Analysis and Solution for Angra 1 Electric Generator Lead Box Vibration

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ABSTRACT:

Hydrogen leakage caused by severe cracks on the Lead Box coupled to the Electric Generator (EG) was the reason for repeated shutdowns of Angra 1 NPP occurring from Dec./2005 to Apr./2006. Lead Box cracking, already identified in other units with large electric generators, is caused by high cycle fatigue due to structural vibration. The root cause is the operational vibration of the Electric Generator highly amplified at the Lead Box.

The first natural frequency measured at the Lead Box was 30.3Hz which was very close to the rotation frequency of the electric generator rotor (30Hz). The standard solution applied in several plants was the mechanical decoupling of the current transformers but this approach, in Angra 1, would require very long time for design elaboration, and special material supply.

As an alternative, the reinforcement of the Lead Box structure at critical locations was analyzed by a detailed finite element model. The Lead Box reinforcement was very effective not only to increase the natural frequency but also to redistribute the stresses at the edges of the structure.

This solution was applied to the Lead Box, during the 2006 refueling outage, together with a recommendation from the manufacturer to perform a Frame Footing Loading. Strain gages and accelerometers were used for the stress and vibration monitoring during the start-up of the plant.

Those measurements showed a significant reduction in vibration amplitudes by a factor of 5, and in peak stress at the Lead Box shell by a factor of 10. The stress level evaluated after the modification was very low in comparison to the fatigue limits so that recurrent failures of the same type are not expected.

INTRODUCTION

The Lead Box is a cylindrical vessel, with semi-elliptical heads connected to the bottom of the electric generator with a flange of almost rectangular shape (see figure 1). Its function is to protect and isolate the phase and neutral leads. There are three vertical nozzles for the neutral leads and three 45^{o} nozzles for phase leads. Current transformers are installed outside the nozzles and they are necessary for the measurement and control of the plant energy generation.

It operates with an internal pressure of 5.27 bar. A through wall crack in the Lead Box causes hydrogen leakage which increases the risk of fire.

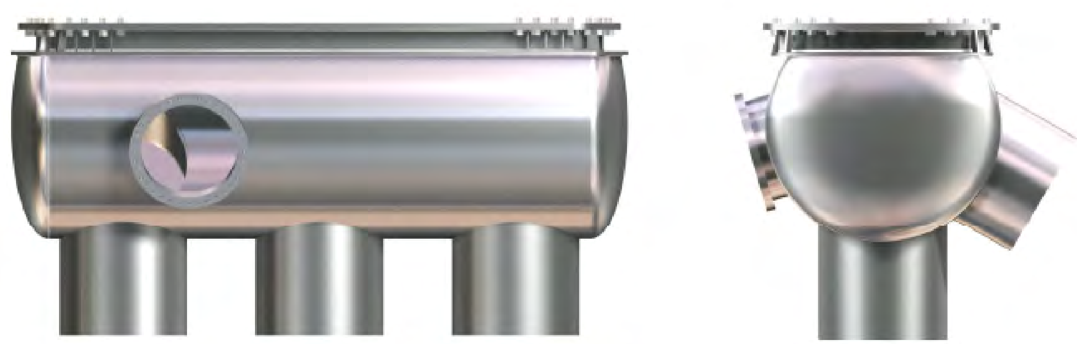

Figure 1. Front and lateral views of the Lead Box.

The Lead Box is a passive component and does not require any special maintenance, however its connection with the Generator is a source of operational vibrations transmitted by the EG casing and rotor which operates with a speed of 1800 rpm. According to the generator manufacturer, fatigue cracking of lead boxes can occur if the generator frame vibration levels are not kept below acceptable limits.

Angra 1 has been in commercial operation since April, 1982 and had not experienced any integrity problem with the Lead Box. After the first event of fatigue cracking occurred in December 2005, there were three more shutdowns, in a 6 months period, caused by the same reason.

SHUTDOWN EVENTS

An increase of the hydrogen consumption was observed after 2005, October 21st. The plant was shutdown on December 26th and an inspection detected a through wall crack in the phase B nozzle. The damaged piece was replaced and the other nozzles were inspected and no indication was found.

After this event there were three more shutdowns caused by through wall cracks located in the corners A and C of the flange connected to the EG base frame.

Event	Shut down	Position
1	Start of H2 Leakage – 21/10/2005	Nozzle – Phase B
	Shutdown of the plant – 26/12/2005	
2	Start of H2 Leakage – 07/01/2006	Upper Flange - Corner A – Upper weld
	Shutdown of the plant – 16/01/2006	
3	Start of H2 Leakage – 24/03/2006	Upper Flange - Corner A – Lower weld
	Shutdown of the plant – 29/03/2006	Upper Flange - Corner C – Upper weld
4	Start of H2 Leakage – 11/04/2006	Upper Flange - Corner C – Upper weld
	Shutdown of the plant – 14/04/2006	Upper Flange - Corner C – Lower weld

Table 1. Events and location of trough wall cracks in the Lead Box.

The figure 2 presents the disposition of the corners A, B, C and D described at the Table 1.

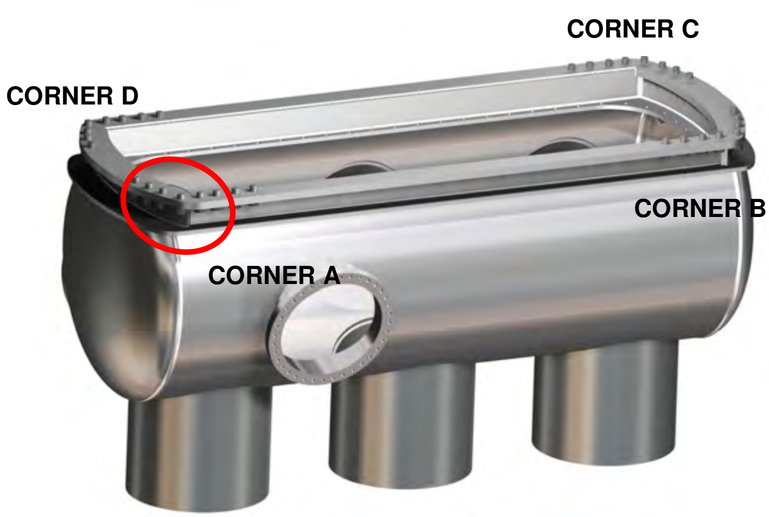

Figure 2 - Disposition of the corners A, B, C and D.

The second event was a through wall crack located in the corner A, upper weld. The crack was fully removed and repaired by welding. The figure 3 shows the location of the crack and a photo of the repair.

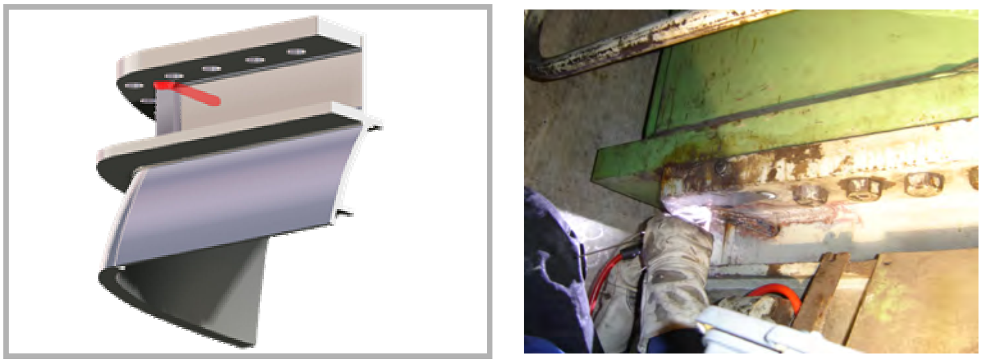

Figure 3: 2nd Event – Position of the crack and photo of the repair

The third event was caused by two through wall cracks. One located in the corner A lower weld and other located in the corner C upper weld. The cracks were fully removed and repaired by welding. The figure 4 shows the location of the crack at corner A and the dimension of the crack.

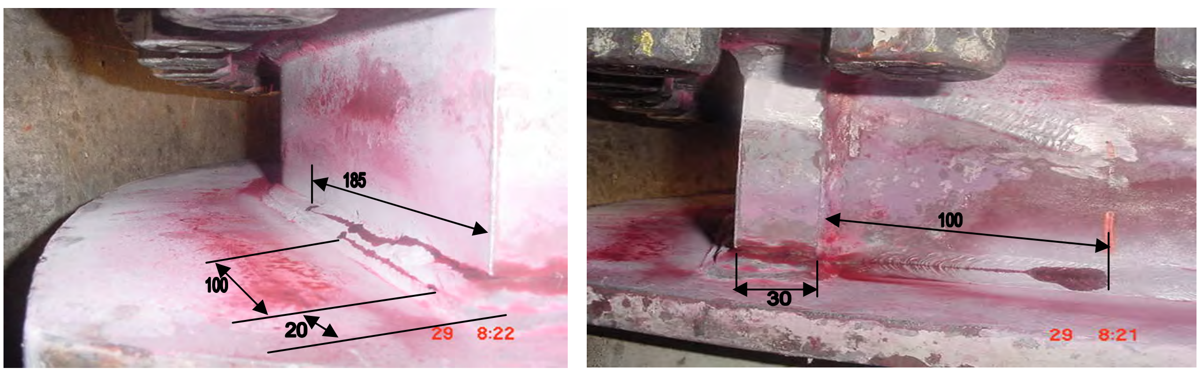

Figure 4: 3rd Event – Cracks at corner A – lower weld

The crack in the corner C upper weld was similar to the one found in the corner A in the 2nd event. One additional shutdown occurred in the 4th event caused by cracks in the corner C (lower and upper weld).

FAILURE CAUSES EVALUATION

A sample removed from the fractured material, in the 3rd event was submitted to metallurgical evaluations. The characteristics of the fracture surface indicated transgranular crack caused by fatigue as can be observed in the Figure 5.

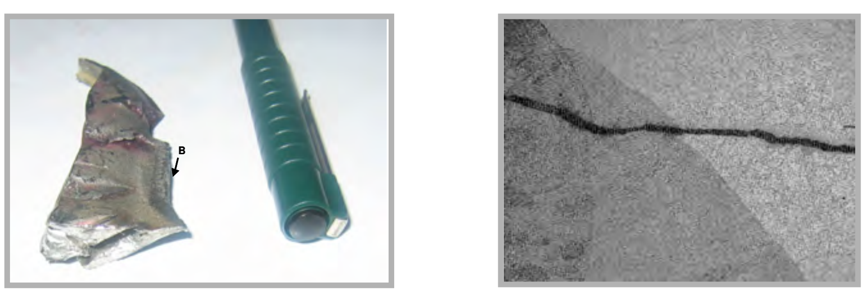

Figure 5: Sample removed and transgranular crack observed from microscope.

After the 3rd event detailed vibration measurements were performed for several points of the Electric Generator casing and Lead Box. The measurements showed a natural frequency of 30,3 Hz for the Lead Box, which was very close to the operating velocity of 1800 rpm (30Hz). Vibrations Measurements during normal operation confirmed very high amplification from EG to the Lead Box.

That result confirmed that a high cycle fatigue degradation mechanism, caused by the primary vibration of the electrical generator and amplified by the resonance effects of the Lead Box, was the main failure cause for the repeated cracks nucleation and quick propagation.

PROPOSED SOLUTIONS

There were 3 solutions: Frame Foot Loading and Current Transformer Decoupling, proposed by the designer of the Electric Generator; and an alternative modification - Stiffening of the Lead Box with Ribs, proposed by ELETRONUCLEAR. Those solutions are described below:

a) Frame Foot Loading – The main purpose of this procedure was to redistribute the Electric Generator weight load over the supporting pads, equalizing right and left sides and concentrating around 70% of the total load on the external pads. The objective would be to reduce the primary vibration of the Electric Generator.

b) Current Transformer Decoupling – This design modification would attach the current transformers to external supports, decreasing the weight and increasing the natural frequency of the Lead Box. Therefore this modification would reduce the amplification factor of the secondary vibration.

c) Stiffening of Lead Box with Ribs – This design modification would increase the natural frequency of the Lead Box and improve the stress distribution in the corners where the cracks occurred.

The Current Transformer Decoupling would be the most effective solution. This procedure was already applied in several power plants, however, an evaluation of the necessary efforts for performing as-built drawings and detailed design for the modifications in conjunction to the expected delay for the acquisition of special parts in austenitic stainless steel led this alternative to be considered not viable to be applied in a short period.

ELETRONUCLEAR decided to implement the Frame Foot Loading to reduce the primary vibration and the Stiffening of the Lead Box with Ribs.

ANALYSYS PERFORMED BY ELETRONUCLEAR

In order to evaluate the effectiveness of the solution – Stiffening of the Lead Box with Ribs, Finite Element Models, using ANSYS FE software, were prepared to represent the original configuration and the modified structure by the introduction of stiffeners at the flange corners. The Figure 6 shows the finite element model for the original design.

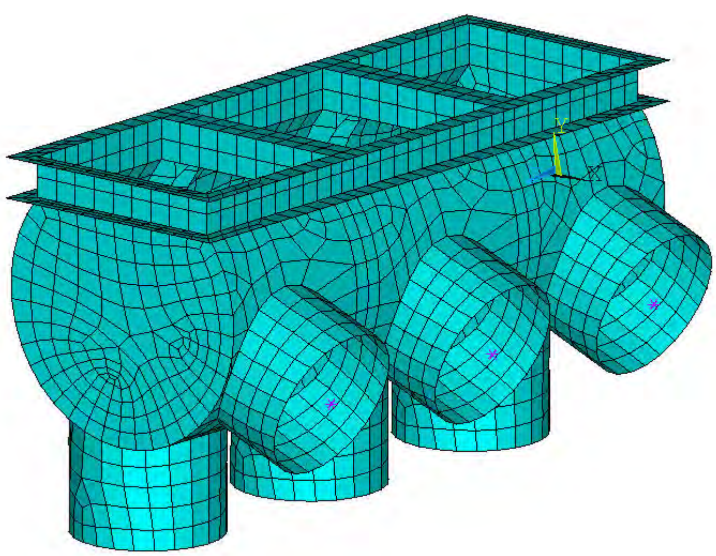

Figure 6: Finite Element Model of the Lead Box – Original Design

The first analysis performed was the extraction of the frequencies and mode shapes. The first mode shape was the rotation of the Lead Box in the plane XY as presented in the figure 7 with a frequency of 30,3 Hz, confirming the measurements obtained in the field.

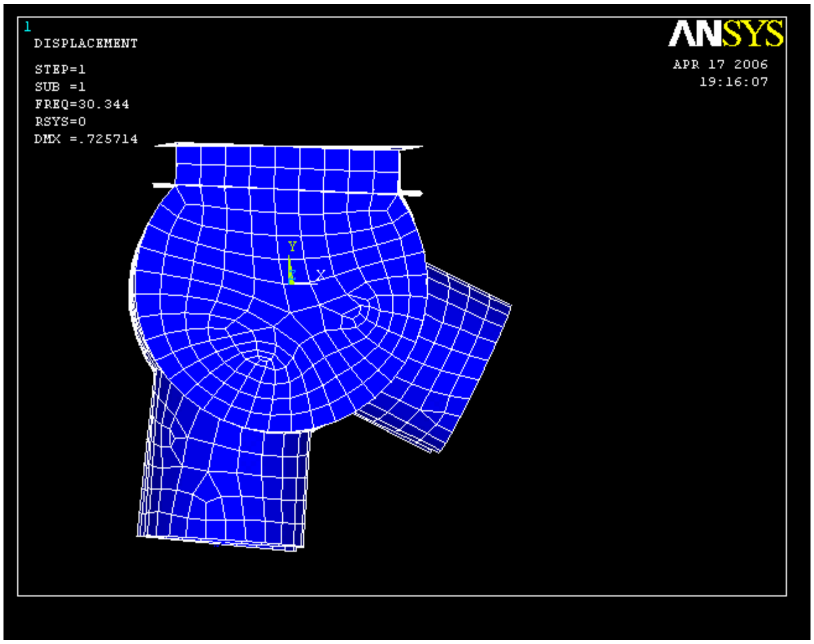

Figure 7 – 1st Mode shape of the Lead Box (Frequency – 30,3 Hz)

The stress distribution of the Lead Box was also determined with the finite element model. The figure 8 shows the high stress concentration around the corners which would be the primary cause of the fatigue.

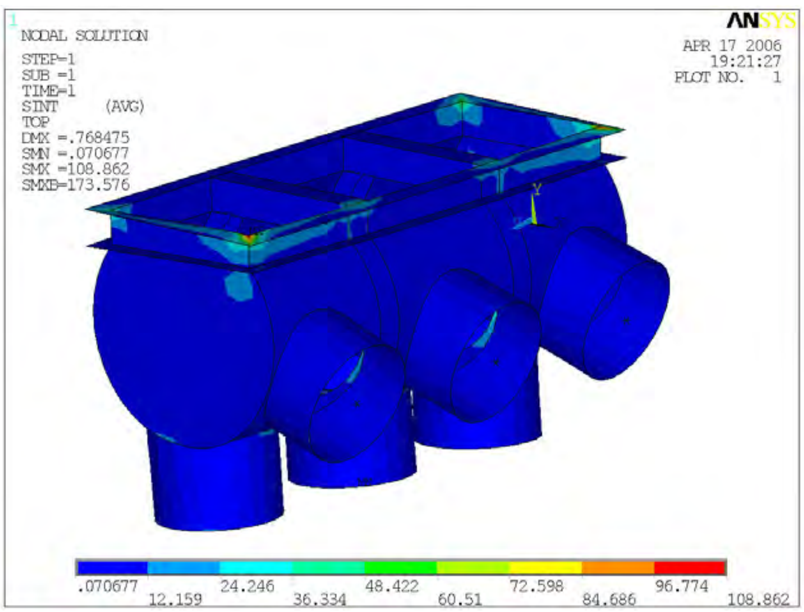

Figure 8 – Stress Distribution of the Lead Box – Original Design.

A model of the Lead Box with the stiffening of the corners with one rib for each, showed a much better behavior. The natural frequency increased from 30,3 to 33,0 Hz which reduced the dynamic amplification factor from 12,2 to 5,3. The maximum stress in the model decreased from 108,8 to 46, 1 N/mm^2. An additional advantage of this second model was that the maximum stress would occur in the ribs and no more in the pressure boundary shell.

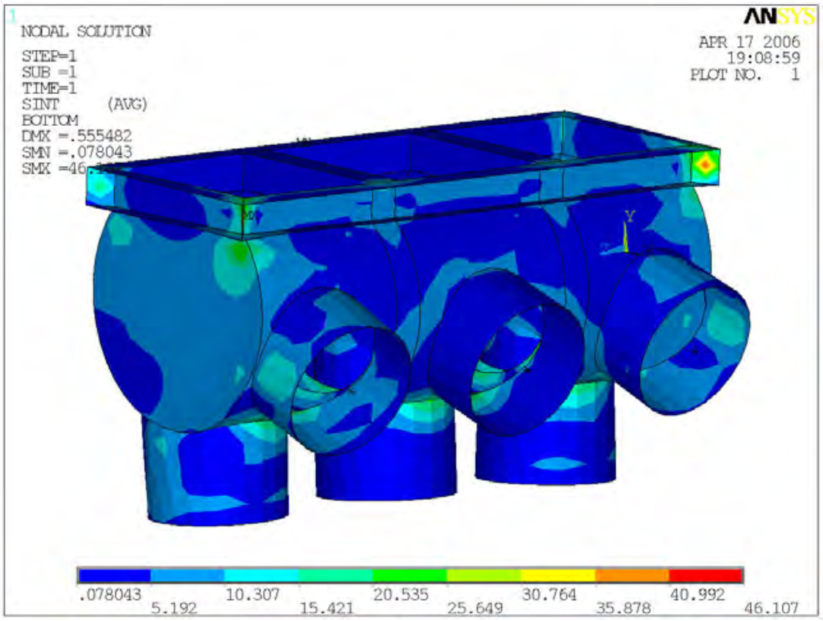

Figure 9 – Stress Distribution of the Lead Box – Stiffned Structure

DESIGN MODIFICATION AND COMISSIONING

The installation of the ribs was performed during Angra 1 Outage, 1P14, in May 2006.

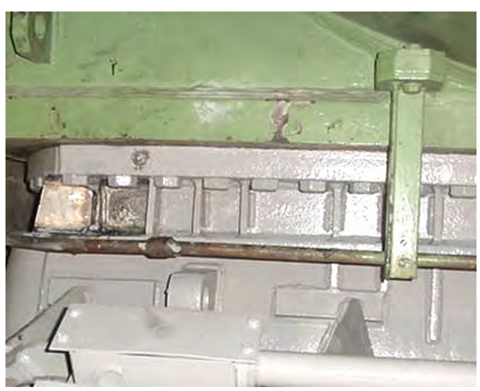

Figure 10 – Stiffenning Ribs installed in the Lead Box flange.

Strain Gage measurements were used to monitor the dynamic behavior of the ribs and shell of the Lead Box, during the start-up of Angra 1. It was measured simultaneously the deformation in 7 points of the Lead Box and 2 points in the EG support pads, during the over-speed test, synchronism and 84% power. The results showed that all the deformations were below the fatigue limits.

Figure 11 – Strain gages installation.

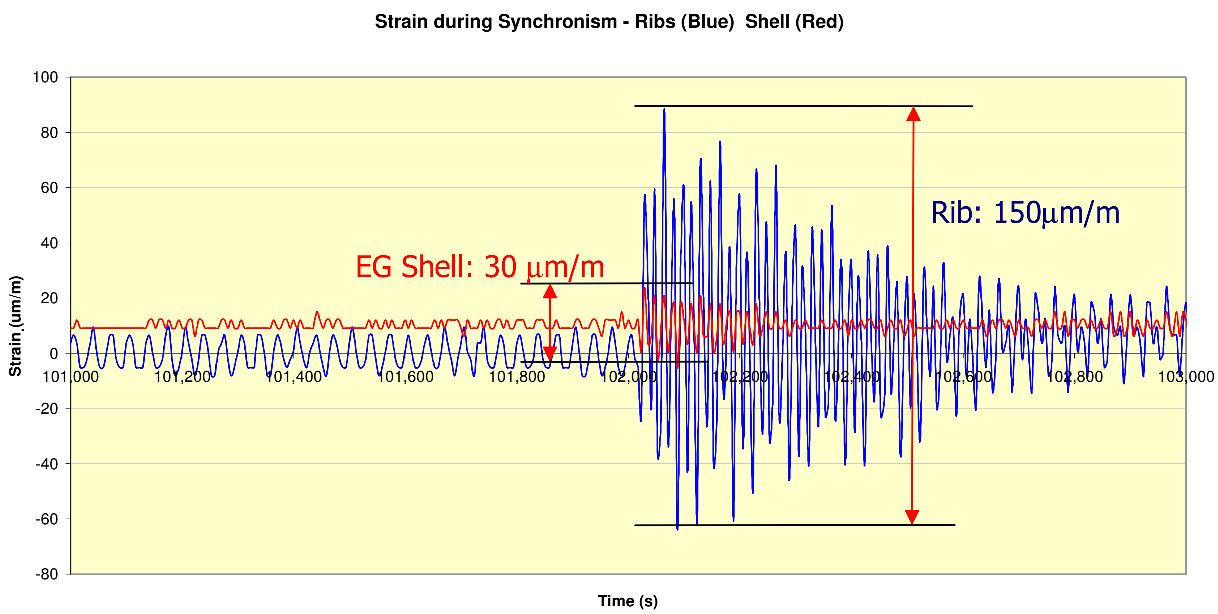

Figure 12 – Deformations in the rib (blue) and in the shell of the Lead Box (red) measured with strain gages

The figure 12 shows the time-history of the deformations during the synchronism of the plant measured at the shell and at the ribs. The maximum value occurred at the rib: 150µm/m while at the shell the deformation was 30 µm/m. The results of the strain-gage measurements showed the cyclic effects of the deformation in the Lead Box, a factor of 5 between the stresses in the rib and in the shell of the Lead Box.

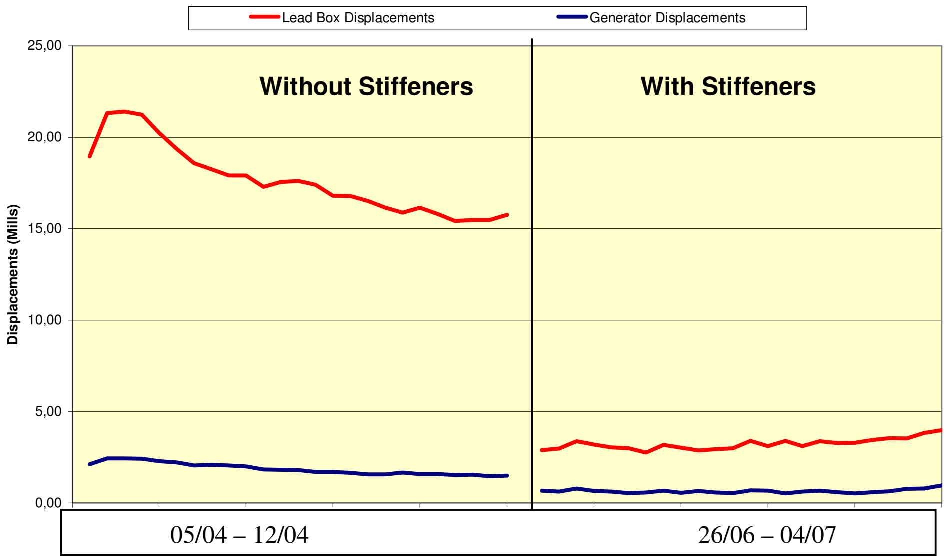

Figure 13 – Lead Box and Generator vibration measurements

Figure 13 compares the evolution of the displacement levels at the Lead Box and at the Electric Generator showing the effectiveness of the applied structural reinforcement. The vibration level of the Lead Box is still being monitored and the vibration amplitudes remain below 5.0 mills which is an acceptable value recommended by the Electric Generator manufacturer. The hydrogen consumption is also within the normal range.

CONCLUSIONS

An innovative, effective and low-cost solution to reduce vibration levels and avoid the consequent fatigue failure of the Lead Box of the Electric Generator was conceived, developed, analyzed and implemented by ELETRONUCLEAR at Angra 1 NNP. The installation of ribs at critical locations of the Lead Box eliminated the root cause of the problem.

Measurements performed during the plant startup, after the 2006 refueling outage, showed a significant reduction in vibration amplitudes by a factor of 5, and in peak stress at the Lead Box shell by a factor of 10. The stress level evaluated after the modification was very low in comparison to the fatigue limits so that recurrent failures of the same type are not expected.

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[2] Zienkiewicz, O.C., Taylor, R. L. and Zhu, J.Z. – Finite Element Method Its Basis & Fundamentals – Elsevier Book Aid International – 6th Edition - 2005