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Seismic analysis of coke ovens batteries

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ABSTRACT: A 1950 and a 1990 design of Coke Ovens batteries in high seismicity areas are compared. The latest design has definite advantages from the standpoints of structural simplicity, operational efficiency and construction costs. The contribution of earthquake engineering to achieve this result, consisted mainly on the analysis to account for the complex interaction of the brickwork and RC working together in the seismic resistant system. A time history analysis considering in the modeling the most relevant non linearity features of the system provided a reliable basis for the seismic design of the new Battery.

1 INTRODUCTION

Coke Ovens Plants are essential units of conventional Steel Plants. In them coal of special properties (coking coals) is heated to coalescence and then quenched under a rain of water. The resulting products are coke, and enriched coal that is fed into the blast furnaces, and large amounts of gas that is the main fuel of the steel plant.

Figure N° 1 is a longitudinal section of the Coke Ovens Battery N° 2 which shows typical features of this large industrial masonry structure where coal is heated.

Main parts are the following: a) the Coke Ovens, slender ovens that are filled with coal through the roof to be then heated by mean of gas burners. b) the Regenerators, where heat from the gases is recovered. c) the Ovens Roof, Ovens Floor and Regenerators Floor, large brick masonry slabs, approximately 1m. thick, that run through the length of the battery. d) the Understructure, in this case reinforced concrete frames that support a RC slab under the Regenerators Floor and are supported by the foundation slab. e) the Pinion Walls, 1m. RC walls at the ends that confine the masonry. f) the Tension Rods, longitudinal steel rods at roof level, with adjustable spring connections to the Pinion Walls.

The Battery shown in Fig. 1 is Compañía Siderúrgica Huachipato CSH, Chile's largest Steel Plant, located in the south of the country in one of the most seismically active areas of the world.

In the transversal direction, seismic forces are resisted by the RC and brick masonry shear walls, that have ample capacity for them. This paper, thereby, deals only with the longitudinal earthquake, that must be resisted by a complex RC-Brick system.

CSH Battery N° 1 shown in figure N° 2 was started in 1950. In it, because of the lack information on fire-brick properties available at the time and the very limited

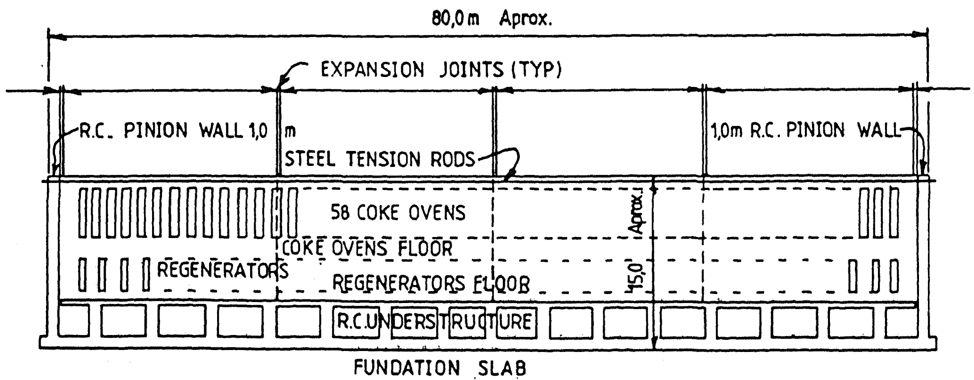

Fig. 1. C.S.H. Coke Ovens Battery N° 2 (1990)

experience on steel plants behavior in major earthquakes, design was very conservative. Pinion walls were assumed to resist all forces. The number of ovens between pinion walls was thereby limited to 13, thus requiring intermediate walls. PW thickness was about 2m. as against 1m. in Battery N° 2.

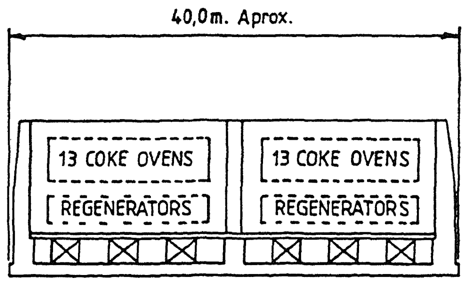

Fig. 2. C.S.H. Coke Ovens Battery N°1 (1950)

Battery N° 1 resisted with negligible damages the great earthquakes of May 21 and 22 1960 (Arze and Vignola, 1960), Richter Kanamori Magnitude 7.5 and 9.5. The second is the largest subduction earthquake registered in present century. When Battery N° 1 was shutdown in 1990, after 40 years of operations, it had probably established a world record of durability. Nevertheless, the operators stated that Pinion Walls every 13 ovens were a drawback from the standpoint of operations and heat efficiency and requested that, if at all possible, Battery N° 2 be designed with only 2 end walls, as is done in non seismic areas.

The authors of this paper were the seismic designers of both batteries. In the second, with the advantage of 40 years of scientific and technological development, they could meet the operators requirements.

2. MAIN DESIGN PROBLEMS

Basically, the structure shown in Fig. N° 1 is a combined system of reinforced concrete walls and frames with brick masonry frames at the Ovens and Regenerators, with rigid slabs at three levels. Nevertheless, due to special structural characteristics of the earthquake resistant system where RC and brickwork are acting together, following problems were critically analyzed:

i) Structural behavior of slender brick columns at high temperature. Coke Oven Batteries, traditionally, are designed for operating forces, in accordance with the Ahlers Theory, that assumes that brick masonry at high temperatures behave elastically in compression, with an allowable unit stress of 0.25 MPa. but have 0 strength in tension. In 1957 Lambert et al published the results of full scale tests run by the British Coke Association, that indicated that firemasonry at operating temperatures have compression capacity considerably in excess of Ahler's assumptions as well as some tension and shear strength. Under these conditions, it was considered safe to do the seismic design assuming Ahlers behavior but increasing the brick allowable compression stress.

ii) Evaluation of tension rods and pinion walls as confining elements. When the Battery is built, bricks are placed with mortar and 50mm. gaps are left in the masonry to allow for expansion, as shown in Fig. 1. Then, the Battery is fired and gradually brought to operating temperature during a heating period of 40 to 50 days. As heating takes place, the gaps close and expansion pressure against the pinion walls is originated. Also the possibility during a major shock, of separation between pinion walls and horizontal diaphragms inducing impacts, must be accounted for in the analysis.

Once the above was stated, the following was necessary: a) A theory, established by Flores 1988, on the non linear elastic behavior of fire brick meeting Ahlers assumptions. b) To perform a historical instead of a modal seismic analysis.

3. DEFINITION OF A DESIGN SPECTRUM

It was developed based on the linear elastic response of the structure to a design ground motion, combined with response modification factors (R).

Although actual response spectra for earthquake motions are quite irregular, they have the general shape of a trapezoid or tent. Theory shows that spectral values may be interpreted as ground motion values affected by amplification factors depending on the frequency region of the spectrum, controlled either by acceleration, velocity or displacement (Chopra and Newmark, 1980).

Following values for the ground motion parameters were determined for the site (Concepción) based on Barrientos (1980) and Arias (1987).

Effective maximum acceleration a=0,35 g.

Maximum velocity in a horizontal direction $(v_H)_{max} = 27$ cm/seg.

Maximum displacement $d_{max} = 3.5$ cm.

- Spectrum amplification factors. The spectrum amplifications factors for acceleration, velocity and displacement (Γ_A, Γ_V, Γ_D) values corresponding to a fractile 84,1% (mean plus one standard deviation) have been taken from the table given by Chopra and Newmark (1980).

A good approximation is obtained by the following relations (Arias 1987)

$$\Gamma_A = 4.38 - 2.394 \log_{10} \epsilon$$
$$\Gamma_V = 3.38 - 1.541 \log_{10} \epsilon \qquad \text{(a)}$$
$$\Gamma_D = 2.73 - 1.038 \log_{10} \epsilon$$

where ϵ is the damping as percent of critical damping.

Equations (a) are valid for values between 0.5% and 20% of critical damping.

A value $\epsilon = 6\%$ was adopted for the Battery design.

- Elastic response spectrum. For the given values following results are obtained:

$\Gamma_A = 2{,}52 \quad \Gamma_V = 2{,}18 \quad \Gamma D = 1{,}92$

$$A = a\Gamma_A = 343 \times 2.52 = 864 \text{ cm/seg}^2$$
$$V = v\Gamma_V = 27 \times 2.18 = 59 \text{ cm/seg}^2$$
$$D = d\Gamma_D = 3.5 \times 1.92 = 6.6 \text{ cm}$$

The control periods are found as follows

$$T_2 = 2\pi V/A = 0.43$$
$$T_3 = 2\pi D/V = 0.71$$
$$T_1 = T_2/3 = 0.14$$

The spectral ordinates can be computed according to the following equations

$$A(T,\epsilon) \begin{cases} a\,|1 + (\Gamma_A - 1)\,T/T_1| & 0 \le T \le T_1 \\ A = a\Gamma_A & T_1 \le T \le T_2 \\ a\Gamma_A\,(T_2/T)^{2/3} & T_2 \le T \le T_3 \\ a\Gamma_A\,(T_2/T_3)^{2/3}\,(T_3/T)^{4/3} & T \ge T_3 \end{cases}$$

In accordance with these recommendations, the elastic response spectrum for $\epsilon = 6\%$ was developed and is shown in Fig. 3.

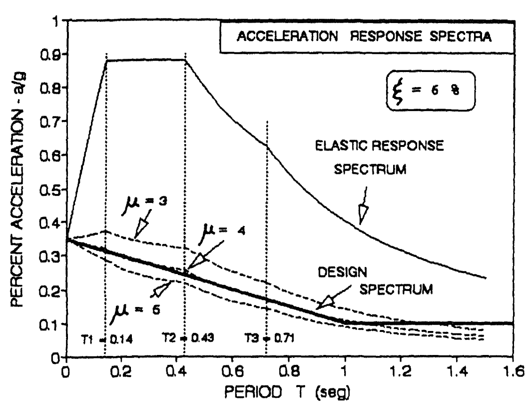

Fig. 3. Acceleration Response Spectra.

- Reduction factor. As already explained, the inelastic design spectrum is derived from the elastic spectrum by means of a reduction factor R, function of ductility.

It has been generally accepted to use a reduction factor (R) with a value independent of the period of the structure (T). Such has been the recommendation of ATC 3 and other recently derived Codes elaborated in California. In those Codes, lists of R values are given in function of materials used and structural systems adopted.

Theoretical considerations show, that the reduction factor R in the short period range should also be dependent of the period T (Bertero, 1986).

In our study the relationship proposed by Arias (1987) was adopted

$$R = 1 + \frac{T}{0.035 + T/(\mu - 1)}$$

Determination of damping and μ values. As will be shown in 5.1 the ductility of the entire structure -brickwork and RC- is taken with the value $\mu = 4$.

Acceleration response spectra are affected for design purposes with damping ratios depending mainly on the type of construction and properties of the material involved in the dynamic shaking. For the coke-oven battery a percentage of critical damping $\epsilon = 6$ was adopted. Considering that the main moving mass is composed of brick work and coal the adopted value seems to be conservative.

With $\epsilon = 6\%$ and $\mu = 4$ the Design Acceleration Spectra can be obtained. In fig. 3 the curve for $\mu = 4$ has been replaced by straight lines for simplicity.

4. PRELIMINARY ANALYSIS

A preliminary Modal Elastic Analysis for the Spectrum established in paragraph 3 was made. (Fig. 4 shows the model selected).

The 3 degrees of freedom model assumes full elastic behavior of all materials and ignores all non lineal characteristics described in 2i) and 2ii).

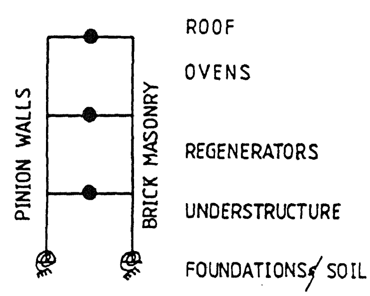

Fig. 4. Elastic model for preliminary modal analysis.

Refined analysis described below proved that the basic elastic assumptions of this model were not met. But, because of its simplicity and speed of process, it proved to be very useful for preliminary design as well as to check the order of magnitude of the results of non linear analysis. Actually, after calibrating through the non linear analysis a value of μ=4, results of both systems had differences within 10%.

5. NON LINEAR ANALYSIS

To cover and discuss the material mentioned under 2i) and 2ii) the subject has been divided into the following sections: 5.1 Equivalent ductility of masonry walls for transverse forces; 5.2 Dynamic analysis of the coke oven battery: Computer model, Seismic input, Design criteria; and 5.3 Results.

5.1 Equivalent ductility of masonry walls for transverse forces

The most significant part of the structure, which deserves special consideration on its relationship: displacement vs. horizontal force, is the coke-oven wall, a vertical member working in bending. The collapse situation for this wall is controlled by the Ahlers limit moment.

This value is defined as the moment the section can develop when the resultant force at the section intercepts the cross section at the edge. When the resultant force goes outside the section the static equilibrium is not possible because tension is not allowed. However, as a matter of fact, dynamic stability remains possible because the action is reversing at each cycle.

In fig. 5 an idealized model of the brick oven wall is shown where fixity at the top and bottom were assumed due to the robustness of the horizontal brick beams. What is required for a dynamic analysis is a complete Q-D diagram. The discrete value of the Alhers moment is not sufficient and represents a condition of collapse where the compressive stress at the bricks edge is infinite. In other words it is required to formulate a model of the brick walls that allows to control deflections and stresses induced by the earthquake. Deflection shall be limited to such a value that the compressive stress a the bricks interfaces shall not be higher than a prescribed allowable value.

There upon, knowing the eccentricity of a normal load applied to the cross section of the brick oven the stresses and curvature of the section can be derived.

Knowing the curvature along the span of the column the force deflection diagram is obtained by double integration. The horizontal deflection was limited to have a compression stress not exceeding 1.0 MPa.

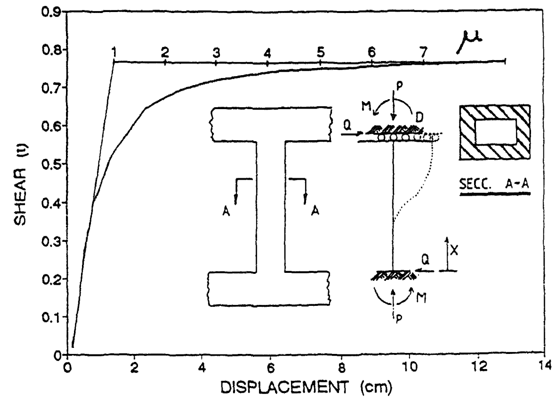

Fig. 5. Coke oven wall. Displacement vs. horizontal force.

The non linear relationship between displacement vs. horizontal force allows to define an equivalent ductility as the ratio of the maximum allowable horizontal displacement to the virtual displacement associated to the elastic range of the curve. As shown in figure 5 equivalent ductilities in the range of 4 to 6 are acceptable. The shape of these curves is very sensitive to the normal force applied. The larger the latter the lesser is the available ductility.

P value in fig. 5 corresponds to the brick dead load applied to the column. The curve shown in this figure belongs to a non linear elastic system with a spring softening characteristic. The restoring force is an odd function; thus $f(-D) = -f(D)$ and can be approximated by expressions such as $k(D-\mu^2 D^2)$ where $\mu = \mu(P)$, P being the normal force.

The equations $mD + K(D-\mu^2 D^2) = F(t)$ has been investigated thoroughly in the literature. Such non linear systems have periods of vibration depending on the amplitude; with increased amplitude the period is longer. For forced vibrations response curves can be obtained where the jump phenomenon is observed.

For impulsive loads, energy considerations show that these soft systems when subject to large displacements for the same value of shear forces, are able to store a higher amount of energy than the elastic systems (with the E tangent value taken at the origin). From this point of view these walls act as seismic isolators reducing the base shear when the displacement is increased.

How much energy these systems can dissipate is an open question. A starting point for evaluating the damping of these systems is the seminal paper of Housner (1963). In this work, related to the rocking response of a simple rigid block a coefficient of restitution, based on the conservation of angular momentum is determined.

5.2 Dynamic analysis of the coke oven battery

a) Computer model

A time history analysis in the longitudinal direction of the structure was required to account for the non linearities considered essential for interpreting the behavior of the system.

Non linear step by step integration methods are computer intensive. For each time step the structure shall be solved many times for convergence. These points to the usage of simplified model and refined finite element meshes shall be discarded for practical reasons.

The model utilized is shown schematically in figure 6.

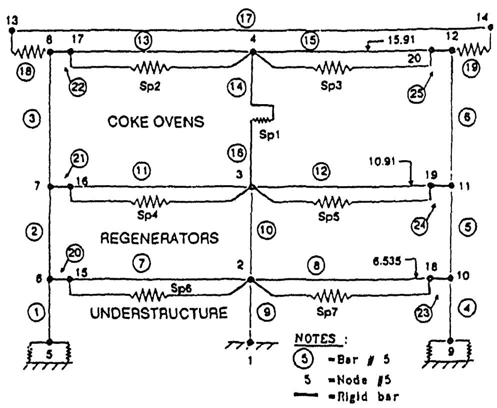

Fig. 6. Non linear model for time history analysis.

In the model the central vertical bar stands for the inner part of the structure: element 9 has the total condensed horizontal stiffness of all reinforced concrete walls under elevation 6.535.

Elements 10 and 16 represent the horizontal stiffness of the two levels of brick walls between elev. 6.535 and 15.91. The upper element is non linear and its force-deflection relationship is as given in section 5.1.

The outer vertical sticks (bars 1, 2, 3 and 4, 5, 6) represents the pinion walls. These elements are standard elastic beams with variable inertia moment on their height.

Slabs at the three elevations were assumed to be monolithically connected with the central bar and were modeled to allow separation with the pinion walls.

To account for this the slabs were modeled as only compression type elements (OCT). Whenever displacements at the end of the slabs elements dictate a tensile condition the algorithm shall be able to eliminate the tensile forces.

The modeling trick to achieve this result was to define the axial stiffness of the element by means of the addition of two springs acting in parallel: a) one elastic spring and b) one bilinear spring; their combined action is shown in figure 7. This scheme, proved to be very practical and no convergence problems develop as proved by tentative runs with a range of different time steps. Elements 20 to 23 are only control elements to recover the internal forces resultant for the composite action of the parallel springs that stands for the slabs.

The tie rods were represented by the axial element 17 and by springs 18 and 19. Initial prestressing of tie rods were introduced in the dynamic analysis by assuming a temperature drop with such a value as to reproduce the initial force level. This procedure does not restrict the tie rods forces to its initial value; during the simulation of the earthquake these forces varies according to the relative displacements of the pinion walls and can be tracked.

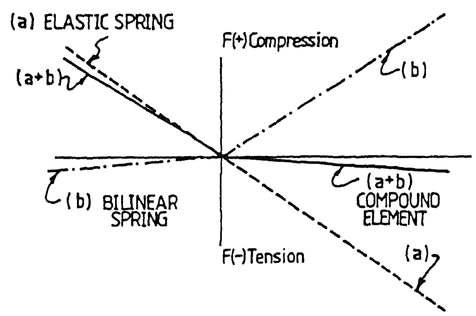

Fig. 7. Only compression type element (OCT) modeling.

b) Seismic input

The determination of the design spectra has been the subject of section 3. of this paper. For the time history analysis the curve with ϵ=6% and R=1 was adopted as the target.

A family of artificial earthquakes with different duration was generated meeting the condition to have their elastic response spectra as the envelope of the target spectra.

c) Seismic design criteria

Following procedure shall be satisfied:

i) The structure is replaced by the model (see 5.2a) and the seismic input is represented by the family of artificial earthquakes generated.

ii) Design the RC structure (pinion walls) to resist the earthquake elastically (R=1) with ϵ=6% (Fig. N° 3).

iii) Design the brickwork (coke oven walls) for an allowable deflection (equivalent ductility not larger than 6).

5.3 Results

Main results are as follows.

The disposition of only two pinion walls at the extremes of the Coke oven battery proved to be an economical and feasible structures. This can be concluded considering that the internal forces on the pinion walls were within reasonable values. In fact, results correlated well with those obtained from a standard modal analysis using a design spectra with $\mu = 4$.

Separation occurs between the inner bricked part of the oven with confining pinion walls. This separation was larger for a minor tie rod prestressing and will mean some minor impacts between both parts. Simple impact forces verifications indicated that these stresses are of no importance and that no stress build-up due to successive impacts is to be expected.

Displacements and forces on brickwork due to swaying of the upper levels of the structures were within the allowable values.

Typical results are as shown in figure 8.

6. CONCLUSIONS

A 1950 and a 1990 design of Coke Ovens batteries in high seismicity areas are compared. The latest design has definite advantages from the standpoints of structural simplicity, operational efficiency and construction costs. These results were made possible because of the engineering progress during the 40 years elapsed between projects, mainly in the following matters: a) Development of advanced dynamic analysis methods. b) Availability of the powerfull tools of computer sciences. c) Actual seismic experience in very strong earthquakes at the site. d) Design spectra based in actual seismic observation, strong motion accelerographs and latest seismic theory. e) Empirical and theoretical research on the structural properties of firebrick masonries at high temperatures.

The possibility of performing non linear analysis allows at the present time to solve problems which previously were only matter of speculation.

For this study a simplified model combining linear and no-linear elements was prepared where special care was taken to avoid numerical no-converging process.

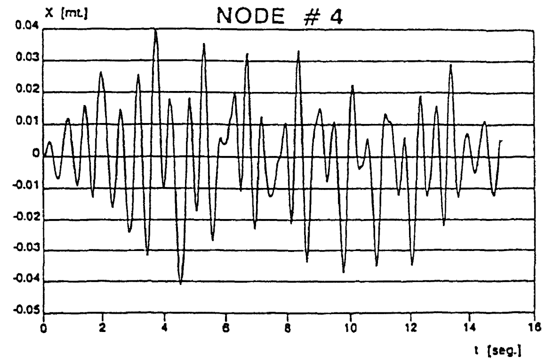

Fig. 8. Horizontal movement of Node # 4 of Fig. 6.

The slender brick columns reaction to horizontal earthquake forces -one example of non linear behavior- has been a subject of special interest.

Considering the surviving of old structures -such as churches- constructed in basis of stacks of bricks or stones the behavior of this type of dynamic systems against earthquake loads is a topic of investigation. Damping forces and P-D effects shall be included as items to be further studied.

It is finally submitted that the work presented may be also a useful contribution for the design of other major masonry structures that are common in industries, such as hot metal furnaces, large field erected boilers, brick lined process vessels, etc.

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