Experimental Study on the Mechanical Behavior and the Feasibility of Monitoring of Building Frames with Steel Knee Brace

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Abstract. After a seismic disaster, building damage assessment is conducted by experts to confirm the safety of building. However, field surveys take a long time and have problems with the quality and safety of the survey. In recent years, to solve these problems, structural health monitoring (SHM), which can diagnose buildings from a distance, is in practical use. Previous study proposed a damage evaluation method focusing on the thermal characteristics caused by elastic-plastic deformation of steel members.

This study focuses on the heat generation characteristics of steel and suggests the monitoring system for damage detection using steel knee brace. By using the knee brace as sacrificial members, the system can be easily replaced and reused after a disaster. And it allows retrofitting to buildings. In this paper, we aim to establish a damage evaluation system based on the relationship between the kinematic mechanism of steel knee brace and the deformation of the framework, and we have conducted static loading experiments with the knee brace attached to the framework to investigate the feasibility of the damage evaluation method.

As a result, it was found that the story drift angle of the framework can be calculated from the deformation of the steel knee brace. It is also shown that the story drift angle of the framework and the damage evaluation of the members are possible from the plastic absorption energy of the knee brace.

Keywords: Steel framed structure, Seismic disaster, Structural health monitoring, Internet of Things, Plastic heat generation characteristics, Story drift angle

1 Introduction

This paper investigates the feasibility of the damage evaluation method using the steel knee brace by conducting static loading tests of frames with steel knee brace attached.

In regions such as Japan, large earthquakes often occur and cause serious damage to the structural components of buildings, so it is necessary to confirm the safety of buildings as soon as possible. In Japan, for example, damage assessments are conducted by experts. However, field surveys require a lot of time and manpower, and the quality and safety of the surveys are also problematic. In recent years, Structural Health Monitoring (SHM) using accelerometers and other devices is being put to practical use, but it is difficult to determine which members in a layer have been damaged.

Therefore, the practical studies have been conducted to realize remote diagnosis using IoT targeting the component level. The previous study proposed a damage evaluation method focusing on the plastic heating of steel members, and experimental and analytical investigations were conducted on steel frames.[1] Damage assessment by temperature measurement is superior in that it can be expected to solve issues such as power saving and securing power sources during disasters by using thermoelectric devices that convert thermal energy into electrical energy. A monitoring method using steel knee braces was also proposed for steel frames covered with interior and exterior materials and paint films.[2]

The Building Standard Law of Japan requires earthquake resistance to protect human lives, and it is insufficient for maintaining the functionality of buildings after an earthquake disaster. Then, in recent years, a design method called "performance-based seismic design" has been developed to consider cost and the seismic performance after a disaster. One of the numerical evaluation criteria is the story drift angle.

This study aims to develop a damage evaluation system based on the relationship between the kinematic mechanism of steel knee braces and the deformation of their frames. The knee brace can be retrofitted to the building and can be replaced after a disaster by using it as a sacrificial component. It is also considered to have little effect on seismic resistance and architectural space. However, when the knee brace is subjected to cyclic loading, unstable deformation due to buckling occurs, which affects the measurement and damage evaluation. Therefore, a steel member is used as the core material and covered with wood to make a knee brace constrained buckling.

2 Outline of Damage Evaluation Methods

2.1 General Description of Damage Evaluation Methods

The flow of damage evaluation method is shown in Fig. 1. Using the kinematic mechanism of the knee brace and the frame, we propose an SHM based on the story drift angle of the building frames. In addition, focusing on heat generation characteristics associated with damage of steel members, the plastic deformation of the steel knee brace is calculated from temperature measurement. Then, we estimate the story drift angle of building frames and evaluate the damage of the members. Damage assessment by temperature measurement is superior in that it can be expected to solve issues such as power saving and securing power sources during disasters by using thermoelectric devices that convert thermal energy into electrical energy.

Figure.1 shows the flow of the damage evaluation method proposed in this study. In this paper, the feasibility of III to V is discussed. The detailed procedure is described in III to V below.

III. Estimation of knee brace deformation

The knee brace deformation per each half cycle is estimated from the absorbed energy by assuming the restoring force characteristics of the knee brace.

IV. Estimation of the strain amplitude, Damage evaluation by Miner's rule

The strain at the end of the member is estimated from the deflection at the center calculated from the knee brace deformation. The degree of damage is calculated using, for example, the S-N curve and Miner's rule. The Miner's rule, which is related to the number of repetitions and the number of times to break, is well known as a damage rule.

V. Estimation of the story drift angle

Using the mechanical mechanism, the story drift angle of frames is calculated from the knee brace deformation.

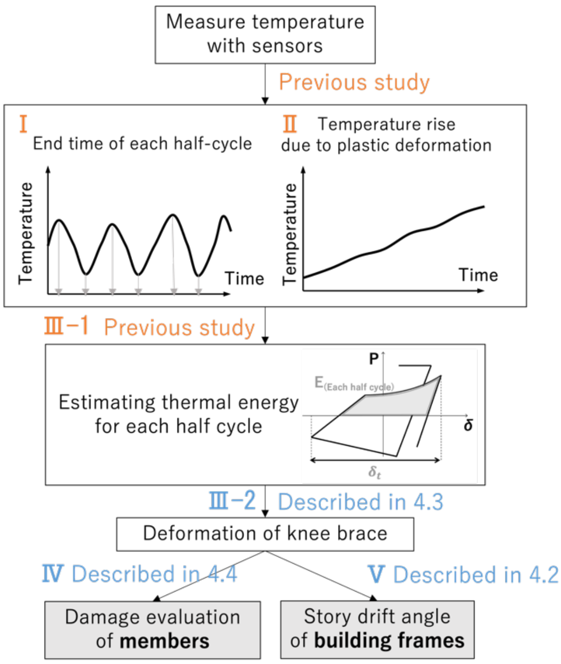

Fig. 1. Flow of damage evaluation method

2.2 Failure Mode of Building Frames with Steel Knee Brace

In single story framework with knee braces, Eqs. (2) and (3) express the collapse load for the principal collapse mode (see Fig. 2).

$$P_1 = \frac{1}{h}\left\{2\,(1+\gamma+2\,\beta)\,M_p + \frac{N_t+N_c}{2}\;l\sin 2\,\Theta\right\} \tag{2}$$

$$P_2 = \frac{2}{h}\;\left(\gamma + \frac{L}{L-2\,l\cos\Theta}\right)\;M_p \tag{3}$$

N_t, N_c: tensile・compressive strength of knee brace
M_p : bending strength of knee brace
β : strength ration of knee brace and beam , $l' = l\,cos\theta$
γ : strength ratio of beam and column

In this proposed method, we determine strength and stiffness under the condition that the knee brace generate plastic heat with elasto-plastic deformation of steel and doesn't affect the seismic performance of the framework.

In order to do that, failure mode 1, which is preceded by the yield of the knee brace, must be dominated. Therefore, it needs to be $P_1 < P_2$, and Eqs. (4) and (5) express the condition of the strength of the framework and members.

$$\frac{(N_t+N_c)\,l}{M_p} < \frac{8\{l' - \beta\,(L-2\,l')\}}{(L-2\,l')\;\sin 2\,\Theta} \tag{4}$$

$$\frac{l'}{L} > \frac{\beta}{(1+2\beta)} \tag{5}$$

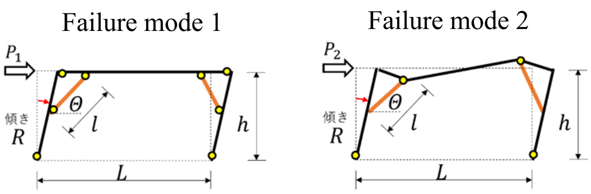

Fig. 2. Failure mode of frameworks with knee brace

2.3 Relationship between Deformation of the Steel Knee Brace and Story drift Angle of the frameworks

Eq. (6) express relationship between the displacement of knee brace and the story drift angle of the framework considering the location of pin-jig and the specimen height.

$$R = \frac{\mathrm{h}}{\mathrm{h}'} \times \left(\frac{l'^2 - \mathrm{b}^2 - \mathrm{c}^2}{2\mathrm{bc}} - \frac{\mathrm{a}}{\mathrm{d}}\right) \tag{6}$$

R : story drift angle h : test specimen height of H-shaped steel h' : test specimen height of column

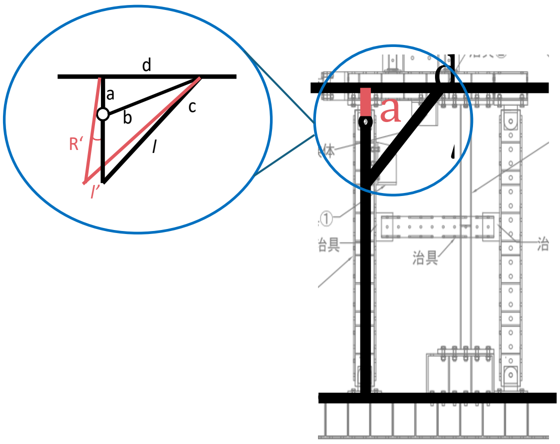

Fig. 3. Failure mode of frameworks with knee brace

3 Method of Static Loading Test

3.1 Setup Diagram

As shown in Table1, the presence or absence of wooden stiffening of the knee brace was the experimental parameters. It is discussed that energy absorption and the effect stiffening depending on with or without the buckling stiffening of the knee brace.

Specimens of knee brace had been fabricated by laser cutting from 3.2mm thick steel of SS400 in the standard of JIS G 3101 into the shape shown in Fig. 4. The material properties of the steel re shown in Table2. The specimen is set up as shown in Fig. 5.

Table1. Parameters

Specimen	Stiffening
P-N	None
P-W	With

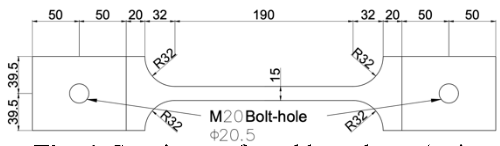

Fig. 4. Specimen of steel knee brace(unit;mm)

Table2. Material properties

	Young's modulus [N/mm^2]	Yield stress [N/mm^2]	Tensile strength [N/mm^2]	Yield strain [μ]
H-shaped steel	245807	338	461	1361
Knee brace	200773	375	458	1173

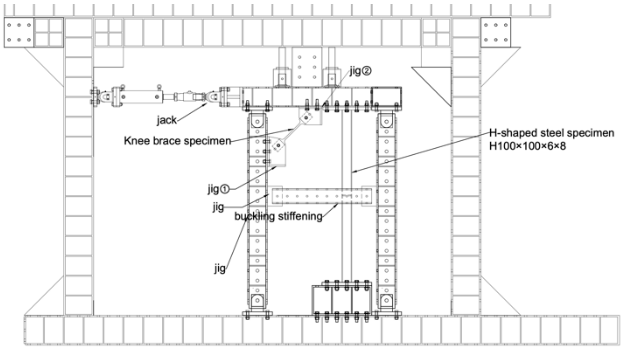

Fig. 5. Setup diagram

3.2 Loading Program

Loading tests were controlled by deformation based on story drift angles which are 1/500, 1/200, 1/150, 1/100, 1/75, 1/50, 1/30 rad. Each is repeated 2 times push and pull. Finally, the load is loaded to the stroke limit of a jack.

3.3 Measurement Method

The load is detected from the load cell built into the jack. The horizontal displacement of stress point is measured by a measure type displacement transducer, and the axial displacement of the knee brace is measured by a displacement transducer. The story drift angle is the horizontal displacement divided by the height from the bottom of the end plate of the H-shaped steel specimen to the center of loading. Also, strain gages are attached as shown in Fig. 6a, 6b for damage evaluation of the H-shaped steel column. Fig. 7 shows strain gages of the knee brace.

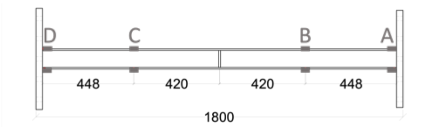

Fig. 6a. Measurement program (H-shaped specimen)

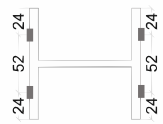

Fig. 6b. Measurement program (cross-section detailed)

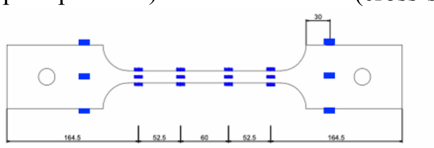

Fig. 7. Measurement program (knee brace)

4 Result and Consideration

4.1 Load-Deformation Curve

Fig. 8a and 8b show the test results of hysteresis loop. When the knee brace is in tension, the general shape is similar. However, in compression, the hysteresis loop of P-W is larger because the knee brace can bear a larger load due to stiffened.

The test results of hysteresis loop of knee brace are shown in Figs. 9a and 9b. Axial load is calculated by values of the strain gauges attached to the elastic region of the steel knee brace. From Figure5, the maximum load on the compression side of P-W is larger than that of P-N. It also indicates that the effect of stiffening is showing.

Fig. 10a, 10b and10c show the ultimate state of buckling. Because of stiffened, significant buckling is prevented.

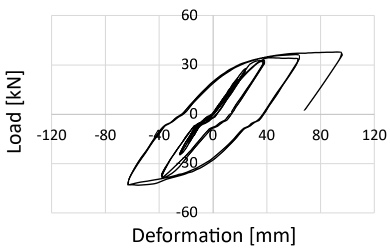

Fig. 8a. P-N hysteresis loop

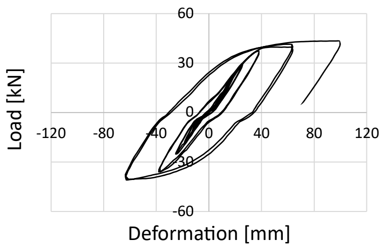

Fig. 8b. P-W hysteresis loop

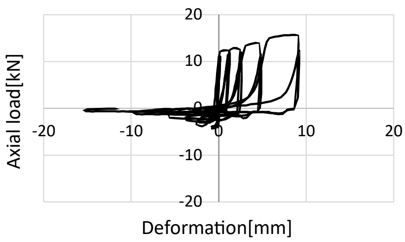

Fig. 9a. Load-deformation curve (knee brace P-N)

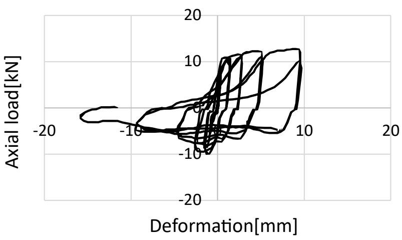

Fig. 9b. Load-deformation curve (knee brace P-W)

Fig. 10a. P-N

Fig. 10b. P-W

Fig. 10c. P-W (detailed)

Fig. 10. Ultimate state of buckling

4.2 Estimation of Story Drift Angle of Building Frames

Figs. 11a and 11b show comparison of the story drift angles estimated from the knee brace axial displacements and those calculated from the horizontal displacements of column. The results show the story drift angle of the framework can be tracked. This is because the knee brace is attached to a column whose head is pin-jointed, so the deformations of the framework and knee brace correspond.

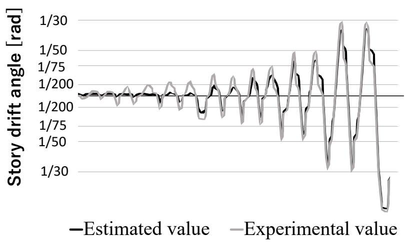

Fig. 11a. Changes of story drift angle (P-N)

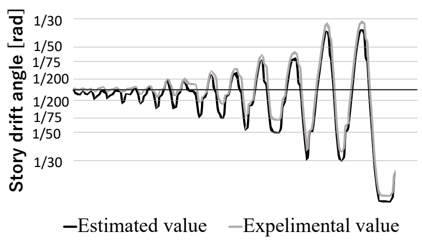

Fig. 11b. Changes of story drift angle (P-W)

4.3 Estimation of Knee Brace Deformation

The knee brace deformation is estimated from the plastic absorption energy for each half cycle. When the knee brace is in compression, restoring force characteristics are assumed from the slenderness ratio of the specimen and shown in Fig. 12. When in tension, hysteretic curve is assumed based on the Wakabayashi model. Then, knee brace deformation is calculated from the plastic absorption energy for each half cycle. (Fig. 13) Comparisons between estimated values and experimental values obtained by displacement are shown in Figs.14a ,14b, 15a and 15b. As a result, it was confirmed that the degree of deformation was evaluated with high accuracy. Accuracy of P-N is better, but P-W can generate more electricity.

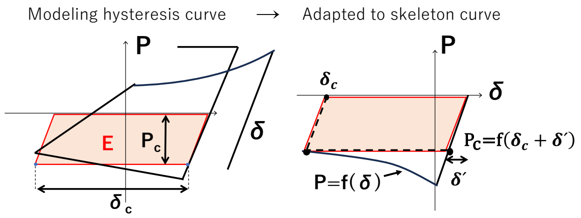

Fig. 12. Modeling hysteretic curve (Compression)

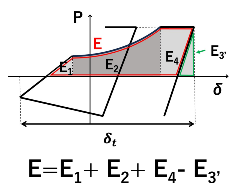

Fig. 13. Modeling hysteretic curve (Tension)

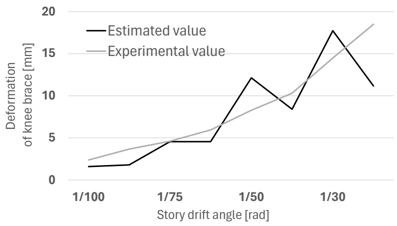

Fig. 14a. Compression

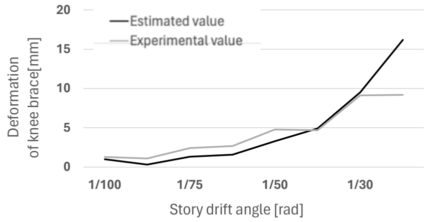

Fig. 14b. Tension

Fig. 14. Estimation of knee brace deformation (P-N)

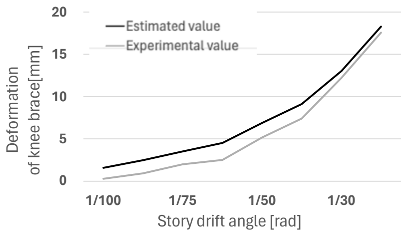

Fig. 15a. Compression

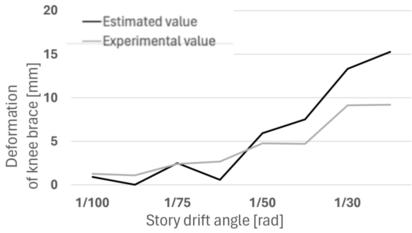

Fig. 15b. Tension

Fig. 15. Estimation of knee brace deformation (P-W)

4.4 Damage Evaluation of Members

The strain amplitude at the end of H-shaped specimen is estimated from the deformation of the knee brace which is calculated from the plastic absorption energy. (Fig. 16)

Eqs. (7) (8) can be derived by principle of visual work. Using these equations, the load applied to the specimen is calculated, and the moment at the end of the specimen is obtained. The moment-curvature relationship and Eq. 9 are then used to calculate the strain amplitude at the end of the specimen.

$$P \times \frac{\delta}{2} = \int_0^{l_2} M(x) \times \varphi(x) dx \tag{7}$$

$$P \times \frac{\delta}{2} = \int_0^{l_1} Px \times \varphi(x) dx + \int_{l_1}^{l_2} Px \times \varphi(x) dx \tag{8}$$

$$\theta_p = \int_{l_1}^{l_2} \varphi(x) dx \tag{9}$$

Figs. 17a and 17b show a comparison of the strain amplitudes in each story drift angle. It was confirmed that estimated value can track experimental value with high accuracy. Although no power generation is available, estimates from the directly measurements of knee brace are more accurate.

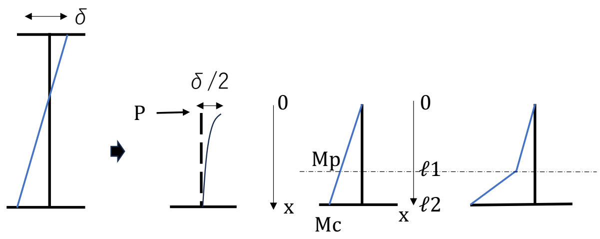

Fig. 16a. Estimation of strain amplitude (P-N)

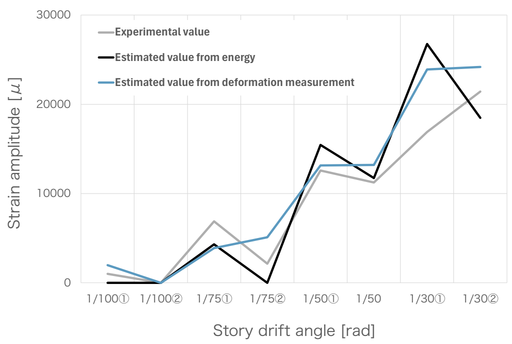

Fig. 17a. Estimation of strain amplitude (P-N)

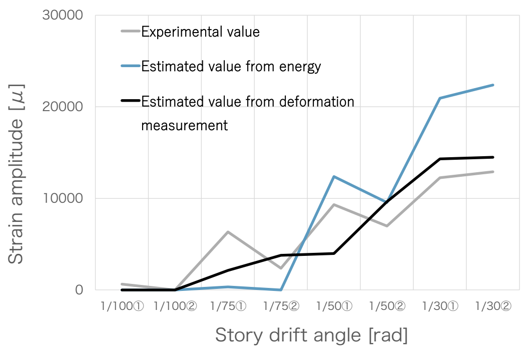

Fig. 17b. Estimation of strain amplitude (P-W)

5 Conclusions

A monitoring system using a knee brace with pinned column-beam connections was proposed and horizontal loading tests were conducted. The validity and feasibility of the evaluation method for members and story drift angles were verified based on the amount of energy absorbed at each half-cycle. As a result, it was shown that the estimation of story drift angle and the evaluation of member damage can be done with high accuracy.

Clearance affects the accuracy of monitoring. In this experiment, we tried to minimize the bolt holes of the gusset plate and the bolt holes of the knee brace to 0.5 mm. However, the setup in the experiment was difficult, and the installation method needs to be improved in the future.

Additionally, in the damage evaluation method described in section 2.1, temperature measurement was tested for members under bending and tension respectively. However, tests in compression and bucking haven't been conducted. It is necessary not only to study theoretically but also to conduct dynamic loading tests.

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