Structural efficiency by analysis: The Fonterra Dryer Plant, Darfield

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2012 NZSEE Conference

ABSTRACT: The Fonterra Darfield Dryer Plant is a large reinforced concrete industrial facility located near the town of Darfield in central Canterbury. The structure consists of precast concrete walls and columns supporting heavily penetrated, irregularly located concrete floor plates.

Dairy dryer buildings are typically founded on shallow foundation beams. Initial elastic analyses indicated that this was not feasible for the Darfield Dryer building due to the large size of the structure, and in particular due to its relatively high aspect ratio. It was thus initially concluded that piled foundations would have to be provided, adding significantly to the cost of the structure.

As an alternative it was suggested that the dryer building should be allowed to rock, thus removing the need for piled foundations. Adoption of the rocking solution required non-linear pushover and time history analyses to be undertaken, which showed that rocking was a viable mechanism for the structure. Despite the relative complexity of these analyses significant cost benefits were obtained, in addition to a superior structural solution being provided.

Design of the Darfield dryer plant occurred in the period after the September 2010 and February 2011 earthquakes but before the revision to zone factors for the Canterbury region. Comment is made regarding the effects of loading changes on the design of the structure. This paper also includes comments comparing the results obtained from the time history analyses with results obtained for the same structure using a recently proposed simplified design approach for rocking structures (Kelly 2009, 2011).

1 INTRODUCTION

This paper discusses the use of non-linear analysis techniques to achieve significant economies during the design of structures, with the paper being focussed on the Fonterra Darfield Dryer Plant. The Fonterra Darfield Dryer Plant is a very large milk powder drying facility currently being constructed and scheduled for completion in September 2012. As shown in Figure 1, the plant is located approximately 5 km north-west of Darfield, and 45 km from Christchurch. The project is Fonterra's first major green field dairy plant in 15 years. The completed plant will process up to 2.2 million litres of milk per day. A planned second stage of the project will treble this capacity at its completion around 2015. It is understood that the combined plant will be the largest dairy dryer plant in New Zealand.

1.1 Structural system

The Darfield dryer main building is a large structure with plan dimensions of approximately 52.6 m by 20.4 m and height to top of parapet of approximately 42.2 m. A substantial access tower with plan dimensions of 5.8 m by 8.9 m and roof height of approximately 39 m is attached to one side of the structure. An overall impression of the complete structure is shown in Figure 2, and construction photos are shown in Figure 3. The primary lateral load resisting system of the main building structure consists of 175 mm thick reinforced concrete walls located around the envelope of the structure.

Additional walls parallel to the short axis of the building are located on two internal grids and rise to approximately 80% of the height of the structure. 600 mm square columns are positioned around the perimeter of the main building and at locations within the structure. The access tower is clad with non-structural precast concrete panels, and is supported by six 600 mm square reinforced concrete columns.

Figure 1: Location of Fonterra Darfield Dryer Plant (courtesy of Google)

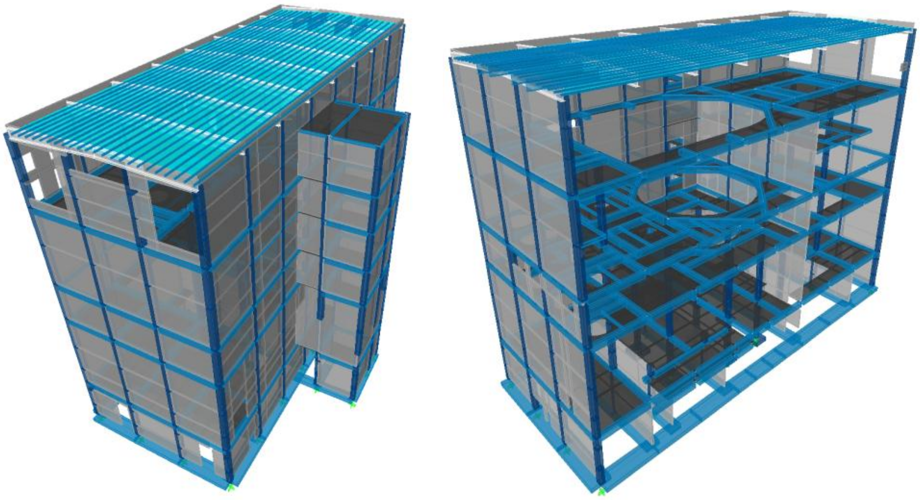

Figure 2: Overall and cutaway views of the Etabs (CSI Berkeley 2010) model for Fonterra Darfield Dryer Building

Figure 3: Fonterra Darfield Dryer Plant during construction (courtesy DLA Architects and Ebert Construction)

There are four main concrete floor levels, one additional substantial floor level constructed of steel decking, and a 5 mm plate steel roof. There are also several elevated lightweight steel platform areas throughout the building. The concrete floors consist of pre-cast concrete slabs with topping thickness varying between 75 mm and 225 mm such that a suitable fall is obtained throughout the structure. The support system for the steel plate roof consists of 150×75×5 RHS purlins and Steltech 1000LB192 rafters.

The building houses specific plant equipment with a total mass of approximately 850 tonnes. Many items of plant spanned across multiple floor levels, resulting in the floor plates being heavily penetrated as can be seen in the cutaway view shown in Figure 2. It is interesting to note that the actual proportion of the mass attributable to plant is less than 10% (see Table 1), despite the impression that the structure contains a large quantity of heavy plant.

Table 1: Total weights associated with gravity load cases

Gravity load component	Load case name	Total weight (kN)
Structure self weight	G	90776
Plant weight	PLANT	8347
Access way self weight	GACCESS	205
Live load on main structure	Q	15740
Live load on access ways	QACCESS	282
Roof live load	ROOFLIVE	269

1.2 Comparison to previous dryer plants

Compusoft Engineering Limited and Silvester Clark Consulting Engineers have previously been involved in the design of a number of other dairy dryer plants. While superficially having similar structural forms, these previous plants have typically had smaller dimensions. Significantly, the Darfield Dryer Plant had a greater aspect ratio than other plants. This greater aspect ratio was the main feature of the Darfield plant that lead to the adoption of non-linear analyses for this project.

2 STRUCTURAL ANALYSIS

Three different analysis techniques were used to develop design actions for the Fonterra Darfield Dryer Plant. These techniques and the reasons for using them are discussed briefly in the following paragraphs, while more detailed inputs and results are discussed in later subsections.

Modal response spectrum analyses were initially conducted, with the expectation that these would provide the design actions for the structure. However, these analyses revealed that the overturning moment imposed on the structure exceeded the capacity of the planned shallow foundations. This lead to the decision to investigate the behaviour of the structure if uplifting of foundations (rocking) was permitted, which required adoption of non-linear analysis methods and the addition of gap elements to model foundation uplift.

The first non-linear analyses undertaken were static pushover analyses, which had the aim of estimating the "ductility" demand placed on the rocking mechanism due to foundation uplift. This demand level was then used to establish the validity of permitting foundation uplift.

After verifying the validity of permitting foundation uplift as a design solution, non-linear time history analyses were conducted using a suite of representative earthquake records.

2.1 Seismic analysis parameters

A standard New Zealand acceleration spectrum (NZS 1170.5 2004) was used as the basis for the analyses undertaken for the Fonterra Darfield Dryer Plant. The dryer is constructed on a deep soil/Class D site (Uma et al. 2010) with the zone factor being Z = 0.3 as specified for Darfield. The resulting acceleration and displacement spectra are shown in Figure 4. The values of $S_a(T)$ shown in Figure 4 are equal to $C_h(T)$.Z.R.N(T,D) with the near fault factor (N) and the return period factor (R) both taken as 1.0.

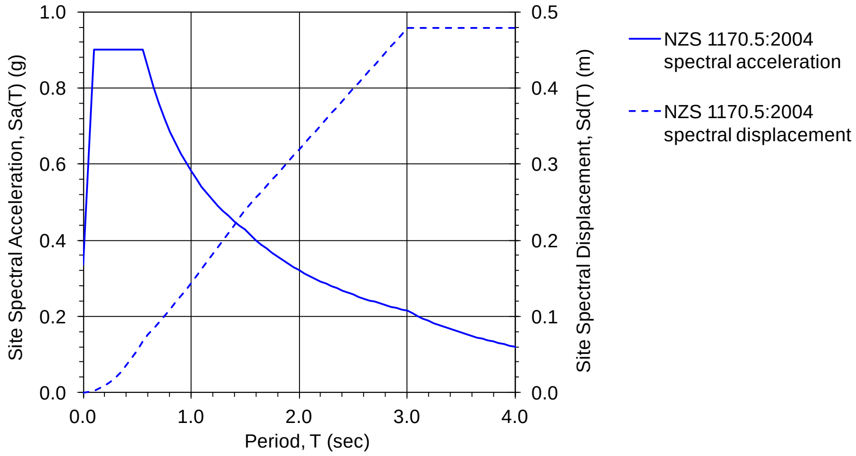

Figure 4: NZS 1170.5:2004 acceleration and displacement spectra for the Fonterra Darfield Dryer Plant site

2.2 **Structural model**

A structural model of the Fonterra Darfield Dryer Plant was developed in the software package Etabs Nonlinear (CSI Berkeley 2010). Screenshots of this model have been shown previously in Figure 2. Area and frame elements were used to accurately represent the structure's lateral force resisting system, including the foundation beams. The components of the main floors in the structure were also represented in the model to allow realistic distribution of imposed actions. Items of plant, gantries, and minor floor levels were not explicitly modelled, with the mass due to these components instead being applied at appropriate support locations. Total weights due to various load types have been listed previously in Table 3. Both translational and vertical mass components were included in the structural analyses.

For analysis and design purposes the structure was initially assumed to be nominally ductile. Modelling showed that the Fonterra Darfield Dryer Plant structure is extremely stiff, having first mode periods of approximately 0.4 seconds when it was assumed that the foundations were fixed. The high stiffness also somewhat complicated analyses as it lead to coupling between horizontal and vertical modes.

Results throughout the remainder of this section are discussed in reference to X and Y axes. The structural model had the X-axis parallel to the longer walls of the structure, and the Y-axis thus parallel to the shorter walls. Discussion is focussed mostly on Y-axis loading, as this was the direction of loading most impacted by adoption of a rocking mechanism.

2.3 **Discussion of response spectrum analysis**

Modal response spectrum analyses for the Darfield Fonterra Dryer Plant were undertaken in accordance with NZS 1170.5:2004, with the structure considered to be irregular for the purposes of base shear scaling. The structure was considered irregular due to the absence of rigid diaphragms and the presence of mass and stiffness irregularities throughout the structure. Ritz vectors were used as the basis of the analysis, with the resulting modes combined using the General Modal Combination method (Gupta 1992) with f_r = 20Hz. Due to the irregularity of the structure and the consequent inappropriateness of lumping mass at "storey" levels a large number of modes had to be considered to ensure an adequate proportion of mass was included in the combination. In practice this lead to 500 mode shapes being calculated, resulting in approximately 99% of the mass being included for each direction of translation.

Maximum base shears and overturning moments resulting from the response spectrum analyses for each direction of loading are shown in Table 2. As expected the maximum base shear for each direction of loading is identical due to both first mode periods falling on the peak acceleration plateau of the design spectrum, resulting in scaling to identical equivalent static base shear values. The minor difference between the maximum overturning moments for the two directions is due to the different mode shapes contributing to the responses.

As noted previously, the results of the modal response analyses indicated that the capacity of the planned shallow foundations for the structure would be insufficient. Specifically, the capacity of the foundations to resist overturning about the X-axis was of the order of 1000 MNm, or 50% of the value required according to the modal response analyses. Accommodating this discrepancy between overturning moment demand and capacity in the design would have had significant impacts on the project (see section 3); thus it was decided to assess the viability of allowing the Fonterra Darfield Dryer Plant to rock.

Table 2: Comparison of base shears and overturning moments for different analysis techniques

	Maximum base shear (MN)		Maximum overturning moment (MNm)	
Analysis type	**along X axis**	**along Y axis**	**about X axis**	**about Y axis**
MRSA	75.6	75.6	1983	1879
Pushover	56.3	31.2	878	1584
Non-linear TH	66.3	52.0	1291	1736

2.4 Discussion of non-linear analyses

The validity of adopting a rocking solution for the Fonterra Darfield Dryer Plant was undertaken in two stages. In the first stage the overall stability of the structure was considered by conducting non-linear static (pushover) analyses for each of the principal loading directions. Following confirmation that adoption of rocking was a sensible approach, time history analyses were undertaken to develop design actions for the structure.

Pushover curves for the Fonterra Darfield Dryer Plant are shown in Figure 5. The curves are plotted as spectral accelerations against spectral displacements. The pushover analyses were undertaken using inverted triangular lateral force distributions. It can clearly be seen that a much higher force has to be applied to initiate X-axis rocking than Y-axis rocking due to the differing aspect ratios of the structure for the two axes.

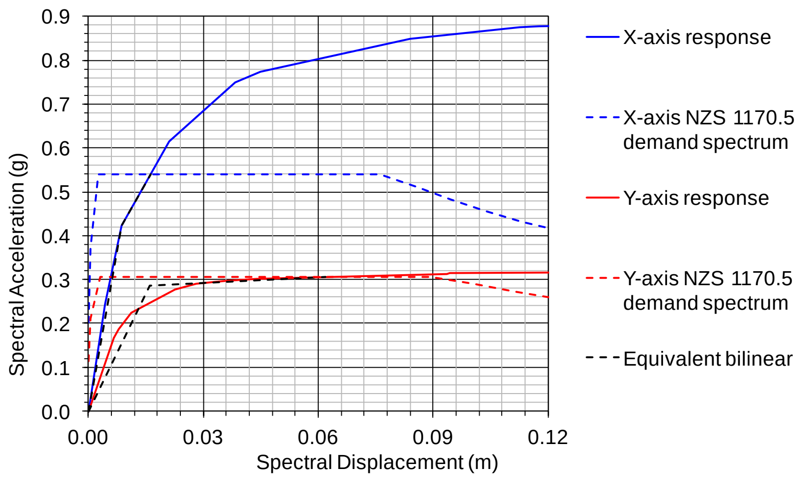

Figure 5: Non-linear pushover curves for the Fonterra Darfield Dryer Plant

In addition to the pushover curves, demand curves based on the design spectrum shown in Figure 4 are also shown in Figure 5. The demand curves were defined by selecting a ductility that resulted in an appropriate intercept between the demand curve and a bilinearisation of the pushover curve. The resulting ductility demands were approximately 1.9 for X-axis loading and 3.9 for Y-axis loading.

The ductility demands estimated from the pushover analyses indicated that rocking response was suitable for the Fonterra Darfield Dryer Plant. However, it was not considered appropriate to use pushover results for design of the structure due to the inability to realistically account for higher mode or vertical earthquake effects, both of which were likely to be significant. Thus time history analyses of the structure were undertaken.

Non-linear time history analyses were undertaken following the procedures outlined by NZS 1170.5:2004, although four rather than three records were used. The four records (summarised in Table 3) were chosen because they were recorded at deep or soft soil sites. Scaling for both directions of loading was undertaken for a period range of 0.16 to 0.52 seconds based on T_1 = 0.4 seconds. A family scale factor of 1.11 was required to ensure that the scaled records enveloped the target spectra as shown in Figure 6. It is evident from Table 3 that all records met the NZS 1170.5 goodness of fit requirement that D1/log(1.5) < 1.0.

Table 3: Earthquake record information for time history analyses

Earthquake	Station	Principal component	k_1	D1/log(1.5)
Christchurch 2011	Cathedral College	N64E	0.90	0.44
Kern County 1952	Taft Lincoln School	NS	2.10	0.36
Lytle Creek 1970	Wrightwood	EW	2.42	0.37
Taiwan 1986	Smart 1	NS	1.96	0.48

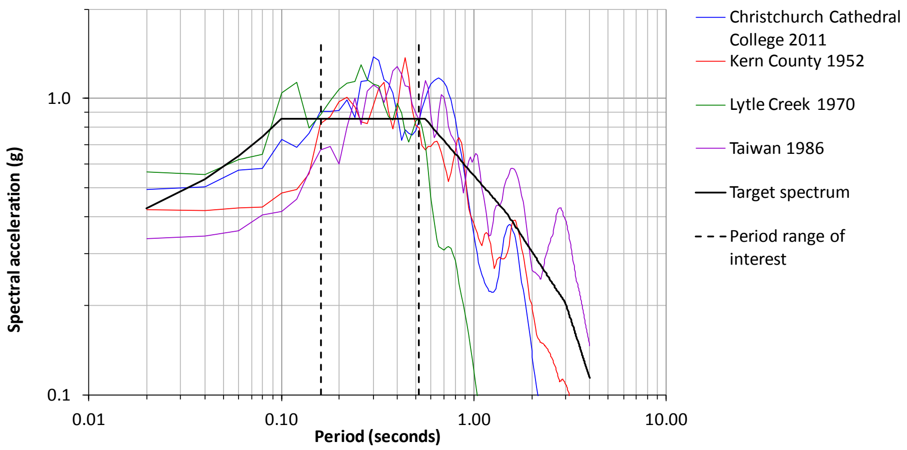

Figure 6: Comparison of scaled earthquake spectra with NZS 1170.5 target spectra

During all time history analyses principal, secondary, and vertical earthquake components were applied simultaneously to the structure. Damping of all modes was set as 5% of critical damping, and the output time step was in all cases set as 0.02 seconds, with this value selected so that it was less than 10% of the fundamental period of the structure. Analysis was undertaken using the Fast Nonlinear Analysis (FNA, or “modal”) method (CSI Berkeley 2011), which resulted in dramatically shorter solution times than would have been the case if conventional direct integration methods had been used.

The results of the time history analyses followed expectations. As shown in Table 2 the base shear forces generated by the time history analyses were lower than the response spectrum analyses, but higher than the pushover analyses. The increased values in comparison to the pushover values were attributed to the effects of higher modes, which are not captured by the pushover analyses. Detailed inspection of the results indicated that the incorporation of the vertical earthquake component in the analyses had been important, with the maximum tension forces in some wall and column elements significantly exceeding the value that would be expected from the weight "hanging" from them.

Rocking response of structures is often associated with period elongation. For the Fonterra Darfield Dryer Plant the period elongation was not significant. It is believed that this is due to the structure being observed to rock only for the few highest peaks of each earthquake record, as can be seen in Figure 7.

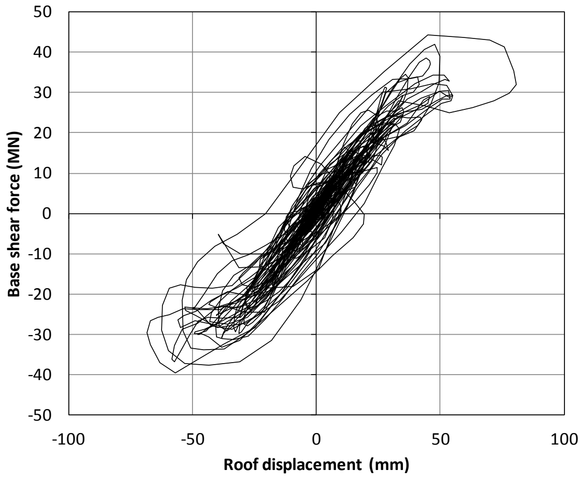

Figure 7: Y-axis base shear versus roof displacement response for Fonterra Darfield Dryer Plant subjected to Taiwan Smart 1 record

3 BENEFITS RESULTING FROM NON-LINEAR ANALYSIS

Time history analysis is undoubtedly more complex to undertake than equivalent static or response spectrum analyses, and thus is more costly for the client than simpler forms of analysis. However, significant benefits can be obtained by the appropriate use of time history analysis. In the case of the Fonterra Darfield Dryer Plant benefits were obtained for two distinct reasons. These are outlined in the following sections.

3.1 Design efficiencies

The use of non-linear analyses resulted in substantial design efficiencies for the Fonterra Darfield Dryer Plant. While some reduction of design actions was achieved due to the increased effective "ductility" provided by the rocking mechanism and as evidenced by the reduced base shear values shown in Table 2, the most significant economy resulting from the non-linear analyses was related to the foundations for the structure. In the period between realisation that the MRSA reactions could not be resisted by the proposed shallow foundations and the validation of the rocking mechanism, parallel work was underway considering the implications of provide piled foundations for the structure. While an exact price for this option cannot be provided, it can be stated that the use of non-linear analysis to avoid piling provided a very high benefit-to-cost ratio.

3.2 Seismic design environment

The Fonterra Darfield Dryer Plant was analysed after the September 2010 Darfield Earthquake, and the February 2011 Lyttelton Earthquake occurred during the period when analyses were being undertaken. This resulted in there being a significant degree of uncertainty regarding appropriate design actions for the structure. As an example, analysis was initially intended to rely on a site specific study by GNS Science (Uma et al. 2010) that specified smaller design actions than NZS 1170.5:2004. Midway through the analyses it was decided that it would be prudent to revert to NZS 1170.5 design actions. This decision was validated by the discussion regarding seismicity and zone factors for Canterbury that has been ongoing since the earthquakes. The use of non-linear analyses to validate rocking behaviour of the structure was felt to mitigate this uncertainty and provide confidence that the structure could be shown to meet code requirements irrespective of any future changes to seismicity for Canterbury.

4 COMPARISON OF ANALYSIS WITH SIMPLIFIED PROCEDURE

Kelly (2009, 2011) has published simplified guidelines intended to allow design of rocking structures without the need for a special study as is currently required by the New Zealand Standard for Structural Design Actions (NZS 1170.5 2004). As has been discussed in this paper, a special study was undertaken for the Fonterra Darfield Dryer Plant. Nonetheless, it is of interest to briefly compare the results of the special study with the outcomes that would have resulted from use of the simplified guidelines:

- The simplified procedure is focussed on structures with discrete stories, which lead to some difficulties in applying it to the Fonterra Darfield Dryer Plant. For these comparisons the structure was treated as having four stories, which corresponded to the number of main floors.
- The simplified method over predicted displacements by approximately 50% in comparison to the results of the time history analyses.
- The dynamic amplification factor obtained by comparing pushover analyses with the time history analyses was approximately 1.2 and 1.66 for X-axis and Y-axis loading respectively. The dynamic amplification factors found from the simplified method were 1.4 and 2.1 respectively.

The points noted above indicated that the aspects of the simplified method considered were conservative with respect to the Fonterra Darfield Dryer Project.

5 CONCLUSIONS

This paper has discussed the application of non-linear analysis techniques to the design of a large industrial structure located in Darfield, Canterbury. Non-linear analyses were adopted for the project after it was found that the desired shallow foundations were unable to resist the design actions developed using response spectrum analyses. Non-linear pushover and time history analyses were used to verify that satisfactory performance could be achieved if the structure was permitted to rock during earthquakes. Installation of piled foundations was proven to be unnecessary by the satisfactory validation of the rocking mechanism, which resulted in significant cost savings. A Further benefit provided by the adoption of a rocking solution was the enhanced ability of the structure to continue to meet code requirements even if design seismicity levels are increased at a future date.

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