Mechanical hysteresis model of a metal-wire Kagome truss for seismic strengthening for building systems

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ABSTRACT
In this study, we introduce a metal-wire Kagome truss damper and investigate its mechanical properties through theoretical analyses and experimental tests. The Kagome damper had high resistance to plastic buckling and low anisotropy. We propose an equation to estimate the yield strength of the damper, which was dependent on the geometric shape and thickness of the metal wire. We conducted cyclic shear loading tests to investigate the energy dissipation capacity and stiffness/strength degradation of the damper through repeated loading. Based on the hysteretic properties revealed by the tests, we found that modification of the ideal truss model with a hinged connection could predict the yield strength and stiffness of the damper. We present a numerical example to improve the seismic performance of a five-story reinforced concrete structure by installing Kagome dampers.

1. Introduction
Earthquakes are among the most hazardous natural disasters and have frequently brought devastation to economies and human life. Although the statistical repeatability and macroscopic distribution of historic earthquakes can be predicted to a certain extent, it is impossible to predict an earthquake at a specific place or time. As occurred in a series of recent earthquakes, the destruction of building structures vividly demonstrates the severity of earthquake damage. Due to long-term experience and studies of earthquakes, it is now somewhat possible to understand their structural behaviors, including damage pattern, and significant efforts to mitigate earthquake damage have been made in the field of seismic design, especially in terms of the design of new buildings. Additionally, it is necessary to retrofit existing structures against earthquakes, and important existing structures are required to be fully operational even under severe earthquake conditions.

Inspired by such concerns, vibration control technology has been recently introduced and utilized in seismic design. The recent seismic design code separates the damping system from the earthquake-resistant system (ASCE 2010). Vibration control is a method that uses a separate structural member or device, with excellent energy dissipation capacity, to protect other structural members. Vibration control can be achieved using passive, active, and semi-active control systems applied to the external power supply, computer, and sensors. Because it may be hard to supply external energy at a stable rate during an earthquake event, passive or semi-active vibration control systems have mainly been used. Passive energy dissipation devices include fluid viscous dampers (Lee and Taylor 2002), viscoelastic dampers (Abbas and Kelly 1993), friction dampers (Wu et al. 2005), and hysteric metallic dampers (Dargush and Soong 1993), and are classified according to the intrinsic properties and energy absorption mechanisms of the materials composing the device. These dampers are further categorized as displacement- or velocity-dependent dampers, depending on the force–response relationship.

To ensure vibration control for large buildings or civil structures, the capacity or maximum force of the damper should be proportionally large. Furthermore, since most damper installation positions are limited, the damper should have high efficiency relative to its size, sufficient wide-band response performance to deal with strain from mm- to cm-level responses, and durability against fatigue caused by aging and repeated vibration.

The Kagome is a truss structure used in sandwich panels for lightweight structural applications in the machinery, shipbuilding, and aerospace industries. The Kagome is a porous structure manufactured to have periodic cells by shrinking the truss structure traditionally used in the building and civil engineering industries to the millimeter scale (Wadley, Fleck, and Evans 2003). It is known to be lighter than pyramid- or octet-type truss structures, yet has similar bending and compressive strength.
A helically shaped wire was inserted and rotated to fabricate the three-dimensional (3D) Kagome truss structure, and its wire crossing points were fixed by the method described in Kang (2011). Choi et al. (2008) and Lee et al. (2008) verified the elastic modulus and compressive strength of the Kagome truss structure by evaluating the wire diameter and pitch ratio, which are factors that affect the compressive behavior of the wire-woven Kagome truss structure (Choi, Joo, and Kang 2008; Lee et al. 2008). Lee et al. experimentally compared the compressive strength of convex- and concave-type Kagome truss structures, and Park et al. studied the effect of wire curvature on the elastic modulus and compressive strength (Lee 2009; Park 2010). Additionally, Lee et al. studied the bending behavior and strength of the wire-woven Kagome structure (Lee 2007; Lee and Kang 2008). Several studies have been conducted on the applicability of damper systems using the shear strain of the Kagome truss structure (Hwang et al. 2010; Ko et al. 2010a, 2010b).

Through previous studies, the dynamic properties of the Kagome truss structure have been identified, focusing on its compressive and bending behaviors. However, only the basic mechanisms underlying the damping caused by shear strain have been identified thus far. To further develop the Kagome damper to improve the seismic performance of building structures, a mathematical model is needed to analyze and evaluate shear hysteretic behaviors with respect to the energy absorption capacity of the damper.

In this study, we present a Kagome truss damper system for vibration control in seismically excited structures, and develop a mechanical model based on hysteretic behaviors and obtained through experimental tests. The yield shear strength, stiffness, and strain capacity were identified by theoretical analysis and experiments. A five-story reinforced concrete (RC) structure excited by earthquake was used to demonstrate the compatibility and effectiveness of the proposed Kagome damper model.

2. Metal-wire Kagome truss damper

2.1. Kagome truss structure features

The Kagome is a lattice structure formed using truss members that do not meet at a node (Figure 1(a)). The term Kagome is derived from the tri-hexagonal tiling pattern used in traditional Japanese basketry. The Kagome truss structure allows for shortening of the truss member length, while the number of members that connect at a node is small. Consequently, the Kagome resists buckling. Compared to the pyramid or octet truss, its core material is lighter, because the number of members is smaller, yet strength is similar. The Kagome damper is assembled with a helical wire in a 3D space in six directions (Figure 1(b)), and its cross-sections are fixed by brazing. The 3D Kagome truss is layered vertically. On each layer, unit cells composed of small tetrahedrons and large octahedrons are arranged continuously and periodically.

2.2. Properties of idealized shear behavior

In this section, shear elastic modulus and strength are derived theoretically using load and displacement in a simplified tetrahedron. Figure 2 illustrates the unit cell, comprising the Kagome damper and the tetrahedron resisting external load from the unit cell. $c$ denotes the length of the truss element, $d$ is the wire diameter, and $b$ is the height of the brazed joint. Assuming that the Kagome damper is an ideal truss structure, the tetrahedron composed of the straight truss element can be considered to estimate the shear force in the unit cell.

(1) Shear elastic modulus

Figure 3 illustrates the force distribution when a compressive load $Q$ and shear force $R$ are applied to the unit cell in the form of a tetrahedron. Simplifying the truss into an ideal truss, it can be assumed that $Q$ and $R$ are applied on a regular tetrahedron. The strain with respect to the load $R$ is used to derive the shear elastic modulus. If the displacement of the tetrahedron in the load direction caused by the load $R$ is $\delta R$, then stiffness can be expressed as follows:

$$ R = \frac{\pi d^2 E_w}{8c} \delta R $$

where $E_w$ is the elastic modulus of the wire. The area of the plane contained in a tetrahedron in a unit cell $A_o$ is $2\sqrt{3}c^2$, and the tetrahedron height $H_o$ is $\sqrt{2/3}c$. When the load $R$ is divided by $A_o$ and the displacement is divided by $H_o$, the shear elastic modulus $G$ in the direction $R$ can be expressed as follows:

$$ G = \frac{\sqrt{2}}{48\pi E_w} \left( \frac{d}{c} \right)^2 $$

(2) Shear strength

To determine the shear strength of the Kagome damper, assuming that the shear force $R$ is applied in the most vulnerable direction, as shown in Figure 3, the member force acting on each member is as follows:

$$ F_1 = -\frac{2}{\sqrt{3}}R, \quad F_2 = \frac{1}{\sqrt{3}}R, \quad F_3 = \frac{1}{\sqrt{3}}R $$

where the (-) sign indicates a compressive force. When the yield load of member 1, which receives the largest compressive force due to the external shear force, is divided by the planar area of the unit
The maximum shear stress can be expressed as follows:

$$R_p = \frac{\pi \sigma_y}{16} \left(\frac{d}{c}\right)^2$$  \hspace{1cm} (4)

where $\sigma_y$ is the yield strength of the wire. As expressed in Equation (4), the shear stress is determined by the length-depth ratio ($\lambda = c/d$). Using Equations (2) and (4), the shear strain of the unit cell when the yield occurs can be obtained as:

$$\varepsilon_y = \frac{3}{\sqrt{2}} \frac{\sigma_y}{E_w}$$  \hspace{1cm} (5)

When the shear force acts under the conditions shown in Figure 3, yield occurs on the member, as shown in Equation (4); however, the unit cell continues to maintain the tensile force through the two

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**Figure 1.** Kagome truss structures and the three-dimensional (3D) form. (a) Comparison of general truss structure and Kagome structure. (b) Production of the 3D Kagome truss structure [10].

**Figure 2.** Shape of the Kagome damper unit cell [13]. (a) Unit cell. (b) Tetrahedron.
remaining truss members. Therefore, after one member yields, the force–displacement relationship is expected to have a bilinear form.

3. Cyclic loading tests

In Section 2.2, all of the moduli representing the shear behavior of the damper are derived based on the elastic behavior of an idealized tetrahedron with length $c$. Factors such as the wire curvature and brazed joint height are not considered. The actual hysteretic behavior and strength of the Kagome damper can be obtained experimentally. The theoretically obtained stress–strain relationship of the Kagome damper is compared with the experimental result. Small-scale Kagome dampers were produced as shown in Figure 4.

Table 1 lists the specifications of the damper, including the thickness of the wire from which it was constructed. Three thicknesses of wire (0.7 mm, 0.9 mm, and 1.2 mm) were used. The wire material was wrought steel (SS400). The dimensions of the truss structure were $150 \times 150 \times 60$ mm and the weight without the top and bottom plates was 0.4 kg. Figure 5 shows the set-up of the shear loading tests on the Kagome damper. Displacement was controlled and the restoring force of the damper measured.

3.1. Shear hysteretic behavior

Figure 6 shows the time histories of load and displacement obtained from the experiment on the Kagome damper with a 1.2-mm thick wire. At the same displacement, three cycles were repeated and the maximum displacement was 10 mm, which corresponded to 20% of the shear strain of the Kagome damper. The duration time of each triangular waveform was 20 seconds and the sampling frequency was 10 Hz. Load increased with increasing displacement, to a maximum of 4 mm (8% strain), and the load then reached the maximum level of approximately 17–18 kN, after which it did not increase with increasing displacement of up to 7 mm. The load began to drop at 8 mm displacement and partial damage to the wire was then observed. At 10 mm of displacement (20% strain), the strength of the damper decreased to approximately 70% of the maximum strength.

Figure 7 shows the stress–strain curve for the damper, obtained using the measured load and displacement shown in Figure 6. We observed that the

![Figure 3. Ideal Kagome equivalent structures [13].](image1)

![Figure 5. Kagome damper shear loading test. (a) Test set-up. (b) Shear behavior of Kagome damper.](image2)

![Table 1. Specifications of the Kagome damper specimen.](table1)

| Item                              | Value                  |
|----------------------------------|------------------------|
| Wire thickness ($d$)              | 0.7 mm, 0.9 mm, and 1.2 mm |
| Helical wire pitch ($2c$)         | 16.2 mm                |
| Strut length of unit cell ($c$)   | 8.1 mm                 |
| Planar area of unit cell          | 227.28 mm²             |
| ($A_0 = 2\sqrt{3}c^2$)            |                        |
| Unit cell quantity                | 110 pieces             |
| Tetrahedron height                | 6.61 mm                |
| ($H_0 = \sqrt{2/3}c$)             |                        |
| Material                          | Wrought steel (SS400)   |
| Dimensions of top and bottom plates | $200 \times 200 \times 5$ mm |
| Core material size                | $200 (B) \times 150 (D) \times 50$ mm (0.4 kg) |
| Unit cell quantity                | 110 pieces             |
| Tetrahedron height                | 6.61 mm                |
| Material                          | Wrought steel (SS400)   |
| Dimensions of top and bottom plates | $200 \times 200 \times 5$ mm |
| Core material size                | $200 (B) \times 150 (D) \times 50$ mm (0.4 kg) |

![Figure 4. Kagome damper specimen.](image3)
Kagome damper had bilinear hysteretic characteristics typical of steel dampers. The area of the damper used to convert the load to stress was not the superficial area listed in Table 1, but rather the effective area derived by the product of the number of unit cells and the area occupied by each unit cell. The effective area was corrected by the area loss generated from the displacement of the unit cell, as follows:

\[
n_e = \frac{BD}{A_o} - \frac{B}{2c} - \frac{D}{\sqrt{3}c} + 1 ,
\]

where \( n_e \) is the number of unit cells, \( B \) is the damper width, and \( D \) is the damper depth. The damper width \( B \) indicates the length of the damper in the direction perpendicular to that of the shear force \( R \). The effective area of the damper can be expressed as:

\[
A_e = n_e A_o = n_e 2\sqrt{3}c^2
\]

Table 2 lists the elastic modulus and strength obtained from the tests using Kagome dampers with different wire thicknesses. To obtain the simple bilinear model, the equivalent elastic modulus, \( E_e \), was calculated using the secant modulus to the actual yielding point. The average value of \( E_e \) was 59% of the elastic modulus of the idealized model, \( E_o \), in Equation (2). The elastic modulus, \( E_o \), was calculated assuming the secant modulus to the yielding point in the bilinear model was approximately 6.3% of \( E_o \).

The average maximum strength \( f_u \) was 92% of that of the ideal model, \( f_o \), in Equation (4).

The difference between the experimental and analytical ideal model results was due to the fact that the ideal model did not consider the wire curvature or strength drop due to brazing. Table 2 shows the averaged elastic modulus ratio after yielding. This averaged value is to be used in the mathematical model of the Kagome damper.

### 3.2. Strength degradation due to repeated loading

The damper can be excited by repeated loading by increasing factors during an earthquake event. The steel Kagome damper can be heated by repeated vibration, leading to detachment of the wire of the

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**Table 2.** Elastic modulus and strength according to wire thickness.

| Wire diameter (d) | Shear elastic modulus (MPa) | Shear strength (MPa) | Elasticity ratio (test) |
|-------------------|-----------------------------|----------------------|------------------------|
|                   | Theoretical (E_o) | Test | Theoretical (f_o) | Test | Theoretical (f_s) | Test | f_y | f_s | f_o | Average: 0.0089 |
| 0.7               | 8.1                | 138.3 | 185.0 | 0.34 | 0.31 | 0.17 | 0.21 | 0.8 | 1.4 |
| 0.9               | 8.1                | 228.5 | 145.5 | 0.57 | 0.61 | 0.29 | 0.38 | 1.3 | 1.7 |
| 1.2               | 8.1                | 406.3 | 205.8 | 1.01 | 0.80 | 0.35 | 0.51 | Average: 0.0825 |

\[
\alpha_1 = \frac{E_e}{E_o} = 59\%
\]

\[
\alpha_2 = \frac{E_h}{E_o} = 6.3\%
\]

\[
\beta_1 = \frac{f_u}{f_o} = 92\%
\]

\[
\beta_2 = \frac{f_y}{f_o} = 45\%
\]

\[
\beta_3 = \frac{f_s}{f_o} = 60\%
\]
damper and damage due to fatigue. Therefore, the damper should have adequate durability against repeated loading, such that stable performance may be expected.

We conducted a repeated loading test using the Kagome damper with a 1.2-mm thick wire. The displacement measured when the damper wire began to fall off after passing the plasticity phase was designated as the maximum displacement (Figure 7; approximately 15% of the strain rate) and the loading frequency was 0.5 Hz. Figure 8 shows the graph of displacement and load for the damper with respect to time.

In Figure 8, note that the strength degraded gradually as the wire began to fall off from 25 repeated vibration cycles, and it dropped to half of the maximum force at 40 cycles. This result implies that the Kagome damper functions well even if some wires are partially damaged. Considering that the repeated maximum displacement causing plastic deformation would be smaller during an actual earthquake load, the Kagome damper is expected to exhibit stable seismic response control performance.

Figure 9 shows the stress–strain hysteretic curve converted from the time histories shown in Figure 8.

The hysteretic curve under the sine excitation is similar to the maximum stress shown in Figure 7. From the experimental tests, we observed that strength degradation began as the wire slowly fell off, and the hysteretic curve deformed accordingly.

### 3.3. Mathematical model of the Kagome damper and a numerical example for seismic retrofitting of building structures

A mathematical model of the Kagome damper is required during the design procedure to improve the seismic performance of existing structures. Mathematical models of Kagome dampers can be divided into three categories: the theoretical equation-based model (KDM1), the shear stress-strain model obtained from the hysteretic curve (KDM2), and the simplified bilinear model (KDM3). KDM2 and KDM3 can be derived from KDM1. The maximum ultimate strain of the damper (εu) should be specified and the elasticity ratio, strength ratio, and post-yield stiffness ratio (Table 2) should be determined. Table 3 lists the parameters for these three models. All of the KDM2 and KDM3 variables are based on the theoretical elastic moduli and yield strengths given by Equations (2) and (4). Therefore, if the experimental values, such as the elasticity ratio and stiffness ratio (Table 2) are provided, mathematical models of the Kagome damper can be constructed.

Numerical analysis was conducted to evaluate the seismic performance of the Kagome damper, and to compare performance between the three mathematical models. The model structure was a five-story pilot structure, as shown in Figure 10. Only the transverse (Y) directional response was considered. Chevron-type braces were installed on the pillar array in the Y direction, and dampers were located between the tops of the braces and the beam center on the first floor. To consider the behavior of each mathematical model separately, we assumed that the stiffness of the brace was sufficiently high to not interact with the mathematical models of the Kagome damper.

The length of the damper was 1 m in the Y direction; its width was 0.3 m, and its height was 0.14 m. We set the Kagome damper to 0.14 m so that the shear strain of the damper would be less than 15%.

### Table 3. Parameters of the three Kagome damper models

| Model | Parameter |
|-------|-----------|
| KDM1  | $f_u$ from Equation (4), $E_0$ from Equation (2), $\varepsilon_u = f_u/E_0$ |
| KDM2  | $f_u = \beta f_0$, $E_u = \alpha E_0$, $\varepsilon_u = (\beta/\alpha)\varepsilon_0$ |
| KDM3  | $f_u = \beta f_0$, $E_u = \alpha E_0$, $\varepsilon_u = 0.15$ |
| Point | $f_u = \beta f_0$, $E_u = \alpha E_0$, $\varepsilon_u = (\beta/\alpha)\varepsilon_0$ |
| H     | $f_u = \varepsilon_u$, $E_u = \beta \varepsilon_u$ |

![Figure 8. Time hysteresis of the Kagome damper under repeated load.](image)

![Figure 9. Hysteresis profile of the Kagome damper under repeated loading.](image)
because the maximum first-floor displacement of the structure without the damper was expected to be 20 mm, which would cause approximately 15% strain of the damper with a 0.14-m height. Table 3 lists the damper parameters, including the elasticity ratio and strength ratio for the three models. The elasticity ratio and the strength ratio were conservatively set to 90% of the averaged value shown in Table 2.

We used the commercial structural analysis program MIDAS Gen, provided by Midas Company, Korea, and the Bouc-Wen model (Wen 1976) to model the Kagome damper, as follows:

\[
F_{\text{damper}} = rKd + (1 - r)f_yz
\]

\[
z = \left[1 - \left|z\right|\alpha \sgn(dz) + \beta\right]d
\]

(8)

where \( r \) is the elasticity ratio, \( K \) is initial stiffness, \( f_y \) is yield strength, and \( z \) is a variable to model non-linear hysteretic behavior. Parameter \( s \) determines the smoothness around the yielding point of the hysteretic curve (a larger \( s \) value induces sharper variation). \( \alpha \) and \( \beta \) are constants dependent on the overall shape of the hysteretic curve. Table 4 lists the building properties. Table 5 lists the values of the modeling parameters used in the numerical example.

Table 6 shows the control results obtained using the three models. As expected, the ideal model was KDM1, having the largest energy absorption capacity and the largest reduction effect on relative displacement at the first floor and base shear force. The simplest bilinear model, KDM3, appeared to have the lowest reduction effect, and KDM2, whose hysteretic curve was quite similar to that of the actual Kagome damper, had a response reduction performance between those of KDM1 and KDM3.

Figure 12 illustrates the hysteretic curves obtained using the three models of the Kagome damper of dimensions 1000 \( \times \) 300 \( \times \) 140 mm. Because the yielding exponent value \( s \) was set to ‘1’ to express non-linear yielding behavior, KDM2 exhibits smooth hysteretic behavior. All models behaved within the maximum shear strain. KDM1 absorbed energy by maintaining maximum strength even when responses

**Table 5.** Kagome damper modeling parameters.

| Item                  | Component | Value |
|-----------------------|-----------|-------|
| Kagome truss structure| Wire thickness (\( d \)) | 1.2 mm |
|                       | Strut (\( c \)) | 8.1 mm |
|                       | Material   | 55400 |
| Damper size           | Length (\( b \)) | 1000 mm |
|                       | Width (\( e \)) | 300 mm |
|                       | Height (\( H \)) | 140 mm |
| KDM1                  | Shear elastic modulus (\( E_s \)) | 406.3 MPa |
|                       | (stress–strain intensity) | 1.01 MPa |
|                       | Yield strength (\( e_y \)) | 0.25% |
|                       | Elasticity ratio | 0.53 |
|                       | \( \alpha \) | 0.057 |
|                       | \( \beta \) | 0.8 |
|                       | \( \beta_1 \) | 0.4 |
|                       | \( \beta_2 \) | 0.55 |
|                       | Post-stiffening elasticity ratio | 0.0089 |
|                       | \( \gamma \) | 0.0825 |
| Damper moduli         | Area (A=BD) | 300,000 mm\(^2\) |
| KDM1                  | Stiffness \( K_1 = E_sA/H \) | 870.6 kN/mm |
|                       | Elasticity ratio after stiffening | 0 |
|                       | Yielding exponent (\( s \)) | 10 |
| KDM2                  | Initial stiffness \( K_2 = E_sA/H \) | 614.4 kN/mm |
|                       | Yield strength \( f_y \) | 154.0 kN |
|                       | Maximum strength \( P_y = \beta P_f \) | 240 kN |
|                       | \( \gamma \) | 0.0089 |
|                       | Yielding exponent (\( s \)) | 1 |
| KDM3                  | Initial stiffness \( K_3 = E_sA/H \) | 49.63 kN/mm |
|                       | Yield strength \( P_y = \beta P_f \) | 166.7 kN |
|                       | Maximum strength \( P_y = \beta P_f \) | 240 kN |
|                       | Elasticity ratio after stiffening | 0.0825 |
|                       | Yielding exponent (\( s \)) | 10 |

*On calculation of the yield strength, the strength was set to point \( H \), as shown in Figure 11, was used to consider the non-linear section between points \( C \) and \( D \) by selecting the yielding exponent 1.

**Table 6.** Control results.

| Damper size (mm) | Mathematical model | Relative displacement at first floor | Base shear force |
|------------------|--------------------|-------------------------------------|-----------------|
| Size             | Disp (mm) | Rate (%) | Shear force (kN) | Rate (%) |
| No control       | - | 19.634 | - | 6959 | - |
| \( B = 750 \)    | KDM1       | 8.639 | 56.0 | 4538 | 34.8 |
| \( D = 200 \)    | KDM2       | 11.422 | 41.8 | 4665 | 33.0 |
| \( D = 300 \)    | KDM3       | 13.831 | 31.8 | 5907 | 15.1 |

Base shear force

1. **Figure 10.** Target structure and damper installation overview.

2. **Figure 11.** Base shear force and control results.

3. **Table 4.** Building properties.

| Structure type | 5-story reinforced concrete pilot building |
|----------------|------------------------------------------|
| Behavior property | Translational and rotational modes in the Y direction |
| Period in the Y direction | 0.419 s |
| First-story height | 2.8 m |
| First-story column size | 400 \( \times \) 400 mm |
| Damper size | 4 dampers installed at tops of chevron braces in the Y direction |

4. **Table 5.** Kagome damper modeling parameters.

| Item                  | Component | Value |
|-----------------------|-----------|-------|
| Kagome truss structure| Wire thickness (\( d \)) | 1.2 mm |
|                       | Strut (\( c \)) | 8.1 mm |
|                       | Material   | 55400 |
| Damper size           | Length (\( b \)) | 1000 mm |
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| KDM1                  | Shear elastic modulus (\( E_s \)) | 406.3 MPa |
|                       | (stress–strain intensity) | 1.01 MPa |
|                       | Yield strength (\( e_y \)) | 0.25% |
|                       | Elasticity ratio | 0.53 |
|                       | \( \alpha \) | 0.057 |
|                       | \( \beta \) | 0.8 |
|                       | \( \beta_1 \) | 0.4 |
|                       | \( \beta_2 \) | 0.55 |
|                       | Post-stiffening elasticity ratio | 0.0089 |
|                       | \( \gamma \) | 0.0825 |
| Damper moduli         | Area (A=BD) | 300,000 mm\(^2\) |
| KDM1                  | Stiffness \( K_1 = E_sA/H \) | 870.6 kN/mm |
|                       | Elasticity ratio after stiffening | 0 |
|                       | Yielding exponent (\( s \)) | 10 |
| KDM2                  | Initial stiffness \( K_2 = E_sA/H \) | 614.4 kN/mm |
|                       | Yield strength \( f_y \) | 154.0 kN |
|                       | Maximum strength \( P_y = \beta P_f \) | 240 kN |
|                       | \( \gamma \) | 0.0089 |
|                       | Yielding exponent (\( s \)) | 1 |
| KDM3                  | Initial stiffness \( K_3 = E_sA/H \) | 49.63 kN/mm |
|                       | Yield strength \( P_y = \beta P_f \) | 166.7 kN |
|                       | Maximum strength \( P_y = \beta P_f \) | 240 kN |
|                       | Elasticity ratio after stiffening | 0.0825 |
|                       | Yielding exponent (\( s \)) | 10 |

*On calculation of the yield strength, the strength was set to point \( H \), as shown in Figure 11, was used to consider the non-linear section between points \( C \) and \( D \) by selecting the yielding exponent 1.

5. **Table 6.** Control results.

| Damper size (mm) | Mathematical model | Relative displacement at first floor | Base shear force |
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| Size             | Disp (mm) | Rate (%) | Shear force (kN) | Rate (%) |
| No control       | - | 19.634 | - | 6959 | - |
| \( B = 750 \)    | KDM1       | 8.639 | 56.0 | 4538 | 34.8 |
| \( D = 200 \)    | KDM2       | 11.422 | 41.8 | 4665 | 33.0 |
| \( D = 300 \)    | KDM3       | 13.831 | 31.8 | 5907 | 15.1 |

Base shear force

6. **Figure 12.** Illustrates the hysteretic curves obtained using the three models of the Kagome damper of dimensions 1000 \( \times \) 300 \( \times \) 140 mm. Because the yielding exponent value \( s \) was set to ‘1’ to express non-linear yielding behavior, KDM2 exhibits smooth hysteretic behavior. All models behaved within the maximum shear strain. KDM1 absorbed energy by maintaining maximum strength even when responses
were small. Conversely, KDM3 had a relatively large elastic range and absorbed the least energy. The dissipated energy was calculated based on the hysteretic curves shown in Figure 12, as:

$$E_D = \int_0^T F(x)dx = \int_0^T F(t)\dot{x}(t)dt$$  \hspace{1cm} (9)

where $F(t)$ is the damper force, $\dot{x}(t)$ is the damper velocity, and $T$ is the earthquake duration.

The results shown in Table 7 indicate that the larger damper absorbed greater energy. However, the energy absorption was not linearly proportional to area. The smaller damper exhibited smaller strength, but experienced larger relative displacement. Consequently, the yield strength of the Kagome damper can be optimally determined by considering both the maximization of energy absorption and the minimization of the structural response.

Energy absorption by KDM2 and KDM3 were approximately 80% and 65% of that of KDM1, respectively. KDM3, used for the simplicity of the mathematical model, was inefficient in absorbing energy because its elastic range was set to longer than that of the actual damper. Whereas the elasticity ratio $\alpha_1$ and the yield ratio $\beta_2$ and $\beta_3$ of KDM2 were approximately half those of the idealized model KDM1, it had higher energy absorption.

Figure 11. Mathematical model profile and variable definition.

Figure 12. Kagome damper hysteresis.

| Damper size | Model | Total $10^4$ (kN mm) | Ratio to KDM1 (%) |
|-------------|-------|----------------------|-------------------|
| $B = 750$ D = 200 | KDM1 | 6.21 | 100 |
|             | KDM2 | 4.94 | 79.55 |
|             | KDM3 | 3.90 | 62.80 |
| $B = 1000$ D = 200 | KDM1 | 6.90 | 100 |
|             | KDM2 | 5.60 | 81.16 |
|             | KDM3 | 4.52 | 65.51 |
| $B = 1000$ D = 300 | KDM1 | 7.74 | 100 |
|             | KDM2 | 6.21 | 80.23 |
|             | KDM3 | 5.30 | 68.48 |
efficiency than KDM3. Since the yield strain of KDM2 was nearly identical to that of the ideal model, its energy absorption efficiency appeared high even within the small range of displacement. KDM2 was able to similarly reproduce the actual behavior of the Kagome damper by controlling the elasticity ratio and the yield ratio of the ideal model.

4. Conclusion

In this study, we presented a Kagome truss damper and identified its hysteretic behaviors experimentally. The hysteretic properties extracted from the experiments were compared to those of the ideal truss model and the damper parameters were modified for implementation of the simplified mathematical model. The elastic modulus and yield strength were smaller than those of the ideal model, due to the decreased wire strength caused by wire curvature and braiding. Three mathematical models were constructed. The first model was based on ideal truss behavior; the second was constructed by modifying the parameters of the ideal model, such as the elasticity ratio, strength ratio, and post-yield stiffness ratio. The third model was a simple bilinear model.

To verify the seismic response control performance of the Kagome damper and the effectiveness of the mathematical models, numerical analyses were conducted using a five-story piloti building structure excited by earthquake. The Kagome damper efficiently reduced the first-story displacement of the piloti structure and the base shear force. The ideal model provided the highest response control performance, but did not consider the degradation of the strength and elasticity of the actual Kagome damper. The simple bilinear model exhibited the lowest control performance, and the model with a hysteretic curve similar to that of actual Kagome damper had a response reduction performance between those of the ideal and bilinear models.

In the cycling loading tests, the Kagome damper maintained its strength sufficient to perform stably during an earthquake. Since the Kagome damper is composed of numerous wires, the function of the damper did not change even if some wires were partially damaged. The Kagome truss structure can be designed to have high shear strain and strength by adjusting the area, height, and diameter of the wire.

References

Abbas, H., and J. M. Kelly. 1993. A Methodology for Design of Viscoelastic Dampers in Earthquake-Resistant Structures. Report No. UCB/ERDC 93/09. Berkeley, CA: Earthquake Engineering Research Center, University of California at Berkeley.

ASCE. 2010. Minimum Design Loads for Buildings and Other Structures. ASCE/SEI7-10, 179–198.

Choi, J.-E., J.-H. Joo, and K.-J. Kang. 2008. “Effect of Wire Diameter to Pitch Ratio on Mechanical Behavior of Wire-Woven Bulk Kagome Truss PCMs under Compression.” In Proceedings and Papers from the Spring Symposium on Material and Destruction Areas of the Korean Society of Mechanical Engineers, 416–421.

Dargush, G. F., and T. T. Soong. 1995. ‘Behaviour of Metallic Plate Dampers in Seismic Passive Energy Dissipation Systems.” Earthquake Spectra 11: 545–568. doi:10.1193/1.1585827.

Hwang, J.-S., J.-H. Kim, K.-J. Kang, and G. D. Ko. 2010. “3D Wired Porous Damper Utilized Vibration Control, Proceedings of the Fall Workshop.” Korean Society of Earthquake Engineers.(September): 449–473.

Kang, K.-J. 2011. Development of Production Technology of Truss Type Periodic Cellular Metal. National Designated Laboratory Project, Korea Science and Engineering Foundation, April 2006 - November.

Ko, G.-D., J.-H. Joo, J.-S. Hwang, and K.-J. Kang. 2010a. Application of Wire-Woven Bulk Kagome as an Anti-Seismic Damper.” In Proceedings and Papers from the Fall Symposium 2010 of the Korean Society of Mechanical Engineers, 221–226. November.

Ko, G.-D., J.-H. Joo, J.-S. Hwang, and K.-J. Kang. 2010b. Application of Wire-Woven Bulk Kagome as a Vibration Control Device for a Building Structure, SB10.

Lee, B.-K., J.-E. Choi, I. Jeon, and K.-J. Kang. 2008. “Analysis of Compressive Characteristics of Wire-Woven Bulk Kagome.” Journal of the Korean Society of Mechanical Engineers, Part A 32: 70–76. doi:10.3795/KSME-A.2008.32.1.070.

Lee, D., and D. P. Taylor. 2002. “Viscous Damper Development and Future Trends.” The Structural Design of Tall Buildings 10: 311–320. doi:10.1002/tal.188.

Lee, M.-J. 2009. “Compressive Characteristics of Two New Types of Periodic Cellular Metals.” Master’s Thesis, Graduate School, Chonnam University, August.

Lee, Y.-H. 2007. Mechanical Behaviors of Bulk Kagome Truss PCMs Woven of Metal Wires, Master Thesis. Chonnam National University. February.

Lee, Y.-H., and K.-J. Kang. 2008. “An Optimal Design of Sandwich Panels with Wire-Woven Bulk Kagome Cores.” Journal of the Korean Society of Mechanical Engineers, Part A 32: 782–787. doi:10.3795/KSME-A.2008.32.9.782.

Park, J.-S. 2010. “Failure Mechanism of Wire-Woven Truss PCM (Periodic Cellular Metal).” Master’s Thesis, Graduate School, Chonnam University, February.

Wadley, H. N. G., N. A. Fleck, and A. G. Evans. 2003. “Fabrication and Structural Performance of Periodic Cellular Metal Sandwich Structures.” Composites Science Technology 63: 2331–2343. doi:10.1016/S0266-3538(03)00266-5.

Wen, Y. K. 1976. “Method for Random Vibration of Hysteretic Systems.” Journal of the Engineering Mechanics Division, Proceedings of ASCE 102 (2), 249–263.

Wu, B., J. Zhang, M. S. Williams, and J. Ou. 2005. “Hysteretic Behaviour of Improved Pall-Typed Frictional Dampers.” Engineering Structures 27: 1258–1267. doi:10.1016/j. enstruct.2005.03.010.

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