REPAIRS ON POWER HOUSE AND BOILER SUPPORT STRUCTURE DAMAGED BY 1965 EARTHQUAKE. VENTANAS 115 MW STEAM ELECTRIC STATION (CHILE)

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ABSTRACT

The factors that determined faults in the Power House and Boiler Support Structure at Ventanas Steam Electric Station during the 1965 earthquake are studied in this paper.

The discrepancies between the static and dynamic design criteria are summarily stated, comparing the results with values obtained from direct experimentation, thus being able to explain the structural damages.

Based on this analysis, the structural repairs were designed, in an attempt to improve their seismic stability.

In conclusion, several recommendations are given for the design and repair of similar structures damaged by earthquakes.

1. INTRODUCTION

1.1 Plant Description. Ventanas Steam Electric Station, located at Quintero bay in Chile's central zone, consists of a 115 MW turbogenerator fed by a 363 tons/hour steam generator.

This equipment is installed in a Power House, with its longitudinal centerline in a north-south direction, and on a Boiler Support Structure, with its longitudinal centerline in an east-west direction.

Subsoil at the Plant's site consist of compact fluvial sand and shore deposits, more than 50 m deep. The water table is 4.30 m down. In order to build the foundations, upper strata of dune sand were removed, backfilling with selected material compacted to 85% relative density.

The Power House and Boiler Support Structure foundations are reinforced concrete uniform mats, with design bearing values of 1.5 kg/cm2 for static loads and 2.0 kg/cm2 for dynamic seismic loads.

The Power House is a 5-level steel structure, 25 m high, with 4,000 tons total weight, including electrical and mechanical equipment. It has a 63 x 20 m rectangular plan, formed by a system of perimetral columns and girders. Horizontal loads are resisted by a triangular diagonals system. Fig. Nº 1 gives a sketch and Photograph Nº 1 shows a general view of this building.

The Boiler Support Structure is 45 m high, 32 x 40 m plan with 3,700 tons total weight, including the boiler. It is formed basically

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by 9-level steel bents, braced by diagonals. These bents, 3 in a north-south direction and 2 in an east-west direction, leave the necessary space at each level for the hanging type boiler. The bents at each level have been braced horizontally by reinforcing the platform framings. Photograph Nº 2 shows a view of the boiler and Fig. Nº 2 gives a sketch of the structure.

Seismic loads are transfered from the boiler to its support structure through a horizontal hinged-tie system with shear load transmitting capacity. These ties are distributed between the boiler and its support structure at three levels and have been installed so as to permit normal thermal displacements.

In both structures the steel shapes meet ASTM-A36 specifications, with ASTM-A325 friction-type high strength bolt connections.

1.2 Earthquake Characteristics. On March 28th, 1965 a Richter Magnitude 7-7.25 earthquake struck Chile's central zone. The epicenter coordinates were determined at 71º 10'W longitude and 32º 30' S latitude, with a focus depth of 61 km (USCGS).

Ventanas Plant is approximately 55 km southwest of the epicenter. The M. Mercalli intensity at the plant was IX, with maximum ground accelerations being estimated at 0.20 g horizontally and 0.15 g vertically.

1.3 Earthquake Effects. The plant was left out of service due to several damages in the structures and equipment.

There was no cracking or settling of the main foundations, or evidence of earthquake-induced liquefaction of the sandy soil. Damages were localized basically in the Boiler and its Support Structure, the Power House and the Piping System.

Damage to mechanical equipment was not excessively serious, and the plant was put back in service in 30 days, after repairs.

At the Power House, nearly 50% of the diagonals located above operating floor level were damaged, by buckling in the minimum flexural rigidity plane. An aspect of this can be seen in Photograph Nº 3.

On the Boiler Structure damages were localized in the diagonals' connection system, with 3 main joints failing due to lateral displacements. In addition, 30% of the friction-type bolts slipped and went into bearing when their slip resistance was exceeded. Photographs Nº 4 and Nº 5 show 2 main joint damages.

Piping, supported by pipe hangers to allow thermal expansion, oscillated violently, banging against adjacent members because they did not have special seismic action control devices, there being only restraints for maximum displacements. These impacts damaged the lagging without affecting the pipes themselves. Photograph Nº 6 shows typical damage.

Among structural members the boiler hinged-tie system also showed secondary damage, due to elongation of pin holes and deformation of supports from overstress.

Before repairing structural damages, and in order to carry out a work that would not be limited simply to recovering the pre-earthquake safety factor, it was decided to study the structures' seismic behavior both theoretically and experimentally, so as to clarify the cause of failures and possible benefits to be obtained with a properly planned repair job.

2. SEISMIC STRUCTURAL ANALYSIS

2.1 Original Design Method. The original seismic design was based on traditional static methods, supposing a 0.15 g basic acceleration.

In the Power House, forces corresponding to this acceleration were considered proportional to the masses gravitating at each level. In the Boiler Structure, forces were distributed according to the 1962 SEAOC Code.

As previously mentioned, these structures are braced by diagonal systems, designed to conform to 1949 AISC Specifications, enlarged for the use of A36 steel and A325 bolts, increasing the allowable stresses by 33%. The same criteria applied to the connection design.

2.2 Dynamic Analysis Method. The original design schemes were compared with those obtained by applying a dynamic calculation method. For this purpose the structures were idealized as discrete-parameter models, represented by lumped-mass multidegree systems. The resulting systems have 5-degrees of freedom for the Power House, and 9 for the Boiler Structure.

In a first stage, the vibration modes and periods were obtained by the normal mode method, and its seismic behavior was then investigated by the spectra-response method. Certain real earthquake and theoretical spectra from seismic codes were chosen, analyzing the models' multiple responses, so as to establish comparison criteria and finally determine a representative envelope.

The real earthquake spectra used were El Centro-1940 and La Ligua (Chile) - 1965. Among theoretical spectra the Chilean Anti-seismic Design Code (Inditecnor 63-9d) and that proposed by G. W. Housner in 1964 were chosen. All the spectra were applied for a 2% damping value, determined by repeated experimental measurements, as will be detailed further down.

2.3 Dynamic Response Computation. The dynamic equations representing the vibration state were formulated by matrix methods, processing and solving them in an IBM-360/40 computer.

The computation gave periods, normal mode shapes and mode shears.

Total shears were obtained by superimposing the mode shears according to the formula proposed in the Chilean Anti-seismic Code:

$$Q = \frac{1}{2} \left(\sum_{1}^{3} Q_i + \sqrt{\sum_{1}^{3} Q_i^{2}} \right)$$

where Q = Shear obtained from the superposition of the modal respondes.

Q_i = Shear corresponding to mode i.

2.4 Power House Studies. Using the above methods, a set of dynamic shear diagrams (See Fig. Nº 3) was developed, determining the bracing system elements' safety factor for these loads.

This calculation was done by obtaining the ultimate loads by the secant formula. The effective length parameter was determined by a theoretical end-restraint coefficient study as a function of the ends' rotational stiffness, finding a restraint degree of about 40%. As respects the total eccentricity, it was fixed at 1/750 of the members' length. Fig. Nº 4 shows a typical variation in the diagonals'safety factor.

2.5 Boiler Structure Studies. Before initiating this structure's dynamic analysis, it was considered necessary to determine the vertical distribution pattern for the hanging boiler's total mass. For this purpose, the relationship between several mass distributions and vibrating periods corresponding to each state was studied, with the conclusion that due to the horizontal hinged-tie system a dynamic mass distribution equal to the static contribution at each level was sufficiently accurate, obtaining a good approximation between calculated and experimentally measured periods.

Following that, periods, vibration modes and dynamic shears were calculated (See Fig. Nº 5), determining the elements' safety margin as for the Power House, also including the connection bolts. The effective length study gave a diagonal end-restraint degree of 60%.

The diagonal connecting joints'lateral stability was also analyzed, considering them as elastic supports with properties defined by the concurring elements' characteristics. The maximum diagonal axial loadings compatible with the connections' lateral resistances were calculated, finding insufficient transverse support capacity precisely in the damaged joints.

Fig. Nº 6 shows a typical variation of the safety factor.

3. EXPERIMENTAL STUDIES.

3.1 Introduction. Simultaneously with the theoretical studies, a series of tests were carried out on the structures,for the purpose of obtaining direct verification of the theoretical assumptions.

These tests included natural period measurements, determination of the normal mode shape and damping coefficients.

This was done by methods based on an analysis of oscillation registers in the structures, induced by natural microtremors, free vibrations and forced vibration.

A horizontal pendulum seismometer with a maximum amplification of 10,000, and mechanical oscillation recorders were used.

Photographs Nº 7 and Nº 8 show some aspects of the tests.

3.2 Power House Tests. Periods and damping coefficients were determined in the structure's two main centerline directions. The free vibration state was produced by sudden movement and bracking of the Power House's overhead travelling crane.

As the bracing system is damaged, experimental period values are higher than those corresponding to the undamaged structure. Under these circumstances, the structure's real condition had to be considered in the theoretical calculations to have a realistic comparison.

This was obtained by varying the damaged diagonals' degree of effectivity, acting on their area participation coefficients. It was determined that the damaged bracing system's effectivity degree is 25% of the original value, percentage for which the experimental and theoretical periods were comparable.

These experimental results are detailed below:

Direction	Periods	Damping Coefficient
N - S	0.8 - 0.9 sec	1.0%
E - W	0.4 - 0.5 sec	0.7%

3.3 Boiler Structure Tests. Measurements were also made in both main directions, with greater detail because of the structure's complexity.

The Boiler and Support Structure's natural period was determined independently by microtremors.

Free vibration measurements of the Boiler-Structure coupled system were made by means of pull-back tests. On the same system, steady-state oscillations were induced with a variable-frequency vibration generator, with which the first-and second - mode periods, damping coefficient and maximum oscillation amplitudes at three elevations were obtained. These last values gave the fundamental mode's approximate configuration.

Theoretical and experimental values were compared by varying the damaged diagonal's area participation coefficient, and the results showed that said diagonals contribute only 40% of their original capacity.

The general data from these tests is:

Microtremors:

Direction	Boiler Period	Support-Structure Period
N - S	0.9 - 1.0 sec	0.16 sec
E - W	0.9 sec	0.10 sec

Free Vibrations:

Direction	Boiler-Structure System's Period	Damping Coefficient
N - S	0.95 sec	3.0%
E - W	0.89 sec	2.3%

Forced Vibrations:

Direction	Boiler-Structure System's Period 1st Mode	Boiler-Structure System's Period 2nd Mode	Damping Coefficient
E - W	0.89 sec	0.30 sec	2.0%

Fundamental mode configuration, E - W direction:

Elevation	Relative Test Values	Relative Theoretical Values
163' - 9"	1.00	1.00
123' - 5"	0.84	0.81
87' - 5"	0.56	0.58

4. DISCUSSION OF SEISMIC ANALYSIS RESULTS

4.1 Response spectra considerations. The spectra used represent different possibilities for the structures' seismic response, from which a probable loading scheme can be developed to obtain comparison criteria with the original static design.

The 1965-La Ligua earthquake spectrum was included, teleseismically recorded at Santiago, approximately 130 km southeast of the epicenter.

As the dynamic analysis was not only for the purpose of studying the responses in the 1965 - earthquake, but to obtain an idea of the general seismic behavior, the spectra recorded at Santiago was considered sufficient. Furthermore, due to the Ventanas subsoil characteristics in relation to Santiago's, it was estimated that the spectra were not basically distorted.

The 1940 - El Centro earthquake spectrum was also included because it is the largest recorded to date. As the analysis has considered only elastic behavior, responses for this earthquake do not represent a realistic situation,as the structure yielded before these values were reached, with the consequent reduction in dynamic response. However it gives an extreme upper level that permits an improvement in the comparison criteria with the possible responses.

4.2 Power House. It can be shown that in this building the original design's loading scheme did not represent a real seismic action. At roof - level dynamic shears are on an average 2.4 times the static values. This difference diminishes towards lower levels, and becomes negative at operating floor level.

The dynamic study showed that in the probable seismic loading scheme the ultimate loads of certain diagonals were exceeded, there being a close correlation between these results and the building's damages.

4.3 Boiler Structure. The dynamic shears at the upper Boiler Structure levels are about 1.5 times the static ones. For the diagonals, this difference is compensated by the original design's safety factors, as its ultimate loads are higher than the dynamic loading. Nevertheless, the resulting safety margin at these levels is not sufficiently reliable.

The bracing connection study showed that their load transfer capacity is lower than the connected members'. This situation is critical for the north and south bents' joints at elevations 131' - 11" and 75' - 5", which have a low lateral stiffness permitting their transverse displacement, due to the axial load shear component, reducing the connected diagonals' capacity. The dynamic loading scheme shows that these joints exceed their ultimate load, and furthermore, certain bolts surpass their slip-resistance, confirming the boiler's damages.

4.4 General Comments. The low estimate for the original design's seismic loadings at the upper levels may have been caused by inadequate valuation of the higher modes, due to the methods used for the seismic loads' vertical distribution.

This fact is specially noticeable in the Power House, where the static forces were calculated proportionally to each floor's mass. This is an adequate solution for rigid structures, where the fundamental mode's influence is decisive;nevertheless this building's period values show that it does not correspond to this type of structure.

For the Boiler this discrepancy is smaller, because the horizontal loads, calculated with a 0.15 g seismic coefficient, were distributed according to the 1962 SEAOC Code,which gives shear diagrams more nearly like those calculated by dynamic methods, specially for intermediate rigidity structures. The Boiler periods show a slight variation from the previous condition, which would explain the smaller differences in the shear diagrams. These comments have been corroborated by the latest modifications to the SEAOC distribution,in which this should be carried out by applying a portion of the total base shear additionally at the upper level, conforming to the structure's elastic characteristics.

As there was sufficient similarity between the experimental and theoretical periods, which is one of the more informative measures of the structure's physical state, the dynamic study can be considered to have a reliable basis. Furthermore, the seismic spectra used considered a 2% damping factor, which is in the range of the experimental measurements. A final confirmation is given by the agreement between the dynamic results and the structure's general damage schemes.

5. REPAIR DESIGN

5.1 Repair Design Shear Envelope. Damage repair has been designed to provide more than a simple return to the original safety factor, in order to improve earthquake-resistance conditions so as to avoid similar damages in future earthquakes, which may occur due to the zone's high seismicity.

Furthermore, these works are justified because their cost and schedule is similar to that required for a limited repair of damaged members and joints.

Considering the seismic analysis results, a series of shear diagrams were prepared for use in redesigning the bracing systems. These diagrams were drawn as average envelopes of the seismic action schemes resulting from the application of selected spectra.

Two of these typical diagrams are shown in Figs. Nº 7 and Nº 8.

It was decided not to modify the horizontal loading structural control system's principle, as this change, tending to obtain greater participation by the bents system, would mean an excessively large work.

In any case, the Power House will be provided with an additional bracing in the central bay of the larger side's perimetral bents, as they do not have an adequate antiseismic structural design due to their great length with bracing in the end bays only.

It was determined that the strengthened bracing systems should resist the loads represented in the shear diagrams with a minimum safety factor of 1.75, referred to their ultimate loads.

This value, which may seem high, was fixed considering that more accurate calculation methods will be used for the elements' redesign, giving due consideration to the diagonals' load eccentricity and end - restraint coefficient, which reduces the usual design's conservative factors idealizing the loads into central forces and the joints as being perfectly hinged.

5.2 Stiffening Effect of Reinforcements. Considering that the planned strengthening will tend to increase the structures' stiffness, which could produce an amplified response, the period's variability was studied as a function of the diagonal system's progressive strengthening, carrying out a computation for several stepped states.

The resulting relationships are plotted in Figs. Nº 9 and Nº 10.

It can be seen that the stiffening effect on the structures tends to level off after a stiffening coefficient of about 85% of that corresponding to the original bracing, with the period's reduction being only 2 x 10^{-2} sec for each 10% additional stiffening above 100%.

These results show that the structures will not fundamentally increase their seismic responses, and therefore the diagonal system's strengthening will be directly effective in improving the earthquake -

resistance conditions.

These assumptions will be checked by a series of direct tests on the repaired structures, which will verify the values obtained or indicate the necessary corrective works to approach the theoretical results.

While this paper is being written, construction drawings and specifications are being prepared for these repairs, and work will start shortly. It is hoped to complete the work before the 4WCEE at Santiago,when drawings and photographs of typical strengthening will be shown, together with test results.

5.3 Work Schedule. Ventanas Plant is an important part in the central zone's generating system, serving the country's most densely populated and industrialized area. Therefore, its integral use is extremely important for this region's normal supply and development.

As the repair work, specially on the Boiler, will interfere with the plant's normal operation, making it necessary to shut it down during certain phases, works must be scheduled in line with the power availability and demand conditions.

A careful time and movement study will be made in order to obtain the best possible work efficiency. The work schedule will be prepared jointly by the Load Dispatching and Construction Departments..

The schedule and progress reports will also be shown at the 4WCEE in Santiago.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Design Methods.

1) The application of equivalent static methods for seismic load valuation showed discrepancies with the dynamic analysis responses,being the dynamic shears at the upper levels clearly higher than the statically calculated values.

For the design of similar structures, it is advisable to compare the static and dynamic values, to obtain load diagrams more representative of the real earthquake action.

2) The bracing connection design will not be limited to the main loading plane only, but an adequate lateral rigidity must be provided to avoid transverse displacements.

6.2 Repairs.

1) For the repair of similar earthquake damaged structures, it is convenient to make a dynamic analysis first, to elucidate the cause of damage. Based on this study, all the earthquake - bracing elements will be given a uniform safety factor.

2) In the structures studied in this paper, it was observed that the planned strengthening's rigidizing effect did not produce an important increase in earthquake-force magnitudes.

In any situation that calls for strengthening repairs, it must be borne in mind that an unfavourable alteration in the seismic responses is possible.

3) After repairs are completed, direct test measurements will be made to determine the reinforcement's effectivity and to check the theoretical estimates. It is always advisable to carry out this experimental checking.

4) The work schedule must be coordinated with the power availability so as to interfere as little as possible with the plant's operation.

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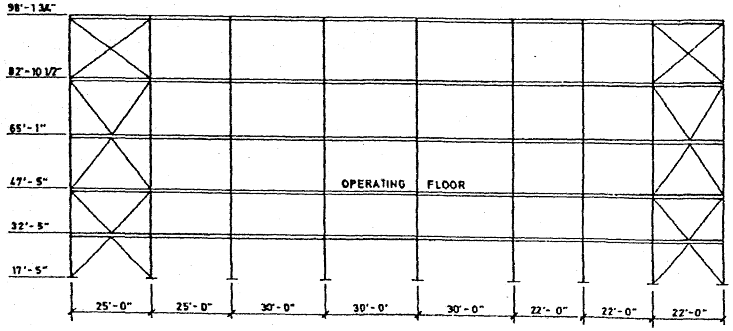
VENTANAS STEAM ELECTRIC STATION
SEISMIC ANALYSIS

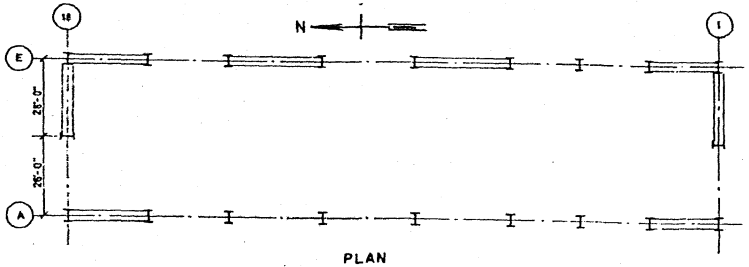
POWER HOUSE

FRAMING ARRANGEMENT AND DIMENSIONS

(Fig. 1)



WEST ELEVATION—BENT A

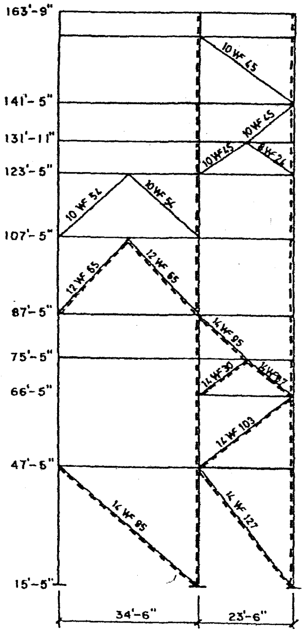


PLAN

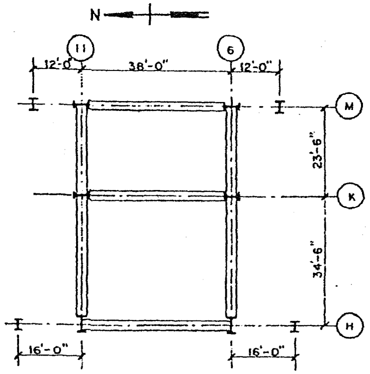
BOILER STRUCTURE

FRAMING ARRANGEMENT AND DIMENSIONS

(Fig. 2)



SOUTH ELEVATION—BENT 6

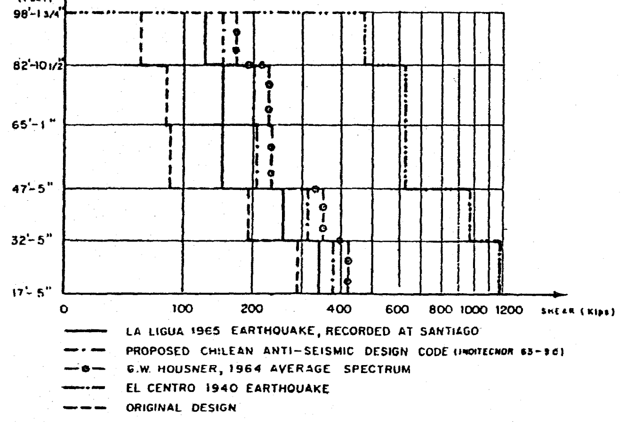


PLAN

POWER HOUSE—BENT A

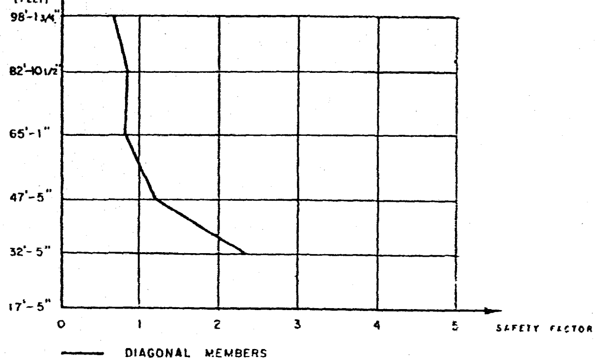
SHEAR DIAGRAMS

(Fig. 3)



DIAGONAL BRACING SAFETY FACTORS

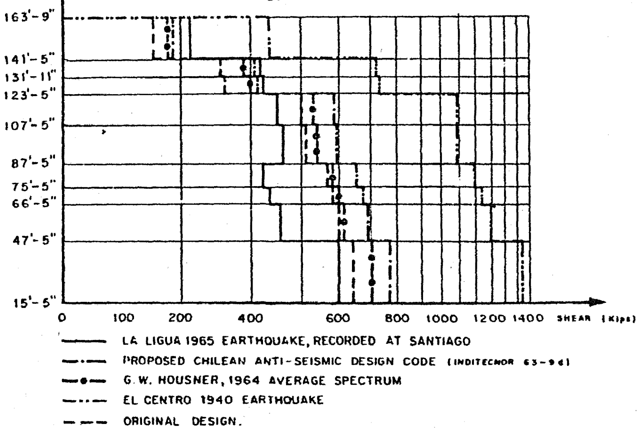
(Fig. 4)



BOILER STRUCTURE- BENT 6

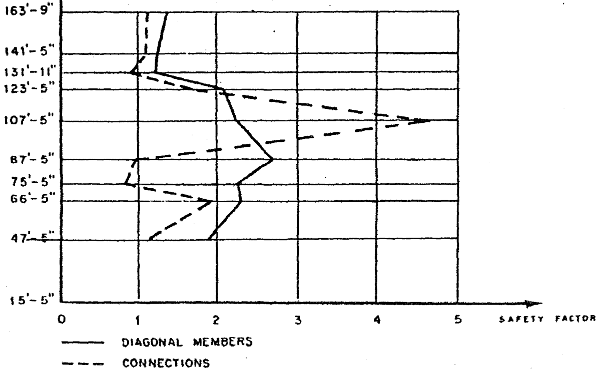
SHEAR DIAGRAMS

(Fig. 5)



DIAGONAL BRACING SAFETY FACTORS

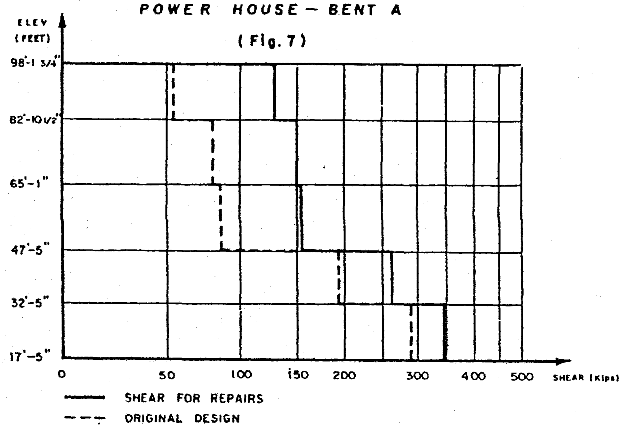
(Fig. 6)



SHEAR DIAGRAMS FOR STRUCTURE REPAIRS

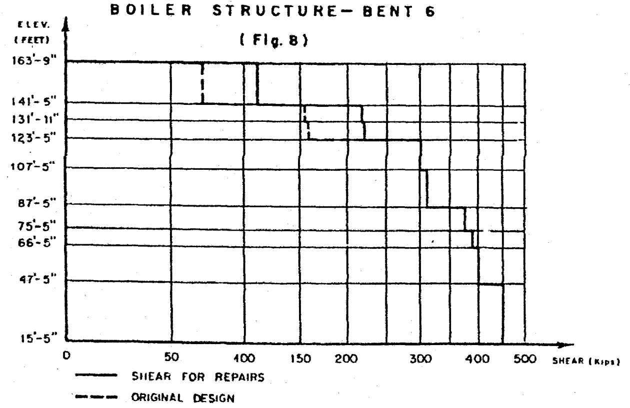
POWER HOUSE – BENT A

(Fig. 7)



BOILER STRUCTURE – BENT 6

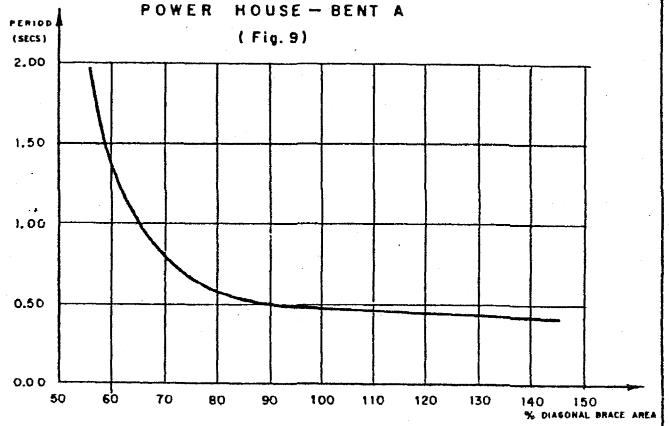
(Fig. 8)



STRUCTURE STIFFENING DUE TO DIAGONAL BRACE STRENGTHENING

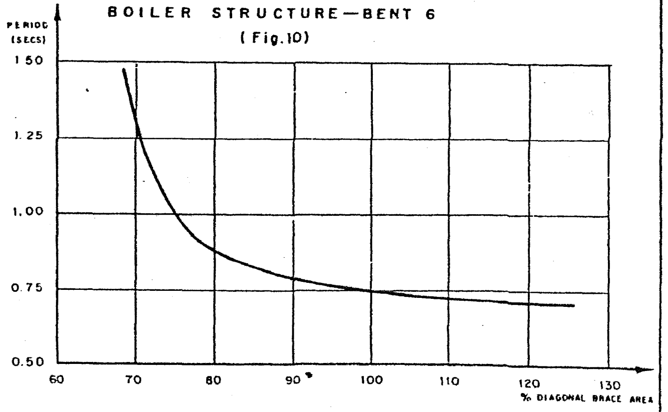
POWER HOUSE – BENT A

(Fig. 9)



BOILER STRUCTURE – BENT 6

(Fig. 10)



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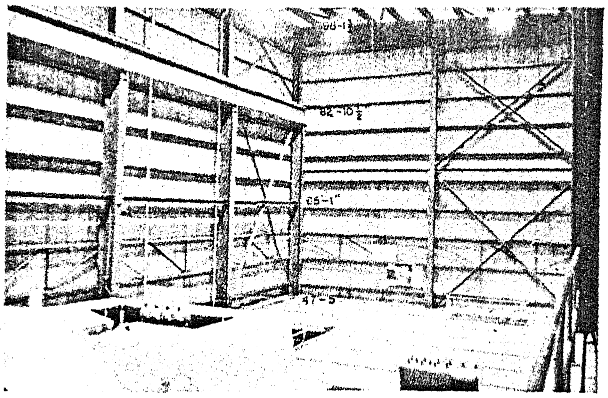
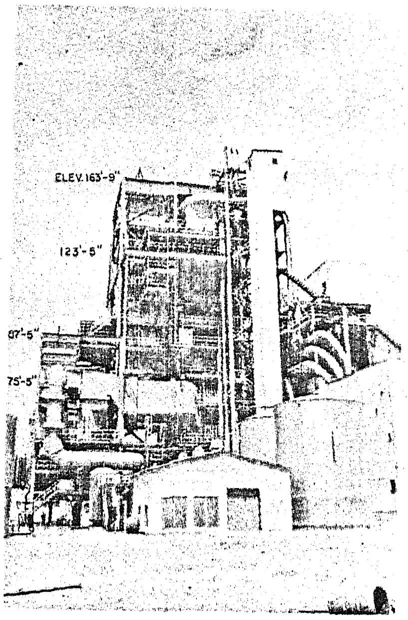
VENTANAS STEAM ELECTRIC STATION

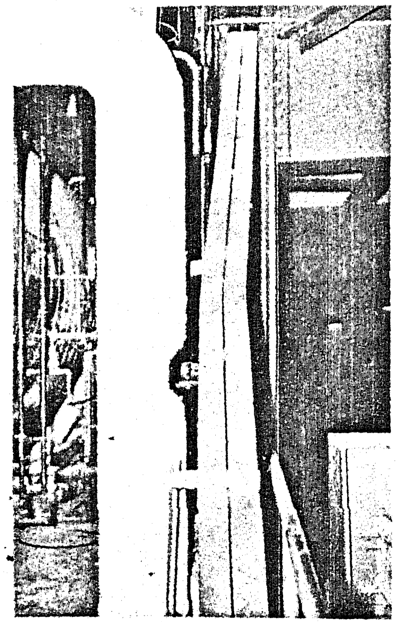
1965 Earthquake Damages



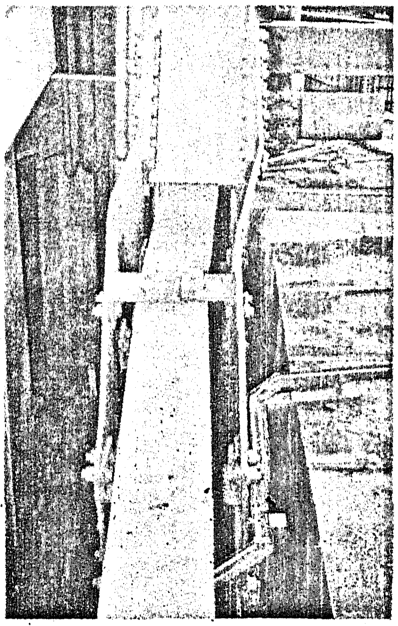
Photograph Nº 1 Inside view of Power House at Operating Floor level. The typical bracing system arrangement can be seen.



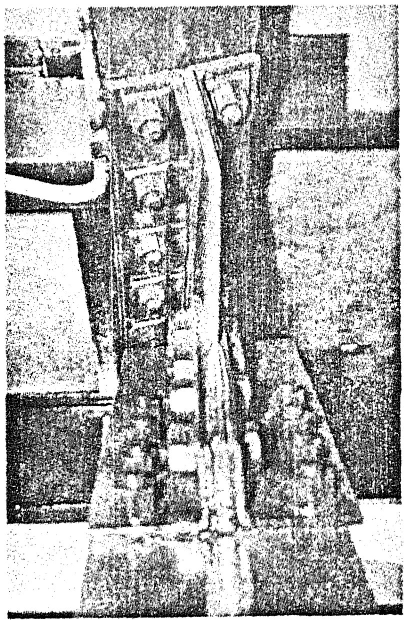
Photograph Nº 2 Boiler Structure North Elevation. The 3 main steam pipes are at far right.



Photograph Nº 3 Buckled diagonal in the Power House. The oscillations damaged the thermal insulation lagging on an adjacent pipe.



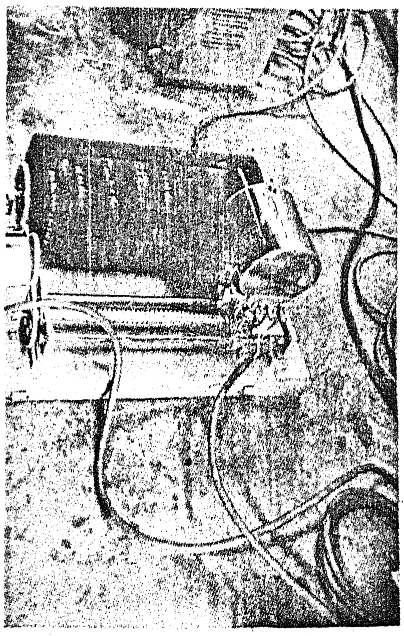
Photograph Nº 4 Boiler Structure diagonal connection at elevation 75' - 5". The girder's lateral deformation and bent gusset can be seen.



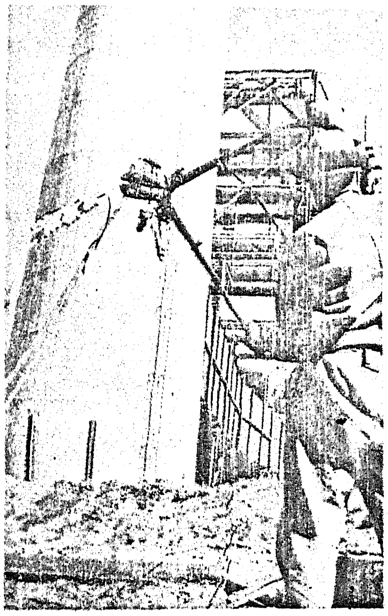
Photograph Nº 5 — Boiler Structure connection detail at elevation 131' - 11". Notice torsion of top girder flange and bent gusset.

Photograph Nº 6 — Damage on Main Steam Pipe lagging at elevation 163' - 9" due to banging against knee brace.

Experimental Measurements



Photograph Nº 7 — Oscillation recorder used for experimental measurements. Some recorded vibrations can be seen.



Photograph Nº 8 — Typical arrangement for Boiler Structure pull - back tests.