STUDY OF EARTHQUAKE RESISTANCE OF BOILERS AND RECOMMENDATIONS FOR THEIR DESIGN

Pavlyk V.S.[1)]

Contemporary power boilers may be compared in power with large hydro-electric power stations. These structures are characterized by a large number of tubes and presence of a screen sealing hermetically the fire chamber and gas piping. Because of high heating and other specific effects, the connection between elements is non-rigid and pliable. This makes difficult choosing assumptions and a design scheme which describe the performance of the structure under seismic effects.

The paper gives a general idea of the structure of boilers, full-scale test results and analyses possible design schemes. Recommendations for the design and structural solutions are suggested.

One of the most widely spread sources of electric power in the present time are steam boilers. Damage of a boiler by an earthquake is associated with a serious accident, deprivation of population and enterprises of heat and electric power at the moment when they are mostly needed. And, finally, it brings about great financial losses.

Power of a large modern boiler of a screen type exceeds 200 thousand kilowatt. It is a structure of 30-50 m height (Fig.1), a metal framework being its main load-carrying structure. Each boiler has a lining which seals the fire chamber and convection shaft hermetically. The latter are vertical chambers filling almost the entire space of the structure. Systems of tubes 2 + 3" dia grouped according to the stages of water and steam heating are located in these chambers.

Pipes of a larger cross-section are laid outside, viz. collecting channels, air piping, etc.

All this equipment is attached to the common carrying framework, at the top of which there is a drum of the boiler, that is a steel cylinder, 1.5-2 m dia, 150 t weight.

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1)Pavlyk V.S., Head of the Central Laboratory of Earthquake-Resistant Construction of the V.A.Kucherenko Central Research Institute for Building Structures (TsNIISK).

Due to the way of fastening the lining boilers are divided into two types. One of the structures is designed to fasten the lining directly to the working systems of the aggregate - vertical pipes of the screens, located along the perimeter of fire chambers and hung from the upper rafters of the framework. The entire fire chamber appears to be suspended as a basket in this case thus ensuring unrestrained deformation of the fire chamber with the change of temperature. Lining of another type is heavier, it is fastened to the framework of the boiler in tiers spaced at 3-4 m. From the technological point of view the lining with metal covering made of separate panels fastened to the framework is more prospective. It permits safe hermetization to be arranged and the boiler to be erected by enlarged blocks.

Because of high heat (the temperature in the fire chambre exceeds 1000°C) lining, steam- and water-tubes of the aggregate must allow for considerable displacements due to temperature deformations. In particular, their fastening to the framework is done pliable, and such elements as the vault, screens, steam-superheaters are completely hung up, the surface of the lingin itself is divided by expansion joints. The presence of non-rigid connections in the structure makes difficult to analyse its deformability and to determine dynamic characteristics of the boiler, which are necessary for design seismic forces to be calculated.

It should apparently be pointed out here that in the Soviet Union the practical design for seismic forces is based on the assumption that buildings and structures are dynamic systems. The motion of the ground base is regarded either as a random stationary process or as a deterministic law in the form of a sum of attenuated sinusoids. The main parameters of this motion are assumed in terms of the records of real earthquakes. According to the Code the design seismic load is determined not only by the spectral curve but due to the periods and modes of natural vibrations of the structure and damping of vibrations.

The above specific features of the structure of boiler-aggregates make their dynamic design scheme very vague, Depending on its representation the design seismic load changes by several times. There were difficulties in designing. In particular, in regions with high seismicity the horizontal load may be so significant - boilers are of large weight - that on weak soils it was impossible to provide for their stability on the ground base.

It would be quite natural to assume that vertical surfaces of the lining influence significantly the horizontal rigidity of the structure, but to what extent - that might be shown by tests only. Such tests have been carried out on full scale with the help of a specially developed vibro-machine, which was staged at some distance from the boiler and set up its vibrations by means of a tight steel rope. The force amplitude reached 1000 kg. Vibrations were measured and recorded by standard electric-dynamic equipment.

The direct objective of the experiment was to determine periods and modes of natural vibrations of boilers, values of damping of vibrations as well as factors influencing the general deformability of these structures. Their structural complexity and presence of bracing with surrounding structures necessitated detailed investigations of vibrations, and there appeared to be rather much work to do.

Tests have been carried out on 15 boilers of the most common types. The table attached gives some idea of them. As can be seen from the oscillograms obtained the vibrations of boilers are complex and multi-frequent. This pattern of vibrations is accounted for by the absence of suffucuently rigid bracing between rather different structures forming the boiler, and is created by turbulent flows in its systems, by pulsation of heating, performance of machines,etc. Application of a vibro-machine on non-working aggregates allowed almost non-distorted resonance vibrations of both boilers in whole and their separate members to be set up. At the top of the framework the amplitude of displacements reached 100 microns.

The observed periods of natural vibrations of boilers are given in the Table. The logarithmic decrement of their damping is equal to $0.2 \div 0.27$. The mode of the main tone vibrations is close to a rectilinear one with a trend to curvature that indicates that in vertical structures general shear deformation prevails. Rotation of boilers on the ground base and torsion in the plan have not been practically observed.

*Comparison of the design and observed periods of na*tural vibrations (see the Table) show that the actual stiffness of the boiler is several times higher than the stiffness of the load-carrying framework only. Since the screens and other systems of pipes are comparatively deformable structures, the main factor that gives such stiffness to the structure may be lining with a sealing layer and panelling.

From the measured periods of vibrations another important conclusion may be drawn viz. aggregates with lining fastened to the piping the fire chamber of which is hung only from the upper floor, do not exhibit, as it might be expected, much smaller stiffness than those with lining attached to the framework. This is due to deformation on lining caused by the vibrations of the suspended fire chamber. Besides, the lining in this structure too is somehow involved into the work by horizontal displacements of the framework through individual, though pliable, contacts with it.

A system of the type shown in Fig.2 may serve as a design scheme of a boiler which depicts rather completely special dynamic features of the structure. Vibrations of such a system may be easily analysed in terms of the equations

$$\begin{cases} M_j \ddot{y}_j + \sum_r (1+i\gamma_j) C_{rj} y_j = -M_j \ddot{y}_o(t) - \sum_K m_{kj} \ddot{y}_{kj} \, ; \\ m_{kj} \ddot{y}_{kj} + (1+i\gamma_{kj}) K_{kj} y_{kj} = -m_{kj} \ddot{y}_o(t) - m_{kj} \ddot{y}_j \, ; \\ j = 1, 2, \ldots n \, ; \quad K = 1, 2, \ldots \ell_j \, ; \end{cases} \qquad (1)$$

where M_j and y_j - total mass of the boiler at the j-level and displacement of its centre as regards the ground base which motion may be described by $\ddot{y}_0(t)$;

C_{rj} and γ_j - total stiffness and characteristic of damping of the system M_j;

m_{kj} and y_{kj} - independent masses of the system M_j connected non-rigidity with the parent structure and their displacements as regards it.

Both exact and approximate solutions are possible for these equations. In particular, determining the general seismic load acting on the boiler, the system M_j may be regarded separately and then the local action of the masses m_{kj} may be allowed for. But in any case the investigation of the dynamics of the system presented in Fig.2 is complicated and even more so if to have in view its torsion too.

For the purposes of practical design a simplified analysis is obviously required. It is reasonable also from the view point that trustworthiness of our knowledge about seismic forces acting on the structure under construction is relatively small and a too detailed representation of the model does not provide increase in safety of the earthquake-resistant design. Below structures are analysed from this point of view.

The study of the overall horizontal stiffness of boilers permits the conclusion to be drawn that the influence of the framework, vertical frames (framework elements with diagonals) and lining (with panelling) is defined by the following ratio of their stiffnesses: 1:(4÷10) : (50÷100).

Bearing in mind this statement and the fact that the mass of boilers is more or less distributed along their height, the periods of natural vibrations of the boiler may be calculated as for a cantilever system in shear.

Vibrations of the first tone are of primary concern as design-calculations show that they characterize seismic stresses in structures practically completely. The period of these vibrations in accordance with the scheme suggested is defined by the formula

$$T=\frac{2\pi H}{\alpha}\sqrt{\frac{m K_1}{F G}}=4\sqrt{mH\frac{H \cdot K_1}{FG}}=1,27\sqrt{Q f_H}, \quad (2)$$

where Q - total weight of the boiler and f_H - a single displacement at the top of the structure depending on the stiffness of the lining and framework. When calculating the stiffness of the lining it is necessary to include its full thickness, and shear modulus G should be taken equal to $4\text{-}5 \cdot 10^3$ kg/sq cm. If metal panelling serves as a sealing layer of the lining, then in the design it would be sufficient to take into account the behaviour in shear of the steel sheet only. The values of periods calculated by the above formula are in rather good agreement with those observed (see the Table).

It is worth nothing that the periods of natural vibrations of boilers differing in structure are within rather narrow limits. Apart from this, as the experience has shown, the mode of the main tone of their vibrations is close to a rectilinear one. There is, therefore, sense to go further and to give a formula to calculate the design seismic load acting on boilers which would not require preliminary determination of their dynamic characteristics.

If to establish the value of the dynamic coefficient $\beta_i = 0.9/T_i$ by the smaller value from the obtained ones of the period of the main tone (T_i = 0.6 sec) and take into account that damping of vibrations of boilers is somewhat lower than that assumed for the standard graph of β_i, then the design formula for the determination of the seismic load on boilers is as follows:

$$S_K=Q_K \cdot K_c \cdot 1,5\beta_i \eta_K = 3Q_K K_c \frac{x_K}{H}, \quad (3)$$

where Q_k - the weight of a part of the boiler related to the k - level and located at the height x_k above the ground;

K_c - the factor of seismicity of the construction region;

H - the boiler height.

The basic structure of the boiler able to resist the seismic load is, evidently, its framework. However the lining, being of relatively small strength is characterized by larger stiffness and, if not to forsee special arrangements, the larger portion of seismic forces acting on the boiler will be transmitted on to the lining. In order to design a proper atructure it is necessary to determine stresses transmitted to the lining through its bracing with the framework. If to denote the stiffness of the bracing by C_k (Fig.3), then the system of equations

$$\frac{S_K^o}{C_K} + \sum_j (\delta_{Kj}^p + \delta_{Kj}^o) S_j^o = \sum_j \delta_{Kj}^p S_j \quad , (K=1,2, \ldots, n) \qquad (4)$$

where δ_{Kj}^p and δ_{Kj}^o are displacements due to a unit force of the framework itself and of the lining, permits the seismic stresses S_K^o in the bracing to be determined. Since we are speaking about the voluminous load S_k, the above scheme should be clarified as, in fact, the mass in the k - level consists of two parts referring respectively to the framework m_k and to the lining m_k. In equations (4), it would be more correct to calculate the displacements δ_{Kj}^p and δ_{Kj}^o not from a unit force P=1, but from its portions $P^p=m_k^p/(m_k^p+m_k^o)$ and $P^o=m_k^o/(m_k^p+m_k^o)$.

Only the metal panelling (steel lining) reinforced with stiffeners is likely to be regarded as a structural element of the lining able to resist seismic forces. With other types of lining the design seismic load should be completely transmitted to the framework of the boiler. In order not to fail under the displacements of the framework such a lining should be sufficiently deformable in its plane. With this in view it should be divided into separate zones of 8-16m square by deformation joints. The required value of shear $|\Delta_K|$ in the horizontal joint at the k-level which should be provided for by its structural design is estimated by the expression:

$$|\Delta_K| = \frac{\Delta_K - |\lambda| h_K}{n_K} \qquad (5)$$

where Δ_K - displacement of the lining in its plane as an elastic structure evaluated at the height h_k under the action of the load S_j^o;

$|\lambda|$ - relative shear deformation allowable for the lining;

n_k - the number of horizontal joints in the lining up to the k-level under consideration.

The resistance of the joint to shear should be designed at least twice less that the stress relevant for the allowable deformation $|\lambda|$ of the panel of the lining. Besides the framework and other building structures of the boiler, all the functional systems of the boiler should be designed for the seismic effect. The direction of the design seismic forces should be assumed such as to cause a most dangerous stressed state in structural elements.

The nodes of fastenings, stresses in which cannot be determined from the general design of the structure, should be calculated for the seismic force equal to $S_k = 5QK_c$.

Let us discuss the main structural requirements, which should be born in mind when designing boilers for seismic regions.

1. Boilers must not have, at least above the floor of a boiler house, rigid bracing with surrounding structures. Compensators should be forseen in the piping attached to the boiler.

2. The framework of the boiler should be sufficiently rigid and have a diagonal lattice to reduce seismic stresses in the lining. It is highly desirable that horizontal stiffness of individual frames of the framework be proportional to the vertical load taken on by it.

3. The lining of the earthquake-resistant boilers should be strong and lightweight and provide safe fastening of the fireproof layer and have higher deformability in its plane; for this purpose it should be divided by special joints.

4. In regions og high seismicity preferrence should be given to panel lining with metal covering fastened to the framework. The connection of such lining with the boiler framework should be elastic and sufficiently pliable in its plane.

5. Lining fastened to the piping may be used only in small boilers. Particular attention should be paid to the safety of its suspension, taking into account, in particular, the vertical action of the seismic load. The fire chamber, suspended in this case, should have elastic supports to the

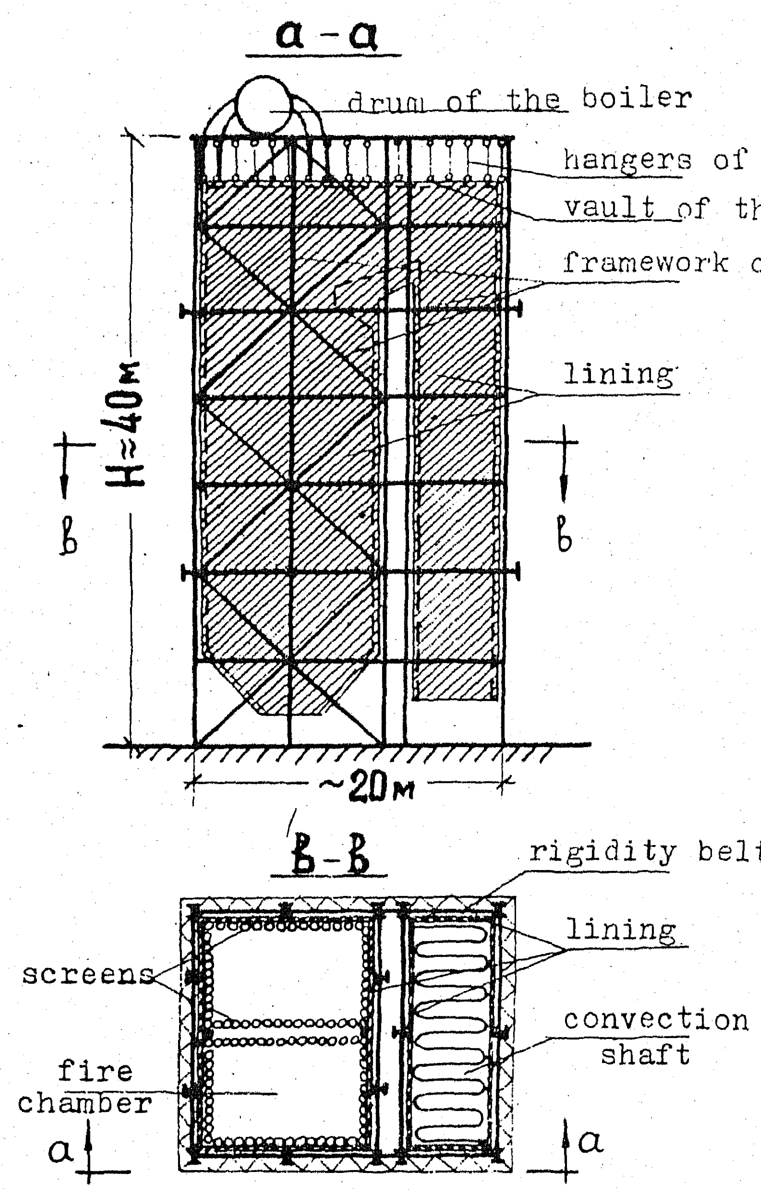
framework elements on several levels.

6. In hinhed supports restrainers of displacements should be designed. Suspended equipment of the boiler should be fixed by special struts to avoid rocking during the earthquake.

In conclusion it should be noted that utilization of induced draught and circulation in technological systems enables a structure of the boiler of horizontal arrangement to be evolved. Such an aggregate would have relatively small height and it would, therefore, be more advantageous from the view point of construction in seismic regions.

Table of characteristics of boilers surveyed

number of boilers tested	General data about the structure of boilers	Steam-production t/hr.	Dimensions in m		Total weight of boiler	Periods of vibrations observed in sec		Design period of the main tone in sec.	
			height	in plan		I tone	II tone	without rigidity of lining	taking into account lining
2	Lining fastened to tubes. Framework without diagonals	160	29.3	11.1x15.3	1220	0.6	0.3	-	-
5	Double cylindrical boiler. Brick lining with metal sheeting fastened to the framework	230	29.8	11x15.6	1968	0.5+0.6	0.3	2.93	0.58
2	Brick lining fastened to the framework. Framework with diagonals	420	35.6	13.9x15.9	3160	0.8	0.4	1.54	0.85
2	Lining attached to tubes. Framework with diagonals	430	36.7	15.7x19.3	3145	0.7+0.9	0.4	1.58	0.89
3	Boiler with two convection channels Lining attached to tubes. Framework with diagonals	640	39.7	17.2x24	7140	0.8	0.3+0.4	-	-
1	Two-vessel boiler. Concrete panel lining with metal sheeting fastened to the framework. Framework with diagonals	970	46.5	19x36	11204	0.7+0.8	-	-	-



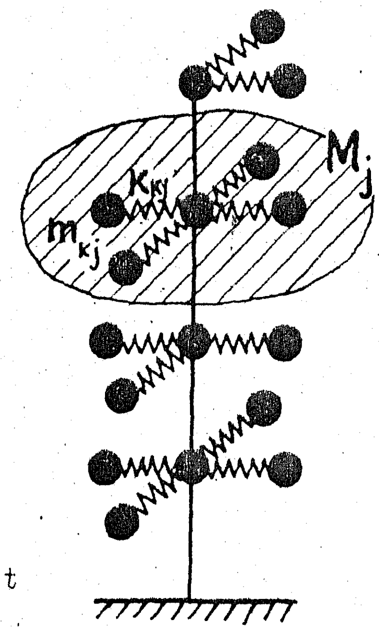


Fig.2 Dynamic model of the boiler structure

Fig.I Consructive scheme of a boiler.

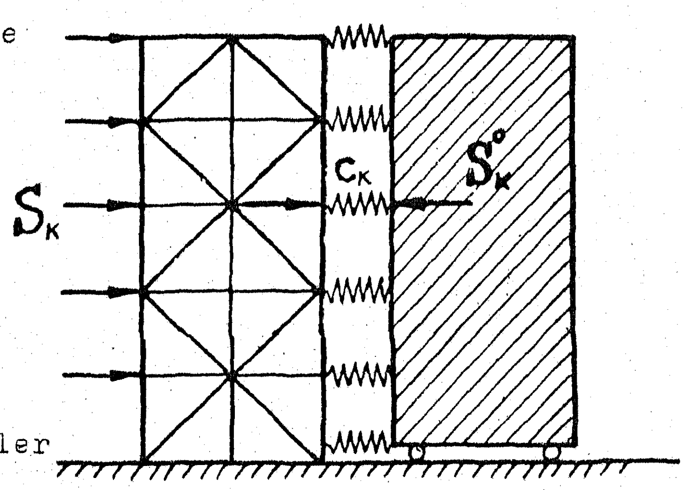


Fig.3 Diagram of joint work of the boiler framework with lining.