# The February 2010 Earthquake in Chile
# Actual versus Designed Response of 2 Concrete Chimneys

## Michael Angelides

Michael is a Civil Engineer with B.Eng. and a M.Eng from McGill University, Canada. In Montreal he worked at orthopedic implant and at satellites design. He returned to Greece in 1989 and joined AMTE. Since 1993 he is the managing director of AMTE, a consulting company specializing in the design of all kinds of industrial projects.


## 1. Introduction

Two reinforced concrete chimneys were designed in 2008 and constructed in 2009 in Chile. In February 2010 an earthquake measuring 8.8 on the Richter scale struck the region. The present paper analyses the behaviour of these chimneys and compares the designed response to the actual response.

## 2. Description of the Project

The two chimneys were designed and built for the thermal power plants of Colbun and Bocamina in Puerto Coronel near Coception, Chile (approximately 500 km south of Santiago). The power plant owners are Colbun S.A. and Endesa, respectively. Both power plant projects had been awarded to Maire Engineering, which contracted the design and construction of the chimneys to Karrena GmbH, Germany. The structural design of the chimneys was carried out by AMTE Consulting Engineers, Greece, on behalf of Karrena. The location of the chimneys with respect to the February 2010 earthquake epicentre is shown in Fig. 2.1.

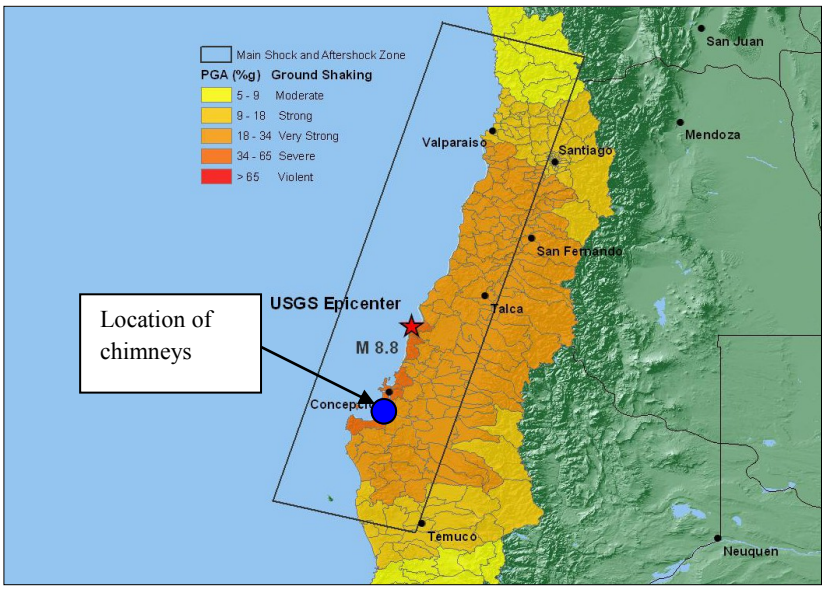


***Fig. 2.1: Location of chimneys with respect to February 2010 earthquake epicenter. (source: AON Benfield)***

The layout of both chimneys has been based on the "New Chimney Design" concept (Hoffmeister and De Kreij, 2008), which essentially eliminates the free space between the liner and the windshield. This is achieved by using a lining consisting of Pennguard blocks attached directly to the inner surface of the concrete windshield. The Pennguard blocks provide for both the thermal insulation and for the acid resistance of the windshield. Furthermore, the low weight of the Pennguard blocks (borosilicate blocks) does not appreciably increase the mass of the structure, which constitutes an advantage for seismic regions (self weight = 1.9 kN/m$^3$×0.054m thickness = 0.10 kN/m$^2$). Since the lining coincides with the inner windshield surface, the "New Chimney Design" concept results into smaller overall reinforced concrete diameters, hence into more flexible structures. This increased flexibility constitutes an additional advantage for seismic excitations, due to the fact that most design response spectra specify significant response reduction at higher natural periods of vibration.

The Colbun chimney is 130 m high and the outer diameter ranges from 11.00 m at the base to 5.90 m at the top. The top 50 m have a constant diameter. The concrete thickness ranges from 40 cm at the base to 25 cm at the top. There are three openings for flue gas duct entry: Two at level +16.50 and one at +46.32. The bottom openings have dimensions 4.0×3.7 m and the top opening has dimensions 3.8×8.3 m. The chimney foundation consists of a circular raft of 26 m external diameter.

The Bocamina chimney is 100 m high and the outer diameter ranges from 10.50 m at bottom to 6.25 m at top. The top 60 m have a constant diameter. The concrete thickness varies from 35 cm at the bottom to 25 cm at the top There are two openings for flue gas duct entry at level +12.50 with dimensions 3.9×8.4. The chimney foundation consists of a circular pilecap over reinforced concrete piles.

The design for the two chimneys was carried out in 2008 and the construction for both chimneys was completed in 2009. The two constructed chimneys are shown in Fig. 2.2.

*Fig. 2.2: Colbun and Bocamina chimneys. (Source: J. Wilson)*

## 3. Design considerations

According to the contractual requirements, the chimneys had to be designed to ACI 307-98 (Standard Practice for the Design and Construction of Reinforced Concrete Chimneys) and to ACI 318-05 (Building Code Requirements for Structural Concrete). Earthquake related issues were specified in the Chilean codes NCh 433 (Earthquake Resistant Design of Buildings) and NCh 2369 (Earthquake Resistant Design of Industrial Installations). Additionally, seismic design specifications had been prepared for these projects by Prof. E. Cruz, who was also the design verification engineer on behalf of the Owner.

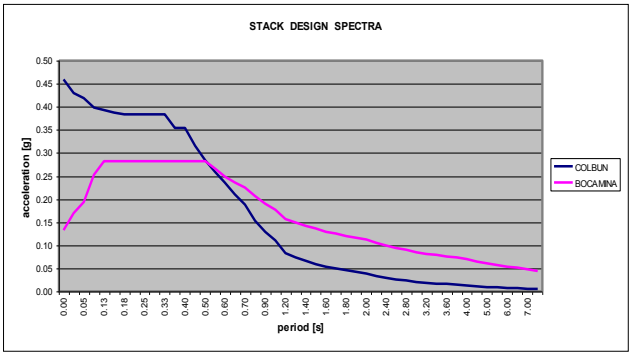


**Fig. 3.1: Design response spectra for the chimneys.**

The project region lies in an area of particular seismicity. Most of the west coast of Chile coincides with the border between the Nazca and the South American tectonic plates (see Fig. 3.2). This border is the source of frequent seismic activity through subduction interaction as the Nazca plate pushes against the Chilean coast. An overview of past earthquake activity reveals that the region gives rise to a major seismic event of magnitude 8.0 or greater every approximately 15 years: 1906 (Valparaiso, M8.0), 1922 (Vallenar, M8.2), 1943 (Coquimbo, M8.2), 1960 (Valdivia, M9.5), 1985 (Santiago, M8.0), 1995 (Antofagasta, M8.0). This indicates that a major earthquake was practically guaranteed to hit the chimneys within their service life.

In consideration of the above observations, the following principles were used for the design of the chimneys: The design was carried out on the basis of forces determined from a response spectrum analysis. The chimneys were detailed for ductile behaviour by limiting the horizontal bar spacing, by increasing the vertical bar splicing and by setting limits on reinforcement ratio with respect to the axial forces at that level. The ductile detailing rules were adapted from the CICIND Code. Finally, the design of reinforcement was carried out with reduced seismic behaviour factors at critical locations, due to the perceived limited capability of the structure to con-

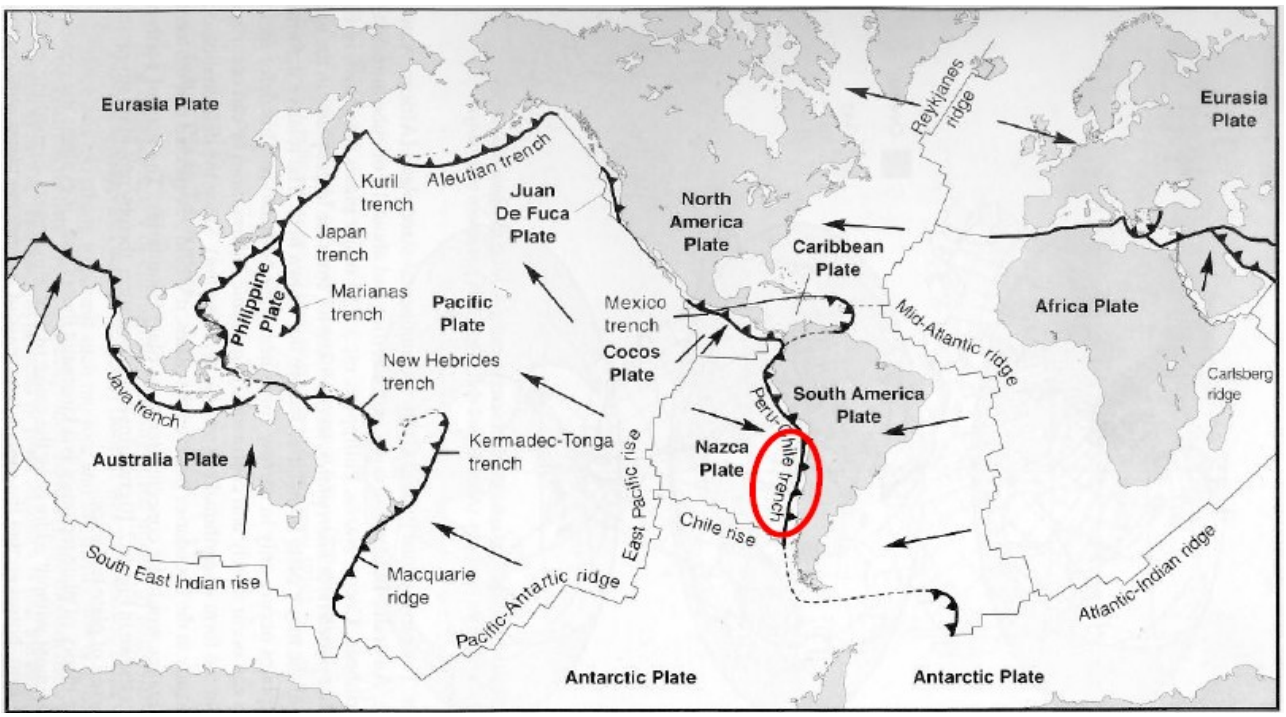


***Fig. 3.2: Global map of tectonic plates with the Chilean Nazca plate boundary highlighted. (Source: G.R. Saragoni)***

sume elastoplastic energy without irreversible damage (Angelides, 2001) and also in order to ensure satisfactory post earthquake response, with particular aim at resisting large aftershocks (see Fig. 3.3).

In consideration of the fact that the design response spectra involved significant reduction of response for high natural periods, the specifications required a minimum guaranteed base shear of 0.15 g for Colbun and 0.10 g for Bocamina.

The final geometry of the chimneys was determined through a series of iterative calculations, in order to arrive at an optimum configuration that would lead to the minimisation of the total construction cost. The total cost consists of the concrete volume, the reinforcement weight, the formwork surface and the lining surface. By assigning unit prices to the above and by varying the diameter and thickness over the height, successive responses and the associated construction costs were calculated. As the variation in geometry directly affected the stiffness and the dynamic behaviour of the chimneys, the iterative calculations were carried out through the use of response spectra analyses using beam element models. The procedure followed the methodology outlined in Angelides (1995) and resulted in the final geometry and reinforcement selections. After the definition of the final geometry, the design was carried out by a 3D finite element model and a dynamic response spectrum analysis.

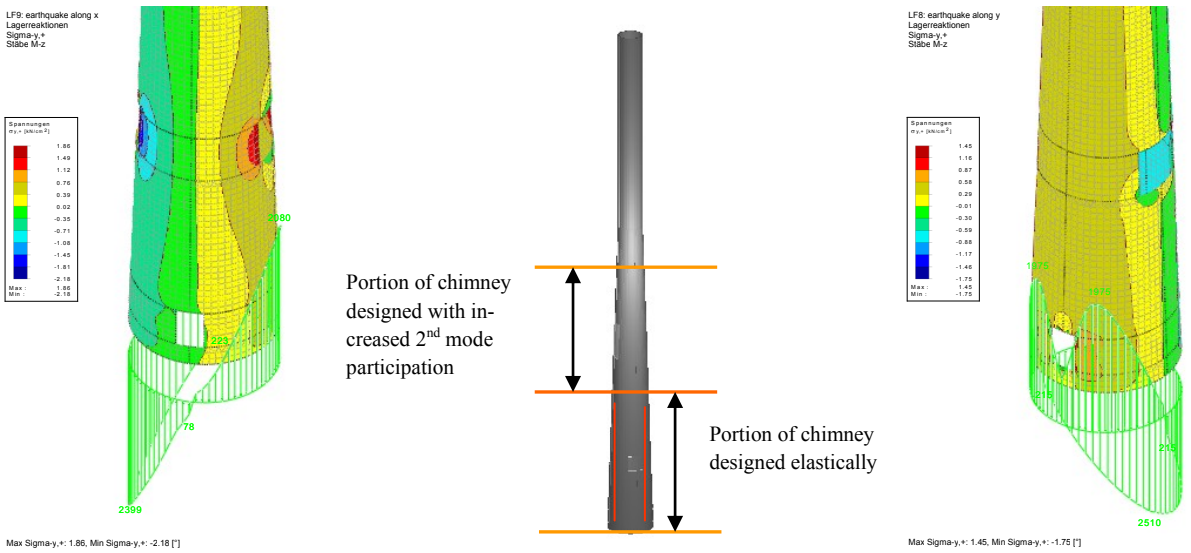


**Fig. 3.3: Design considerations.**

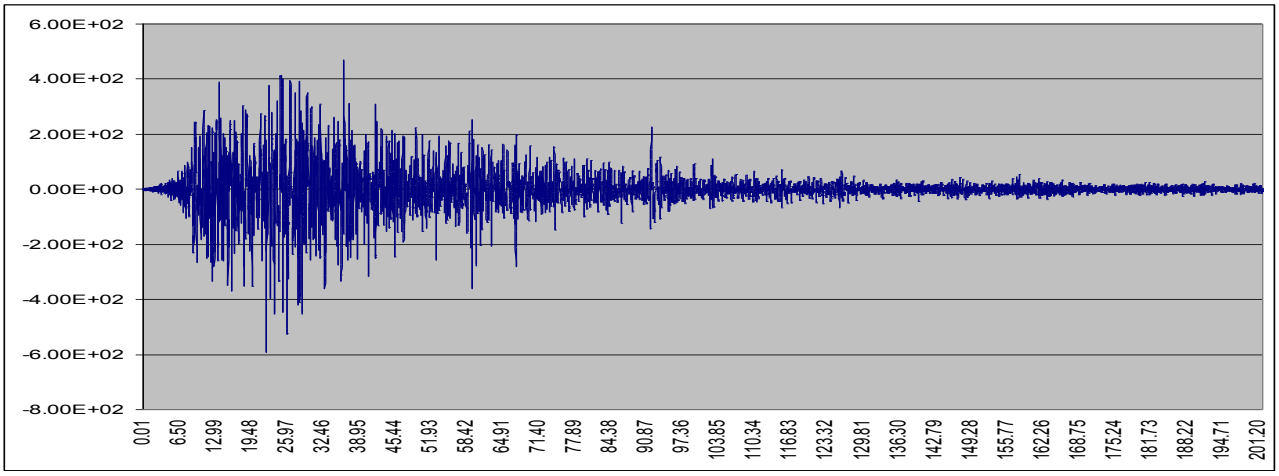


*Fig. 4.1: Horizontal acceleration record from Colegio San Pedro, Conception station. Maximum = 0.594 g.*

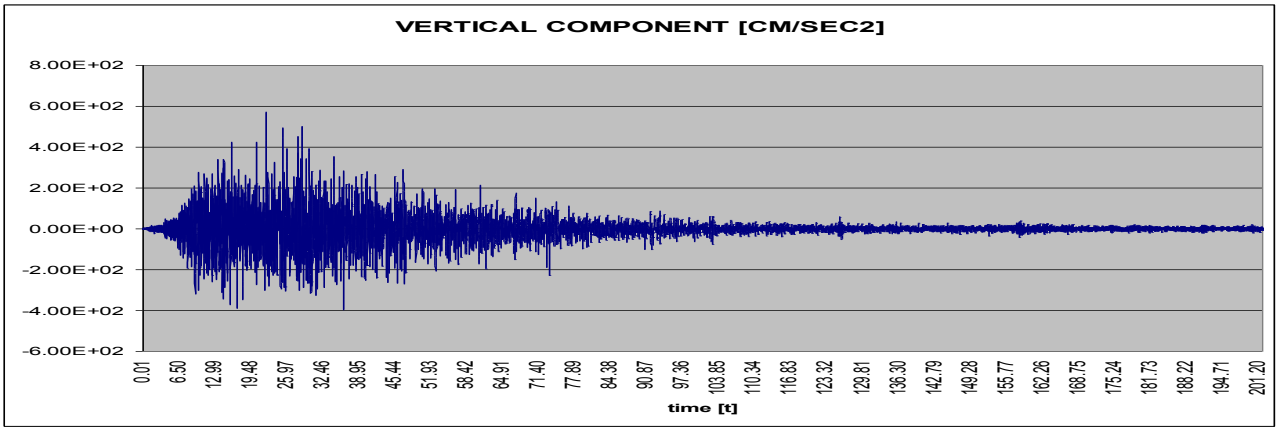


**Fig. 4.2: Vertical acceleration record from Colegio San Pedro, Conception station. Maximum = 0.571 g**

## 4. The February 2010 Earthquake

At 03:34 on Saturday, February 27, 2010 an earthquake measuring 8.8 on the Richter scale struck the west coast of Chile. The epicentre was located off Maule (105 km NNE of Conception) at a depth of 35 km (data from USGS). This earthquake is currently listed by the USGS as the fifth largest globally since 1900. The direct consequences included 450 deaths and more than 30 billion US dollars financial losses.

The recorded ground motion lasted for more than 200 sec, while the strong motion itself lasted more than 50 sec. Fig. 4.1 depicts the graph of horizontal accelerations recorded in Conception (in Colegio San Pedro) and Fig. 4.2 depicts the vertical accelerations from the same recording station. The maximum horizontal acceleration was 0.594 g and the maximum vertical acceleration was 0.571 g. While these recordings were made in the city of Conception, hence approximately 20 to 30 km north of the chimney locations, they are considered representative of the ground motion that the chimneys were subjected to.

The response spectra corresponding to the recorded ground motion at the Colegio San Pedro station have been calculated and are plotted in Fig. 4.3 for different values of the behaviour factor (q or R). The contractual design spectra are also included in this figure, for comparison. It is directly apparent from this figure that, for the natural vibration period range of the chimneys at hand (2.1 sec for the Colbun chimney and 1.7 sec for the Bocamina chimney), the design spectrum is compatible with the calculated ground motion spectrum for a behaviour factor of 3.0 (such as the value specified in the Code).

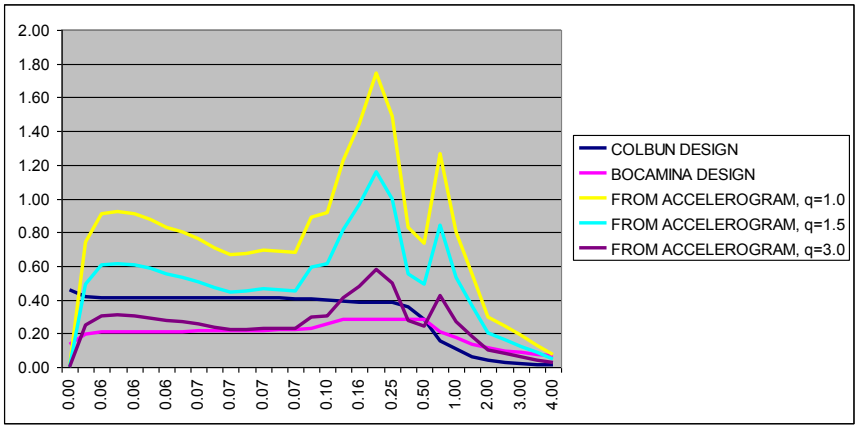


*Fig. 4.3: Contractual versus actual response spectra.*

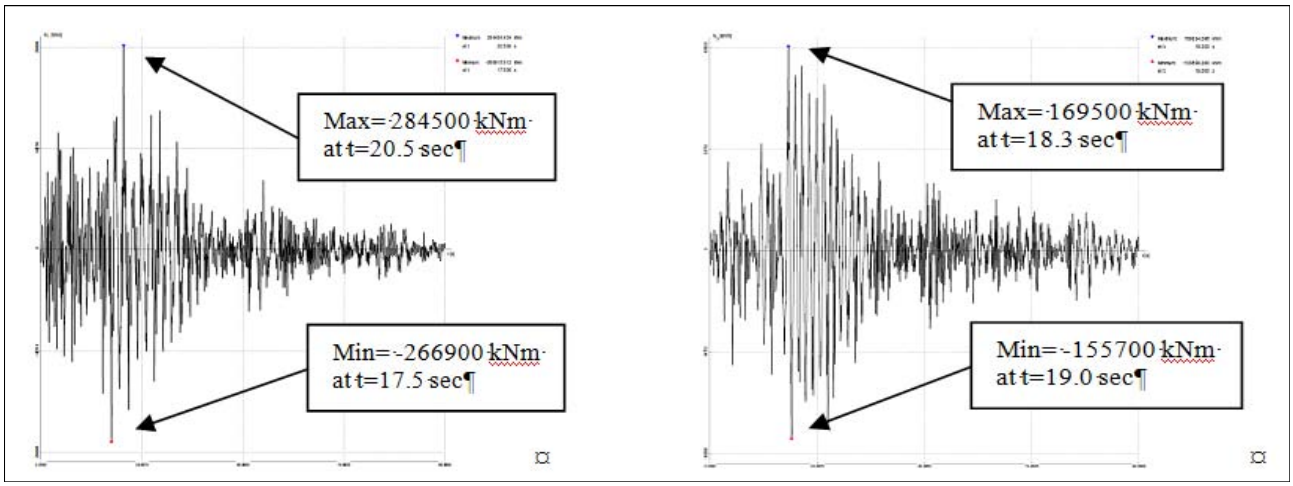


*Fig. 5.1: Time history of base moments (elastic response).*

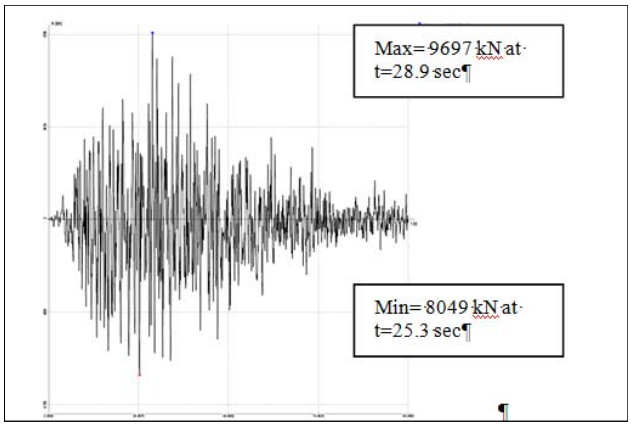


*Fig. 5.2: Time history of axial forces at level +20.00 (elastic response). Bocamina chimney.*

## 5. Actual response

In order to calculate the actual response of the chimneys, time history analyses were carried out on the basis of the accelerograms recorded at the Colegio San Pedro Station. The results indicated that the developed forces were in the order of the design spectrum values for a behaviour factor of 3.0. However, significant vertical axial forces were also developing which were critical for the reinforcement stresses. Fig. 5.1 depicts the calculated elastic time history of base moments for the two chimneys, while Fig. 5.2 depicts the calculated elastic time history of axial forces for the Bocamina chimney.

Fig. 5.3 illustrates the difference between the design moment level and the calculated elastic response for the base of the Colbun chimney. The design moment level (red line) corresponds to a behaviour factor of 3.0. The design spectrum moments (orange line) are the moments calculated from the design spectrum without the scaling up prescribed in the project specifications to guarantee a minimum base shear of 0.15 g. In the same graph on the right part of Fig. 5.3 are also superimposed the provided capacity moments (purple line) on the basis of the reinforcements designed in consideration of reduced behaviour factors, as outlined in Section 3.

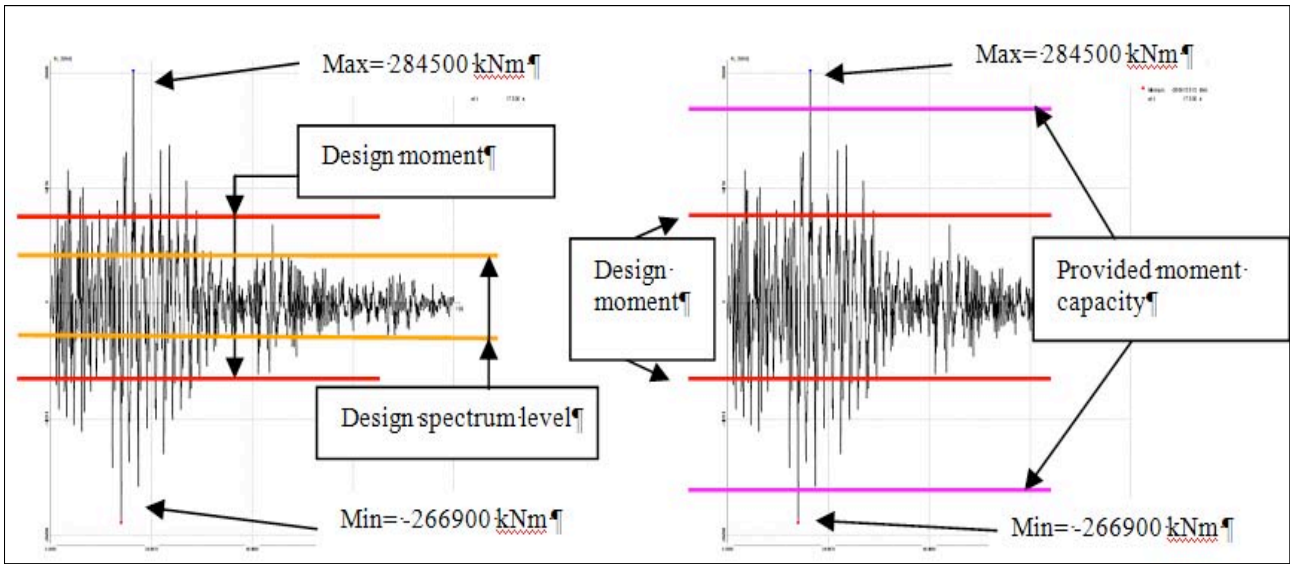


**Fig. 5.3: Time history of base moments (elastic response) versus design moments. Colbun chimney.**

The development of elastic stresses during an earthquake event would lead to reinforcement stresses beyond the yield strength of the material. The actual section capacity provided however allows the redistribution of stresses in a way that the maximum moments may be carried at lower reinforcement stresses.

It was also evident from the calculations that the vertical accelerations played a significant part in the structural response. In the case of the Bocamina chimney in particular, the response may have led to the development of elastic axial forces in the order of 1.0 g. It appears that the piled foundation may have contributed to this increased axial response in Bocamina, since the raft foundation at Colbun probably provided damping through rocking action, as illustrated in Fig. 5.4.

After the earthquake, both chimneys were inspected and no structural damage was reported. The Colbun chimney did not develop any cracking, while in the Bocamina chimney hairline horizontal cracks developed, an indication of higher stressing of the vertical bars caused by the increased axial tensions due to the vertical acceleration. These observations are in line with the calculated actual response.

## 5. Conclusions

The chimneys were subjected to significantly high horizontal ground motion, as well as to very high vertical ground motion. The provision for reduced behaviour factors, along with ductile reinforcement detailing allowed for a safe response to extreme seismic loadings.

## 6. Acknowledgements

I am particularly indebted to Prof. Ernesto Cruz in Santiago, Chile for constructive discussions and guidance throughout the design process. I would also like to thank Karrena GmbH for a good cooperation and for an excellent execution of the project that contributed to the overall success. I am grateful to Prof. Nikos Gerolymos at the National Technical University of Athens for providing the digital acceleration records from the Chilean earthquake. Finally, I would like to acknowledge the valuable contribution of Lena Zannaki at AMTE in the design calculations of both chimneys.

## 7. References

[1] ACI, “ACI 307-98: Standard Practice for the Design and Construction of Reinforced Concrete Chimneys”, 1998.

[2] ACI, “ACI 318-05: Building Code Requirements for Structural Concrete”, 2005.

[3] M. Angelides, “Cost Optimisation Methods in Chimney Design”, CICIND 43rd Meeting, Paris, April 1995.

[4] M. Angelides, “Earthquake Capacity Design Considerations”, CICIND 55th Meeting, Antalya, April 2001.

[5] AON Benfield, “Event Recap Report: 02/27/10 Chile Report”.

[6] CICIND, “Model Code for Concrete Chimneys”, 2001.

[7] E. Cruz, “Bocamina II New Coal Power Plant Seismic Design Criteria”, 2008.

[8] E. Cruz, “Coronel Thermo-Electric Power Station Seismic Design Criteria”, 2007.

[9] H. Hoffmeister, A. De Kreij, “Chimney for Wet Stack Operation”, CICIND Report, Volume 24, Number 2, July 2008.

[10] Instituto Nacional de Normalixacion, “NCh 433: Diseño sismico de edificios (Earthquake resistant design of buildings)”, Santiago, Chile, 1997.

[11] Instituto Nacional de Normalizacion, “NCh 2369: Diseño sismico de estructuras e instalaciones industriales (Earthquake resistant design of industrial installations)”, Santiago, Chile, 2003.

[12] R. Leon, “The February 27, 2010 Chile Earthquake”, School of Civil and Environmental Engineering, Georgia Tech, Atlanta, 2010.

[13] G.R. Saragoni and S. Ruiz, “The 2010 Chile, Mw=8.8 Earthquake”, International Atomic Energy Agency, 2010.

[14] J. Wilson, “Performance of Pennguard Lined Tall Reinforced Concrete Chimney Structures in the 2010 Chilean Earthquake”, Swinburne University of Technology, Victoria, Australia, 2010.