PERFORMANCE OF ENGINEERED TIMBER STRUCTURES IN THE CANTERBURY EARTHQUAKES

Andrew Buchanan[1], David Carradine[2] and Justin Jordan[3]

SUMMARY

The September 2010 and February 2011 earthquakes in Canterbury, New Zealand resulted in significant ground excitations that caused severe geotechnical effects and widespread structural damage. This paper outlines the various forms of damage to different types of engineered timber structures, including timber water tanks. Most of the damage resulted from lateral spreading and high levels of horizontal and vertical ground acceleration. The response of these building types is discussed. Engineered timber structures generally performed well both for life safety and serviceability, with most buildings ready for occupation within a short time following the events.

INTRODUCTION

This paper is a review of the performance of engineered timber structures in the Canterbury earthquakes of 4 September 2010 (referred to as the "2010 earthquake") and 22 February 2011 (referred to as the "2011 earthquake"). For buildings, all the reported damage is from the 2011 earthquake unless noted otherwise. Details of the earthquakes including severity and seismological aspects are described by others [1 and 2]. This paper includes engineered timber buildings using glue laminated (glulam) and laminated veneer lumber (LVL), and engineered timber tanks. Domestic house construction is only included to show some unique performance characteristic of timber building components used in residential applications. A full evaluation of the performance of houses during the 2010 earthquake [3] and the 2011 earthquake [4] are provided in other publications. Performance of churches, including some timber structures, is also covered elsewhere [5].

PORTAL FRAME BUILDINGS

Industrial Buildings

In general, timber portal frame buildings performed well during the earthquakes with minimal damage.

Figure 1(a) shows an industrial building constructed of glue laminated portal frames with nailed steel plates as moment resisting connections and deep timber trusses spanning between the frames. Some shear cracking was observed in columns of two of the frames, as seen in Figure 1(c) and 1(d). Investigations revealed that since the construction of the building nearly 30 years ago one bay of steel "X" bracing had been removed and could have affected the performance of the building, particularly the lateral displacement of the rafter at the knee joint shown in Figure 1(b), since repaired. The building had no restriction on use following the earthquake and repairs to the cracked columns will be executed using long fully threaded screws or epoxied steel rods.

School Halls

Many school halls in the Christchurch region have glulam portal frames. Most had no damage at all. The only damage observed during inspections of many of these buildings was caused by minor lateral movement of foundations, as shown in Figures 2 and 3. The damage in Figure 2 was caused by the 2010 earthquake. Figures 3(a), 3(b) and 3(c) are all the same school building, where the only damage was the minor foundation movement shown in Figure 3(c). A similar school hall suffered no structural damage despite the displacement of ceiling tiles shown in Figure 3(d).

Swimming Pool Buildings

Several glulam swimming pool buildings were inspected. The only damage was very minor, such as shown in Figure 4(a) and 4(b). Based on current knowledge, none of these buildings have required repairs and they have continued to be occupied.

---

[1] *Professor of Timber Design, Department of Civil and Natural Resources Engineering. University of Canterbury, Christchurch (Fellow).*

[2] *Timber Design Engineer, Department of Civil and Natural Resources Engineering, University of Canterbury, Christvhurch (Member).*

[3] *Managing Director, Service Contracts Manager, Timbertank Enterprises, Auckland (Member).*

(a) Overall structure showing glulam portal frames and truss purlins.

(b) Local lateral displacement of rafter at knee joint.

(c) Vertical shear crack in column (location shown by arrow).

(d) Detail of shear cracks in another column of the same building.

Figure 1: ***Damage to an industrial timber portal frame building.***

(a) No damage to curved portal frames.

(b) Minor lateral movement of foundations.

Figure 2: ***School hall with curved glulam portal frames, damaged in the 2010 earthquake.***

(a) School hall portal frames.

(b) No damage to nailed knee joint.

(c) Minor foundation movement visible at floor level.

(d) No damage to portal frames despite ceiling tiles displaced by shaking.

Figure 3: School halls with straight glulam portal frames.

(a) Re-opening of old shrinkage crack at epoxy rod connection to foundation.

(b) Minor gap opening due to lateral movement.

Figure 4: Minor damage to the glulam structure in a swimming pool building.

(a) Timber frames with damaged masonry infill walls.

(b) Portal frame knee joint and purlin blocking.

Figure 5: Performance of nail-laminated portal frames.

(a) Test building under construction in the University of Canterbury labs.

(b) Building being tested under simulated seismic loading.

(c) Finished building, at night.

(d) CEO Robert Finch at his office desk.

Figure 6: EXPAN on the University of Canterbury campus.

Community Buildings

Other portal frame structures are also part of the stock of single storey engineered timber structures around Christchurch and some of these were investigated and shown to have minimal damage, particularly to the timber portal frames. One example was an older building located in the Eastern suburb of Shirley and used for sports activities, which was comprised of a series of nail-laminated frames having a span of approximately 13m (Figure 5). This type of construction was described by Walford [6] and proved to be a robust and seismically resistant system. The building consisted of seven frames having masonry infill between them to provide lateral bracing. While the masonry walls were damaged the frames remained intact and were in no danger of failure.

MULTI-STOREY TIMBER BUILDINGS

The only modern multi-storey timber building subjected to the 2011 earthquake was the EXPAN building on the University of Canterbury campus. This is a two storey post-tensioned timber building, being developed and promoted by the Structural Timber Innovation Company Ltd (STIC), a government and industry funded research consortium, marketing this type of building as the “EXPAN building system incorporating Pres-Lam technology”. The building started life as an experimental test building as shown in Figures 6(a) and 6(b), now reassembled as the STIC head office shown in Figures 6(c) and 6(d). Additional details on this building are provided by Newcombe et al. [7] and Smith et al. [8]. During the 2010 earthquake the building had been deconstructed for removal to the new building site, so it was not affected by the earthquake.

Seismic design for re-erection as a real office building used the then current New Zealand Building Code (i.e., hazard factor Z = 0.22). The building was estimated to have a fundamental period of 0.34 seconds, it was given an importance level of 2, and it was designed for a 10 year design life (i.e., $R_{ULS} = 0.75$) (Holmes Consulting Group, pers. com.). The Ultimate Limit State (ULS) design spectrum derived for this condition is shown by the solid black line in Figure 7(b).

In the February 2011 earthquake, the building suffered no damage to the structure, the interior linings or the exterior cladding. Since then the building has been instrumented with accelerometers for monitoring movement during aftershocks. The most significant event captured by the instruments to date was the M6.3 aftershock of 13 June 2011, registering peak ground accelerations of 0.18g and 0.16g in the X and Y direction respectively, as shown in Figure 7(a). When this motion is compared to the ULS design spectrum, a close fit is found as shown in Figure 7(b). Once again no damage to either the structure or architectural fittings was found.

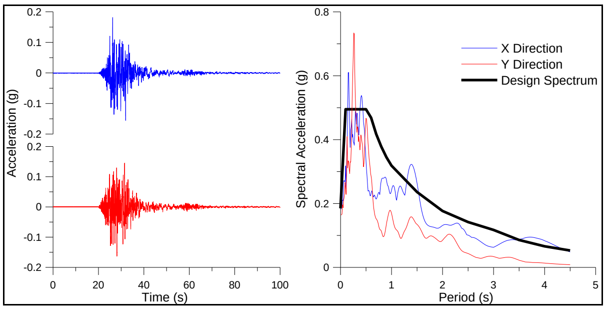

Figure 7: Response of EXPAN building to M6.3 aftershock of 13 June 2011, (a) Base accelerations in X and Y directions; (b) Acceleration response spectra (right).

TIMBER HOUSE CONSTRUCTION

The performance of residential houses is described elsewhere [4]. In general, timber houses performed well during the earthquakes with a very limited number suffering collapse. A relevant aspect of house performance is the performance of manufactured trusses, which are frequently used for roof systems in houses but also in larger timber buildings.

No damage was observed in any pressed metal plate trusses, as used in most residential houses. One case of damage to a bolted truss connection in an architecturally designed house is shown in Figure 8, after emergency repair with a screwed steel plate.

Figure 8: Emergency repair to a bolted rafter connection in a private house.

(a) Damage to Mandeville Bridge following 2010 earthquake.

(b) Condition of repaired Mandeville Bridge as of July 2011.

Figure 9: Performance of pedestrian timber bridge in Kaiapoi.

(a) Base Isolation sliding of 50 mm for 400 m^3 tank in Kaiapoi. No damage to tank.

(b) Base isolation sliding of 20 mm for 180 m^3 tank near Darfield. No damage to tank.

Figure 10: Performance of timber tanks during 2010 and 2011 earthquakes.

TIMBER BRIDGES

Timber bridges were evaluated following the 2010 Earthquake [9] and were found to have been damaged primarily due to lateral spreading of embankment supports and some lateral movement of piers, as shown in Figure 9. Timber bridges assessed were pedestrian bridges and therefore designed to less rigorous standards than vehicle bridges. Many of these bridges have also been relatively quickly repaired (Figure 9(b)).

TIMBER TANKS

Timber stave tanks are the most popular form of timber tank used in New Zealand. They consist of a barrel wall of vertical timber staves prestressed by circumferential steel cables, with an internal plastic liner to retain the liquid. Most are used for storing water.

“Timbertank” is the trade name for tanks of this type manufactured by Timbertank Enterprises Ltd [10]. Similarly, “Woodpak” was the name for a similar tank, fabricated with plywood roofs, but these have not been manufactured for nearly 20 years.

Timbertanks have a double liner system on a sand cushion, sitting on a compacted hard fill foundation. In a typical tank, the barrel wall stands near the centre of a circular concrete ring 900 mm wide, but the barrel is free to slide with predetermined friction. In an earthquake, the barrel wall staves and the sand cushion can move sideways up to 300 mm on the concrete ring. A sand cushion, 150 mm deep, carries the plastic liner and keeps it away from the sliding parts.

Timbertanks have been developing their seismic protection since the 1987 Edgecumbe earthquake with the help of Trevor Kelly of Holmes Consulting Group. In the Edgecumbe earthquake, out of 30 tanks in the earthquake-affected area, only two tanks failed. One slid into a concrete slab knocking it down, and the second was pushed off its site by a landslide. Timbertanks are inherently base isolated so that the ground can move under the tank thus absorbing energy, hence minimising slosh waves. The base isolation on a sand base has worked very well in earthquakes. It is assumed that the tank slides on its base when the P-wave arrives. With the slower moving S waves, a significant slosh wave can be formed if the resonant frequency of the liquid in the tank matches that of the earthquake. This was the case in the 2011 earthquake which delivered a sustained 3 second period vibration. After a visual wave tank testing program, Timbertanks has developed a slosh wave spoiling seismic baffle. A computational fluid dynamics (CFD) program is also being developed, which will model earthquake attack on any style of tank design.

Timber stave tanks generally performed very well in the Canterbury earthquakes. Out of more than 30 tanks in the Canterbury region, six Timbertanks and one Woodpak tank were damaged in the 2010 earthquake, and none were damaged in the 2011 earthquake or any subsequent aftershocks. For the tanks that performed well, all showed signs of lateral sliding of 20 to 60 mm, as shown in Figure 11.

Figure 11: Pipe damage due to rotation of 100 m^3 tank at West Melton. No damage to tank.

Figure 12: Damage to 210 m^3, 7.75 m diameter tank in Hornby caused by a 3 sec slosh wave in the 2010 earthquake. The liner ruptured. The broken timbers have been replaced and the tank is working again now with a baffle system installed.

(a) View showing movement to the right (north-east direction): 2010.

(b) Large lateral displacement and twisting movement: 2010.

(c) Shear cracking in timber staves 2010.

Figure 13: Damage to 400 m^3 tank at Northland Mall.

The 400 m^3 tank at Kaiapoi, shown in Figure 10(a), moved to expose the pale concrete, and it has run over the orange power chord. This confirms that the tank moved backwards and forwards. The horizontal pale lines on the barrel staves in this photo are old cable marks as this tank was rebuilt and increased in size from 300 m^3 to 400 m^3 in 2009. As another typical example, the 180 m^3 tank in Figure 10(b), located 10 km from Darfield, only moved 20 mm in the 2010 earthquake. Figure 10 shows the sliding of a 100 m^3 tank in West Melton. The shaking pushed back the backfill 70 mm around the tank, and the tank rotated on its site by 170 mm.

Of the seven tanks which lost content, four were laterally displaced by about 1 m, but remained structurally intact. Liners were ruptured and they lost water (7.8 m, 11.2 m, 11.2 m, and 11.5 m diameters). Two badly damaged tanks (6.9 m and 10.5 m diameters) were tied to heavy steel pipes and fences, and were backfilled with soil up to 500 mm deep, thus preventing base isolation. The combined effect of this base-fixity, exposed to the 2010 earthquake 3 second period slosh waves, rocked the tanks and led to failure initiated by liner hernia. One other damaged tank (9.45 m diameter) was significantly damaged by a slosh wave (Figure 12).

Figure 13 shows extensive damage to the 400m^3 sprinkler fire-fighting water supply tank at Northland Mall in Papanui in the 2010 earthquake. In the left photo (a), the tank has moved to the right (North-East). The centre photo (b) shows that the steel external inlet has moved 1.35 m from the tank wall and the tank has rotated 2.25 m to the right. The right photo (c) shows shear cracking in the timber staves over a 3 m wide area on the far side of the tank from the road. This tank was repaired in November 2010. The tank was craned back on to site. Stave shear, which assists energy dissipation, was corrected, and shear cracked timbers were cut out and replacement tongue and groove boards were butted in, with staggered end joints, and the cables were re-tensioned. Baffle foundations were installed, a new liner was installed, and the seismic baffle was fitted as shown in Figure 14.

After the 2011 earthquake, the only visible sign of damage was a 2 m area of back-fill pushed back 25 mm. This movement was so small and local it may be more related to the barrel adjusting its shape. A visual observation of the tank during the 2011 earthquake reports that the tank was seen to be shaking and rocking and water was spilling out of the roof. Once the earthquake finished the tank remained vertical and water tight.

Figure 14: The newly-installed seismic baffle in the tank at Northlands Mall.

CONCLUSIONS

Engineered timber structures behaved remarkably well in the Canterbury earthquakes. There currently exist only a small number of such structures in the region, but more are likely in the future. The seismic design of future timber structures will be influenced by the excellent observed performance and lessons learned in 2010 and 2011.

ACKNOWLEDGEMENTS

Thanks to Will Parker at Opus International Consultants for photographs of glulam school buildings. Thanks to Tobias Smith for the report on the 13 June aftershock.

REFERENCES

1. Berrill, J.B. (2011). Some Aspects of the M6.3 February 22nd 2011 Earthquake. http://www.csi.net.nz/documents/Some%20Aspects%20of%20the%20Feb22%20M6-3_R3.pdf

2. Allen, J. et al. (2010). Geotechnical reconnaissance of the 2010 Darfield (Canterbury) Earthquake, *Bulletin of NZSEE*, Vol. **43**, No. 4, 243-320.

3. Buchanan, A.H. and M.P. Newcombe (2010). The Performance of Residential Houses in the Darfield (Canterbury) Earthquake, *Bulletin of NZSEE*, Vol. **43**, No. 4, 387-392.

4. Buchanan, A. H., Carradine, D.M., Beattie, G.J. and Morris, H.W. (2011). Performance of Houses During the Christchurch Earthquake of 22 February 2011, *Bulletin of NZSEE*, Vol. **44**, No. 4, December 2011 (this issue).

5. Anagnostopoulou, M., Bruneau, M. and Gavin, H.P.. (2010). Performance of Churches During the Darfield Earthquake of September 04, 2010, *Bulletin of NZSEE*, Vol. **43**, No. 4, 374-381.

6. Walford, G. B. (1966). A Woolshed with Nail-Laminated Portal Frames. *New Zealand Timber Development Association Bulletin*, Vol **2**, No. 8, 10-12.

7. Newcombe, M.P., Pampanin, S., and Buchanan, A.H. (2010). *Experimental Testing of a Two-Storey Post-Tensioned Timber Building.* 9th US National & 10th Canadian Conference on Earthquake Engineering, Toronto, Canada, 8.

8. Smith, T.R., Wong, M., Newcombe, D., Carradine, S., Pampanin and Buchanan, A.H.. (2011). Demountability, Relocation and Re-use of a High Performance Timber Building. *Proceedings, Ninth Pacific Conference on Earthquake Engineering*, NZSEE, April 2011, Auckland. Paper 187.

9. Palermo, A., Le Heux, M., Bruneau, M., Anagnostopoulou, M., Wotherspoon, L. and Hogan, L.. (2010). Preliminary Findings on Performance of Bridges in the Darfield Earthquake, *Bulletin of NZSEE*, Vol. **43**, No. 4, 412-420.

10. Timbertank Enterprises Ltd: www.timbertanks.co.nz