Japan Kobe Earthquake Shake Table Simulation

Earthquake Performance of Multi-storey
Cross Laminated Timber Buildings

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On October 23rd 2007, a seven storey Cross Laminated Timber building was tested on the world's largest earthquake shake table at Miki near Kobe in Japan. Cross laminated timber construction and the preliminary earthquake and fire tests are overviewed. The huge E-Defense shake table facility in Japan and the test building are described and the earthquake records used to test the building. The building performed well when subjected to the severe Kobe earthquake record. It had some minor softening and no residual deformation. Accelerations measured within the building were large and need further design consideration.

Background

Professor Ario Cecotti of the Trees and Timber Institute (CNR Ivalsa[1]) in Italy has undertaken a substantial research programme into the German / Austrian cross-laminated timber technology (Project SOFIE[2]). The project was sponsored by the Province of Trento to use Italian wood in the cross-laminated timber panels shipped to Japan for the full scale earthquake test buildings. Two years ago, a three storey building was tested in Tsukuba. This was preliminary to the seven storey tests at Miki in collaboration with three Japanese partners, the *National Research Institute for Earth Science and Disaster Prevention* NIED, the *Building Research Institute* BRI, and *Shizuoka University.* Hugh and Pierre were privileged to be able to take up the invitation to observe the final test which drew substantial media attention. It was timed to fit an "Italian Spring" promotion in Japan with representatives present from the Province of Trento and the Italian embassy.

Cross laminated Timber Construction

Cross-laminated timber consists of strips of lumber stacked on top of each other at a 90° angle and glued together under high pressure to become large-sized solid cross-laminated boards. Depending on requirements, the board can have three, five or seven layers. The strips vary in thickness between 19 and 40 mm (see Figure 1). As for the glue-laminated technology, cross-laminated boards can be fabricated using low-grade lumber within the core of the boards and with higher grade pieces on the outside. This has the advantage that a wider range of board densities can be used for this engineered wood product.

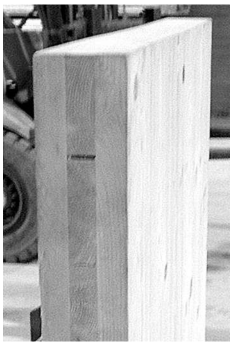

Figure 1. Detail of cross-laminated board.(Middle board has tension rings running in opposite direction to outside two boards)

Cross-lamination of the strips minimises shrinkage and swelling while increasing static strength and shape retention properties. The loads can be transferred on all sides, as a true plate and sheet action. Some forms of cross-laminated boards are fabricated using aluminium nails to permit machining without damaging the cutting tools.

The separate layers of lumber are glued using interior/exterior polyurethane adhesives. The glues are formaldehyde and solvent free adhesives. The solid cross-laminated boards are usually fabricated in industrial quality but visible interior application standards are also possible on demand but require extra care during handling.

The boards can be trimmed to size at the manufacturing site or cut on site (see Figure 2). The fabrication of large elements and the prefabrication of wall segments in factories protected from the weather are requirements that can also apply to timber construction. These boards have the advantage that they can be delivered to the construction site easily and quickly and ready for finishing (see Figure 3). They can be manufactured with the maximum length, width and depth of 16.5 m, 2.95 m and 0.6 m respectively.

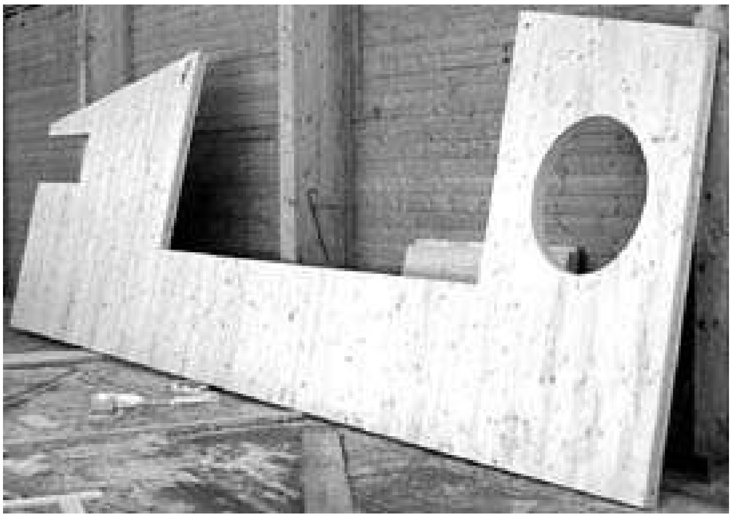

Figure 2. Cross-laminated panel cut to shape and ready for delivery.

Figure 3. Cross-laminated industrial building under construction.

Since they are structural elements as such, they can be used as both building envelopes and structural members. For spans too long or loads too high, their use can be combined with other structural members such as sawn timbers or more commonly glue-laminated columns, beams and trusses.

Research Background

The mechanics behind the cross-laminated technology are not different from beam and plate theories. However, one has to take into account the reduced stiffness of the laminations that are laid at 90°. The cross layers result in increased deflections for a given element depth. As well, rolling shear, as for plywood, becomes important and must be verified.

Most of the research has been done in Germany and Austria. It is already accepted within the German design code. Research has shown that the cross-laminated board elements includes the laminating effect of the glue-laminated beams and the system effect observed for equally spaced similar members (Jobstl et al., 2006). More research on various connections techniques is being undertaken presently.

Three Storey Building Tests

In 2006, the Italian Trees and Timber Institute – CNR Ivalsa, initiated the testing project to evaluate the seismic resistance of a three storey timber building, constructed using cross-laminated boards (see Figure 4). The building was approximately 7m x 7m in plan.

Following the results of a series of pseudo-dynamic tests on small cross-laminated board assemblies, the research team subjected the three storey cross-laminated timber building specimen to a series of seismic records on the Tsubuka, Japan shake table. The building performed adequately, returning to its original position after both the El-Centro and Kobe earthquakes.

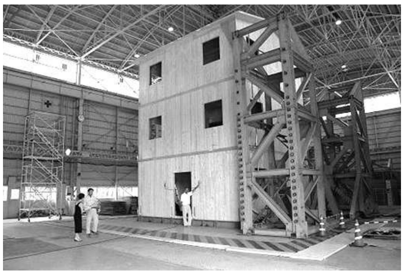

Figure 4. Three storey cross-laminated building tested on second largest shake table in Tsukuba Japan.

The building was then moved to another location in order to conduct a fire test (see Figure 5). The test consisted of initiating a fire in one of the corner rooms of the building. Mattresses and wood were added to simulate a typical bedroom contents. All walls and ceilings were covered with gypsum boards. The temperature in the test room attained 1000°C. The temperature in all of the adjacent rooms remained at approximately 20°C. The fire was allowed to proceed for more than an hour. A significant amount of char formed on the surfaces of the cross-laminated building elements, following the failure of the gypsum board fastenings. The building passed the required fire test.

Seven Storey Test building

A seven storey building using cross-laminated components was fabricated and shipped from Italy. A five storey section was built and lifted onto the shake table. The top two storeys were then lifted on top and connected. The whole 23.2m high building was erected in a little over a week (see Figure 6).

Figure 5. Three storey cross-laminated building fire tested after the earthquake tests.

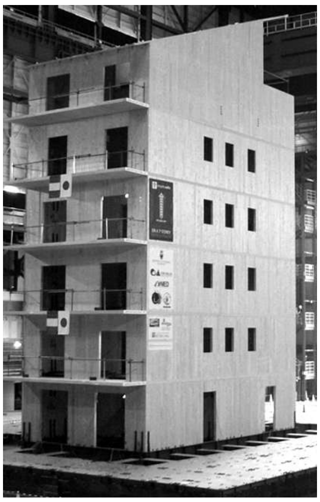

Figure 6. Photograph of test building in the test facility.

The fourth floor typical plan is shown in Figure 7 although level two had less cross walls and was the lowest in stiffness. The building used 250m^3 of timber and weighed 120 tonnes. Each floor had an additional 30T of mass to simulate the weight of concrete floor topping, linings and internal fixtures. The lower walls and all floors were 142mm thick and upper level cross-laminated walls were thinner.

Figure 7. Level 4 layout of seven storey
cross-laminated test building.

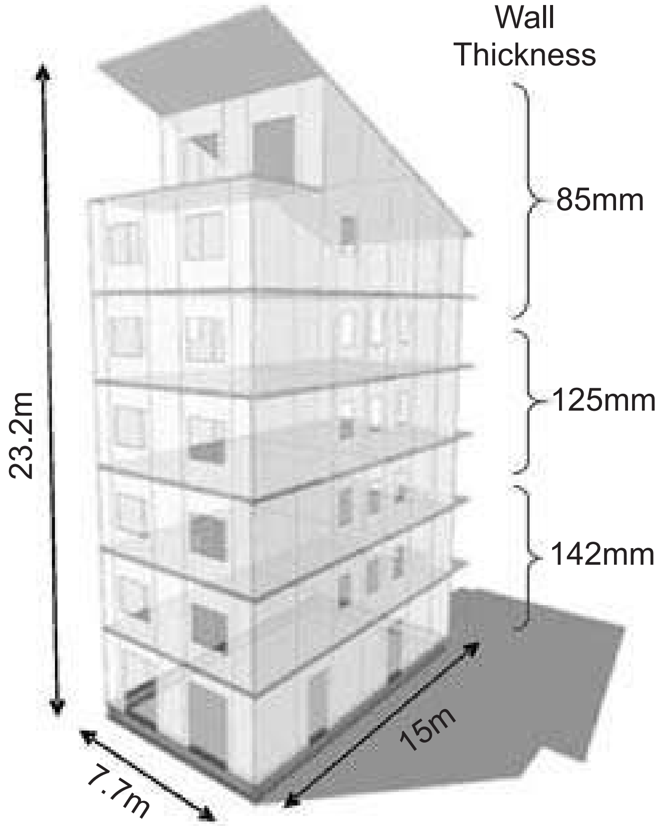

Figure 8. Seven storey cross-laminated test
building dimensions and wall thicknesses.

E-defense Facility

The tests on the seven storey building were undertaken on the largest earthquake shake table in the world, located at Miki near Kobe in Japan (see Figure 9). This facility is vast. It was excavated about 10 storeys deep in order to reach bedrock and to install the 8m long hydraulic rams. The table size is 20m x 15m (about the playing area of a tennis court) and can carry a 1200T building. It can apply vertical accelerations of around 2g and horizontal accelerations of 1g. It can move up to 1m horizontally and has 6 axes of motion (Figure 10). This facility was constructed so that full-scale three storey reinforced concrete buildings could be tested under realistic seismic conditions.

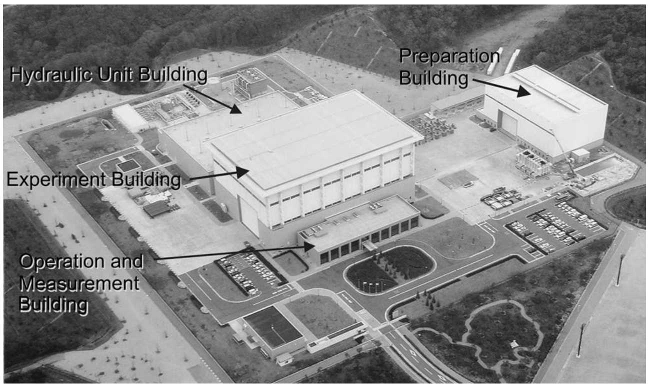

Figure 9. Aerial photograph of huge E-defense shake table facility.

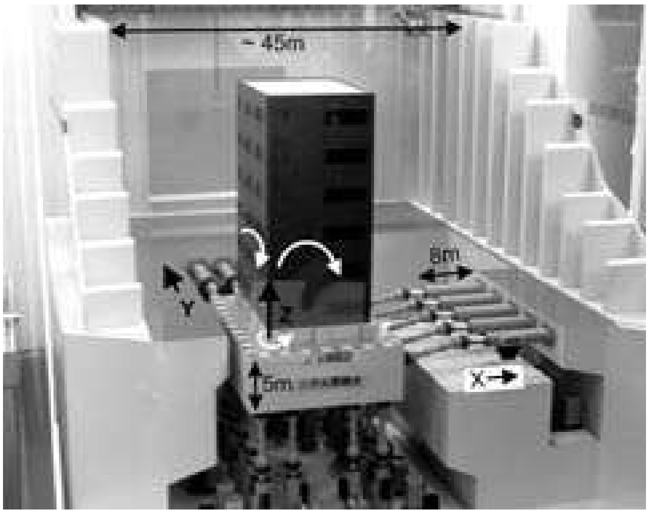

Figure 10. Model of E-defense shake table showing axes of motion and scale.

Earthquake Records

In October 2007, the seven storey building was subjected to a 50% Kobe record on October 20 and the full Kobe 3-D record was applied at the first test we witnessed on October 23rd. This is a well recorded, severe near fault record that is well in excess of what is anticipated in Italy but which has a huge significance in Japan. As extracted from Kitada et al.[3] and shown in Figure 11, the maximum horizontal accelerations are 0.82g N-S and 0.60g E-W. The maximum vertical acceleration was 0.34g.

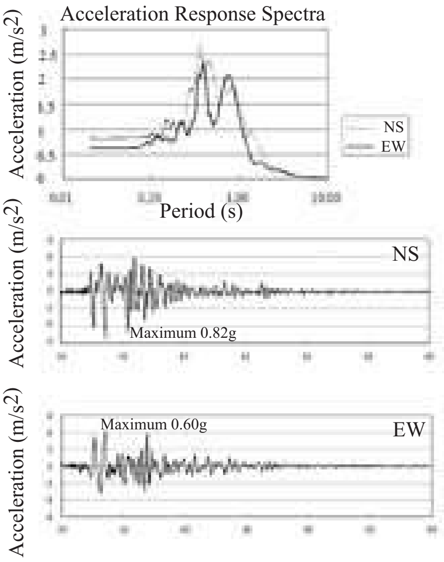

Figure 11. Horizontal acceleration record and response spectra for the 1995 Kobe earthquake.

Test Results

Official publications are not yet available but it was clear that the seven storey building performed very well and appeared to respond little beyond the elastic range with major components clearly stable and responding well. The building made loud noises as it moved but there was no damage visible from the viewing area. The team of researchers who had access to the test specimen reported that some of the screw connections for the panel hold-downs needed to be repositioned as they had failed. This is considered minor as long as the overall integrity of the building was retained. Moreover, one could easily plan for the easy re-location of these hold-downs in future construction.

Shortly after the 100% Kobe earthquake test, the coordinators reported that there was no residual deformation, the maximum inter-storey drift was 40mm, and the maximum lateral deformation did not exceed 300mm. Engineers operating the facility reported that this was the tallest building they have tested and that its performance was much better than a pre-stressed concrete building subjected to the same record two weeks earlier.

The maximum accelerations within the building from the Kobe input were 4g in the X direction and 2g in the Y direction. Before the tests, a modest 0.3g excitation was applied to determine the building response frequency - in one direction this was 2.5 Hz. Following the test, it was measured at 2Hz, indicating a softening of the structure attributed to connection loosening.

The second test of the day had lower accelerations which meant that there was significantly less response. We would have preferred to see larger earthquake inputs to see the collapse mechanism or significant loading into the inelastic range. The success meant that the building was going to be reassembled as a student accommodation facility in Italy.

Conclusions

In this test, the cross-laminated technology proved adequate in resisting the seismic actions imposed and in the ability to offer the flexibility to engineers to re-position hold-down anchors following a major seismic event. The fact that none of the cross-laminated boards were damaged significantly and that the whole structure was dismantled, shipped back and re-used in Italy is a proof that wood structures can be used efficiently in structures and that they can be recycled. All of these cross-laminated boards could be used in other structures, under different environments.

The earthquake test clearly demonstrated that the building was very stable under this severe level of shaking. The video sequences showed that this deformation was more severe than we could see from the observation point but it was well within acceptable limits. Video of the interior of the building showed a table moving very rapidly about a meter and chairs being thrown to the ground. The 4g accelerations within the building would endanger the lives of building occupants in New Zealand or Japan, the maximum earthquake anticipated in Europe is nearer 0.3g so there is less potential danger. As a stiff lightweight system and with the addition of a lower floor, this building would be ideally suited to a seismic isolation system.

This event demonstrated the ability of the timber construction industry to adapt to new markets. An engineered timber material was pre-fabricated in Italy and then shipped in containers to Japan for erection. This building was subjected to two of the most severe recent Japanese earthquakes and survived without significant damage or residual displacements and then, was shipped back to be re-used as a student residence in Italy. This is a great example of sustainable construction. New Zealand, with its vast timber resources, should develop this technology for domestic construction and export markets.

References

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