Seismic Behaviour of Guided Supports of Steam Generator Boilers and Design Using Energy Dissipators

J. Nazal[1], A. Mora[2]

[1] *Structural Engineer, Nazal Ingenieros S.p.A., jnazal@nazal.com*
[2] *Structural Engineer, Nazal Ingenieros S.p.A., amora@nazal.com*

Abstract

Steam generator boilers are widely used in the electric power generation industry. They use heat to evaporate water and supply high-pressure steam - under controlled conditions - to a turbine-generator set that produces the electricity.

Steam generator boilers in coal-fired power stations are traditionally supported by means of hangers connected to the main girders at the top of the steel support structure in such a way that vertical and horizontal displacements due to thermal expansion and contraction are allowed. Typically, guided supports distributed in height are provided to limit the excessive demands on attached piping and equipment due to the pendulum type of movement created by wind and earthquake actions. Evidence from past earthquakes shows that these guided supports play a fundamental role as seismic fuses, and that premature failure of their connections to the main structure, or the simple separation of two guiding elements, could precipitate local failure in the boiler wall tube and unexpected impact forces.

The purpose of this research is to contribute to the understanding of the seismic behaviour of boilers and, based on the evidence of recent earthquakes, implement the use of friction devices to reduce the seismic demand in the equipment and ensure stable and reliable hysteretic energy dissipation.

Keywords: Energy dissipators, Steam generator boilers, Power generation facilities.

1. Introduction

In recent years, several thermal power plants have been built in high risk seismic areas in Chile. They mainly consist of a steam-generator system, a steam turbine-generator set, a fuel handling system, a water circulating system and an emission control system, among other facilities and equipment that are critical to generate electrical power. The steam-generator boiler is, however, the one that poses the most difficult challenge for structural engineers, because the two traditional analysis tools, Equivalent Lateral Force (ELF) and Modal Response Spectrum (MRS) procedures may not provide a reliable means to predict the large deformations of the suspended mass, impact forces and the force distribution across the members of the steel support structure.

Therefore, the design approach of choice has traditionally consisted of the use of low response modification coefficients and design provisions aimed towards limiting the dynamic response in the inelastic range. Guiding elements and links are usually designated as “fuse” elements (i.e. deformation controlled elements), and then designed to undergo inelastic deformations that exceed the elastic limit of the material without significantly damaging their connections to the main structure and neighbouring elements, such that the load paths of the inelastic forces to the vertical systems - and ultimately to the foundations - remain essentially elastic.

Nevertheless, large deflections, premature failure of the connections between guiding elements and the main structure, or the increase of the gap between two guiding elements that are meant to hold the suspended boiler in place, can precipitate undesirable impact forces and local damages in the tube wall. For these reasons, there has been considerable engineering effort to estimate the maximum forces that can be developed by guiding elements, as well as the response accelerations and deformations of the internal pressure parts of boilers. In Chile, most of these efforts have been based on a variety of design philosophies that ultimately depend upon the judgement of the engineering and the peer review teams. Hence, the seismic behaviour reported for a few tailored guiding element designs differ.

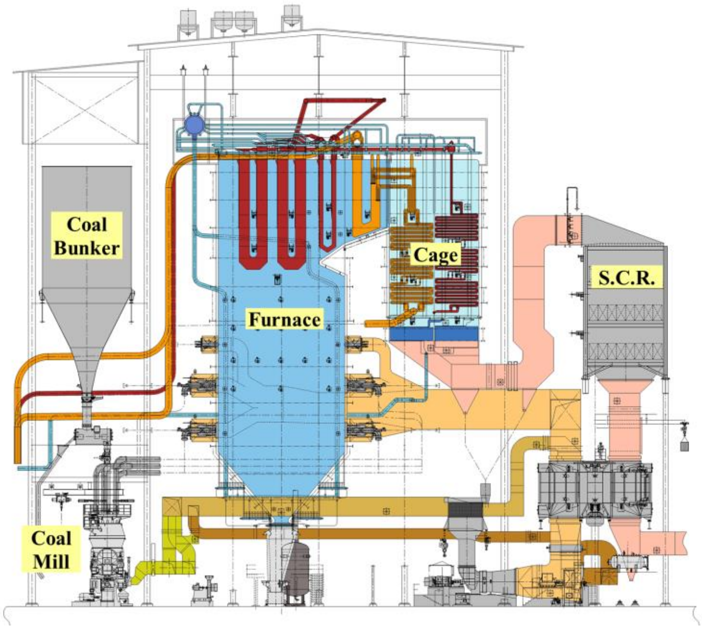

Fig. 1 – Coal-fired Steam Generator (Courtesy of Doosan Heavy Industries)

This work deals with the numerical study of the seismic behaviour of a traditionally designed boiler that is being built in Mejillones, northern Chile, when provided with supplemental energy dissipation devices. The advantages and limitations of the use of friction dissipators implemented herein are investigated in the light of reported damage due to recent seismic events, as well as the feasibility of their installation within areas highly congested with piping and structural components inside the building.

2. Organization

The structural system analysed in this research is a steel building with a large boiler hanging from the roof, as shown in Fig. 1. The building also supports four coal bunkers, a selective catalytic reduction unit, an air pre-heater, a steam drum and other heavy components that make the mass distribution highly irregular.

The following table summarises the masses obtained from the original analysis model done by Doosan Heavy Industries (DHI).

Table 1. Summary of operating weights

Component / Equipment	Operating weight [kN]
Boiler	37,300
Steel structure and others	124,150
Total	161,450

The original analysis and design were carried out by DHI following the provisions for Steel Ordinary Concentrically Braced Frames (OCBF) set out in Chapter 15 of ASCE7/2010, and Chapter F1 of AISC341/2010. The Seismic Design Category of the building is D and, even though the height of the building exceeds the structural height limit for "OCBFs with permitted height increase" (up to 160 feet) by approximately 30 feet, the owner's representative accepted the use of performance coefficients $R = 2.5$, $\Omega_o = 2.0$ and $C_d = 2.5$ after being requested by the boiler supplier. The decision to not adopt the performance coefficients assigned to "OCBFs with unlimited height" was somehow critical to keep the size of base plates and concrete pedestals within reasonable limits, so as to not impair the installation of ancillary equipment, and ensure reasonable clearance for maintenance access at ground level.

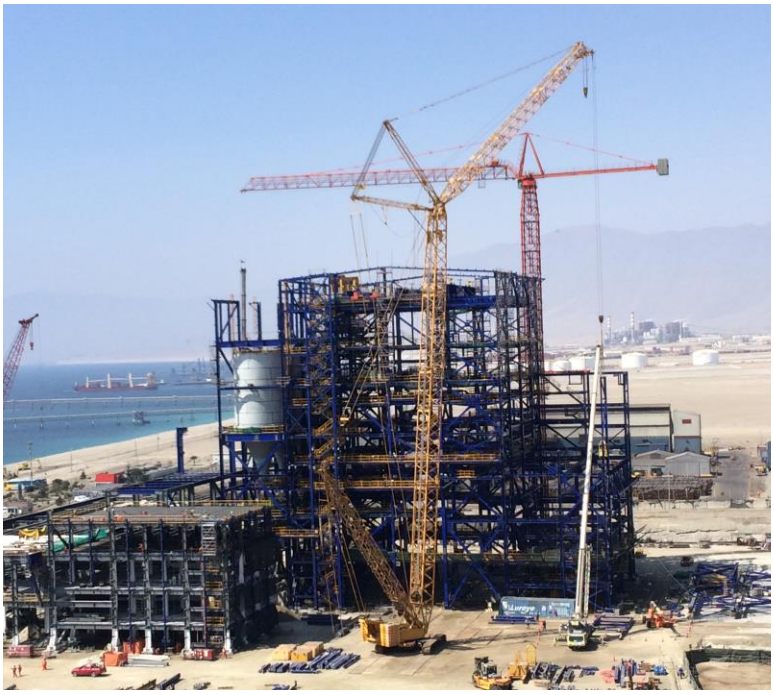

Fig. 2 – Photo of the Boiler Building during construction.

The procedure followed in the design of the steel structure and verification of seismic performance of the boiler internal parts was a linear Modal Response Spectrum analysis. Since the performance objective of the power plant is to prevent disruption of the facility function after the occurrence of an earthquake of intensity comparable to that of the Design Earthquake (DE), the importance factor that was adopted for the design was 1.5. Because of this, structural members and their connections were designed to sustain a seismic force equal to either 1.2 or 0.6 times the unfactored elastic earthquake force. Consequently, the structure is likely to respond in the elastic range, making the estimation of the "real" maximum base shear and accelerations from the MRS analysis relatively straight forward.

3. Implementation of Energy Dissipators

The original finite element model developed by DHI has 691,126 degrees of freedom, which posed a major challenge in terms of the computational effort required. Hence, the portion of the model that represents the suspended boiler that captures the actual geometry of the internal tubes and walls, was reduced to an equivalent springs and lumped mass model.

In the selection of a suitable supplemental energy dissipator, the criterion used was to find a hysteretic device that could take advantage of the relative displacements between the boiler and the steel structure. Amongst the wide variety of dampers that currently exist, the Symmetric Friction Connection damper (SFC) seems a good choice for its simplicity and low hysteretic degradation [3, 5].

Eight artificial accelerograms compatible with the project design spectrum from reference [13] were generated using the methodology set out in reference [8]. Although it is always desirable to utilise actual recorded earthquakes for nonlinear response history analyses, one of the purposes of this work is to compare the results of the original MRS analysis with those obtained from the boiler building with friction dissipators.

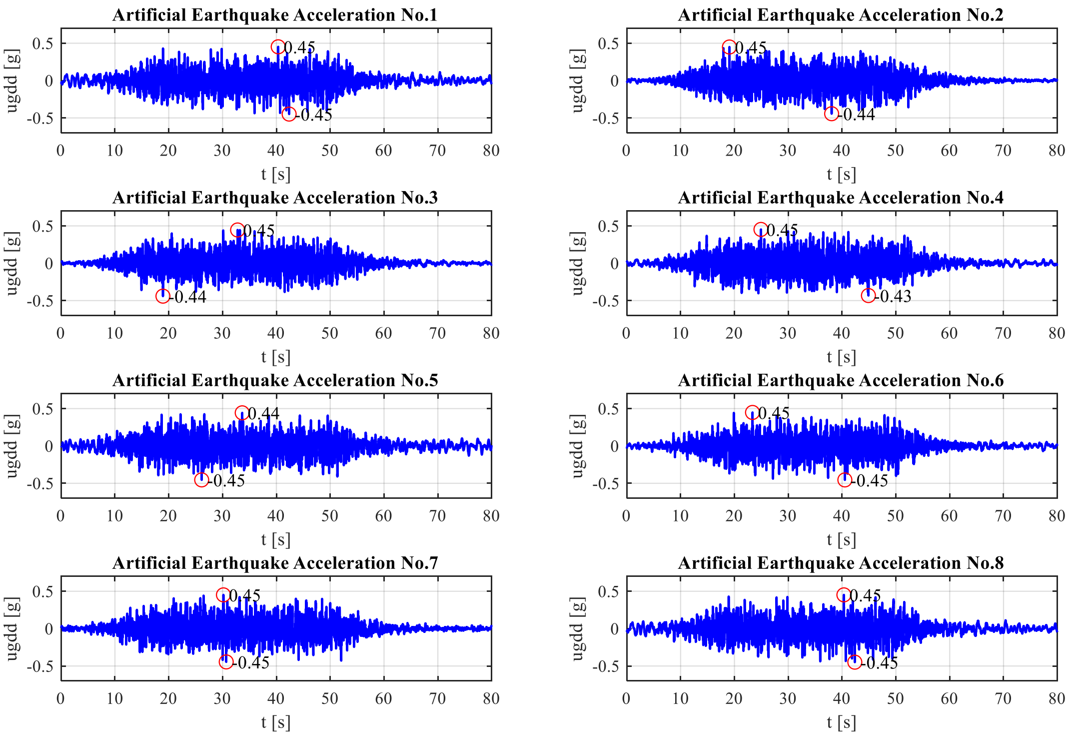

Fig. 3 – Artificial accelerograms.

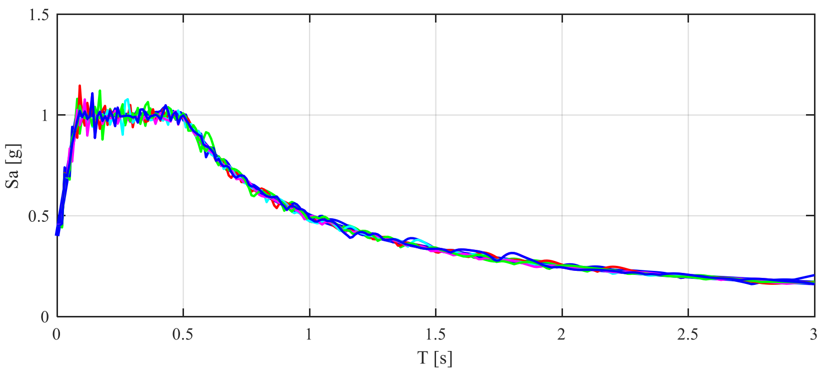

Fig. 4 – Adjusted Response Spectra.

The location and mechanical properties of the friction devices are based on the original design, so as to not significantly alter the behaviour of the equipment when subject to thermal movement and wind action. The yield point of the friction devices is, in many cases, close to the forces taken by the original guided members - like the detail shown in Fig. 5 - under reduced earthquake forces, although the final design of the dampers is the result of several iterations.

The software used to solve the following equation of motion was MATLAB.

$$M\ddot{u} + C\dot{u} + Ku + L^{T}f(v) = -Mr\ddot{u}_{g} \tag{1}$$

$$v = Lu \tag{2}$$

Where f(v) represents the inelastic forces in the SFC dampers and L^{T} the equilibrium matrix, or equivalently, the transpose of the kinematic transformation matrix [11].

The value of the damping ratio considered for all the modes is 5%; whereas the damping matrix was derived from the Caughey's series [4]. This approach showed better correlation with the results from the MRS analysis, for which the damping ratio was assumed constant for all modes, than the traditional Rayleigh's method.

The integration method for obtaining the dynamic response of the system was the Newmark-β method [10] with γ-damping [7], because of its simplicity and robustness. Since the analysis was performed over a system with a significant number of degrees of freedom, the time interval was reduced at those integration steps where the convergence could not be achieved for large $\Delta t/T$ ratios. The integration parameters adopted to deal with the large values of $\Delta t/T$ associated with higher modes were $\beta = 0.3025$ and $\gamma = 0.60$.

Additionally, the system of equations described in (1) was reduced using a sequence of 1000 Load Dependent Ritz Vectors [9, 12]. Thus, the equations (1) and (2) were rewritten as follows:

$$\Psi^T M\Psi\ddot{z} + \Psi^T C\Psi\dot{z} + \Psi^T K\Psi z + \Psi^T L^T f(v) = -\Psi^T Mr\ddot{u}_g \quad (3)$$

$$v = L\Psi z \quad (4)$$

where Ψ corresponds to the set of Load Dependent Ritz Vectors.

The solution of these coupled equations is therefore computed with considerably less numerical effort since the total number of degrees of freedom of the simplified model is still large (36057 degrees of freedom).

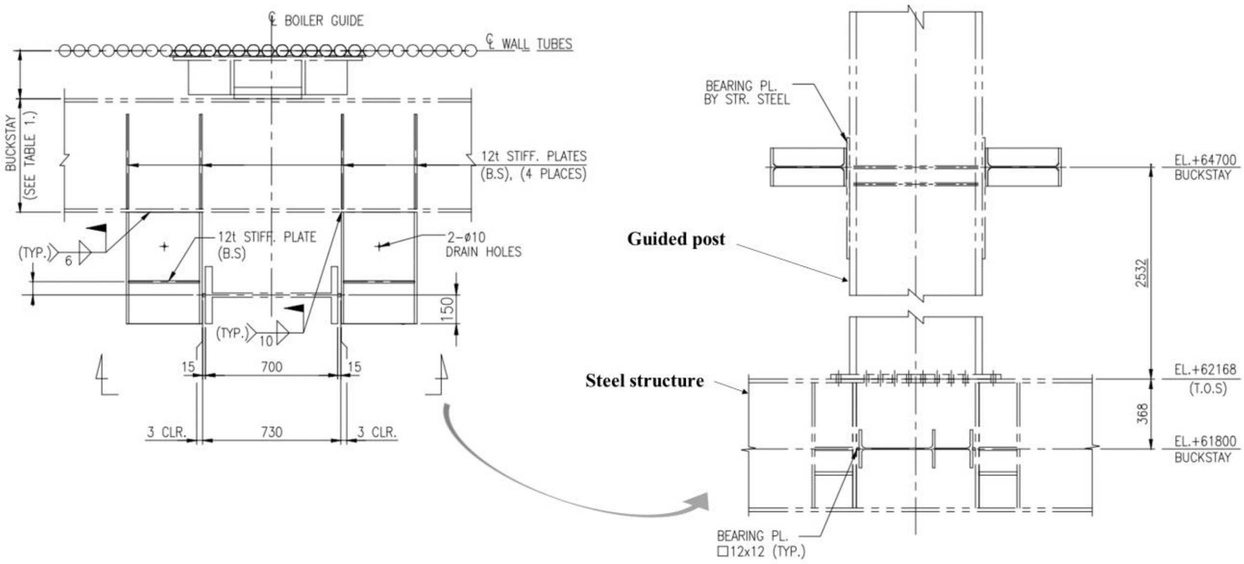

Fig. 5 – Typical guided support.

The frictional dissipator model adopted to replace the structural fuses given by the guided supports is outlined in Fig.6 together with a concept design of the connection between the buckstay beam and the steel structure. The behaviour of the dissipator element can be idealised by an elasto-plastic curve without degradation with parameters k_e and f_{rs}. The parameter k_e represents the stiffness of a strut member and the plates that connect to a rigid steel element that is responsible for coupling the movement of the SFCs and the steel structure; whereas f_{rs} is the sliding force or maximum force that can be developed by the plates in contact.

The stub beam shown in Fig.6 is connected to the buckstay beam through a sliding connection with a low friction coefficient. The latter can be achieved by using a Polytetrafluoroethylene (PTFE) sheet of 6mm thickness etched on the stub end plate to make it bondable. A stainless steel (e.g., AISI 304, polished on one side with a grade #8 finish) plate of 6mm in thickness can be tig welded along the edges to the buckstay beam, and then buffed in order to retain the original finish along the edges.

The number of bolts required in the stub-to-buckstay connection shall be determined based on the bending moment created by the eccentricity of the connection and the maximum friction force that the SFC dissipator can deliver, multiplied by a safety factor essentially dictated by judgment.

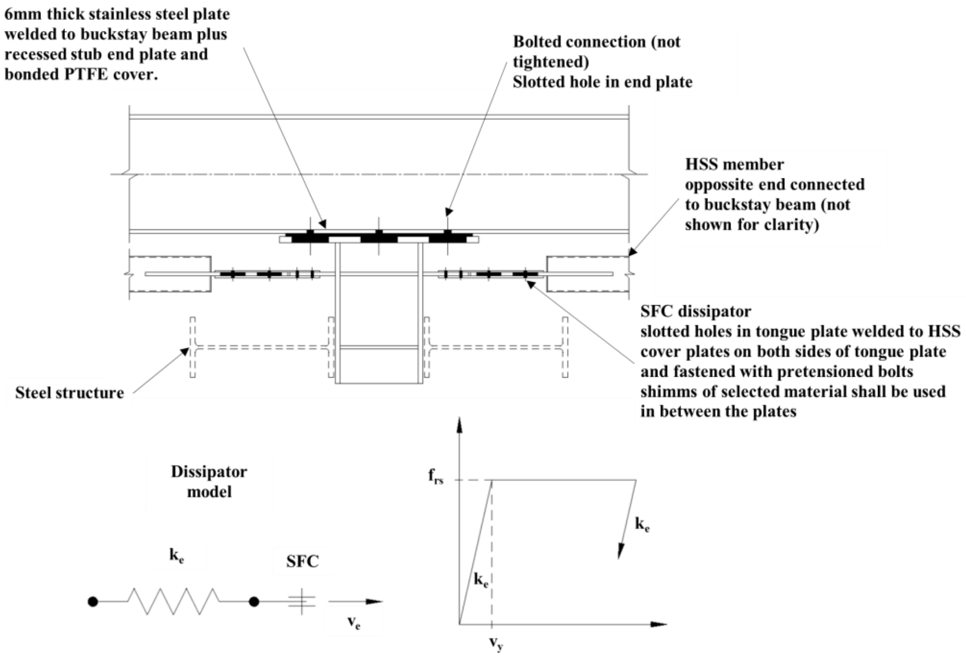

Fig.6 – Friction dissipator model consisting of a strut member plus an SFC in series.

The sliding force developed by the dissipator is function of the friction coefficient between the selected shim material and the three steel plates (tongue plate and cover plates), multiplied by the clamping force in the bolts. The most common choices of shim material compatible with low and medium carbon steel are brass, bronze, cast iron, and aluminium. As for the bolts, high strength bolts to ASTM F3125 grades A325 or A490 can be used depending on the clamping force needed to achieve the desired sliding force in the device.

4. Analysis results

The performance goals for the supplemental energy dissipation system investigated are two: reduction of the base shear, which is expected to have a positive impact on the size of foundations and concrete pedestals; and reduction of the average accelerations in the boiler buckstay beams, which is thought to increase the level of protection of the internal pressure parts.

Table 2 summarises the horizontal base reactions obtained from the linear response history analysis (LRHA) and the nonlinear response history analysis (NRHA) and shows a comparison between the base shear that resulted from linear (LRHA and MRS) and non-linear analyses techniques (NRHA).

Table 2. Horizontal base reactions obtained from the analyses

Analysis Case	Type	Base Shear [kN]	Analysis Case	Type	Base Shear [kN]	LRHA vs. NRHA [%]	MRS* vs. NRHA [%]
LRHA01X	Linear	53,961	NRHA01X	Non-Linear	41,179	↓23.7%	↑ 22.6%
LRHA01Y	Linear	55,051	NRHA01Y	Non-Linear	36,921	↓33.0%	↑ 16.4%
LRHA02X	Linear	58,674	NRHA02X	Non-Linear	44,468	↓24.3%	↑ 32.4%
LRHA02Y	Linear	50,907	NRHA02Y	Non-Linear	37,802	↓25.8%	↑ 19.2%
LRHA03X	Linear	56,147	NRHA03X	Non-Linear	44,825	↓20.2%	↑ 33.5%
LRHA03Y	Linear	55,679	NRHA03Y	Non-Linear	34,896	↓37.4%	↑ 10.0%
LRHA04X	Linear	54,425	NRHA04X	Non-Linear	42,505	↓22.0%	↑ 26.6%
LRHA04Y	Linear	53,343	NRHA04Y	Non-Linear	34,657	↓35.1%	↑ 9.3%
LRHA05X	Linear	56,460	NRHA05X	Non-Linear	45,158	↓20.1%	↑ 34.5%
LRHA05Y	Linear	52,483	NRHA05Y	Non-Linear	35,420	↓32.6%	↑ 11.7%
LRHA06X	Linear	56,240	NRHA06X	Non-Linear	44,023	↓21.8%	↑ 31.1%
LRHA06Y	Linear	50,563	NRHA06Y	Non-Linear	34,928	↓31.0%	↑ 10.1%
LRHA07X	Linear	52,078	NRHA07X	Non-Linear	39,533	↓24.1%	↑ 17.7%
LRHA07Y	Linear	51,457	NRHA07Y	Non-Linear	34,120	↓33.7%	↑ 7.6%
LRHA08X	Linear	53,961	NRHA08X	Non-Linear	41,179	↓23.7%	↑ 22.6%
LRHA08Y	Linear	55,051	NRHA08Y	Non-Linear	36,921	↓33.0%	↑ 16.4%

(*) MRS analysis performed by DHI using the software package SAP2000. Base reactions were reduced by (R/I) are 33,598kN and 31,730kN in the "x" and "y" direction respectively.

The base shear of the boiler structure versus time obtained for artificial accelerogram No.1 using Newmark's integration scheme with γ-damping is shown in Fig.7.

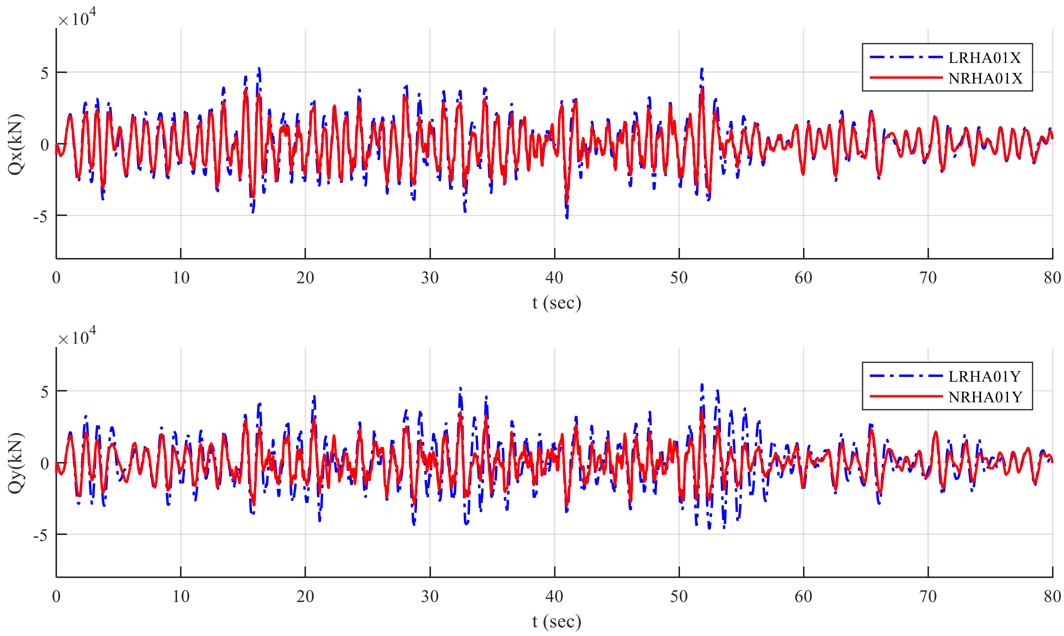

Fig. 7 – Horizontal base reactions for the artificial accelerogram No.1.

The boiler deflections relative to the steel structure can be directly computed from the time response of the SFC dampers. The displacements plotted in Fig.8 correspond to the different levels at which either guided supports or SFC dampers are connected to the boiler, represented by its main components in terms of mass and overall size: the furnace and the cage.

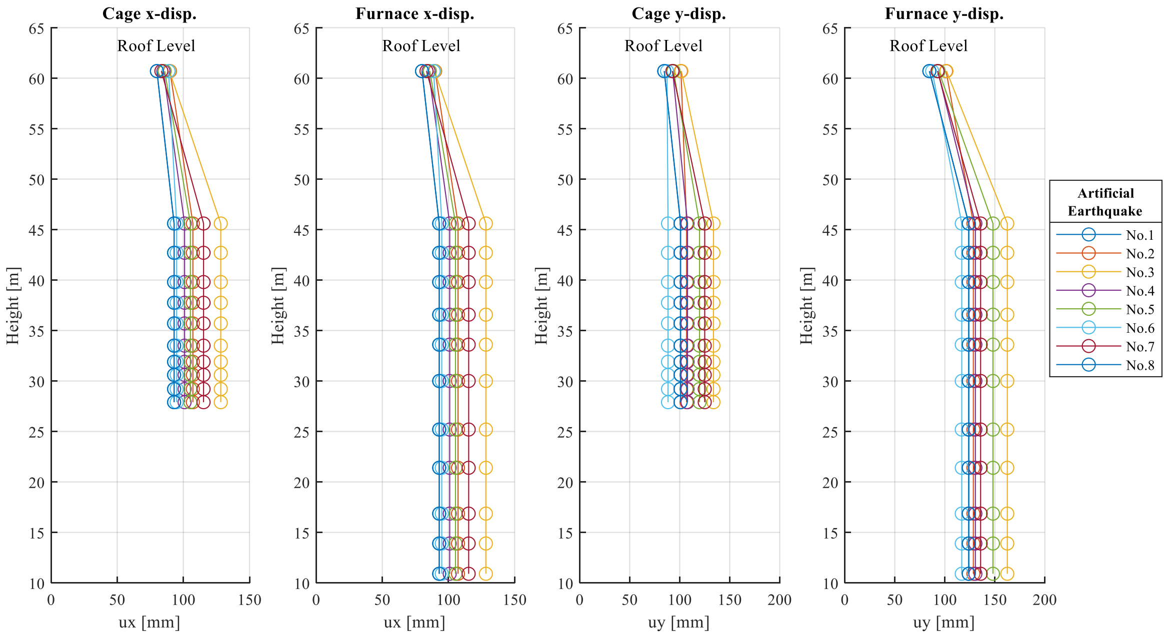

Fig. 8 – Boiler's cage and furnace displacements.

Unlike traditional guided supports, in the case of SFC dampers, permanent displacements may be more economical and simpler to deal with as the repairing works will only consist of loosening and re-tightening bolts to the desired pretension level. Nonetheless, there may be cases in which the extension of the damage could compromise the structural integrity of the device. For those cases, a full replacement of plates and bolts could be necessary. Furthermore, when working on the detailed design of the dampers, the engineer should impose a hierarchy of failure on the structure, buckstay beams and connections so as to ensure a desirable ultimate behaviour.

The maximum hysteretic response of the SFC dampers can be outlined through the examples shown in Fig. 9 and 10. For the sake of simplicity, the hysteretic response curves were normalised with respect to the slip force and a clearance of 200mm between the steel structure and the boiler that represents the typical case. These examples also depict the reduced effectiveness of the dissipators set in the x-direction of the structure as compared with those oriented in the y-direction. The reason is that the locations of the guided supports were originally established to sustain primarily the action of the wind, not earthquakes. It was later, during the detailed design phase, when the necessary upgrades on the guided supports were done in order to attain the desired ductile mode of failure, regardless the demand/capacity ratios of some of the elements.

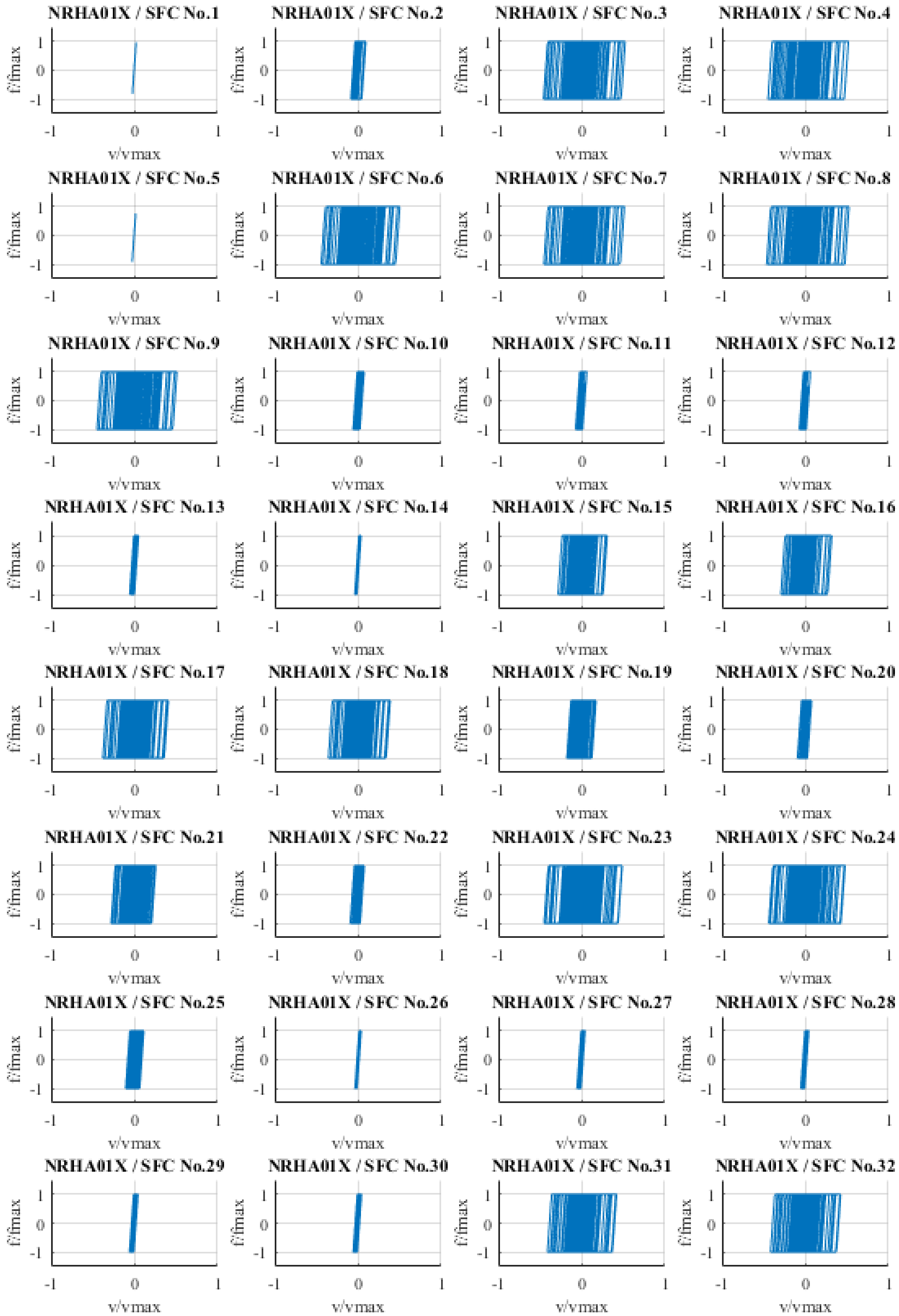

Fig. 9 – Normalised SFCs' hysteretic responses for artificial earthquake No.1 in the x-direction.

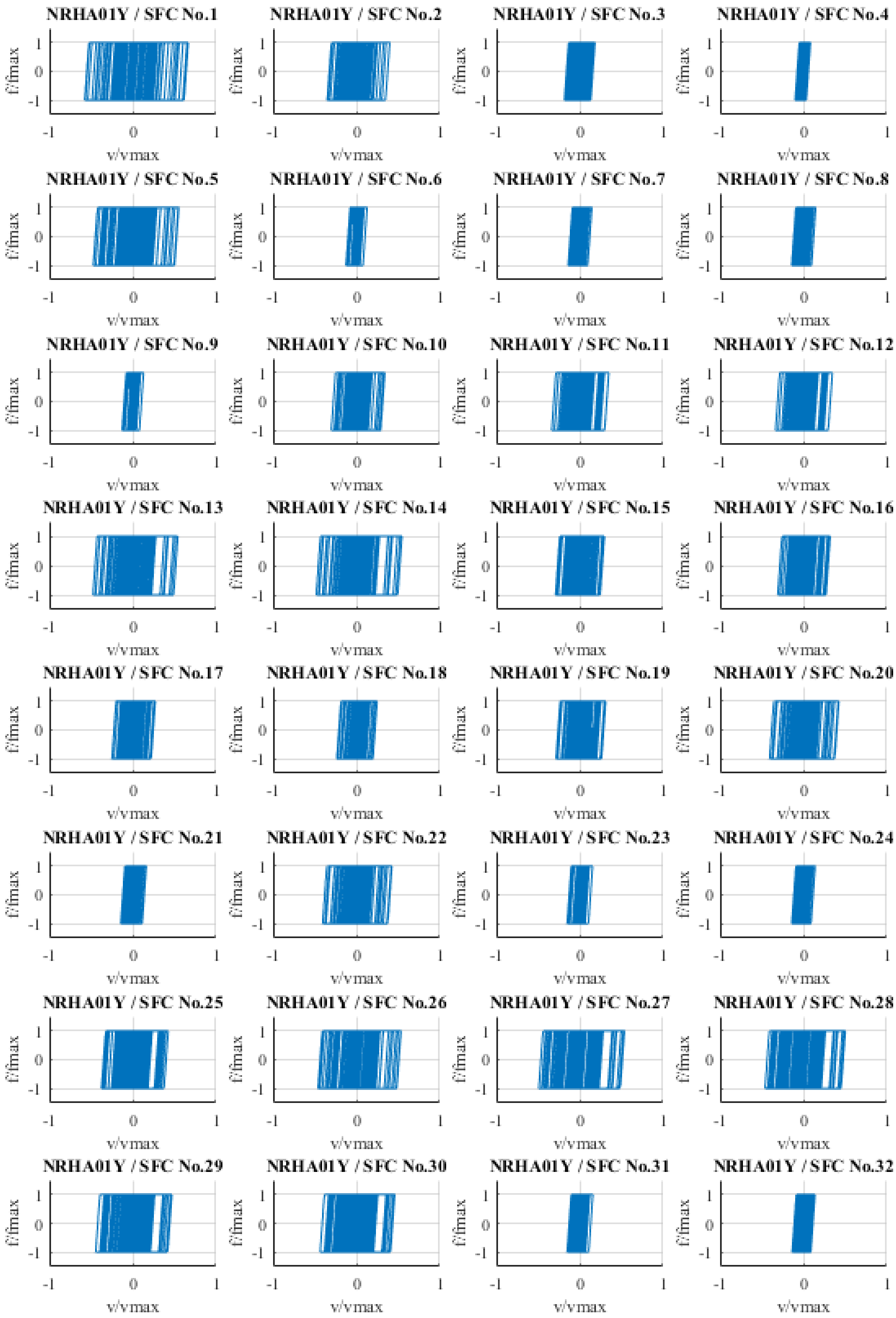

Fig. 10 – Normalised SFCs' hysteretic responses for artificial earthquake No.1 in the y-direction.

5. Summary and Conclusions

In order to provide adequate earthquake resistance, boiler buildings are traditionally designed to have high strength and stiffness to resist lateral loads. This is achieved by using diagonal braces and guided supports specially designed to sustain inelastic deformations and dissipate energy. This design strategy aims towards ensuring that inelastic deformations only occur in the braces and the guiding members. The drawback of this approach is that the use performance coefficients, such as R or Ω_0, is generally based upon the expectation of a global plastic mechanism, which is unlikely to occur considering the complex geometry and irregular mass distribution of boiler buildings. Moreover, the estimation of the maximum forces developed in the designated conventional seismic fuses, may be largely exceeded during a real event.

The use of supplemental hysteretic energy dissipating devices - like the SFC - take advantage of the large relative displacements between the suspended boiler and the support structure to dampen the dynamic response. For instance, the reduction in the horizontal base reactions of the boiler building when provided with SFCs is about 20% up to 35% under earthquake loads. This is particularly true as the original member design has been carried out adopting a very low response reduction coefficient, which renders the behaviour of the structure essentially elastic when subject to an earthquake of size comparable to that of the design earthquake.

In addition to the above, the slip strength of the SFC permits relatively precise estimation of the maximum forces that can enter force-controlled elements such as columns, buckstay beams and connections, which are considerably less than the amplified forces prescribed in the seismic code.

6. References

[1] American Institute of Steel Construction (AISC) (2016). Seismic Provisions for Structural Steel Buildings, ANSI/AISC 341-16, AISC, Chicago, IL.

[2] American Society of Civil Engineers (ASCE) (2016). "Minimum Design Loads and Associated Criteria for Buildings and Other Structures." ASCE/SEI Standard 7-16, ASCE, Reston, VA.

[3] Beziat, A., Mora, A., Chase, J. G., Macrae, G. A., Rodgers, G. W., & Clifton, C. (2012). Performance Analysis of Energy Dissipators and Isolators Placed in Bridges to Prevent Structural Damage in Columns, (May 2013), 37-41.

[4] Caughey TK. Classical normal modes in damped linear dynamic systems. Journal of Applied Mechanics (ASME) 1960; 27(2):269-271.

[5] Grigorian, C. E., Yang, T. S., & Popov, E. P. (1993). Slotted Bolted Connection Energy Dissipators. Earthquake Spectra.

[6] Hanson, R. D., and Soong, T. T., 2001. Seismic Design with Supplemental Energy Dissipation Devices, Earthquake Engineering Research Institute, Oakland, CA, 135 pp

[7] Hilber, H. M., Hughes, T. J. R., & Taylor, R. L. (1977). Improved numerical dissipation for time integration algorithms, 5(April 1976), 283-292.

[8] Jennings, P. C., Housner, G. W., & Tsai, N. C. (n.d.). Simulated earthquake motions.

[9] P. Leger, E.L. Wilson, R.W. Clough, The use of load dependent vectors for dynamic and earthquake analyses, Earthquake Engineering Research Center Report, University of California, Berkeley, UCB/EERC-86/04, 1986.

[10] Newmark, N. M. (1959). A Method of Computation for Structural Dynamics. Journal of the Engineering Mechanics.

[11] J.S. Przemieniecki, Theory of Matrix Structural Analysis (McGraw-Hill, New York, 1968).

[12] Wilson, E. L., Yuan, M.-W., & Dickens, J. M. (1982). Dynamic analysis by direct superposition of Ritz vectors. Earthquake Engineering & Structural Dynamics, 10(6), 813-821.

[13] Seismic Design Specifications for GDF Suez Power Plants in the North of Chile, Rev.1.

