

EVALUATION OF DYNAMIC CHARACTERISTICS OF HIGH DAMPING RUBBER BEARING AND PROPOSAL OF HYSTERESIS MODEL CONSIDERING DEPENDENCE ON SHEAR STRAIN AND HARDENING EFFECT

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Kyeonghoon Park

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HARDENING EFFECT**

A Thesis Submitted
In Partial Fulfillment of the Requirements
For the Degree of
Doctor of Engineering

By
Kyeonghoon Park



to the
DEPARTMENT OF CIVIL AND STRUCTURAL ENGINEERING
GRADUATE SCHOOL OF ENGINEERING
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DEPARTMENT OF CIVIL AND STRUCTURAL ENGINEERING
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CERTIFICATE

The undersigned hereby certify that they have read and recommended to the Graduate School of Engineering for the acceptance of this thesis entitled, “*Evaluation of dynamic characteristics of high damping rubber bearing and proposal of hysteresis model considering dependence on shear strain and hardening effect*” by **Kyeonghoon Park** in partial fulfillment of the requirements for the degree of **Doctor of Engineering**.

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ABSTRACT

In regions prone to seismic activity, the imperative for seismic retrofitting and specialized structural design has become increasingly vital. The need for seismic retrofitting and advanced design strategies is further underscored by the aging infrastructure in many seismic-prone areas, as older buildings may not meet current seismic safety standards. As a result, the development of resilient and earthquake-resistant structures has become paramount to mitigate the potential human, economic, and societal losses stemming from seismic events. Seismic retrofitting and design practices aim to enhance the structural integrity of buildings and infrastructure, reducing the risk of collapse and ensuring the safety and well-being of occupants, thus addressing a critical need in these vulnerable regions. In this dissertation, the focus is on HDR (High Damping Rubber) bearings designed using high damping rubber. HDR is a type of rubber bearing used in seismic isolation systems, designed to possess high damping properties that dissipate seismic energy and prevent the transmission of earthquake forces. However, the hysteresis behavior of HDR is highly dependent on the maximum experienced strain, making it highly nonlinear. Consequently, the impact of HDR's hysteresis characteristics on the design is significant, leading to ongoing research on hysteresis models that account for HDR's nonlinearity. The main objective of this research is to investigate the mechanical characteristics and nonlinear behavior of HDR through dynamic loading tests. To investigate hysteretic characteristics of the HDR, a dynamic loading test was conducted according to ISO22762-1 and the Japan Road Association: Design Specifications for Highway Bridges, Part V Seismic Design. Subsequently, based on the experimental results, the aim is to propose a hysteresis model for HDR that incorporates its nonlinearity and to provide a systematic modeling approach. Finally, the proposed hysteresis model will be validated by conducting dynamic analysis and comparing the results with experimental data to assess their accuracy and practicality.

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Chapter 1

Introduction

1.1 Background

Research in many related fields has been continued to minimize the damage to buildings and structures through earthquake-resistant design to prepare for earthquakes. Earthquake-resistant design involves the planning and construction of structures to minimize damage and ensure the safety of occupants during earthquakes. This design approach considers the dynamic forces generated by seismic events and aims to enhance a structure's ability to withstand and absorb these forces without significant damage. Common strategies include incorporating flexible building materials, damping systems, and bracing techniques to mitigate the impact of ground shaking. Engineers also assess the seismic hazard of a region and design structures, accordingly, adhering to specific building codes and standards to enhance overall resilience to earthquakes.

After the Kobe Earthquake that occurred in Japan, it is true that seismic isolation design, which is a method to further improve stability against earthquakes, has been attracting attention rather than structures built with earthquake-resistant design. This earthquake occurred on January 17, 1995, and had a magnitude of 6.9. It struck the city of Kobe and surrounding areas in Japan, causing significant destruction and loss of life. This earthquake resulted in considerable damage to civil engineering structures, such as road bridges, thereby sparking interest in seismic isolation structures and devices. Seismic isolation is a technical strategy employed to mitigate the potential damage caused by earthquakes to structures. This innovative approach seeks to impede the transmission of seismic vibrations to buildings and bridges, thereby minimizing

the risk of structural damage during seismic events. The implementation of seismic isolation involves the use of specialized devices known as seismic isolators or bearings. These devices are strategically placed between the structure and its foundation. They are designed to absorb seismic energy or dampen the seismic motion, with the ultimate objective of reducing the horizontal forces and movements generated by earthquakes. The key benefits of employing seismic isolation in structural design include damage reduction, improved maintainability, and continued operation. Seismic isolation significantly minimizes structural damage caused by seismic activities, enhancing the overall safety and resilience of the structure. At the same time, structures equipped with seismic isolation systems benefit from extended lifespans, and any necessary post-earthquake maintenance or repairs are often facilitated. In addition, Seismic isolation enables structures to remain operational during and after seismic events, contributing to the overall functionality and usability of the facility. This innovative technology finds widespread application in various structures, including buildings and bridges, proving particularly effective in regions prone to frequent seismic activity. The use of seismic isolation reflects a proactive and strategic approach to earthquake-resistant design, ensuring the safety and longevity of critical infrastructure in seismic-prone areas. Among the isolators for seismic isolation, laminated rubber bearings stand out for their ability to deform horizontally, providing seismic isolation performance in the structural foundation. These bearings consist of thin rubber sheets interleaved with steel plates, offering high vertical rigidity to support the superstructure efficiently. Additionally, their flexible rigidity in the horizontal direction during seismic events prolongs the structure's period, thereby minimizing earthquake-induced damage. Laminated rubber bearings come in various types, such as Natural Rubber Bearings (NRB), Lead Rubber Bearings (LRB), and High Damping Rubber bearings (HDR), each employing distinct materials.

NRB, utilizing natural rubber, lacks inherent damping ability, necessitating parallel design with energy-absorbing devices like dampers for effective seismic isolation. A natural rubber bearing is a type of seismic isolation device used in civil engineering and structural design to mitigate the impact of seismic forces on structures. It is

designed to provide flexibility and damping, allowing the building or structure to move independently of the ground motion during an earthquake. The bearing is typically made of layers of natural rubber and reinforcing materials, and it is installed between the superstructure and the foundation. The key characteristics of natural rubber bearings include their ability to absorb and dissipate seismic energy, thus reducing the transmitted forces to the structure. This flexibility helps in isolating the structure from the ground motion, preventing or minimizing damage during an earthquake. Natural rubber bearings are known for their cost-effectiveness, simplicity, and effectiveness in providing seismic protection to a wide range of structures, including buildings, bridges, and infrastructure. Engineers consider factors such as building weight, flexibility, and displacement requirements when selecting and designing natural rubber bearings for seismic applications.

LRB is a type of seismic isolation device used in structural engineering to mitigate the impact of seismic forces on buildings and infrastructure. It is designed to provide flexibility and damping, allowing the structure to move independently of the ground motion during an earthquake. The key feature of lead rubber bearings is the use of a lead core, which contributes to their effectiveness in absorbing and dissipating seismic energy. The lead core is surrounded by layers of natural rubber and reinforcing materials. The lead component enhances the energy dissipation capacity of the bearing, making it particularly effective in isolating the structure from seismic vibrations. Lead rubber bearings are commonly used in the base isolation of buildings and bridges. The advantages of lead rubber bearings include their ability to provide both horizontal and vertical flexibility, allowing for multidirectional movement during an earthquake. This flexibility helps in reducing the transmitted seismic forces to the structure, thereby minimizing damage. Lead rubber bearings are known for their durability, cost-effectiveness, and versatility in a variety of structural applications, contributing to the overall resilience of buildings and infrastructure in earthquake-prone regions.

HDR bearing is a type of seismic isolation device utilized in structural engineering to mitigate the impact of seismic forces on buildings and infrastructure. The primary purpose of these bearings is to provide flexibility and energy dissipation, allowing a

structure to absorb and dissipate seismic energy during an earthquake. The high damping rubber bearing consists of layers of rubber with high damping properties, typically made of a combination of natural rubber or synthetic rubber materials. The damping effect is essential for reducing the amplitude and duration of vibrations induced by seismic activity. Unlike traditional base isolators, which primarily rely on isolating the structure, HDR bearings enhance the dissipation of energy through the inherent damping characteristics of the rubber layers. The key features of high damping rubber bearings include their ability to absorb and dissipate a significant amount of seismic energy, offering improved resilience to structures. These bearings are particularly effective in reducing the transmitted seismic forces and displacements to the structure, thereby minimizing the potential for structural damage. The application of high damping rubber bearings is common in the seismic retrofitting of existing structures and the base isolation of new buildings. They contribute to enhancing the seismic performance and overall safety of structures in earthquake-prone regions. The growing popularity of HDR stems from its remarkable damping performance, ease of construction and management, and the use of environmentally friendly materials. However, the intricate behavior of high damping rubber bearings introduces complexities, with dependencies and nonlinear characteristics arising from factors such as temperature, surface pressure, and shear strain. The structure of the HDR bearings is designed to provide high damping and energy absorption capacities, while also providing structural support to the bridge. During an earthquake, the HDR bearing compresses and deforms, thereby absorbing and reducing the seismic energy and energy transfer to the bridge structure, respectively, and protecting it from damage. However, the addition of carbon black and silica to rubber introduces different dependencies, thereby making evaluating the bearing response difficult (Murota et al., 2021, Chen et al., 2022). Addressing these complexities is crucial for an accurate seismic isolation design using HDR. This research focuses on modeling the hysteresis curve of HDR for dynamic analysis, considering the nonlinearities induced by shear strain dependencies. Additionally, the study delves into the hardening phenomenon observed in rubber bearings subjected to significant deformation, which compromises

the long periodization and damping advantages essential for effective seismic isolation. Comprehensively understanding and modeling these factors aims to enhance the precision and efficacy of seismic isolation designs incorporating HDR.

1.2 Objectives and Scope

The hysteresis models for dynamic analysis were crafted by accounting for the material characteristics and nonlinearity inherent in HDR. Various studies have been undertaken to formulate hysteretic models for laminated rubber bearings. Given the pronounced nonlinearity of HDR, predicting its response to shear deformation is inherently complex. The bilinear model has become the most widely utilized and convenient choice for seismic isolation design. However, it is important to note that this model has limitations when it comes to precisely capturing the dynamic characteristics of HDR bearings and their dependence on various factors. To address these limitations and account for the nonlinearity of HDR bearings, Fujisawa et al. (1993) introduced the double-target model concept. Additionally, Ohtori et al. (1995) proposed an enhanced version, expanding on the bilinear model through dynamic load experiments. This historical model offers a method to independently establish the initial loading path, considering the Mullin effect on HDR. Sanò (1995) assessed HDR bearing mechanical properties through dynamic loading experiments, proposing a hysteresis model for dynamic analysis of seismic behavior in isolated structures. Koo (1998) introduced a nonlinear rate model accounting for the hysteresis of rubber bearings and conducted seismic wave analysis using data from the 1985 Mexico earthquake. Tsai (2003) suggested a rate-dependent hysteretic model by modifying Wen's model and reproducing experimental results. Takenaka (2001) introduced a simplified historical model, the modified HD model, for LRB, aiming to streamline the intricate parameter settings found in existing historical models. While current models effectively depict the mechanical characteristics and dependence on High Damping Rubber (HDR), their practical application is constrained due to the complexity of parameter settings, posing challenges in seismic design implementations. To address this limitation, Mazda (2015) introduced a simplified

bilinear double-target model, streamlining parameter settings for use in seismic response analyses of seismically isolated structures. Referencing the enhanced double-target model, this approach simplifies the intricacies present in current hysteresis models, allowing for a more straightforward practical implementation (Park et al., 2020). Naito et al. (2017) introduced a hysteresis model incorporating the hardening phenomenon within the double-target model, utilizing experimental findings from LRB. Based on the current research, hysteresis models have been developed and proposed for various types of laminated rubber bearings.

In the case of high damping rubber bearings, previous studies indicate strong nonlinearity concerning shear strain, and a hardening phenomenon occurs at significant shear strains. Consequently, developing a hysteresis model that adequately considers these characteristics presents challenges. Simultaneously, the bilinear model is commonly employed as a hysteresis model for laminated rubber bearings, including high damping rubber bearings. While the bilinear model is advantageous due to its simplicity and fewer required parameters, its accuracy diminishes when applied to materials with nonlinearities, such as dependence on shear deformation and hardening phenomena observed in high damping rubber bearings. Thus, there is a need to propose a hysteresis model that enhances seismic safety and facilitates accurate analysis, accounting for the specific characteristics of high damping rubber bearings such as dependence on shear strain, hardening phenomenon and independent behavior. Additionally, if a model that can consider the nonlinearity of HDR with a small number of parameters, such as a bilinear model, is proposed, it is expected that the stability against earthquakes will improve because the accuracy of the analysis results will increase.

This research endeavors to advance our understanding of high damping rubber by developing an advanced nonlinear hysteresis model. The focal points of this model include a meticulous consideration of HDR's dependence on experienced shear strain and an in-depth exploration of the associated hardening effect. The dynamic loading tests will be instrumental in providing real-world insights into how HDR responds to varying dynamic conditions.

Through these experiments, capturing the complexities of HDR behavior, including its capacity to absorb and dissipate energy, as well as any changes induced by shear strain and the hardening phenomenon under dynamic loads is the goal. The comprehensive data obtained from these experiments will not only serve to validate the proposed nonlinear hysteresis model but also contribute to a more holistic understanding of HDR's dynamic performance. By correlating empirical findings with theoretical modeling, our research aims to bridge the gap between laboratory experiments and practical applications, offering valuable insights for seismic design and engineering. Furthermore, this research aligns with broader goals of optimizing seismic isolation system performance. The proposed nonlinear model, enriched by experimental data, aspires to be a versatile tool for engineers and designers seeking to enhance the resilience of structures against seismic forces. Through this multifaceted approach, our research aims to make a substantive contribution to the field, fostering advancements in seismic design methodologies and the effective utilization of HDR in seismic isolation applications.

1.3 Organization of Thesis

1.3.1 Chapter overview

Chapter 1 introduced the research background, the scope, and the objectives of this dissertation. Literature reviews relating to seismic isolation and laminated rubber bearings were summarized. The organization of the dissertation was illustrated at the end.

Chapter 2 described the characteristic verification test for dependence on the shear strain of HDR conducted using scaled-down HDR specimens. These HDR specimens, one-sixth the size of full-scale HDR bearings, were manufactured by Yokohama Rubber Co. Ltd., Japan. Based on the dynamic loading tests, HDR's representative nonlinear characteristics, including its dependence on strain rate and the presence of hardening phenomenon, were elucidated. To capture HDR's historical characteristics, progressively increasing sine waves were employed as input waveforms. The test results allowed for the assessment of HDR's mechanical properties and enabled a quantitative evaluation of its nonlinearity.

Chapter 3 evaluated the mechanical characteristics of HDR based on experimental results. The equivalent stiffness, absorption energy, damping ratio, and strain energy, which crucially influence the material and dynamical characteristics of HDR, were evaluated using the data from each experimental result. A comparative analysis was conducted for each cycle and step, allowing for a quantitative assessment of the nonlinearity and dependence on shear strain of HDR through the evaluation of its mechanical characteristics.

Chapter 4 proposed an advanced hysteresis model called the trilinear double target model that takes into account the dependence on the experienced shear strain and hardening phenomenon of HDR. A proposed hysteresis model was developed that can consider and reproduce each independent dependence on shear strain in the positive and negative directions from the origin. Especially, the maximum experienced shear strain of HDR is not determined by the absolute value of the shear strain in either direction, but the maximum experienced shear strain for the shear strain in the positive and negative directions from the origin was set independently. As a result, in the

proposed HDR hysteresis model, the nonlinear hysteresis characteristics due to the shear strain experienced in one direction did not affect the opposite direction. Finally, the validity of the proposed hysteresis model was assessed by reproducing the experimental results and evaluating the mechanical properties.

Chapter 5 explained dynamic loading tests conducted to examine the response of HDR under seismic shear deformation. The main purpose of these dynamic loading tests was to validate the actual behavior of HDR and assess the suitability of the proposed hysteresis model. The input waves utilized in this dynamic loading test were based on assumed design ground motions.

Chapter 6 summarized the work presented in this dissertation, and further research topics that emerged from this work were proposed.

1.3.2 Flow of the Research

Fig.1.1 shows the flow chart of the research. I conduct dynamic loading tests to gather hysteretic data, aiming to verify and understand the characteristics of the materials under consideration. After obtaining the dynamic loading test data, the focus shifts to evaluating the mechanical properties of high damping rubber bearings. This step involves analyzing how the material responds to shear deformation. Continuously, utilizing the gathered data, a nonlinear hysteresis model is designed. This model aims to capture and represent the complex, nonlinear behavior observed in the mechanical properties, providing a mathematical representation of the system. Finally, the designed hysteresis model is then subjected to an assessment of its validity and effectiveness. This involves testing the model against real-world scenarios or comparing its predictions to empirical observations. The goal is to ensure that the model accurately reflects the mechanical behavior of the high damping rubber bearings. the research progresses from experimental verification of characteristics through dynamic loading tests, followed by an in-depth evaluation of mechanical properties. The findings are then used to formulate a nonlinear hysteresis model, and finally, the validity and effectiveness of the model are thoroughly assessed to ensure its reliability in representing the observed behaviors.

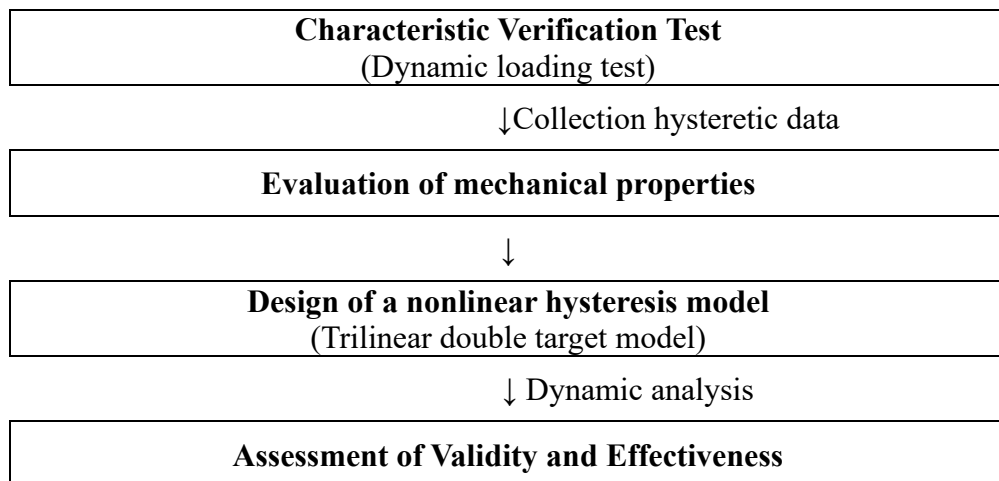


Fig.1.1 The flow chart of the research

Chapter 2

Characteristic Verification Test for Dependence on Shear Strain of HDR

2.1 Introduction

To investigate the hysteretic behavior and nonlinear characteristics of the HDR, a dynamic loading test was conducted on a scaled-down specimen according to ISO22762-1: Elastomeric seismic protection isolators – Part 1: Test methods (2010) and the Japan Road Association: Design Specifications for Highway Bridges, Part V Seismic Design. The loading test aimed to validate the performance of the HDR in seismic applications and provide insights into the behavior of the material under different loading conditions. Hence, in this chapter, dynamic loading tests were conducted with two types of input waves. The first involves validating the dynamic characteristics of HDR using sine waves. The experiment aims to acquire historical data, allowing for the quantitative assessment and confirmation of the nonlinear characteristics of HDR. Subsequently, based on this experimental dataset, a hysteresis model is introduced to enhance the accuracy of predicting horizontal load behavior. This model takes into account the inherent nonlinearity associated with HDR, providing a more precise representation of its dynamic response. Subsequently, the second experiment entails a dynamic loading test utilizing random waves. The input wave for this experiment is crafted based on the bearing's response to the design earthquake motion. The primary objective of this loading experiment is twofold: firstly, to gather historical data on the actual behavior of the HDR test specimen under arbitrary horizontal loads, such as those induced by earthquakes, and secondly, to

validate the proposed history model considering the nonlinearity of HDR presented in this thesis. The HDR historical data obtained from this experiment is deemed to be closer to reality, offering a more accurate representation of the dependency and nonlinearity inherent in HDR. The HDR bearings exhibit highly nonlinear behavior owing to their unique compositions and designs. Moreover, the restoring force of the HDR bearing is highly dependent on the amplitude and frequency of external loads, thereby making them highly nonlinear. The relationship between the restoring force and displacement of the bearing is also in turn highly nonlinear, and the stiffness of the bearing changes depending on the level of the deformation. Additionally, the HDR bearings exhibit a strain-dependent behavior, wherein the maximum empirical strain affects the mechanical properties of the bearing. This is a representative dependence and hysteresis characteristic of the HDR bearing based on the Mullins effect. The Mullins effect is a phenomenon observed in the mechanical behavior of elastomers, specifically in the context of rubber materials. Named after the scientist Robert L. Mullins, this effect refers to the softening or reduction in the stiffness of rubber during cyclic loading or deformation (Mullins et al., 1969, Lake et al., 1967, Nairn et al., 1995). It is characterized by a decrease in the material's elastic modulus and tensile strength over successive loading cycles. The Mullins effect is typically associated with the irreversible changes in the microstructure of rubber, specifically related to the breaking and reforming of filler-filler and filler-polymer bonds within the material. During the initial loading cycles, these bonds break, leading to a reduction in stiffness. Subsequent unloading and reloading cycles cause the creation of new bonds and a partial recovery of the material's mechanical properties, but typically not to their original values. This leads to a cumulative softening effect over multiple loading cycles. The Mullins effect refers to the change in strength and stiffness observed between the first loading cycle of a virgin specimen and subsequent loading cycles. This effect is attributed to the irreversible deformation of the material caused by the breaking of the chemical bonds within its molecular structure. The properties calculated from the first-cycle data are commonly referred to as virgin properties, whereas those calculated from subsequent cycles are referred to as Mullins effect

properties (Hwang et al., 2002, Jankowski et al., 2003). Understanding the Mullins effect is important in terms of accurately modeling the mechanical behavior of materials, such as HDR, under cyclic loading conditions (Quang et al., 2015, Li et al., 2022). In addition, the duration of ground motion has an impact on the nonlinearity of high damping rubber. Li et al. (2022) demonstrated that an increase in earthquake intensity leads to noticeable stiffness degradation in HDR bearing. This degradation's influence on structural responses becomes more pronounced when subjected to extended periods of ground motion. The hardening phenomenon is a crucial nonlinear behavior that requires close attention when modeling the mechanical characteristics of HDR bearing (Alhan et al., 2016). The hardening effect in rubber materials is characterized by an increase in stiffness and resistance to deformation over time, particularly during repeated loading cycles. Unlike the Mullins effect, which involves softening, the hardening phenomenon is influenced by several mechanisms that induce changes in the rubber's molecular structure. One contributing factor to the hardening effect is strain-induced crystallization. When rubber undergoes repeated deformation, especially at high strain levels, the molecular chains within the material align and crystallize. This alignment enhances stiffness and resilience, leading to an overall hardening effect. Chemical cross-linking is another mechanism influencing rubber hardening. The introduction of cross-linking agents or exposure to specific environmental conditions can create additional chemical bonds between polymer chains. These cross-links restrict the movement of polymer segments, making the material stiffer and less prone to deformation. Furthermore, changes in the molecular structure of rubber can contribute to its hardening. External factors such as temperature, pressure, or exposure to certain substances can induce alterations in the arrangement of polymer chains. These changes result in a more organized and rigid structure, contributing to the overall hardening of the material. In practical applications, understanding the hardening effect is crucial, especially in scenarios where maintaining consistent mechanical properties of rubber over time is essential. This knowledge is pertinent, for instance, in the design and durability assessment of engineering components or automotive parts subjected to repeated loading cycles.

Several studies have been conducted on the hardening phenomenon that occurs in laminated rubber bearings in a large shear strain range (Naito et al, 2017, Chen et al., 2022). The degree of hardening in the HDR bearing depends on different factors, including the amplitude and frequency of loading, temperature, and loading duration. A thorough understanding of the hardening phenomenon is essential for developing accurate models that can predict the dynamic response of the HDR bearing during seismic events, such as earthquakes. Studies on the evaluation and modeling of the hysteretic characteristics of HDR by bidirectional loading tests have been conducted (Damian et al. 2004, Ragni et al. 2009, Dang et al. 2016). However, in this study, a unidirectional loading test was conducted to investigate the nonlinear characteristics of shear deformation. This test followed the Shear Deformation Test Standard outlined in the Manual of Highway Bridge Bearing, Japan Road Association. Additionally, other studies have explored the nonlinearity of the HDR bearings and their long-term performance and temperature dependence in terms of durability (Gu et al., 2006, Alejandro et al., 2007, Paramashant et al., 2011, Saito et al., 2018). For instance, one study inspected the HDR bearings used in bridges in accelerated thermal oxidation tests to quantitatively evaluate their performance over time. The results of this study show that a prediction model can be used to assess the performance of the HDR bearings over time. In previous studies, different loading experiments were conducted to investigate the dynamic characteristics of the HDR bearings, obtain nonlinear hysteresis data, and conduct dynamic evaluations. These experiments included unidirectional and bidirectional loading tests using scaled-down HDR test specimens, considering the shear deformation axis and performance of the test equipment. Troy et al. (2001) investigated different nonlinearities by simultaneously performing unidirectional and bidirectional loading tests on the cyclic behavior of the HDR. Shoji et al. (2001) investigated not only the bearing hysteresis characteristics but also the behavior of a pier using pier and bearing test specimens in an HDR experiment. Bhuiyan et al. (2009) performed a cyclic shear, multistep relaxation, and simple relaxation test to evaluate the mechanical properties and conducted a seismic analysis. Yamamoto et al. (2009, 2012) conducted experiments using a full-scale HDR bearing

to obtain actual hysteresis curves that considered the scale effect. Another loading experiment was conducted to evaluate the mechanical properties of the HDR under temperature dependence by installing a temperature-control device (Saito et al., 2018, Paramashant et al., 2011). In this study, to confirm the nonlinear hysteretic characteristics of the HDR, a dynamic load test was conducted following JIS K 6411, which is a performance verification test standard for laminated rubber used in seismic bearings for road bridge seismic isolation in Japan (Japan Road Association, 2002; Japan Road Association, 2004).

2.2 Test Setup

2.2.1 Experimental apparatus

Fig. 2.1 shows the test setup and mounting of the HDR specimen. A load cell installed under the test specimen was used to measure the vertical load, and the horizontal displacement was measured on both sides of the test specimen. In the experimental arrangement, the application of shearing deformation to the HDR specimen while under a vertical load led to vibrations in the hydraulic jack. Consequently, in this dynamic loading tests, L-shaped steel plates were strategically reinforced on both sides of the hydraulic jack to effectively mitigate shaking and ensure stability. Oil was applied to the rail to minimize the friction force and energy loss between the sliding bed and shaking table. Additionally, to consider the temperature dependence, a heating device was set up to maintain a constant ambient temperature (Park et al. 2020). To comply with the standards of the Japan Road Association, the vertical compressive stress was set to 6.0 N/mm^2 , which corresponds to the design dead load reaction force. During the loading test, a constant 60 kN vertical load was applied to the specimens using a hydraulic jack. The hybrid actuator is illustrated in Fig. 2.1 and Fig. 2.2. Table 2.1 shows the properties of the 20kN Hybrid Actuator with shear strain applied. It was capable of applying a maximum tensile and compressive load of $\pm 20 \text{ kN}$ with a stroke of $\pm 400 \text{ mm}$. The allowable frequency range was 0.01 to 10 Hz. Fig. 2.3 shows the load cell that measured the vertical load. The product number of this load cell is

1511026213 and was manufactured by CHUO PRECISION INDUSTRIAL CO., LTD. The product name is Tension/compression type load cell and it can measure a rated load of up to 200kN. Fig. 2.4 illustrates a hydraulic jack designed to exert a vertical load. The hydraulic jack was strategically positioned to maintain a constant vertical load of 60 kN in adherence to experimental standards. To address minor variations over time, precautions were implemented to sustain the stability of the vertical load throughout the experiment. Fig. 2.5 shows the newly designed L type plates in this experiment. As a result of conducting the test with the same test device as in the previous experiment, shaking occurred in the area where the hydraulic jack that applies a vertical load was installed. As a result, it was confirmed that noise occurred in the HDR hysteresis curve obtained from the experimental results. Therefore, in this experiment, L type plates were installed on both sides of the hydraulic jack and firmly fixed in order to minimize the effect of noise caused by shaking. Fig. 2.6 represents a precision measuring instrument strategically installed for gauging the horizontal displacement of the HDR specimen. Notably, measurements were meticulously conducted on both sides of the shaking table to enhance precision and ensure the accuracy of the recorded data. Fig. 2.7 shows temperature measurement. When conducting the characteristic verification test, the ambient temperature and the temperature of the HDR specimen were checked to keep them constant.



Fig. 2.1 Test setup

Table 2.1 Properties of 20kN Hybrid Actuator

Particulars	Specifications
Rated load	20kN (tension/compression)
Stroke	400mm (mechanical stroke)
Velocity range	$V=0.5\sim235\text{mm/sec}$
Excitation frequency	0.01~10Hz
Setting load accuracy	$\pm1.0\%\text{FS}$
Positioning accuracy	$\pm0.05\text{mm}/20\text{kN load}$

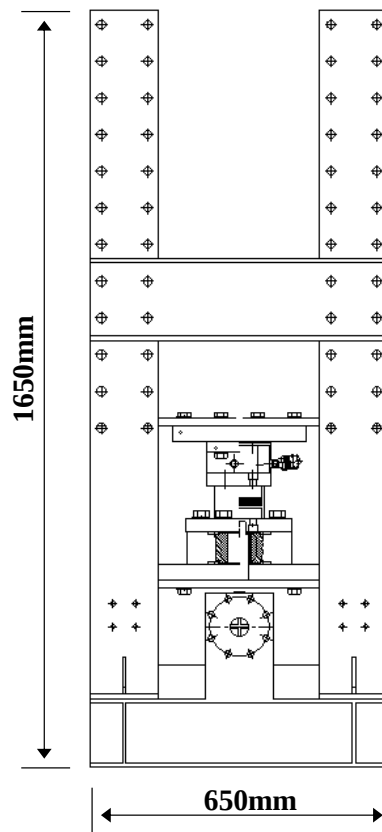
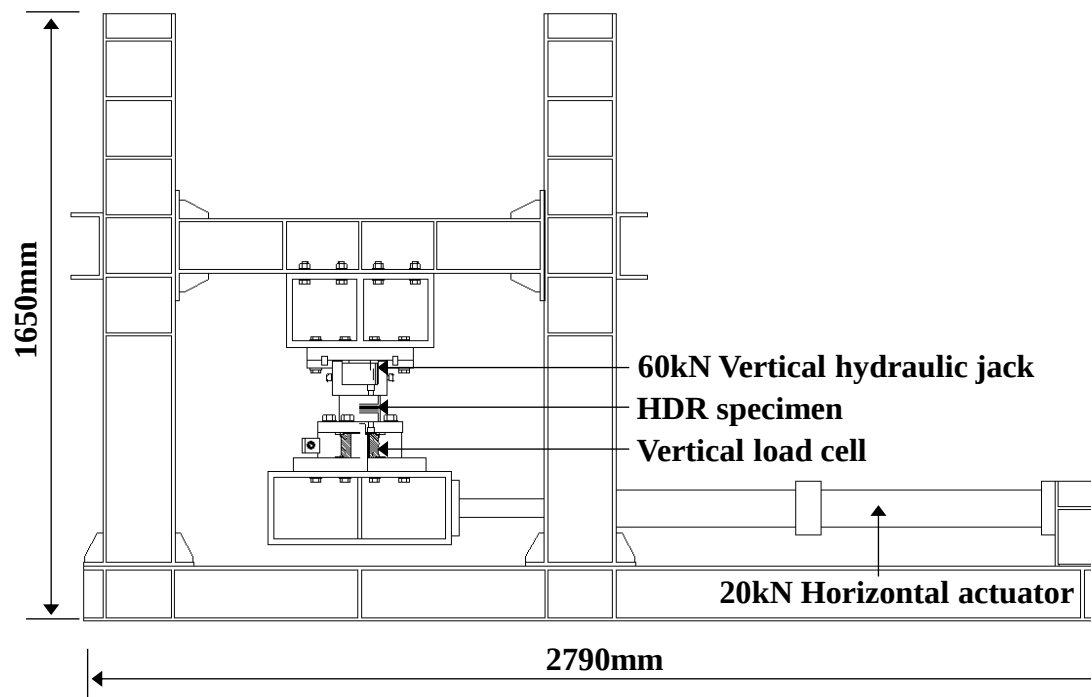


Fig. 2.2 Hybrid actuator

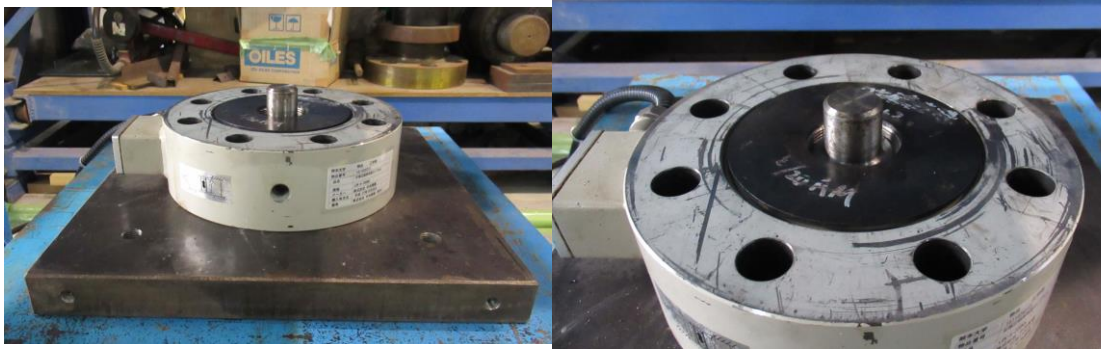


Fig. 2.3 Load cell



Fig. 2.4 Hydraulic jack



Fig. 2.5 L type plates

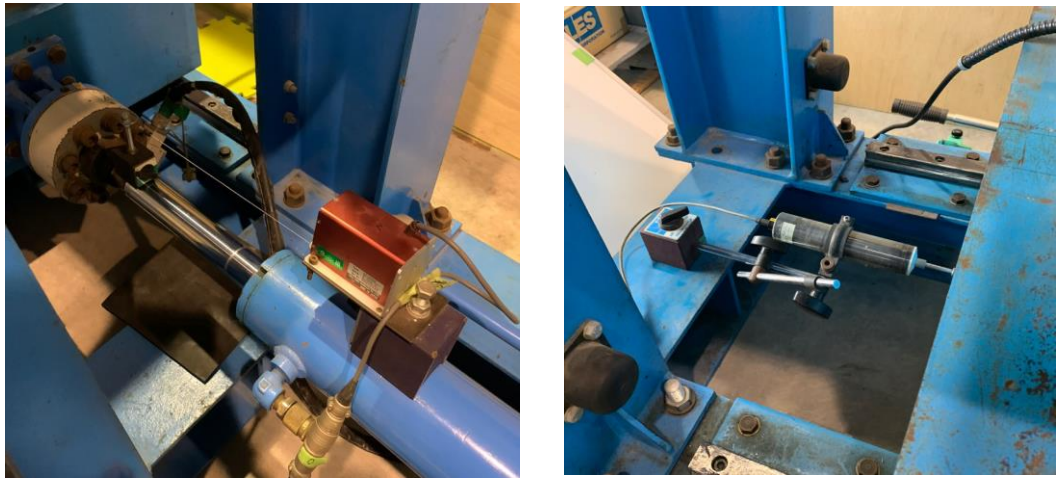


Fig. 2.6 Displacement measurement



Fig. 2.7 Temperature measurement

2.2.2 Specimen configuration

The loading test utilized three HDR specimens with a cross-sectional area of $100 \times 100 \text{ mm}^2$, comprising four high-damping rubber layers, each of thickness 4 mm, and steel plates of thickness 2.3 mm. The nominal shear moduli of the specimens were 0.8 MPa. The specimens were manufactured by Yokohama Rubber Co. Ltd., Japan, which is a well-known manufacturer of high-quality rubber. The test specimens were carefully designed and manufactured to satisfy the requirements for conducting dynamic loading tests on HDR bearings. The HDR specimens are shown in Figs. 2.8-2.9, and the dimensions and material properties of the HDR specimens are presented in Table 2.2.

Table 2.2 Dimension and material properties of HDR specimens

Particulars	Specifications
Number of specimens	3
Rubber Type	HDR
Cross-section A (mm ²)	100×100
Number of rubber layers	4
Thickness of one rubber layer (mm)	4
Total rubber thickness h (mm)	16
Thickness of one steel plate t_e (mm)	2.3
Nominal shear modulus G (MPa)	0.8

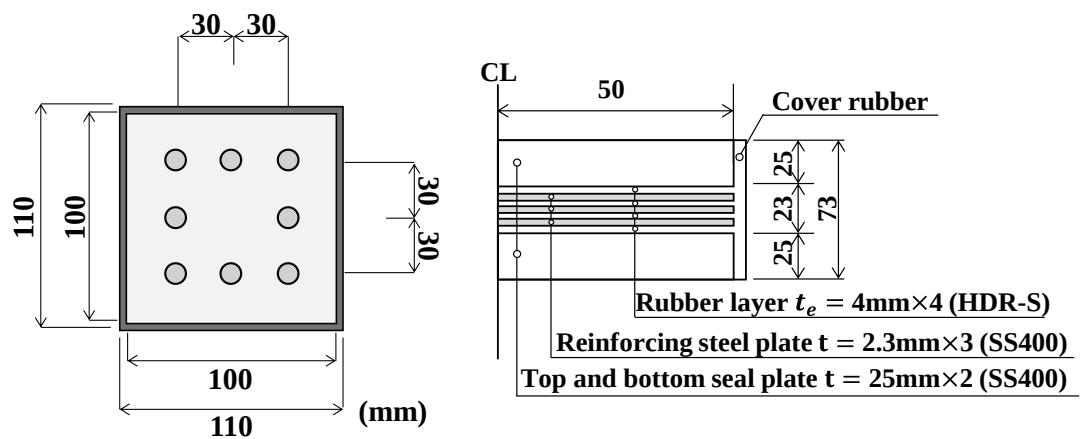


Fig. 2.8 HDR specimen cross section

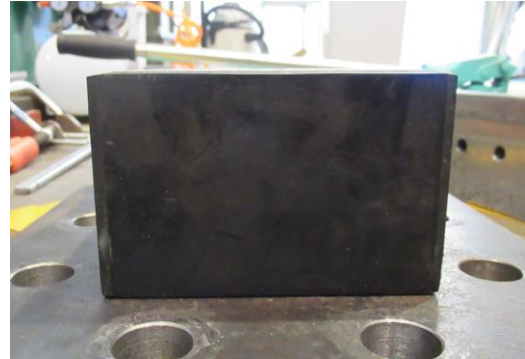
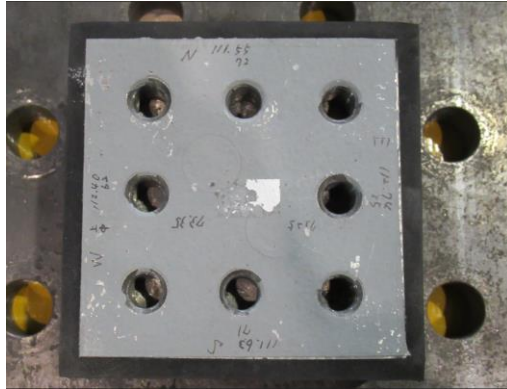


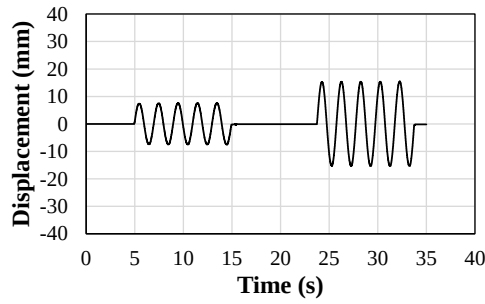
Fig. 2.9 HDR specimen

2.3 Test Program

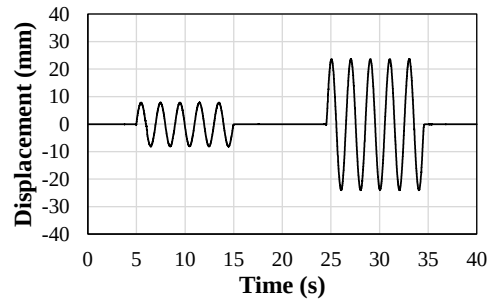
Fig. 2.10 shows the details of the waveforms and test program conducted to investigate the hysteretic characteristics and nonlinearity of the HDR based on the Manual for Highway Bridges Bearings and Design Specifications for Highway Bridges. Table 2.3 shows the details of the test program. The test program comprised exciting the HDR specimen with a sinusoidal wave (0.5 Hz) five times each and loading it in the STEP 1 to 4 sequence. Each step had a 10-second interval, and 30 min elapsed between each loading step (Peng et al. 2015). The shear strain was applied to the specimen as a gradually increasing sine wave from 50% to 250% shear strain. Furthermore, to investigate the dependence of the HDR on the shear strain, larger shear strains were gradually applied after each step, starting from the initial shear strain. This loading plan permitted the comparison of the shear strains of a similar size for each step and investigated the effect of the shear deformation experienced by HDR test specimens in the past. Additionally, large shear strains of 200% and 250% were applied after Step 3 to confirm the hardening phenomenon of the HDR. The test program and waveforms were designed to provide a comprehensive understanding of the HDR behavior under cyclic loading conditions.

Table 2.3 The details of the test program

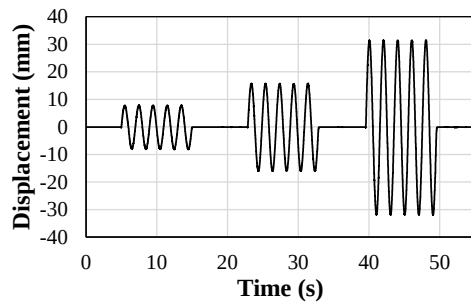
Frequency (0.5Hz)	Strain rate (Displacement)			
STEP1	50% (8mm)	100% (16mm)		
STEP2	50% (8mm)	150% (24mm)		
STEP3	50% (8mm)	100% (16mm)	200% (32mm)	
STEP4	50% (8mm)	100% (16mm)	150% (24mm)	250% (40mm)



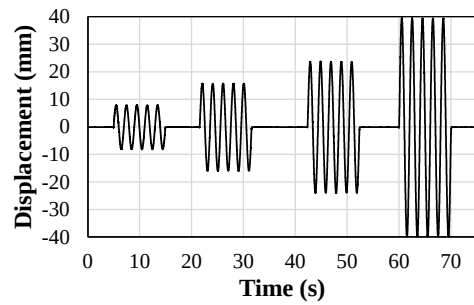
(a) STEP1 ($\pm 50\%$, $\pm 100\%$)



(b) STEP2 ($\pm 50\%$, $\pm 150\%$)



(c) STEP3 ($\pm 50\%$, $\pm 100\%$, $\pm 200\%$)

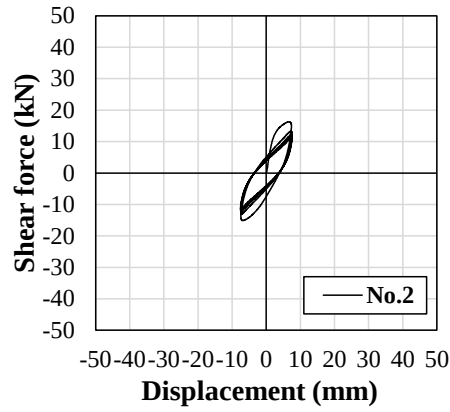


(d) STEP4 ($\pm 50\%$, $\pm 100\%$, $\pm 150\%$, $\pm 250\%$)

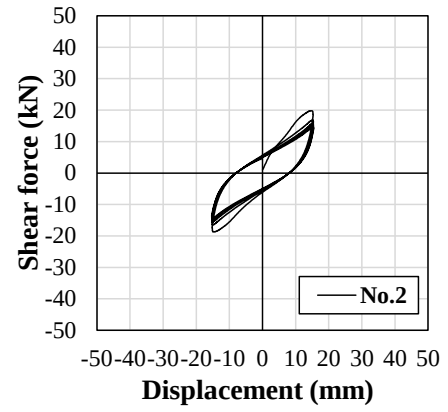
Fig. 2.10 The waveforms of the sinusoidal wave

2.4 Test results

The following are the results of the characteristic verification test for HDR specimens No.2 to No.4. The hysteresis curve for the shear strain applied to each step is shown for each specimen. In this study, it was confirmed that noise due to shaking did not occur in the hysteresis curves of the three HDR test specimens due to the influence of the L type plates installed to obtain accurate experimental results. Figs. 2.11-2.13 show the results of STEP1 of the loading plan. Figs. 2.14-2.116 showcase the outcomes of STEP2 of the loading plan. Subsequently, Figs. 2.17-2.19 show the results of STEP3 of the loading plan. Additionally, Figs. 2.20-2.22 present the results of STEP 4 of the loading plan. Fig.2.23 shows the experimental results for all steps.

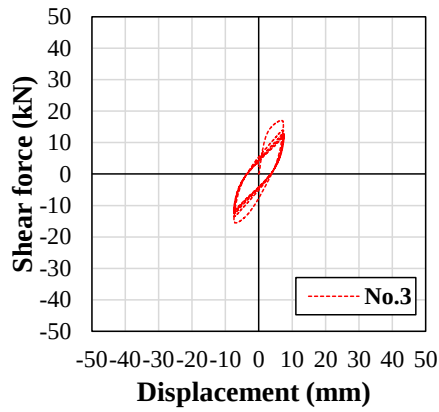


(a) $\pm 50\%$ Shear strain

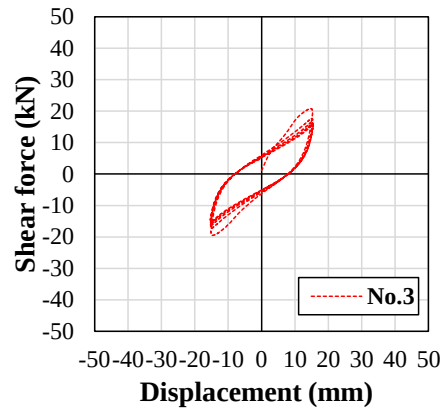


(b) $\pm 100\%$ Shear strain

Fig. 2.11 STEP1 (No.2 Specimen)

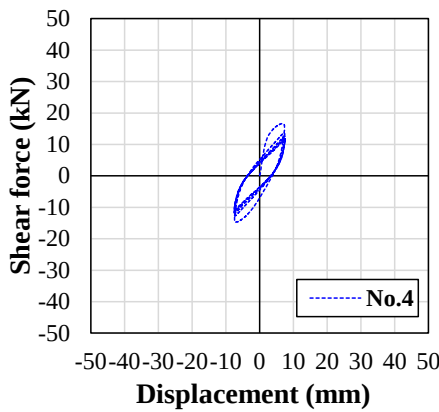


(a) $\pm 50\%$ Shear strain

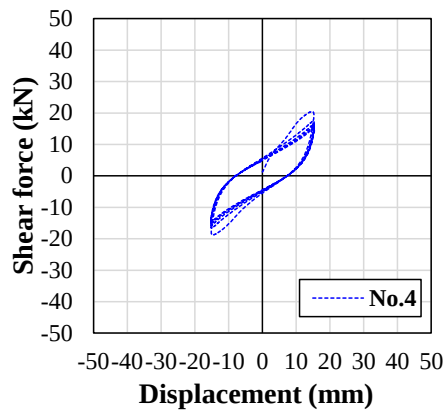


(b) $\pm 100\%$ Shear strain

Fig. 2.12 STEP1 (No.3 Specimen)

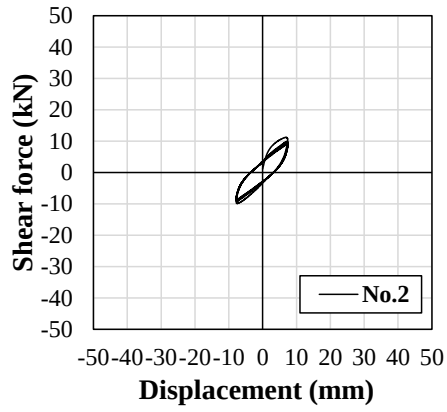


(a) $\pm 50\%$ Shear strain

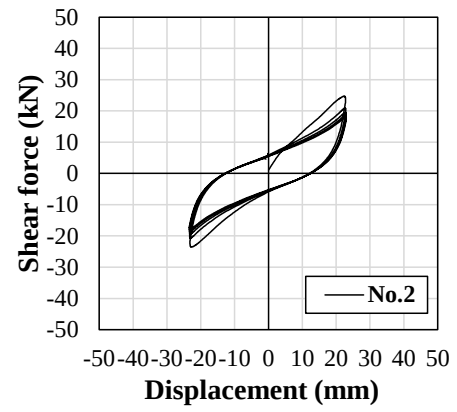


(b) $\pm 100\%$ Shear strain

Fig. 2.13 STEP1 (No.4 Specimen)

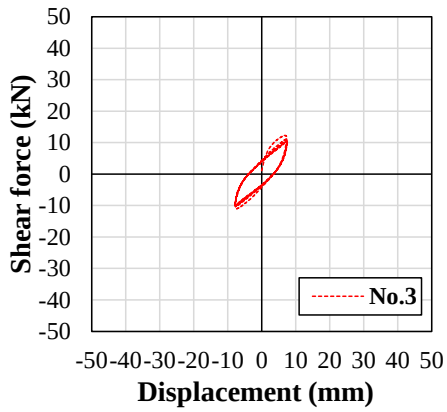


(a) $\pm 50\%$ Shear strain

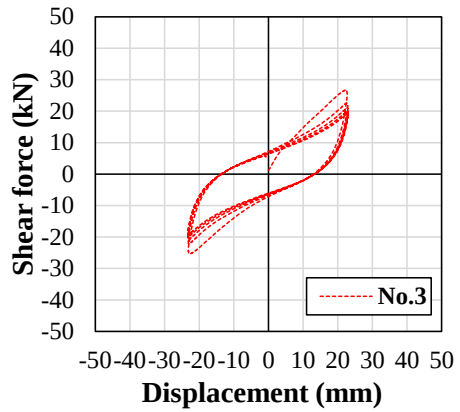


(b) $\pm 150\%$ Shear strain

Fig. 2.14 STEP2 (No.2 Specimen)

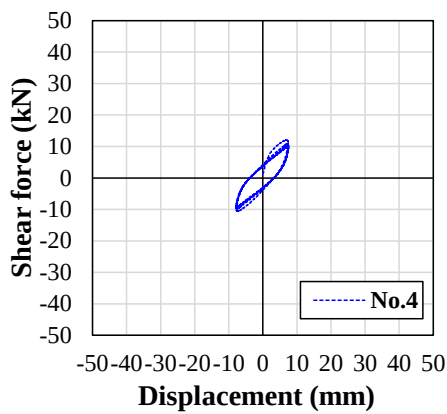


(a) $\pm 50\%$ Shear strain

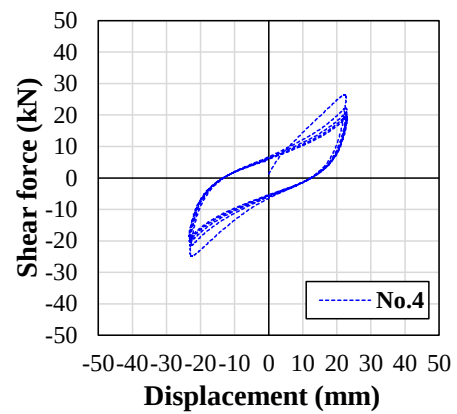


(b) $\pm 150\%$ Shear strain

Fig. 2.15 STEP2 (No.3 Specimen)

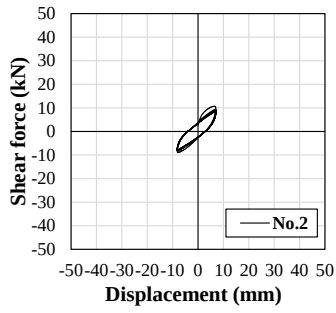


(a) $\pm 50\%$ Shear strain

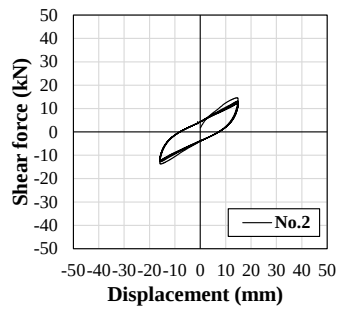


(b) $\pm 150\%$ Shear strain

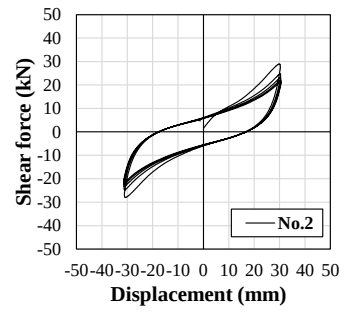
Fig. 2.16 STEP2 (No.4 Specimen)



(a) $\pm 50\%$ Shear strain

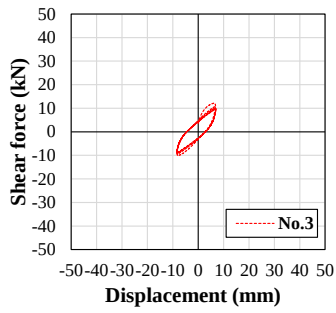


(b) $\pm 100\%$ Shear strain

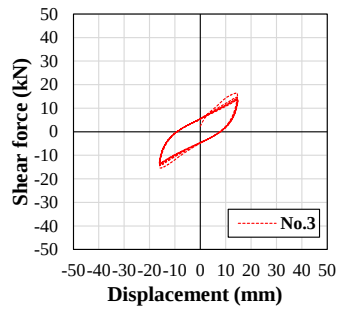


(c) $\pm 200\%$ Shear strain

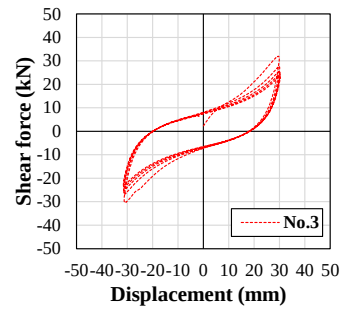
Fig. 2.17 STEP3 (No.2 Specimen)



(a) $\pm 50\%$ Shear strain

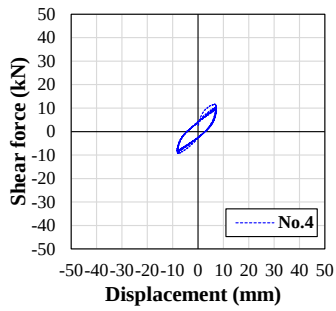


(b) $\pm 100\%$ Shear strain

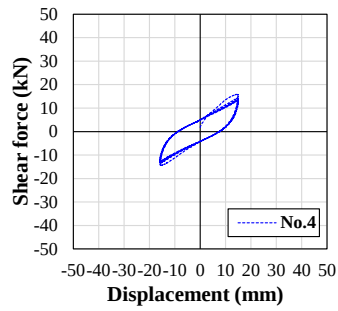


(c) $\pm 200\%$ Shear strain

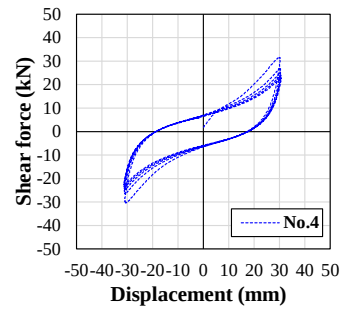
Fig. 2.18 STEP3 (No.3 Specimen)



(a) $\pm 50\%$ Shear strain

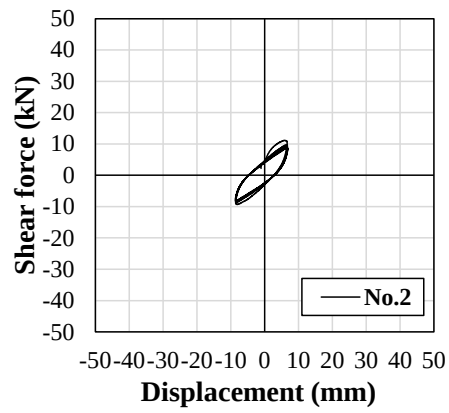


(b) $\pm 100\%$ Shear strain

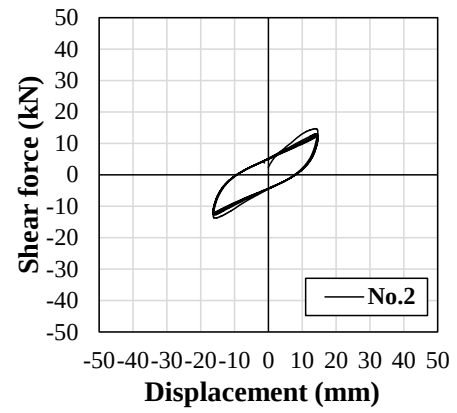


(c) $\pm 200\%$ Shear strain

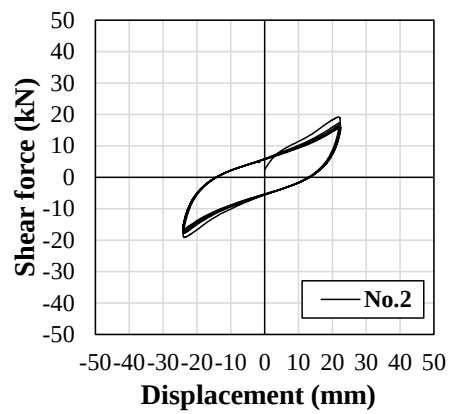
Fig. 2.19 STEP3 (No.4 Specimen)



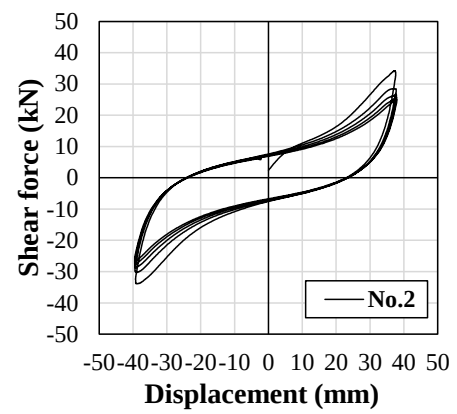
(a) $\pm 50\%$ Shear strain



(b) $\pm 100\%$ Shear strain

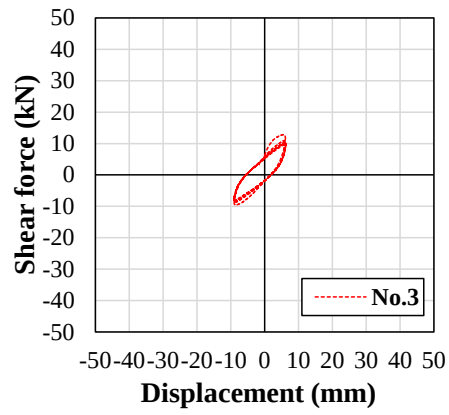


(c) $\pm 150\%$ Shear strain

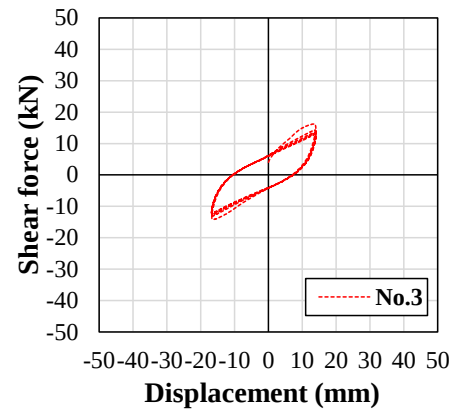


(d) $\pm 250\%$ Shear strain

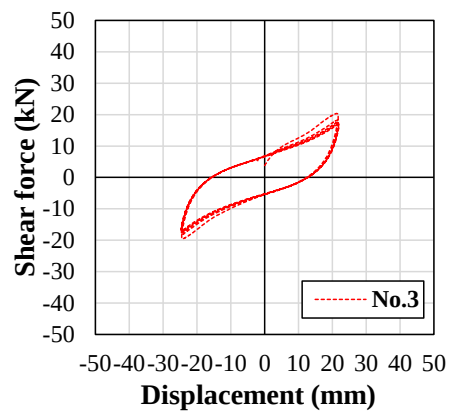
Fig. 2.20 STEP4 (No.2 Specimen)



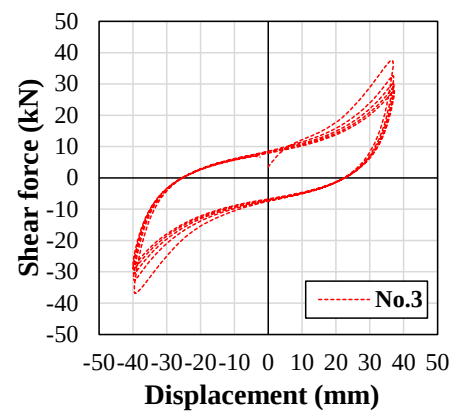
(a) $\pm 50\%$ Shear strain



(b) $\pm 100\%$ Shear strain

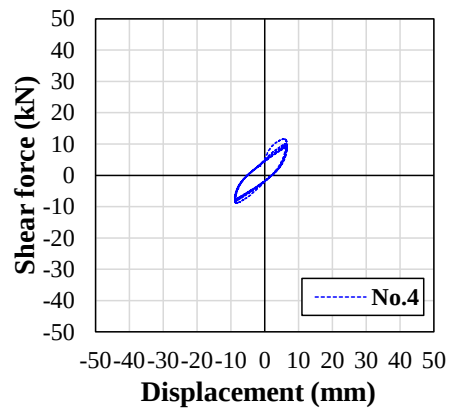


(c) $\pm 150\%$ Shear strain

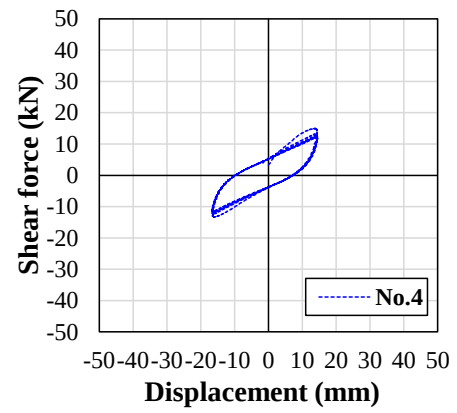


(d) $\pm 250\%$ Shear strain

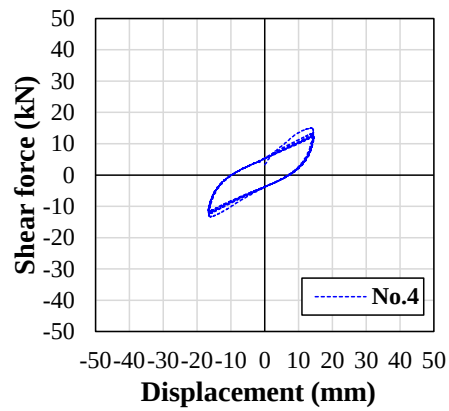
Fig. 2.21 STEP4 (No.3 Specimen)



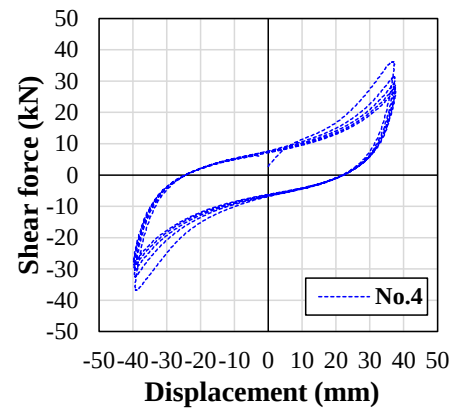
(a) $\pm 50\%$ Shear strain



(b) $\pm 100\%$ Shear strain

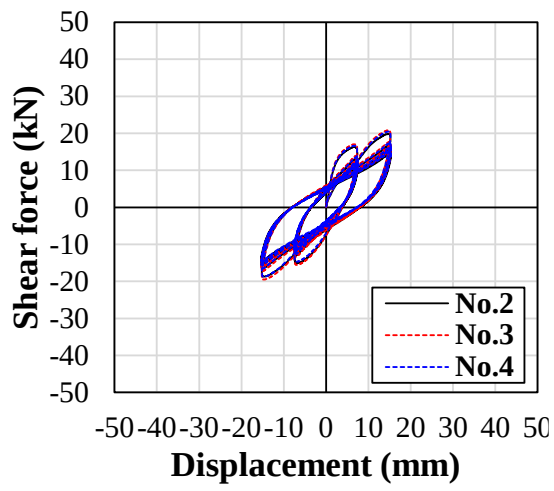


(c) $\pm 150\%$ Shear strain

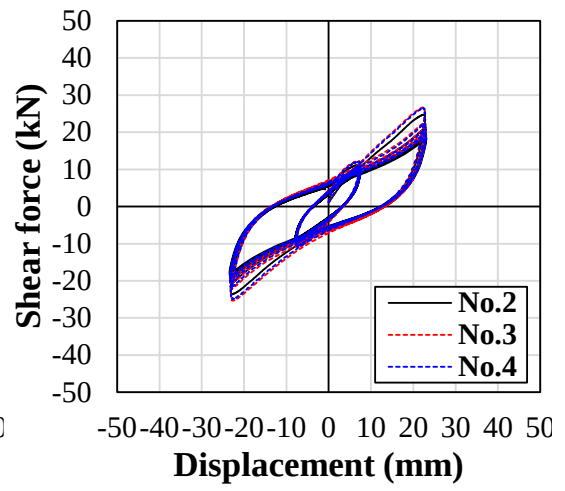


(d) $\pm 250\%$ Shear strain

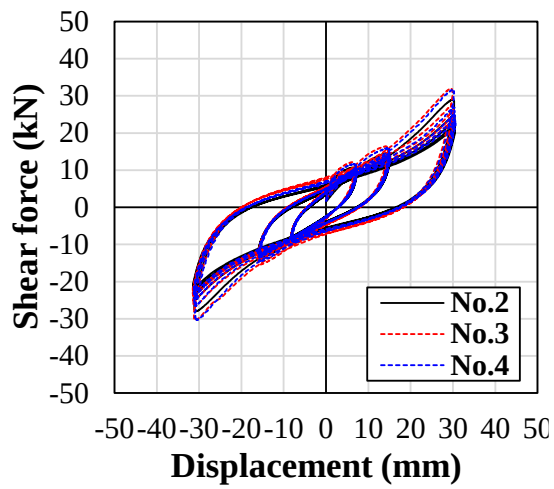
Fig. 2.22 STEP4 (No.4 Specimen)



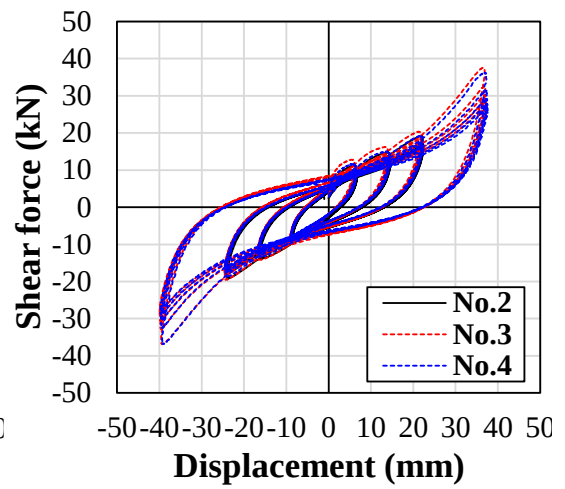
(a) STEP1



(b) STEP2



(c) STEP3



(d) STEP4

Fig. 2.23 Experimental results of all STEP (No.2, No.3, No.4)

2.5 Comparison of Shear Force

In the hysteresis curve of high damping rubber, shear force represents the amount of force or stress associated with deformation or displacement. This model is related to the energy loss occurring within the system. High damping rubber materials actually absorb and dissipate energy in the dynamic response of the system, increasing damping. The significance of shear force lies in the resistance generated within the system as the rubber material deforms or moves, indicating the internal damping characteristics of the rubber material. Therefore, through shear force, one can measure and understand the dynamic properties and energy absorption capacity of the system. In a reflective perspective, shear force data obtained through this model plays a crucial role in evaluating the stability, damping characteristics, and efficiency of structures or systems, especially in dynamic environments such as earthquakes. Analyzing shear force information obtained from the hysteresis model of high damping rubber provides insights into improving the system's performance and enhancing stability.

2.5.1 50% Shear strain

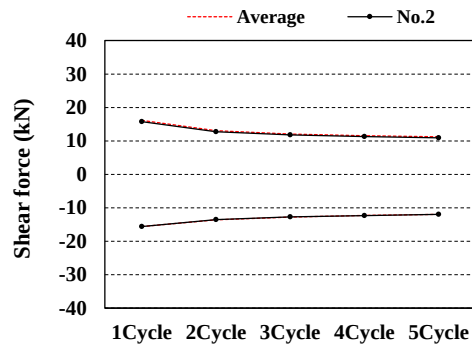
The experimental results for shear force at 50% shear strain in STEP1 exhibit a consistent decreasing trend, as illustrated in Fig.2.24, depicting shear force results for each cycle at 50% shear strain in STEP1. Table 2.4 shows the result of shear force at 50% shear strain in STEP1 for each cycle. The analysis encompasses both the extent of reduction for each subsequent value relative to the initial shear force of 16.1 and the average reduction. The shear force for the second cycle is 13.1, signifying a reduction of approximately 18.6%. Subsequently, the shear force for the third cycle is 12.1, indicating a decrease of about 24.8% from the initial value. In the fourth cycle, the shear force is 11.6, reflecting a reduction of around 28.6% compared to the initial value. The shear force of the fifth cycle is 11.2, demonstrating a decrease of roughly 30.4% from the initial value. The experimental results for negative shear force at 50% shear strain in STEP1 showcase a distinctive increasing trend, presenting the shear force outcomes for each cycle at 50% shear strain in STEP1. The analysis considers both the magnitude of increase for each subsequent value relative to the initial shear force of -

15.6 and the average increase. The shear force for the second cycle is -13.6, reflecting an increase of approximately 12.8%. Following this, the shear force for the third cycle is -12.8, indicating a rise of about 17.9% from the initial value. In the fourth cycle, the shear force is -12.3, demonstrating an increase of around 21.2% compared to the initial value. The shear force of the fifth cycle is -12.0, highlighting an increase of roughly 23.1% from the initial value.

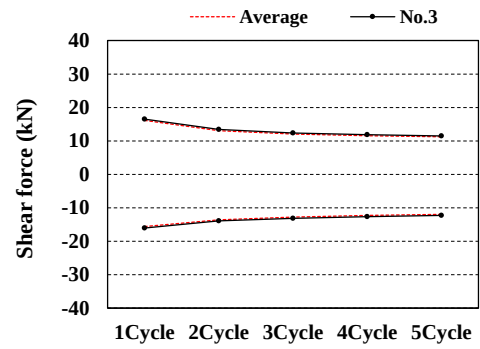
The experimental results for positive shear force at 50% shear strain in STEP2 reveal a consistent decreasing trend, as illustrated in Fig.2.25, presenting the shear force outcomes for each cycle at 50% shear strain in STEP2. Table 2.5 shows the result of shear force at 50% shear strain in STEP2 for each cycle. The analysis encompasses both the extent of reduction for each subsequent value relative to the initial shear force of 11.3 and the average reduction. The shear force for the second cycle is 10.1, indicating a decrease of approximately 10.6%. Subsequently, the shear force for the third cycle is 9.7, reflecting a reduction of about 14.2% from the initial value. In the fourth cycle, the shear force is 9.4, demonstrating a decrease of around 16.8% compared to the initial value. The shear force of the fifth cycle is 9.2, highlighting a decrease of roughly 18.6% from the initial value. The experimental results for negative shear force at 50% shear strain in STEP2 depict a consistent increasing trend, illustrating the shear force outcomes for each cycle at 50% shear strain in STEP2. The analysis involves evaluating the extent of decrease or increase for each subsequent value relative to the first cycle's value of -11.0. The shear force for the second cycle is -10.3, indicating an increase of approximately 6.4% from the initial value. Subsequently, the shear force for the third cycle is -10.0, representing an increase of about 9.1% from the initial value. In the fourth cycle, the shear force is -9.8, demonstrating an increase of around 11.8% compared to the initial value. The shear force of the fifth cycle is -9.7, highlighting an increase of roughly 12.7% from the initial value. These results signify a consistent upward pattern in negative shear force values as the cycles progress in STEP2. The observed increases indicate a systematic trend in the data, providing valuable insights into the material behavior under the specified shear strain conditions.

The experimental results for positive shear force at 50% shear strain in STEP3 reveal a consistent decreasing trend, as depicted in Fig.2.26, presenting the shear force outcomes for each cycle at 50% shear strain in STEP3. Table 2.6 shows the result of shear force at 50% shear strain in STEP3 for each cycle. The analysis involves assessing the extent of reduction for each subsequent value relative to the initial shear force of 11.0 and the average reduction. The shear force for the second cycle is 9.5, indicating a decrease of approximately 13.6%. Subsequently, the shear force for the third cycle is 9.0, reflecting a reduction of about 18.2% from the initial value. In the fourth cycle, the shear force is 8.8, demonstrating a decrease of around 20.0% compared to the initial value. The shear force of the fifth cycle is 8.6, highlighting a decrease of roughly 21.8% from the initial value. The experimental results for negative shear force at 50% shear strain in STEP3 exhibit a decreasing trend. Analyzing the data relative to the first cycle's value of -9.9, subsequent cycles show reductions. Cycle 2 and Cycle 3 demonstrate decreases of approximately 7.1% and 9.1%, respectively, compared to the initial value. Cycles 4 and 5 maintain a consistent shear force of -8.8.

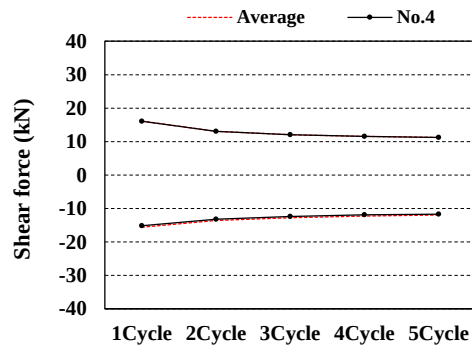
The experimental results for positive shear force at 50% shear strain in STEP4 reveal a consistent decreasing trend, as illustrated in Fig.2.27. Table 2.7 presents the shear force outcomes for each cycle at 50% shear strain in STEP4. Analyzing the data relative to the first cycle's value of 11.3, subsequent cycles show reductions. Cycle 2 and Cycle 3 demonstrate decreases of approximately 13.3% and 18.6%, respectively, compared to the initial value. In Cycle 4, the shear force is 8.9, indicating a decrease of around 21.2% from the initial value. Finally, in the fifth cycle, the shear force is 8.7, highlighting a decrease of roughly 22.1% from the initial value. The experimental results for negative shear force at 50% shear strain in STEP4 exhibit a consistent increasing trend. Analyzing the data with respect to the first cycle's value of -9.7, subsequent cycles demonstrate increases. Cycle 2 and Cycle 3 show increases of approximately 7.2% and 10.3%, respectively, compared to the initial value. In Cycle 4, the shear force is -8.6, indicating an increase of around 11.3% from the initial value. Finally, in the fifth cycle, the shear force is -8.4, highlighting an increase of roughly 13.4% from the initial value.



No.2 Specimen



No.3 Specimen

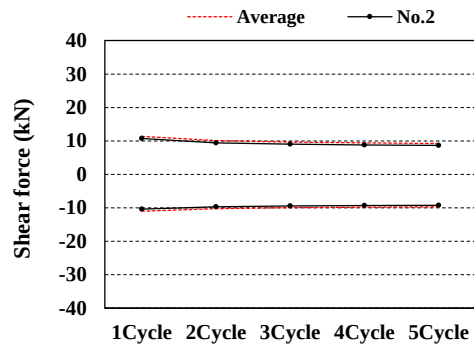


No.4 Specimen

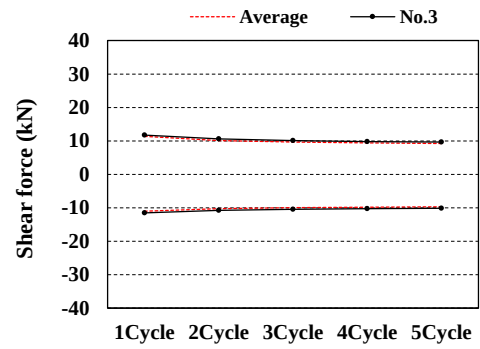
Fig. 2.24 The result of shear force at 50% shear strain in STEP1

Table 2.4 The result of shear force at 50% shear strain in STEP1 for each cycle

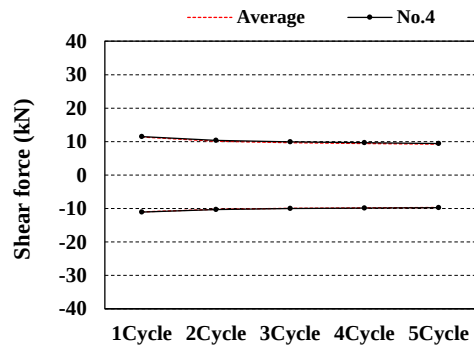
Shear force (kN)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	15.8	12.8	11.8	11.3	10.9
	-15.6	-13.6	-12.7	-12.3	-12.0
No.3	16.5	13.4	12.4	11.9	11.5
	-16.1	-13.9	-13.1	-12.6	-12.3
No.4	16.1	13.1	12.1	11.6	11.2
	-15.2	-13.2	-12.4	-11.9	-11.7
Average	16.1	13.1	12.1	11.6	11.2
	-15.6	-13.6	-12.8	-12.3	-12.0



No.2 Specimen



No.3 Specimen

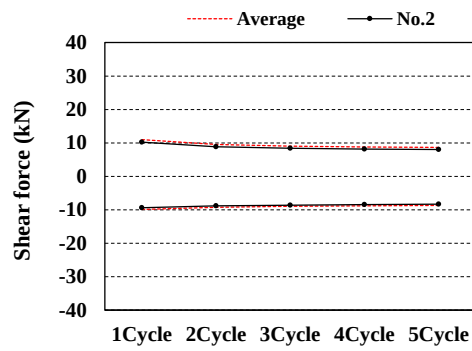


No.4 Specimen

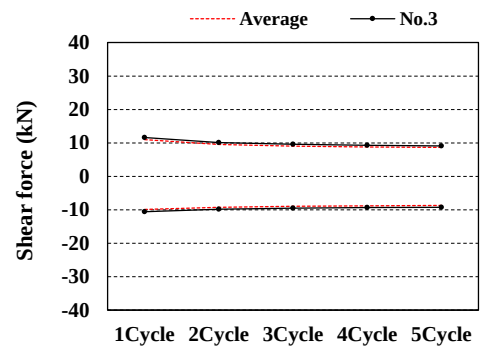
Fig. 2.25 The result of shear force at 50% shear strain in STEP2

Table 2.5 The result of shear force at 50% shear strain in STEP2 for each cycle

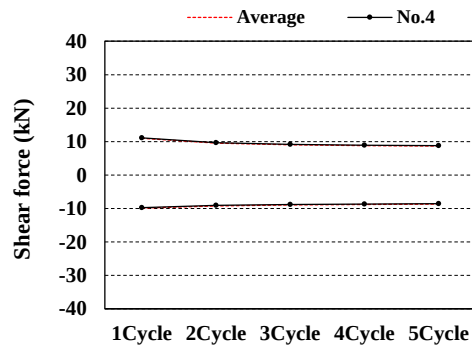
Shear force (kN)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	10.7	9.4	9.0	8.8	8.6
	-10.4	-9.7	-9.5	-9.3	-9.3
No.3	11.8	10.6	10.1	9.8	9.6
	-11.5	-10.8	-10.5	-10.3	-10.1
No.4	11.5	10.3	9.9	9.6	9.4
	-11.1	-10.3	-10.0	-9.9	-9.8
Average	11.3	10.1	9.7	9.4	9.2
	-11.0	-10.3	-10.0	-9.8	-9.7



No.2 Specimen



No.3 Specimen

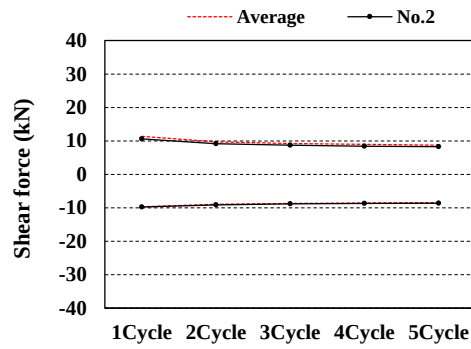


No.4 Specimen

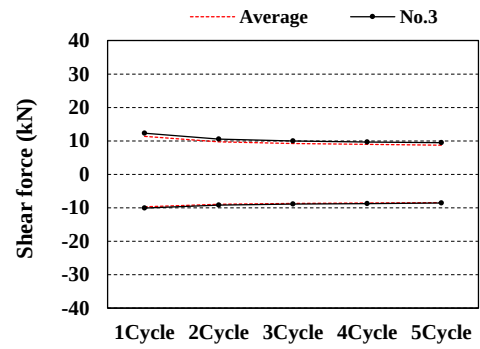
Fig. 2.26 The result of shear force at 50% shear strain in STEP3

Table 2.6 The result of shear force at 50% shear strain in STEP3 for each cycle

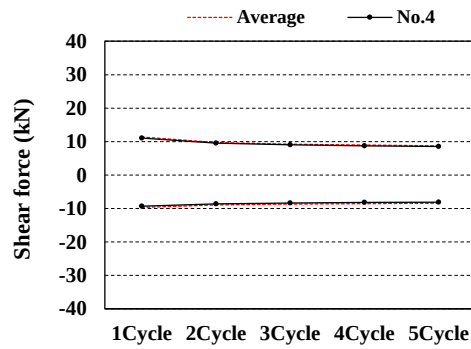
Shear force (kN)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	10.2	8.8	8.4	8.2	8.0
	-9.4	-8.9	-8.6	-8.5	-8.3
No.3	11.6	10.1	9.6	9.3	9.1
	-10.6	-9.8	-9.5	-9.4	-9.2
No.4	11.1	9.6	9.1	8.9	8.8
	-9.7	-9.1	-8.8	-8.7	-8.5
Average	11.0	9.5	9.0	8.8	8.6
	-9.9	-9.2	-9.0	-8.8	-8.7



No.2 Specimen



No.3 Specimen



No.4 Specimen

Fig. 2.27 The result of shear force at 50% shear strain in STEP4

Table 2.7 The result of shear force at 50% shear strain in STEP4 for each cycle

Shear force (kN)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	10.6	9.2	8.7	8.4	8.3
	-9.8	-9.1	-8.8	-8.7	-8.6
No.3	12.3	10.5	10.0	9.7	9.5
	-10.1	-9.2	-8.9	-8.7	-8.6
No.4	11.1	9.5	9.0	8.7	8.5
	-9.3	-8.6	-8.4	-8.2	-8.1
Average	11.3	9.7	9.2	8.9	8.7
	-9.7	-9.0	-8.7	-8.6	-8.4

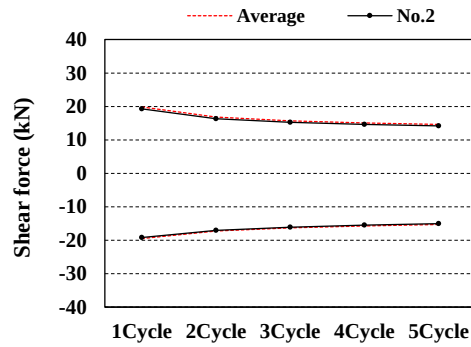
2.5.2 100% Shear Strain

The experimental results for positive shear force at 100% shear strain in STEP1 exhibit a consistent decreasing trend. Fig. 2.28 indicates the result of shear force at 100% shear strain in STEP1. Table 2.8 shows the result of shear force at 50% shear strain in STEP1 for each cycle. The analysis, based on the first cycle's value of 19.8, reveals that the shear force for the second cycle is 16.8, indicating a decrease of approximately 15.2%. Subsequently, for the third cycle, the shear force is 15.7, reflecting a reduction of about 20.2% from the initial value. In the fourth cycle, the shear force is 15.1, demonstrating a decrease of around 23.7% compared to the initial value. The shear force of the fifth cycle is 14.6, highlighting a decrease of roughly 26.3% from the initial value. The experimental results for negative shear force at 100% shear strain in STEP1 reveal an increasing trend. The analysis, based on the first cycle's value of -19.5, shows that the shear force for the second cycle is -17.3, indicating an increase of approximately 11.3%. Subsequently, for the third cycle, the shear force is -16.3, reflecting an increase of about 16.4% from the initial value. In the fourth cycle, the shear force is -15.7, demonstrating an increase of around 19.0% compared to the initial value. The shear force of the fifth cycle is -15.3, highlighting an increase of roughly 21.5% from the initial value.

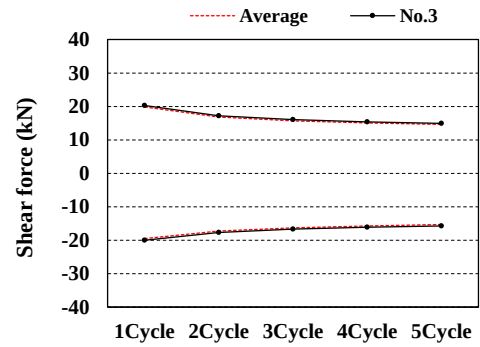
The experimental results for positive and negative shear force at 100% shear strain in STEP3 are depicted in Fig. 2.29. Table 2.9 provides detailed shear force outcomes for each cycle at 100% shear strain in STEP3. Analyzing the data with respect to the first cycle's value of 15.1, subsequent cycles demonstrate a decrease. In Cycle 2, the shear force is 13.5, indicating a decrease of approximately 10.6% from the initial value. Subsequently, in Cycle 3, the shear force is 12.9, reflecting a reduction of about 14.6% from the initial value. In the fourth cycle, the shear force is 12.6, demonstrating a decrease of around 16.6% compared to the initial value. The shear force of the fifth cycle is 12.4, highlighting a decrease of roughly 17.9% from the initial value. The experimental results for negative shear force at 100% shear strain in STEP3 are presented as follows. In the first cycle, the shear force is -15.0. Analyzing the subsequent cycles relative to the initial value, in the second cycle, the shear force is -

14.0, showing a decrease of approximately 6.7%. Moving on to the third cycle, the shear force is -13.6, indicating a reduction of about 9.3% from the initial value. In the fourth cycle, the shear force is -13.4, reflecting a decrease of around 10.0% compared to the initial value. Finally, in the fifth cycle, the shear force is -13.2, highlighting a decrease of roughly 12.0% from the initial value.

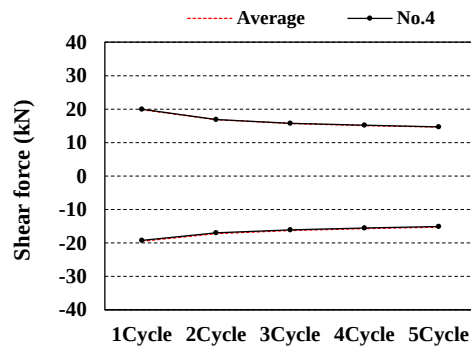
The experimental results are positive shear force at 100% shear strain in STEP4 are presented as follows. In the first cycle, the shear force is 14.8. Analyzing the subsequent cycles relative to the initial value, in the second cycle, the shear force is 13.0, showing a decrease of approximately 12.2%. Moving on to the third cycle, the shear force is 12.4, indicating a reduction of about 16.2% from the initial value. In the fourth cycle, the shear force is 12.1, reflecting a decrease of around 18.2% compared to the initial value. Finally, in the fifth cycle, the shear force is 11.9, highlighting a decrease of roughly 19.6% from the initial value. The average reduction across all values is approximately 15.0%, illustrating a consistent decreasing trend in the shear force throughout the experiment. This analysis provides valuable insights into the progressive changes in shear force over multiple cycles, emphasizing a prevalent pattern of decreasing values. In the experimental results for negative shear force at 100% shear strain in STEP4, the values for each cycle, relative to the first cycle, demonstrate a decreasing trend. The percentage decrease for each subsequent cycle compared to the initial cycle is as follows: the 2nd Cycle decreased by approximately 7.4%, the 3rd Cycle by approximately 9.9%, the 4th Cycle by approximately 11.3%, and the 5th Cycle by approximately 12.7%. On average, the negative shear force experienced a reduction of approximately 10.6% across all cycles. This consistent decrease in negative shear force values suggests a systematic trend in the experimental outcomes.



No.2 Specimen



No.3 Specimen

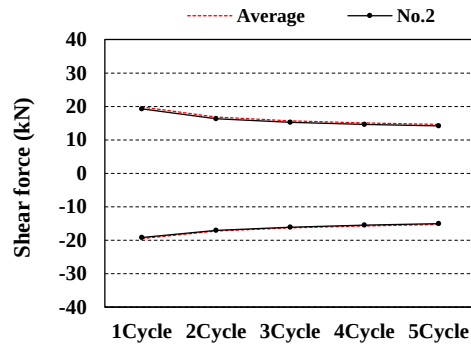


No.4 Specimen

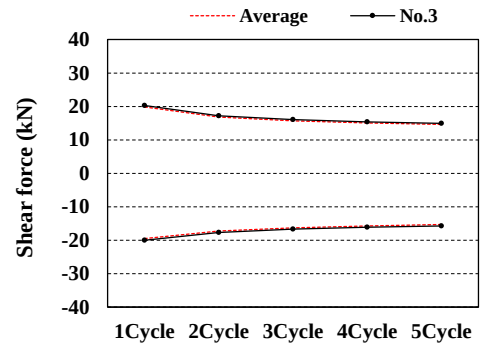
Fig. 2.28 The result of shear force at 100% shear strain in STEP1

Table 2.8 The result of shear force at 100% shear strain in STEP1 for each cycle

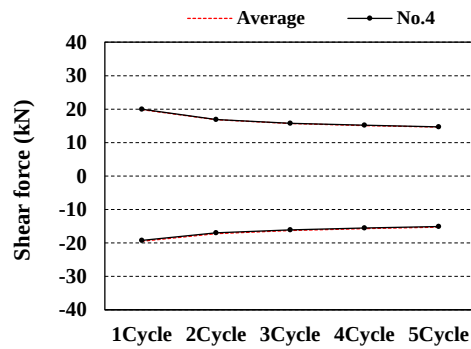
Shear force (kN)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	19.3	16.3	15.3	14.7	14.2
	-19.2	-17.0	-16.1	-15.5	-15.1
No.3	20.3	17.2	16.0	15.4	14.9
	-20.0	-17.7	-16.7	-16.1	-15.7
No.4	19.9	16.9	15.8	15.2	14.7
	-19.3	-17.0	-16.1	-15.5	-15.1
Average	19.8	16.8	15.7	15.1	14.6
	-19.5	-17.3	-16.3	-15.7	-15.3



No.2 Specimen



No.3 Specimen

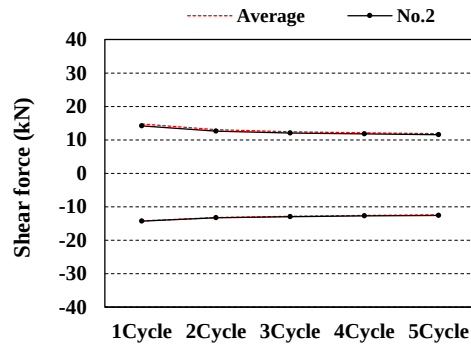


No.4 Specimen

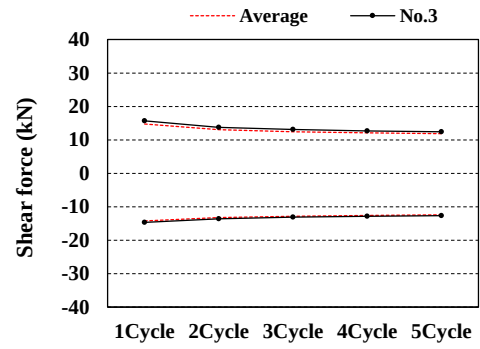
Fig. 2.29 The result of shear force at 100% shear strain in STEP3

Table 2.9 The result of shear force at 100% shear strain in STEP3 for each cycle

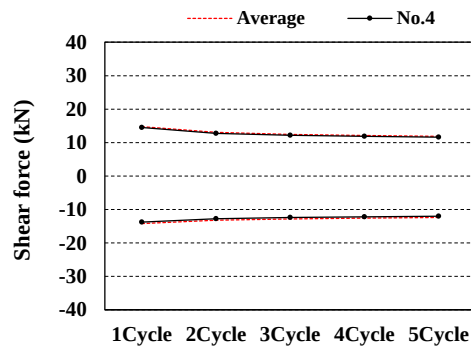
Shear force (kN)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	14.1	12.7	12.1	11.9	11.7
	-14.3	-13.3	-13.0	-12.7	-12.6
No.3	15.9	14.1	13.6	13.2	12.9
	-15.9	-14.8	-14.3	-14.1	-13.9
No.4	15.3	13.7	13.1	12.8	12.6
	-14.9	-13.9	-13.5	-13.2	-13.1
Average	15.1	13.5	12.9	12.6	12.4
	-15.0	-14.0	-13.6	-13.4	-13.2



No.2 Specimen



No.3 Specimen



No.4 Specimen

Fig. 2.30 The result of shear force at 100% shear strain in STEP4

Table 2.10 The result of shear force at 100% shear strain in STEP4 for each cycle

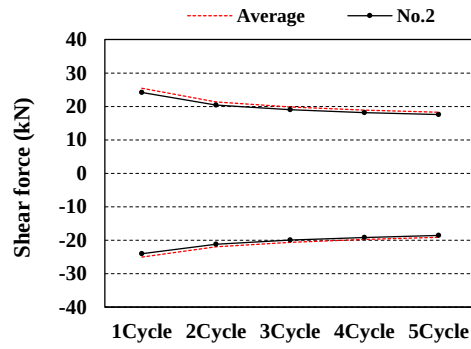
Shear force (kN)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	14.2	12.6	12.1	11.8	11.6
	-14.3	-13.3	-13.0	-12.7	-12.6
No.3	15.7	13.7	13.1	12.7	12.5
	-14.6	-13.6	-13.1	-12.9	-12.6
No.4	14.5	12.8	12.2	11.9	11.6
	-13.8	-12.8	-12.4	-12.2	-12.1
Average	14.8	13.0	12.4	12.1	11.9
	-14.2	-13.2	-12.8	-12.6	-12.4

2.5.3 150% Shear Strain

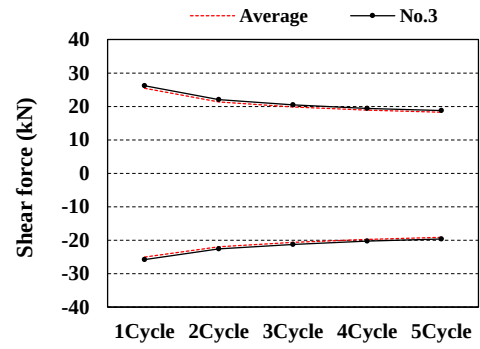
The experimental results for positive shear force at 150% shear strain in STEP2 reveal a consistent decreasing trend. The analysis, based on the first cycle's value of 25.4, shows that the shear force for the second cycle is 21.4, indicating a decrease of approximately 15.7%. Subsequently, for the third cycle, the shear force is 19.9, reflecting a reduction of about 21.5% from the initial value. In the fourth cycle, the shear force is 18.9, demonstrating a decrease of around 25.6% compared to the initial value. The shear force of the fifth cycle is 18.3, highlighting a decrease of roughly 27.2% from the initial value. The average reduction across all values is approximately 22.5%, emphasizing the overarching diminishing trend observed in the data throughout the experiment. This comprehensive analysis provides insights into the progressive changes in shear force over multiple cycles, emphasizing a consistent pattern of decreasing values. The experimental results for negative shear force at 150% shear strain in STEP2 reveal a consistent increasing trend. The analysis, based on the first cycle's value of -25.1, shows that the shear force for the second cycle is -22.0, indicating an increase of approximately 12.4%. Subsequently, for the third cycle, the shear force is -20.6, reflecting an increase of about 17.3% from the initial value. In the fourth cycle, the shear force is -19.8, demonstrating an increase of around 21.1% compared to the initial value. The shear force of the fifth cycle is -19.1, highlighting an increase of roughly 23.9% from the initial value. The average increase across all values is approximately 18.7%, emphasizing the consistent upward trend observed in the data throughout the experiment. This comprehensive analysis provides insights into the progressive changes in shear force over multiple cycles, emphasizing a pattern of increasing values.

In the experimental results for positive shear force at 150% shear strain in STEP4, the values for each cycle, relative to the first cycle, exhibit a decreasing trend. Fig.2.32 shows the result of shear force at 150% shear strain in STEP4. Table 2.12 shows the result of shear force at 150% shear strain in STEP4 for each cycle. The percentage decrease for each subsequent cycle compared to the initial cycle is as follows: the 2nd Cycle decreased by approximately 10.5%, the 3rd Cycle by approximately 14.1%, the

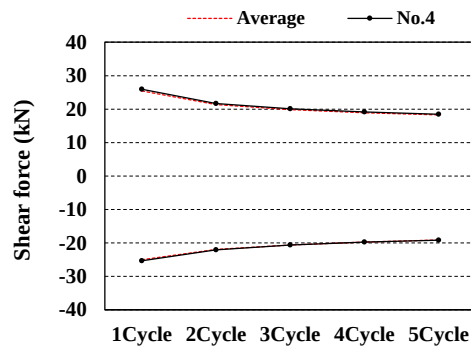
4th Cycle by approximately 16.8%, and the 5th Cycle by approximately 17.8%. On average, the positive shear force experienced a reduction of approximately 15.3% across all cycles. This consistent decrease in positive shear force values suggests a systematic trend in the experimental outcomes. In the experimental results for negative shear force at 150% shear strain in STEP4, the values for each cycle, relative to the first cycle, show an increasing trend. The percentage increase for each subsequent cycle compared to the initial cycle is as follows: the 2nd Cycle increased by approximately 6.6%, the 3rd Cycle by approximately 9.2%, the 4th Cycle by approximately 11.2%, and the 5th Cycle by approximately 12.8%. On average, the negative shear force experienced an increase of approximately 10.2% across all cycles. This consistent rise in negative shear force values suggests a systematic trend in the experimental outcomes.



No.2 Specimen



No.3 Specimen

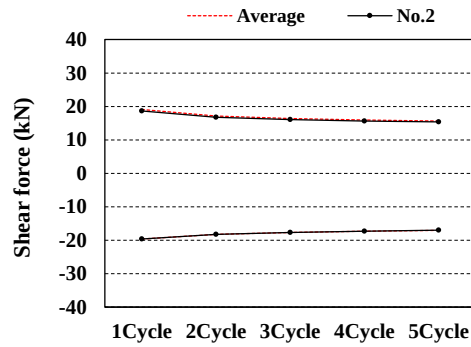


No.4 Specimen

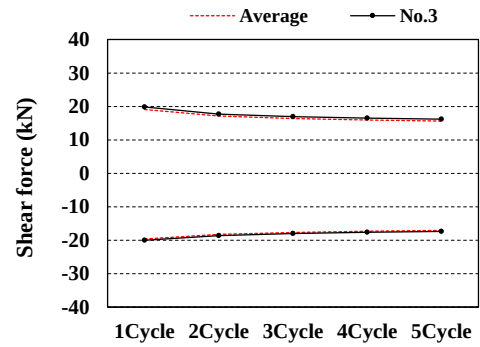
Fig. 2.31 The result of shear force at 150% shear strain in STEP2

Table 2.11 The result of shear force at 150% shear strain in STEP2 for each cycle

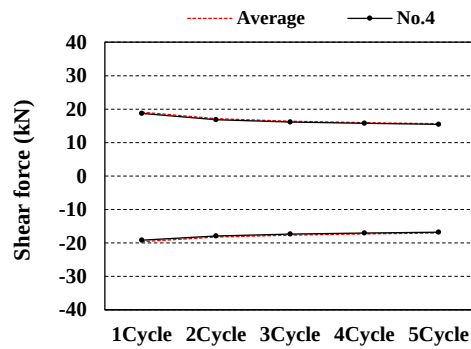
Shear force (kN)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	24.2	20.4	19.0	18.2	17.6
	-24.1	-21.2	-19.9	-19.2	-18.6
No.3	26.2	22.1	20.5	19.4	18.8
	-25.8	-22.6	-21.3	-20.3	-19.7
No.4	25.9	21.7	20.1	19.1	18.5
	-25.3	-22.1	-20.7	-19.8	-19.2
Average	25.4	21.4	19.9	18.9	18.3
	-25.1	-22.0	-20.6	-19.8	-19.1



No.2 Specimen



No.3 Specimen



No.4 Specimen

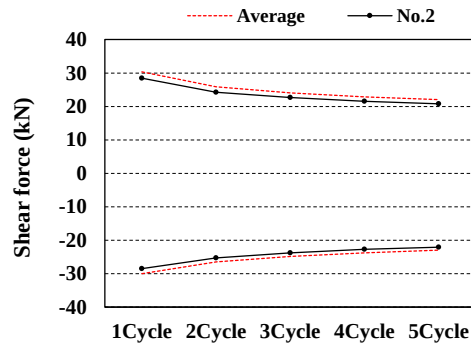
Fig. 2.32 The result of shear force at 150% shear strain in STEP4

Table 2.12 The result of shear force at 150% shear strain in STEP4 for each cycle

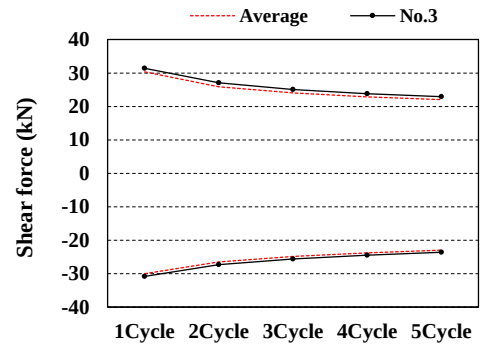
Shear force (kN)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	18.7	16.8	16.1	15.6	15.4
	-19.6	-18.3	-17.7	-17.3	-17.0
No.3	19.8	17.7	17.0	16.5	16.2
	-20.0	-18.6	-18.0	-17.6	-17.4
No.4	18.7	16.8	16.1	15.8	15.4
	-19.2	-17.9	-17.4	-17.1	-16.8
Average	19.1	17.1	16.4	16.0	15.7
	-19.6	-18.3	-17.7	-17.3	-17.1

2.5.4 200% Shear Strain

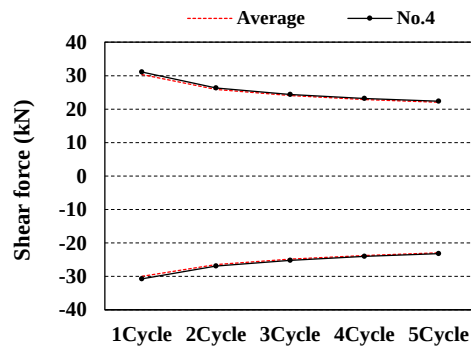
The experimental results for positive shear force at 200% shear strain in STEP3 reveal a consistent decreasing trend. Fig.2.33 depicts the result of shear force at 200% shear strain in STEP3. Table 2.13 shows the result of shear force at 200% shear strain in STEP3 for each cycle. The analysis, based on the first cycle's value of 30.3, shows that the shear force for the second cycle is 25.9, indicating a decrease of approximately 14.5%. Subsequently, for the third cycle, the shear force is 24.0, reflecting a reduction of about 20.7% from the initial value. In the fourth cycle, the shear force is 22.9, demonstrating a decrease of around 24.4% compared to the initial value. The shear force of the fifth cycle is 22.0, highlighting a decrease of roughly 27.3% from the initial value. The average reduction across all values is approximately 21.7%, emphasizing the overarching diminishing trend observed in the data throughout the experiment. This comprehensive analysis provides insights into the progressive changes in shear force over multiple cycles, emphasizing a consistent pattern of decreasing values. In the experimental results for negative shear force at 150% shear strain in STEP4, the values for each cycle, relative to the first cycle, show an increasing trend. The percentage increase for each subsequent cycle compared to the initial cycle is as follows: the 2nd Cycle increased by approximately 6.6%, the 3rd Cycle by approximately 9.2%, the 4th Cycle by approximately 11.2%, and the 5th Cycle by approximately 12.8%. On average, the negative shear force experienced an increase of approximately 10.2% across all cycles. This consistent rise in negative shear force values suggests a systematic trend in the experimental outcomes.



No.2 Specimen



No.3 Specimen



No.4 Specimen

Fig. 2.33 The result of shear force at 200% shear strain in STEP3

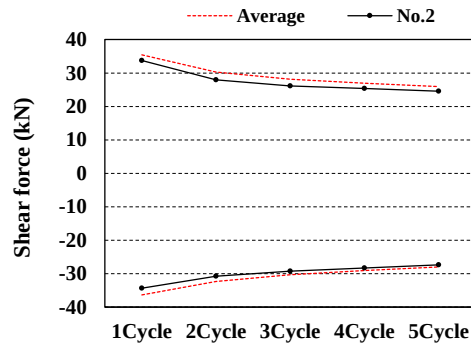
Table 2.13 The result of shear force at 200% shear strain in STEP3 for each cycle

Shear force (kN)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	28.5	24.3	22.7	21.6	20.8
	-28.5	-25.3	-23.8	-22.7	-22.1
No.3	31.4	27.1	25.1	23.8	22.9
	-30.8	-27.3	-25.6	-24.5	-23.6
No.4	31.1	26.3	24.4	23.2	22.4
	-30.8	-27.0	-25.2	-24.0	-23.2
Average	30.3	25.9	24.0	22.9	22.0
	-30.0	-26.5	-24.9	-23.8	-23.0

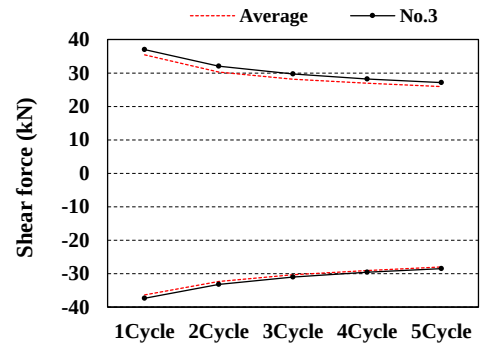
2.5.5 250% Shear Strain

The experimental results for positive shear force at 250% shear strain in STEP4 reveal a consistent decreasing trend. The analysis, based on the first cycle's value of 35.5, shows that the shear force for the second cycle is 30.3, indicating a decrease of approximately 14.6%. Subsequently, for the third cycle, the shear force is 28.2, reflecting a reduction of about 20.1% from the initial value. In the fourth cycle, the shear force is 27.0, demonstrating a decrease of around 23.9% compared to the initial value. The shear force of the fifth cycle is 26.0, highlighting a decrease of roughly 26.8% from the initial value. The average reduction across all values is approximately 21.4%, emphasizing the overarching diminishing trend observed in the data throughout the experiment. This comprehensive analysis provides insights into the progressive changes in shear force over multiple cycles, emphasizing a consistent pattern of decreasing values.

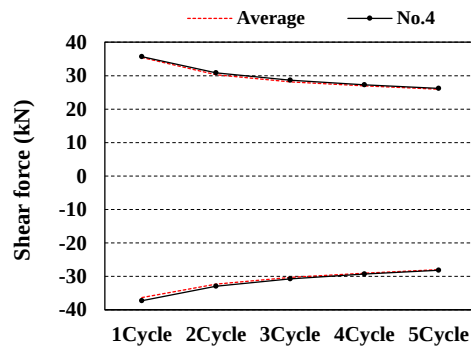
The experimental results for negative shear force at 250% shear strain in STEP4 reveal a consistent increasing trend. The analysis, based on the first cycle's value of -36.3, shows that the shear force for the second cycle is -32.3, indicating an increase of approximately 11.0%. Subsequently, for the third cycle, the shear force is -30.3, reflecting an increase of about 16.7% from the initial value. In the fourth cycle, the shear force is -29.1, demonstrating an increase of around 19.9% compared to the initial value. The shear force of the fifth cycle is -28.0, highlighting an increase of roughly 22.8% from the initial value. The average increase across all values is approximately 17.6%, emphasizing the consistent upward trend observed in the data throughout the experiment. This comprehensive analysis provides insights into the progressive changes in shear force over multiple cycles, emphasizing a pattern of increasing values.



No.2 Specimen



No.3 Specimen



No.4 Specimen

Fig. 2.34 The result of shear force at 250% shear strain in STEP4

Table 2.14 The result of shear force at 250% shear strain in STEP4 for each cycle

Shear force (kN)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	33.7	28.0	26.1	25.4	24.6
	-34.4	-30.8	-29.3	-28.3	-27.4
No.3	37.0	32.0	29.7	28.2	27.2
	-37.4	-33.2	-31.0	-29.6	-28.5
No.4	35.7	30.9	28.6	27.3	26.2
	-37.3	-33.0	-30.7	-29.3	-28.2
Average	35.5	30.3	28.2	27.0	26.0
	-36.3	-32.3	-30.3	-29.1	-28.0

2.5 Summary

The hysteresis behavior of the HDR was investigated by gradually increasing the shear strain, and the results for all three specimens were consistent. It was observed that the shear force and area of the hysteresis curve decreased after the initial history owing to the Mullins effect. Notably, a considerable decrease in the shear force was observed in the hysteresis curve during the step wherein the HDR specimen experienced shear deformation for the first time. This is evident when comparing the hysteresis results of 50, 100, and 150% shear strain for each step. Here, the rate of the shear force reduction decreases as the next step progresses. The hardening phenomenon, which is a nonlinear characteristic of the HDR specimen, was confirmed at the shear strains of 200 and 250%. Particularly, the stiffness increases rapidly after a shear strain of approximately 150% or more. These results confirm the dependence of the HDR on the shear deformation and hysteretic characteristics. The initial loading histories correspond to the maximum shear strains that were first applied to the specimen, that is, 50 and 100% of the shear strain in STEP 1, and 150% in STEP 2. The subsequent histories correspond to the test results, wherein a similar shear strain was applied again in the next step after the HDR specimen had already experienced a large shear strain. The subsequent histories comprised 50, 100, and 150% shear strain in STEPs 2, 3, and 4, respectively. The experimental results of the initial loading histories revealed that the maximum shear forces for the maximum displacements on the positive and negative sides proceeding in opposite directions were similar. Furthermore, a decrease in the maximum shear force after one cycle, owing to the Mullins effect, appears simultaneously on the positive and negative sides. These results suggest that the dependence on the shear strain is independent and that the maximum displacement on one side does not affect that on the other side. If the HDR is assumed to have dependent hysteresis characteristics, wherein the maximum displacement on one side also affects the other side, the hysteresis curve of the initial loading histories should confirm similar results as the subsequent histories. However, the experimental results showed that the strain dependence in one direction had no effect in the opposite direction. Hence, it can be concluded that the dependence on the shear strain is independent of the HDR specimens.

Chapter 3

Mechanical properties of HDR

3.1 Introduction

In this research, the mechanical characteristics of absorption energy, equivalent stiffness, damping ratio, and strain energy, which can identify the characteristics of HDR in the development and improvement of high damping rubber bearings, were verified. Based on the experimental results, mechanical properties were evaluated by referring to Japan Road Association: Design Specifications of Highway Bridges, Part V Seismic Design and Japan Road Association: Manual of highway bridge bearing. The evaluation of the mechanical characteristics of high damping rubber bearings is crucial for several reasons. Firstly, these bearings play a pivotal role in structural engineering, especially in seismic-resistant designs. The ability of high damping rubber bearings to absorb and dissipate energy during seismic events significantly influences the overall seismic performance of structures. Secondly, understanding the dynamic behavior of high damping rubber bearings is essential for optimizing their design and placement in structures. This evaluation helps ensure that these bearings provide effective isolation and damping, reducing the transmission of harmful vibrations to the structure and its components. Furthermore, assessing the mechanical properties of high damping rubber bearings contributes to the development of reliable and resilient infrastructure. By comprehensively evaluating their stiffness, damping capacity, and other dynamic characteristics, engineers can make informed decisions in the design and retrofitting of structures, ultimately enhancing their ability to withstand seismic activities and other dynamic loads. Finally, the assessment of the mechanical

characteristics of high damping rubber bearings is critical for ensuring their effectiveness in seismic applications, optimizing their design, and enhancing the overall resilience of structures in dynamic loading scenarios.

3.1.1 Overview of High Damping Rubber (HDR)

In this research, the mechanical properties of the HDR were thoroughly assessed using different criteria such as the equivalent stiffness, equivalent damping constant, and strain energy calculated from the experimental data (Dall'Asta. 2006). Fig. 3.1 shows a diagram that briefly explains the mechanical characteristics of the hysteresis curve of the HDR. These characteristics are fundamental for exploring the hysteresis behavior of the HDR. Further, they provide a quantitative evaluation of the nonlinearity of the material. To ensure the accuracy of the results, the frictional force generated in the sliding bed of the hybrid actuator was considered during the dynamic loading tests. Particularly, the decrease in the non-constant shear force during unloading from the maximum load of the HDR hysteresis curve was attributed to the friction force, with an average value of 0.5 kN applied across all the specimens. Here, the friction force is defined as f .

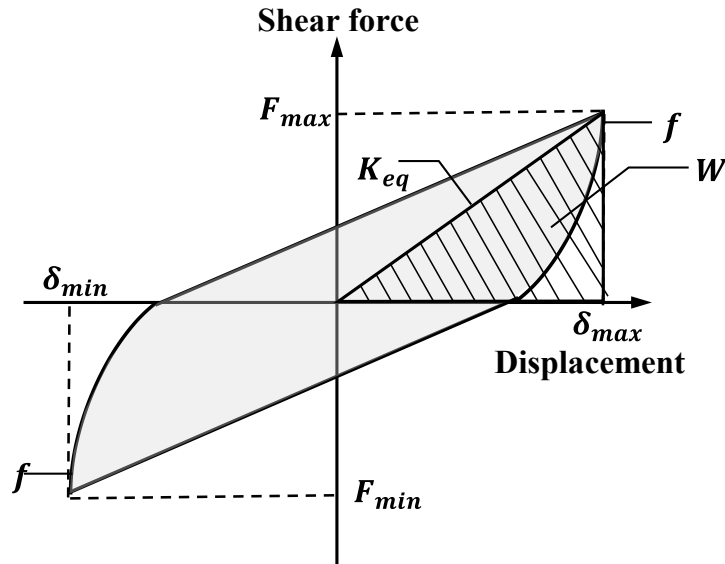


Fig. 3.1 Mechanical characteristics of the HDR

3.2 Evaluation results of mechanical properties

High Damping Rubber (HDR) possesses absorption energy, indicating its capability to absorb and dissipate energy when exposed to dynamic forces, such as vibrations or impacts. This property, known as hysteresis loss, contributes to HDR's effectiveness in responding to shocks or vibrations and enhancing the overall protection of structures and equipment. Equivalent stiffness represents the overall stiffness of a system, combining the effects of various components or materials. HDR's equivalent stiffness helps accurately assess and design the total stiffness of a structure or system. The damping ratio reflects HDR's ability to reduce oscillations and dissipate energy. A high damping ratio is crucial when HDR is exposed to dynamic forces like earthquakes, as it enables the system to effectively control vibrations while maintaining stability. Strain energy signifies the work done on HDR during deformation. This parameter is utilized to evaluate the elasticity and durability of HDR, providing insights into how the material deforms, stores, and releases energy. These characteristics play a vital role in evaluating the dynamic behavior and performance of HDR in various engineering applications, particularly in contributing to the stability and effective response of structures and systems to diverse dynamic loads.

3.2.1 Absorption energy

The absorption energy was determined by analyzing the area of hysteresis curve derived from the experimental results of the HDR specimen. Integration was applied to calculate the area between two adjacent points. This approach allowed for the assessment of the energy absorbed by HDR, offering insights into its performance. Examining and contrasting absorption energy across different shear strain rates at each step allows us to ascertain the influence of HDR's sensitivity to shear strain rate.

$$\Delta W = \frac{1}{2} (x_n - x_{n-1}) (F_n + F_{n-1}) \quad (3.1)$$

- x_n : Displacement at the current step
 x_{n-1} : Displacement at the previous step
 F_n : Shear force at the current step
 F_{n-1} : Shear force at the previous step

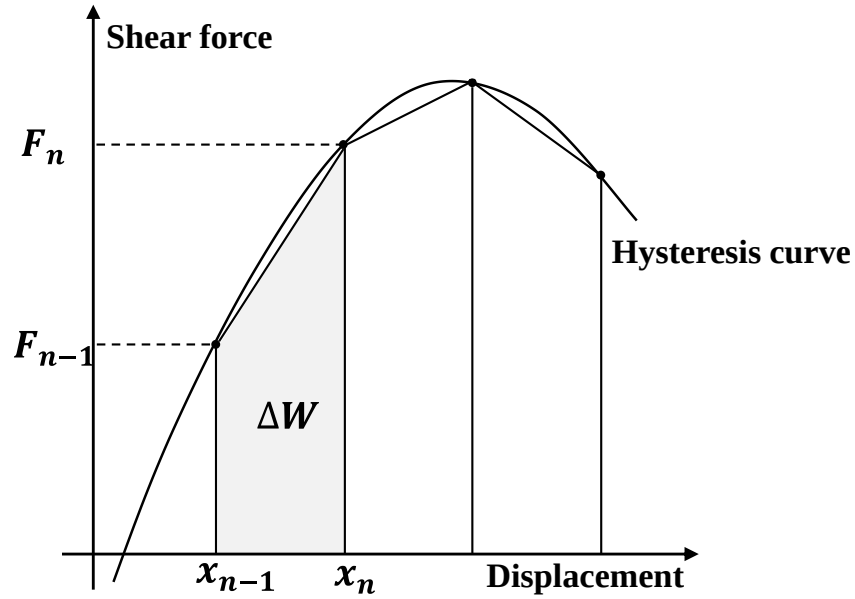


Fig. 3.2 Mechanical characteristics of the HDR

From the results of the characteristic verification test of HDR specimens No. 2 to No. 4, the absorption energy of each step was calculated, and the average was analyzed. Fig. 3.3 and Table 3.1 show the result of the absorption energy at 50% shear strain in STEP1. The mechanical characteristics evaluation results for absorption energy at 50% shear strain in STEP1 indicate a consistent decreasing trend across successive cycles. The absorption energy values exhibit a decreasing trend with each subsequent cycle compared to the preceding one. On average, the values decrease by approximately 15.83%. This suggests a progressive reduction in the material's ability to absorb energy over successive loading cycles, indicating potential fatigue or degradation in its mechanical characteristics. Fig. 3.4 and Table 3.2 show the result of the absorption energy at 50% shear strain in STEP2. The absorption energy values at 50% shear strain in STEP2 demonstrate a consistent decrease with each successive cycle when compared to the preceding one. On average, the values decrease by approximately

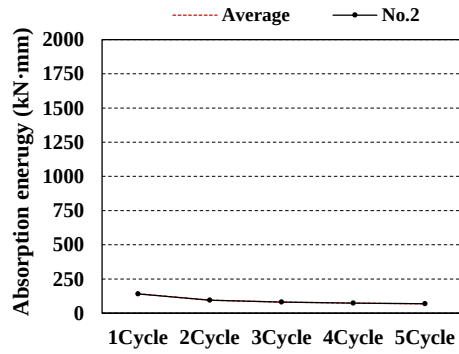
8.82%. This trend implies a gradual reduction in the material's capacity to absorb energy over repeated loading cycles, suggesting potential fatigue or degradation in its mechanical characteristics. Fig. 3.5 and Table 3.3 show the result of the absorption energy at 50% shear strain in STEP3. In this experimental data, the rate of change is calculated based on the values of the preceding cycle, and the overall average is computed. The absorption energy values at 50% shear strain in STEP3 exhibit a consistent decrease with each successive cycle when compared to the preceding one. On average, the values decrease by approximately 10.14%. This trend suggests a progressive reduction in the material's ability to absorb energy over repeated loading cycles, indicating potential fatigue or degradation in its mechanical characteristics. Fig. 3.6 and Table 3.4 show the result of the absorption energy at 50% shear strain in STEP4. The absorption energy values at 50% shear strain in STEP4 demonstrate a consistent decrease with each successive cycle when compared to the preceding one. On average, the values decrease by approximately 10.61%. This trend suggests a progressive reduction in the material's ability to absorb energy over repeated loading cycles, indicating potential fatigue or degradation in its mechanical characteristics.

The absorption energy at 100% shear strain can be confirmed in STEP1, STEP3 and STEP4. In this experimental data, the rate of change is calculated based on the values of the preceding cycle, and the overall average is computed. Fig. 3.7 and Table 3.5 show the result of the absorption energy at 100% shear strain in STEP1. The absorption energy values at 100% shear strain in STEP1 consistently diminish with each successive cycle compared to the preceding one. On average, the values experience a decrease of approximately 8.55%. This trend indicates a progressive reduction in the material's capacity to absorb energy over repeated loading cycles, suggesting potential fatigue or degradation in its mechanical characteristics. Fig. 3.8 and Table 3.6 show the result of the absorption energy at 100% shear strain in STEP3. The absorption energy values at 100% shear strain in STEP3 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 5.04%. This trend suggests a progressive decline in the material's ability to absorb energy over repeated loading cycles, indicating potential

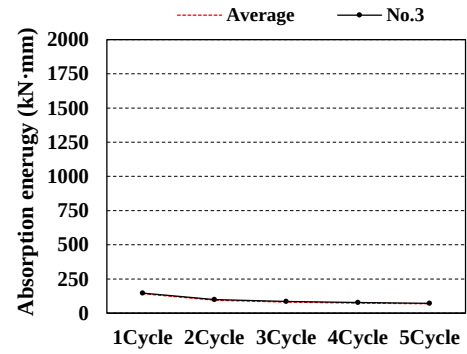
fatigue or degradation in its mechanical characteristics. Fig. 3.9 and Table 3.7 show the result of the absorption energy at 100% shear strain in STEP4. The absorption energy values at 100% shear strain in STEP4 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 5.57%. This trend suggests a progressive decline in the material's ability to absorb energy over repeated loading cycles, indicating potential fatigue or degradation in its mechanical characteristics. Fig. 3.10 and Table 3.8 show the result of the absorption energy at 150% shear strain in STEP2. The absorption energy values at 150% shear strain in STEP2 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 7.83%. This trend suggests a progressive decline in the material's ability to absorb energy over repeated loading cycles, indicating potential fatigue or degradation in its mechanical characteristics. Fig. 3.11 and Table 3.9 show the result of the absorption energy at 150% shear strain in STEP4. The absorption energy values at 150% shear strain in STEP4 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 4.29%. This trend suggests a progressive decline in the material's ability to absorb energy over repeated loading cycles, indicating potential fatigue or degradation in its mechanical characteristics.

Fig. 3.12 and Table 3.10 show the result of the absorption energy at 200% shear strain in STEP3. The absorption energy values at 200% shear strain in STEP3 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 6.50%. This trend suggests a progressive decline in the material's ability to absorb energy over repeated loading cycles, indicating potential fatigue or degradation in its mechanical characteristics.

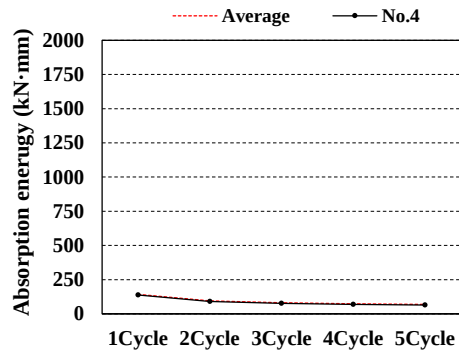
Fig. 3.13 and Table 3.11 show the result of the absorption energy at 250% shear strain in STEP4. The absorption energy values at 250% shear strain in STEP4 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 6.66%. This trend suggests a progressive decline in the material's ability to absorb energy over repeated loading cycles, indicating potential fatigue or degradation in its mechanical characteristics.



(a) No.2 Specimen



(b) No.3 Specimen

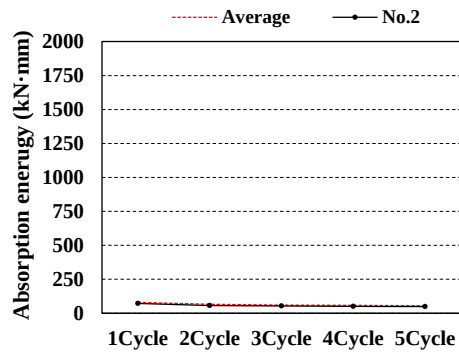


(c) No.4 Specimen

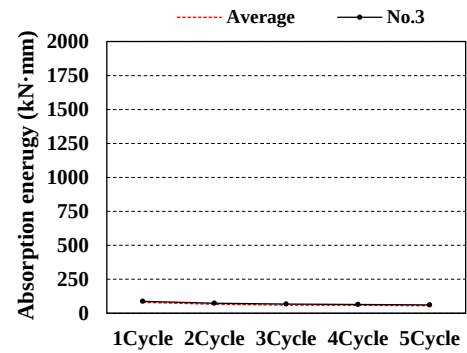
Fig. 3.3 The result of the absorption energy at 50% shear strain in STEP1

Table 3.1 The result of the absorption energy at 50% shear strain in STEP1 for each cycle

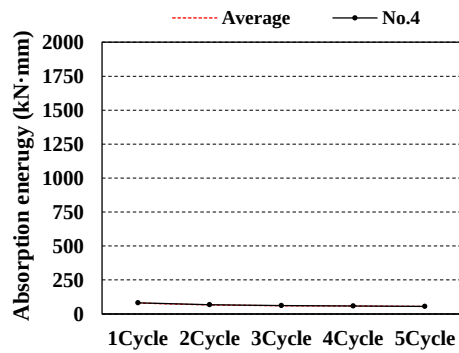
Absorption energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	140	95	81	74	70
No.3	147	100	85	78	72
No.4	138	90	77	70	65
Average	142	95	81	74	69



(a) No.2 Specimen



(b) No.3 Specimen

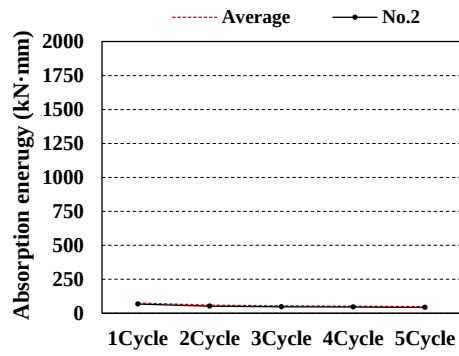


(c) No.4 Specimen

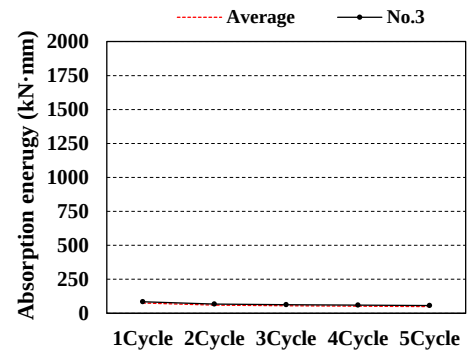
Fig. 3.4 The result of the absorption energy at 50% shear strain in STEP2

Table 3.2 The result of the absorption energy at 50% shear strain in STEP2 for each cycle

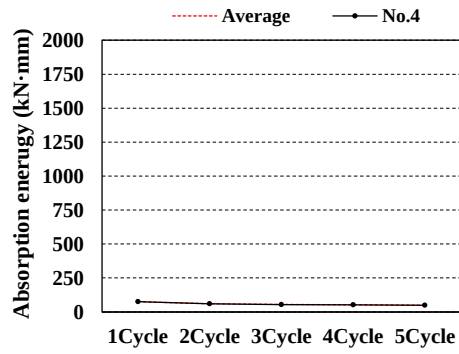
Absorption energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	72	57	53	51	49
No.3	88	73	68	65	62
No.4	81	67	61	58	55
Average	80	66	61	58	55



(a) No.2 Specimen



(b) No.3 Specimen

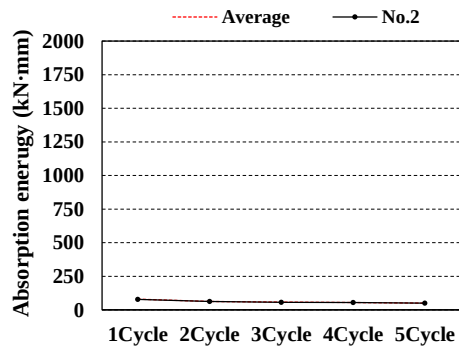


(c) No.4 Specimen

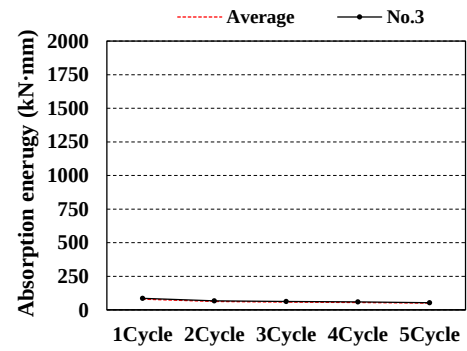
Fig. 3.5 The result of the absorption energy at 50% shear strain in STEP3

Table 3.3 The result of the absorption energy at 50% shear strain in STEP3 for each cycle

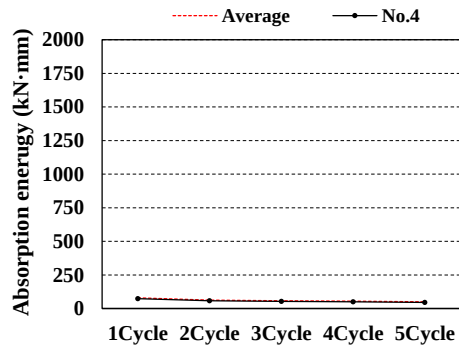
Absorption energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	67	52	48	46	43
No.3	85	68	63	60	56
No.4	75	60	54	52	49
Average	76	60	55	53	49



(a) No.2 Specimen



(b) No.3 Specimen

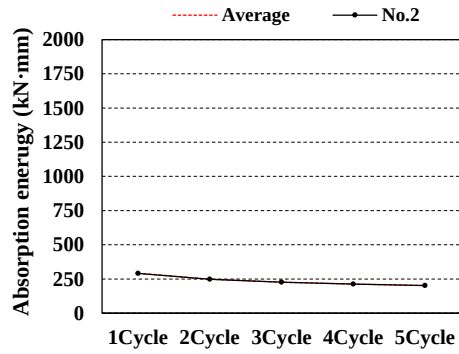


(c) No.4 Specimen

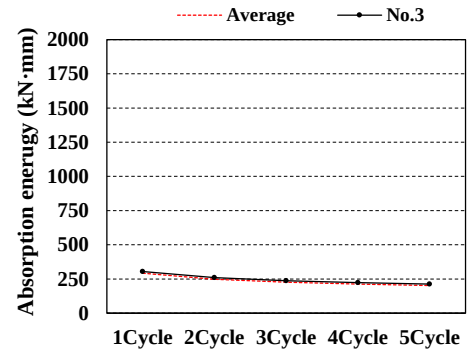
Fig. 3.6 The result of the absorption energy at 50% shear strain in STEP4

Table 3.4 The result of the absorption energy at 50% shear strain in STEP4 for each cycle

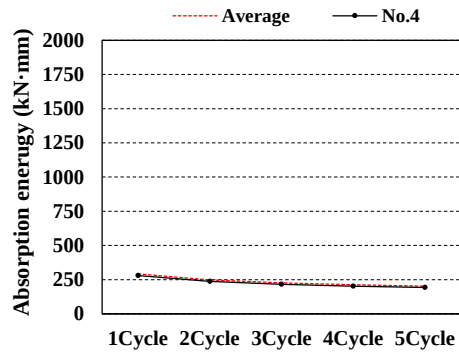
Absorption energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	79	63	57	54	50
No.3	85	68	63	60	54
No.4	74	58	53	50	45
Average	79	63	58	55	50



(a) No.2 Specimen



(b) No.3 Specimen

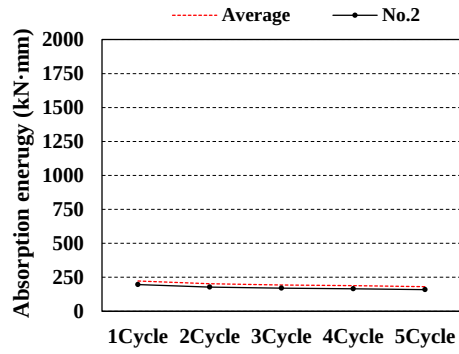


(c) No.4 Specimen

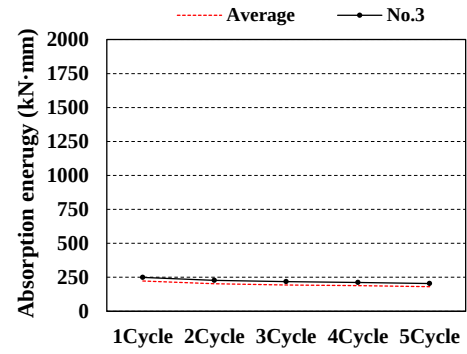
Fig. 3.7 The result of the absorption energy at 100% shear strain in STEP1

Table 3.5 The result of the absorption energy at 100% shear strain in STEP1 for each cycle

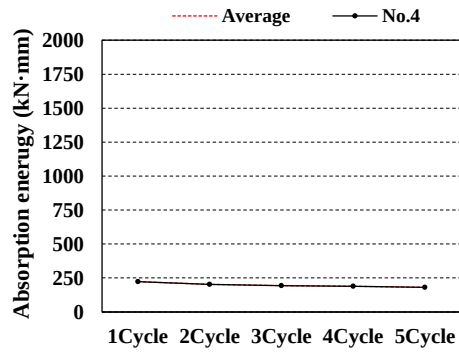
Absorption energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	291	248	226	213	203
No.3	305	260	238	224	212
No.4	281	237	216	203	193
Average	292	248	227	213	203



(a) No.2 Specimen



(b) No.3 Specimen

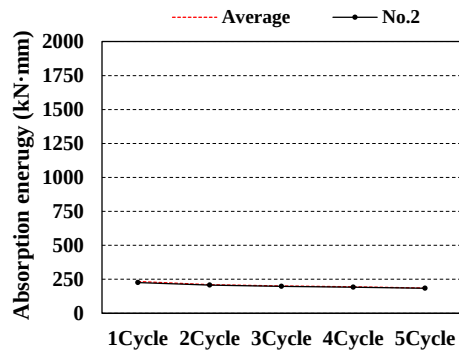


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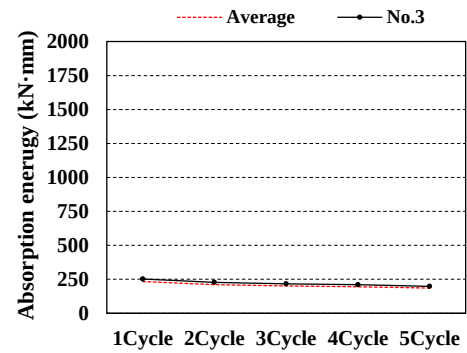
Fig. 3.8 The result of the absorption energy at 100% shear strain in STEP3

Table 3.6 The result of the absorption energy at 100% shear strain in STEP3 for each cycle

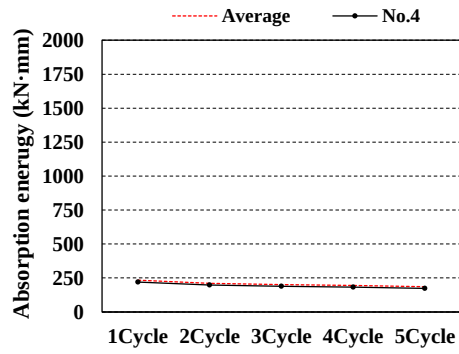
Absorption energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	196	177	170	165	159
No.3	250	228	218	211	204
No.4	223	202	193	188	181
Average	223	202	194	188	181



(a) No.2 Specimen



(b) No.3 Specimen

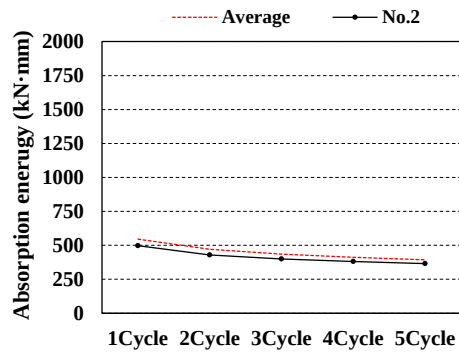


(c) No.4 Specimen

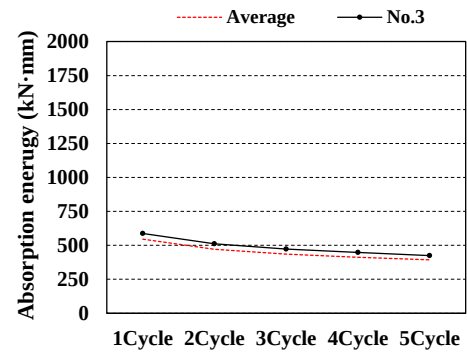
Fig. 3.9 The result of the absorption energy at 100% shear strain in STEP4

Table 3.7 The result of the absorption energy at 100% shear strain in STEP4 for each cycle

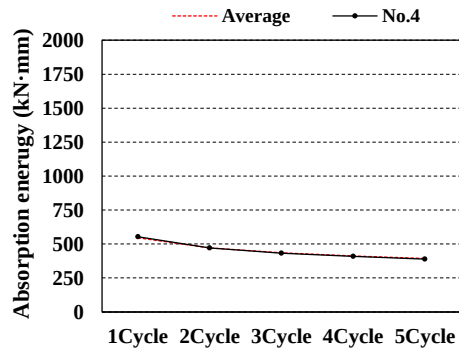
Absorption energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	226	207	198	191	184
No.3	252	227	217	210	199
No.4	220	198	188	183	174
Average	233	211	201	195	185



(a) No.2 Specimen



(b) No.3 Specimen

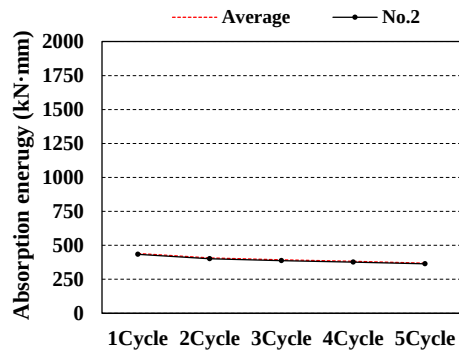


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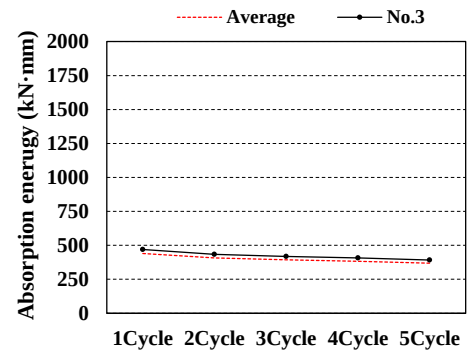
Fig. 3.10 The result of the absorption energy at 150% shear strain in STEP2

Table 3.8 The result of the absorption energy at 150% shear strain in STEP2 for each cycle

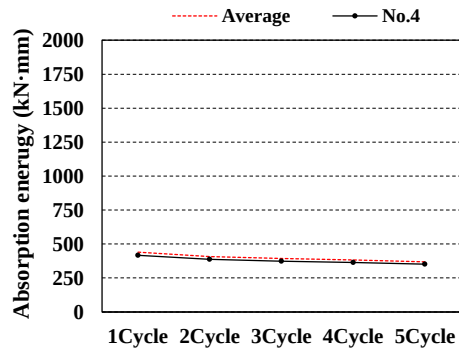
Absorption energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	497	429	399	381	366
No.3	588	512	473	448	425
No.4	554	470	432	409	389
Average	546	470	435	413	393



(a) No.2 Specimen



(b) No.3 Specimen

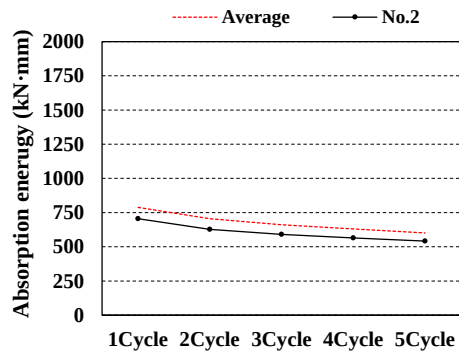


(c) No.4 Specimen

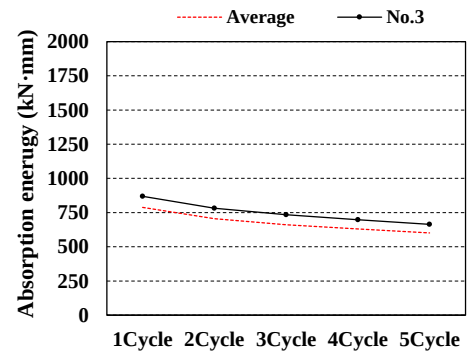
Fig. 3.11 The result of the absorption energy at 150% shear strain in STEP4

Table 3.9 The result of the absorption energy at 150% shear strain in STEP4 for each cycle

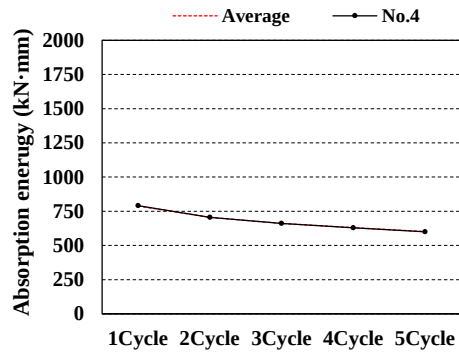
Absorption energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	434	401	387	377	364
No.3	469	434	419	408	392
No.4	417	387	373	364	351
Average	440	407	393	383	369



(a) No.2 Specimen



(b) No.3 Specimen

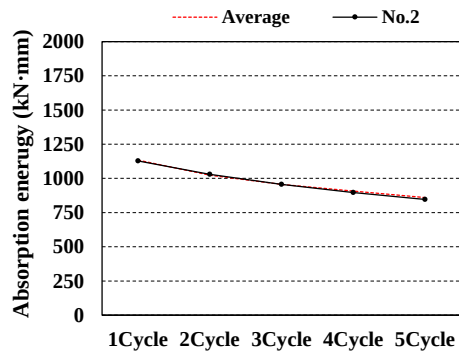


(c) No.4 Specimen

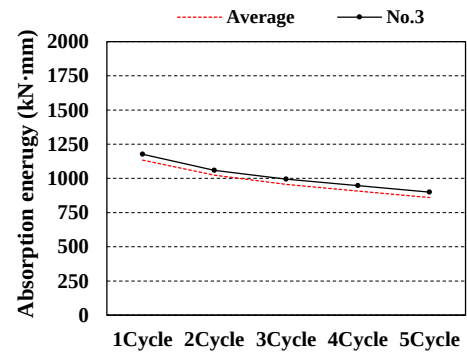
Fig. 3.12 The result of the absorption energy at 200% shear strain in STEP3

Table 3.10 The result of the absorption energy at 200% shear strain in STEP3 for each cycle

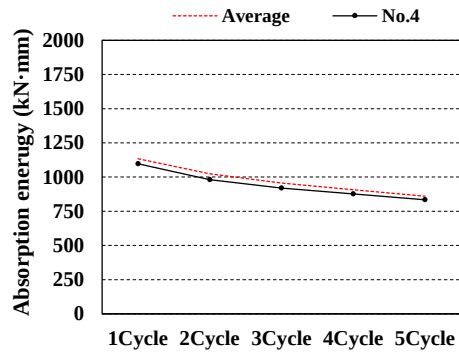
Absorption energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	706	627	590	565	541
No.3	868	782	734	697	665
No.4	792	705	660	629	599
Average	789	705	662	630	602



(a) No.2 Specimen



(b) No.3 Specimen



(c) No.4 Specimen

Fig. 3.13 The result of the absorption energy at 250% shear strain in STEP3

Table 3.11 The result of the absorption energy at 250% shear strain in STEP4 for each cycle

Absorption energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	1128	1030	956	897	846
No.3	1177	1058	994	947	899
No.4	1097	981	920	877	834
Average	1134	1023	957	907	860

3.2.2 Equivalent stiffness

Equivalent Stiffness, a crucial metric in material mechanics, gauges the HDR material's resistance to deformation when subjected to dynamic loads. This parameter signifies the material's capability to withstand displacements and revert to its original position. Calculated from the slope of the initial linear segment of the hysteresis curve, the equivalent stiffness quantifies the relationship between applied shear strain and the restoring force of the HDR. Notably, higher values of equivalent stiffness correlate with enhanced resistance to deformation. The equivalent stiffness K_{eq} was calculated using equation (3.2) as expressed below:

$$K_{eq} = \frac{F_{max} - F_{min} - 2f}{\delta_{max} - \delta_{min}} \quad (3.2)$$

where F_{max} and F_{min} represent the maximum and minimum shear force, respectively, and δ_{max} and δ_{min} correspond to the maximum and minimum displacements, respectively.

Fig. 3.13 and Table 3.11 show the result of the absorption energy at 250% shear strain in STEP4. The values at 250% shear strain in STEP4 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 8.14%. This trend suggests a progressive decline in the material's characteristics over repeated cycles, indicating potential fatigue or degradation in its mechanical properties. Fig. 3.15 and Table 3.13 show the result of the equivalent stiffness at 50% shear strain in STEP2. The values at 50% shear strain in STEP2 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 4.34%. This trend suggests a progressive decline in the material's characteristics over repeated cycles, indicating potential fatigue or degradation in its mechanical properties. Fig. 3.16 and Table 3.14 show the result of the equivalent stiffness at 50% shear strain in STEP3. The equivalent stiffness values at 50% shear strain in STEP3 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 5.08%. This trend suggests a progressive

decline in the material's stiffness over repeated cycles, indicating potential fatigue or degradation in its mechanical properties. Fig. 3.17 and Table 3.15 show the result of the equivalent stiffness at 50% shear strain in STEP4. The equivalent stiffness values at 50% shear strain in STEP4 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 5.47%. This trend suggests a progressive decline in the material's stiffness over repeated cycles, indicating potential fatigue or degradation in its mechanical properties.

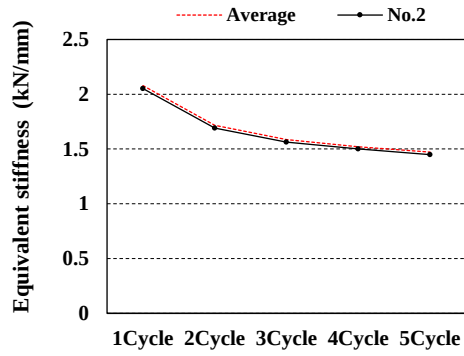
Fig. 3.18 and Table 3.16 show the result of the equivalent stiffness at 100% shear strain in STEP1. The equivalent stiffness values at 100% shear strain in STEP1 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 6.95%. This trend suggests a progressive decline in the material's stiffness over repeated cycles, indicating potential fatigue or degradation in its mechanical properties. Fig. 3.19 and Table 3.17 show the result of the equivalent stiffness at 100% shear strain in STEP3. The equivalent stiffness values at 100% shear strain in STEP3 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 4.46%. This trend suggests a progressive decline in the material's stiffness over repeated cycles, indicating potential fatigue or degradation in its mechanical properties. Fig. 3.20 and Table 3.18 show the result of the equivalent stiffness at 100% shear strain in STEP4. The equivalent stiffness values at 100% shear strain in STEP4 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 4.66%. This trend suggests a progressive decline in the material's stiffness over repeated cycles, indicating potential fatigue or degradation in its mechanical properties.

Fig. 3.21 and Table 3.19 show the result of the equivalent stiffness at 150% shear strain in STEP2. The equivalent stiffness values at 150% shear strain in STEP2 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 7.71%. This trend

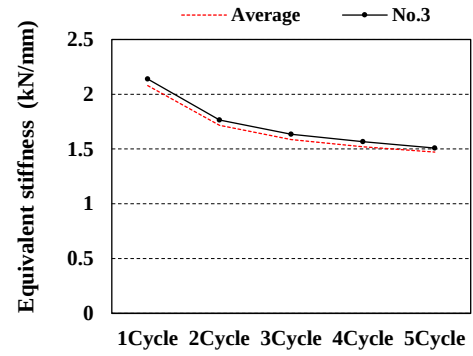
suggests a progressive decline in the material's stiffness over repeated cycles, indicating potential fatigue or degradation in its mechanical properties. Fig. 3.22 and Table 3.20 show the result of the equivalent stiffness at 150% shear strain in STEP4. The equivalent stiffness values at 150% shear strain in STEP4 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 4.24%. This trend suggests a progressive decline in the material's stiffness over repeated cycles, indicating potential fatigue or degradation in its mechanical properties.

Fig. 3.23 and Table 3.21 show the result of the equivalent stiffness at 200% shear strain in STEP3. The equivalent stiffness values at 200% shear strain in STEP3 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 7.41%. This trend suggests a progressive decline in the material's stiffness over repeated cycles, indicating potential fatigue or degradation in its mechanical properties.

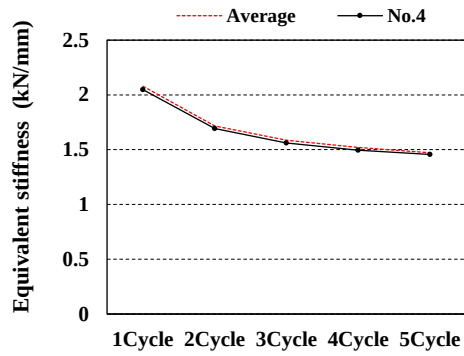
Fig. 3.24 and Table 3.22 show the result of the equivalent stiffness at 250% shear strain in STEP4. The equivalent stiffness values at 250% shear strain in STEP4 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 6.86%. This trend suggests a progressive decline in the material's stiffness over repeated cycles, indicating potential fatigue or degradation in its mechanical properties.



(a) No.2 Specimen



(b) No.3 Specimen

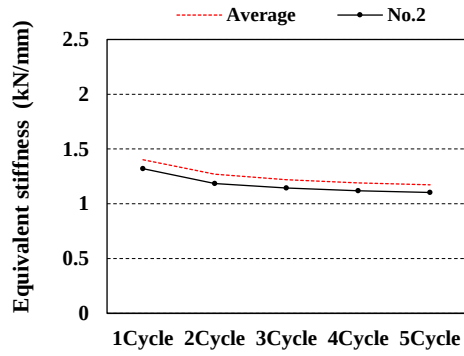


(c) No.4 Specimen

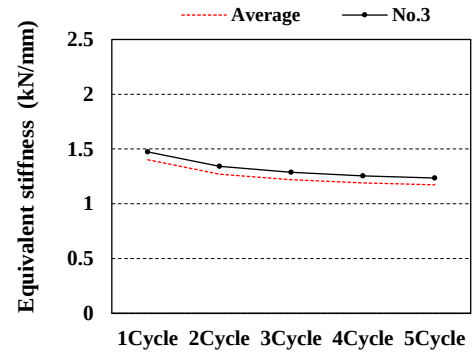
Fig. 3.14 The result of the equivalent stiffness at 50% shear strain in STEP1

Table 3.12 The result of the equivalent stiffness at 50% shear strain in STEP1 for each cycle

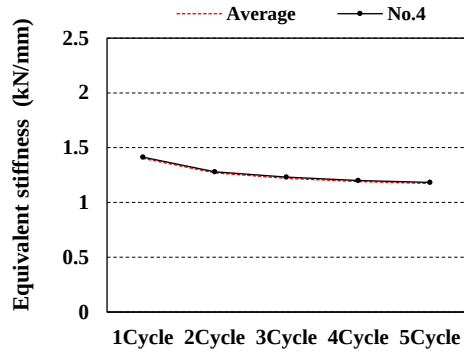
Equivalent stiffness (kN/mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	2.05	1.69	1.56	1.50	1.45
No.3	2.14	1.76	1.63	1.57	1.51
No.4	2.05	1.69	1.56	1.49	1.46
Average	2.08	1.72	1.59	1.52	1.47



(a) No.2 Specimen



(b) No.3 Specimen

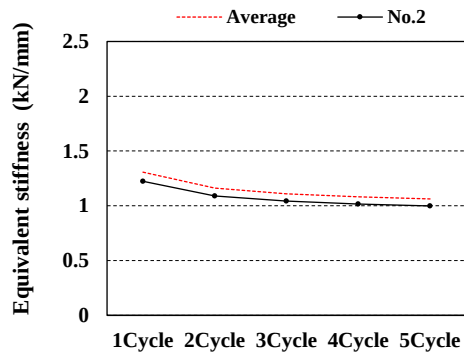


(c) No.4 Specimen

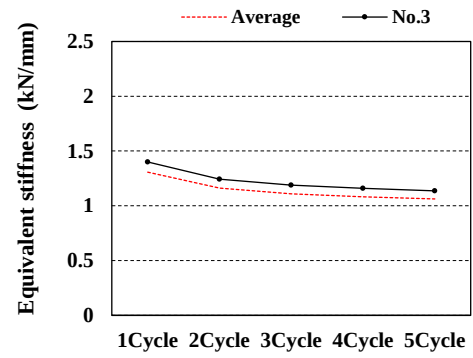
Fig. 3.15 The result of the equivalent stiffness at 50% shear strain in STEP2

Table 3.13 The result of the equivalent stiffness at 50% shear strain in STEP2 for each cycle

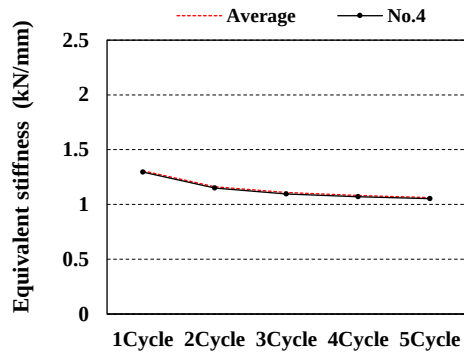
Equivalent stiffness (kN/mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	1.32	1.19	1.14	1.12	1.10
No.3	1.47	1.34	1.29	1.25	1.23
No.4	1.41	1.28	1.23	1.20	1.18
Average	1.40	1.27	1.22	1.19	1.17



(a) No.2 Specimen



(b) No.3 Specimen

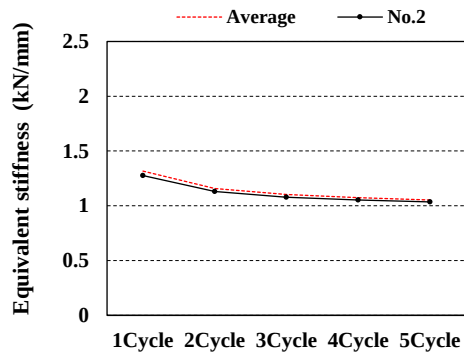


(c) No.4 Specimen

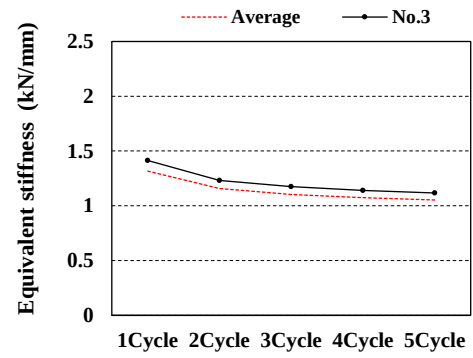
Fig. 3.16 The result of the equivalent stiffness at 50% shear strain in STEP3

Table 3.14 The result of the equivalent stiffness at 50% shear strain in STEP3 for each cycle

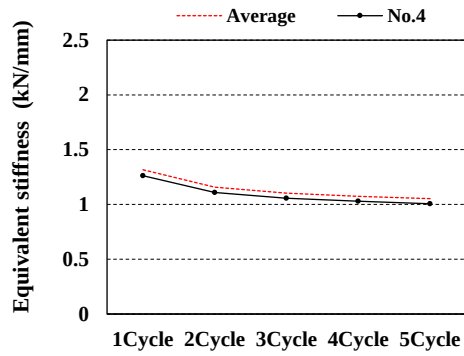
Equivalent stiffness (kN/mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	1.22	1.09	1.04	1.02	1.00
No.3	1.40	1.24	1.19	1.16	1.14
No.4	1.29	1.15	1.10	1.07	1.05
Average	1.31	1.16	1.11	1.08	1.06



(a) No.2 Specimen



(b) No.3 Specimen

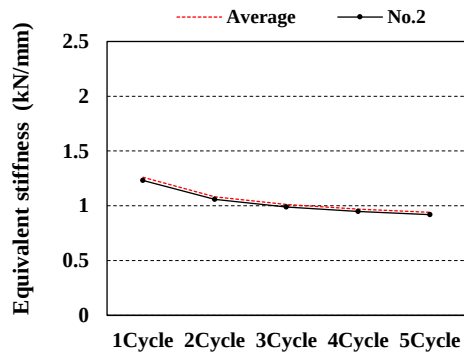


(c) No.4 Specimen

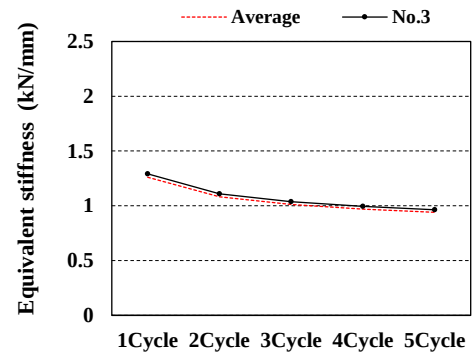
Fig.3.17 The result of the equivalent stiffness at 50% shear strain in STEP4

Table 3.15 The result of the equivalent stiffness at 50% shear strain in STEP4 for each cycle

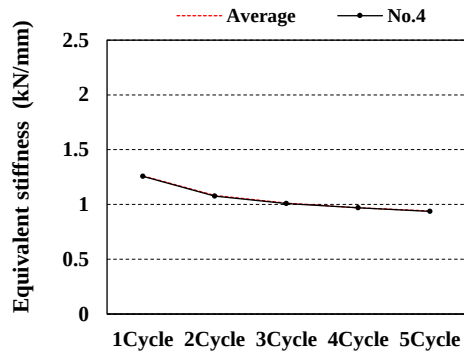
Equivalent stiffness (kN/mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Specimen					
No.2	1.28	1.13	1.08	1.05	1.04
No.3	1.41	1.23	1.17	1.14	1.12
No.4	1.26	1.11	1.06	1.03	1.01
Average	1.32	1.16	1.10	1.07	1.05



(a) No.2 Specimen



(b) No.3 Specimen

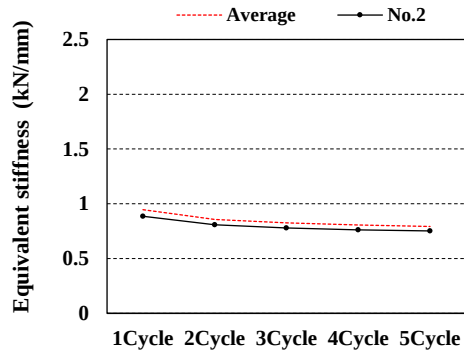


(c) No.4 Specimen

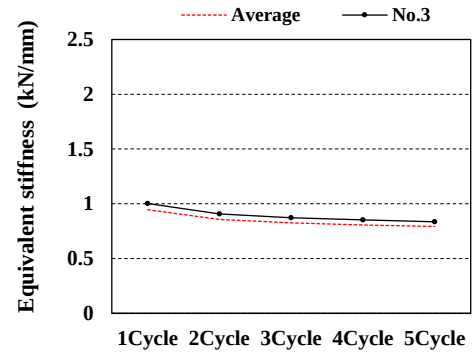
Fig. 3.18 The result of the equivalent stiffness at 100% shear strain in STEP1

Table 3.16 The result of the equivalent stiffness at 100% shear strain in STEP1 for each cycle

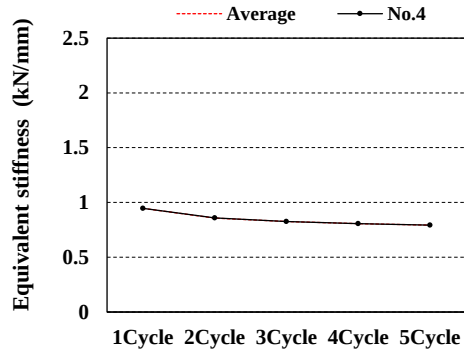
Equivalent stiffness (kN/mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	1.23	1.06	0.99	0.95	0.92
No.3	1.29	1.11	1.04	0.99	0.96
No.4	1.26	1.08	1.01	0.97	0.94
Average	1.26	1.08	1.01	0.97	0.94



(a) No.2 Specimen



(b) No.3 Specimen

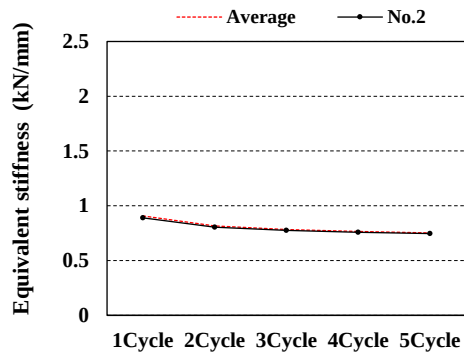


(c) No.4 Specimen

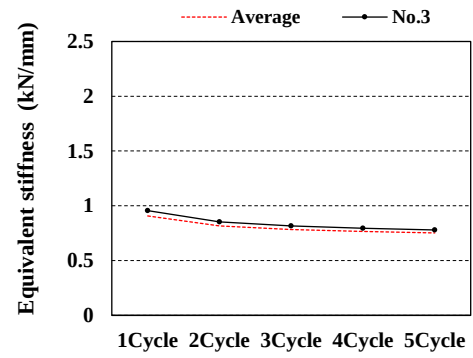
Fig. 3.19 The result of the equivalent stiffness at 100% shear strain in STEP3

Table 3.17 The result of the equivalent stiffness at 100% shear strain in STEP3 for each cycle

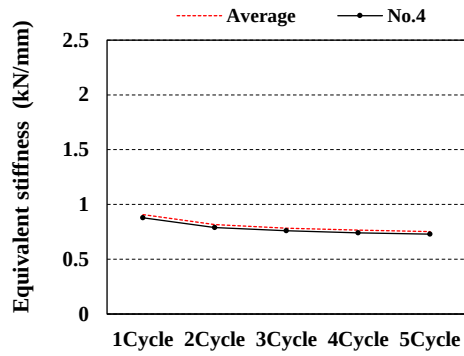
Equivalent stiffness (kN/mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.89	0.81	0.78	0.76	0.75
No.3	1.00	0.91	0.87	0.85	0.84
No.4	0.95	0.86	0.83	0.81	0.79
Average	0.95	0.86	0.83	0.81	0.79



(a) No.2 Specimen



(b) No.3 Specimen

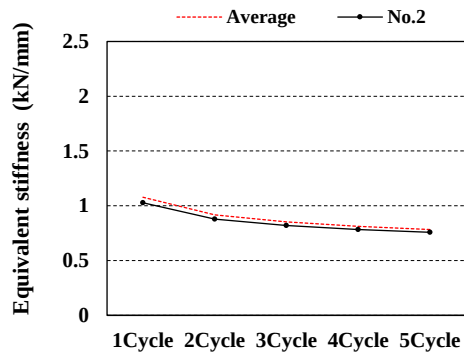


(c) No.4 Specimen

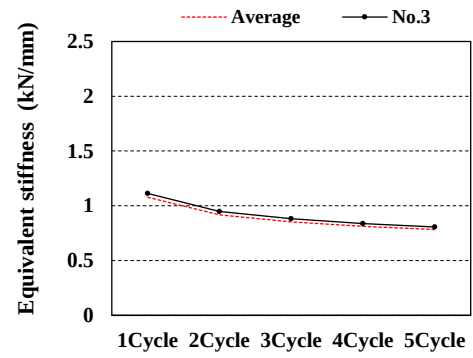
Fig. 3.20 The result of the equivalent stiffness at 100% shear strain in STEP4

Table 3.18 The result of the equivalent stiffness at 100% shear strain in STEP4 for each cycle

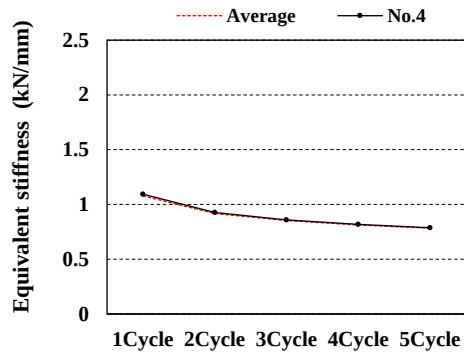
Equivalent stiffness (kN/mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.89	0.80	0.78	0.76	0.75
No.3	0.96	0.85	0.82	0.80	0.78
No.4	0.88	0.79	0.76	0.74	0.73
Average	0.91	0.82	0.78	0.77	0.75



(a) No.2 Specimen



(b) No.3 Specimen

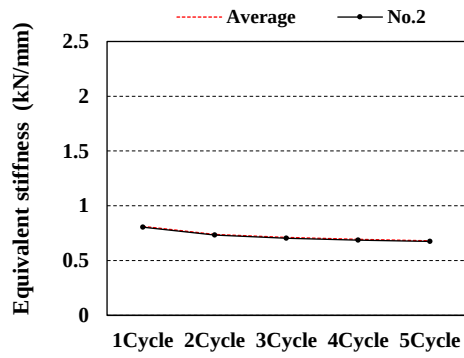


(c) No.4 Specimen

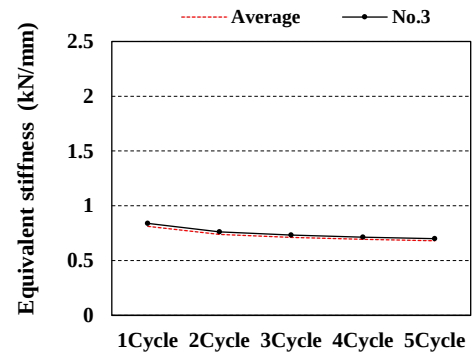
Fig. 3.21 The result of the equivalent stiffness at 150% shear strain in STEP2

Table 3.19 The result of the equivalent stiffness at 150% shear strain in STEP2 for each cycle

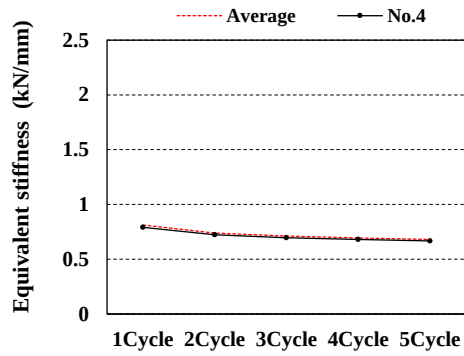
Equivalent stiffness (kN/mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	1.03	0.88	0.82	0.78	0.76
No.3	1.11	0.95	0.88	0.84	0.81
No.4	1.09	0.93	0.86	0.82	0.79
Average	1.08	0.92	0.85	0.81	0.78



(a) No.2 Specimen



(b) No.3 Specimen

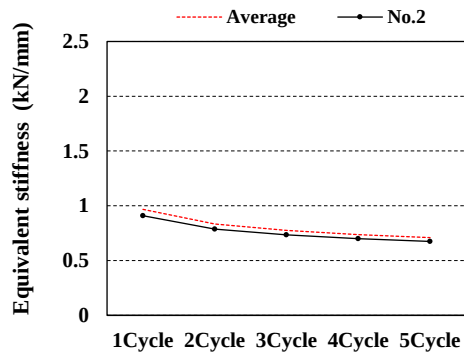


(c) No.4 Specimen

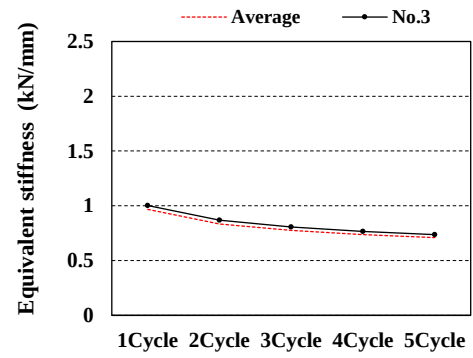
Fig. 3.22 The result of the equivalent stiffness at 150% shear strain in STEP4

Table 3.20 The result of the equivalent stiffness at 150% shear strain in STEP4 for each cycle

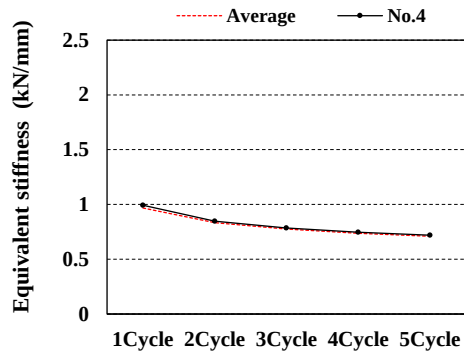
Equivalent stiffness (kN/mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.80	0.73	0.70	0.69	0.67
No.3	0.84	0.76	0.73	0.71	0.70
No.4	0.79	0.72	0.70	0.68	0.67
Average	0.81	0.74	0.71	0.69	0.68



(a) No.2 Specimen



(b) No.3 Specimen

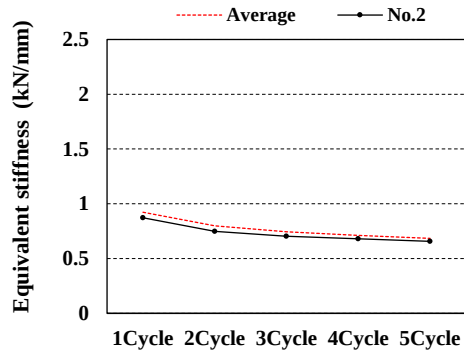


(c) No.4 Specimen

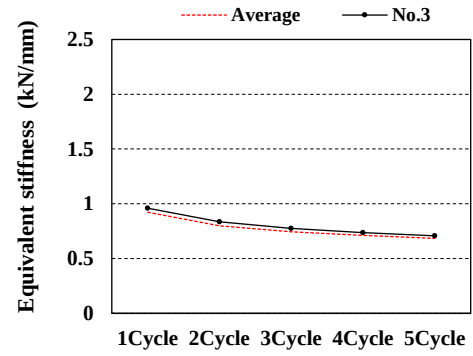
Fig. 3.23 The result of the equivalent stiffness at 200% shear strain in STEP3

Table 3.21 The result of the equivalent stiffness at 200% shear strain in STEP3 for each cycle

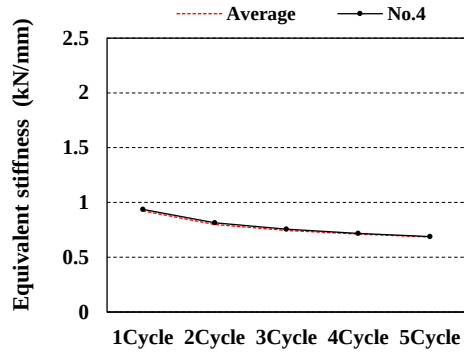
Equivalent stiffness (kN/mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.91	0.79	0.74	0.70	0.68
No.3	1.00	0.87	0.81	0.77	0.74
No.4	0.99	0.85	0.79	0.75	0.72
Average	0.97	0.83	0.78	0.74	0.71



(a) No.2 Specimen



(b) No.3 Specimen



(c) No.4 Specimen

Fig. 3.24 The result of the equivalent stiffness at 250% shear strain in STEP4

Table 3.22 The result of the equivalent stiffness at 250% shear strain in STEP4 for each cycle

Equivalent stiffness (kN/mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.87	0.75	0.70	0.68	0.66
No.3	0.96	0.84	0.78	0.74	0.71
No.4	0.94	0.82	0.76	0.72	0.69
Average	0.92	0.80	0.75	0.71	0.69

3.2.3 Damping ratio

Damping ratio serves as a crucial indicator, measuring the energy dissipation capacity of HDR materials under dynamic loads. This ratio specifically denotes the material's proficiency in either absorbing or dissipating energy during dynamic loading scenarios. Typically derived from the area enclosed within the hysteresis curve, which signifies the energy dissipated per cycle, the equivalent damping ratio is a key parameter. Importantly, a higher equivalent damping ratio is indicative of an increased capability to absorb and dissipate energy, leading to superior damping performance and minimized structural response. The equivalent damping ratio H_{eq} was calculated using equation (3.3) as expressed below:

$$H_{eq} = \frac{1}{4\pi} \left(\frac{\Delta W'}{W} \right) \quad (3.3)$$

$$\Delta W' = \Delta W - 4fD \quad (3.4)$$

where W represents the strain energy and $\Delta W'$ represents the effective area (the area of the hysteresis curve accounting for the frictional force of the hybrid actuator) The effective area $\Delta W'$ was calculated using equation (3.4).

Fig. 3.25 and Table 3.23 show the result of the damping ratio at 50% shear strain in STEP1. The damping ratio values at 50% shear strain in STEP1 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 9.65%. This trend suggests a progressive decline in the material's damping ability over repeated cycles, indicating potential changes in its energy dissipation characteristics or possible deterioration. Fig. 3.26 and Table 3.24 show the result of the damping ratio at 50% shear strain in STEP2. The damping ratio values at 50% shear strain in STEP2 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 4.92%. This trend suggests a progressive decline in the

material's damping ability over repeated cycles, indicating potential changes in its energy dissipation characteristics or possible deterioration. Fig. 3.27 and Table 3.25 show the result of the damping ratio at 50% shear strain in STEP3. The damping ratio values at 50% shear strain in STEP3 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 5.76%. This trend suggests a progressive decline in the material's damping ability over repeated cycles, indicating potential changes in its energy dissipation characteristics or possible deterioration. Fig. 3.28 and Table 3.26 show the result of the damping ratio at 50% shear strain in STEP4. The damping ratio values at 50% shear strain in STEP4 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 6.41%. This trend suggests a progressive decline in the material's damping ability over repeated cycles, indicating potential changes in its energy dissipation characteristics or possible deterioration.

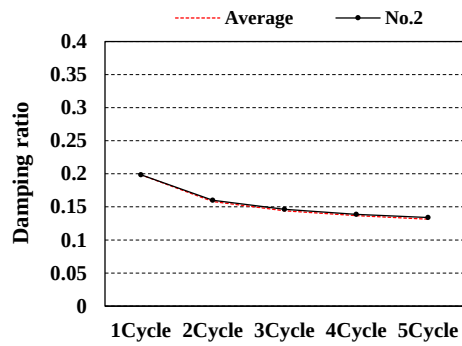
Fig. 3.29 and Table 3.27 show the result of the damping ratio at 100% shear strain in STEP1. The damping ratio values at 100% shear strain in STEP1 consistently decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 2.28%. This trend suggests a minor decline in the material's damping ability over repeated cycles, indicating potential changes in its energy dissipation characteristics or possible minor deterioration. Fig. 3.30 and Table 3.28 show the result of the damping ratio at 100% shear strain in STEP3. The damping ratio values at 100% shear strain in STEP3 show a gradual decrease with each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 0.91%. This trend suggests a subtle decline in the material's damping ability over repeated cycles, indicating potential minor changes in its energy dissipation characteristics. Fig. 3.31 and Table 3.29 show the result of the damping ratio at 100% shear strain in STEP4. The damping ratio values at 100% shear strain in STEP4 exhibit no change in the second cycle, followed by a gradual decrease in each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 1.18%. This trend suggests a subtle

decline in the material's damping ability over repeated cycles, indicating potential minor changes in its energy dissipation characteristics.

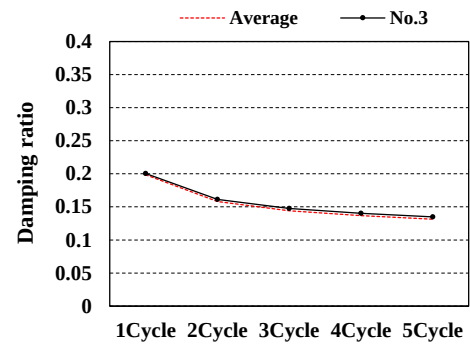
Fig. 3.32 and Table 3.30 show the result of the damping ratio at 150% shear strain in STEP2. The damping ratio values at 150% shear strain in STEP2 exhibit no change in the second cycle, followed by a gradual decrease in each successive cycle compared to the preceding one. On average, the values experience a reduction of approximately 0.82%. This trend suggests a subtle decline in the material's damping ability over repeated cycles, indicating potential minor changes in its energy dissipation characteristics. Fig. 3.33 and Table 3.31 show the result of the damping ratio at 150% shear strain in STEP4. The damping ratio values at 150% shear strain in STEP4 show a slight increase in the second cycle, followed by no significant change in the subsequent cycles. On average, the values experience a minimal decrease of approximately 0.15%. This trend suggests stability in the material's damping ability over repeated cycles, with minor fluctuations.

Fig. 3.34 and Table 3.32 show the result of the damping ratio at 200% shear strain in STEP3. The damping ratio values at 200% shear strain in STEP3 show a gradual increase in the second cycle, followed by minor fluctuations in the subsequent cycles. On average, the values experience a slight increase of approximately 0.46%. This trend suggests variability in the material's damping ability over repeated cycles, with a tendency toward increased damping in certain cycles.

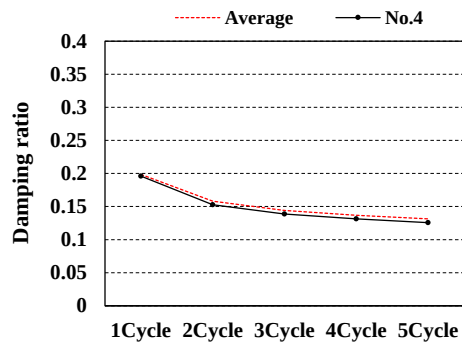
Fig. 3.35 and Table 3.33 show the result of the damping ratio at 250% shear strain in STEP4. The damping ratio values at 250% shear strain in STEP4 exhibit a notable increase in the second cycle, followed by minor fluctuations with both increases and decreases in the subsequent cycles. On average, the values experience a slight overall increase of approximately 0.21%. This suggests some variability in the material's damping ability over repeated cycles, with a tendency toward increased damping in certain cycles.



(a) No.2 Specimen



(b) No.3 Specimen

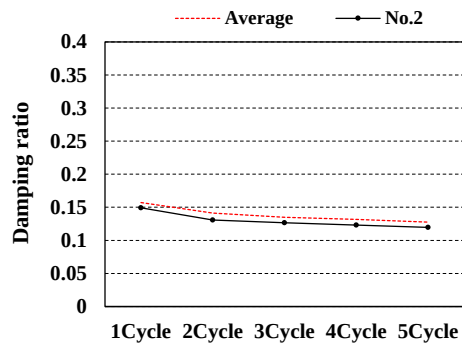


(c) No.4 Specimen

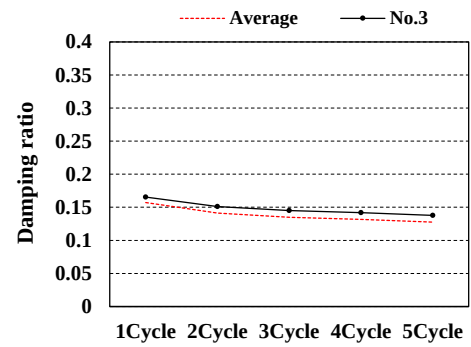
Fig.3.25 The result of the damping ratio at 50% shear strain in STEP1

Table 3.23 The result of the damping ratio at 50% shear strain in STEP1 for each cycle

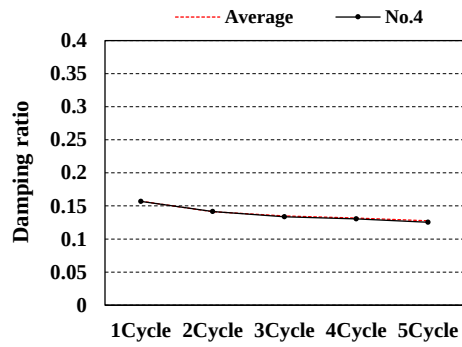
Damping ratio	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.199	0.160	0.146	0.139	0.134
No.3	0.200	0.161	0.148	0.140	0.135
No.4	0.196	0.153	0.139	0.131	0.126
Average	0.198	0.158	0.144	0.137	0.131



(a) No.2 Specimen



(b) No.3 Specimen

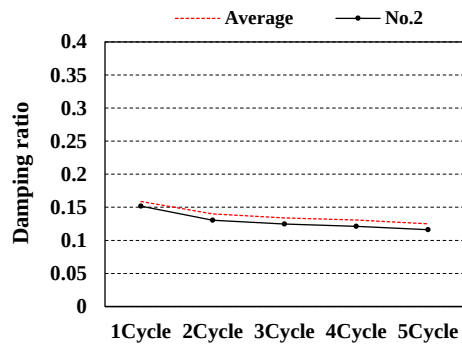


(c) No.4 Specimen

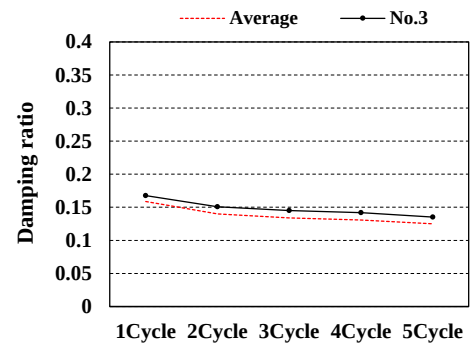
Fig. 3.26 The result of the damping ratio at 50% shear strain in STEP2

Table 3.24 The result of the damping ratio at 50% shear strain in STEP2 for each cycle

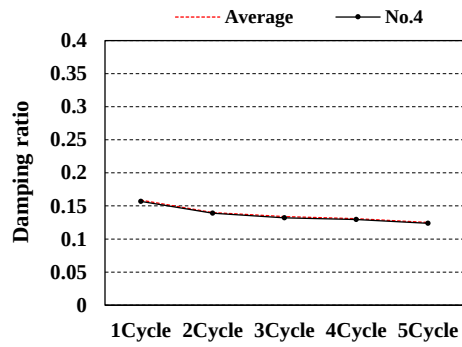
Damping ratio	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.149	0.131	0.126	0.123	0.120
No.3	0.165	0.151	0.145	0.142	0.138
No.4	0.157	0.142	0.134	0.130	0.125
Average	0.157	0.141	0.135	0.132	0.128



(a) No.2 Specimen



(b) No.3 Specimen

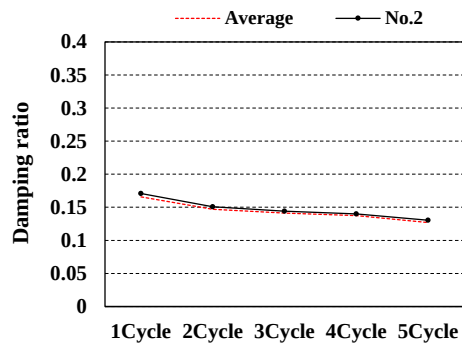


(c) No.4 Specimen

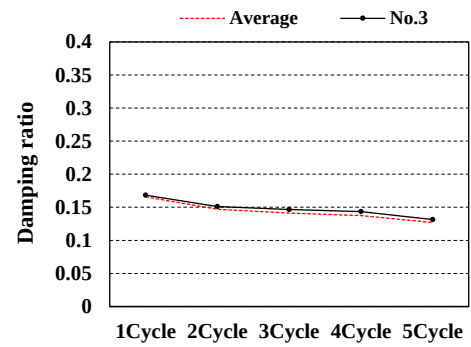
Fig. 3.27 The result of the damping ratio at 50% shear strain in STEP3

Table 3.25 The result of the damping ratio at 50% shear strain in STEP3 for each cycle

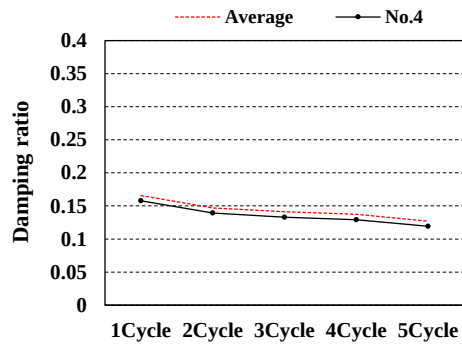
Damping ratio	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.152	0.130	0.125	0.121	0.116
No.3	0.168	0.151	0.145	0.142	0.135
No.4	0.157	0.139	0.132	0.129	0.124
Average	0.159	0.140	0.134	0.131	0.125



(a) No.2 Specimen



(b) No.3 Specimen

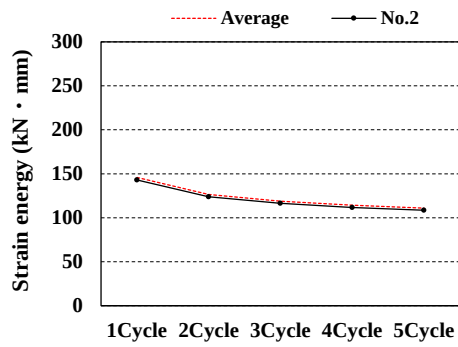


(c) No.4 Specimen

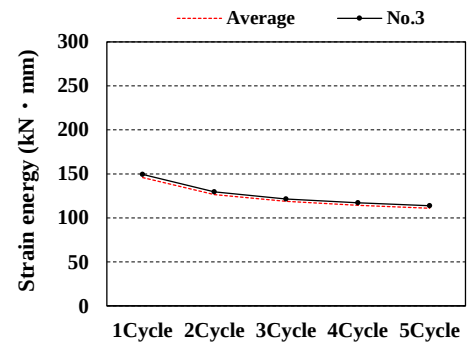
Fig. 3.28 The result of the damping ratio at 50% shear strain in STEP4

Table 3.26 The result of the damping ratio at 50% shear strain in STEP4 for each cycle

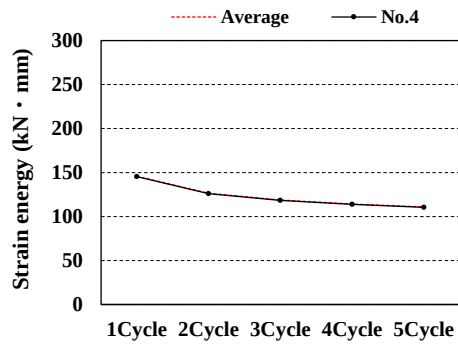
Damping ratio	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.171	0.151	0.144	0.140	0.130
No.3	0.168	0.151	0.147	0.144	0.131
No.4	0.158	0.139	0.133	0.129	0.119
Average	0.166	0.147	0.141	0.138	0.127



(a) No.2 Specimen



(b) No.3 Specimen

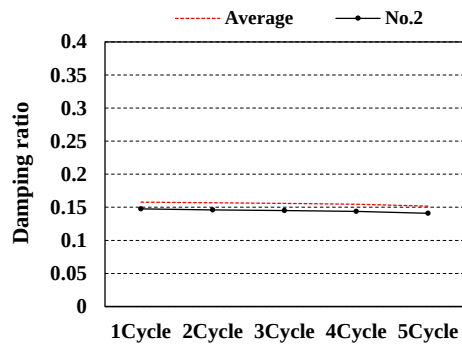


(c) No.4 Specimen

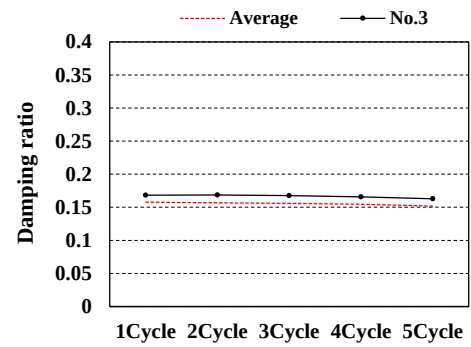
Fig. 3.29 The result of the damping ratio at 100% shear strain in STEP1

Table 3.27 The result of the damping ratio at 100% shear strain in STEP1 for each cycle

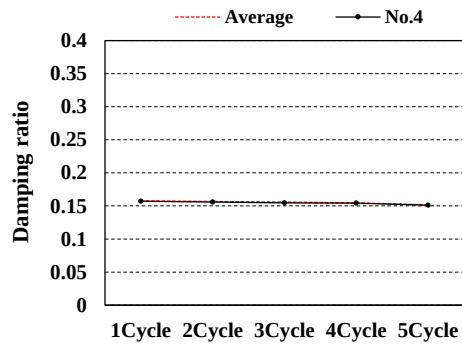
Damping ratio	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.162	0.159	0.155	0.152	0.149
No.3	0.163	0.160	0.156	0.153	0.148
No.4	0.154	0.150	0.145	0.142	0.139
Average	0.159	0.156	0.152	0.149	0.145



(a) No.2 Specimen



(b) No.3 Specimen

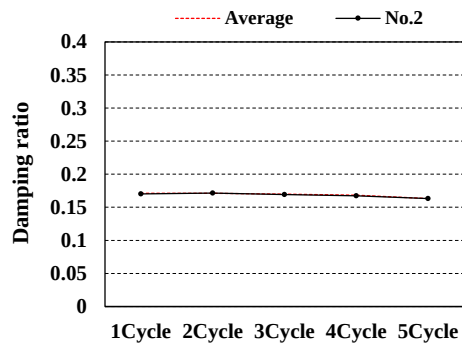


(c) No.4 Specimen

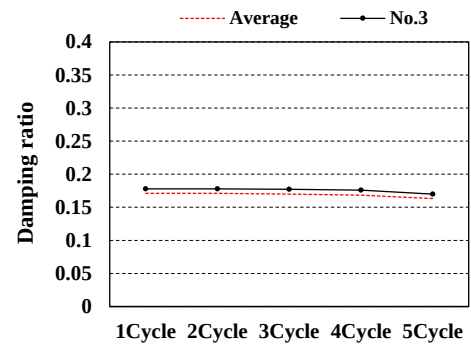
Fig. 3.30 The result of the damping ratio at 100% shear strain in STEP3

Table 3.28 The result of the damping ratio at 100% shear strain in STEP3 for each cycle

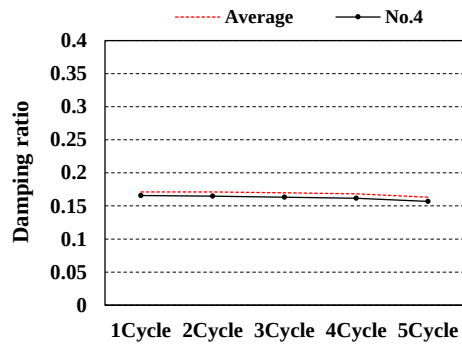
Damping ratio	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.148	0.146	0.145	0.144	0.141
No.3	0.168	0.169	0.168	0.166	0.163
No.4	0.157	0.156	0.155	0.154	0.151
Average	0.158	0.157	0.156	0.154	0.152



(a) No.2 Specimen



(b) No.3 Specimen

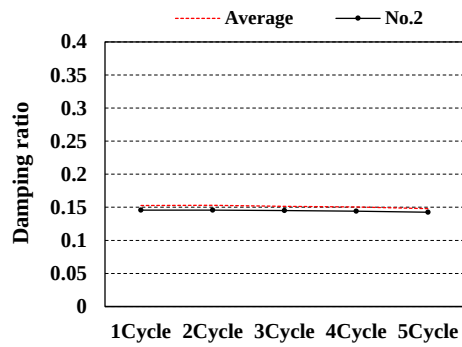


(c) No.4 Specimen

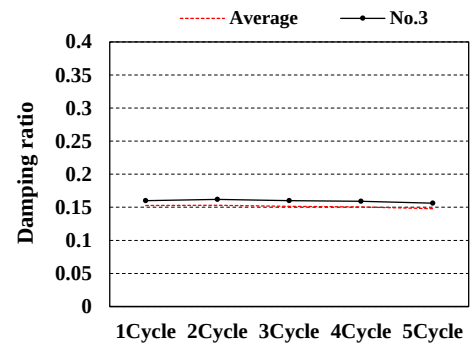
Fig. 3.31 The result of the damping ratio at 100% shear strain in STEP4

Table 3.29 The result of the damping ratio at 100% shear strain in STEP4 for each cycle

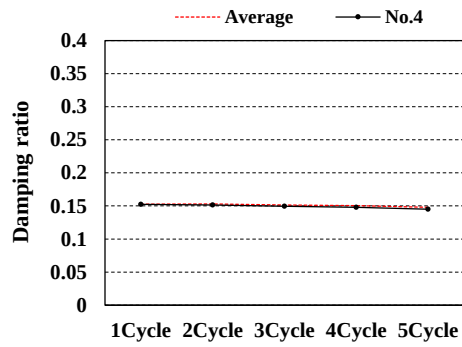
Damping ratio	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.170	0.171	0.169	0.167	0.163
No.3	0.178	0.178	0.177	0.176	0.170
No.4	0.166	0.165	0.163	0.162	0.157
Average	0.171	0.171	0.170	0.168	0.163



(a) No.2 Specimen



(b) No.3 Specimen

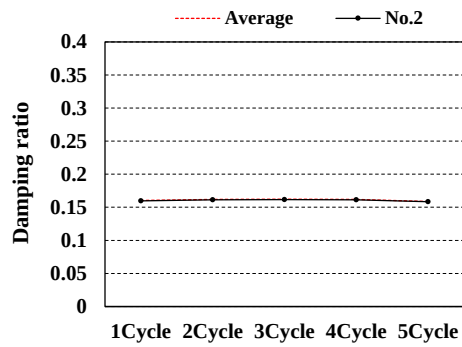


(c) No.4 Specimen

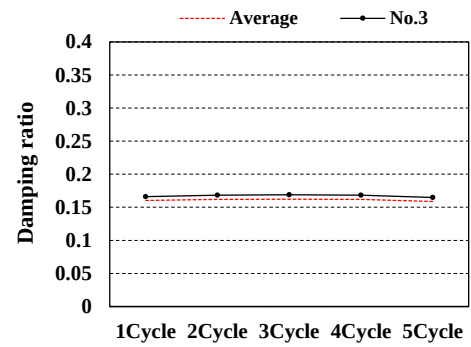
Fig. 3.32 The result of the damping ratio at 150% shear strain in STEP2

Table 3.30 The result of the damping ratio at 150% shear strain in STEP2 for each cycle

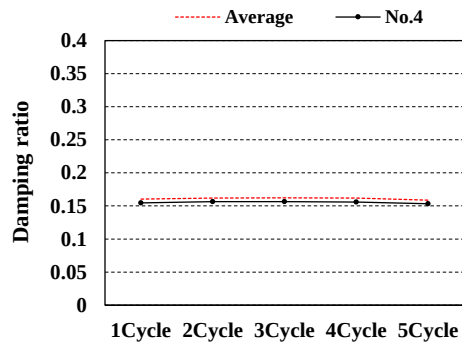
Damping ratio	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.146	0.146	0.145	0.144	0.143
No.3	0.160	0.162	0.160	0.159	0.156
No.4	0.152	0.152	0.149	0.148	0.145
Average	0.153	0.153	0.151	0.150	0.148



(a) No.2 Specimen



(b) No.3 Specimen

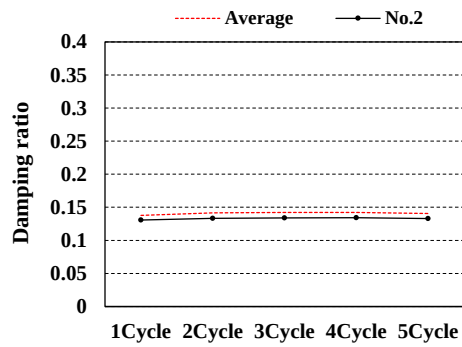


(c) No.4 Specimen

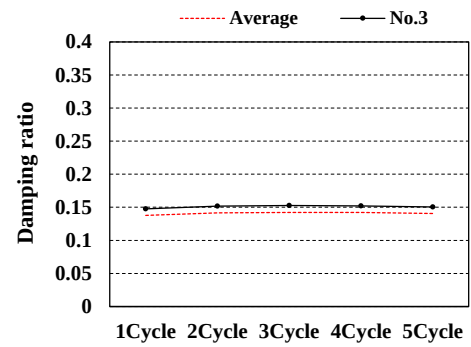
Fig. 3.33 The result of the damping ratio at 150% shear strain in STEP4

Table 3.31 The result of the damping ratio at 150% shear strain in STEP4 for each cycle

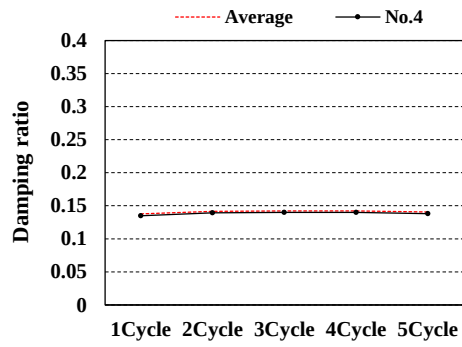
Damping ratio	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.160	0.161	0.162	0.161	0.159
No.3	0.166	0.168	0.169	0.168	0.165
No.4	0.155	0.156	0.156	0.156	0.153
Average	0.160	0.162	0.162	0.162	0.159



(a) No.2 Specimen



(b) No.3 Specimen

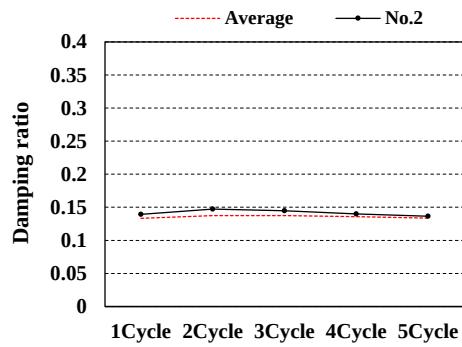


(c) No.4 Specimen

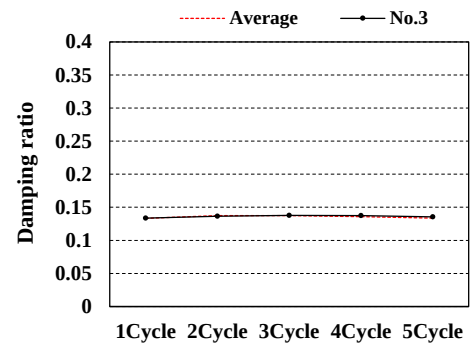
Fig. 3.34 The result of the damping ratio at 200% shear strain in STEP3

Table 3.32 The result of the damping ratio at 200% shear strain in STEP3 for each cycle

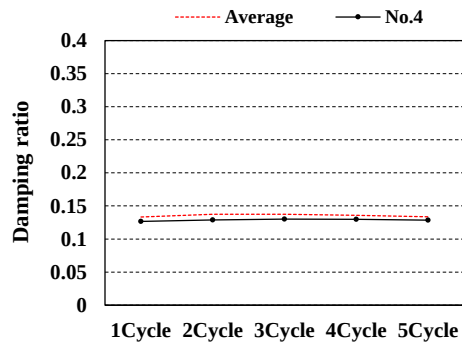
Damping ratio	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.131	0.133	0.134	0.134	0.133
No.3	0.148	0.152	0.153	0.152	0.150
No.4	0.135	0.139	0.140	0.140	0.138
Average	0.138	0.141	0.142	0.142	0.140



(a) No.2 Specimen



(b) No.3 Specimen



(c) No.4 Specimen

Fig. 3.35 The result of the damping ratio at 250% shear strain in STEP4

Table 3.33 The result of the damping ratio at 250% shear strain in STEP4 for each cycle

Damping ratio	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	0.139	0.147	0.145	0.140	0.136
No.3	0.134	0.136	0.138	0.138	0.136
No.4	0.127	0.129	0.130	0.130	0.129
Average	0.133	0.138	0.137	0.136	0.134

3.2.4 Strain energy

Strain Energy, a pivotal concept, pertains to the energy stored within HDR materials when subjected to dynamic loading. It serves as a gauge of the material's adeptness in both storing and releasing energy during cyclic deformation. The quantification of Strain Energy involves integrating the area under the hysteresis curve, effectively encapsulating the energy input into the HDR material. This metric assumes significance as it provides a comprehensive measure of the material's overall energy dissipation capacity and durability. Notably, Strain Energy is a crucial parameter in evaluating the dynamic characteristics of HDR materials, working in conjunction with equivalent stiffness and equivalent damping ratio. These parameters collectively play a pivotal role in delineating the response of HDR materials and their efficacy in applications such as seismic isolation systems. In the broader context of HDR-based systems, the dynamic characteristics, including equivalent stiffness, equivalent damping ratio, and strain energy, are instrumental in the evaluation, design, and optimization processes. Their meticulous consideration ensures the attainment of adequate stiffness, damping, and energy dissipation, thereby contributing to effective vibration isolation and structural protection in diverse applications. W represents the strain energy. W is the energy absorbed based on the equivalent stiffness in the HDR hysteresis curve.

$$W = \frac{1}{2} K_{eq} D^2 \quad (3.5)$$

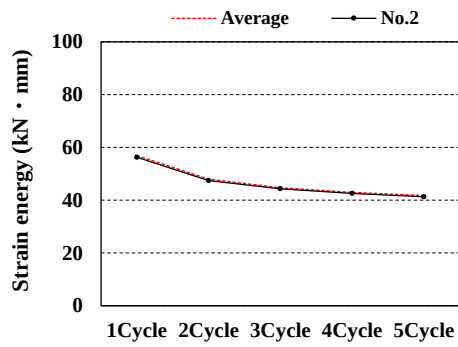
where K_{eq} is the equivalent stiffness calculated using Eq. (3.2). The parameter D is the average value of δ_{max} and δ_{min} . To analyze the nonlinearity of the HDR, a comparison was made between the results of the first and third loops at different shear strains. Here, the first loop displayed the most distinct nonlinear characteristics, whereas the third loop exhibited a relatively stable behavior. By examining the mechanical properties at different stages of loading, the changes in behavior and extent of nonlinearity in the HDR can be identified and quantified. This approach provides

valuable insights into the dynamic behavior of the HDR, particularly in relation to the Mullins effect and hardening phenomenon.

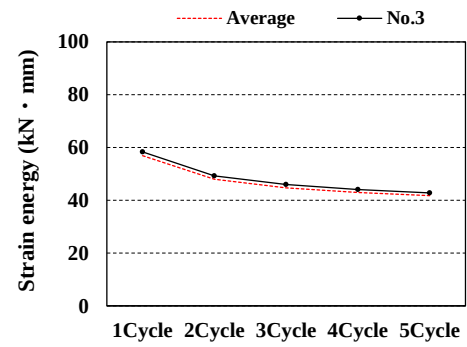
Here is the analysis of the mechanical characteristics evaluation results for the given experimental data, focusing on the shear strain. In this analysis, the rate of change is calculated based on the values of the preceding cycle, and the overall average is computed. Fig. 3.36 and Table 3.34 show the result of the strain energy at 50% shear strain in STEP1. The strain energy values at 50% shear strain in STEP1 exhibit a continuous decrease in each cycle compared to the preceding one, with an average rate of change of approximately -7.20%. This suggests a consistent reduction in the material's strain energy over repeated cycles, indicating potential changes in its deformation characteristics. Fig. 3.37 and Table 3.35 show the result of the strain energy at 50% shear strain in STEP2. The strain energy values at 50% shear strain in STEP2 consistently decrease in each cycle compared to the preceding one, with an average rate of change of approximately -4.53%. This suggests a continuous reduction in the material's strain energy over repeated cycles, indicating potential changes in its deformation characteristics. Fig. 3.38 and Table 3.36 show the result of the strain energy at 50% shear strain in STEP3. The strain energy values at 50% shear strain in STEP3 consistently decrease in each cycle compared to the preceding one, with an average rate of change of approximately -4.91%. This indicates a continuous reduction in the material's strain energy over repeated cycles, suggesting potential alterations in its deformation characteristics. Fig. 3.39 and Table 3.37 show the result of the strain energy at 50% shear strain in STEP4. The strain energy values at 50% shear strain in STEP4 consistently decrease in each cycle compared to the preceding one, with an average rate of change of approximately -4.91%. This indicates a continuous reduction in the material's strain energy over repeated cycles, suggesting potential alterations in its deformation characteristics.

Fig. 3.40 and Table 3.38 show the result of the strain energy at 100% shear strain in STEP1. The strain energy values at 100% shear strain in STEP1 consistently decrease in each cycle compared to the preceding one, with an average rate of change of approximately -6.52%. This suggests a continuous reduction in the material's strain

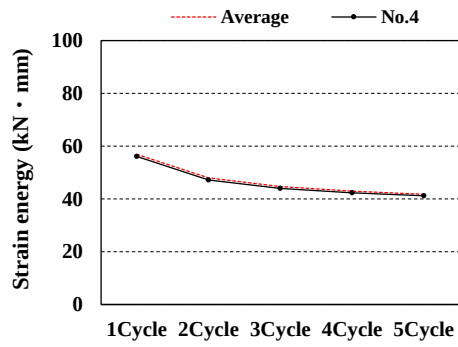
energy over repeated cycles, indicating potential changes in its deformation characteristics. Fig. 3.41 and Table 3.39 show the result of the strain energy at 100% shear strain in STEP3. The strain energy values at 100% shear strain in STEP3 consistently decrease in each cycle compared to the preceding one, with an average rate of change of approximately -3.99%. This indicates a continuous reduction in the material's strain energy over repeated cycles, suggesting potential alterations in its deformation characteristics. Fig. 3.42 and Table 3.40 show the result of the strain energy at 100% shear strain in STEP4. The strain energy values at 100% shear strain in STEP4 consistently decrease in each cycle compared to the preceding one, with an average rate of change of approximately -4.41%. This suggests a continuous reduction in the material's strain energy over repeated cycles, indicating potential changes in its deformation characteristics. Fig. 3.43 and Table 3.41 show the result of the strain energy at 150% shear strain in STEP2. The shear strain values at 150% shear strain in STEP2 consistently decrease in each cycle compared to the preceding one, with an average rate of change of approximately -7.06%. This suggests a gradual reduction in the material's shear strain over repeated cycles, indicating changes in its deformation characteristics. Fig. 3.44 and Table 3.42 show the result of the shear strain at 150% shear strain in STEP4. The shear strain values at 150% shear strain in STEP4 consistently decrease in each cycle compared to the preceding one, with an average rate of change of approximately -4.02%. This suggests a gradual reduction in the material's shear strain over repeated cycles, indicating changes in its deformation characteristics. Fig. 3.45 and Table 3.43 show the result of the shear strain at 200% shear strain in STEP3. The shear strain values at 200% shear strain in STEP3 consistently decrease in each cycle compared to the preceding one, with an average rate of change of approximately -6.95%. This indicates a diminishing trend in shear strain over repeated cycles, suggesting potential changes in the material's deformation behavior. Fig. 3.46 and Table 3.44 show the result of the shear strain at 250% shear strain in STEP4. The shear strain values at 250% shear strain in STEP4 consistently decrease in each cycle compared to the preceding one, with an average rate of change of approximately -6.72%. This indicates a diminishing trend in shear strain over repeated cycles, suggesting potential changes in the material's deformation behavior.



(a) No.2 Specimen



(b) No.3 Specimen

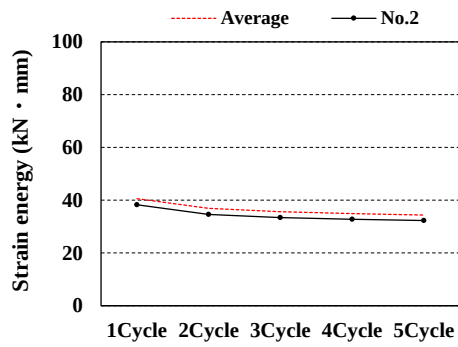


(c) No.4 Specimen

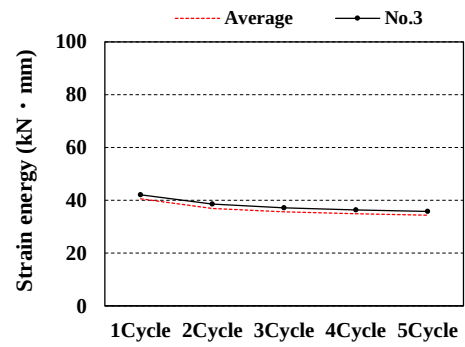
Fig. 3.36 The result of the strain energy at 50% shear strain in STEP1

Table 3.34 The result of the strain energy at 50% shear strain in STEP1 for each cycle

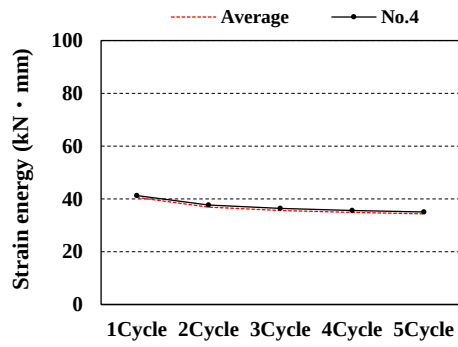
Strain energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	56	47	44	43	41
No.3	58	49	46	44	43
No.4	56	47	44	42	41
Average	57	48	45	43	42



(a) No.2 Specimen



(b) No.3 Specimen

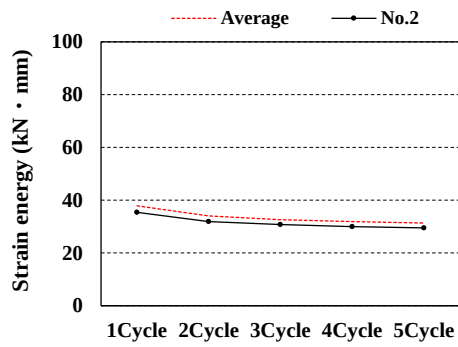


(c) No.4 Specimen

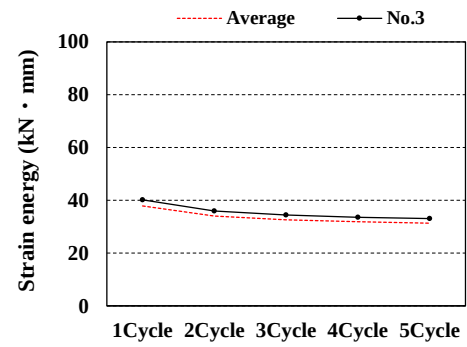
Fig. 3.37 The result of the strain energy at 50% shear strain in STEP2

Table 3.35 The result of the strain energy at 50% shear strain in STEP2 for each cycle

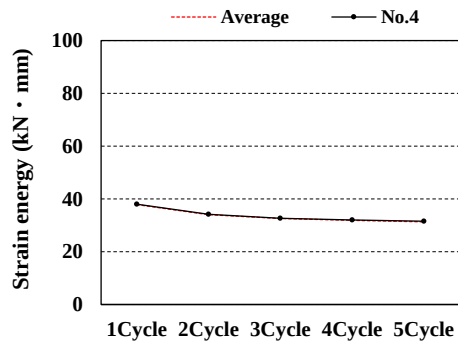
Strain energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	38	35	33	33	32
No.3	42	39	37	36	36
No.4	41	38	36	36	35
Average	41	37	36	35	34



(a) No.2 Specimen



(b) No.3 Specimen

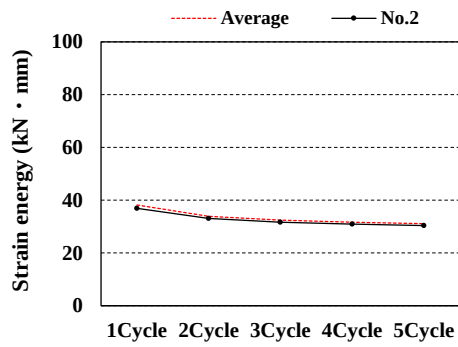


(c) No.4 Specimen

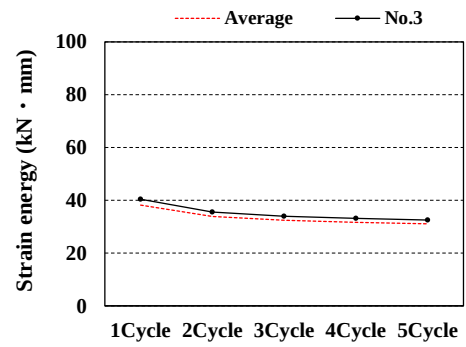
Fig. 3.38 The result of the strain energy at 50% shear strain in STEP3

Table 3.36 The result of the strain energy at 50% shear strain in STEP3 for each cycle

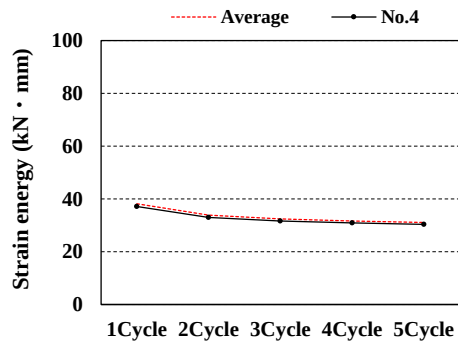
Strain energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	35	32	31	30	29
No.3	40	36	34	34	33
No.4	38	34	33	32	32
Average	38	34	33	32	31



(a) No.2 Specimen



(b) No.3 Specimen

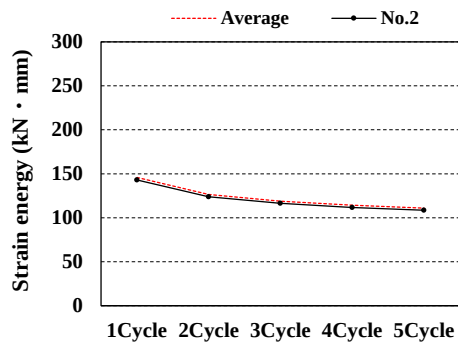


(c) No.4 Specimen

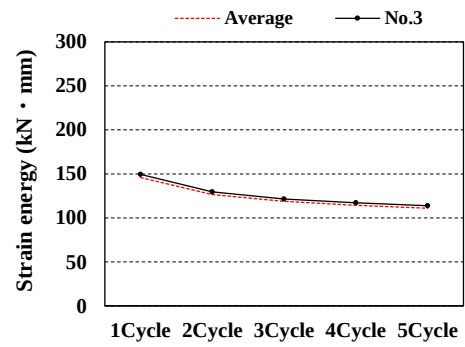
Fig. 3.39 The result of the strain energy at 50% shear strain in STEP4

Table 3.37 The result of the strain energy at 50% shear strain in STEP4 for each cycle

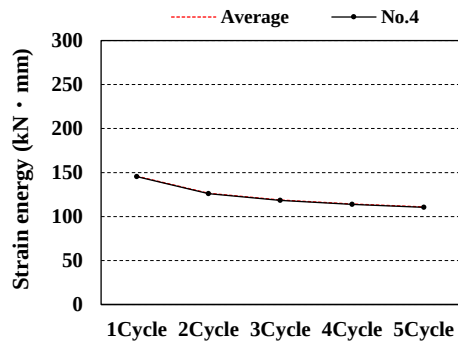
Strain energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	37	33	32	31	30
No.3	40	36	34	33	33
No.4	37	33	32	31	30
Average	38	34	32	32	31



(a) No.2 Specimen



(b) No.3 Specimen

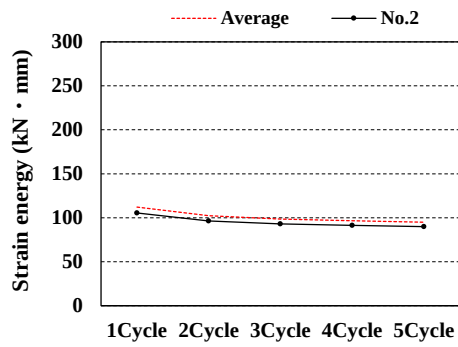


(c) No.4 Specimen

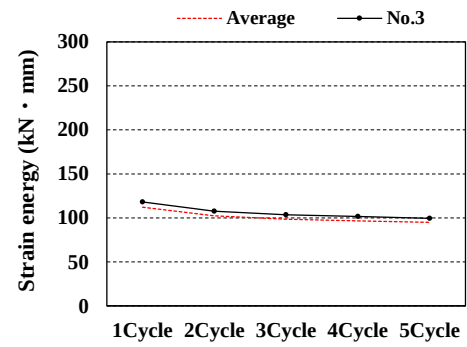
Fig. 3.40 The result of the strain energy at 100% shear strain in STEP1

Table 3.38 The result of the strain energy at 100% shear strain in STEP1 for each cycle

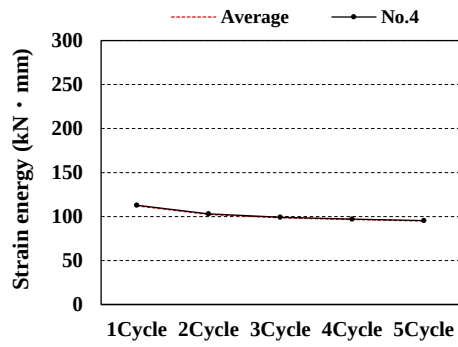
Strain energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	143	124	116	112	109
No.3	149	129	121	117	114
No.4	145	126	118	114	110
Average	146	126	119	114	111



(a) No.2 Specimen



(b) No.3 Specimen

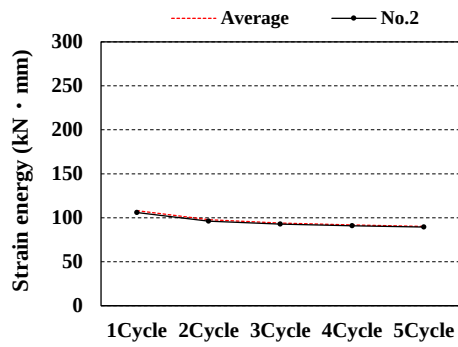


(c) No.4 Specimen

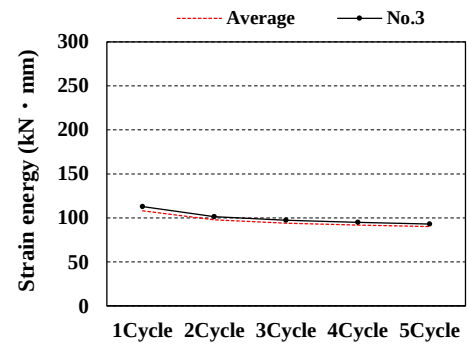
Fig. 3.41 The result of the strain energy at 100% shear strain in STEP3

Table 3.39 The result of the strain energy at 100% shear strain in STEP3 for each cycle

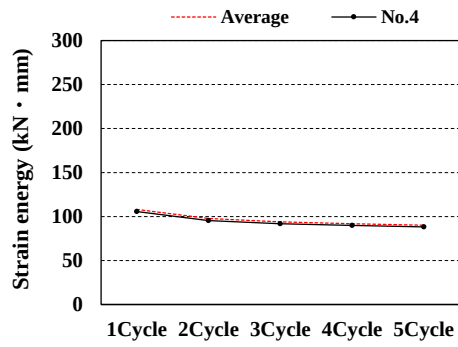
Strain energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	105	96	93	91	90
No.3	118	108	104	102	99
No.4	113	103	99	97	96
Average	112	102	99	97	95



(a) No.2 Specimen



(b) No.3 Specimen

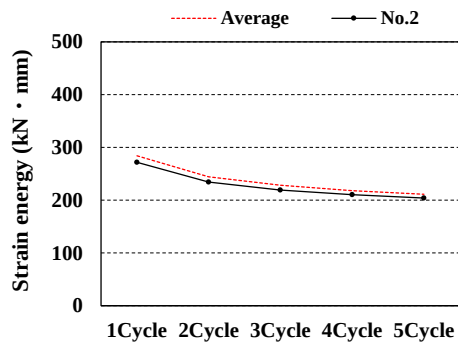


(c) No.4 Specimen

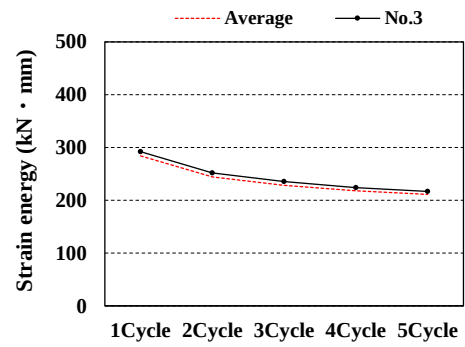
Fig. 3.42 The result of the strain energy at 100% shear strain in STEP4

Table 3.40 The result of the strain energy at 100% shear strain in STEP4 for each cycle

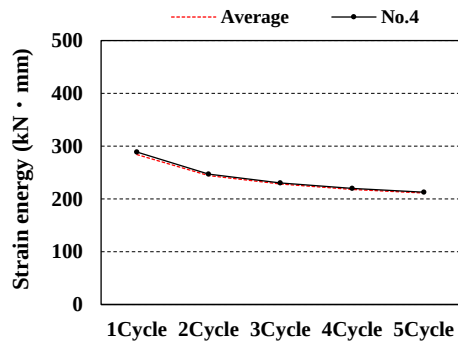
Strain energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	106	96	93	91	90
No.3	113	101	97	95	93
No.4	106	95	92	90	88
Average	108	98	94	92	90



(a) No.2 Specimen



(b) No.3 Specimen

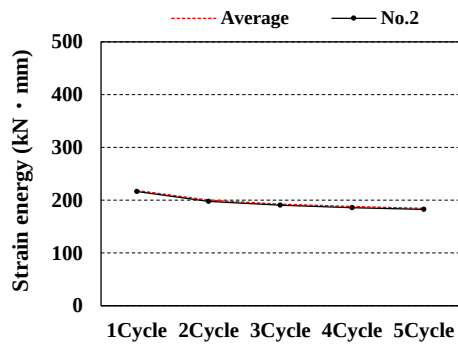


(c) No.4 Specimen

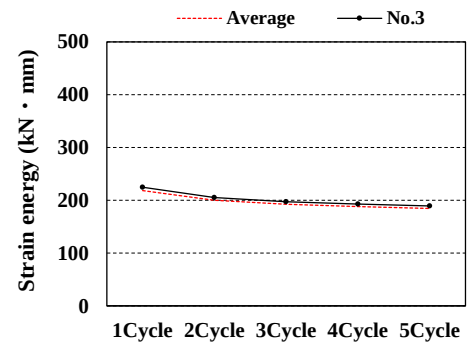
Fig. 3.43 The result of the strain energy at 150% shear strain in STEP2

Table 3.41 The result of the strain energy at 150% shear strain in STEP2 for each cycle

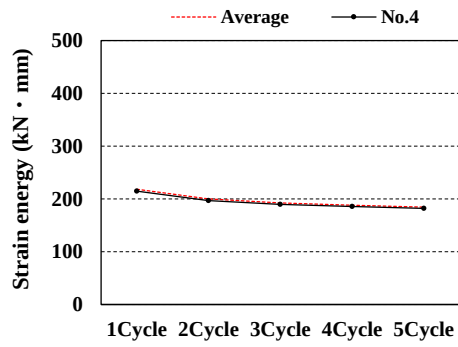
Strain energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	272	234	219	210	204
No.3	292	252	235	224	217
No.4	289	247	230	220	213
Average	284	244	228	218	211



(a) No.2 Specimen



(b) No.3 Specimen

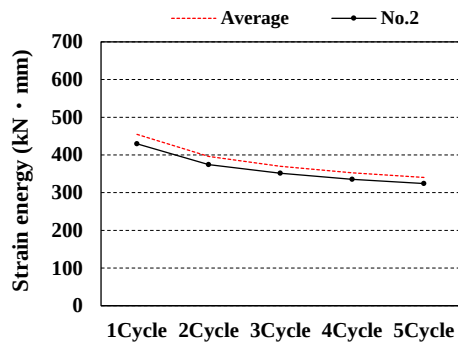


(c) No.4 Specimen

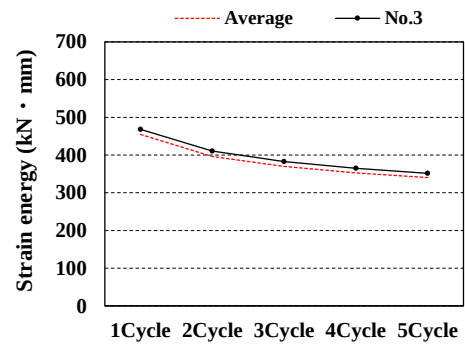
Fig. 3.44 The result of the strain energy at 150% shear strain in STEP4

Table 3.42 The result of the strain energy at 150% shear strain in STEP4 for each cycle

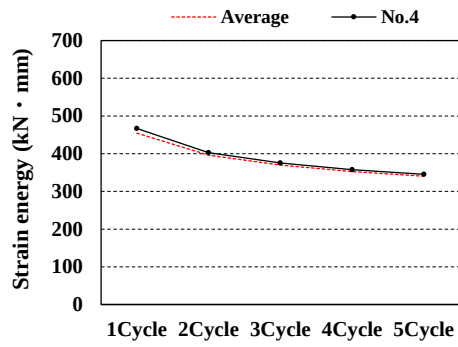
Strain energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	216	198	191	186	183
No.3	225	205	197	193	189
No.4	215	197	190	186	182
Average	219	200	193	188	185



(a) No.2 Specimen



(b) No.3 Specimen

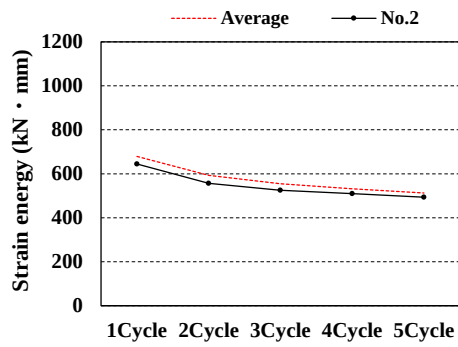


(c) No.4 Specimen

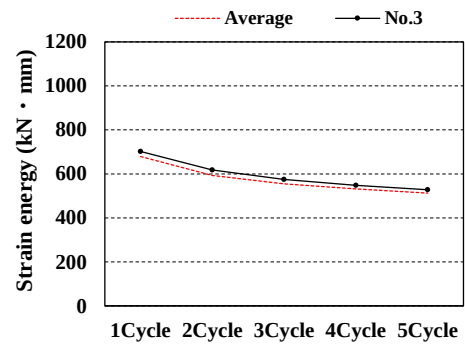
Fig. 3.45 The result of the strain energy at 200% shear strain in STEP3

Table 3.43 The result of the strain energy at 200% shear strain in STEP3 for each cycle

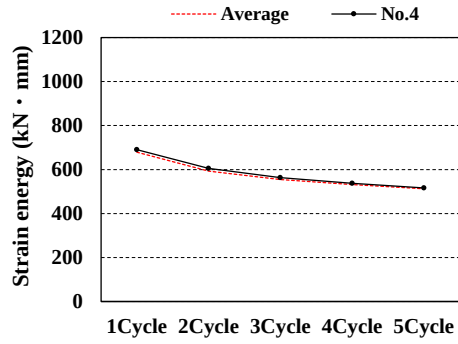
Strain energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	430	374	351	335	324
No.3	468	410	383	365	352
No.4	467	403	375	358	345
Average	455	396	370	353	340



(a) No.2 Specimen



(b) No.3 Specimen



(c) No.4 Specimen

Fig. 3.46 The result of the strain energy at 250% shear strain in STEP4

Table 3.44 The result of the strain energy at 250% shear strain in STEP4 for each cycle

Strain energy (kN · mm)	Cycle				
Specimen	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
No.2	644	557	525	510	493
No.3	702	617	575	548	528
No.4	690	606	564	537	516
Average	679	593	555	532	512

3.3 Comparison of Mechanical Characteristics for each STEP

Fig. 3.47 represents comparison of the positive shear force for each step at 50% shear strain. Table 3.45 and Table 3.46 show the result of the positive shear force for each step of 1cycle and 3cycle at 50% shear strain. Similar to the shear force trend, it shows a decreasing trend with each step.

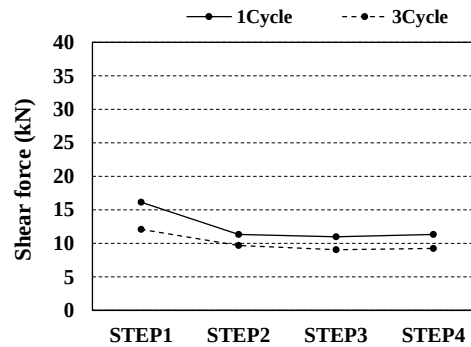


Fig. 3.47 Comparison of the positive shear force for each step at 50% shear strain

Table 3.45 The result of the positive shear force for each step of 1cycle at 50% shear strain

Shear force (kN)	1Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	15.8	10.7	10.2	10.6
No.3	16.5	11.8	11.6	12.3
No.4	16.1	11.5	11.1	11.1
Average	16.1	11.3	11.0	11.3

Table 3.46 The result of the positive shear force for each step of 3cycle at 50% shear strain

Shear force (kN)	3Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	11.8	9.0	8.4	8.7
No.3	12.4	10.1	9.6	10.0
No.4	12.1	9.9	9.1	9.0
Average	12.1	9.7	9.0	9.2

Fig. 3.48 represents comparison of the negative shear force for each step at 50% shear strain. Table 3.47 and Table 3.48 show the result of the negative shear force for each step of 1cycle and 3cycle at 50% shear strain. Similar to the shear force trend, it shows a increasing trend with each step.

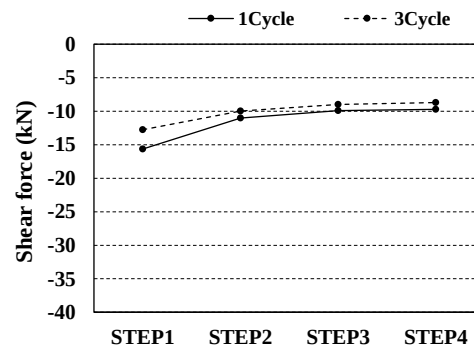


Fig. 3.48 Comparison of the negative shear force for each step at 50% shear strain

Table 3.47 The result of the negative shear force for each step of 1cycle at 50% shear strain

Shear force (kN)	1Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	-15.6	-10.4	-9.4	-9.8
No.3	-16.1	-11.5	-10.6	-10.1
No.4	-15.2	-11.1	-9.7	-9.3
Average	-15.6	-11.0	-9.9	-9.7

Table 3.48 The result of the negative shear force for each step of 3cycle at 50% shear strain

Shear force (kN)	3Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	-12.7	-9.5	-8.6	-8.8
No.3	-13.1	-10.5	-9.5	-8.9
No.4	-12.4	-10.0	-8.8	-8.4
Average	-12.8	-10.0	-9.0	-8.7

Fig. 3.49 represents comparison of the absorption energy for each step at 50% shear strain. Table 3.49 and Table 3.50 show the result of the absorption energy for each step of 1cycle and 3cycle at 50% shear strain. Similar to the shear force trend, it shows a decreasing trend with each step.

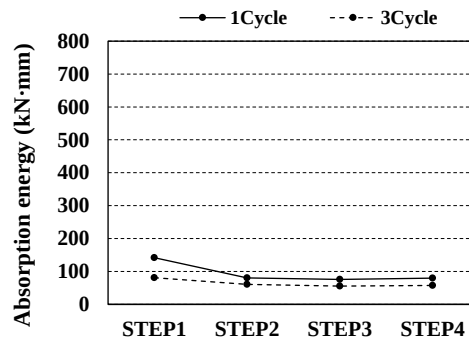


Fig. 3.49 Comparison of the absorption energy for each step at 50% shear strain

Table 3.49 The result of the absorption energy for each step of 1cycle at 50% shear strain

Absorption energy (kN · mm)	1Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	15.8	10.7	10.2	10.6
No.3	16.5	11.8	11.6	12.3
No.4	16.1	11.5	11.1	11.1
Average	16.1	11.3	11.0	11.3

Table 3.50 The result of the absorption energy for each step of 3cycle at 50% shear strain

Absorption energy (kN · mm)	3Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	11.8	9.0	8.4	8.7
No.3	12.4	10.1	9.6	10.0
No.4	12.1	9.9	9.1	9.0
Average	12.1	9.7	9.0	9.2

Fig. 3.50 represents comparison of the strain energy for each step at 50% shear strain. Table 3.51 and Table 3.52 show the result of the strain energy for each step of 1cycle and 3cycle at 50% shear strain. Similar to the shear force trend, it shows a decreasing trend with each step.

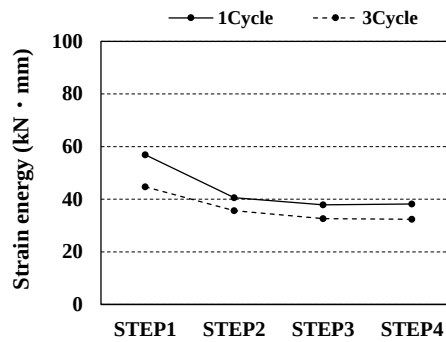


Fig. 3.50 Comparison of the strain energy for each step at 50% shear strain

Table 3.51 The result of the strain energy for each step of 1cycle at 50% shear strain

Strain energy (kN · mm)	1Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	56	38	35	37
No.3	58	42	40	40
No.4	56	41	38	37
Average	57	41	38	38

Table 3.52 The result of the strain energy for each step of 3cycle at 50% shear strain

Strain energy (kN · mm)	3Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	44	33	31	32
No.3	46	37	34	34
No.4	44	36	33	32
Average	45	36	33	32

Fig. 3.51 represents comparison of the equivalent stiffness for each step at 50% shear strain. Table 3.53 and Table 3.54 show the result of the equivalent stiffness for each step of 1cycle and 3cycle at 50% shear strain. Similar to the shear force trend, it shows a decreasing trend with each step.

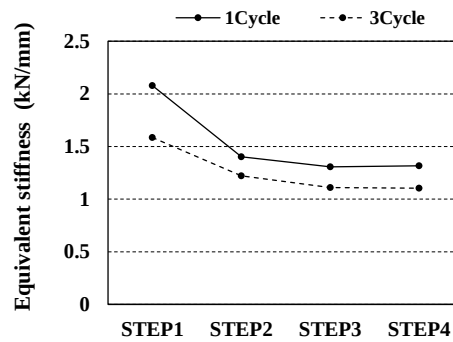


Fig. 3.51 Comparison of the equivalent stiffness for each step at 50% shear strain

Table 3.53 The result of the equivalent stiffness for each step of 1cycle at 50% shear strain

Equivalent stiffness (kN/mm)	1Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	2.05	1.32	1.22	1.28
No.3	2.14	1.47	1.40	1.41
No.4	2.05	1.41	1.29	1.26
Average	2.08	1.40	1.31	1.32

Table 3.54 The result of the equivalent stiffness for each step of 3cycle at 50% shear strain

Equivalent stiffness (kN/mm)	3Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	1.56	1.14	1.04	1.08
No.3	1.63	1.29	1.19	1.17
No.4	1.56	1.23	1.10	1.06
Average	1.59	1.22	1.11	1.10

Fig. 3.52 represents comparison of the damping ratio for each step at 50% shear strain. Table 3.55 and Table 3.56 show the result of the damping ratio for each step of 1cycle and 3cycle at 50% shear strain. Similar to the shear force trend, it shows a decreasing trend with each step.

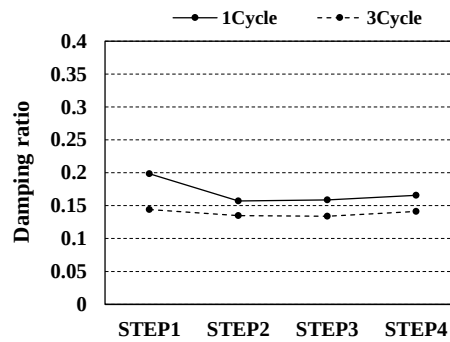


Fig. 3.52 Comparison of the damping ratio for each step at 50% shear strain

Table 3.55 The result of the damping ratio for each step of 1cycle at 50% shear strain

Damping ratio	1Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	0.199	0.149	0.152	0.171
No.3	0.200	0.165	0.168	0.168
No.4	0.196	0.157	0.157	0.158
Average	0.198	0.157	0.159	0.166

Table 3.56 The result of the damping ratio for each step of 3cycle at 50% shear strain

Damping ratio	3Cycle			
Specimen	STEP1	STEP2	STEP3	STEP4
No.2	0.146	0.126	0.125	0.144
No.3	0.148	0.145	0.145	0.147
No.4	0.139	0.134	0.132	0.133
Average	0.144	0.135	0.134	0.141

Fig. 3.53 represents comparison of the positive shear force for each step at 100% shear strain. Table 3.57 and Table 3.58 show the result of the positive shear force for each step of 1 cycle and 3 cycle at 100% shear strain. Similar to the trend of 50% shear strain, it shows a tendency to decrease with each step.

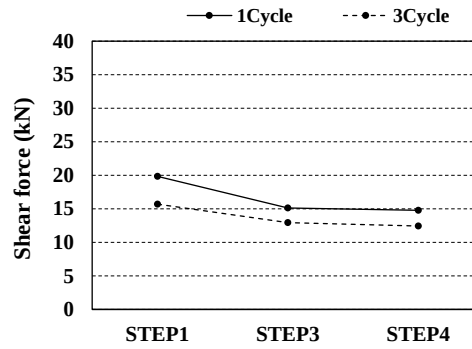


Fig. 3.53 Comparison of the positive shear force for each step at 100% shear strain

Table 3.57 The result of the positive shear force for each step of 1cycle at 100% shear strain

Shear force (kN)	1Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	19.3	14.1	14.2
No.3	20.3	15.9	15.7
No.4	19.9	15.3	14.5
Average	19.8	15.1	14.8

Table 3.58 The result of the positive shear force for each step of 3cycle at 100% shear strain

Shear force (kN)	3Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	15.3	12.1	12.1
No.3	16.0	13.6	13.1
No.4	15.8	13.1	12.2
Average	15.7	12.9	12.4

Fig. 3.54 represents comparison of the negative shear force for each step at 100% shear strain. Table 3.59 and Table 3.60 show the result of the negative shear force for each step of 1 cycle and 3 cycle at 100% shear strain. Similar to the trend of 50% shear strain, it shows a tendency to increase with each step.

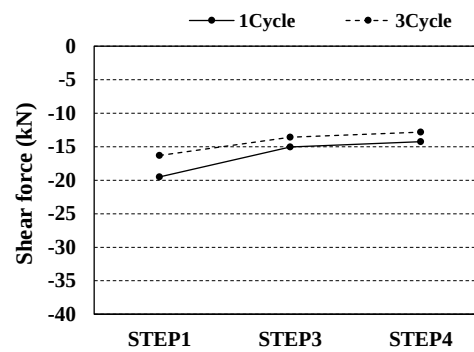


Fig. 3.54 Comparison of the negative shear force for each step at 100% shear strain

Table 3.59 The result of the negative shear force for each step of 1 cycle at 100% shear strain

Shear force (kN)	1Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	-19.2	-14.3	-14.3
No.3	-20.0	-15.9	-14.6
No.4	-19.3	-14.9	-13.8
Average	-19.5	-15.0	-14.2

Table 3.60 The result of the negative shear force for each step of 3 cycle at 100% shear strain

Shear force (kN)	3Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	-16.1	-13.0	-13.0
No.3	-16.7	-14.3	-13.1
No.4	-16.1	-13.5	-12.4
Average	-16.3	-13.6	-12.8

Fig. 3.55 represents comparison of the absorption energy for each step at 100% shear strain. Table 3.61 and Table 3.62 show the result of the absorption energy for each step of 1cycle and 3cycle at 100% shear strain. Similar to the trend of 50% shear strain, it shows a tendency to decrease with each step.

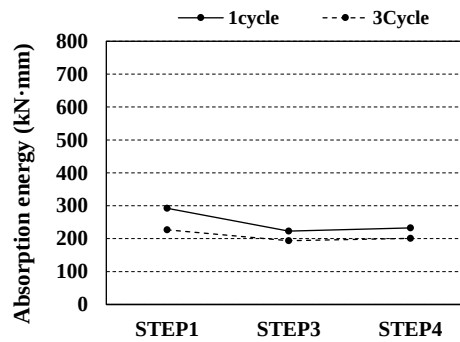


Fig. 3.55 Comparison of the absorption energy for each step at 100% shear strain

Table 3.61 The result of the absorption energy for each step of 1cycle at 100% shear strain

Absorption energy (kN · mm)	1Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	291	196	226
No.3	305	250	252
No.4	281	223	220
Average	292	223	233

Table 3.62 The result of the absorption energy for each step of 3cycle at 100% shear strain

Absorption energy (kN · mm)	3Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	226	170	198
No.3	238	218	217
No.4	216	193	188
Average	227	194	201

Fig. 3.56 represents comparison of the strain energy for each step at 100% shear strain. Table 3.63 and Table 3.64 show the result of the strain energy for each step of 1cycle and 3cycle at 100% shear strain. Similar to the trend of 50% shear strain, it shows a tendency to decrease with each step.

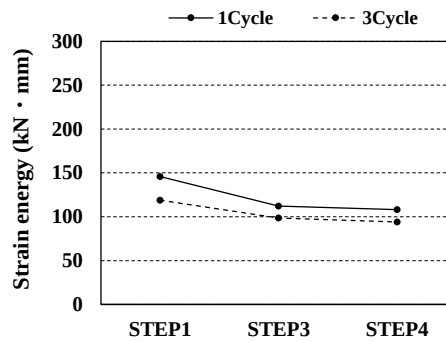


Fig. 3.56 Comparison of the strain energy for each step at 100% shear strain

Table 3.63 The result of the strain energy for each step of 1cycle at 100% shear strain

Strain energy (kN · mm)	1Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	143	105	106
No.3	149	118	113
No.4	145	113	106
Average	146	112	108

Table 3.64 The result of the strain energy for each step of 3cycle at 100% shear strain

Strain energy (kN · mm)	3Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	116	93	93
No.3	121	104	97
No.4	118	99	92
Average	119	99	94

Fig. 3.56 represents comparison of the equivalent stiffness for each step at 100% shear strain. Table 3.63 and Table 3.64 show the result of the equivalent stiffness for each step of 1cycle and 3cycle at 100% shear strain. Similar to the trend of 50% shear strain, it shows a tendency to decrease with each step.

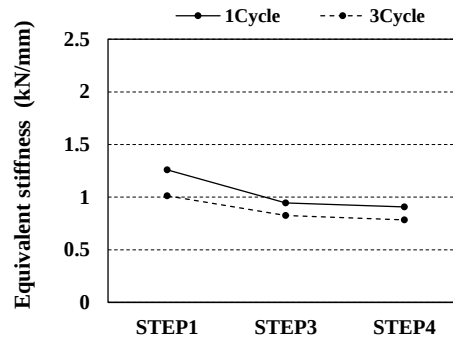


Fig. 3.57 Comparison of the equivalent stiffness for each step at 100% shear strain

Table 3.65 The result of the equivalent stiffness for each step of 1cycle at 100% shear strain

Equivalent stiffness (kN/mm)	1Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	1.23	0.89	0.89
No.3	1.29	1.00	0.96
No.4	1.26	0.95	0.88
Average	1.26	0.95	0.91

Table 3.66 The result of the equivalent stiffness for each step of 3cycle at 100% shear strain

Equivalent stiffness (kN/mm)	3Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	0.99	0.78	0.78
No.3	1.04	0.87	0.82
No.4	1.01	0.83	0.76
Average	1.01	0.83	0.78

Fig. 3.58 represents comparison of the equivalent stiffness for each step at 100% shear strain. Table 3.67 and Table 3.69 show the result of the equivalent stiffness for each step of 1cycle and 3cycle at 100% shear strain. Similar to the trend of 50% shear strain, it shows a tendency to decrease with each step.

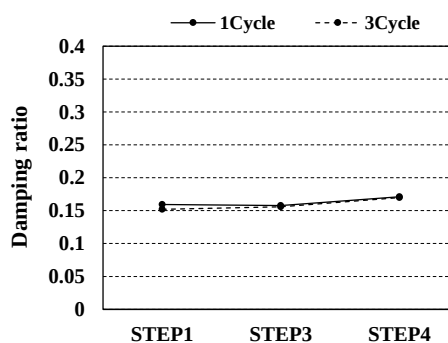


Fig. 3.58 Comparison of the damping ratio for each step at 100% shear strain

Table 3.67 The result of the damping ratio for each step of 1cycle at 100% shear strain

Damping ratio	1Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	0.162	0.148	0.170
No.3	0.163	0.168	0.178
No.4	0.154	0.157	0.166
Average	0.159	0.158	0.171

Table 3.68 The result of the damping ratio for each step of 3cycle at 100% shear strain

Damping ratio	3Cycle		
Specimen	STEP1	STEP3	STEP4
No.2	0.155	0.145	0.169
No.3	0.156	0.168	0.177
No.4	0.145	0.155	0.163
Average	0.152	0.156	0.170

Fig. 3.59 represents comparison of the positive shear force for each step at 150% shear strain. Table 3.69 and Table 3.70 show the result of the positive shear force for each step of 1cycle and 3cycle at 100% shear strain. Similar to the trend of 50% shear strain and 100% shear strain, it shows a tendency to decrease with each step.

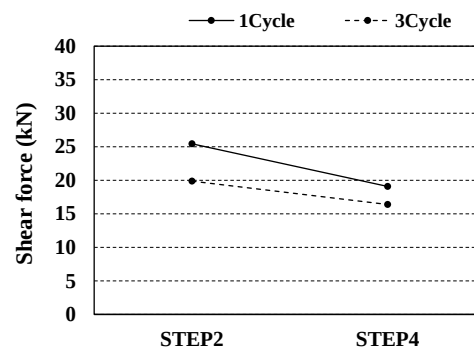


Fig. 3.59 Comparison of the positive shear force for each step at 150% shear strain

Table 3.69 The result of the positive shear force for each step of 1cycle at 150% shear strain

Shear force (kN)	1Cycle	
Specimen	STEP2	STEP4
No.2	24.2	18.7
No.3	26.2	19.8
No.4	25.9	18.7
Average	25.4	19.1

Table 3.70 The result of the positive shear force for each step of 3cycle at 150% shear strain

Shear force (kN)	3Cycle	
Specimen	STEP2	STEP4
No.2	19.0	16.1
No.3	20.5	17.0
No.4	20.1	16.1
Average	19.9	16.4

Fig. 3.60 represents comparison of the negative shear force for each step at 150% shear strain. Table 3.71 and Table 3.72 show the result of the negative shear force for each step of 1 cycle and 3 cycle at 150% shear strain. Similar to the trend of 50% shear strain and 100% shear strain, it shows a tendency to increase with each step.

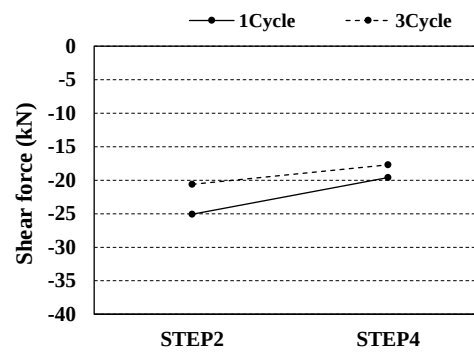


Fig. 3.60 Comparison of the negative shear force for each step at 150% shear strain

Table 3.71 The result of the negative shear force for each step of 1 cycle at 150% shear strain

Shear force (kN)	1Cycle	
Specimen	STEP2	STEP4
No.2	-24.1	-19.6
No.3	-25.8	-20.0
No.4	-25.3	-19.2
Average	-25.1	-19.6

Table 3.72 The result of the negative shear force for each step of 3 cycle at 150% shear strain

Shear force (kN)	3Cycle	
Specimen	STEP2	STEP4
No.2	-19.9	-17.7
No.3	-21.3	-18.0
No.4	-20.7	-17.4
Average	-20.6	-17.7

Fig. 3.61 represents comparison of the absorption energy for each step at 150% shear strain. Table 3.73 and Table 3.74 show the result of the absorption energy for each step of 1cycle and 3cycle at 150% shear strain. Similar to the trend of 50% shear strain and 100% shear strain, it shows a tendency to decrease with each step.

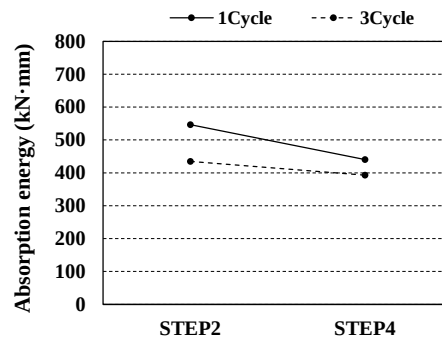


Fig. 3.61 Comparison of the absorption energy for each step at 150% shear strain

Table 3.73 The result of the absorption energy for each step of 1cycle at 150% shear strain

Absorption energy (kN · mm)	1Cycle	
Specimen	STEP2	STEP4
No.2	497	434
No.3	588	469
No.4	554	417
Average	546	440

Table 3.74 The result of the absorption energy for each step of 3cycle at 150% shear strain

Absorption energy (kN · mm)	3Cycle	
Specimen	STEP2	STEP4
No.2	399	387
No.3	473	419
No.4	432	373
Average	435	393

Fig. 3.62 represents comparison of the strain energy for each step at 150% shear strain. Table 3.75 and Table 3.76 show the result of the strain energy for each step of 1cycle and 3cycle at 150% shear strain. Similar to the trend of 50% shear strain and 100% shear strain, it shows a tendency to decrease with each step.

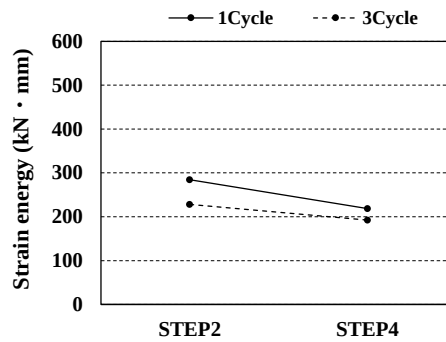


Fig. 3.62 Comparison of the strain energy for each step at 150% shear strain

Table 3.75 The result of the strain energy for each step of 1cycle at 150% shear strain

Strain energy (kN · mm)	1Cycle	
Specimen	STEP2	STEP4
No.2	272	216
No.3	292	225
No.4	289	215
Average	284	219

Table 3.76 The result of the strain energy for each step of 3cycle at 150% shear strain

Strain energy (kN · mm)	3Cycle	
Specimen	STEP2	STEP4
No.2	219	191
No.3	235	197
No.4	230	190
Average	228	193

Fig. 3.63 represents comparison of the equivalent stiffness for each step at 150% shear strain. Table 3.77 and Table 3.78 show the result of the equivalent stiffness for each step of 1cycle and 3cycle at 150% shear strain. Similar to the trend of 50% shear strain and 100% shear strain, it shows a tendency to decrease with each step.

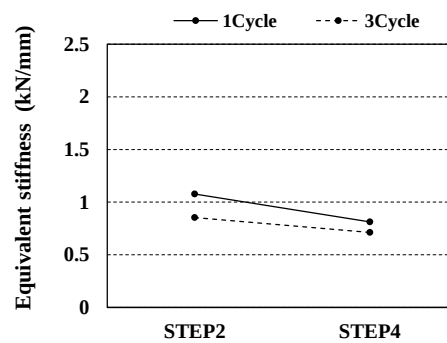


Fig. 3.63 Comparison of the equivalent stiffness for each step at 150% shear strain

Table 3.77 The result of the equivalent stiffness for each step of 1cycle at 150% shear strain

Equivalent stiffness (kN/mm)	1Cycle	
Specimen	STEP2	STEP4
No.2	1.03	0.80
No.3	1.11	0.84
No.4	1.09	0.79
Average	1.08	0.81

Table 3.78 The result of the equivalent stiffness for each step of 3cycle at 150% shear strain

Equivalent stiffness (kN/mm)	3Cycle	
Specimen	STEP2	STEP4
No.2	0.82	0.70
No.3	0.88	0.73
No.4	0.86	0.70
Average	0.85	0.71

Fig. 3.64 represents comparison of the damping ratio for each step at 150% shear strain. Table 3.79 and Table 3.80 show the result of the damping ratio for each step of 1 cycle and 3 cycle at 150% shear strain. The results of the damping ratio of 150% shear strain show the same results with no change between cycles.

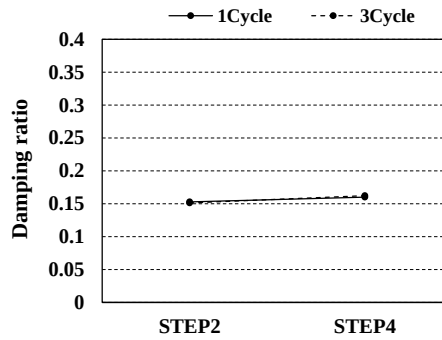


Fig. 3.64 Comparison of the damping ratio for each step at 150% shear strain

Table 3.79 The result of the damping ratio for each step of 1 cycle at 150% shear strain

Damping ratio	1Cycle	
Specimen	STEP2	STEP4
No.2	0.146	0.160
No.3	0.160	0.166
No.4	0.152	0.155
Average	0.153	0.160

Table 3.80 The result of the damping ratio for each step of 3 cycle at 150% shear strain

Damping ratio	3Cycle	
Specimen	STEP2	STEP4
No.2	0.145	0.162
No.3	0.160	0.169
No.4	0.149	0.156
Average	0.151	0.162

3.4 Summary

The mechanical characteristics of the HDR specimens were examined by comparing the initial loading histories with subsequent histories for shear strains of 50, 100, and 150%. This chapter shows a comparison of the strain energy, equivalent stiffness, and equivalent damping ratio for cases with shear strains of 50, 100, and 150%, respectively, wherein the mechanical properties are compared with the results of the dynamic load test. In all the cases, the strain energy and equivalent stiffness decreased as the steps progressed, and even with a similar shear strain, the mechanical properties decreased when a large shear strain was already experienced. Additionally, by comparing one and three cycles of the hysteresis curve within a similar step, the mechanical properties decrease after the one cycle even within a similar hysteresis loop of the shear deformation. Here, the value of the one cycle is greater than the value of the third cycle. In the case of the equivalent damping ratio, this trend could be confirmed only in the experimental results of the shear strain of 50%, and after that, the characteristic values of the first and third cycles are similar. From the experimental results, it was possible to quantitatively evaluate each mechanical and history characteristic of HDR, and as a result, the nonlinearity of HDR depending on the shear strain rate was confirmed. In summary, the evaluation of HDR's mechanical properties is integral to ensuring its effectiveness in energy absorption, contribution to overall stiffness, control of vibrations, and resilience under dynamic loading conditions. This comprehensive assessment is essential for informed decision-making in engineering applications where HDR is employed for its unique damping characteristics.

Chapter4

Nonlinear Hysteresis Model for HDR

4.1 Introduction

In contemporary civil engineering, structures are continually evolving to enhance resistance against dynamic loads such as earthquakes, wind, and other external forces. Among various technological innovations, high damping rubber bearings have been recognized as effective means to improve seismic resilience in structural systems. This study aims to investigate the nonlinear modeling and dynamic analysis of civil structures employing high damping rubber bearings. Natural disasters, particularly earthquakes, pose a significant threat to civil structures. High damping rubber bearings have gained attention as a viable mitigation strategy, as they absorb dynamic loads and possess nonlinear characteristics that have the potential to enhance structural performance. Past research primarily focused on the static properties of rubber bearings, relying on linear models. However, to effectively respond to the diverse dynamic loads encountered in real-world scenarios, nonlinear modeling is imperative. Recent studies emphasize the need for nonlinear models, exploring the dynamic characteristics of various rubber bearings. The primary objective of this chapter is to develop a nonlinear model for civil structures utilizing high damping rubber bearings in both design and dynamic analysis. Specifically, effective modeling techniques accommodating various dynamic load conditions will be developed, and design guidelines contributing to safety and performance enhancement will be derived. This research will employ a combination of experiments and simulations to account for the nonlinear characteristics of high damping rubber bearings. The outcomes will serve as a basis for developing practical design guidelines applicable to real-world scenarios.

4.1.1 Motivation for Hysteresis Modeling

In the realm of structural engineering, the necessity for secure and resilient designs is paramount, especially when faced with dynamic loads such as seismic events. The development of nonlinear history models becomes imperative to ensure a thorough understanding of structural behavior under various loading conditions. This section will delve into the reasons why the development of nonlinear history models is crucial for achieving safe and robust structural designs. This study aims to enhance understanding of the effective utilization of high damping rubber bearings in seismic design and dynamic analysis. By presenting innovative principles for structural design focused on safety and durability, the study is expected to contribute to the improvement of seismic resilience in structures.

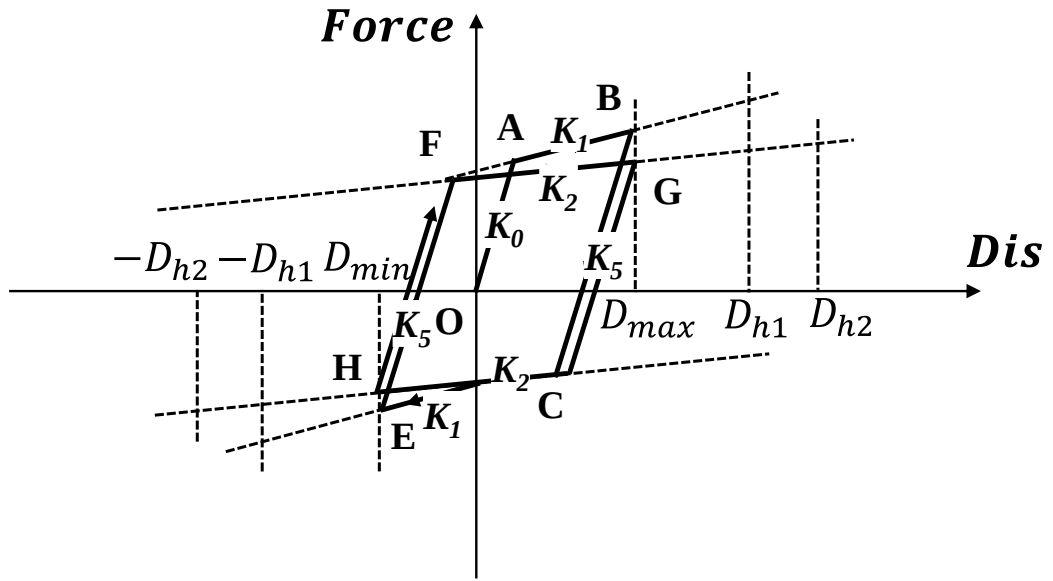
4.1.2 Literature Review on Existing Models

The dynamic analysis of the structures for the seismic assessment and design requires an accurate hysteresis model for the HDR bearings. Hysteretic models based on different dynamic load experiments were proposed to apply HDR bearings to the dynamic analysis of civil structures. The models were developed by considering the material characteristics and nonlinearity of the HDR. Different studies have been conducted to develop the hysteretic models of the laminated rubber bearings, including HDR. Owing to the strong nonlinearity of the HDR, predicting its behavior under shear deformation is complicated. Thus, the bilinear model is the most widely applied and convenient model for the seismic isolation design. However, this model has limitations in terms of accurately considering the dynamic characteristics of the HDR bearings and their dependence on different factors. To overcome these limitations and consider the nonlinearity of the HDR bearings, Fujisawa et al. (1993) proposed the concept of a double-target model and Ohtori et al. (1995) proposed an improved double target that expanded the bilinear model based on dynamic load experiments. This model is a history model proposed as an approach for separately setting the initial loading path to consider the Mullin effect on the HDR. Sanò (1995) evaluated the mechanical properties of the HDR bearings based on the dynamic loading experiments and

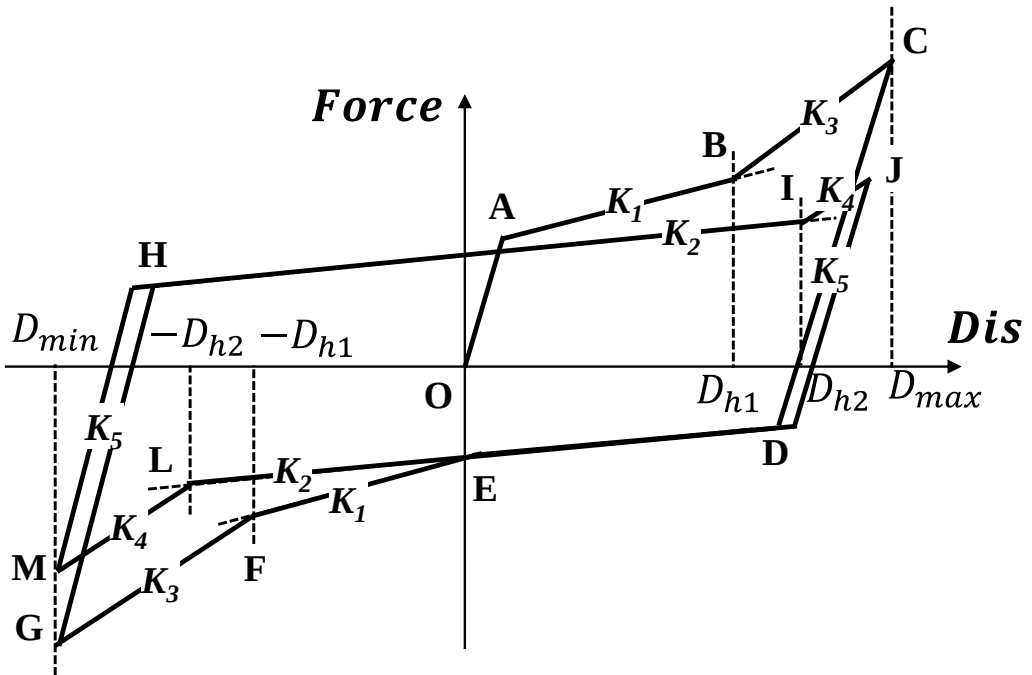
proposed a constitutive model. Koo (1998) proposed a nonlinear rate model considering the hysteretic characteristics of the rubber bearings and performed an analysis using seismic waves from the 1985 Mexico earthquake. Tsai (2003) proposed a hysteretic model that considered the rate-dependent effect by modifying Wen's model and reproducing experimental results. Takenaka (2001) proposed a modified HD model, which is a history model for LRB, to simplify the complicated parameter settings of the existing history models. Although existing models can capture the mechanical characteristics and dependence of the HDR, their practical use is limited owing to the complex parameter settings involved, thereby making their application in seismic designs challenging. To overcome this limitation, Mazda (2015) proposed a bilinear double-target model that simplifies the parameter setting and can be used in the seismic response analysis of seismically isolated structures. By referencing the improved double-target model, this model eliminates the complexity associated with the existing models and permits an easier practical implementation. (Mazda et al., 2016, Park et al., 2020). Naito et al. proposed a hysteretic model that considers the hardening phenomenon in the double-target model using the experimental results of the LRB (Naito et al, 2017). In this study, the mechanical properties were evaluated by dynamic loading tests using HDR specimens. An objective parameter-setting method based on the experimental results and a history model considering the dependence of the Mullins effect and hardening phenomenon was proposed. Moreover, this approach is anticipated to provide an objective method for proposing a hysteretic model that considers not only HDR but also the hysteretic characteristics of materials or devices exhibiting nonlinearity and energy absorption capacity during shear deformation.

4.2 Concept of Proposed Hysteresis Model

This nonlinear hysteresis model is an extension of the Bilinear model, designed to consider the nonlinearity of high damping rubber. To propose a design model considering the nonlinearity of HDR and to replicate dynamic loading experiment results, a nonlinear hysteresis model was devised by setting parameters based on dynamic loading experiment results. This hysteresis model takes into account the dependence on shear strain and the hardening phenomenon, allowing for the consideration of both aspects. In the dynamic loading test, the first loop of the hysteresis curve is considered the initial state, with the positive shear strain side representing the forward direction and the negative shear strain side representing the backward direction. Subsequent loops are assumed to represent the steady-state hysteresis curve. Fig. 4.1 illustrate the conceptual diagram of the hysteresis curves for the model proposed in this study. Fig. 4.1 (a) shows the concept diagram of the hysteresis model before the hardening phenomenon, and Fig. 4.1(b) shows the concept diagram of the hysteresis model after the hardening phenomenon. Previous research determined the stiffness based on the maximum experienced shear strain of HDR, choosing the larger absolute value between positive and negative maximum shear strains as the maximum experienced shear strain. However, our study, considering dynamic loading experiment results and mechanical property evaluations, revealed that the dependence of HDR shear strain on the positive maximum shear strain did not significantly affect the negative shear strain. Consequently, the proposed nonlinear hysteresis curves for HDR are expected to reproduce independent behaviors for positive and negative shear strains, reflecting actual HDR hysteresis curves more accurately.



(a) The hysteresis model before the hardening phenomenon



(b) The hysteresis model considering the hardening phenomenon

Fig. 4.1 The concept diagram for HDR bearings

4.2.1 Rule of hysteresis model

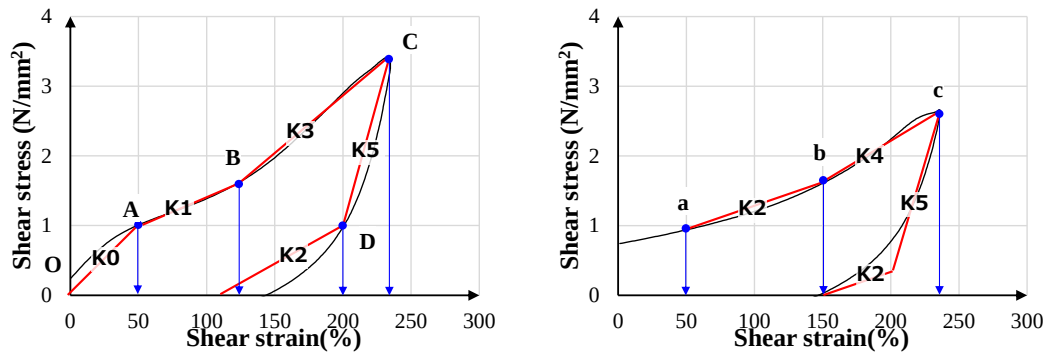
In this research, the proposed HDR hysteresis model reproduces independent behaviors based on experimental results, contrary to the conventional approach that relies on the absolute value of the maximum shear strain. Fig. 4.1(a) depicts a scenario where the shear strain experienced by HDR is less than the hardening strain. In the first loop, the linear segment from O to A progresses with the initial stiffness K_0 until passing the initial yield point, then transitions to the secondary stiffness K_1 until point B. Subsequently, when the progression direction reverses after reaching the maximum shear strain, it proceeds in the opposite direction with the unloading stiffness K_5 . If K_5 is greater than the secondary stiffness K_2 of the normal skeleton curve, the stiffness becomes K_2 .

The diagram in Fig. 4.1(b) illustrates the concept of the hysteresis model when HDR exhibits behavior beyond the hardening strain. In the linear segment of the first loop from O to A, it progresses with the initial stiffness K_0 until passing the initial yield point, then transitions to the secondary stiffness K_1 until point B. If the shear strain exceeds the initial hardening strain Dh_1 , the model proceeds with the hardening stiffness K_3 until reaching the maximum shear strain C. When the shear deformation is reversed, and the model's progression direction changes, the model's intercept stress decreases and proceeds with the unloading stiffness K_5 until C. If K_5 becomes greater than the secondary stiffness K_2 of the normal skeleton curve, the progression stiffness becomes K_2 . Afterward, upon encountering hardening in the normal skeleton curve at E, it progresses with the stiffness K_4 .

4.3 Parameter Setting

4.3.1 Calibration Process

The proposed parameters for the hysteresis curves are presented in Table 4.1-4.2. The conceptual diagram of the model used when setting parameters in this section is Fig. 4.2, which considers the hardening phenomenon. In this research, parameter settings were determined based on dynamic loading tests, specifically focusing on the most pronounced nonlinearity of HDR observed in the results of STEP4 with a shear strain of 250%. To account for the dependence on shear strain in HDR, parameters were separately configured for the experimental data of 1 cycle and 3 cycle. Additionally, hardening deformation was set to design the model to exhibit hardening phenomena under specific conditions. The intercept stress of the initial curve and the steady state curve was a fixed value based on the experimental results.



(a) The hysteresis curve for the initial hysteresis curve

(b) The hysteresis curve for the steady state hysteresis curve

Fig. 4.2 The concept diagram for parameter setting

Table 4.1 The parameters for the initial hysteresis curve

Parameters		Displacement (mm)	Shear force (kN)	Shear strain (%)	Shear stress (N/mm ²)
K0=K5	Initial stiffness	0.0	0.0	0	0.00
O-A	7016	8.0	10.1	50	1.01
K1	Secondary stiffness	8.0	10.1	50	1.01
A-B	830	20.0	16.3	125	1.63
K3	Hardening stiffness	20.0	16.3	125	1.63
B-C	1606	37.5	33.9	235	3.39
K5	Unloading stiffness	37.5	33.9	235	3.39
C-D	7016	32.0	9.8	200	0.98

Table 4.2 The parameters for the steady state hysteresis curve

Parameters		Displacement (mm)	Shear force (kN)	Shear strain (%)	Shear stress (N/mm ²)
K2	Secondary stiffness	8.0	9.4	50	0.94
a-b	668	24.0	16.1	150	1.61
K4	Hardening stiffness	24.0	16.1	150	1.61
b-c	1232	37.7	26.6	236	2.66

4.4 Validation of proposed hysteresis model

4.4.1 Analytical condition

A structural model of the 1-dof system is shown in Fig. 4.3. To reproduce the results of the dynamic load test, a vertical load of 60 kN was applied to the structural model of the one material point and a trilinear double target model reflecting the HDR characteristics was applied to the spring element. The input wave had a similar waveform to that used in the dynamic loading experiment. To reproduce the experimental results obtained using the trilinear double target model, a sine wave with a shear strain of 250%, which is the standard for the proposed hysteresis model, and the shear strain applied in STEP3 and STEP4 was prepared as the input wave. Based on the results of the dynamic loading test, it was possible to objectively calculate the parameters of the hysteretic model. Eight parameters were required in the trilinear double target model.

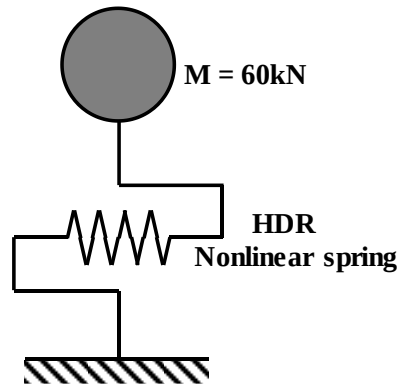
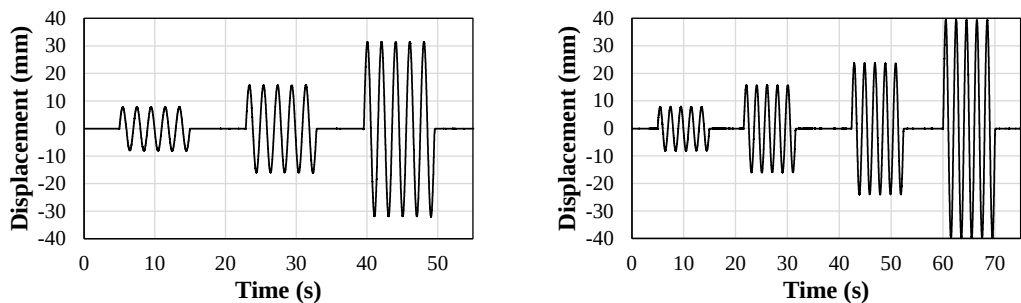


Fig. 4.3 Structural model (1-dof System)

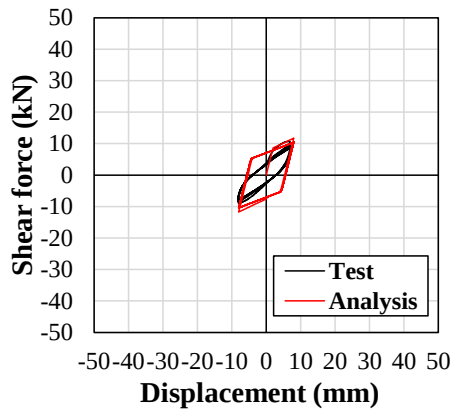


(a) STEP3 ($\pm 50\%$, $\pm 100\%$, $\pm 200\%$) (b) STEP4 ($\pm 50\%$, $\pm 100\%$, $\pm 150\%$, $\pm 250\%$)

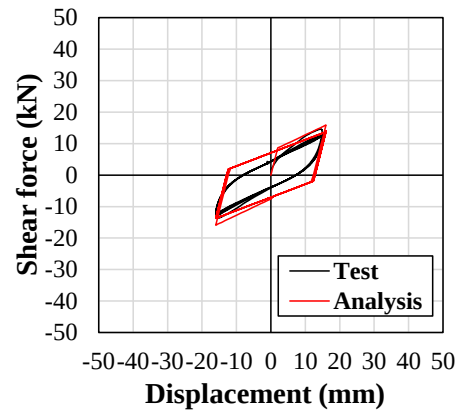
Fig. 4.4 The input wave for dynamic analysis

4.4.2 Analysis results

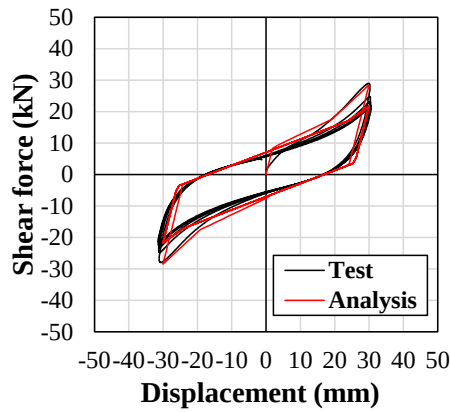
Fig. 4.5 represents the comparison of experimental results and analysis results in STEP3. Test represents the results of the dynamic loading test conducted in Chapter 2, and Analysis represents the trilinear double target model, the proposed hysteresis model. As a result of comparing the experimental results and analysis results of STEP3, it was possible to reproduce the dependence of HDR on shear strain and the hardening phenomenon at a shear strain of 200%. However, at relatively low shear strains such as 50% shear strain and 100% shear strain, a hysteresis curve larger than the actual experimental results was obtained.



(a) $\pm 50\%$ shear strain



(b) $\pm 100\%$ shear strain



(c) $\pm 200\%$ shear strain

Fig. 4.5 The comparison of experimental results and analysis results in STEP3

Fig. 4.6 represents the comparison of experimental results and analysis results in STEP4. Test represents the results of the dynamic loading test conducted in Chapter 2, and Analysis represents the trilinear double target model, the proposed hysteresis model. As a result of comparing the experimental results and analysis results of STEP4, it was possible to reproduce the dependence of HDR on shear strain and the hardening phenomenon at shear strains of 150% and 250%. Because shear strain of 250% hysteresis data was used to set the parameters of the proposed hysteresis model, the analysis results closest to the experimental results were obtained at a shear strain rate of 250%. However, as in STEP3, at relatively low shear strains such as 50% shear strain and 100% shear strain, a hysteresis curve larger than the actual experimental results was obtained.

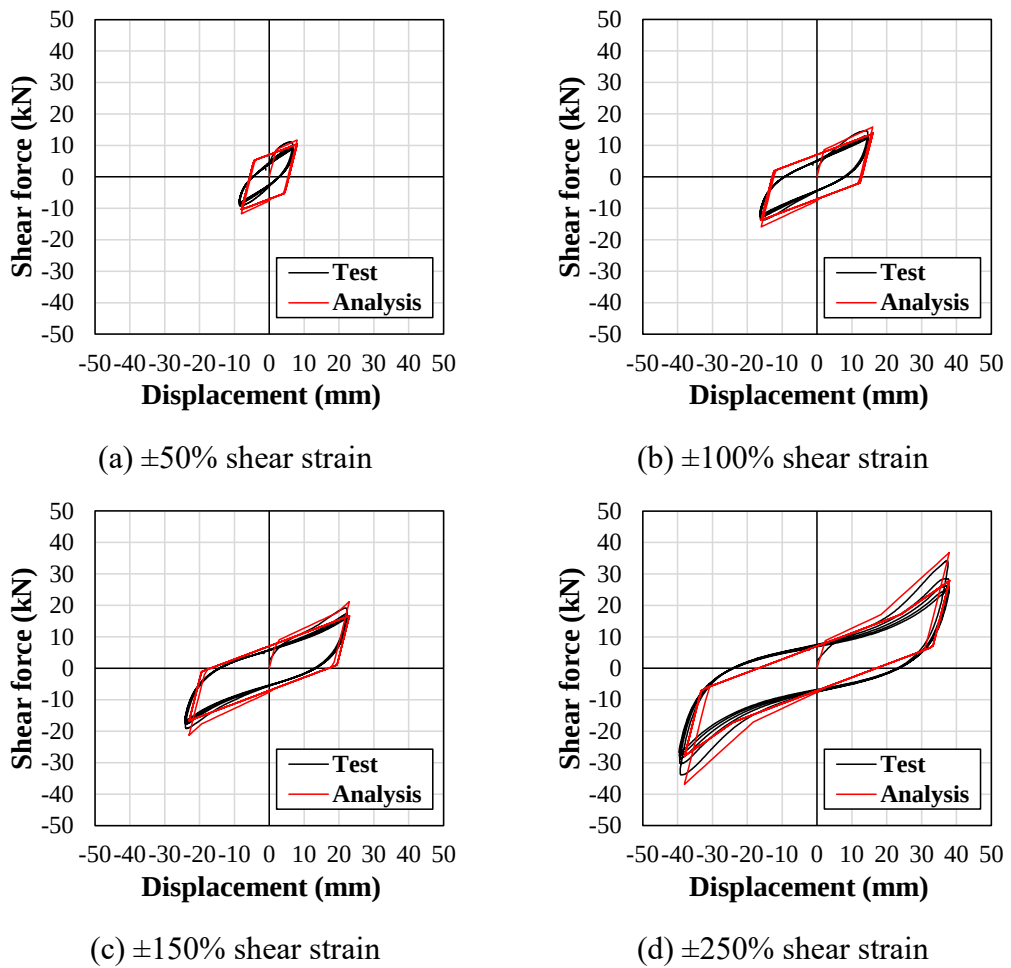


Fig. 4.6 The comparison of experimental results and analysis results in STEP4

4.4.3 Evaluation of mechanical properties

50% Shear strain (STEP3)

In order to confirm the validity of the proposed history model, the trilinear double target model, the mechanical properties of HDR were evaluated based on the analysis results. Fig. 4.7 represents the comparison of shear force for 50% shear strain in STEP3. Table 4.3 shows the experimental and analysis results of shear force for 50% shear strain of each cycle in STEP3. In the case of shear force, it shows high agreement with the experimental results.

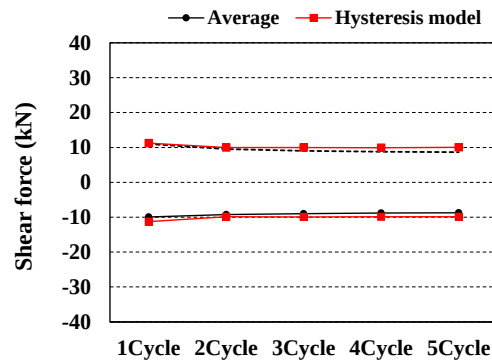


Fig. 4.7 The comparison of shear force for 50% shear strain in STEP3

Table 4.3 The experimental and analysis results of shear force for 50% shear strain of each cycle in STEP3

Shear force (kN)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	11.0	9.5	9.0	8.8	8.6
	-9.9	-9.2	-9.0	-8.8	-8.7
Hysteresis model	11.2	10.0	10.0	9.9	10.1
	-11.2	-9.9	-9.9	-9.9	-9.9

Fig. 4.8 represents the comparison of absorption energy for 50% shear strain in STEP3. Table 4.4 shows the experimental and analysis results of absorption energy for 50% shear strain of each cycle in STEP3. In the case of absorption energy, higher results were obtained than the experimental results.

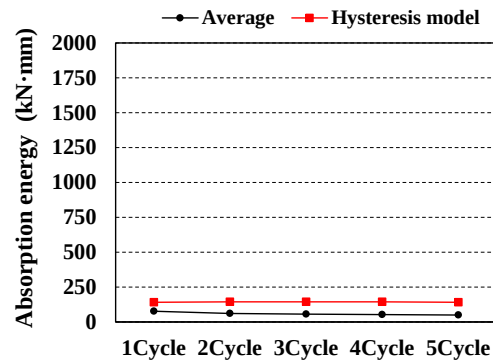


Fig. 4.8 The comparison of absorption energy for 50% shear strain in STEP3

Table 4.4 The comparison of absorption energy between experimental results and analysis results at 50% shear strain in STEP3

Absorption energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	76	60	55	53	49
Hysteresis model	141	143	143	144	141

Fig. 4.9 represents the comparison of equivalent stiffness for 50% shear strain in STEP3. Table 4.5 shows the experimental and analysis results of equivalent stiffness for 50% shear strain of each cycle in STEP3. In the case of shear force, it shows high agreement with the experimental results.

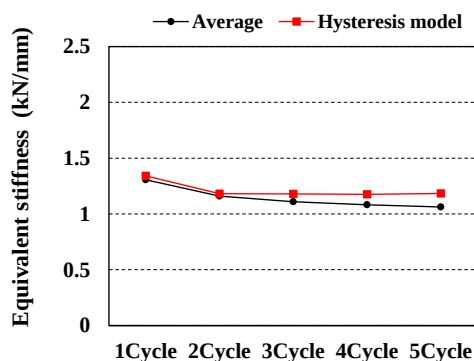


Fig. 4.9 The comparison of equivalent stiffness for 50% shear strain in STEP3

Table 4.5 The comparison of equivalent stiffness between experimental results and analysis results at 50% shear strain in STEP3

Equivalent stiffness (kN/mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	1.31	1.16	1.11	1.08	1.06
Hysteresis model	1.34	1.18	1.18	1.18	1.18

Fig. 4.10 represents the comparison of strain energy for 50% shear strain in STEP3. Table 4.6 shows the experimental and analysis results of strain energy for 50% shear strain of each cycle in STEP3. In the case of shear force, it shows high agreement with the experimental results.

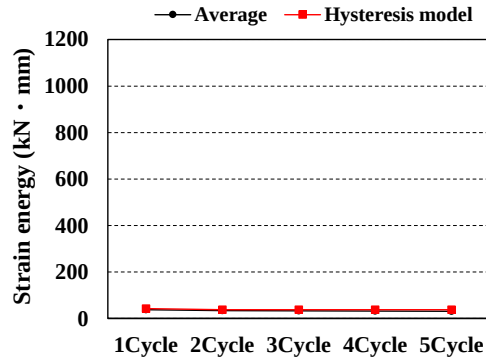


Fig. 4.10 The comparison of strain energy for 50% shear strain in STEP3

Table 4.6 The comparison of strain energy between experimental results and analysis results at 50% shear strain in STEP3

Strain energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	38	34	33	32	31
Hysteresis model	43	38	38	38	38

Fig. 4.11 represents the comparison of damping ratio for 50% shear strain in STEP3. Table 4.7 shows the experimental and analysis results of damping ratio for 50% shear strain of each cycle in STEP3. In the case of absorption energy, higher results were obtained than the experimental results.

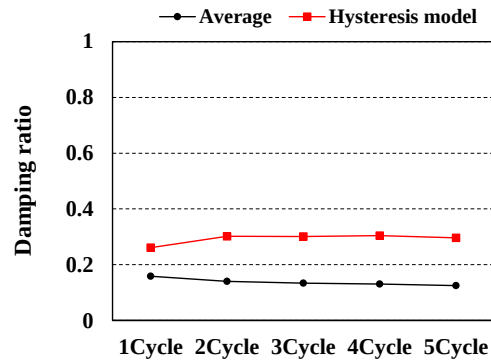


Fig. 4.11 The comparison of damping ratio for 50% shear strain in STEP3

Table 4.7 The comparison of damping ratio between experimental results and analysis results at 50% shear strain in STEP3

Damping ratio	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.159	0.140	0.134	0.131	0.125
Hysteresis model	0.261	0.302	0.301	0.304	0.296

100% Shear strain (STEP3)

Fig. 4.12 represents the comparison of shear force for 100% shear strain in STEP3. Table 4.8 shows the experimental and analysis results of shear force for 100% shear strain of each cycle in STEP3. In the case of shear force, it shows high agreement with the experimental results.

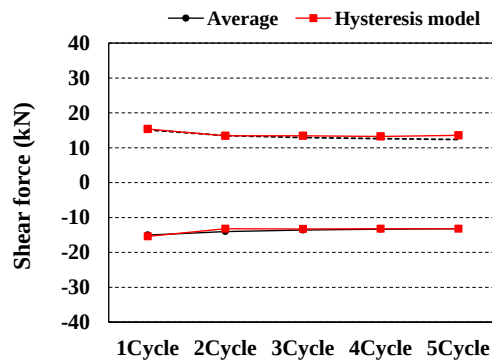


Fig. 4.12 The comparison of shear force for 100% shear strain in STEP3

Table 4.8 The experimental and analysis results of shear force for 100% shear strain of each cycle in STEP3

Shear force (kN)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	15.1	13.5	12.9	12.6	12.4
	-15.0	-14.0	-13.6	-13.4	-13.2
Hysteresis model	15.4	13.4	13.4	13.2	13.6
	-15.4	-13.2	-13.2	-13.2	-13.2

Fig. 4.13 represents the comparison of absorption energy for 100% shear strain in STEP3. Table 4.9 shows the experimental and analysis results of absorption energy for 100% shear strain of each cycle in STEP3. In the case of absorption energy, higher results were obtained than the experimental results.

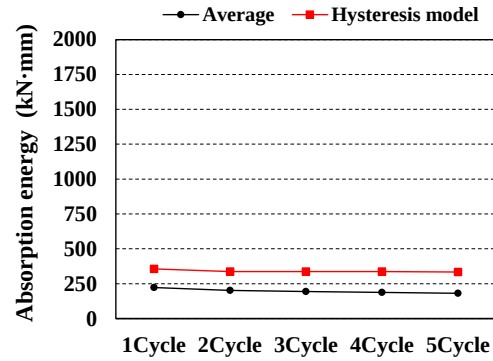


Fig. 4.13 The comparison of absorption energy for 100% shear strain in STEP3

Table 4.9 The comparison of absorption energy between experimental results and analysis results at 100% shear strain in STEP3

Absorption energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	223	202	194	188	181
Hysteresis model	356	337	337	337	333

Fig. 4.14 represents the comparison of equivalent stiffness for 100% shear strain in STEP3. Table 4.10 shows the experimental and analysis results of equivalent stiffness for 100% shear strain of each cycle in STEP3. In the case of shear force, it shows high agreement with the experimental results.

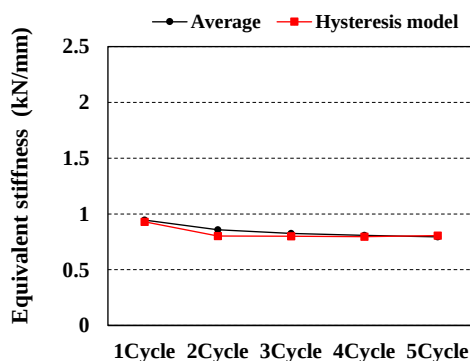


Fig. 4.14 The comparison of equivalent stiffness for 100% shear strain in STEP3

Table 4.10 The comparison of equivalent stiffness between experimental results and analysis results at 100% shear strain in STEP3

Equivalent stiffness (kN/mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.95	0.86	0.83	0.81	0.79
Hysteresis model	0.93	0.80	0.80	0.80	0.81

Fig. 4.15 represents the comparison of strain energy for 100% shear strain in STEP3. Table 4.11 shows the experimental and analysis results of strain energy for 100% shear strain of each cycle in STEP3. In the case of shear force, it shows high agreement with the experimental results.

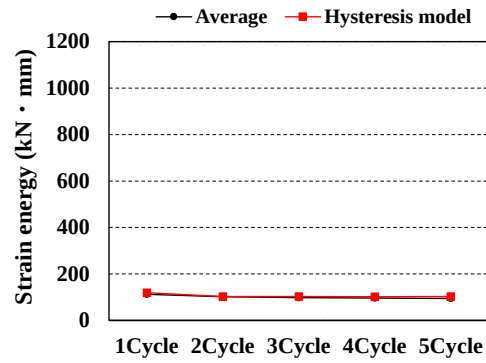


Fig. 4.15 The comparison of strain energy for 100% shear strain in STEP3

Table 4.11 The comparison of strain energy between experimental results and analysis results at 100% shear strain in STEP3

Strain energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	112	102	99	97	95
Hysteresis model	119	103	103	102	103

Fig. 4.16 represents the comparison of damping ratio for 100% shear strain in STEP3. Table 4.12 shows the experimental and analysis results of damping ratio for 100% shear strain of each cycle in STEP3. In the case of absorption energy, higher results were obtained than the experimental results.

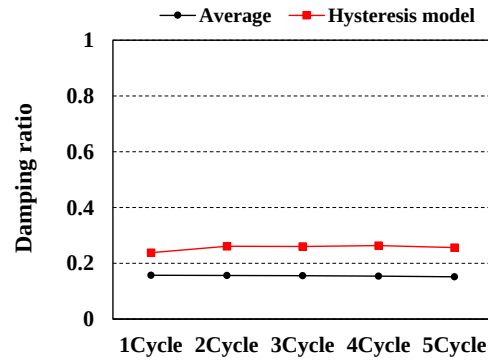


Fig. 4.16 The comparison of damping ratio for 100% shear strain in STEP3

Table 4.12 The comparison of damping ratio between experimental results and analysis results at 100% shear strain in STEP3

Damping ratio	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.158	0.157	0.156	0.154	0.152
Hysteresis model	0.238	0.261	0.261	0.264	0.257

200% Shear strain (STEP3)

Fig. 4.17 represents the comparison of shear force for 200% shear strain in STEP3. Table 4.13 shows the experimental and analysis results of shear force for 200% shear strain of each cycle in STEP3. In the case of shear force, it shows high agreement with the experimental results.

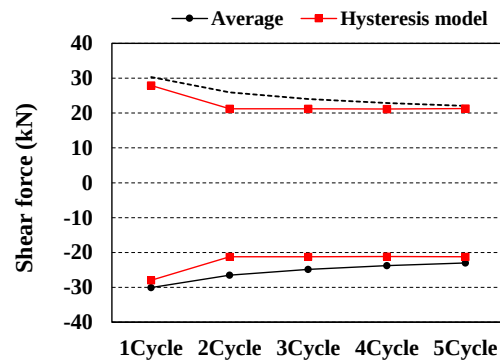


Fig. 4.17 The comparison of shear force for 200% shear strain in STEP3

Table 4.13 The experimental and analysis results of shear force for 200% shear strain of each cycle in STEP3

Shear force (kN)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	30.3	25.9	24.0	22.9	22.0
	-30.0	-26.5	-24.9	-23.8	-23.0
Hysteresis model	27.9	21.2	21.2	21.2	21.3
	-28.0	-21.2	-21.2	-21.2	-21.2

Fig. 4.18 represents the comparison of absorption energy for 200% shear strain in STEP3. Table 4.14 shows the experimental and analysis results of absorption energy for 200% shear strain of each cycle in STEP3. In the case of shear force, it shows high agreement with the experimental results.

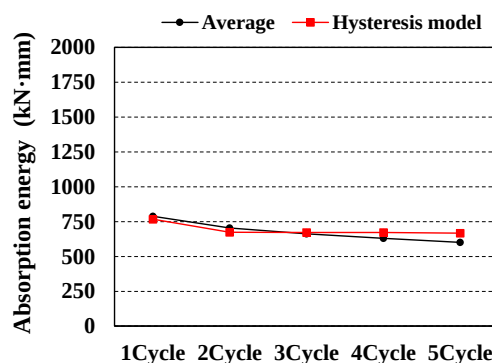


Fig. 4.18 The comparison of absorption energy for 200% shear strain in STEP3

Table 4.14 The comparison of absorption energy between experimental results and analysis results at 200% shear strain in STEP3

Absorption energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	789	705	662	630	602
Hysteresis model	767	673	673	673	666

Fig. 4.19 represents the comparison of equivalent stiffness for 200% shear strain in STEP3. Table 4.15 shows the experimental and analysis results of equivalent stiffness for 200% shear strain of each cycle in STEP3. In the case of shear force, it shows high agreement with the experimental results.

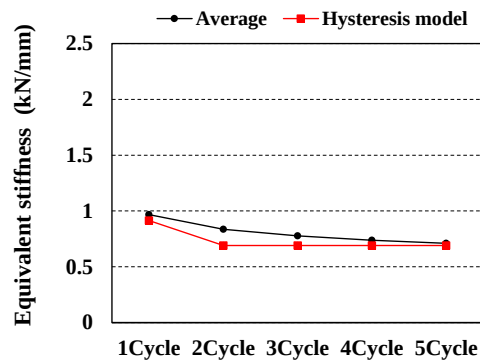


Fig. 4.19 The comparison of equivalent stiffness for 200% shear strain in STEP3

Table 4.15 The comparison of equivalent stiffness between experimental results and analysis results at 200% shear strain in STEP3

Equivalent stiffness (kN/mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.97	0.83	0.78	0.74	0.71
Hysteresis model	0.91	0.69	0.69	0.69	0.69

Fig. 4.20 represents the comparison of strain energy for 200% shear strain in STEP3. Table 4.16 shows the experimental and analysis results of strain energy for 200% shear strain of each cycle in STEP3. In the case of strain energy, lower results were obtained than the experimental results.

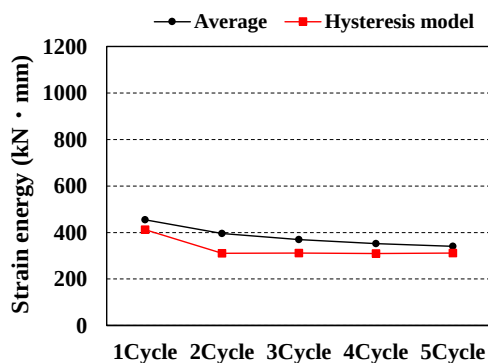


Fig. 4.20 The comparison of strain energy for 200% shear strain in STEP3

Table 4.16 The comparison of strain energy between experimental results and analysis results at 200% shear strain in STEP3

Strain energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	455	396	370	353	340
Hysteresis model	412	311	311	310	311

Fig. 4.21 represents the comparison of damping ratio for 200% shear strain in STEP3. Table 4.17 shows the experimental and analysis results of damping ratio for 200% shear strain of each cycle in STEP3. In the case of strain energy, results were obtained that were almost identical to the experimental results.

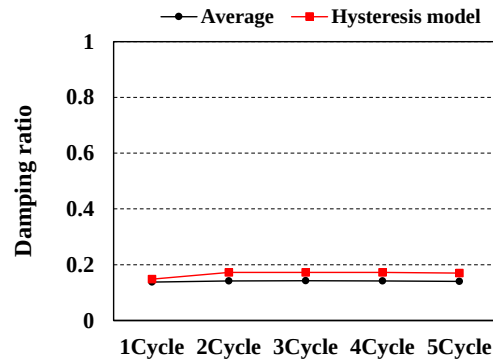


Fig. 4.21 The comparison of damping ratio for 200% shear strain in STEP3

Table 4.17 The comparison of damping ratio between experimental results and analysis results at 200% shear strain in STEP3

Damping ratio	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.138	0.141	0.142	0.142	0.140
Hysteresis model	0.148	0.172	0.172	0.173	0.170

50% Shear strain (STEP4)

Fig. 4.22 represents the comparison of shear force for 50% shear strain in STEP4. Table 4.18 shows the experimental and analysis results of shear force for 50% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

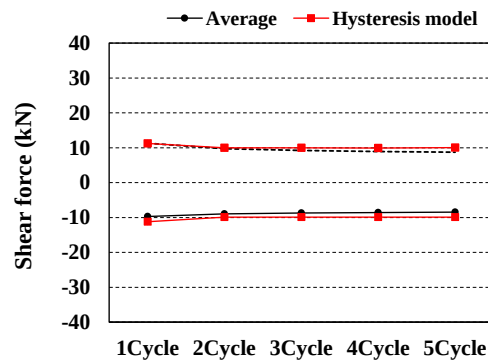


Fig. 4.22 The comparison of shear force for 50% shear strain in STEP4

Table 4.18 The experimental and analysis results of shear force for 50% shear strain of each cycle in STEP4

Shear force (kN)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	11.3	9.7	9.2	8.9	8.7
	-9.7	-9.0	-8.7	-8.6	-8.4
Hysteresis model	11.2	10.0	10.0	9.9	10.1
	-11.2	-9.9	-9.9	-9.9	-9.9

Fig. 4.23 represents the comparison of absorption energy for 50% shear strain in STEP4. Table 4.19 shows the experimental and analysis results of absorption energy for 50% shear strain of each cycle in STEP4. In the case of absorption energy, higher results were obtained than the experimental results.

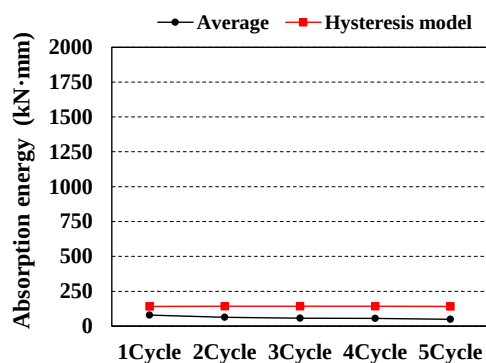


Fig. 4.23 The comparison of absorption energy for 50% shear strain in STEP4

Table 4.19 The comparison of absorption energy between experimental results and analysis results at 50% shear strain in STEP4

Absorption energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	79	63	58	55	50
Hysteresis model	141	143	143	144	141

Fig. 4.24 represents the comparison of equivalent stiffness for 50% shear strain in STEP4. Table 4.20 shows the experimental and analysis results of equivalent stiffness for 50% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

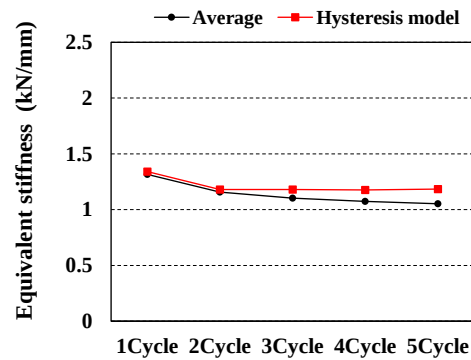


Fig. 4.24 The comparison of equivalent stiffness for 50% shear strain in STEP4

Table 4.20 The comparison of equivalent stiffness between experimental results and analysis results at 50% shear strain in STEP4

Equivalent stiffness (kN/mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	1.32	1.16	1.10	1.07	1.05
Hysteresis model	1.34	1.18	1.18	1.18	1.18

Fig. 4.25 represents the comparison of strain energy for 50% shear strain in STEP4. Table 4.21 shows the experimental and analysis results of strain energy for 50% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

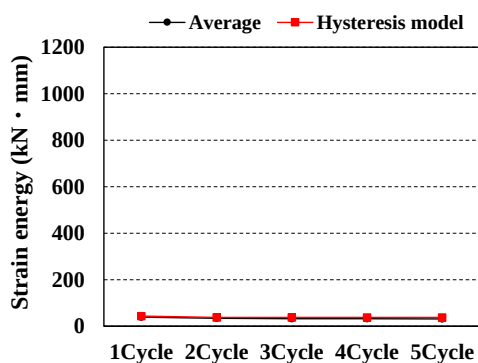


Fig. 4.25 The comparison of strain energy for 50% shear strain in STEP4

Table 4.21 The comparison of strain energy between experimental results and analysis results at 50% shear strain in STEP4

Strain energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	38	34	32	32	31
Hysteresis model	43	38	38	38	38

Fig. 4.26 represents the comparison of damping ratio for 50% shear strain in STEP4. Table 4.22 shows the experimental and analysis results of damping ratio for 50% shear strain of each cycle in STEP4. In the case of absorption energy, higher results were obtained than the experimental results.

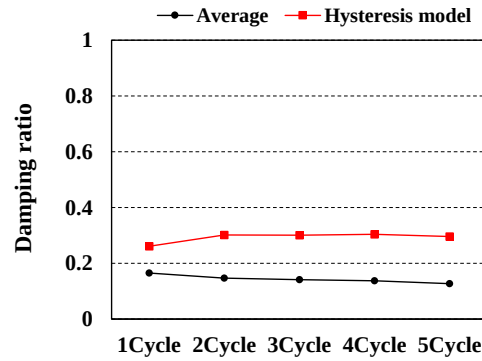


Fig. 4.26 The comparison of damping ratio for 50% shear strain in STEP4

Table 4.22 The comparison of damping ratio between experimental results and analysis results at 50% shear strain in STEP4

Damping ratio	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.159	0.140	0.134	0.131	0.125
Hysteresis model	0.261	0.302	0.301	0.304	0.296

100% Shear strain (STEP4)

Fig. 4.27 represents the comparison of shear force for 100% shear strain in STEP4. Table 4.23 shows the experimental and analysis results of shear force for 100% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

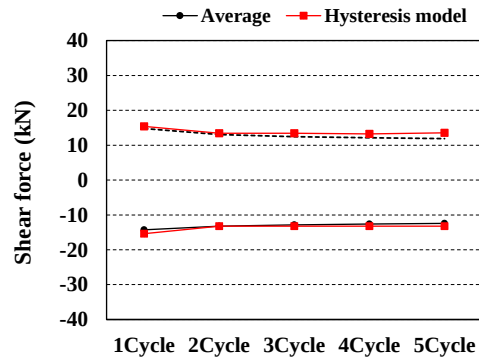


Fig. 4.27 The comparison of shear force for 100% shear strain in STEP4

Table 4.23 The experimental and analysis results of shear force for 100% shear strain of each cycle in STEP4

Shear force (kN)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	14.8	13.0	12.4	12.1	11.9
	-14.2	-13.2	-12.8	-12.6	-12.4
Hysteresis model	15.4	13.4	13.4	13.2	13.6
	-15.4	-13.2	-13.2	-13.2	-13.2

Fig. 4.28 represents the comparison of absorption energy for 100% shear strain in STEP4. Table 4.24 shows the experimental and analysis results of absorption energy for 100% shear strain of each cycle in STEP4. In the case of absorption energy, higher results were obtained than the experimental results.

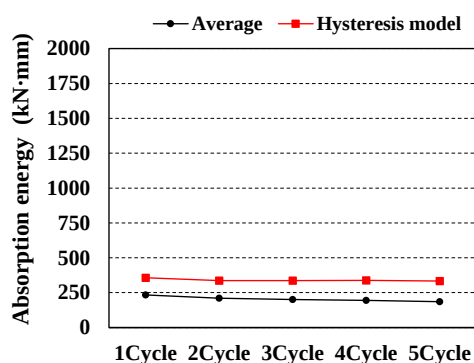


Fig. 4.28 The comparison of absorption energy for 100% shear strain in STEP4

Table 4.24 The comparison of absorption energy between experimental results and analysis results at 100% shear strain in STEP4

Absorption energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	233	211	201	195	185
Hysteresis model	356	337	337	337	333

Fig. 4.29 represents the comparison of equivalent stiffness for 100% shear strain in STEP4. Table 4.25 shows the experimental and analysis results of equivalent stiffness for 100% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

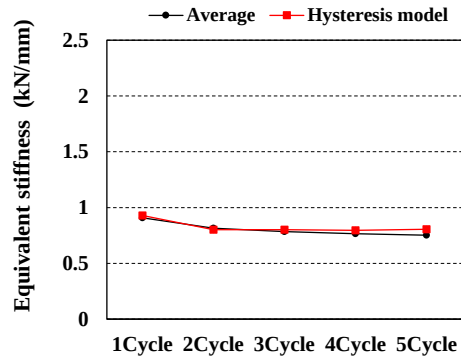


Fig. 4.29 The comparison of equivalent stiffness for 100% shear strain in STEP4
Table 4.25 The comparison of equivalent stiffness between experimental results and analysis results at 100% shear strain in STEP4

Equivalent stiffness (kN/mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.91	0.82	0.78	0.77	0.75
Hysteresis model	0.93	0.80	0.80	0.80	0.81

Fig. 4.30 represents the comparison of strain energy for 100% shear strain in STEP4. Table 4.26 shows the experimental and analysis results of strain energy for 100% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

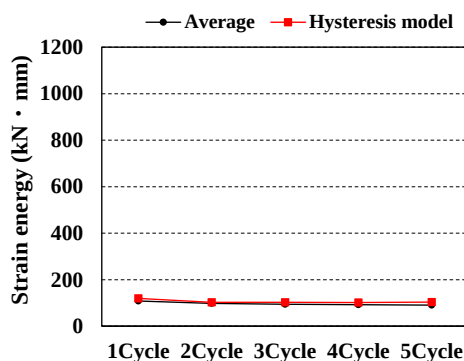


Fig. 4.30 The comparison of strain energy for 100% shear strain in STEP4

Table 4.26 The comparison of strain energy between experimental results and analysis results at 100% shear strain in STEP4

Strain energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	108	98	94	92	90
Hysteresis model	119	103	103	102	103

Fig. 4.31 represents the comparison of damping ratio for 100% shear strain in STEP4. Table 4.27 shows the experimental and analysis results of damping ratio for 100% shear strain of each cycle in STEP4. In the case of absorption energy, higher results were obtained than the experimental results.

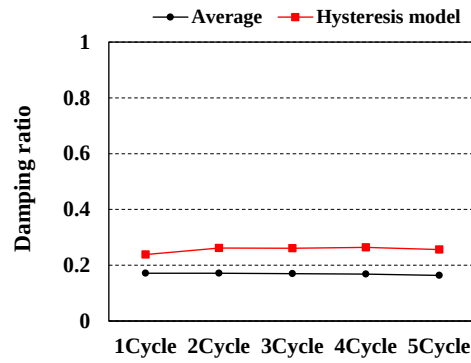


Fig. 4.31 The comparison of damping ratio for 100% shear strain in STEP4

Table 4.27 The comparison of damping ratio between experimental results and analysis results at 100% shear strain in STEP4

Damping ratio	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.171	0.171	0.170	0.168	0.163
Hysteresis model	0.238	0.261	0.261	0.264	0.257

150% Shear strain (STEP4)

Fig. 4.32 represents the comparison of shear force for 150% shear strain in STEP4. Table 4.28 shows the experimental and analysis results of shear force for 150% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

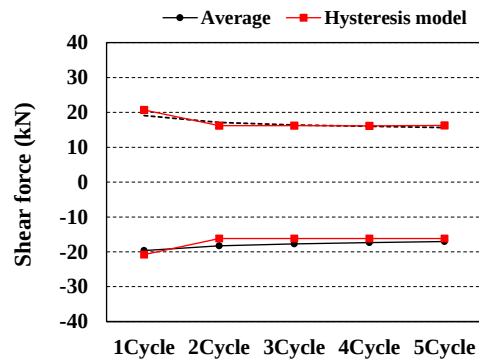


Fig. 4.32 The comparison of shear force for 150% shear strain in STEP4

Table 4.28 The experimental and analysis results of shear force for 150% shear strain of each cycle in STEP4

Shear force (kN)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	19.1	17.1	16.4	16.0	15.7
	-19.6	-18.3	-17.7	-17.3	-17.1
Hysteresis model	20.7	16.2	16.2	16.2	16.2
	-20.8	-16.2	-16.2	-16.2	-16.2

Fig. 4.33 represents the comparison of absorption energy for 150% shear strain in STEP4. Table 4.29 shows the experimental and analysis results of absorption energy for 150% shear strain of each cycle in STEP4. In the case of absorption energy, higher results were obtained than the experimental results.

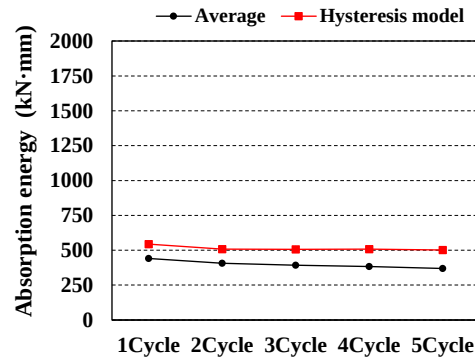


Fig. 4.33 The comparison of absorption energy for 150% shear strain in STEP4

Table 4.29 The comparison of absorption energy between experimental results and analysis results at 150% shear strain in STEP4

Absorption energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	440	407	393	383	369
Hysteresis model	544	507	507	507	502

Fig. 4.34 represents the comparison of equivalent stiffness for 150% shear strain in STEP4. Table 4.30 shows the experimental and analysis results of equivalent stiffness for 150% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

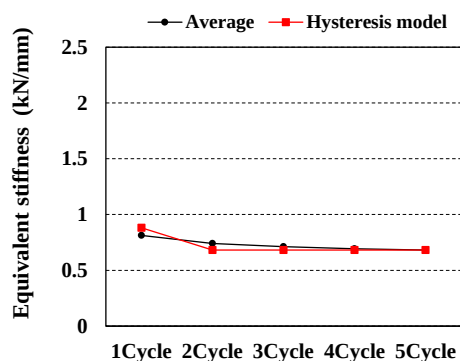


Fig. 4.34 The comparison of equivalent stiffness for 150% shear strain in STEP4

Table 4.30 The comparison of equivalent stiffness between experimental results and analysis results at 150% shear strain in STEP4

Equivalent stiffness (kN/mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.81	0.74	0.71	0.69	0.68
Hysteresis model	0.88	0.68	0.68	0.68	0.68

Fig. 4.35 represents the comparison of strain energy for 150% shear strain in STEP4. Table 4.31 shows the experimental and analysis results of strain energy for 150% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

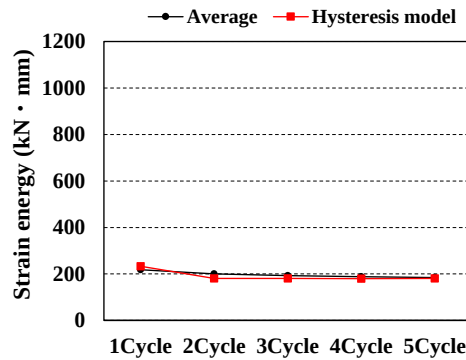


Fig. 4.35 The comparison of strain energy for 150% shear strain in STEP4

Table 4.31 The comparison of strain energy between experimental results and analysis results at 150% shear strain in STEP4

Strain energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	219	200	193	188	185
Hysteresis model	233	180	181	180	181

Fig. 4.36 represents the comparison of damping ratio for 150% shear strain in STEP4. Table 4.32 shows the experimental and analysis results of damping ratio for 150% shear strain of each cycle in STEP4. In the case of absorption energy, higher results were obtained than the experimental results.

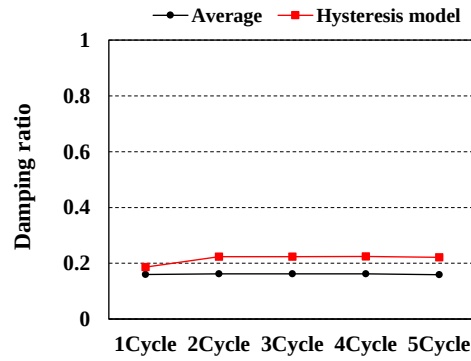


Fig. 4.36 The comparison of damping ratio for 150% shear strain in STEP4

Table 4.32 The comparison of damping ratio between experimental results and analysis results at 150% shear strain in STEP4

Damping ratio	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.160	0.162	0.162	0.162	0.159
Hysteresis model	0.186	0.224	0.223	0.224	0.221

250% Shear strain (STEP4)

Fig. 4.37 represents the comparison of shear force for 250% shear strain in STEP4. Table 4.33 shows the experimental and analysis results of shear force for 250% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

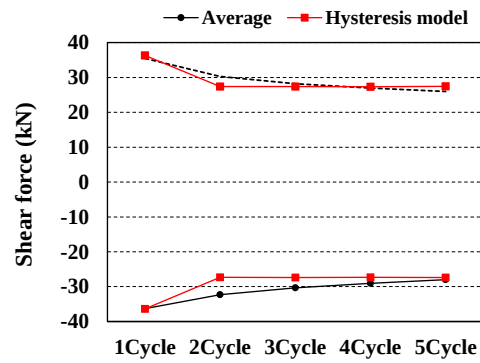


Fig. 4.37 The comparison of shear force for 250% shear strain in STEP4

Table 4.33 The experimental and analysis results of shear force for 250% shear strain of each cycle in STEP4

Shear force (kN)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	35.5	30.3	28.2	27.0	26.0
	-36.3	-32.3	-30.3	-29.1	-28.0
Hysteresis model	36.3	27.4	27.4	27.3	27.4
	-36.4	-27.3	-27.4	-27.3	-27.4

Fig. 4.38 represents the comparison of absorption energy for 250% shear strain in STEP4. Table 4.34 shows the experimental and analysis results of absorption energy for 250% shear strain of each cycle in STEP4. In the case of absorption energy, higher results were obtained than the experimental results.

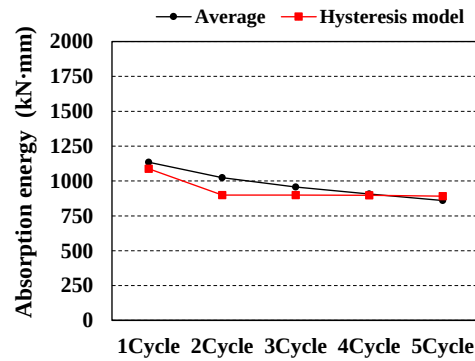


Fig. 4.38 The comparison of absorption energy for 250% shear strain in STEP4

Table 4.34 The comparison of absorption energy between experimental results and analysis results at 250% shear strain in STEP4

Absorption energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	1134	1023	957	907	860
Hysteresis model	1087	899	898	898	891

Fig. 4.39 represents the comparison of equivalent stiffness for 250% shear strain in STEP4. Table 4.35 shows the experimental and analysis results of equivalent stiffness for 250% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

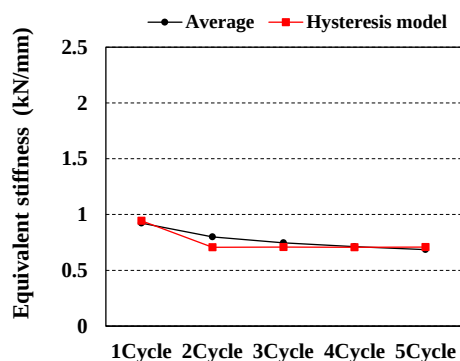


Fig. 4.39 The comparison of equivalent stiffness for 250% shear strain in STEP4

Table 4.35 The comparison of equivalent stiffness between experimental results and analysis results at 250% shear strain in STEP4

Equivalent stiffness (kN/mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.92	0.80	0.75	0.71	0.69
Hysteresis model	0.94	0.71	0.71	0.71	0.71

Fig. 4.40 represents the comparison of strain energy for 250% shear strain in STEP4. Table 4.36 shows the experimental and analysis results of strain energy for 250% shear strain of each cycle in STEP4. In the case of shear force, it shows high agreement with the experimental results.

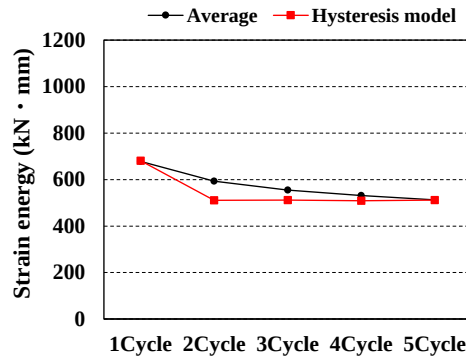


Fig. 4.40 The comparison of strain energy for 250% shear strain in STEP4

Table 4.36 The comparison of strain energy between experimental results and analysis results at 250% shear strain in STEP4

Strain energy (kN · mm)	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	679	593	555	532	512
Hysteresis model	681	511	512	509	512

Fig. 4.41 represents the comparison of damping ratio for 250% shear strain in STEP4. Table 4.37 shows the experimental and analysis results of damping ratio for 250% shear strain of each cycle in STEP4. In the case of absorption energy, higher results were obtained than the experimental results.

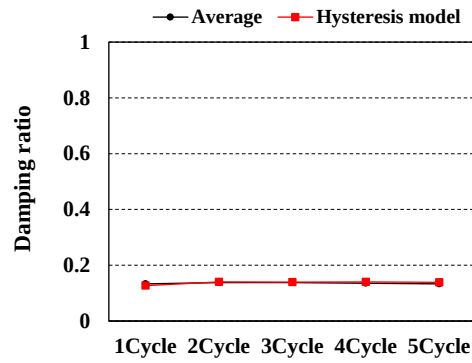


Fig. 4.41 The comparison of damping ratio for 250% shear strain in STEP4

Table 4.37 The comparison of damping ratio between experimental results and analysis results at 250% shear strain in STEP4

Damping ratio	Cycle				
	1Cycle	2Cycle	3Cycle	4Cycle	5Cycle
Average (No.2-No.4)	0.133	0.138	0.137	0.136	0.134
Hysteresis model	0.127	0.140	0.140	0.140	0.139

4.5 Summary

In this chapter, the trilinear double target model is introduced, designed to account for the nonlinear hysteresis characteristics of HDR bearings. This model extends the basic bilinear model, capturing the Mullins effect and hardening phenomenon observed in dynamic loading tests. The dynamic analysis aims to evaluate the performance of this newly proposed model in handling complex nonlinear behavior in HDR bearings, focusing on predictive accuracy and responsiveness. To validate the model, the results of dynamic loading experiments are compared with calculated mechanical characteristic values from the trilinear double target model. Using the same sine wave input as in the dynamic loading experiment, the one-mass model of the SDOF system is simulated with spring elements incorporating HDR bearing characteristics. The results demonstrate commendable predictive accuracy of the trilinear double target model under conditions similar to the dynamic loading test. Reproducing experimental results for STEP3 and STEP4 reveals high accuracy, particularly at shear strains exceeding 150%. Notably, at shear strain rates of 200% and 250%, the model accurately predicts shear strain rate dependence and the hardening phenomenon. Comparison of mechanical properties at a shear strain of 250% shows substantial consistency with experimental values, affirming that the trilinear double target model effectively reproduces the hysteresis characteristics of HDR bearings.

Chapter 5

Dynamic Loading Test by Design Seismic Motion

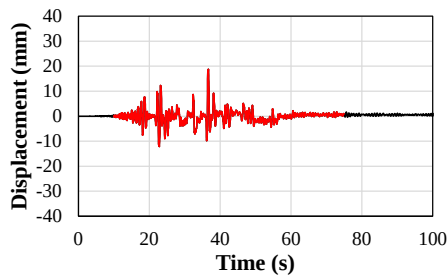
5.1 Introduction

The second dynamic loading test aimed to simulate earthquake conditions by applying shear deformation to the HDR specimen using random waves, thereby obtaining data that closely resembled the actual behavior of the HDR. The random wave used in the test assumed a TYPE 2 design earthquake, as specified in the manual for highway bridge bearings and design specifications for highway bridges. In the Japanese road bridge specifications, the design ground motion for the seismic design is divided into TYPE 1 and 2 based on their frequency and intensity of occurrence. TYPE 1 earthquakes are medium-scale earthquakes with a relatively high likelihood of occurrence, whereas TYPE 2 earthquakes are large-scale earthquakes, such as plate boundaries and inland earthquakes. For this test, the waveform data used were selected to display the hysteretic characteristics of the HDR, excluding the residual displacement. The No. 4 HDR test specimen was used, and it was assumed that the Mullin effect could be expected, as in the virgin material, because it was more than a year after the dynamic load test using a sine wave was performed (Dall'Asta et al. 2006, Pablo et al. 2007). The amount of data input into the actuator was limited; hence, shear strain was applied as a history to confirm the nonlinearity of the HDR among the random waves. The area marked in red in Fig. 5.1-5.2 was extracted and applied as an input wave.

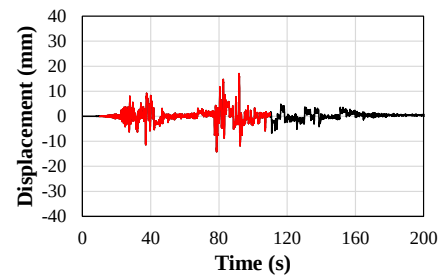
5.2 Test Program

5.2.1 Design Seismic Motion

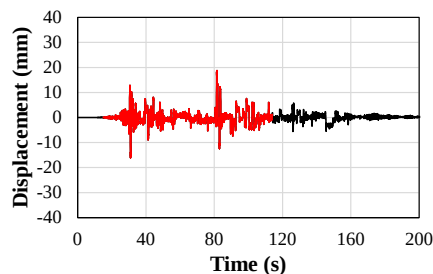
In seismic design practices in Japan, two key categories of seismic motions, known as TYPE 1 and TYPE 2, play crucial roles. The TYPE 1 seismic motion is representative of the standard seismic force specified in domestic building regulations, reflecting typical seismic conditions in specific regions. Most structures are designed with this motion in mind, serving as the basis for assessing seismic safety and earthquake resistance. On the other hand, the more formidable TYPE 2 seismic motion is employed for structures of heightened importance, such as hospitals, schools, and emergency shelters. This motion, being more powerful, ensures that these critical facilities are designed to withstand even the impact of strong earthquakes. Together, TYPE 1 and TYPE 2 seismic motions contribute to the development of resilient buildings and provide essential standards for earthquake preparedness in various structures across Japan.



(a) Case 1

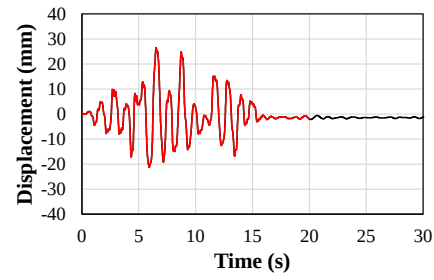


(b) Case 2

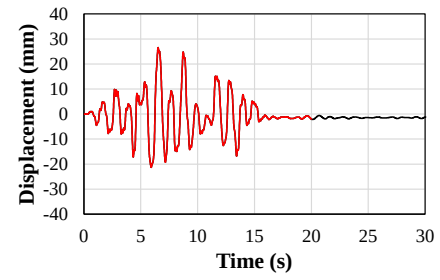


(c) Case 3

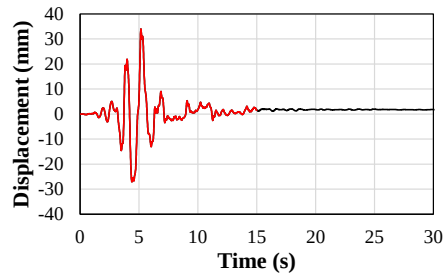
Fig. 5.1 The waveforms of the seismic wave (TYPE1)



(a) Case 1



(b) Case 2



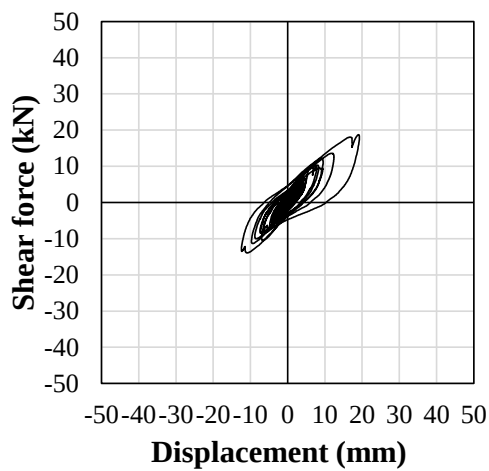
(c) Case 3

Fig. 5.2 The waveforms of the seismic wave (TYPE2)

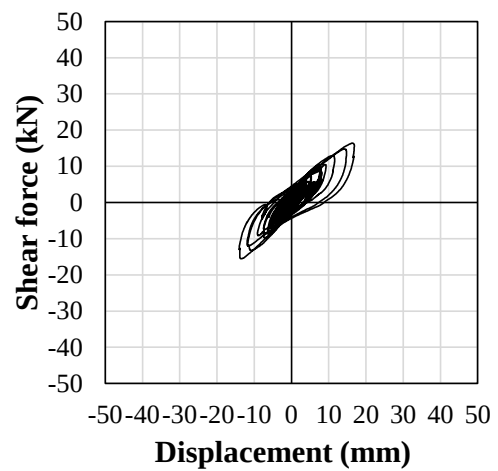
5.3 Test Result

5.3.1 TYPE1 Seismic Motion

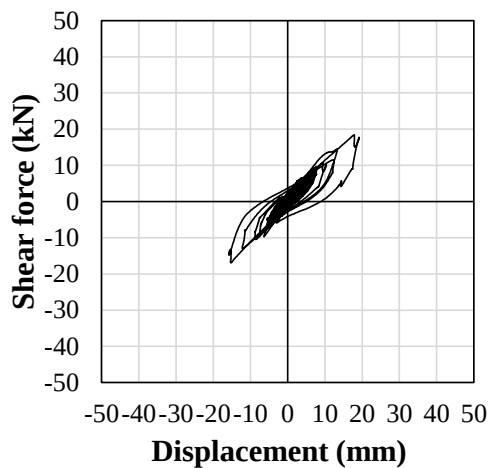
Fig. 5.3 shows Test results by TYPE1 seismic wave. It is possible to check the actual behavior of the shear deformation of the HDR specimen for each case. Through the dynamic loading test, HDR history data for a relatively small range of shear deformation was obtained.



(a) Case1



(b) Case2



(c) Case3

Fig. 5.3 Test results by TYPE1 seismic wave

5.3.2 TYPE2 Seismic Motion

Fig. 5.4 shows Test results by TYPE2 seismic wave. It is possible to check the actual behavior of the shear deformation of the HDR specimen for each case. Through the dynamic loading test, HDR history data for a relatively large range of shear deformation was obtained. In particular, the nonlinear characteristics of the HDR bearing were confirmed in TYPE2 seismic motion.

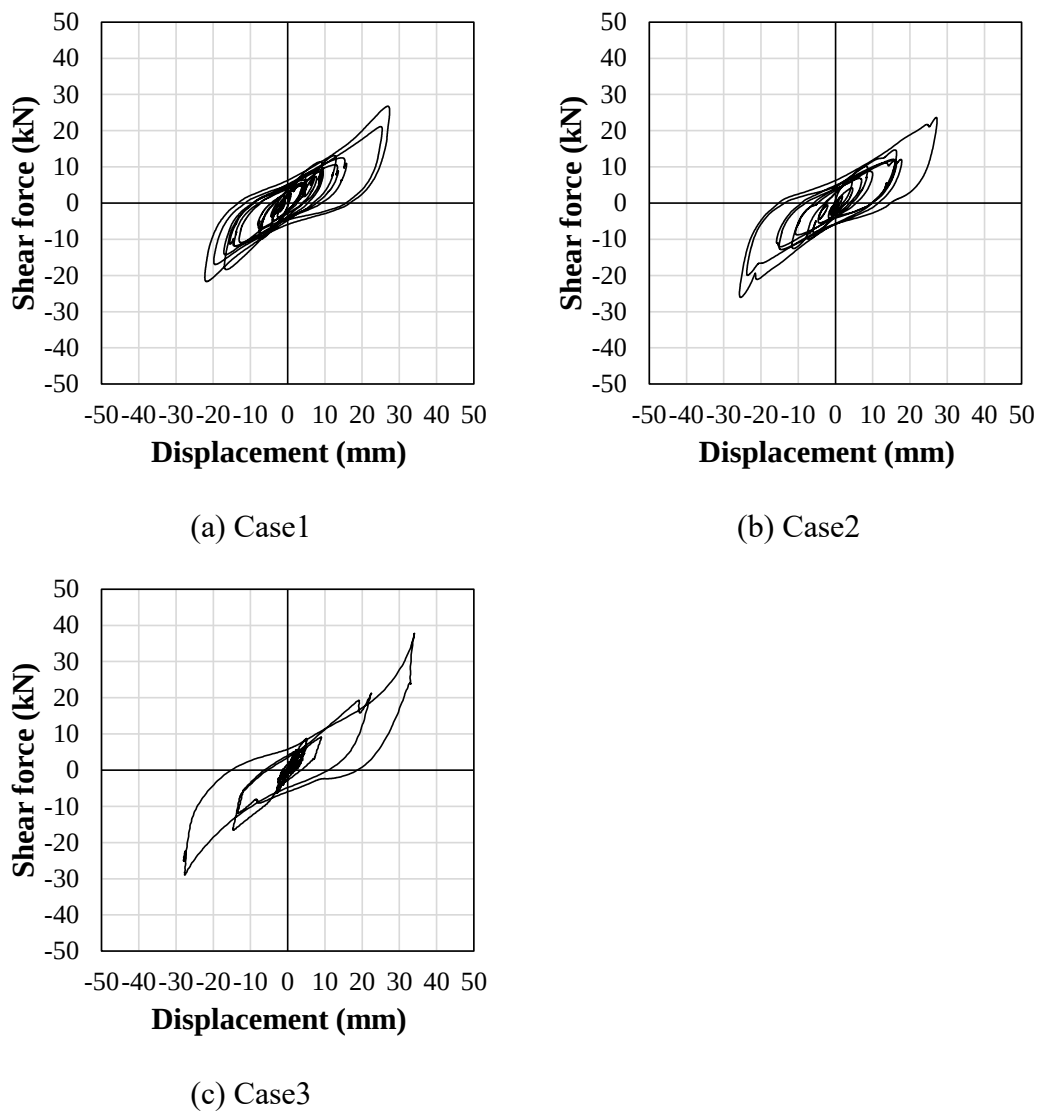


Fig. 5.4 Test results by TYPE2 seismic wave

5.4 Validation of proposed hysteresis model

5.4.1 Analytical condition

To validate the appropriateness of the proposed seismic response model, dynamic loading experiments were conducted using six cases of random waves assumed to represent design earthquake vibrations. The results of these experiments were then reproduced using the Trilinear double target model. The parameters for the seismic response model in this dynamic analysis were determined considering the dependence on the nonlinearity of the HDR bearing's shear deformation and the occurrence of hardening phenomena. Table 5.1 shows the parameters for the hysteresis model. Because the dynamic loading test conducted in this section had the same experimental conditions except for the input wave as the characteristic verification test conducted previously, the parameters of the same HDR specimen were applied. Based on the results of dynamic loading experiments with a shear strain of 250%, conducted previously, the parameters for each case were calculated. Fig. 5.5 depicts the structural model, illustrating a Single Degree of Freedom (SDOF) system. The mass of the single point is 60 kN, equivalent to the vertical load applied to the HDR specimen in the dynamic loading test. Additionally, parameters for the spring element were set based on the rubber layer and area of the HDR. Fig. 5.6 shows hysteresis model for HDR specimen. Fig. 5.7-5.8 show the waveforms of seismic waves for TYPE1 and TYPE2, respectively.

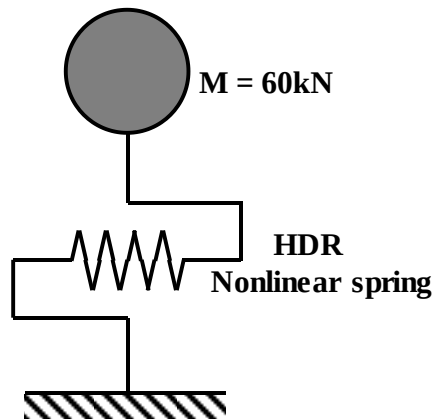


Fig. 5.5 Structural model (1-dof System)

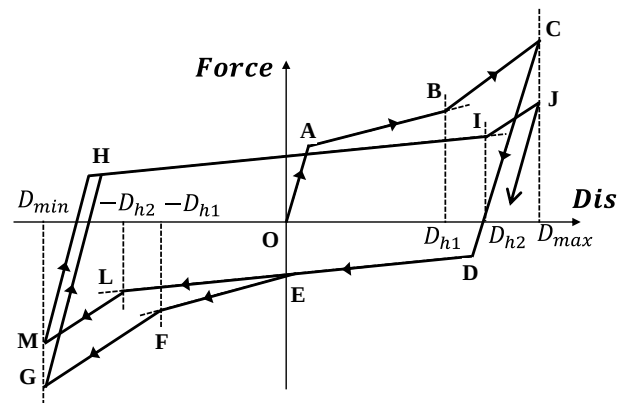
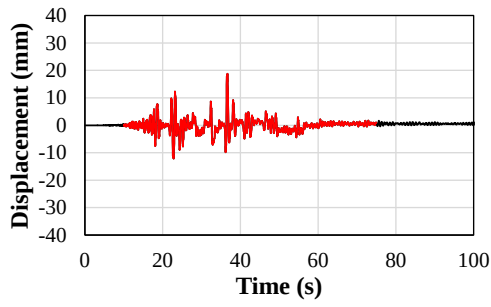


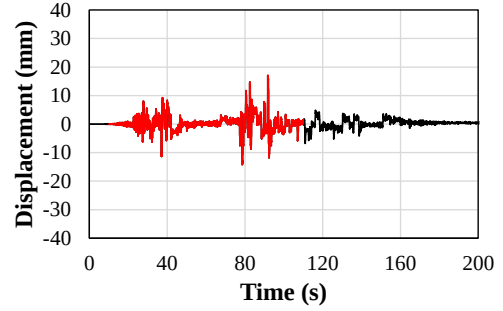
Fig. 5.6 Hysteresis model (Trilinear double target model)

Table 5.1 The parameters for the hysteresis model

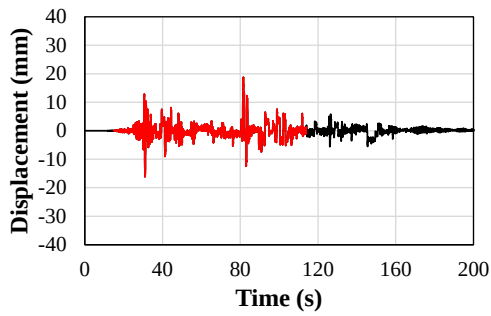
		Displacement (mm)	Shear force (kN)	Shear strain (%)	Shear stress (N/mm ²)
K0=K5	Initial stiffness	0.0	0.0	0	0.00
O-A	7016	8.0	10.1	50	1.01
K1	Secondary stiffness	8.0	10.1	50	1.01
A-B	830	20.0	16.3	125	1.63
K3	Hardening stiffness	20.0	16.3	125	1.63
B-C	1606	37.5	33.9	235	3.39
K5	Post-yield stiffness	37.5	33.9	235	3.39
C-D	7016	32.0	9.8	200	0.98
K2	Secondary stiffness	8.0	9.4	50	0.94
a-b	668	24.0	16.1	150	1.61
K4	Hardening stiffness	24.0	16.1	150	1.61
b-c	1232	37.7	26.6	236	2.66



(a) Case 1

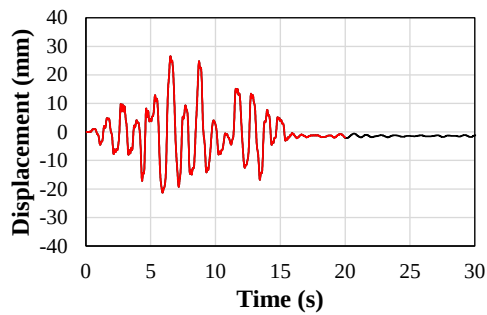


(b) Case 2

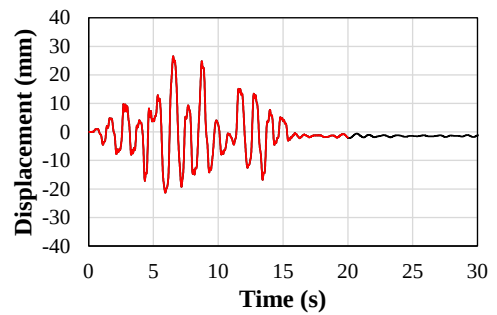


(c) Case 3

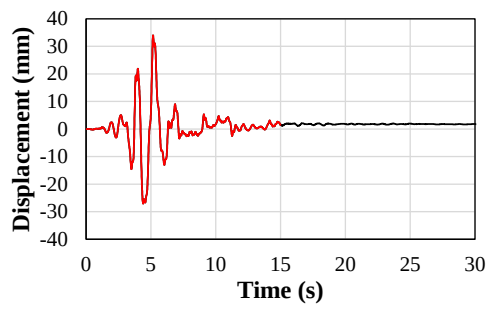
Fig. 5.7 The waveforms of the seismic wave (TYPE1)



(a) Case 1



(b) Case 2

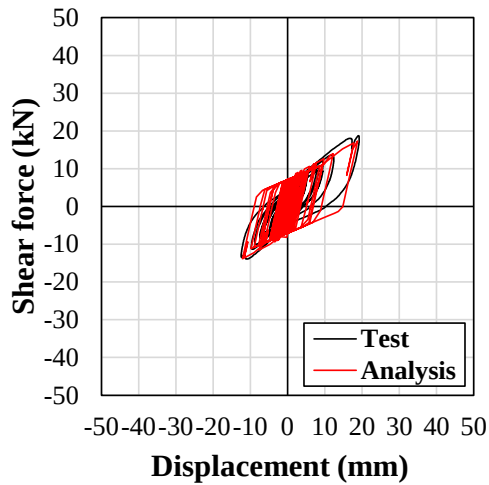


(c) Case 3

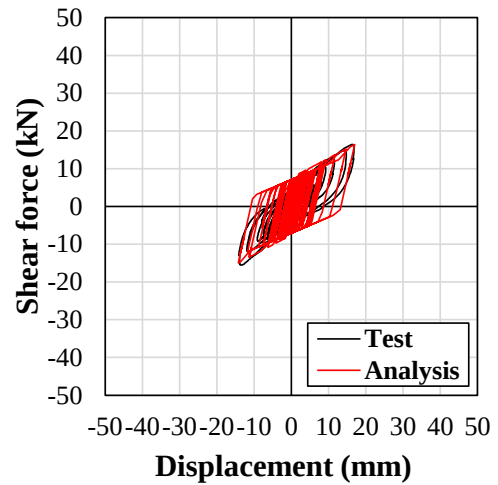
Fig. 5.8 The waveforms of the seismic wave (TYPE2)

5.4.2 Analysis results

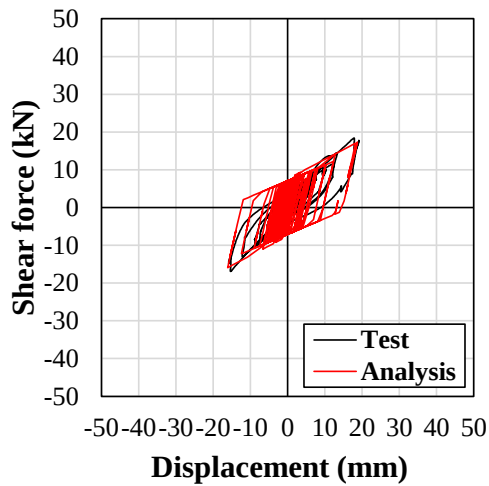
Figs. 5.9-5.10 show the analysis results of the seismic loading tests which portray the shear force-displacement curve of the HDR test specimen when a random wave assuming TYPE 1 and 2 design earthquakes was input.



(a) Case1

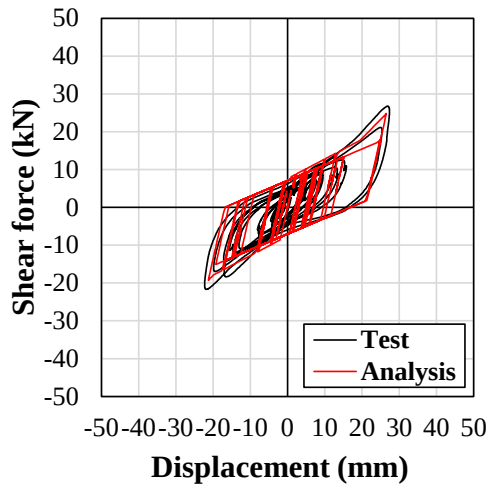


(b) Case2

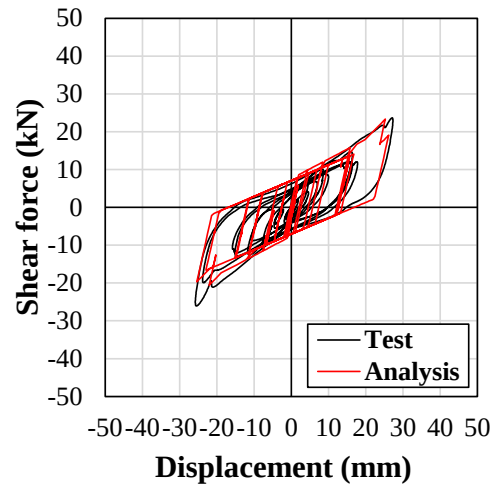


(c) Case3

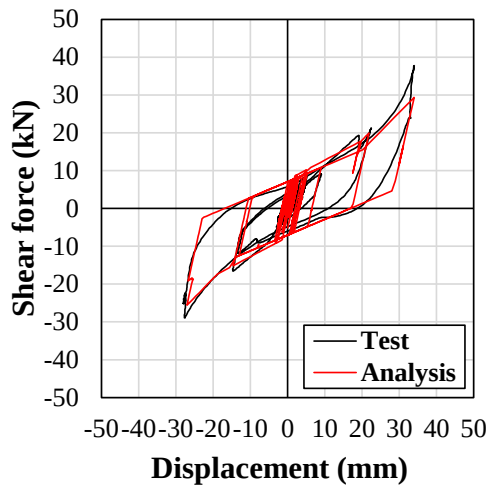
Fig. 5.9 The analysis results of TYPE1 seismic motion



(a) Case1



(b) Case2



(c) Case3

Fig. 5.10 The analysis results of TYPE2 seismic motion

5.5 Summary

This hysteresis curve closely resembles the actual behavior of the HDR during an earthquake, and the test results confirm the dependence and nonlinearity owing to the Mullins effect and hardening of the HDR. Given that the parameters of the proposed history model were tailored to a shear strain of 250%, the historical performance of a typical bilinear model becomes evident in the instance of TYPE1, characterized by a relatively modest shear strain. Conversely, for TYPE2, subjected to a shear strain of approximately 200%, analysis results similar to the actual behavior of HDR bearings were obtained.

Chapter 6

Conclusions

The dependence on the past shear deformation and hardening phenomenon of the HDR bearings was investigated by evaluating their mechanical properties based on dynamic loading tests. A trilinear double-target model considering the nonlinearities of the HDR was proposed, and an objective parameter-setting method was devised based on the experimental results. The dynamic loading tests conducted in this study experimentally confirmed the dependence on the experienced shear strain. The results showed a clear distinction between the first and subsequent cycles of the loading plan, thereby revealing that the mechanical characteristics of the HDR were such that the value of the first cycle was greater than that of the subsequent cycles. Further, the tests revealed that hardening occurred when a certain level of shear deformation was achieved. The hardening time of the first cycle was shorter than that of the subsequent cycles. These findings provide important insights into the nonlinear behavior of the HDR and highlight the need for the accurate modeling of these characteristics. An improved trilinear double-target model for the HDR that can account for both the Mullins effect and hardening phenomenon was presented in this study. Based on the experimental results, the model parameters were obtained from the hysteresis curve at 250% shear strain, wherein the nonlinear behavior of the HDR was most pronounced. With the proposed model, it is possible to accurately reproduce the dependence owing to the Mullins effect and hardening phenomenon, which is a hysteretic characteristic of the HDR.

In the Characteristic Verification Test for Dependence on shear strain of HDR, the investigation into the hysteresis behavior of HDR involved a gradual increase in shear strain, and this behavior remained consistent across all three specimens. Notably, the shear force and area of the hysteresis curve exhibited a decrease post-initial history,

attributed to the Mullins effect. Particularly noteworthy was a significant reduction in shear force during the initial shear deformation step of the HDR specimen, evident when comparing hysteresis results at 50%, 100%, and 150% shear strains for each step. Notably, the rate of shear force reduction decreased as subsequent steps progressed. The nonlinear characteristic of HDR, known as the hardening phenomenon, was confirmed at shear strains of 200% and 250%, with stiffness exhibiting a rapid increase after a shear strain of approximately 150% or more. These results underscore the HDR's dependence on shear deformation and its inherent hysteretic characteristics. The loading histories, corresponding to maximum shear strains initially applied to the specimen (50% and 100% in STEP 1, and 150% in STEP 2), were followed by subsequent histories in which similar shear strains were applied after the HDR specimen had already experienced significant shear strain. These subsequent histories comprised 50%, 100%, and 150% shear strains in STEPs 2, 3, and 4, respectively. Experimental results from initial loading histories revealed similar maximum shear forces for maximum displacements on the positive and negative sides, occurring in opposite directions. Furthermore, a decrease in maximum shear force after one cycle, attributed to the Mullins effect, occurred simultaneously on both sides. These findings suggest that dependence on shear strain is independent, with the maximum displacement on one side having no effect on the other side. Contrary to an assumption of dependent hysteresis characteristics, where the maximum displacement on one side affects the other side, the experimental results demonstrated that strain dependence in one direction had no impact in the opposite direction. Thus, it can be concluded that the dependence on shear strain is independent for HDR specimens. In the Mechanical Properties of HDR, the examination of mechanical characteristics in HDR specimens involved a thorough analysis comparing initial loading histories with subsequent histories at shear strains of 50%, 100%, and 150%.

In Mechanical Properties of HDR, the characteristics of HDR bearings were investigated based on experimental results. This chapter presents a comprehensive comparison of strain energy, equivalent stiffness, and equivalent damping ratio for shear strains of 50%, 100%, and 150%, respectively. The mechanical properties are juxtaposed with the outcomes of the dynamic loading test. Across all cases, both strain

energy and equivalent stiffness exhibited a consistent decrease as the testing steps progressed. Notably, even with similar shear strains, the mechanical properties decreased when subjected to larger shear strains. Additionally, upon comparing one and three cycles of the hysteresis curve within the same step, a discernible decrease in mechanical properties after one cycle was observed, with the value of the one cycle surpassing that of the third cycle. Regarding the equivalent damping ratio, this trend was evident only in the experimental results of a shear strain of 50%, while subsequent to that, the characteristic values of the first and third cycles showed similarity. This observation highlights a nuanced behavior in the damping ratio, distinct from the consistent trends observed in strain energy and equivalent stiffness across different shear strains.

In the Nonlinear Hysteresis Model for HDR, the Trilinear double target model is introduced, crafted to address the nonlinear hysteresis characteristics of HDR bearings. Departing from the basic bilinear model, this advanced model adeptly captures both the Mullins effect and the hardening phenomenon identified in dynamic loading tests. The dynamic analysis aims to scrutinize the efficacy of this novel model in navigating the intricate landscape of nonlinear behaviors exhibited by HDR bearings, focusing on evaluating its prowess in predictive accuracy and responsiveness. To substantiate the model's validity, the results of dynamic loading experiments are compared with meticulously calculated mechanical characteristic values from the Trilinear double target model. Employing the same sine wave input as in the dynamic loading experiment, the one-mass model of the SDOF system is simulated with spring elements embodying the distinctive characteristics of HDR bearings. The results of the analysis unveil commendable predictive accuracy of the Trilinear double target model under conditions mirroring those of the dynamic loading test. Reproducing experimental outcomes for STEP3 and STEP4 reveals an impressive level of precision, particularly evident at shear strains surpassing 150%. Remarkably, at shear strain rates of 200% and 250%, the model adeptly anticipates shear strain rate dependencies and accurately reflects the associated hardening phenomenon. A meticulous comparison of mechanical properties at a shear strain of 250% reveals substantial consistency with experimental values, robustly affirming that the Trilinear double target model serves

as an effective tool for replicating the hysteresis characteristics inherent in HDR bearings.

In the Dynamic Loading Test by Design Seismic Motion, this chapter presents the analysis results of seismic loading tests, illustrating the shear force-displacement curve of the HDR test specimen subjected to random wave inputs simulating TYPE 1 and 2 design seismic motion. The resulting hysteresis curve closely mirrors the actual behavior of the HDR during seismic events, affirming the dependence and nonlinearity attributed to the Mullins effect and hardening phenomenon in the HDR. Given that the parameters of the proposed history model were specifically calibrated for a shear strain of 250%, a discernible resemblance to the historical performance of a typical bilinear model emerges in the case of TYPE1, characterized by a relatively moderate shear strain. In contrast, for TYPE2, exposed to a shear strain of approximately 200%, the analysis yields results akin to the authentic behavior of HDR bearings during seismic loading, providing a comprehensive insight into the system's dynamic response.

Finally, the primary objective of this study was to introduce a hysteresis model capable of accurately predicting the dynamic behavior of HDR bearings, which hold considerable significance in seismic isolation systems. The investigation into the nonlinear history of HDR bearings involved a comprehensive verification experiment utilizing an HDR test specimen and a dynamic loading experiment employing random waves. Through these experiments, the mechanical properties of HDR bearings were meticulously evaluated, elucidating their pronounced dependence on shear deformation and revealing the associated hardening phenomenon. Furthermore, the Trilinear double target model was proposed, specifically designed to encapsulate the mechanical characteristics intrinsic to HDR bearings. The results from dynamic analysis and mechanical property evaluation using this proposed model not only aligned with characteristic test outcomes but also, remarkably, demonstrated accuracy in predicting random shear deformations akin to those experienced during earthquakes. This substantiates the efficacy of the Trilinear double target model in faithfully reproducing the intricate history of HDR bearings under varied conditions.

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