Seismic Reinforcement of Existing Japanese Wooden Houses Using External Galvanized Thin Steel Plates

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SUMMARY:
In order to accelerate the seismic reinforcement of wooden houses in Japan, a new strengthening method using external galvanized thin steel plates was developed. The method has the potential to improve various aspects of housing, including heat insulation and durability. Existing houses hold the current finish covered with galvanized thin steel plates, which function as both lateral load carrying elements and a new exterior architectural finish. The steel plates are screwed into newly placed wooden frames, which are connected to the existing frames via the existing finish. A connecting method between the existing and new wooden frames was developed and the bearing performance was experimentally examined. Furthermore, a shear wall test was also conducted to evaluate the lateral load carrying capacity. Applying this method, an existing two-story wooden house was strengthened.

Keywords: Existing wooden houses, Seismic reinforcement, Thin steel plates, Shear wall, Architectural finish

1. INTRODUCTION

There are approximately 24.5 million wooden houses in Japan, of which roughly 40 percent are considered to have inadequate seismic-resisting performance. Therefore, seismic strengthening of these wooden houses is an urgent priority. However, progress has stalled for various reasons, including cost and inconvenience of reinforcement work. There are several seismic strengthening methods in Japan. In an existing method, steel braces are attached outside the houses (Umeno, et al, 2009). Although this construction is able to be cost-effective, it only focuses on improving of seismic resistance and not on the overall housing environment. House owners reportedly wish to improve not only seismic strength but also other aspects such as the thermal environment and aesthetics. In another existing method, structural plywood with attached thermal insulation is installed (Uematu, et al, 2009). This method is intended to improve multiple aspects of the housing environment, but requires the removal of the existing architectural finish and may be costly.

In this research, a new seismic reinforcing method using galvanized thin steel plates is developed. The galvanized thin steel plates function as both lateral load carrying elements and an architectural finish. The new outermost layer provides various functions including thermal insulation, durability, fire-resistance, and aesthetics. These steel plates are commonly used in Japanese modern houses for roofs and walls, hence their application for seismic reinforcement is able to be easily accepted by those in construction, including providers and workers. The reinforcement is applied over the existing finish and eases the inconvenience for residents, since they would not be required to temporarily move out during construction.

2. COMPOSITION OF THE REINFORCING METHOD

Figure 2.1. illustrates the composition of the reinforcing method. The exterior galvanized thin steel plates are screwed into the new frame. The new wooden frame is then placed to connect to existing wooden frame and existing and new beams are connected via developed steel connections. Existing foundation and ground sill are typically deteriorated in old Japanese houses, and a new foundation is cast to hold the new frame in place. If the existing foundation and ground sill remain in good condition, the new frames are able to be connected to the existing ground sill without construction of the new foundation.

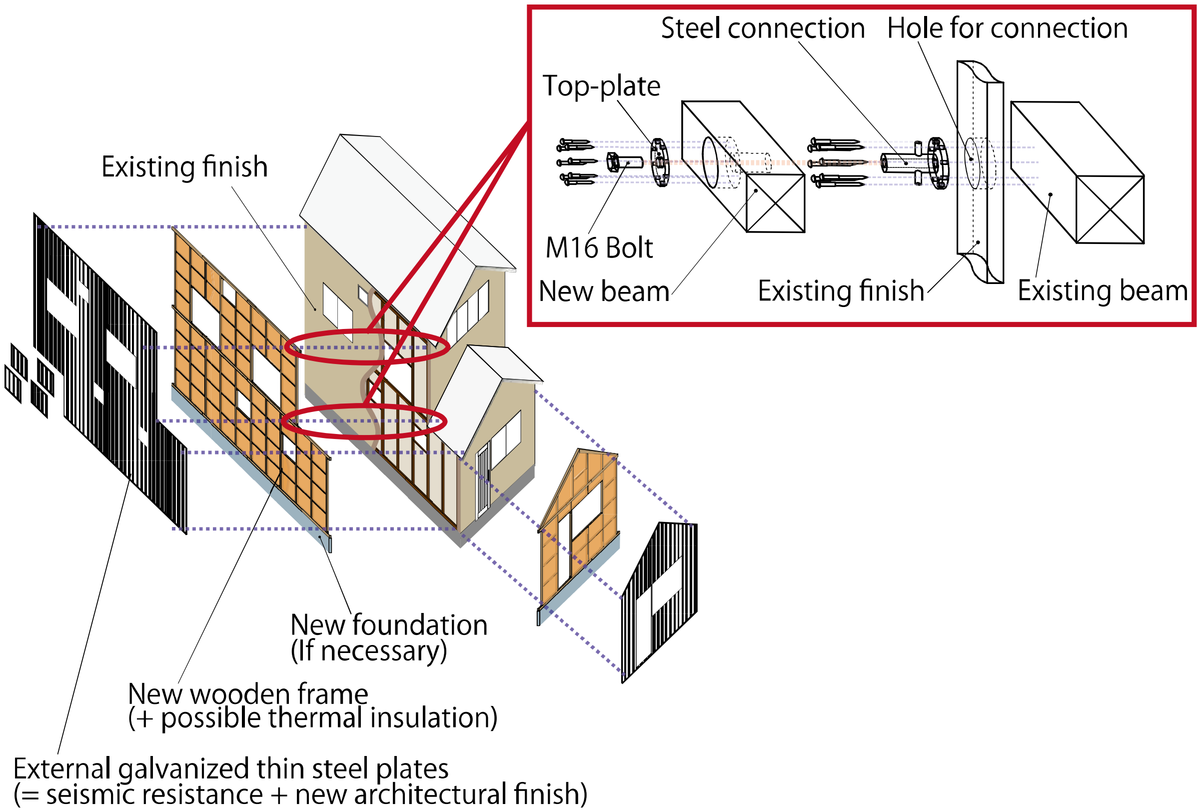
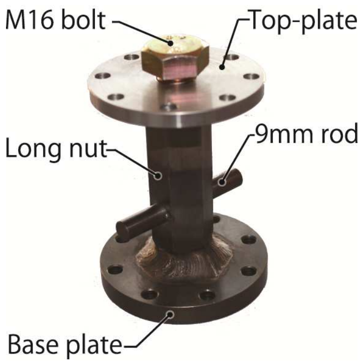
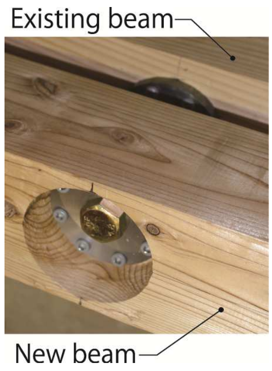


Figure 2.1. Composition of the reinforcing method

3. CONNECTION BETWEEN EXISTING AND NEW WOODEN FRAMES

Figures 3.1. and 3.2. show the steel connection between existing and new frames. An M16 long nut is welded to a 9mm thick round plate (base-plate) and a 9mm diameter rod penetrates the long nut. Another 6mm thick round plate (top-plate) is tied onto an M16 bolt. Figures 2.1. and 3.3. show the placement and lateral load transfer system of the connection. The base-plate is screwed onto the existing beam via a hole in the existing finish and a hole with two diameter sizes along with the hole length is drilled into the new beam. The two hole sizes are slightly larger than the top-plate and long nut. The top-plate is bolted to the nut and screwed onto the new beam. The 9mm rod functions to maintain the gap for the existing finish. The seismic lateral load is transferred from the existing beam to the new beam and the eccentricity of the two beams induces moment in the connection (Figure 3.3.). The moment between the connection and beams is carried by pull-out tensile force by screws and compressive contacting pressure.





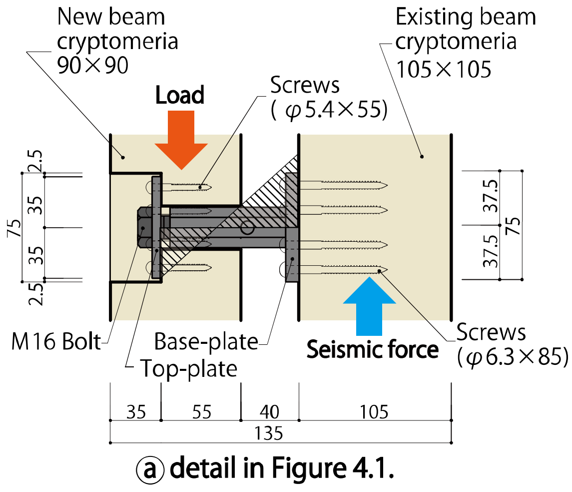


Figure 3.1. Steel connection **Figure 3.2.** Connected beams **Figure 3.3.** Load transfer system

4. CONNECTION EXPERIMENT

In order to investigate the bearing performance of the connection, a monotonic loading test was conducted. Figures 4.1. and 4.2. illustrate the steel connection specimens, whereby existing and new beams connected with two steel connections were vertically set in the loading machine. The top of the new beam was pushed down by the actuator and relative vertical displacements were measured between existing and new beams. Two specimens were tested under similar conditions.

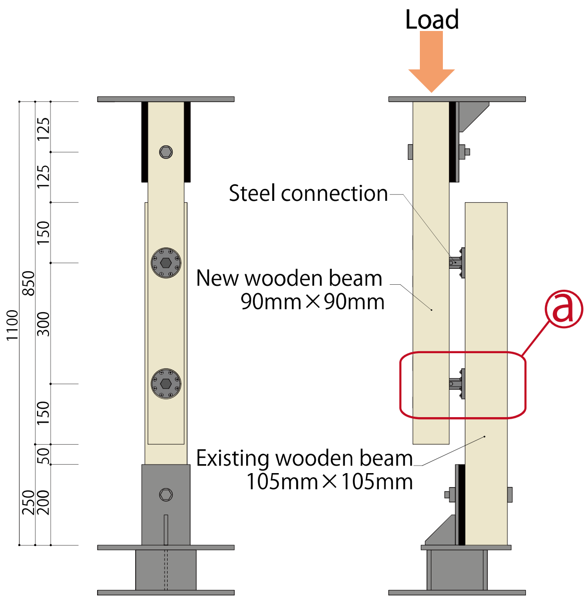


Figure 4.1. Specimen of the steel connection **Figure 4.2.** Test in Lab

The load-displacement relationships of the tests are shown in Figure 4.3. and pictures of the damaged connection during the test are shown in Figure 4.4. As Figure 4.3. shows, no significant difference is observed in the load-displacement relationships in the two tests. Pulling out of the screws (ϕ 6.3×85) and rocking of the connection were first observed when an 18kN load was applied per connection, i.e. a total load of 36 kN ((B) in Figure 4.3. and Figure 4.4.). The damage increased and the peak load was observed with relative displacements of 32 and 27mm. The maximum bearing loads were 24 and 26kN. No significant strength deterioration was observed until the relative displacement of 45mm. The bearing strength of the connection was identified at about 18kN per piece.

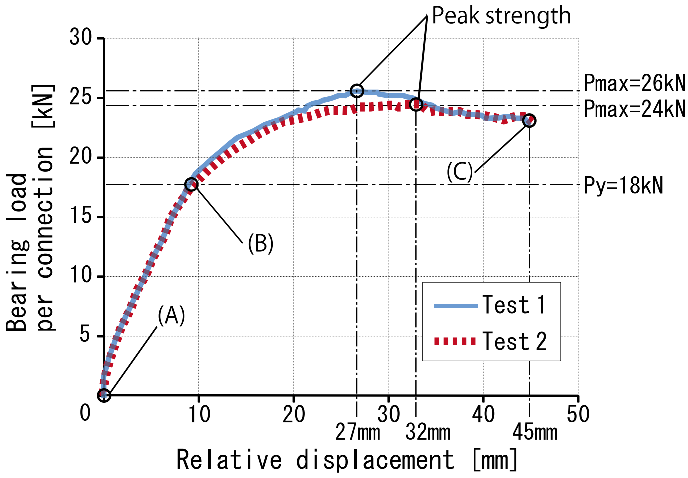


Figure 4.3. Load-displacement relationships

(A) No loading

(B) Elastic limit (9mm/18kN)

(C) Maximum displacement (45mm/23.5kN)

Figure 4.4. Damaged connection during the test

5. SHEAR WALL EXPERIMENT

Following the experiment of the connection, the shear performance of the wall was examined. A shear wall test was conducted referring to the statement of the operating procedures of the wooden shear wall test, which explains the shear performance evaluation of the wooden shear wall, as well as testing procedures. Figure 5.1. shows the tested shear wall. The height from ground sill to beam was 2730mm and the width between the columns was 910mm. The new wooden frame connected the existing wooden frame via two steel connections. Galvanized thin steel plates (0.8mm thickness) were separated into four and screwed into the new frame. A static cyclic load was applied to the left end of the existing beam by a hydraulic jack. Three possible failure mechanisms are predicted for the shear wall test. They are failure at the steel connections between the existing and new beams (mode 1), bending failure at the ground sill around the column anchors with the pull-out tensile force induced by the overturning moment (mode 2), and bearing failure in the screw connections between the thin steel plates and new wooden frames (mode 3). In Mode 3, further detailed failure mechanisms are considered as tear-out the steel plates, failure of the wooden frames, shear yielding of the screws, and combinations of them. Among these mechanisms, tear-out of the steel plates is a preferred mode, because the steel plates are replaceable after large earthquakes. Sizes of the screws and their pitch were designed as $\phi 5 \times 35$ and 227mm intervals, which make the tear-out of the plates the dominating mechanism. Using the bearing strength of the screw connection calculated, corresponding ultimate lateral strength of the shear wall was predicted as 7.5kN. The lateral strength with Mode 1 and Mode2 were 36kN and 10kN, respectively, where the Mode 1 strength was derived from the test results of the connection. The strength with these modes is greater than that with the screw failure. Consequently, it was the predicted dominating failure mechanism.

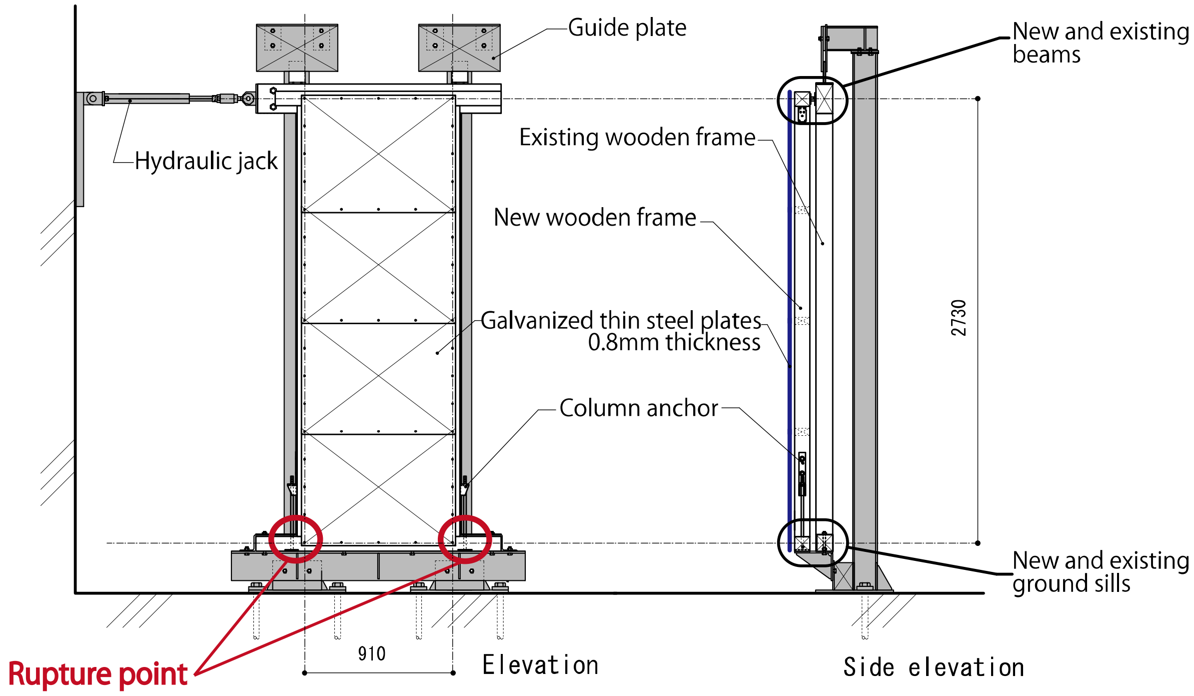


Figure 5.1. Specimen of shear wall test

Figure 5.2. shows the envelope of the lateral load-displacement relationships. The maximum (Pmax) lateral load of 11.7kN was observed with rotation deformation of 4.7% and the test load was significantly decreased below 80% of maximum load (0.8Pmax) by the rupture of the new ground sill near the anchor (Figure 5.3.), although, the limit state was designed with breakage at the screws between the galvanized thin steel plates and the new frame. One possible reason for this failure mechanism is that the strength of the screw connection may be greater than the calculated value. Moreover, the test load was gradually increased until 6.6% (Figure 5.4.). The lateral strength for the shear wall design was identified at about 5.8kN per meter based on the statement of operating procedures. Also, the rupture of the new ground sill considered attributable to the high aspect ratio of the specimen and the lateral strength may be higher in the actual design mechanism.

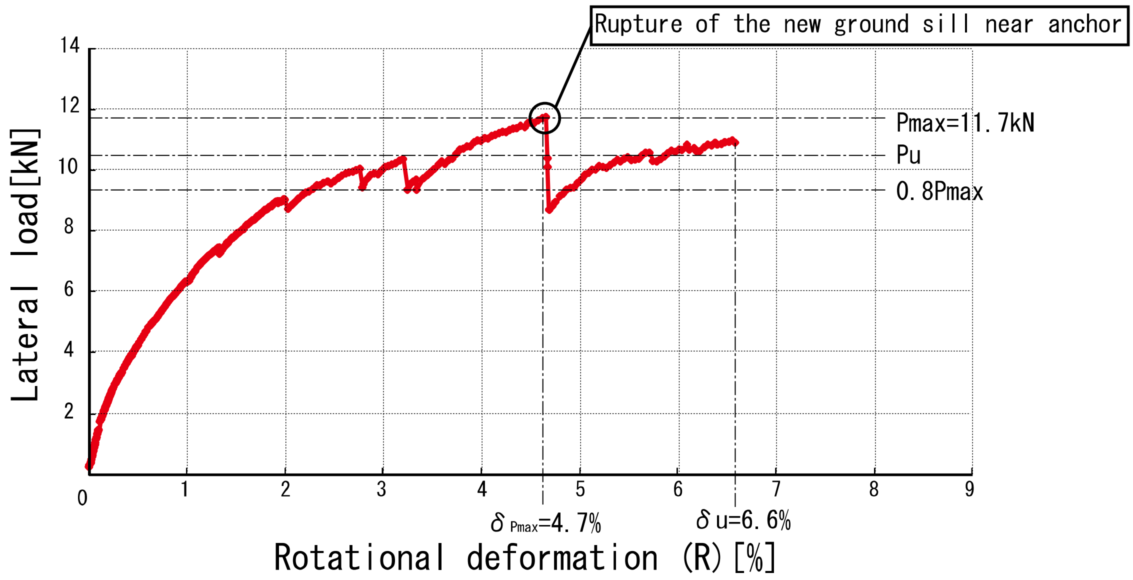


Figure 5.2. Envelope of the lateral load-displacement relationships

Figure 5.3. Rupture near anchor

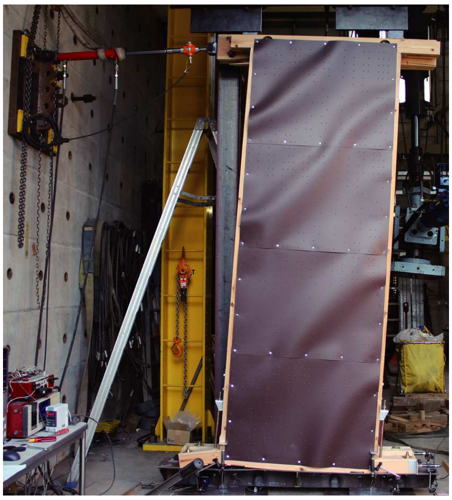


Figure 5.4. Limit state (R=1/15)

6. APPLICATION

The reinforcing method was applied to an existing two-story wooden house. The lateral strength of the wall reinforced using this method was evaluated based on the shear wall test. Consequently, the seismic resistance of this house was improved and verified by conducting a simple seismic performance evaluation of the building before and after the strengthening. Figure 6.1. shows this house before and after strengthening. Because of practical and financial reasons, only a part of the exterior walls of the existing house was covered with the galvanized thin steel plates. The seismic strength of the house was improved with the covered part as indicated in Figure 6.2. The existing architectural finish is wooden board painted in brown. Harmonizing the color, steel plates in brown with round emboss patterns were primarily used with secondary use of green plates as shown in Figure 6.1. During the construction, it appeared that the house was slightly tilted and gaps between the right vertical new wooden frames varied on the height. Also, the levels of the existing beams on the second floor were not uniform. Difficulty was found in adjusting these irregularities and flexibility in the connecting mechanism is needed for future improvement of the method. In addition, fabrication of 0.8mm thick steel plate on site was not possible and use of thinner plates is to be studied.

Before strengthening

After strengthening

Figure 6.1. Reinforcing method application

Figure 6.2. Reinforced part

7. CONCLUSION

In order to accelerate the seismic strengthening of existing wooden houses in Japan, a new reinforcing method using external galvanized thin steel plates was developed. The galvanized thin steel plates are placed over the existing architectural finish and function not only as seismic lateral load carrying elements but also as a new architectural finish. Therefore, the method has the potential to improve various aspects of housing environments including heat insulation and aesthetics, as well as seismic resistance. The following knowledge was obtained in this research.

1) In the reinforcing method, new wooden frames are placed outside the existing finish, and galvanized thin steel plates are screwed onto them. A prototype steel connection between existing and new beams was developed and the bearing performance of the connection was examined by monotonic loading tests. The failure mechanism of the connection is pull-out of the screws (ϕ 6.3 $\times$ 85) and rocking of the connections. The bearing strength is approximately 18kN per connection.
2) A full-scale shear wall test was conducted in order to investigate the lateral load carrying capacity of the wall. Failure of the screws between the thin steel plate and the new wooden frame was expected to be the mechanism; however, it was the rupture of the ground sill around the anchor of the columns. For design use, the lateral strength of the shear wall was identified at 5.8kN per meter. Considering the unique failure mechanism of the shear wall in the test with a high aspect ratio of the specimen, the actual design mechanism may differ and the lateral strength was able to be higher.
3) The developed method was applied to a two-story wooden house. A simple seismic performance evaluation of the building before and after strengthening was conducted and the effect was verified.

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