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ORIGINAL ARTICLE

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# Development of LVL frame structures using glued metal plate joints II: strength properties and failure behavior under lateral loading

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**Abstract** In past years high priority was given to developing a seismic design for wood structures, including research on the response of wood structures to earthquakes. In this study a new type of portal frame with relatively large span was developed for the traditional Japanese wooden houses with large openings at the front to strengthen the structure. Stainless steel plates coated with zinc and glued with epoxy adhesives on laminated veneer lumber (LVL) members, composed of Douglas fir veneer and bonded with phenol-formaldehyde resin, were used. The connection between the frame's beam and columns and between the columns and groundsills was mechanical, with bolts. The subject of this research was to analyze strength properties and failure behavior of glued LVL metal joints used as structural components and to evaluate the response of LVL portal frames under cyclic lateral loading. The results show that portal frames using glued LVL metal plates have a good multiplier for the shear walls and may be applied to traditional Japanese structures. The equivalent viscous damping provided good energy dissipation in the frames. The joints displayed good mechanical behavior during tests; moreover, the structures demonstrated high strength, stiffness, and ductility, which are necessary for a seismic design.

**Key words** LVL portal frames · Glued metal plate joints · Lateral cyclic loading

## Introduction

Japan has a tradition of wood construction. Kataoka et al.[1] estimated the total number of wooden houses in Japan at 30 million in 1996, and timber construction has been increasing.

It is known that Japan is situated in an active seismic zone, and for that reason the performance of wooden frame structures in the presence of earthquakes is of great importance. Many wood structures seem to have good performance and durability during seismic disturbances, especially those of traditional construction (e.g., pagodas), which represent an image of beauty and strength in Japanese traditional architecture. On the other hand, many wooden buildings are not strong against earthquakes. In fact, past records show that some of them severely suffered or collapsed during earthquakes. It is true that many of these widely damaged or collapsed constructions were old houses incorporating weak points[2] that contributed to the lack of seismic performance. Some of the deficiencies are nonreinforced continuous or noncontinuous foundations, too heavy roof, improper or total absence of braces to reinforce the bearing wall, imbalanced location of resistance wall, houses with wide frontage erected on small lots. Among these weaknesses, of great interest are the traditional structures with large openings for garages, stores, and so on that are currently being constructed.

The idea of the present research was to use laminated veneer lumber (LVL) portal frames at the openings of the structure to compensate for the missing wall and strengthen the structure. An easy-to-build frame, glued inside the workshop and then assembled on site, was our goal. The joints used at the portal frames were glued metal-plate joints, studied thoroughly by the authors in the first part of our research.[3] Gluing performed inside the workshop is presumed to add reliability to the metal-plate joints, and the ease and rapidity of the assembly on site is expected to surpass technical and economic problems. The new type LVL portal frame is presented here, and the response of the frame to lateral cyclic loading is analyzed.

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## Materials and methods

### Test materials

Nine portal frame specimens were built (three sizes of glued metal plate × three frame replications), each composed of one top LVL member of 2970 × 270 × 120 mm and two foot LVL members of 3116 × 270 × 120 mm. Douglas fir (*Pseudotsuga menziesii*, Franco) veneers and phenol-formaldehyde resin were used for the LVL members, with density[4] 620 kg/m$^3$ and modulus of elasticity (MOE)[4] 120 t/cm$^2$.

Two kinds of metal plates were used:

1. The plates glued on the LVL were stainless steel (SS400), provided by the Sumikin Kohzai Co. They had special mechanical plating treatment consisting of zinc and chrome coating, as explained in the first part of this research[3] and as studied by Sano et al.[5] The plates had different lengths (270, 390, and 540 mm) but the same width (270 mm) and thickness (4.5 mm). All these plates were cleaned with lacquer thinner before gluing.
2. The connection plates were stainless steel plates (SS540) 9 mm thick used as joint parts to bring together the beam and columns.

An epoxy resin of R114 type with a viscosity of 7000–10 000 cp, provided by Dainippon Ink Chemical, was chosen. This thermosetting resin, harder than the epoxy resin TE134 (Oshika Shinko) and more liquid than the epoxy resin E250 (Konishi), with a longer pot life and shorter curing time, proved to have better properties than the other two resins and was selected for the frames.

### Preparation of test specimens

The specimens passed through two main phases during preparation: gluing and assembly (Fig. 1). It is recommended that the gluing (Fig. 1a) be performed indoors to gain better reliability of the glued joints. The top and foot LVL members, with the same final thickness appearance of LVL 120E (JAS), were at first composed of two identical elements of LVL 60E (JAS) and were processed and glued with metal plates separately. The metal plates were glued on one side at both extremities of each LVL element, which were then stored for curing one above another inside the factory at 20°C and a high relative humidity for 1 week (specimens were prepared in Chiba Prefecture, Japan during summer). After curing, the joint zone on which the adhesive trickled was sanded until a flat surface was obtained.

The LVL elements were then fixed together two by two with nails, forming the beams and the columns, the top member and foot members, respectively (Fig. 1b). These LVL members were finally assembled together using the connection steel plates and mechanically fastened with bolts (M20 × $\phi$21).

Details of the assembled LVL portal frame are shown in Fig. 2. The frames were separated into three groups LAM 1/2/3, LAM 4/5/6, and LAM 7/8/9, depending on the size of steel plates glued on the LVL elements 270 × 270 × 4.5 mm (L1), 390 × 279 × 4.5 mm (L2), and 540 × 270 × 4.5 mm (L3), respectively.

### Measurements and test procedure

Fourteen transducers were used to measure total displacement at the top of the frame (1, 14) and the rotation angles and shear displacements between frame members (8–13) and between columns and steel framework (2–7), as shown in Fig. 3. The actual shear deformation was estimated as the difference between total displacement at the top of the frame and displacement of the foot member, as follows:

$$\gamma = \frac{\text{no.1} - \text{no.14}}{2965}(\text{rad})$$

where 2965 represents the distance in millimeters between transducers 1 and 14. All the transducers were finally connected to an electronic data analyzer that was linked to a computer.

The steel framework was a square-like steel frame composed of two beams and two cross beams. The hydraulic jack actuator (push 20 tons; pull 20 tons; stroke 200 mm) was arranged parallel with the top LVL member and freely fixed at the midpoint of the member. A manual hydraulic pump, Riken P-50 type, was used for applying oil pressure to the jack. Loading was controlled by displacement and applied twice each toward the positive and negative directions up to the amplitudes of horizontal displacement that correspond to the angles of shear displacement (Table 1).

**Table 1.** Cycles of loading for the LVL portal frames

| Cycle no. | Displacement angle R (rad) | Horizontal displacement $\delta$ (mm) | Cycles passed by group specimens LAM 1/2/3 | LAM 4/5/6 | LAM 7/8/9 |
|---|---|---|---|---|---|
| 1 | ±1/240 | 12.4 | ● | ● | ● |
| 2 | ±1/170 | 17.5 | │ | │ | │ |
| 3 | ±1/120 | 24.8 | │ | │ | │ |
| 4 | ±1/85 | 35.0 | │ | │ | │ |
| 5 | ±1/60 | 49.5 | │ | │ | │ |
| 6 | ±1/42.5 | 70.0 | ▼ | │ | │ |
| 7 | ±1/30 | 99.0 | | ▼ | │ |
| Last | Until failure | | | | ▼ |

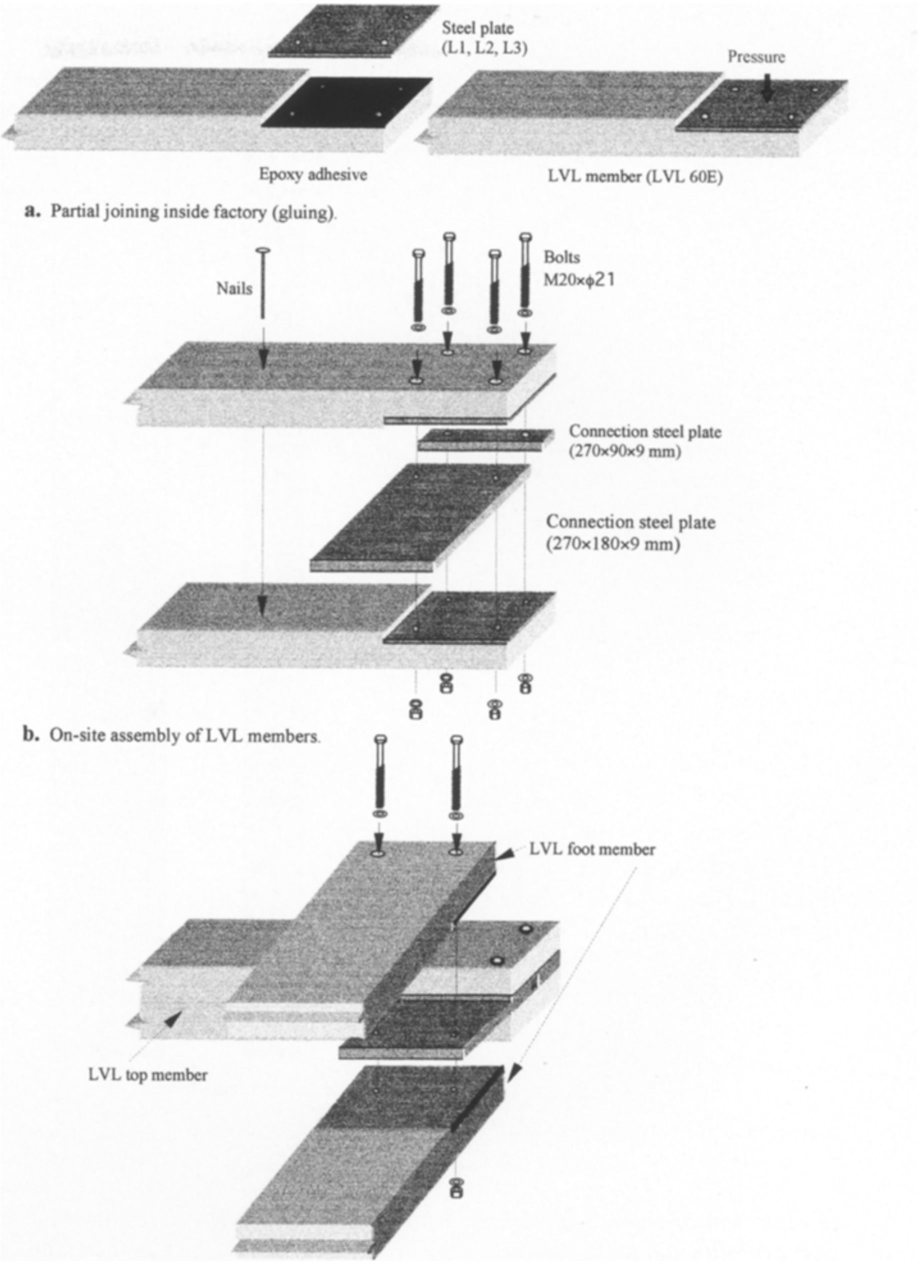


**Fig. 1.** Preparation of test specimens in sequence. See Fig. 2 for explanation of symbols

The cycles passed by each group of specimens were marked in the same table.

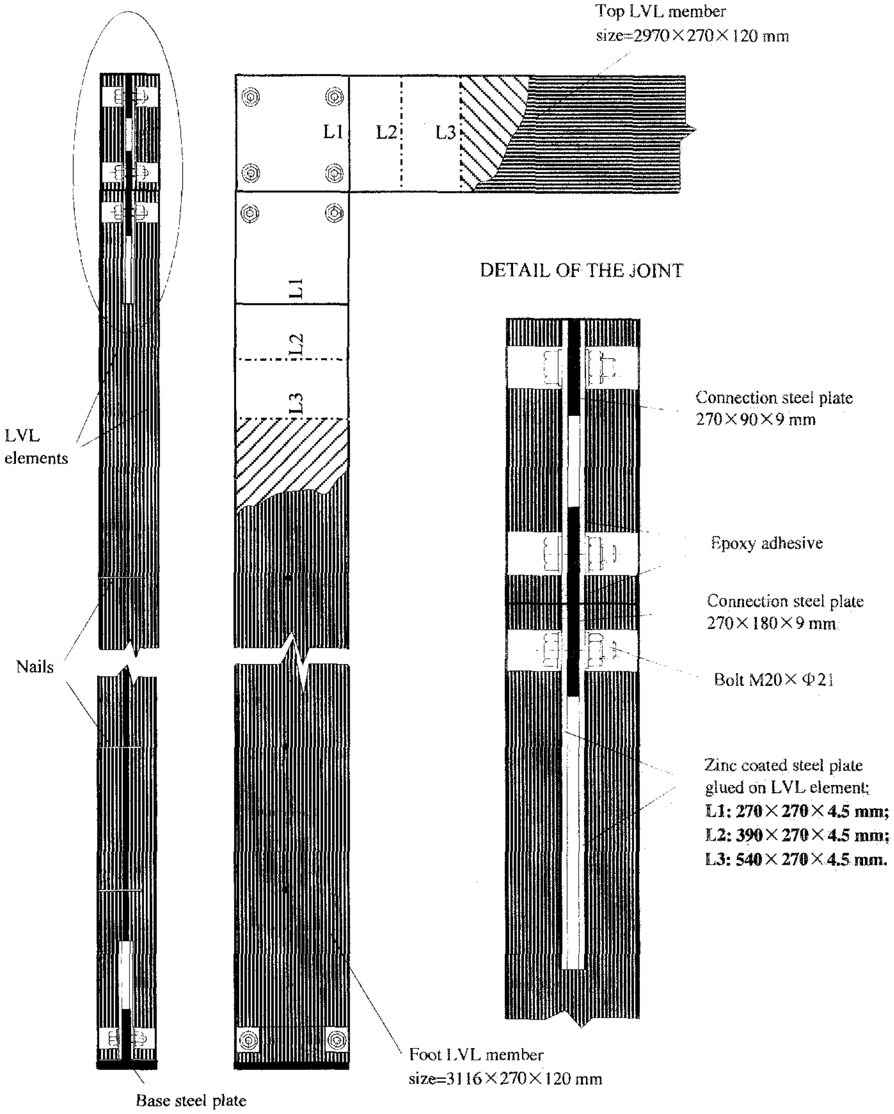
The laterally loaded symmetrical frame of uniform cross section shown in Fig. 4 was chosen as the model of the frames. It was assumed that the connections between beam and columns and between the columns and groundsills are perfectly rigid. Furthermore, the shear deformation of the beam and columns and the rigid elements in the panel zone of the joints were neglected. The effect of the eccentric loading at the middle of the top member changes the maximum bending moment $\mathcal{M}_A(=-\mathcal{M}_B)$ and $\mathcal{M}_C(=-\mathcal{M}_D)$ with 1.16% and 1.48%, respectively. Moreover, the eccentric loading had an insignificant effect on the frame's theoretical stiffness. In the view of these facts, the effect of the eccentric loading was ignored.

## Results and discussion

### Strength and stiffness of LVL portal frames

The mechanical behavior of the frames under lateral cyclic loading was examined with the help of seismic performance indicators. In general, the most important indicators are strength and stiffness characteristics, deformation capacity, and energy dissipation capacity.

**Fig. 2.** Details of the LVL portal frames



*Comparison of theoretical stiffness without joint rotation with experimental stiffness*

Figure 5 shows the relation between the shear deformation angle of the top LVL member and the lateral force. It can be easily seen that the strength of the structure increased with increasing length of the glued metal plates.

The experimental results of the cyclic loading for all the LVL portal frames are shown in Table 2. The allowable shear force was estimated as three-fourths of the load at 1/120 displacement.

The experimental stiffness line ($K_R$) and the theoretical stiffness line ($K_T$) are plotted in Fig. 5. The experimental stiffness line represents the line that passes through 0.1 $P_{max}$ and 0.4 $P_{max}$ of the envelope curve obtained experimentally. This line was compared with the theoretical stiffness line obtained analytically without joint rotation, which represents the ratio between lateral load and maximum displacement in the force direction. Values of $K_R$ together with $K_T$ and ($K_T/K_R$) ratio are given in Table 3. The analytical results were identified by means of comparisons with the experimental results, and they were close enough to demonstrate good stiffness of the frames. Experimental and analytical results agreed closely.

*Ultimate load and deformation capacity*

Figure 6 shows the definition of the ultimate load[6] ($P_u$) obtained by bilinear approximation using the envelope curves. The ultimate displacement ($\delta_u$) corresponding to $0.8P_{max}$ was obtained first and then the experimental stiffness line configured, as previously described. Finally, the ultimate load was found so it had the same energy dissipation as the envelope curves up to $\delta_u$.

The ductility factor ($\mu$) is commonly used to measure the deformation capacity in joints and structures. It is evaluated as the ratio between the ultimate slip ($\delta_u$) and the critical slip ($\delta_u'$), where the latter represents the ratio between $P_u$ and $K_R$. The symbolic representation for ductility factor follows, and its values are plotted in Table 4.

**Table 2.** Experimental results of the cyclic loading tests

| Specimen code | Size of the glued plates (mm) | Load at 1/120 rad. $P_{120}$ (kgf) | Max. load in positive dir. $+P_{max}$ (kgf) | Max. load in negative dir. $-P_{max}$ (kgf) | Allowable shear force $Q_a$ (kgf) |
|---|---|---|---|---|---|
| LAM 1 | 270 × 270 × 4.5 (L1) | 2280 | 2670 | 2250 | 1710 |
| LAM 2 | | 2160 | 2560 | 2190 | 1620 |
| LAM 3 | | 2200 | 2700 | 2220 | 1650 |
| LAM 4 | 390 × 270 × 4.5 (L2) | 1650 | 3100 | 2710 | 1238 |
| LAM 5 | | 2590 | 4190 | 3770 | 1943 |
| LAM 6 | | 2480 | 4080 | 3230 | 1860 |
| LAM 7 | 540 × 270 × 4.5 (L3) | 2600 | 5670 | 4590 | 1950 |
| LAM 8 | | 2610 | 5590 | 4710 | 1958 |
| LAM 9 | | 2700 | 5570 | 4850 | 2025 |

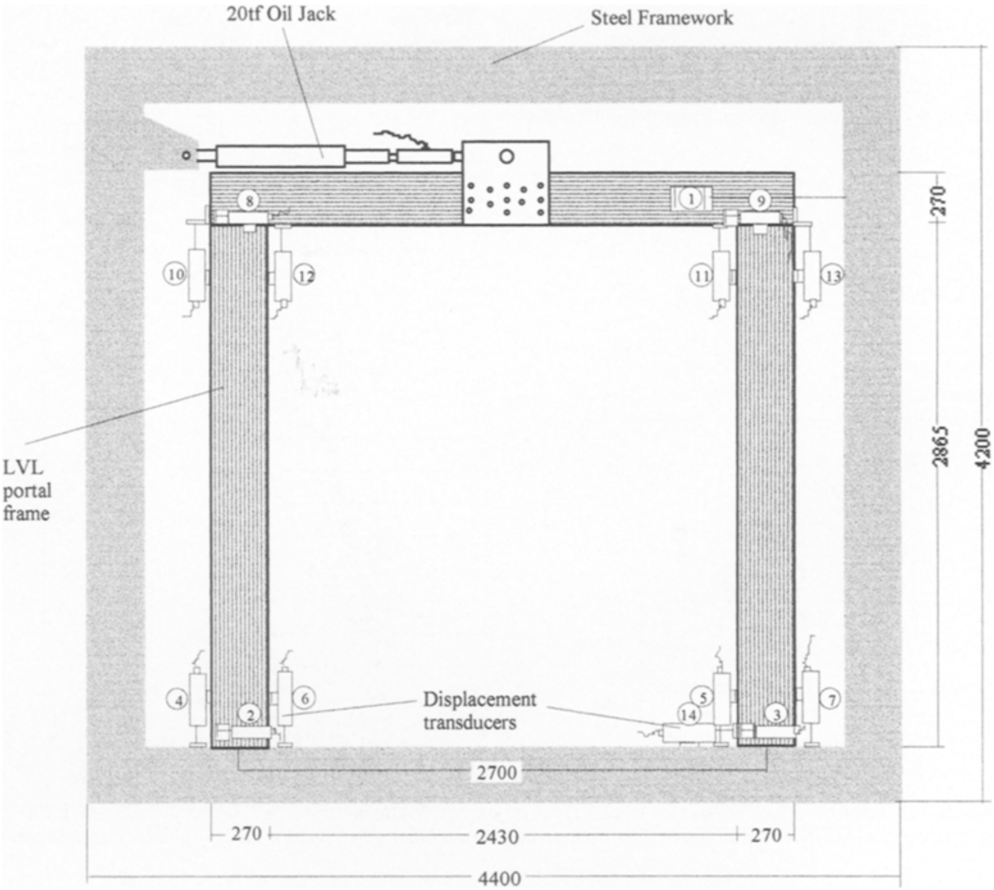


**Fig. 3.** Test setup for the LVL portal frames

$$\mu = \frac{\delta_u}{\delta'_u} \tag{1}$$

The ductility factor increased with increasing length of the glued metal plates, showing that the amount of dissipated energy increased with increasing length of the glued metal plates. Better ductility was obtained for the portal frames glued with the longest metal plates (L3); hence their behavior during earthquakes is better than that of the other two portal frames with shorter metal plates.

The structural behavior factor ($D_s$), or load reduction factor, depends entirely on the ductility and type of structure and represents the resistance reserve capacity of a structure after leaving the elastic behavior. It is estimated from the ductility factor as follows:

$$\mathrm{Ds} = \frac{1}{\sqrt{2\mu - 1}} \tag{2}$$

The structural behavior factor calculated for each specimen is also given in Table 4. According to Notification No. 1792,[7] $D_s$ values for wooden portal frames are situated on a scale from 0.45 to 0.30, where 0.30 stands for excellent ductility. When comparing our results, excellent, fair, and poor re-

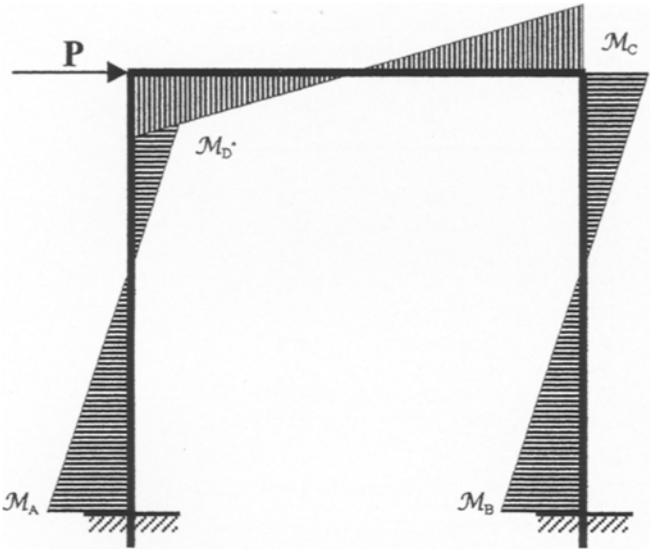


**Fig. 4.** Frame model and bending moment diagram

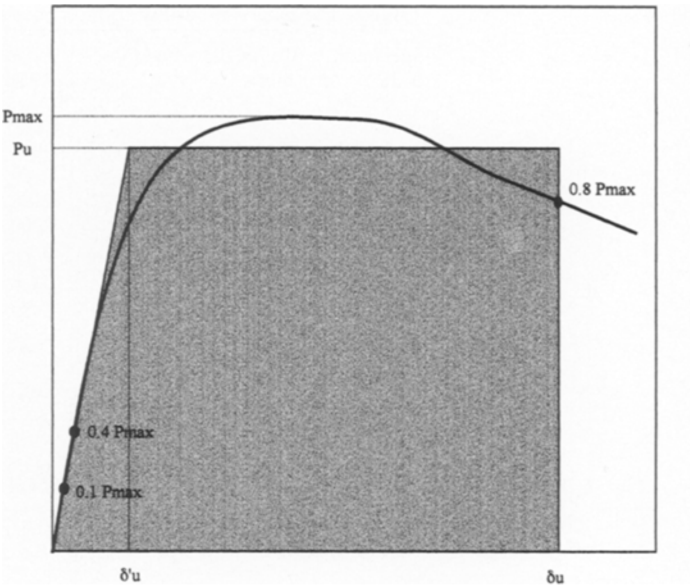


**Fig. 6.** Definition of the ultimate load. (From Yasumura,[6] with permission)

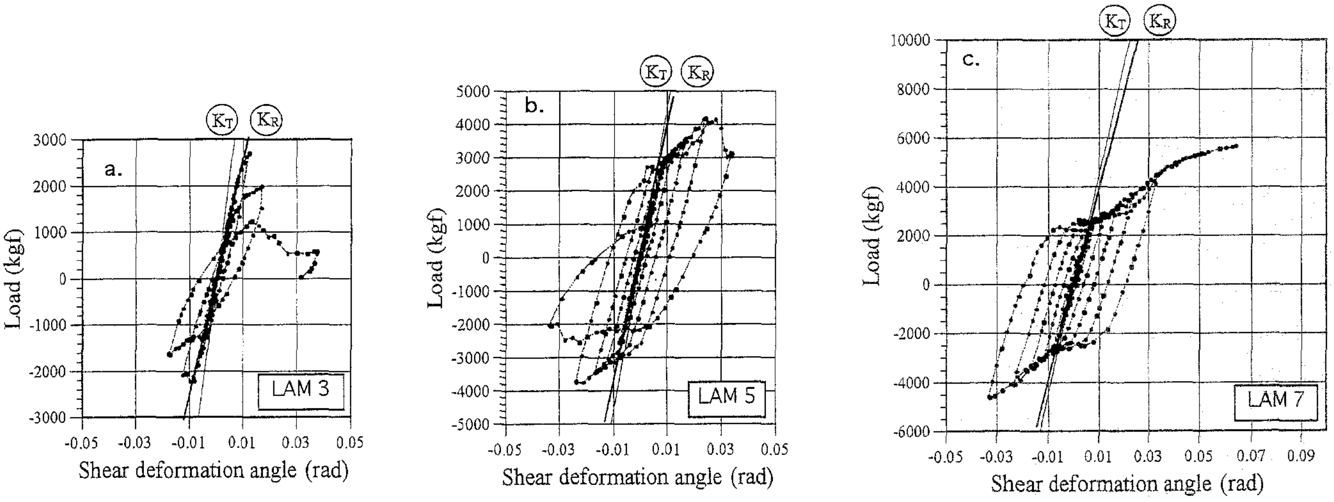


**Fig. 5.** Load deformation relation for the LVL portal frames. Metal plate size: **a** 270 × 270 × 4.5 mm. **b** 390 × 270 × 4.5 mm. **c** 540 × 270 × 4.5 mm. $K_T$: theoretical stiffness (thin lines); $K_R$: real stiffness (thick lines). See Table 2 and Fig. 2 for explanation of symbols

**Table 3.** Real and theoretical stiffness of portal frames

| Specimen code | Size of the glued plates (mm) | Real stiffness: $K_R$ (kg/mm) | Theoretical stiffness: $K_T$ (kg/mm) | $K_T/K_R$ |
|---|---|---|---|---|
| LAM 1 | 270 × 270 × 4.5 (L1) | 124 (0.042)[a] | 151 (0.051)[a] | 1.22 |
| LAM 2 | | 106 (0.036) | | 1.42 |
| LAM 3 | | 100 (0.034) | | 1.51 |
| LAM 4 | 390 × 270 × 4.5 (L2) | 80 (0.027) | 151 (0.051) | 1.89 |
| LAM 5 | | 130 (0.044) | | 1.16 |
| LAM 6 | | 115 (0.039) | | 1.31 |
| LAM 7 | 540 × 270 × 4.5 (L3) | 118 (0.040) | 151 (0.051) | 1.28 |
| LAM 8 | | 133 (0.045) | | 1.13 |
| LAM 9 | | 120 (0.040) | | 1.26 |

$K_T$ represents the rapport between lateral load and maximum displacement in the force direction

[a] Numbers in parentheses are in kilograms per rad

**Table 4.** Ultimate load, ductility, and structural behavior factors

| Specimen code | Ultimate load $P_u$ (kgf) | Critical displacement $\delta'_u$ (mm) | Ultimate displacement $\delta_u$ (mm) | Ductility factor $\mu$ | Behavior factor Ds |
|---|---|---|---|---|---|
| LAM 1 | 2327 | 18.8 | 60.0 | 3.2 | 0.4 |
| LAM 2 | 2279 | 21.5 | 47.1 | 2.2 | 0.5 |
| LAM 3 | 2431 | 24.3 | 48.9 | 2.0 | 0.6 |
| LAM 4 | 2388 | 29.9 | 69.5 | 2.3 | 0.5 |
| LAM 5 | 3644 | 28.0 | 97.0 | 3.5 | 0.4 |
| LAM 6 | 3563 | 31.0 | 93.2 | 3.0 | 0.4 |
| LAM 7 | 4783 | 40.5 | 189.0 | 4.7 | 0.3 |
| LAM 8 | 4804 | 36.1 | 175.7 | 4.9 | 0.3 |
| LAM 9 | 4726 | 39.4 | 177.4 | 4.5 | 0.3 |

$\delta'_u$ represents the ratio between $P_u$ and $K_R$

sults were obtained for the portal frames glued with the longest (L3), medium (L2), and shortest metal plate (L1), respectively.

*Equivalent viscous damping*

One of the dynamic characteristics that describe the energy dissipation capacity of a structure is the equivalent viscous damping, defined in Fig. 7. The equivalent viscous damping represents the dissipated energy ($E_d$) divided by the maximum energy stored ($E_m$), which is the potential energy in the positive and negative halves of a cycle. These energies can be calculated from the hysteresis loops; $E_d$ is the loop area ACDF, and $E_m$ is the triangle areas OBA and OED. It was estimated with the next formula for each loop:

$$h_{eq} = \frac{E_d}{2\pi \times E_m} \tag{3}$$

The equivalent viscous damping results are shown in Fig. 8. Distinct values, varying from 5% to 25%, were obtained for each group of specimens based on their glued metal plate lengths L1, L2, and L3. The equivalent viscous damping for arched frames and frames with moment resisting joints, obtained by Yasumura[6] was relatively low (2%–6%); however, our results could be compared with the results obtained for braced frames (15%–20%) or shear walls (10%–18%) by the same author.

The equivalent viscous damping found was almost constant regardless to the shear deformation, proving good energy dissipation of the LVL portal frame. The large deformation allowed indicates good behavior during earthquakes.

*Multiplier for the shear walls*

In Japan it is common to evaluate the strength of a wooden construction with walls by the multiplier for the shear walls. The frames studied in the present research do not have walls; and at a first glance, it might be difficult to understand the presence of the multiplier for the shear walls. Thinking of the practical purpose of this research – that is, replacing the missing walls of a structure with wide openings – it was assumed that the multiplier may estimate the strength factor of the LVL frames regarding the lateral strength of the shear walls.

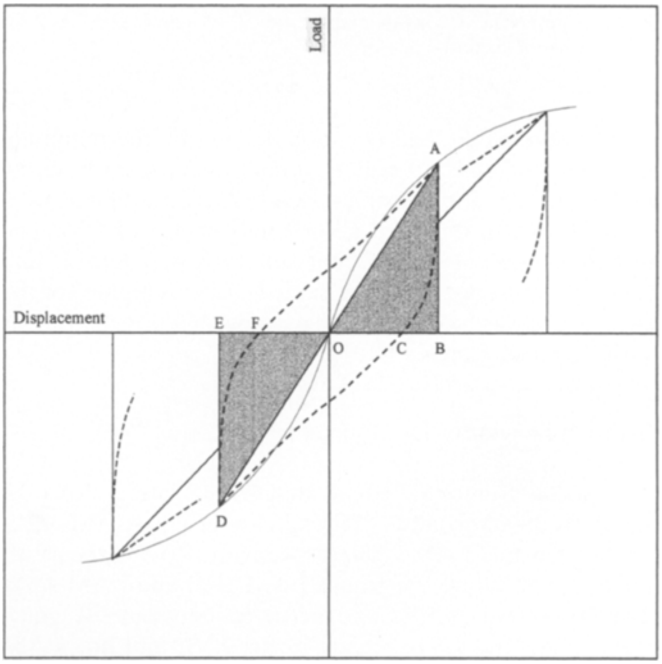


**Fig. 7.** Method of obtaining equivalent viscous damping

According to the literature,[8] Article 46, Section 3 of the Enforcement Order of Building Standard Law[9] of Japan indicates the multiplier for the shear walls. In conformity with Article 46, 1 m of shear wall subjected to lateral loading should resist 130 kgf load at 1/120 displacement angle and corresponds to a multiplier of 1.

The multiplier for the frames ($m_{frame}$) was expressed by the admissible strength ($P_a$) and then divided by the frame span ($l$ = 2.97 m) and by the lateral load to which 1 m of shear wall should resist (130 kgf):

$$m_{frame} = \frac{P_a}{l \times 130} \tag{4}$$

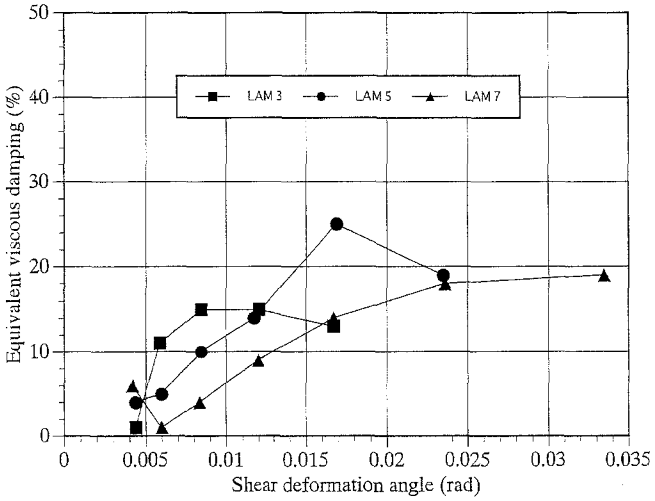


**Fig. 8.** Equivalent viscous damping ratio. See Table 2 and Fig. 2 for explanation of symbols

The admissible load ($P_a$) was defined by the minimum between load at 1/120 rad ($P_{120}$) multiplied by a variability factor of 0.75, and maximum load ($P_{max}$) multiplied by a safety factor of 0.66 and a variability factor of 0.75. The multiplier was calculated separately for plates L1, L2, and L3. The results are shown in Table 5. The multiplier for the shear walls was found to be high, especially for the frames with L3 metal plates.

**Table 5.** Multiplier for the shear walls

| Specimen code | Admissible load $P_a$ (kgf) | Multiplier for shear wall $m_{frame}$ |
|---|---|---|
| LAM 1 | 1335 | 3.5 |
| LAM 2 | 1280 | 3.3 |
| LAM 3 | 1350 | 3.5 |
| LAM 4 | 1238 | 3.2 |
| LAM 5 | 1943 | 5.0 |
| LAM 6 | 1860 | 4.8 |
| LAM 7 | 1950 | 5.1 |
| LAM 8 | 1958 | 5.1 |
| LAM 9 | 2025 | 5.2 |

$P_a = \min(3/4P_{1/120} \text{ and } 1/2P_{max})$

### Failure behavior of LVL portal frames

The portal frames failed at an average lateral force of 2600 kgf, 3800 kgf, and >5500 kgf for groups LAM 1/2/3, LAM 4/5/6, and LAM 7/8/9, respectively. Rolling shear was the cause of failure for groups LAM 1/2/3 and LAM 4/5/6. The failure was brittle and occurred between the glued metal plate and LVL, mostly in the LVL and not at the interface (Fig. 9). During loading a number of cracks developed in the LVL parallel to the glued plate at the connection between the frame's top and the foot members as well as between the foot members and the steel framework. They extended until the whole layer near the glued metal plate slipped out. In the case of group LAM 7/8/9, some local buckling of the glued plate L3 was observed near the bolt (Fig. 10). During loading, contact pressure developed between the foot member and the steel framework, and the steel plates glued on the LVL member started to buckle. This group of specimens did not fail because the tests were stopped after completion of the last cycle owing to large displacements. The glued joints had good behavior during tests; moreover, the knife test performed after the experiment was finished revealed good adhesion between LVL and the metal plate. Failure in wooden material is commonly considered a sign of properly chosen adhesive for wood adhesive joints.

In the case of portal frames glued with the longest metal plates (LAM 7/8/9), the mechanical connection created good strength and ultimate displacement, which caused yielding of the steel plates and consequently dissipation of large amounts of energy. This phenomenon did not happen for the groups glued with shorter metal plates (LAM 1/2/3 and LAM 4/5/6), because they failed before the yielding of the steel plates. It is worth mentioning that the above results were obtained for specimens without reinforcement, whereas in practice the addition of drift pins to the mechanical connection with bolts is strongly recommended to avoid the brittle status of the failure.

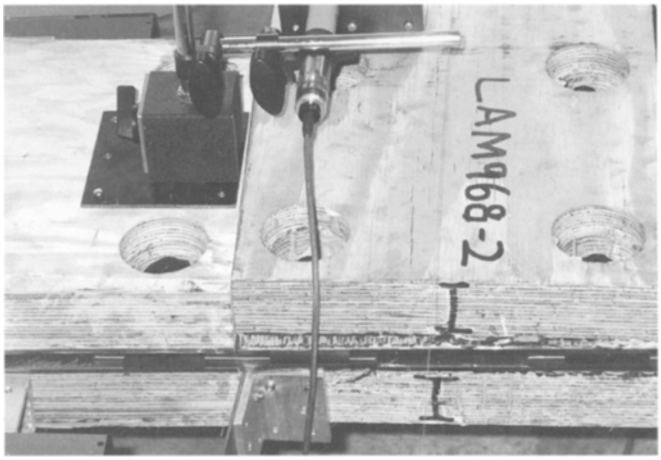


**Fig. 9.** Failure mode of portal frames LAM1/2/3 and LAM4/5/6

## Conclusions

The results showed that LVL portal frames using glued metal plates at joints behaved well during tests and may be applied to traditional Japanese structures. Four major conclusions may be drawn from this research:

1. The LVL portal frames with L3 steel plates proved to be ductile and rigid and they allowed a large deformation during cyclic lateral loading. The worse results obtained for medium (L2) and short (L1) plates are due to the rolling shear between the plates and LVL.
2. The equivalent viscous damping ratio of the LVL portal frames was found to be almost constant, showing good energy dissipation by hysteresis damping.

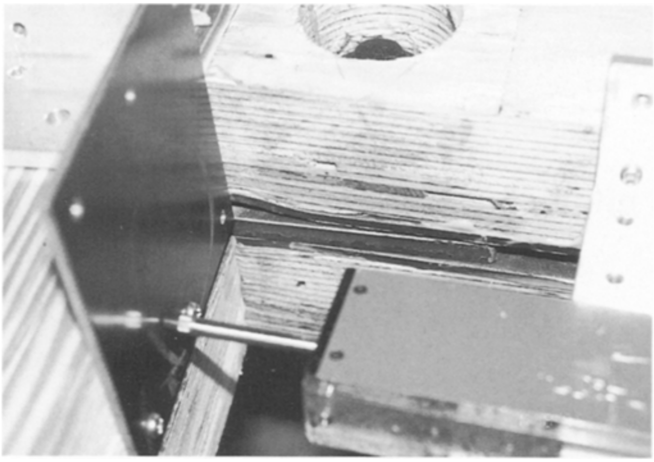


**Fig. 10.** Local buckling of the glued plate L3

3. The multiplier for the shear walls was high compared with the prescribed multiplier for frames with walls, to compensate for the missing walls and to assume the load carrying for the structure.
4. The ductility and behavior factors estimated for the LVL portal frames were high, ensuring that the structures can survive without fatal damage, even if violent earthquakes occur.

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