Earthquake Damage Reduction in Timber Frame Houses Using Small-Size Fluid Damper

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Timber frame structures are common traditional methods of housing construction, which use squared-off timber beams, columns, and walls as lateral load-bearing members. The seismic performance of timber frame houses can be secured by the load-bearing capacity of erected braces and walls; however, past major earthquakes have caused severe damage to earthquake-resistant timber frame houses. This study investigates the effect of small-size fluid dampers on the earthquake damage reduction in a timber frame house through earthquake response analyses. A detailed analytical model was generated based on an actual two-story timber frame house, which was designed for the highest seismic grade using the latest Japanese standards. Time-history response analyses were carried out for the analytical model subjected to the 2016 Kumamoto earthquake with and without small-size fluid dampers. The small-size fluid damper is equipped with a relief mechanism for the damping force, and its damping property can be expressed using the Maxwell model. Four or seven fluid dampers were installed in the first story of the model to investigate their effect on the earthquake damage reduction. The results of the earthquake response analyses show that the four and seven fluid dampers can reduce the maximum first-story drift angle by approximately one-third and half, respectively. The dampers suppress the residual deformation, control the elongation of the fundamental period during the response, and restrain the amplitude growth. A small-size fluid damper has an equivalent quake resistance to a conventional structural wall with a wall ratio of 3 plus.
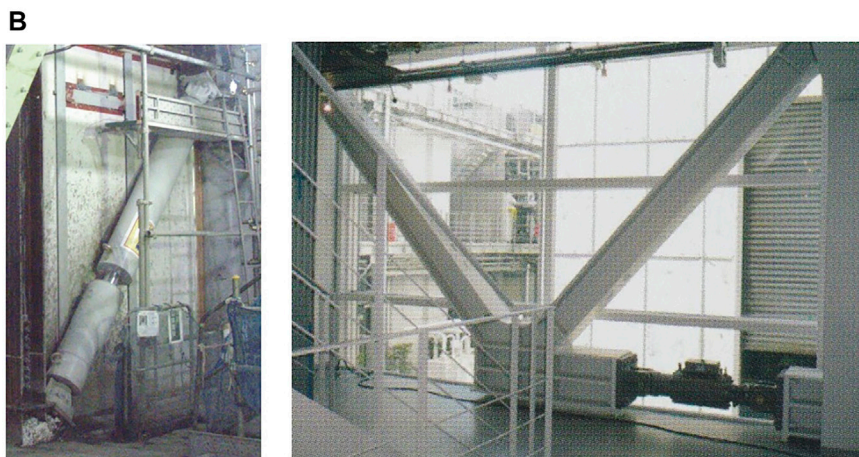
Keywords: earthquake damage, timber frame house, fluid damper, response analysis, the 2016 Kumamoto earthquake, inter-story drift, wall ratio

INTRODUCTION

Various dampers and energy dissipation devices, such as viscoelastic, metallic hysteretic, friction, and fluid dampers have been developed and are widely used to reduce the impact of earthquakes on buildings. Dampers connected to structural frames dissipate seismic energy, thereby reducing a building's kinetic energy and vibration. This method is called building passive control. In Japan, the number of applications of dampers for structures has increased considerably since the 1995 Kobe earthquake (Kasai et al., 2008, 2009). The building passive control method is used mainly in high-rise buildings to protect building structures and contents against major earthquakes. According to the Japan Society of Seismic Isolation (JSSI), the total number of buildings installed with dampers exceeds 1,500 in Japan by 2019. Metallic hysteretic, fluid viscous (oil), and viscous liquid dampers account for 36%, 21%, and 18% of all dampers,
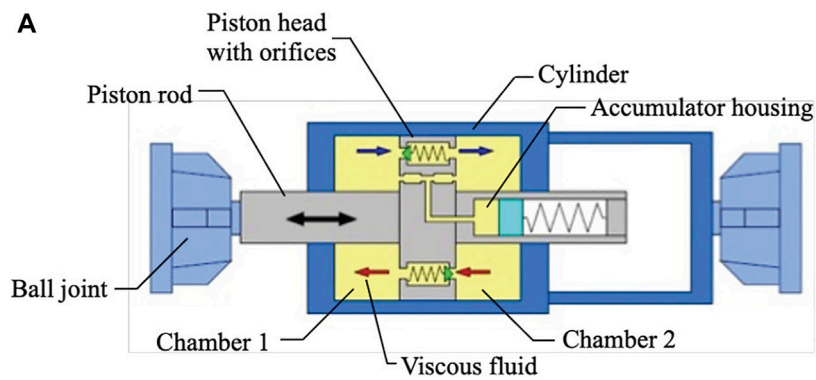
FIGURE 1 | Fluid damper for buildings. **(A)** Schematic diagram of fluid damper. **(B)** Configurations of fluid damper

respectively (MENSHIN, No.113, 2021). Design manuals for building passive control have been published in Japan in 2013 and 2016.

A fluid viscous damper is a hydraulic device and is sometimes referred to as an oil damper. The research of fluid viscous dampers for building applications has begun based on technology mainly from the mechanical engineering since the 1990s (Constantinou and Symans, 1992, 1993; Taylor and Constantinou, 1995; Seleemah and Constantinou, 1997; Soong and Dargush, 1997; Fu and Kasai, 1998). During the last 2 decades, the studies have been carried out on device developments, seismic performances, applications for tall buildings, response analyses and experiments (Lee and Taylor, 2001; Lin and Chopra, 2002; Soong and Spencer, 2002; McNamara and Taylor, 2003; Sorace and Terenzi, 2008; Liang et al., 2012; Seo et al., 2014; Tubaldi et al., 2014; Dong et al., 2016).

Fluid viscous dampers have also been utilized for seismic enhancement and retrofit (Uriz and Whittaker, 2001; Martinez-Rodrigo and Romero, 2003; Sorace and Terenzi,

2009; Rama Raju et al., 2014; Lavan, 2015; Lavan, 2015; Pollini et al., 2016, 2017; Impollonia and Palmeri, 2018; Impollonia and Palmeri, 2018; Tabar et al., 2021). Design procedures and optimum design methods have been studied for supplemental dampers in a structure (Tsuji and Nakamura, 1996; Uetani et al., 2003; Lavan and Levy, 2005, 2006; Silvestri and Trombetti, 2007; Hwang et al., 2008; Takewaki, 2009; Design of Seismic Isolation and Response Control, 2016; Hao and Zhang, 2016; Kawamoto et al., 2016; Parcianello et al., 2017; Wang and Mahin, 2018; De Domenico et al., 2019; De Domenico and Ricciardi, 2019; Idels and Lavan, 2020; De Domenico and Hajirasouliha, 2021).

This study focuses on a small-size fluid damper installed in a timber frame house. Timber frame structures are common traditional methods of housing construction in Japan, which use squared-off timber beams, columns, and walls as lateral load-bearing members. The seismic performance of timber frame houses can be secured by the load-bearing capacity of erected braces and walls; however, past major earthquakes such as the 2016 Kumamoto earthquake have caused severe damage to earthquake-resistant timber frame houses.
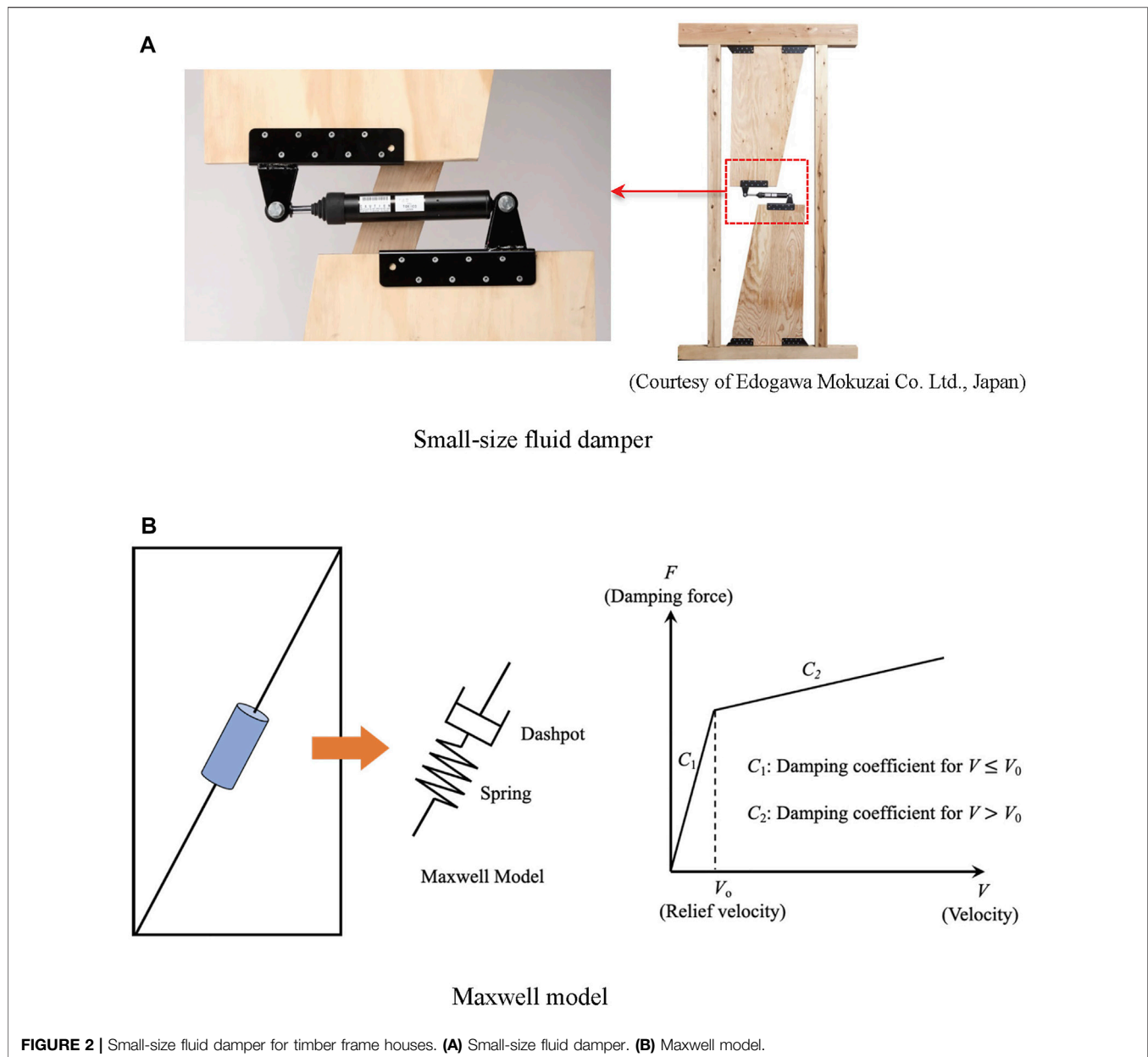
FIGURE 2 | Small-size fluid damper for timber frame houses. **(A)** Small-size fluid damper. **(B)** Maxwell model.
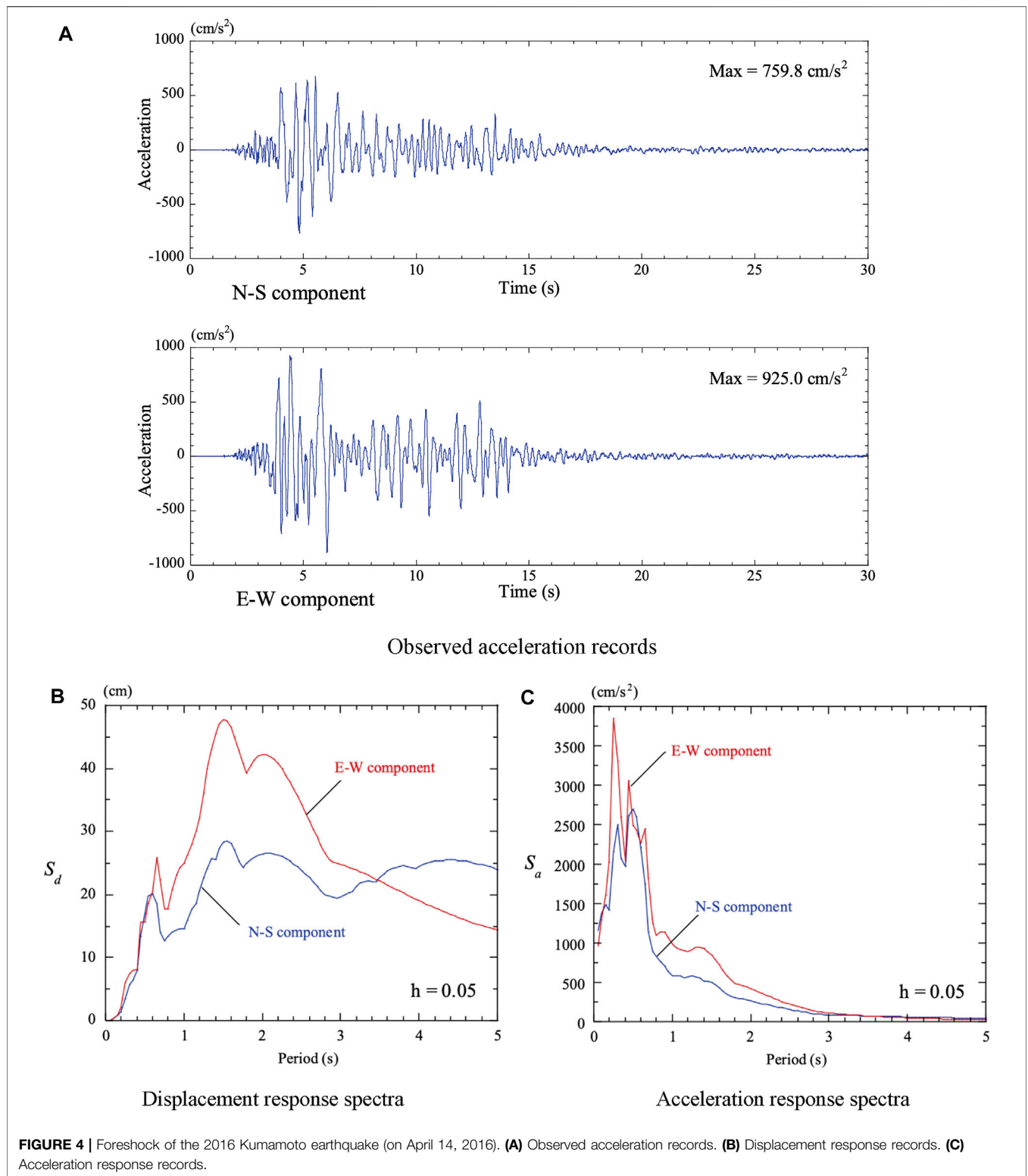
The 2016 Kumamoto earthquake occurred beneath Kumamoto City of Kumamoto Prefecture in the Kyushu region, Japan, and was a series of earthquakes: a foreshock earthquake on April 14, and a main earthquake on April 16, 2016. Earthquakes exceeding the JMA Seismic Intensity 7 occurred twice, and the maximum magnitude was 7.3. The earthquake resulted in 273 deaths and 2,809 people in total were injured. Numerous structures collapsed or suffered severe damage (Yamada et al., 2017), including the Great Aso Bridge, Kumamoto Castle, and Aso Shrine. More than 8,500 houses totally collapsed, and approximately 35,000 houses were partly destroyed. Even timber frame houses that were designed by the latest quake-proof standards and built after 2000 were destroyed.
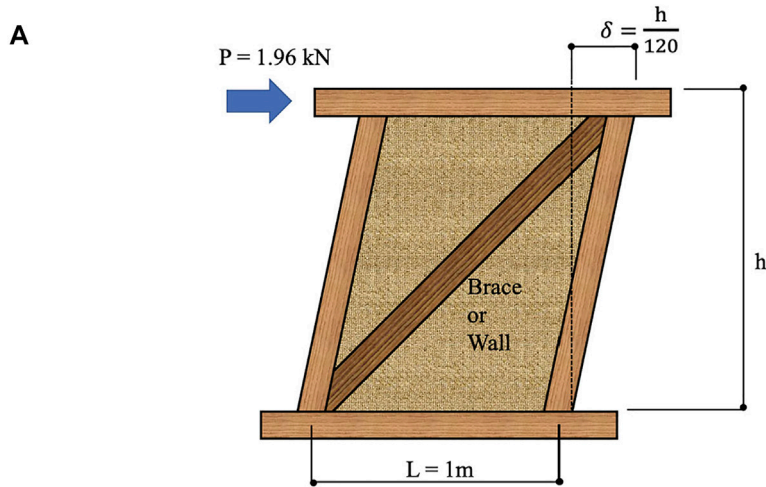
In previous studies on small-size fluid dampers (Matsuno et al., 1999, 2000), shaking table tests and simulation analyses were carried out on a one-story timber test structure with an area of 7.5 m² subjected to the 1995 Kobe earthquake. They demonstrated that two dampers installed in the test structure reduced the story drift by approximately half. To promote the application, further studies are required on the effect of the small-size damper installed on a two-story timber frame house subjected to more severe earthquakes.

In this study, the effectiveness of a small-size fluid damper in reducing oscillations was investigated by earthquake response analyses of a two-story timber frame house subjected to the 2016 Kumamoto earthquake and other major earthquakes. The house is an actual two-story timber

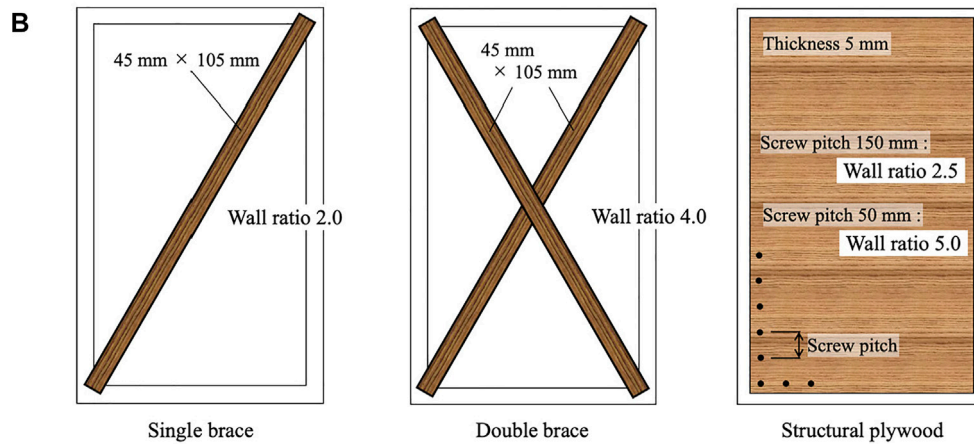**FIGURE 3** | Damage of timber frame houses by the 2016 Kumamoto Earthquake.

FIGURE 4 | Foreshock of the 2016 Kumamoto earthquake (on April 14, 2016). **(A)** Observed acceleration records. **(B)** Displacement response records. **(C)** Acceleration response records.

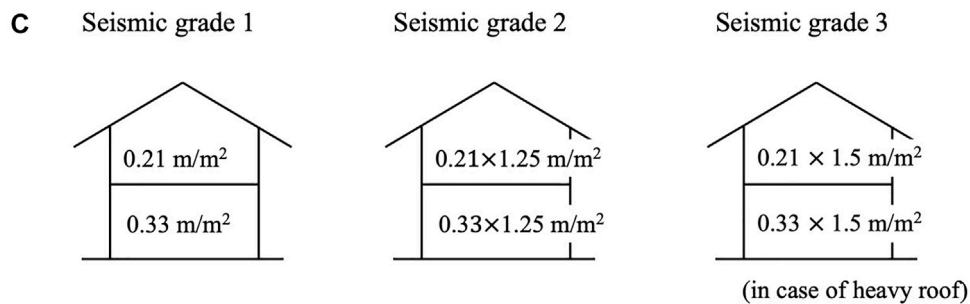**FIGURE 5 |** Wall ratio and necessary wall length of timber frame houses. **(A)** Definition of the 'wall ratio' unit for a brace or wall in timber frame houses. **(B)** Brace and wall specifications and wall ratios. **(C)** Necessary wall length per unit floor area of a two-story timber frame house for seismic load.
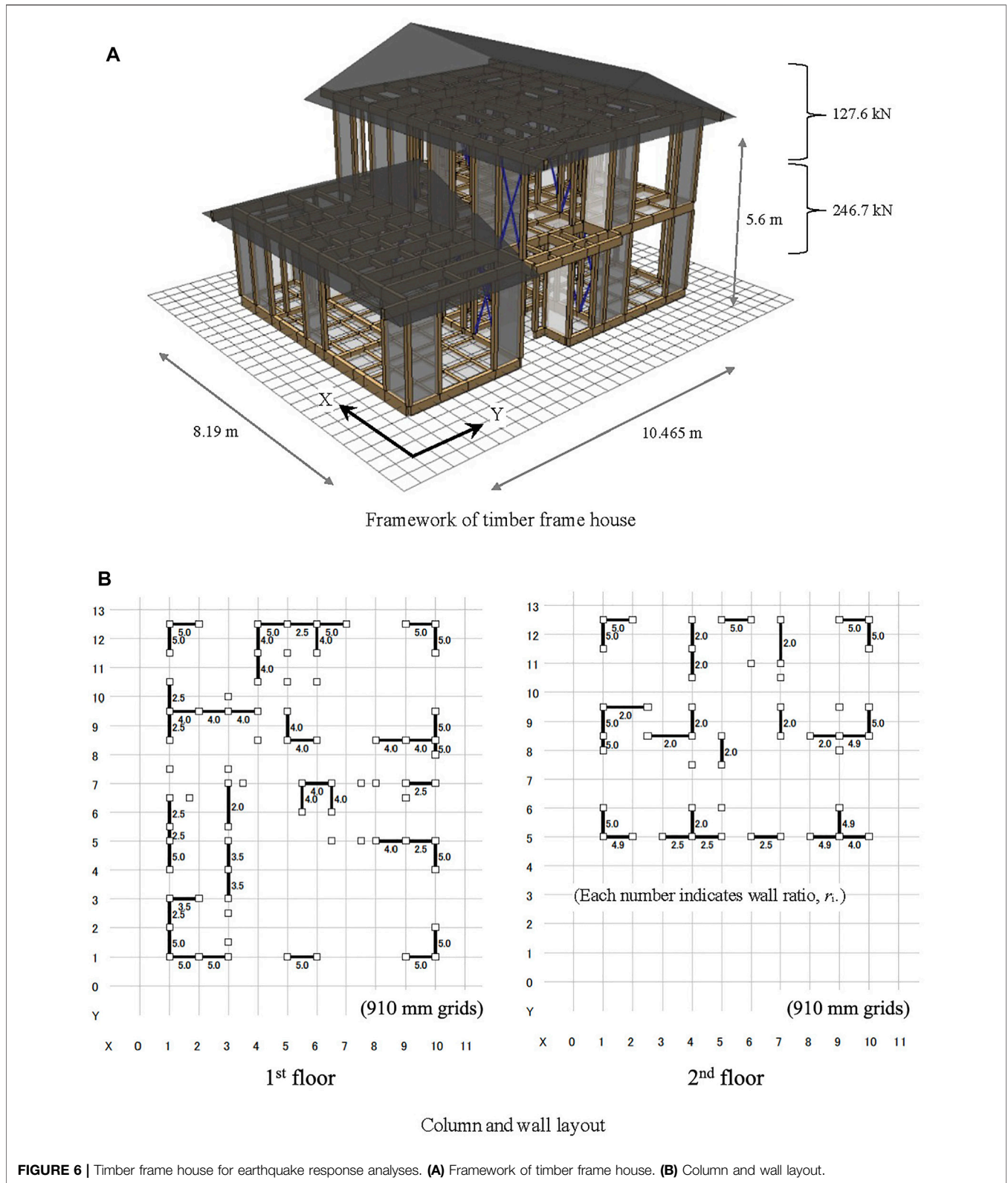
FIGURE 6 | Timber frame house for earthquake response analyses. **(A)** Framework of timber frame house. **(B)** Column and wall layout.

TABLE 1 | Existing and necessary wall lengths and their ratios.

Floor	Floor area (m²)	Direction	Existing wall length L_E (m)	Necessary wall length L_N (m)[a] for seismic grade 3	L_E/L_N
1st floor	84.05	X-dir	75.5	55.8	1.35
		Y-dir	75.3		1.35
2nd floor	53.00	X-dir	44.8	27.5	1.63
		Y-dir	43.1		1.57

[a]Taking the attic story area into account.

frame house that was designed and built for seismic grade 3 (the highest grade) using the latest Japanese standards. Interstory drift angles and response accelerations of the house were evaluated by a collapse analysis program that was developed exclusively for timber frame houses. Moreover, this study investigated the relationship between the number of dampers on the first floor and the maximum story drift and estimated the earthquake-resistance performance of a small-size fluid damper in comparison with a conventional structural wall.

SMALL-SIZE FLUID DAMPER

Figure 1A shows a schematic of the general type fluid damper. The damper consists of a piston rod, a cylinder divided into two chambers by a piston head with orifices, a viscous fluid, and accumulating housing. The damping force is induced by the flow of a viscous fluid through the orifices, and can be designed to be proportional to the relative velocity of the piston head owing to the special orifice geometry. A fluid damper is installed diagonally in a brace configuration or horizontally with diagonal bracing, as shown in **Figure 1B**.

A small-size fluid damper was developed based on a general type fluid damper and used mainly for timber frame houses in Japan to reduce earthquake damage, as shown in **Figure 2A** (Matsuno et al., 1999, 2000). Similar to the general type fluid damper, the small-size fluid damper is installed inter-story, either horizontally (**Figure 2A**) or diagonally (**Figure 2B**), and induces a damping force that is proportional to the relative velocity of the piston rod.

As shown in **Figure 2B**, a mechanical model for the small-size fluid damper can be expressed by the Maxwell model that connects a dashpot and a spring in series. The spring represents the stiffness of the connection member or rod. For the dashpot, the relationship between the damping force and the relative velocity is given by a bilinear model (**Figure 2B**), where the gradient, that is, the damping coefficient, changes when the velocity reaches the relief velocity. The damping force is expressed using the following equation:

$$
\begin{aligned}
F &= C_1 \times V \text{ for } V \leq V_0 \\
&= C_2 \times V \text{ for } V > V_0
\end{aligned} \tag{1}
$$

where C_1 and C_2 indicate the initial and second damping coefficients, respectively, V is the relative velocity of the dashpot, and V_0 indicates the relief velocity (Matsuno et al., 1999; Manual for Design and Construction of Passively-Controlled Buildings, 3rd Edition, 2013).

THE 2016 KUMAMOTO EARTHQUAKE

The 2016 Kumamoto earthquake occurred beneath Kumamoto City of Kumamoto Prefecture in the Kyushu region, Japan, and was a series of earthquakes: a foreshock earthquake on April 14, and a main earthquake on April 16, 2016. Earthquakes exceeding the JMA Seismic Intensity 7 occurred twice, and the maximum magnitude was 7.3. More than 8,500 houses totally collapsed, and approximately 35,000 houses were partly destroyed, as shown in **Figure 3**. Even timber frame houses that were designed by the latest quake-proof standards and built after 2000 were destroyed.

The records of the foreshock earthquake observed at Mashiki Town in Kumamoto Prefecture, shown in **Figure 4A**, were used in the response analyses. The displacement response spectra and the acceleration response spectra of the observed records are shown in **Figure 4B, C**.

DESIGN CRITERIA FOR TIMBER FRAME HOUSES IN JAPAN

Timber frame structures are common traditional methods of housing construction in Japan. The seismic performance of timber frame houses can be secured by the load-bearing capacity of erected braces and walls. The lateral resistance of a timber frame house depends on the braces and walls placed in each story. The Japanese design criteria define wall ratio as the load-bearing capacity of a brace or wall, as shown in **Figure 5A**. One-meter-long wall of wall ratio 1 undergoes a drift angle of 1/120 when subjected to a lateral force of 1.96 kN. **Figure 5B** shows some specifications of the braces and walls with the granted wall ratios. The necessary wall length, L_N (m), per unit floor area (m²) of a two-story timber frame house is provided for each seismic grade, as shown in **Figure 5C**. The L_N for seismic grade 3 is 1.5 times more than that of seismic grade 1. By placing enough braces and walls, the seismic resistance of a timber frame house
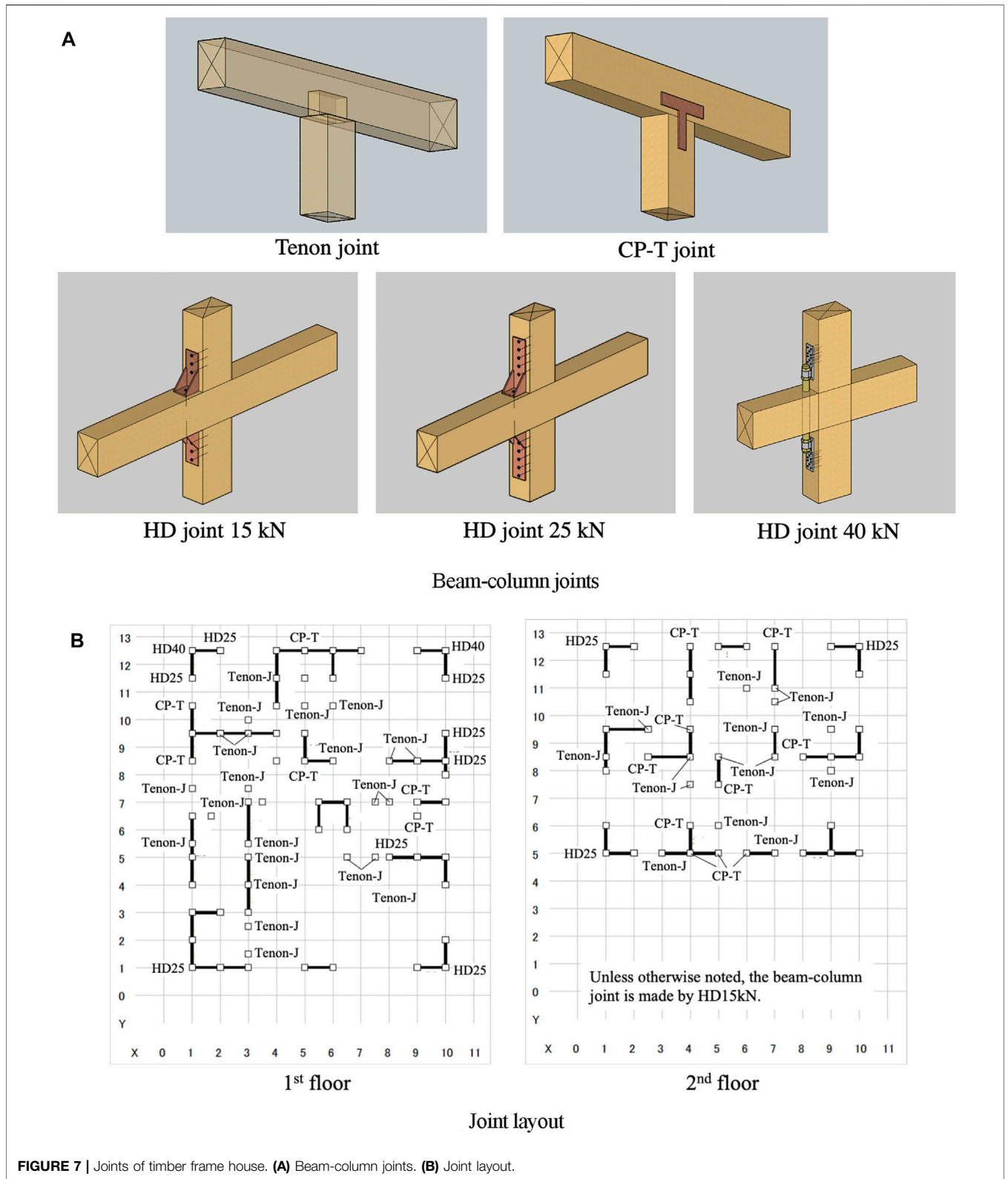
FIGURE 7 | Joints of timber frame house. (A) Beam-column joints. (B) Joint layout.
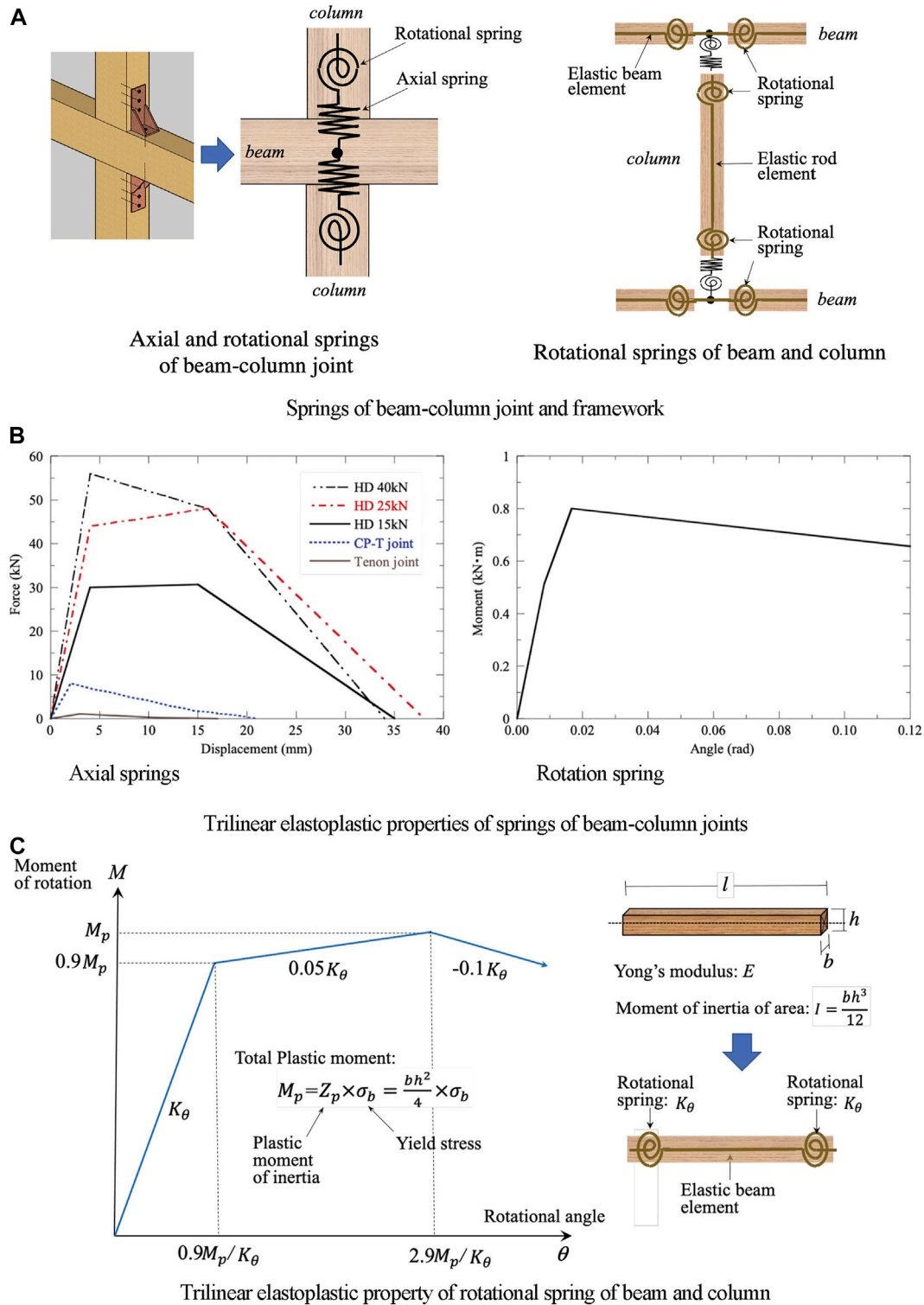
FIGURE 8 | Analytical models of joints and framework. **(A)** Springs of beam-column joint and framework. **(B)** Trilinear elastoplastic properties of springs of beam-column joints. **(C)** Trilinear elastoplastic property of rotational spring of beam and column.
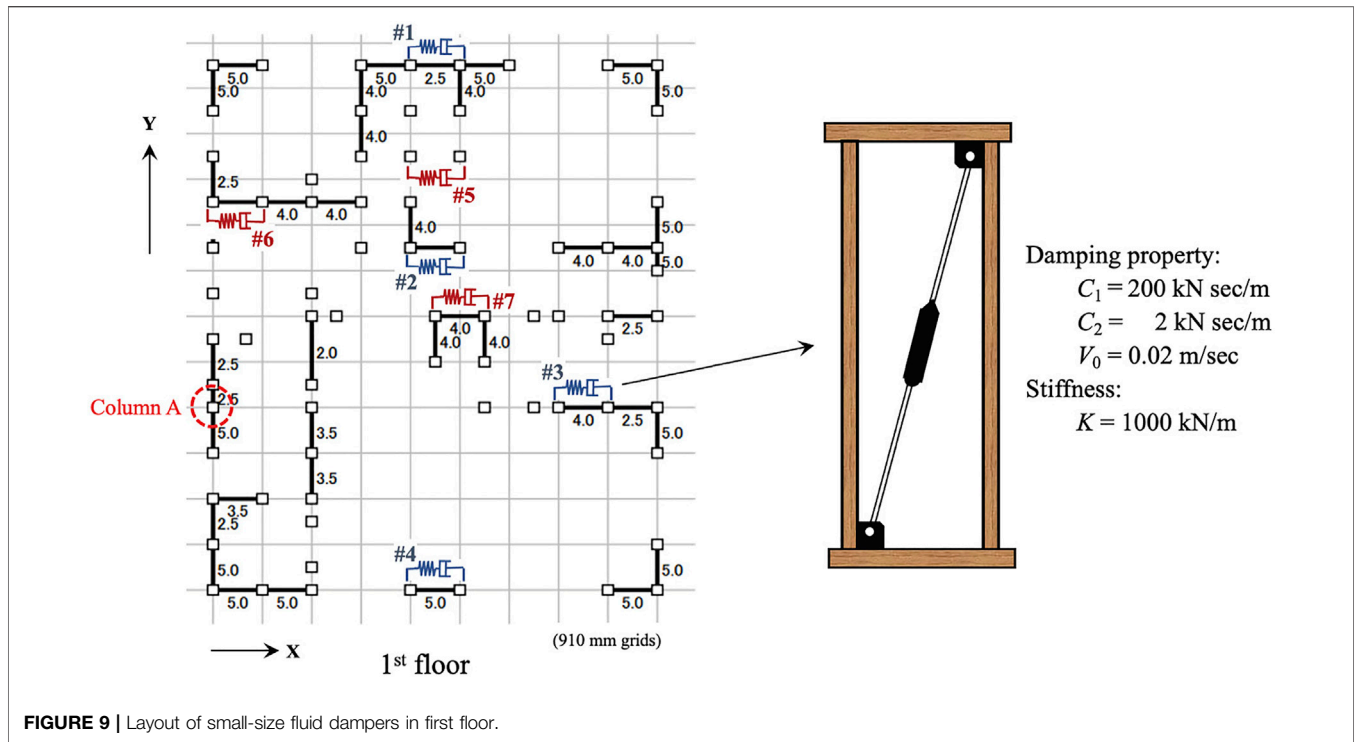
FIGURE 9 | Layout of small-size fluid dampers in first floor.

can be assured by satisfying the following equation in each floor and direction.

Necessary wall length, L_N (m), for target seismic grade

$$\leq \quad \text{Existing Wall length, } L_E(m) = \sum_{i=1}^{n} l_i \times r_i \qquad (2)$$

where l_i indicates the length (m) of each brace or wall, n indicates the total number of braces and walls, and r_i is the wall ratio.

TIMBER FRAME HOUSE MODEL

The framework of the timber frame house used in this study is shown in **Figure 6A**. The house is an actual two-story timber frame house that was designed and built for seismic grade 3 (the highest grade) using the latest Japanese standards. The columns are made of Japanese cedar and the cross-section size is 12 cm × 12 cm. The beams are made of Douglas fir. The Young's modulus and the bending yield stress of the columns and beams are 7500 N/mm^2 and 24 N/mm^2, respectively. The weights of the second story and the rooftop are 246.7 and 127.6 kN, respectively, as shown in **Figure 6A**.

Figure 6B shows the wall layout and wall ratio of each wall of the timber frame house used in this study. The walls were uniformly placed on each floor. **Table 1** shows the existing wall length L_E using **Eq. 2** and the necessary wall length L_N for seismic grade 3 in each floor and direction. Every ratio of L_E/L_N is greater than one, which proves that the timber frame house secures seismic grade 3.

A beam and a column are connected by using a tenon joint or joint metals such as "CP-T" and "Hold-Down (HD)" joints

shown in **Figure 7A, B** shows the joint layout of the timber frame house. In earthquake response analyses in the study, each beam-column joint is expressed by an axial spring and a rotational spring with trilinear elastoplastic properties shown in **Figure 8A, B**. Every timber beam or column is converted into an elastic bar element with rotational springs at both ends shown in **Figure 8A, C**.

As shown in **Figure 9**, small-size fluid dampers are placed at locations #1 to #7 on the first floor in the X-direction, because in the preliminary response analyses the inter-story drifts of the first story in the X-direction were dominant and the house model broke down in the X-direction (as shown later in **Figure 10A, 11A**). In this study, a small-size fluid damper is installed diagonally in a brace configuration and acquires the properties given in **Figure 9**. The properties of the damper were based on the performance tests of the manufactured small-size damper. The target maximum story drift angle is specified as 1/30 because a timber frame house is most likely to be severely damaged or broke down when the story angle exceeds 1/30. Considering the wall layout (**Figure 6B**) and the realistic installation cost, the number of dampers is limited to seven. The following three cases of placing dampers in the first story in the X-direction are considered in this study:
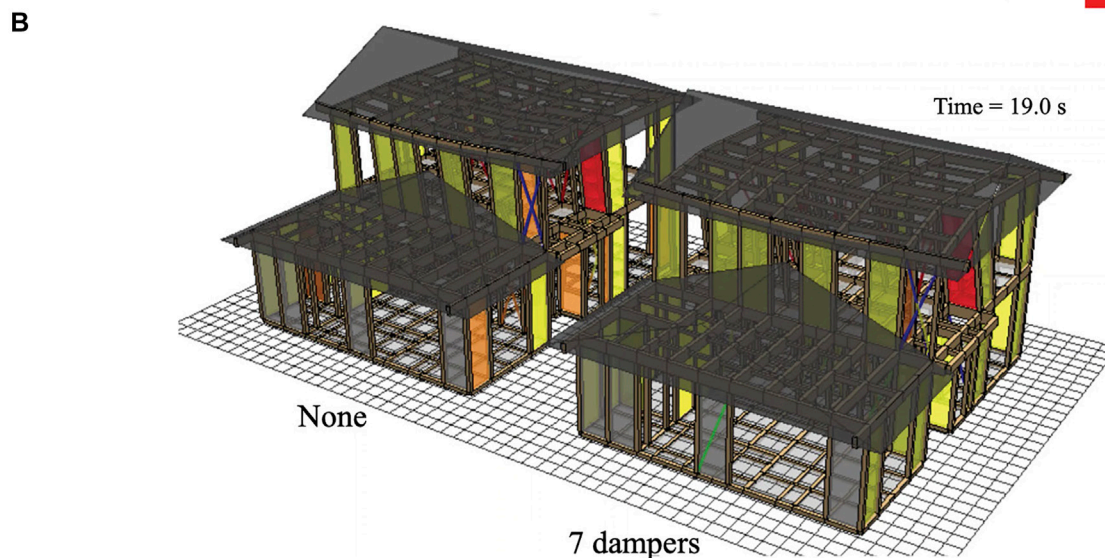
None: No damper is installed, i.e., the original timber frame house.

Four dampers: Four dampers are installed at locations #1 to #4 in the first story in the X-direction.

Seven dampers: Seven dampers are installed at locations #1 to #7 in the first story in the X-direction.
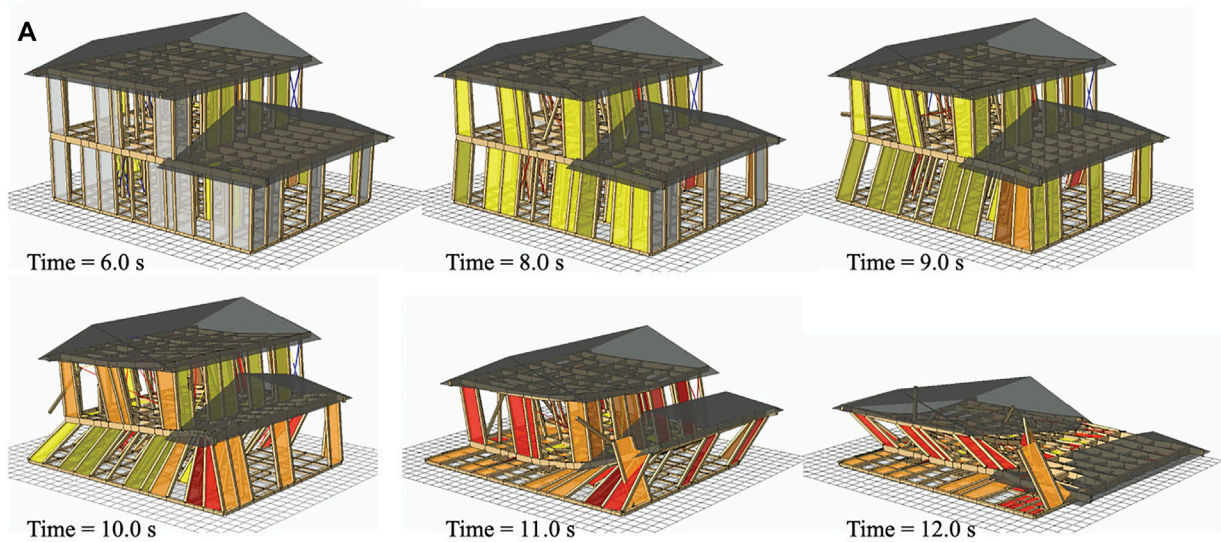
FIGURE 10 | 3D pictures of earthquake response analyses of the timber frame house. **(A)** Collapsing process of the timber frame house without dampers(100 % of the foreshock of the 2016 Kumamoto earthquake). **(B)** Comparison of earthquake response of the timber frame houses with and without dampers.
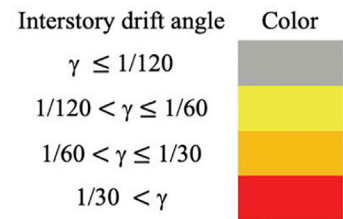
FIGURE 11 | Results of earthquake response analyses of the timber house with and without dampers. **(A)** Loci of 1st-story dri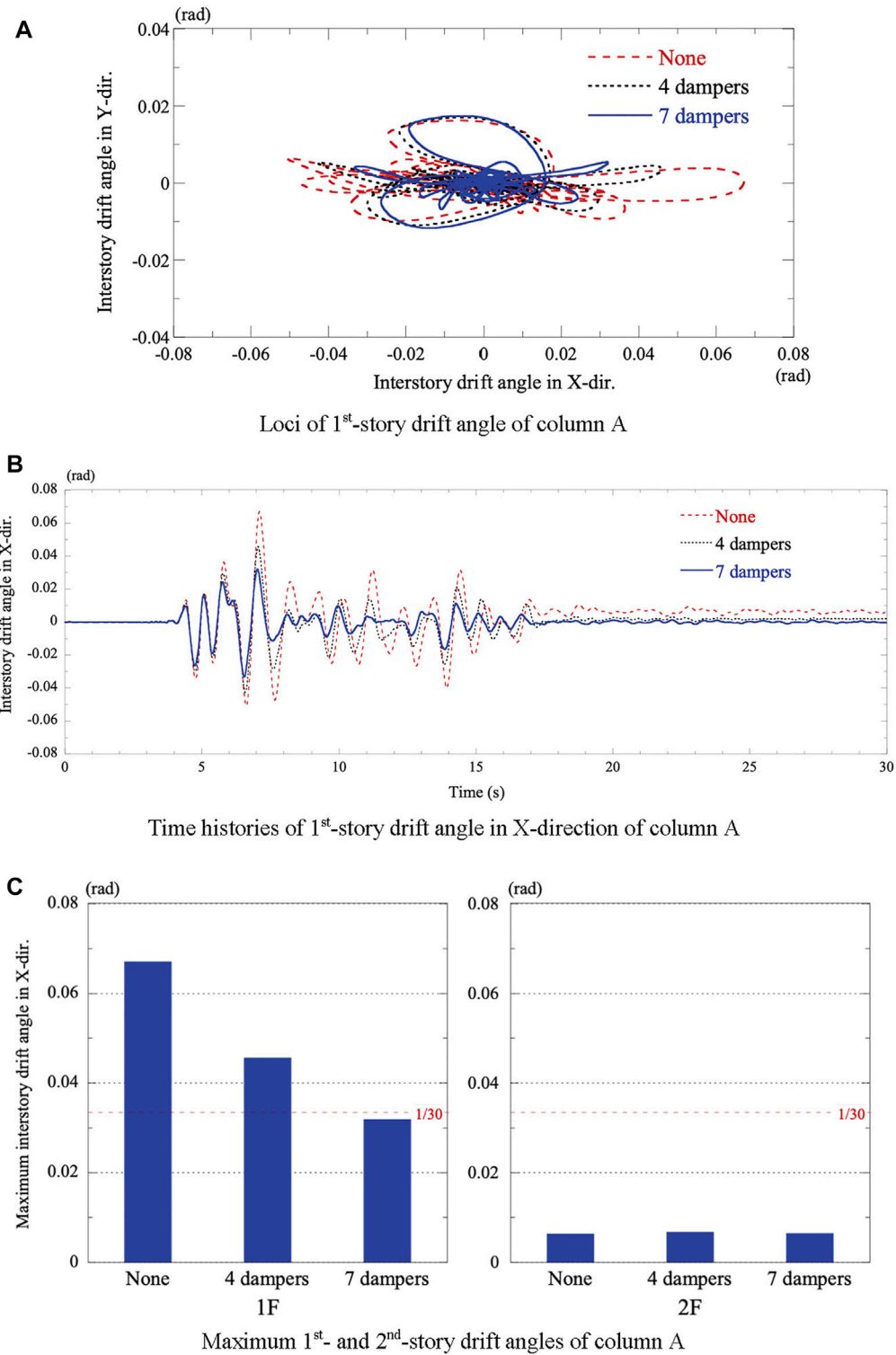ft angle of column A. **(B)** Time histories of 1st-story drift angle in X-direction of column A. **(C)** Maximum 1st- and 2nd-story drift angles of column A.

FIGURE 12 | Maximum 1st- and 2nd-story drift angles of column A of the timber house. with and without dampers. **(A)** El Centro 1940 NS, Taft 1952 EW, and Hachinohe 1968 NS: Vmax = 50 cm/s. **(B)** JMA Kobe 1995, 85% and 50% of the foreshock of the 2016 Kumamoto earthquake [θ=45o].
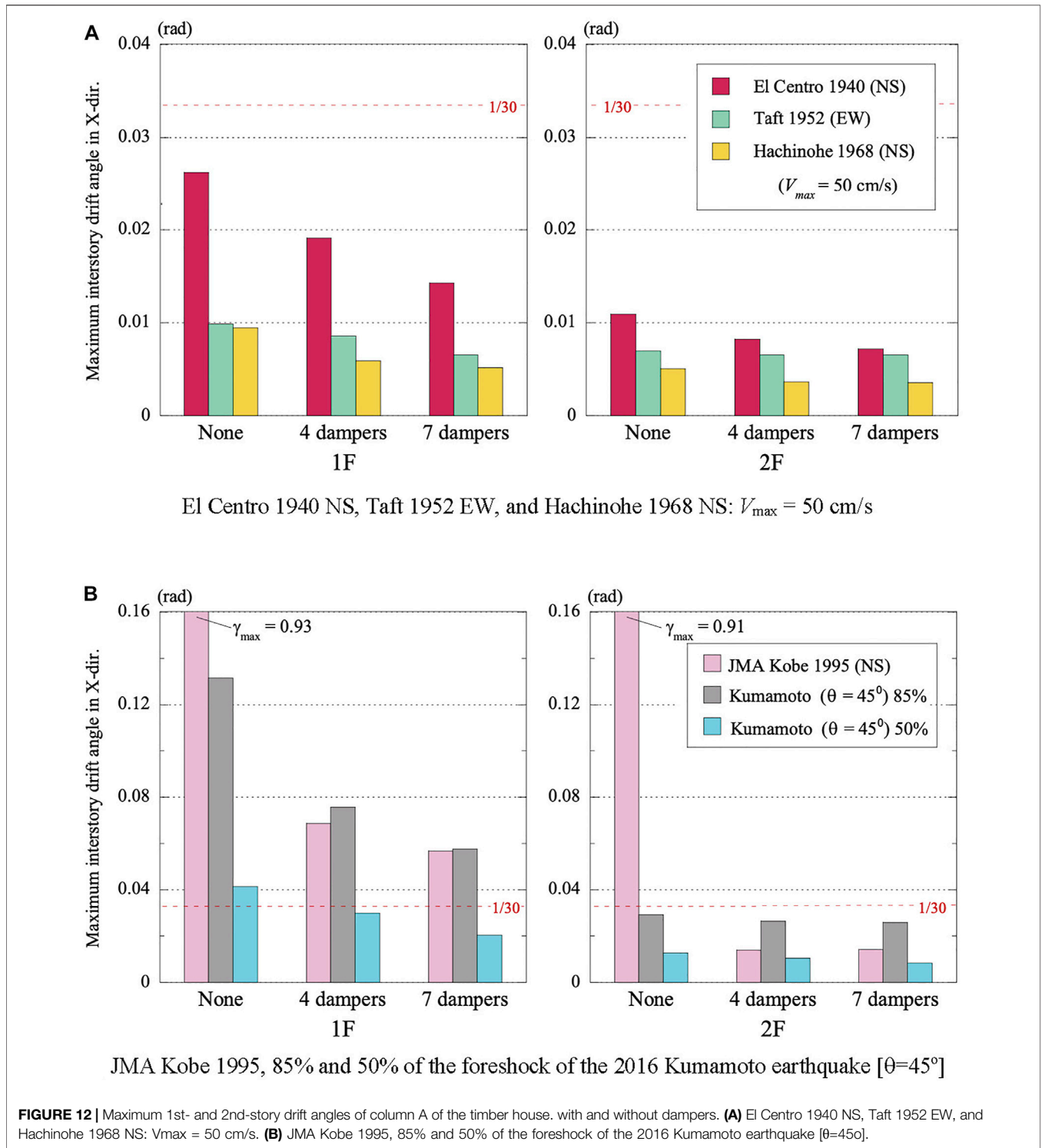
EARTHQUAKE RESPONSE ANALYSES OF A TIMBER FRAME HOUSE

In this study, a collapse analysis program for timber structures "wallstat" is used for earthquake response analyses. The "wallstat" program was developed by Prof. Takafumi Nakagawa of Kyoto University to assess the damage status and the likelihood of collapse of a timber structure when subjected to an earthquake motion (Nakagawa and Ohta, 2010; Suzuki and Nakagawa, 2020). The program utilizes the distinct element method, which is a non-

FIGURE 13 | Maximum 2nd-floor and rooftop acceleration of the timber frame house.

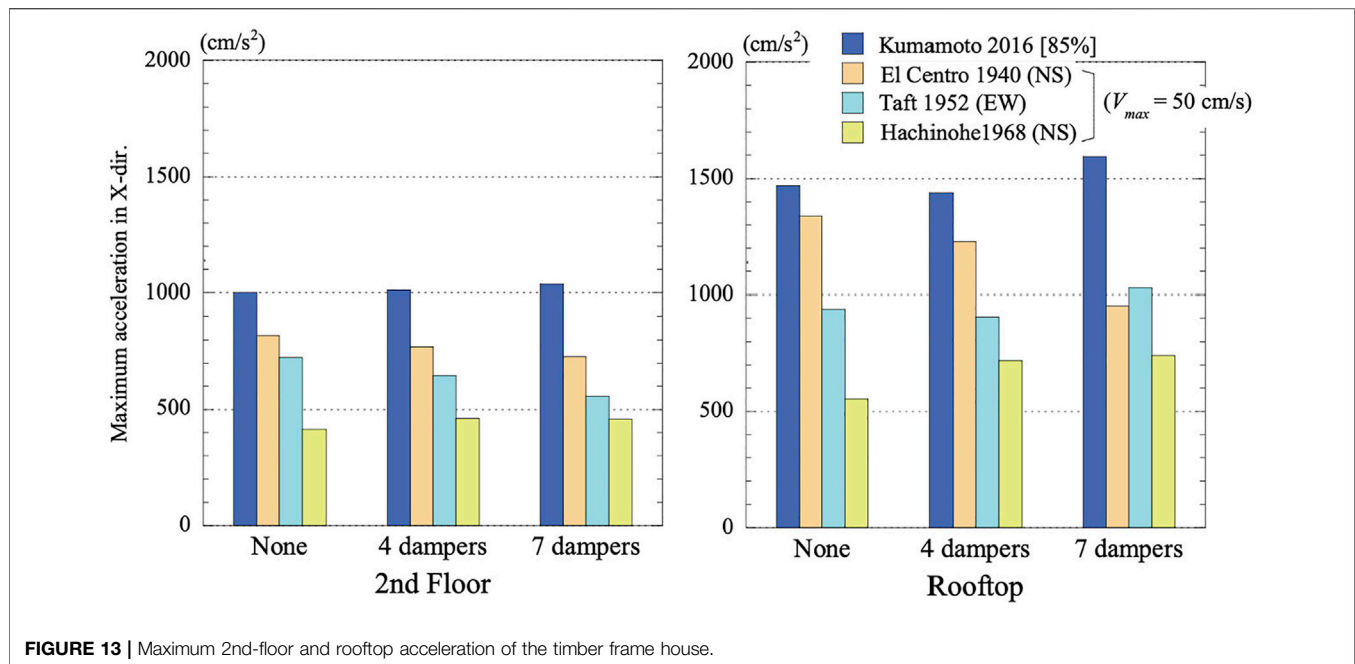continuum analysis method and is applicable to large deformation and collapse analysis.

The "wallstat" program can analyze a timber frame house model installed with fluid dampers or elastoplastic dampers. A fluid damper is expressed by either the Maxwell model that connects a dashpot and a spring in series or the Voigt model that connects a dashpot and a spring in parallel. An elastoplastic damper is represented by a bilinear model. In this study, the Maxwell model was used for the installed small-size fluid damper, as mentioned in *Small-Size Fluid Damper*.

The validity of the "wallstat" program was verified through the comparison between the simulation results and the shaking table tests of full-size housing models (Nakagawa et al., 2006, 2007; Fukumoto et al., 2008). Destructive damage of timber frame houses by the 2016 Kumamoto Earthquake was analyzed by the "wallstat" program (Nakagawa, 2017; Namba et al., 2020). The program is a free software that researchers and engineers can download from the website with the manual, and is now widely used by housing makers to demonstrate the earthquake-proofing performance of timber frame houses in high seismic grades.

Figure 10A shows the collapsing process of the house model without dampers when subjected to 100% of the foreshock of the 2016 Kumamoto Earthquake. Similarly, the house model installed with seven dampers (**Figure 9**) broke down under the same input. The results demonstrate that the foreshock (**Figure 4**) was quite severe for two-story timber frame houses. In this study, 85% of the foreshock records were used for the earthquake response analyses: the N-S component in the *X*-direction and the E-W component in the *Y*-direction.
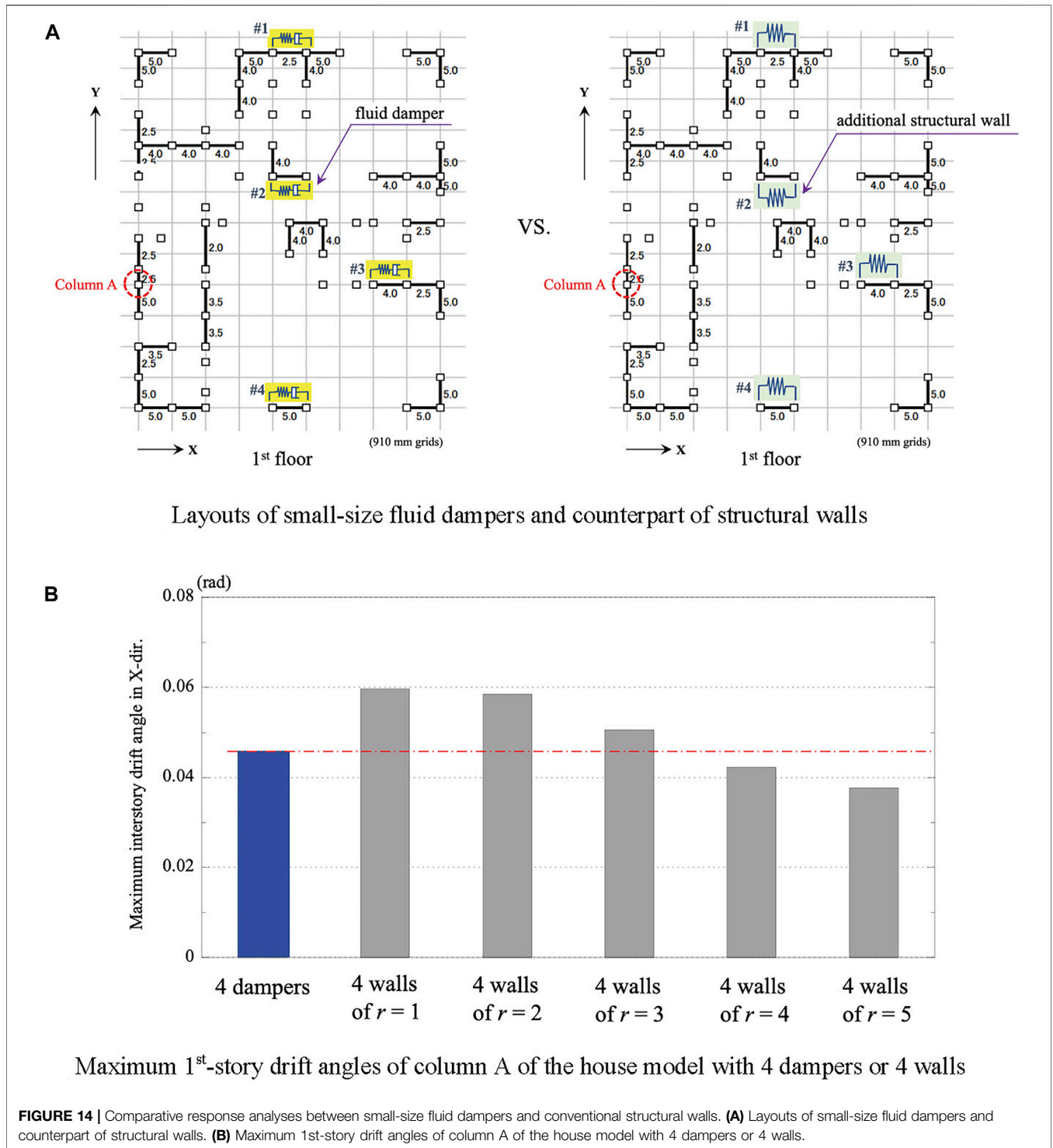
EFFECTS OF SMALL-SIZE FLUID DAMPERS IN EARTHQUAKE DAMAGE REDUCTION

Figure 10B shows a comparison of earthquake responses between the house model without dampers and that installed with seven dampers after being subjected to 85% of the foreshock records. **Figure 11A, B** show the loci and time-histories in the *X*-direction, respectively, for the first-story drift angle of column A for the three cases: none, four dampers, and seven dampers. **Figure 11C** shows the maximum values of the first- and second-story drift angle of column A for each case. For the model without dampers, the first-story drift angle reached 1/15, and the structure was on the verge of collapse.

These results indicate that the installed fluid dampers are effective in reducing the first-story drift angle but have no effect on the second-story drift angle. The maximum first-story drift angle is reduced from 1/15 to 1/22 (approximately 70%) owing to the four dampers, and from 1/15 to 1/31 (approximately 50%) owing to the seven dampers. In addition, the dampers have a favorable effect on suppressing residual deformation, as shown in **Figure 11B**.

Figure 11B also shows that the fundamental period of the house model in the *X*-direction was approximately 0.6 s for small amplitudes and became longer for large oscillations owing to the elastoplastic properties of the beam-column joint. In the case of the model without dampers, the fundamental period nearly doubled when the first-story drift angle was at its maximum. The installed dampers controlled the elongation of the fundamental period and restrained the amplitude growth.

Figure 12A shows the maximum values of the first- and second-story drift angle of column A of the house model

Layouts of small-size fluid dampers and counterpart of structural walls

Maximum 1st-story drift angles of column A of the house model with 4 dampers or 4 walls

FIGURE 14 | Comparative response analyses between small-size fluid dampers and conventional structural walls. **(A)** Layouts of small-size fluid dampers and counterpart of structural walls. **(B)** Maximum 1st-story drift angles of column A of the house model with 4 dampers or 4 walls.

subjected to the three major earthquakes in the *X*-direction; El Centro 1940 (NS), Taft 1952 (EW), and Hachinohe 1968 (NS) whose peak velocity is normalized to 50 cm/s. The maximum story drift angles are much less than those of the house subjected to 85% of the foreshock of the

2016 Kumamoto Earthquake. As for El Centro 1940 (NS) input, the maximum first-story drift angle is reduced from 1/38 to 1/52 (approximately 73%) owing to the four dampers, and from 1/38 to 1/70 (approximately 54%) owing to the seven dampers.

Figure 12B shows the maximum values of the first- and second-story drift angle of column A of the house subjected to JMA Kobe 1995 (NS) in the *X*-direction, and to the 85 and 50% of the foreshock of the 2016 Kumamoto Earthquake at an angle of attack of 45°. As for JMA Kobe (NS) and 85% of Kumamoto input, the house model without dampers broke down, and the dampers can reduce the first-story drift angle effectively, but even the seven dampers cannot prevent serious damage.

Figure 13 shows the maximum acceleration values of the second floor and the rooftop of the house subjected to the 85% of the foreshock of the 2016 Kumamoto Earthquake and to the three major earthquakes whose peak velocity is normalized to 50 cm/s. These results indicate that the dampers have no effect in reducing the response acceleration. It may be because the fundamental period of the house model with dampers remains shorter and the damping effect is relatively small.

The Japanese design method for timber frame houses (in *Design Criteria for Timber Frame Houses in Japan*) considers the braces and walls as the load-bearing members against earthquakes, and takes no account of the damping property of dampers. Only the stiffness or load-bearing capacity of dampers can be taken into account as structural braces or walls. Some dampers using viscoelastic material or high-damping rubber obtain a certificate of wall ratio as a structural member. The small-size fluid damper does not own stiffness property, but the equivalent wall ratio can be estimated in terms of the maximum earthquake response.

To estimate the equivalent wall ratio of a small-size fluid damper, a series of comparative response analyses were carried out between a small-size fluid damper and a conventional structural wall. **Figure 14A** shows the layout of the four fluid dampers and the counterpart of four additional structural walls with a specified wall ratio, *r*. The maximum values of the first-story drift angle of column A were obtained from earthquake response analyses of the model installed with four additional structural walls by varying its wall ratio, *r*, from 1 to 5. **Figure 14B** shows the maximum first-story drift angles for the five cases with four additional structural walls and that for the case of four dampers. The results imply that a small-size fluid damper in the study has an equivalent quake resistance to a conventional structural wall of *r* = 3 plus.

CONCLUSION

In this study, the effectiveness of a small-size fluid damper in reducing oscillations was investigated by earthquake response analyses of a two-story timber frame house subjected to 85% of the foreshock records of the 2016 Kumamoto earthquake and other major earthquakes. The analytical model was based on an actual two-story timber frame house that was designed based on the latest Japanese standards for the highest seismic grade. The small-size fluid damper in this study was developed for timber frame houses based on a general type of fluid damper, and was installed diagonally in a brace configuration in the first story in the *X*-direction of the model. The mechanical model for the small-size fluid damper is expressed by the Maxwell model whose

dashpot induces a damping force that is proportional to the relative velocity. A collapse analysis program for timber structures "wallstat" was used for earthquake response analyses.

The followings are the main conclusions of the study of the house model subjected to 85% of the foreshock records of the 2016 Kumamoto earthquake:

1) For the house model without dampers, the first-story drift angle reached 1/15, and the structure was on the verge of collapse. The fundamental period in the *X*-direction was approximately 0.6 s for small amplitudes and nearly doubled when the first-story drift angle was at its maximum.
2) The small-size fluid dampers in the first story are effective in reducing the first-story drift angle but have no effect on the second-story drift angle. As for The maximum first-story drift angle is reduced from 1/15 to 1/22 (approximately 70%) owing to the four dampers, and from 1/15 to 1/31 (approximately 50%) owing to the seven dampers.
3) The small-size fluid dampers have a favorable effect on suppressing the residual deformation. They controlled the elongation of the fundamental period during the response and restrained the amplitude growth, but have no effect in reducing the response acceleration.
4) In the light of maximum interstory drifts during an earthquake, a small-size fluid damper in the study has an equivalent quake resistance to a structural wall with a wall ratio of 3 plus.

Earthquake response analyses of a timber frame house model in the study demonstrated that the small-size fluid damper can prevent extensive damage and collapse up to 85% of the observed foreshock records of the 2016 Kumamoto earthquake, and reduce the first-story drift according to the number of installed dampers. The damper owns an equal effect on the other major earthquakes.

The small-size fluid damper can be installed inter-story, either horizontally or diagonally, together with a conventional structural wall. Another merit is that the damper can be applied to an existing house as a seismic retrofitting measure. The cost of installation of the damper is a little higher than that of the conventional structural walls, but should be acceptable considering the effects in reducing oscillations. The damper is useable for 60 years in the maintenance-free condition. There is room for further research for applications of the small-size fluid damper to low-rise structures made of laminated wood members. The results of this study can help further the applications of small-size fluid dampers.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

FUNDING

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