 721

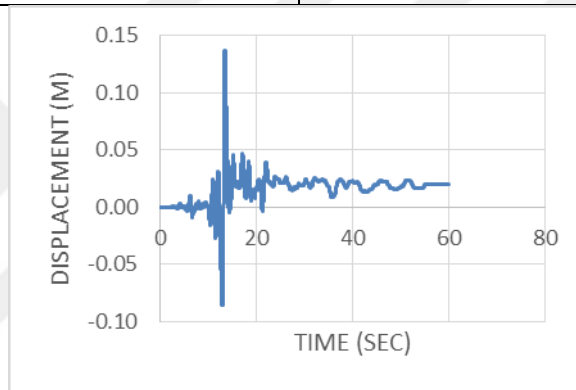


Figure B- 289: Bearing displacement time history of material C TFPB under RSN 721

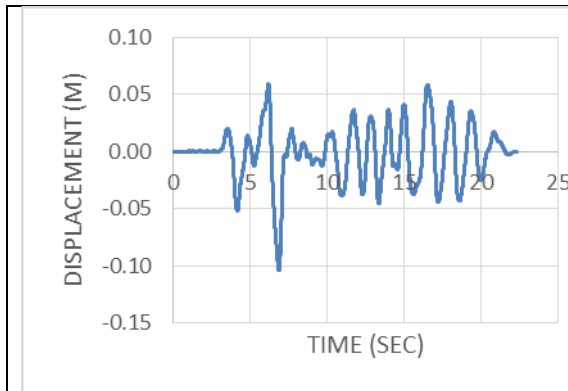


Figure B- 70: Bearing displacement time history of material A TFPB under RSN 725

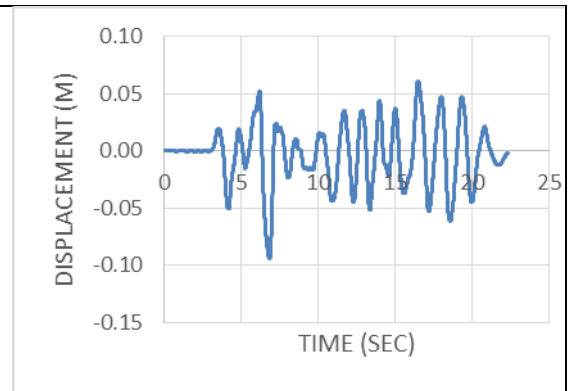


Figure B- 71: Bearing displacement time history of material B TFPB under RSN 725

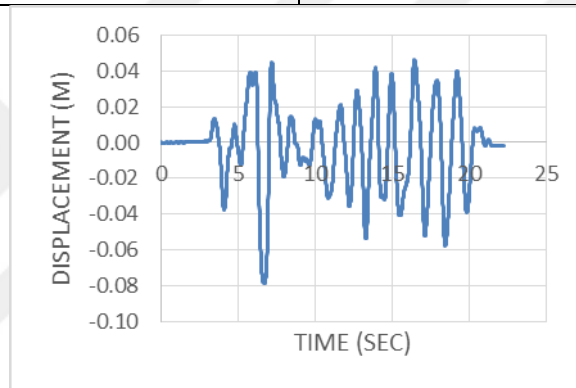


Figure B- 72: Bearing displacement time history of material C TFPB under RSN 725

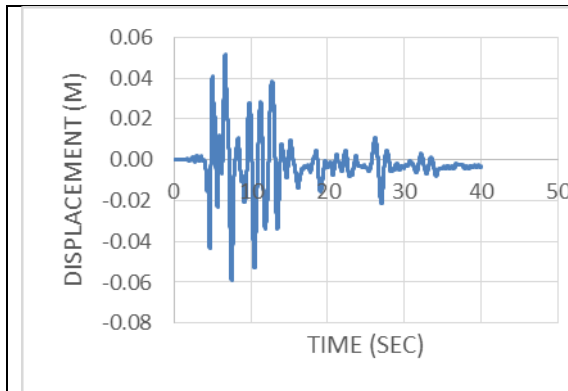


Figure B- 73: Bearing displacement time history of material A TFPB under RSN 767

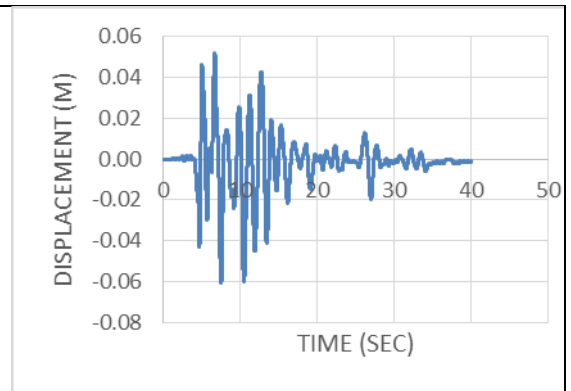


Figure B- 74: Bearing displacement time history of material B TFPB under RSN 767

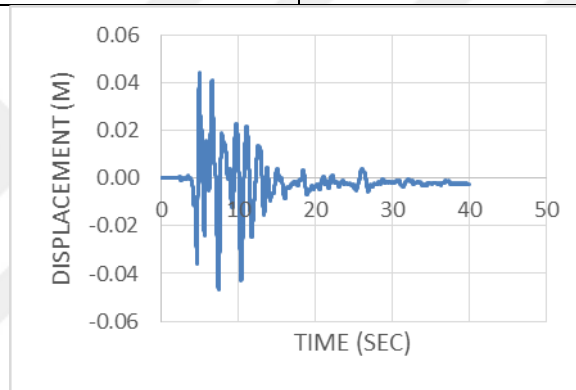


Figure B- 75: Bearing displacement time history of material C TFPB under RSN 767

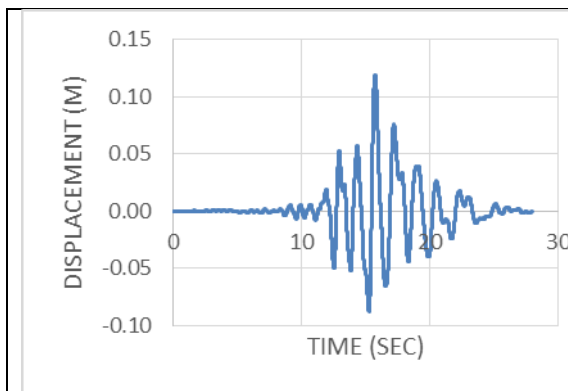


Figure B- 76: Bearing displacement time history of material A TFPB under RSN 848

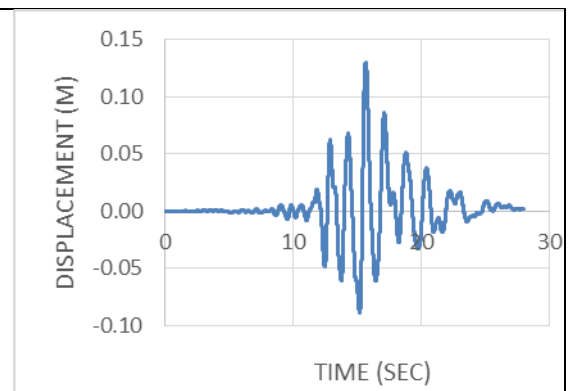


Figure B- 77: Bearing displacement time history of material B TFPB under RSN 848

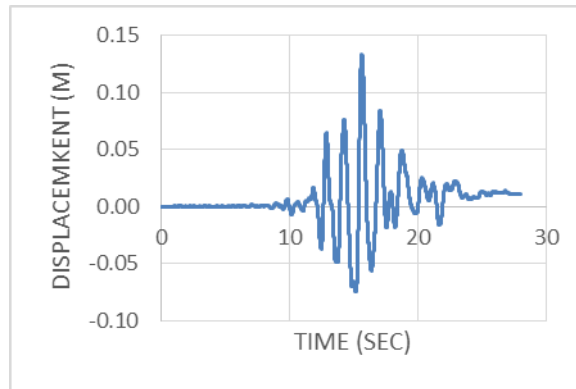


Figure B- 78: Bearing displacement time history of material C TFPB under RSN 848

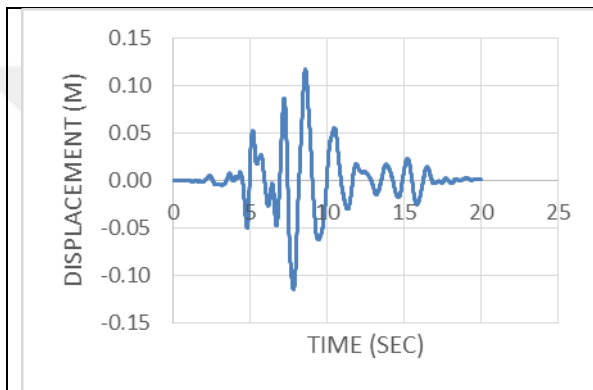


Figure B- 79: Bearing displacement time history of material A TFPB under RSN 960

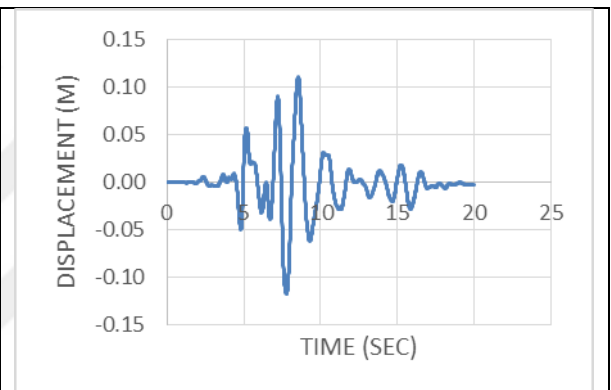


Figure B- 80: Bearing displacement time history of material B TFPB under RSN 960

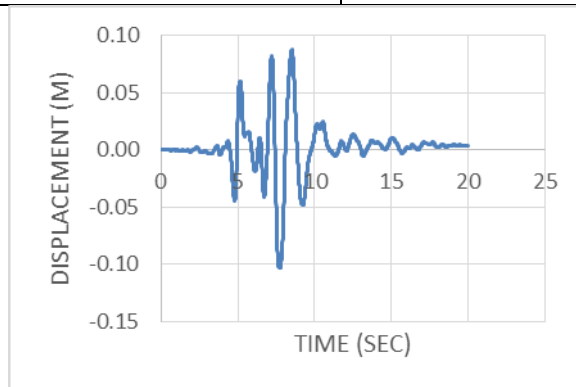


Figure B- 81: Bearing displacement time history of material C TFPB under RSN 960

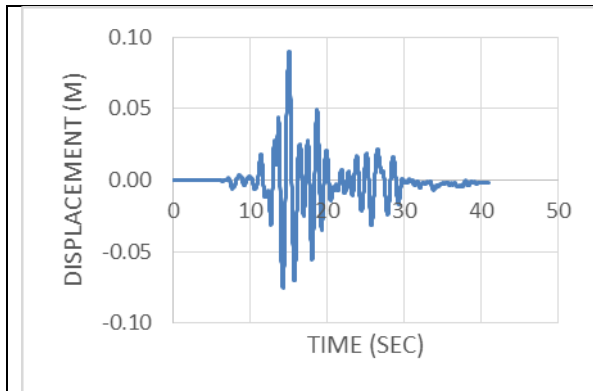


Figure B- 82: Bearing displacement time history of material A TFPB under RSN 1116

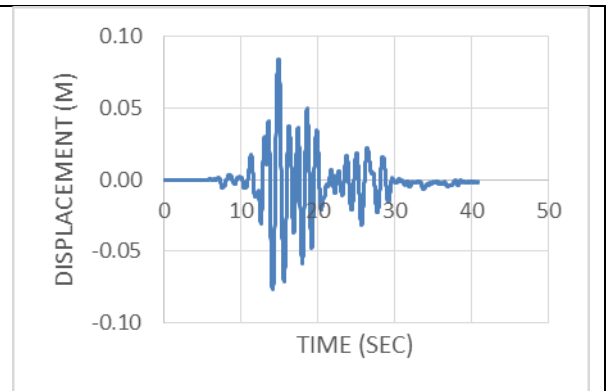


Figure B- 83: Bearing displacement time history of material B TFPB under RSN 1116

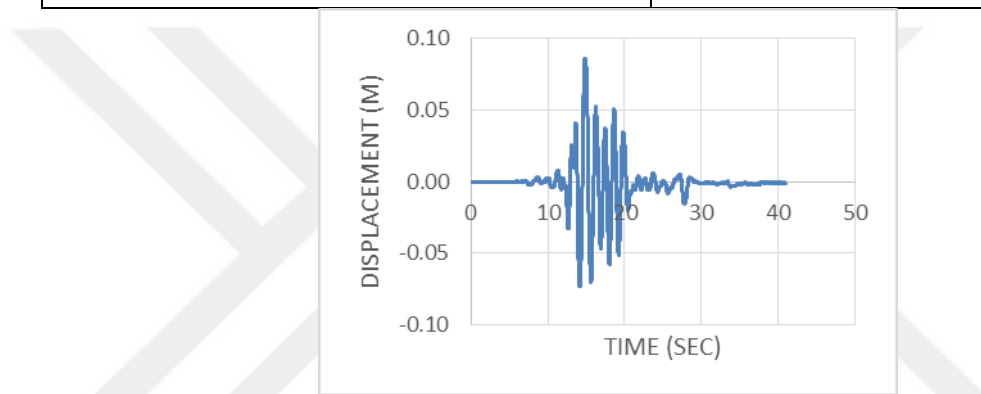


Figure B- 84: Bearing displacement time history of material C TFPB under RSN 1116

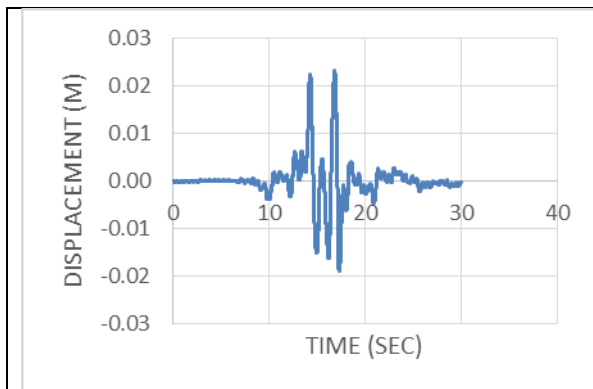


Figure B- 85: Bearing displacement time history of material A TFPB under RSN 1148

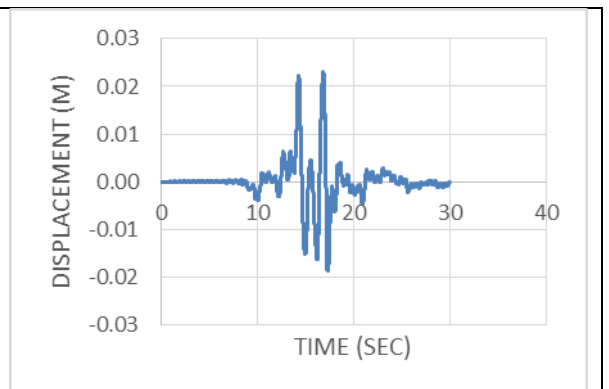


Figure B- 86: Bearing displacement time history of material B TFPB under RSN 1148

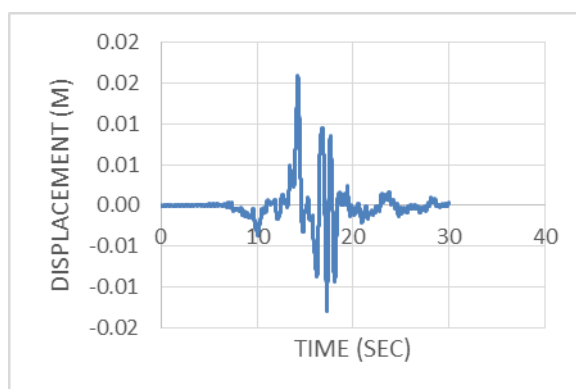


Figure B- 87: Bearing displacement time history of material C TFPB under RSN 1148

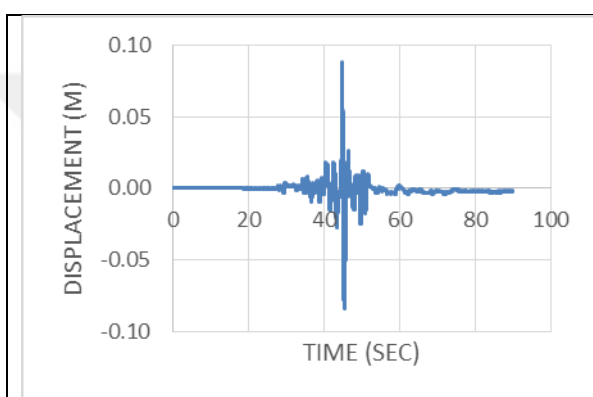


Figure B- 88: Bearing displacement time history of material A TFPB under RSN 1485

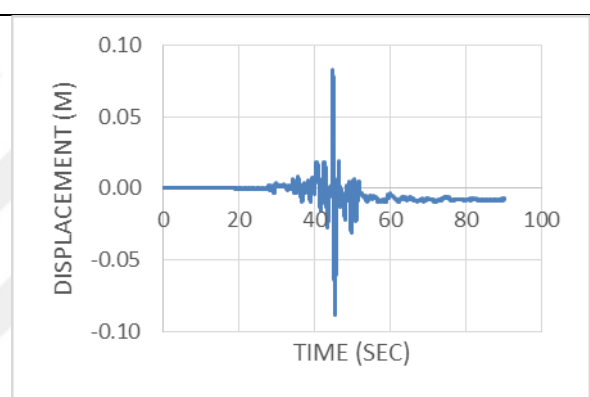


Figure B- 89: Bearing displacement time history of material B TFPB under RSN 1485

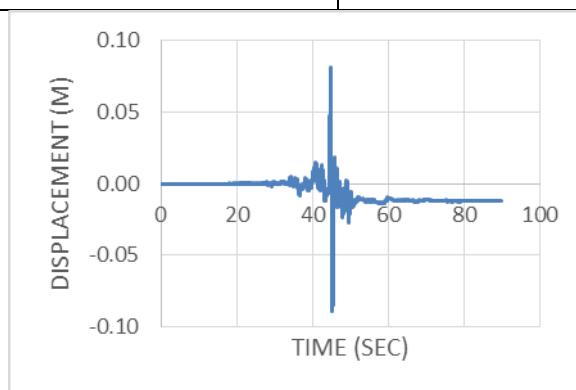
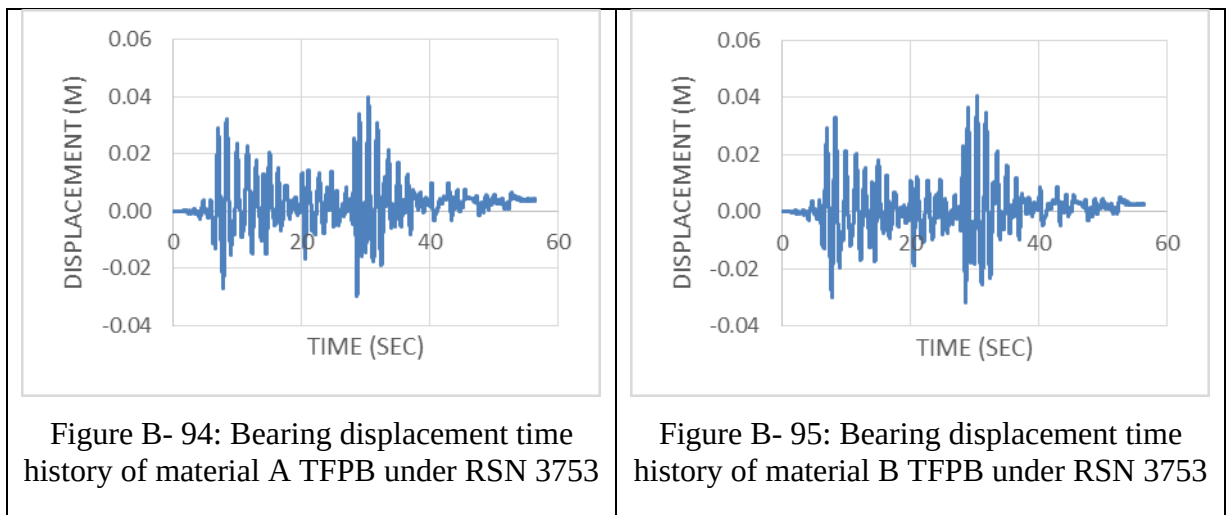
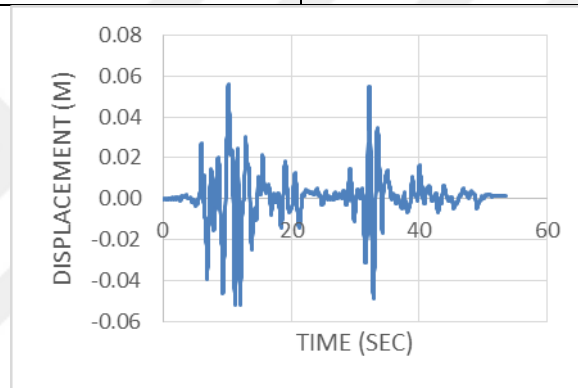
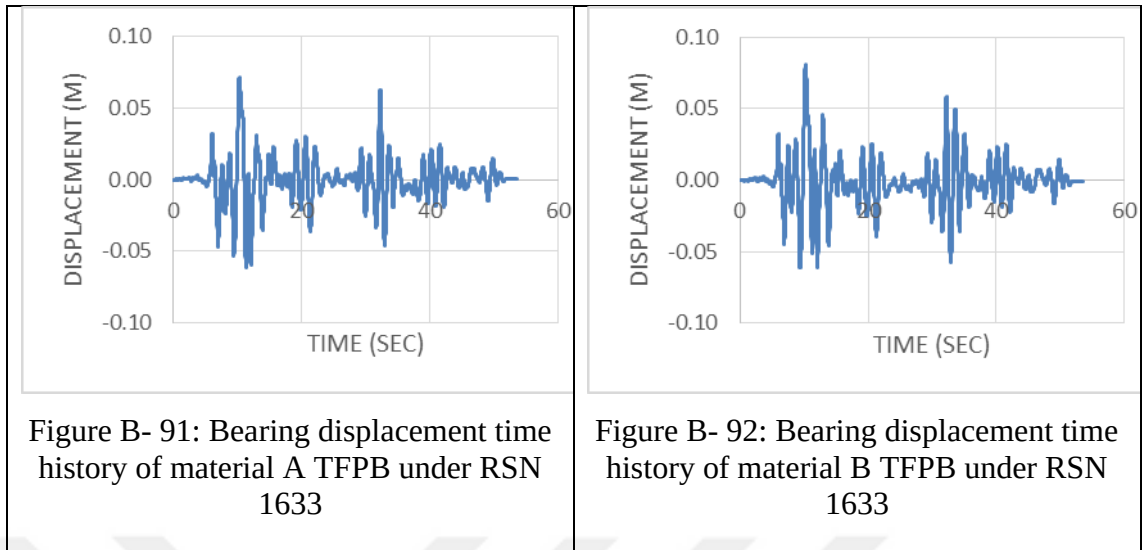


Figure B- 90: Bearing displacement time history of material C TFPB under RSN 1485



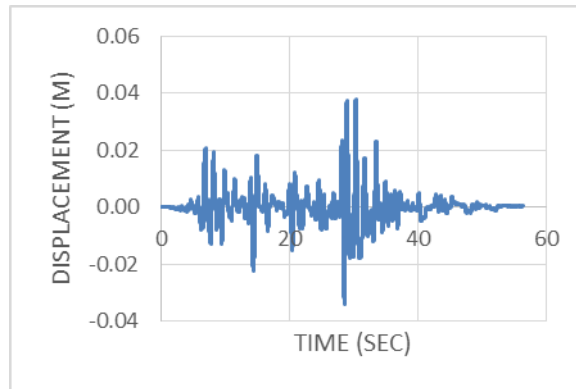


Figure B- 96: Bearing displacement time history of material C TFPB under RSN 3753

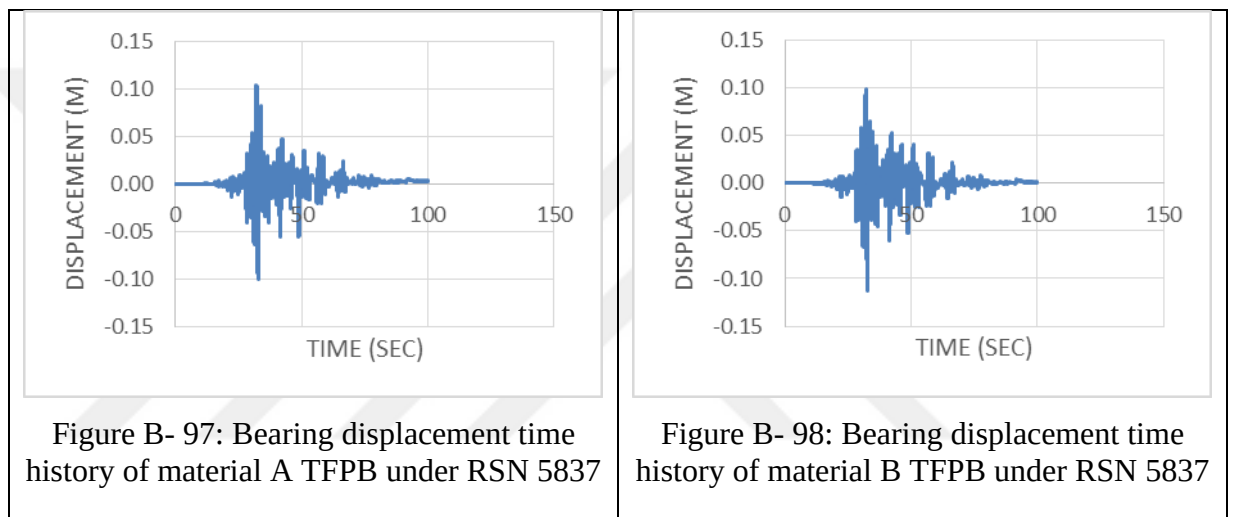


Figure B- 97: Bearing displacement time history of material A TFPB under RSN 5837

Figure B- 98: Bearing displacement time history of material B TFPB under RSN 5837

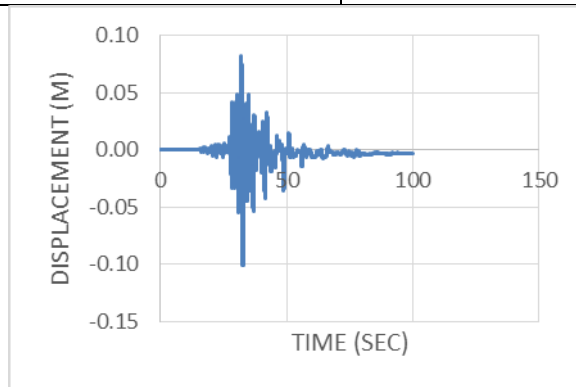


Figure B- 99: Bearing displacement time history of material C TFPB under RSN 5837

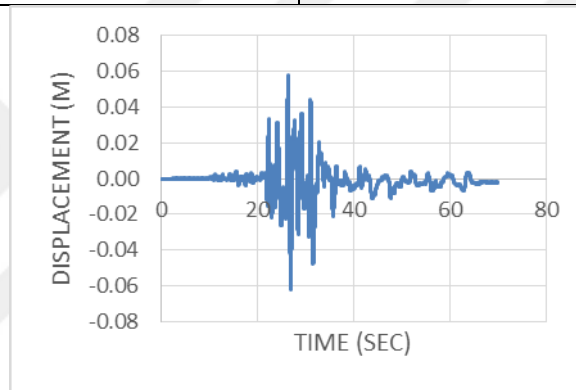
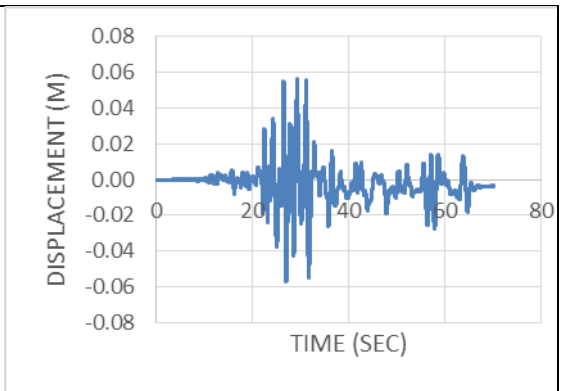
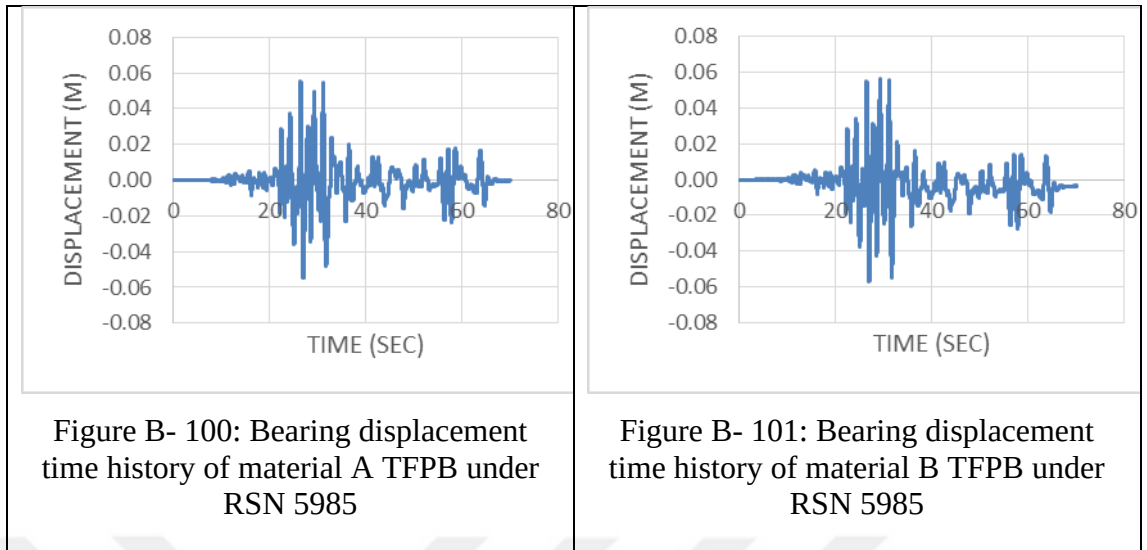
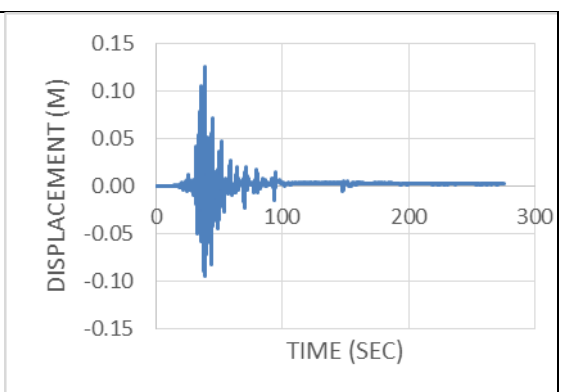
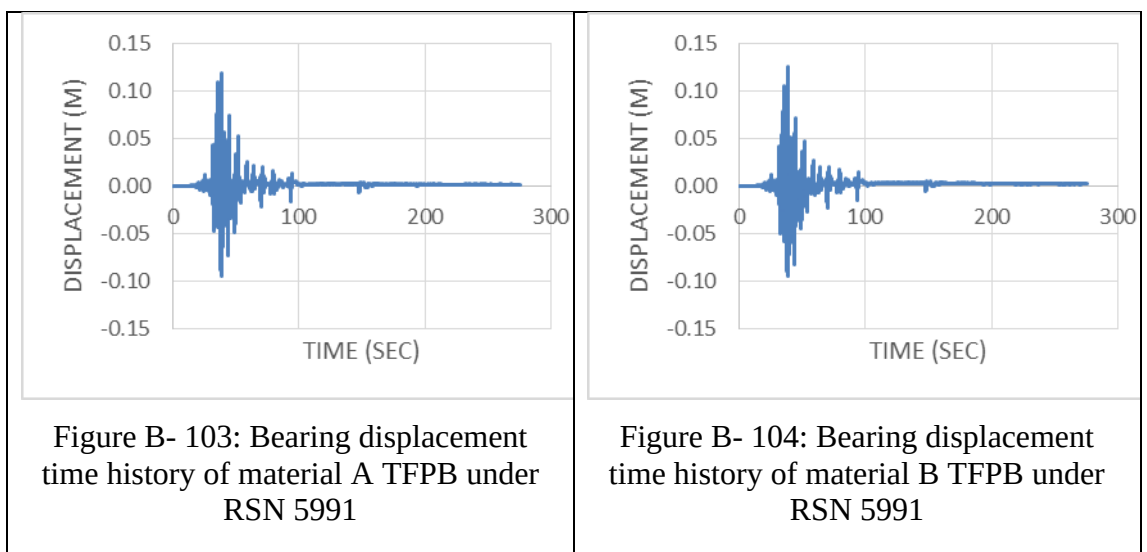


Figure B- 102: Bearing displacement time history of material C TFPB under RSN 5985



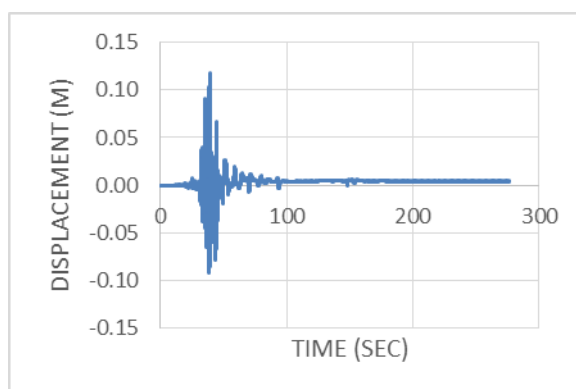


Figure B- 105: Bearing displacement time history of material C TFPB under RSN 5991

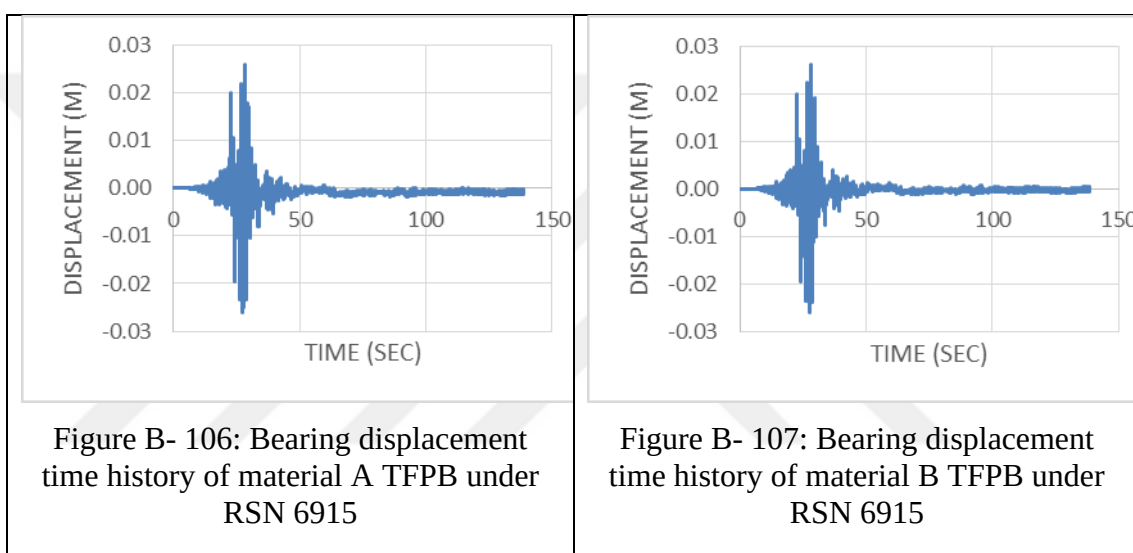


Figure B- 106: Bearing displacement time history of material A TFPB under RSN 6915

Figure B- 107: Bearing displacement time history of material B TFPB under RSN 6915

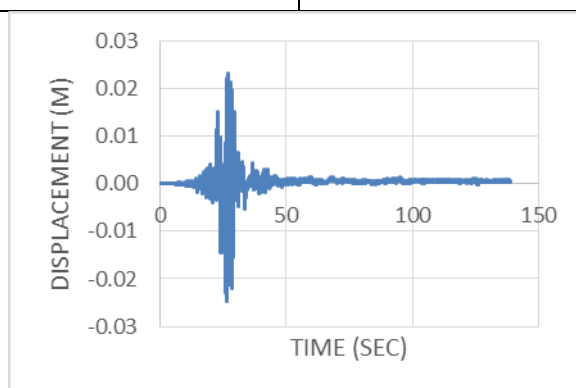


Figure B- 108: Bearing displacement time history of material C TFPB under RSN 6915