BASE-ISOLATION OF TIMBER-STAVE RESERVOIRS

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Abstract
The base-isolated timber stave reservoir is now firmly established in the Pacific as a proven choice for the storage of water volumes up to 3megalitre. It must be noted that the now highly rationalised timber structure may well meet performance criteria better than those built from alternative materials.

Keywords: Reservoir, Tank, Wood, Water, Earthquake, Cyclone.

History

Though having served humankind well for the best part of a millennium, the timber stave tank had recently been neglected in favour of steel and stressed concrete alternatives. Well directed production over the last twenty five years from a base in New Zealand has given timber construction an assured new life.

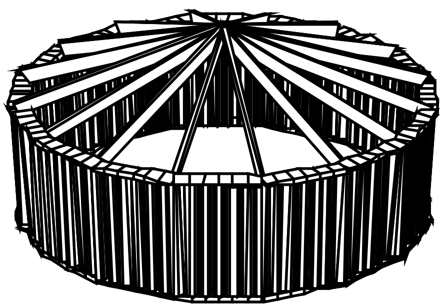

Figure 1 - Computer model of staves and rafters showing independence of floor construction.

Although a continual theoretical and research program has paralleled the building of now more than four thousand such tanks and reservoirs throughout the Pacific, acceptance of theoretical justification by the engineering profession has been slow.

About 1970 a client request to have water storage provided on a site difficult of access led to the architect, Morton Jordan, using surplus tongue and groove mill flooring to form a floorless vertical barrel lined with a polythene water barrier (Fig 1). The 22.5° conical roof built from timber weatherboard shingles in sixteen segments, completed a unit so successful that the experiments continued with formation of a company to focus effort on this specific product.

Early engineering attention was concerned mostly with hydrostatic loading, and the provision of economic banding using steel cable and friction grips. As the size of the tanks grew rapidly from 2metre diameter to 4metre and more, the requirements of seismic codes in New Zealand became the prime engineering concern. Engineers at the time generally dismissed this method of construction as having no future in seismic performance. Those closest to the actual construction realised however that the modest prestress given to the hoops resulted in a barrel which was able to span soft ground under a significant arc of the perimeter. Over a period of several years, site observation showed that the moisture swollen timbers on the inner face were maintaining a very significant vertical shear resistance along the tongue and groove joint.

This prompted studies directed by the author of the loss of cross-grain stress induced by initial prestress in cable bands (Olliver and Bosman 1991). The results suggest that regardless of initial moisture content and of subsequent moisture cycling, a residual cross-grain prestress of no less than 500kPa could be relied on from an initial prestress of 2000kPa.

Concurrently, computer models were being developed which related seismic shear to vertical shear between staves. A simple model is shown in Figure 2. This is a circular rigid joint frame exposing vertical elastic shear in the barrel. Shear force in the horizontal members is of course that to which the stave interface is subject during seismic shear. It should at this stage be noted that the seismic shear is limited in magnitude by the base-isolation mechanism which is a feature naturally arising from this construction. Such a mechanism was predicted in a paper to the Pacific Timber Engineering Conference in 1984 (Jordan and Granwal 1984). In 1987 a substantial seismic shock hit the Ohope coastal township of New Zealand in an area where over thirty such tanks and reservoirs existed. Two 500 cubic metre reservoirs had only recently been completed for the local water supply authority. Though full, and sliding approximately 100mm, they continued to function. Another reservoir restricted by access steps in a manner which prevented sliding had collapsed. Yet another farm reservoir had been set 400mm below ground, and though racked approximately 200mm out of plumb, continued to function. The liner in a small tank feeding a nearby orchard had ruptured whilst sliding. No sand plug had been provided during erection. The remaining timber tanks and reservoirs survived without damage. Advances had been made in construction detailing prior to this earthquake so as to enable sliding without liner rupture or stave racking, but significant advances have since been made as a result of the observations made subsequent to that Edgecumbe earthquake. In follow-up studies a small experimental tank was statically forced to slide while full of water, and as predicted a full hysteresis loop was obtained.

Elastic foundations indicated in Figure 2 below were used in Multiframe analyses in lieu of true friction elements. The common view that rocking will take place has never been held by those familiar with the tanks in their base isolated form, and this simple analysis will show, for proportions usually built, that the vertical ground springs are seldom in tension over more than a fifth of the perimeter; a reasonable assurance that wholesale lifting will not take place.

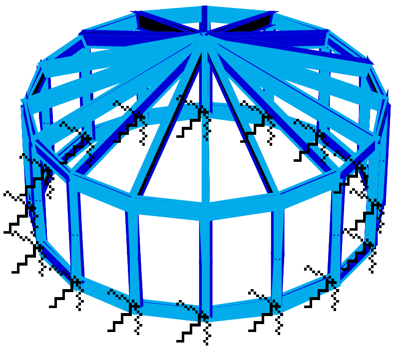

Figure 2 - Rigid joint model with ground springs.

It is currently considered that the diaphragm triangulation of the roof rafters and barrel rim boards is very significant in maintaining the circular shape of the barrel during sliding, as there is little control of barrel shape other than from the hydrostatic pressure exerted by the fluid contained.

It should be noted however that there is significant sliding resistance from the sand plug placed under the liner. This was originally intended to prevent a hydrostatic hernia at the junction of the floor and wall. Although this plug is never more than 100mm deep, it is subject in a full tank to substantial hydrostatic pressure, and so provides a useful measure of seismic resistance in early cycling.

The effects of this can be seen in Figure 3 which is the analytical result of self weight of the barrel, seismic load from the water and experimental levels of sand plug resistance. It can be seen that the rim level controlled by the triangulated cone roof maintains a near true circle, while the base is subject to considerable distortion. It is intended with finite element studies to predict more carefully the actual sand resistance, and to attach the computer model to the ground with friction blocks rather than springs as in the analysis results shown.

The participation of the thin plastic liner in this process is difficult to quantify, most effort to date having gone into detailing the floor-to-wall junction so as to eliminate rupture during frictive sliding.

Custom made friction grips are preferred to the less ductile grips used in the pre-stressing industry. Should there be overstress in a particular cable it is preferred that the grip slides rather than the high tensile cable should snap.

These tanks are now used commonly as fire fighting reservoirs in industry. Placement in a petrochemical plant prompted fire analysis. Rate of charring taken in conjunction with expected draw-down and heat transfer through the water and steel cables showed a satisfactory performance in response to 8kW of radiant heat energy per square metre. Timber tanks used in this manner now have the full confidence of the insurance industry in New Zealand.

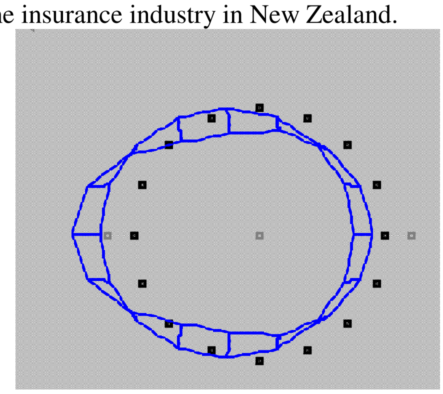

Figure 3 - Seismic deformation at rim and base.

Rafters initially were of sawn timber until the tank diameter forced a rethink. Weatherboard shingles in the roof have remained consistently the same, and need a groove in the side of the rafter to be successfully fixed. To facilitate easy lifting of lightweight components now free spanning over 23metre, a customised plywood I-beam was devised using the traditional "on edge" rafter at shingle level. To maintain gluing pressures during fabrication of the rafters a half finger joint was devised in which only one side of the ply was tapered, and offered to an unsymmetrical groove as in Figure 4. This solved the difficulties experienced with gluing ply in a parallel sided groove. The plywood web is modularised from available ply sheets, and is deliberately not continuous, but generally separated by 300mm (See Figure 5). This gives facility for slinging and foothold during the construction process.

With diameters now exceeding 20metre and anticipated spans to 30metre, some of the under purlins are also made up as ply beams, though with a straightforward rectangular top chord. Note that the bottom chord is "on the flat" so as to increase lateral stability.

Roofs initially pitched in place on top of the barrel became more cost-efficient on longer spans by building on ground and lifting into place with long-reach cranes. The largest reservoir built to date is in a remote island location, and rafters were craned into place individually.

The 1958 version of the Douglas Fir Use Book showed a 600,000gallon 68foot diameter water storage tank. In the early stages of constructing the plastic lined barrel with a free-span conical roof, this volume was considered out of reach. Both of these parameters have been exceeded by 10% in recent constructions, and could now confidently be extended by 30%.

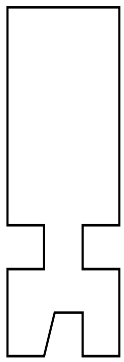

Figure 4 - Cross-section of upper chord.

The issue of cyclonic resistance has recently emerged as perhaps the dominant issue for large diameter constructions. To date a number of tanks on tropical sites have required holding down cables to satisfy increasingly demanding cyclone codes. These need not interfere with the base isolation freedom if they are splayed outwards from the rim of the barrel to fixings on the outer edge of the foundation ring beam. These cables are necessarily prestressed, and with angle change during sliding would seem to contribute favourably to redistribute "rocking" pressures. This phenomenon is listed for study once a comprehensive fluid/structure finite element model is obtained.

Wind pressures on the surface of the roof itself are a subject of considerable interest. The prevailing roof style of wooden weatherboard shingles provides a symmetrical permeability to the roof surface. This decreases internal pressures significantly. Although a dedicated hoop cable is routinely provided at the edge of the roof prior to lifting, wind uplift on the longest rafters has been provided for by hoop cables at third points, and another near the apex junction.

The intensity with which society is now pursuing low embodied energy and re-useability of building components highly favours this method of construction. Controlled drinking and waste water is becoming a pressing issue for humankind. An economic and provably resilient method to provide fluid containment such as that described in this paper cannot be overlooked.

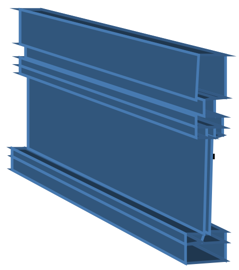

Figure 5 - View of built-up plywood rafter.

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