The 1987 Edgecumbe earthquake caused significant damage to industrial structures on the Tasman Pulp and Paper mill in Kawerau. More than 20 years later, the massive top-hung No.2 Recovery Boiler was ready for its final major maintenance refit which entailed replacement of about half its pressure parts. Owners Carter Holt Harvey had to decide on what associated seismic strengthening would be appropriate to bring the boiler and boilerhouse (the support structure) up to acceptable standards for the last 20 years of their life. Designed in the 1960s to much less than current seismic standards, the 1000-tonne boiler had swung violently in 1987 within the thermal expansion guides which retain it within the 1500 tonne 10-storey steel support structure. The guides were severely damaged as was some of the internal piping - but not sufficient for there to be an explosion. Similar recovery boilers suffered similar damage in the 2010 Chile earthquake.

In the 2009 pre-Christchurch earthquake environment, the owner commissioned seismic assessments and concept studies that looked at both what the appropriate level of strengthening should be, and the possible benefits of retrofitting both the support structure and the guides. As a pro-active, long-term and prudent owner prepared to act in advance of government regulation in order to protect its personnel and assets, the company’s site engineering team determined the solution’s scope by working alongside its consultants. This paper describes the assessments, studies, and the multi-million dollar solutions which included the retrofit of the guides with lead-rubber bearings which will cocoon the boiler in any future shakes.

1 BACKGROUND

1.1 Original Design

Designed in the 1960s to NZSS 1900 Chapter 8, the 1000-tonne top-hung boiler had swung violently in the 1987 Edgecumbe earthquake within its thermal expansion guides which separate it from the 1500 tonne, 50 metres high steel support structure.

The guides, which were not specifically designed to be ductile, are on all four sides of the rectangular boiler at five levels, and allow the boiler to expand vertically up to 150 mm and 13 mm horizontally. The boiler is effectively a pendulum hanging within a cross-braced steel structure. Within the boiler, the many boiler tubes hang in loops from the top steam drums and are lightly restrained laterally. The external walls of the boiler are water-filled vertical tubes, and there are substantial external horizontal rectangular rings at the guide levels that stabilise the walls and transfer the guide forces to them. The boiler is fuelled by the wood residues in the syrup from the pulp cooking process, and the molten salts accumulate on the floor of the boiler from where they are “recovered” for re-use. If there were to be an accidental release of water (e.g., from earthquake damage) within the boiler, the molten salts would react with the water, causing the boiler to explode. One corner seam of the boiler is designed to split preferentially in the direction that has the least consequence, and there is an international history of such boilers failing this way.
1.2 1987 Earthquake Damage

The boiler suffered some damage to both the internal boiler tubes and their supports, and to the guides. The boiler walls came very close to impacting the surrounding floors at the lower levels, but there was not a significant loss of water containment. The intensity of shaking at the site was thought to be close to the design levels current in 1987. Insurance considerations meant that the guides were returned to their pre-earthquake conditions in order that production be resumed as quickly as possible.

Photos from 1987 of the structure, guide damage, and boiler inspection
Model of the support structure

1.3 Seismic assessment

In the 2009 pre-Christchurch earthquake environment, planning for the final 20-year major replacement of its pressure parts was underway. Owners Carter Holt Harvey had to decide on what associated seismic strengthening would be appropriate to bring this up to acceptable standards for its last 20 years of life.

Checks during design of temporary works identified inconsistencies in the original seismic design. The structure was found to be able to handle less than 25% of the current code (NZS 1170.5) loadings for a 50-year life. The structure could therefore be classified as “Earthquake Prone” (i.e., < 33%) in terms of the regulations of the Building Act 2004.

Determining the seismic resilience of the complex boiler itself (and the replacement parts) was not easy, particularly because the standard international designs commonly incorporate nominal/low capacity seismic detailing. This encouraged following the concept of cocooning the suspended boiler in a yielding guide system to limit the seismic loads that could be developed between boiler and support structure.

2 STRENGTHENING ALTERNATIVES INVESTIGATED

A number of options were considered for improving the seismic performance of the boiler and its support structure. Four were investigated analytically:

2.1 Conventional strengthening of the support structure

- Building strengthened to 67% of current code.
- Boiler will also be subjected to 67% of current code.

There were serious issues with strengthening the boiler to this load level because of the significant work that would be required to both mechanical and piping aspects of the boiler shell and internals.

2.2 Conventional strengthening of building plus load-limiting guides

- Building strengthened to 67% of current code.
- Boiler will be subjected to lower seismic forces (i.e., within allowable stresses for a pressure vessel).
2.3 Base isolation of support structure

- Issues with:
  - Physical space required for installing lead-rubber bearings
  - Providing clearances
  - Seismic loads attracted to gravity supports
  - Modifications required to piping, spouts, blowers, etc.
- Boiler will be subjected to lower seismic forces (i.e., within allowable stresses for a pressure vessel).

**View of spout level at which base isolation was contemplated**

2.4 Bracing modifications or buckling-restrained braces

- Increase the strength of the support structure
- Make the support structure as ductile as possible
- Issues with predicted magnitude of secondary moments and shears ruled this option out.
Possible bracing modifications
Example of a buckling-restrained brace and structure with same

3 OPTION SELECTED

The costing and practicality of the options was looked at carefully. While some of the strengthening was to be carried out during a period of replacement of major parts of the boiler, some aspects could be carried out while it was operational. The existing support equipment, controls and piping are not easy to work around – as can be seen from the accompanying photographs.

It was decided to proceed with conventional strengthening of the support structure and to install new load-limiting guides. Essentially, this meant that the existing conventional guides would be replaced with ones incorporating lead-rubber bearings. The geometry of the existing guides varied from position to position, and the ones at the steam drum levels would be in a hotter than average environment. The conventional use of lead-rubber bearings is in a foundation/support location where the bearing is heavily axially loaded. Carter Holt Harvey had previous experience with such bearings when it retrofitted the 800 tonne No. 8 Power Boiler at the Kinleith mill site a year earlier. The need to develop a detail where the bearing’s stability was ensured by some sort of confinement became apparent when the possible configurations were developed such as those shown in the diagrams below.

- Conventional guides (± 15 mm laterally,
  ± 150 mm vertically)
- Guides incorporating lead-rubber bearings

These potential issues of no axial load and secondary tension being generated in bearings were overcome by including a stepping mounting system. This resulted in a tri-linear force-displacement relationship.

4 SEISMIC CRITERIA FOR DESIGN OF REMEDIAL WORKS

The appropriate level of seismic strengthening was investigated carefully. The owner, being the operator of a number of large industrial sites, had a well-developed understanding of its health and safety responsibilities, and was able to bring that understanding to bear on the selection of the seismic
strengthening level. The limited remaining life of the recovery boiler, the requirements of the various Acts, and the Kawerau District Council’s earthquake-prone policy were all taken into account. The strengthening level (two-thirds of new building standard) was twice the minimum level that could have been legally chosen.

Because of uncertainties in the knowledge of the subsoil conditions beneath the existing structure, a site investigation was undertaken, and an up-to-date understanding of the seismic hazard for the region was also obtained incorporating the latest models of attenuation across the central North Island volcanic plateau.

The following parameters were used in the final analyses for design of the strengthening:

- Subsoil class – type D confirmed by deep bore hole and down-hole seismic testing
- Hazard factor $z = 0.25$ established by a site-specific seismic hazard analysis (c.f. 0.29 from code)
- 1170.5 spectra
- Design working life of 25 years
- Consequence of failure considered to be “ordinary”, hence Normal Importance Level ($I = 2$)
- Annual Probability of Exceedance for ULS $1/250$
- Annual Probability of Exceedance for SLS $1/25$
- Building ductility $\mu = 1.0$ (elastic)
- Remedial works designed for a minimum of 67% NBS

5 DETERMINATION OF DESIGN FORCES AND DISPLACEMENTS

5.1 Analyses undertaken

A series of non-linear time-history analyses were undertaken to identify where the support structure should be strengthened, to determine the appropriate parameters for the energy-absorbing guides, and to confirm that the strengthened structure would perform satisfactorily.

5.2 Boiler accelerations and relative displacements

It was important that the strengthened structure should protect the boiler from experiencing high inertial loadings. The following table shows the maximum seismic effect experienced by the boiler in the analyses:

<table>
<thead>
<tr>
<th>Location</th>
<th>Rel. displ.(mm)</th>
<th>Boiler accel. (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7th floor</td>
<td>167</td>
<td>0.03</td>
</tr>
<tr>
<td>5th floor</td>
<td>119</td>
<td>0.03</td>
</tr>
<tr>
<td>3rd floor</td>
<td>67</td>
<td>0.03</td>
</tr>
<tr>
<td>Mezz. floor</td>
<td>45</td>
<td>0.14</td>
</tr>
<tr>
<td>Spout floor</td>
<td>39</td>
<td>0.31</td>
</tr>
</tbody>
</table>
6 DETAILS OF STRENGTHENING

The extent of the structural strengthening can be gathered from the cost which was of the order of 10 million dollars. The opportunity was also taken to replace structural members which had corroded after more than 40 years exposure to the process.

The manufacture of a few of the lead-rubber bearings was not without some problems because of their unusual aspect ratio, and the light axial load on them. The supplier was eventually able to provide bearings for the unusual operating conditions by modifying his normal manufacturing techniques. Sample bearings were extensively tested as part of the design development, and all bearings underwent full load testing before acceptance.

Measurement of actual working temperatures showed that they were in a range where there was no concern.

The photo above shows one typical guide installation containing lead-rubber bearings. The diagram shows the use of twin bearings to provide a stable energy-absorbing guide.

The photo above shows typical strengthening of a brace in the support structure.

7 SUMMARY

A large industrial structure and the process within have had their life extended in a manner which exceeds the minimum seismic standards applicable. In a pre Christchurch earthquakes environment, the owner was able to investigate a number of options and levels of strengthening to be in a position to choose rationally a solution compatible with his health and safety policies and the prevailing requirements under the Building Act. An innovative solution was developed to protect an industry-standard boiler of low inherit seismic resilience in an economical manner. This was achieved by close co-operation between the owner’s technical staff and his consultant engineers.