Ensuring Earthquake Resistance of Fossil Power Plants Steel Frames and Steam Boilers

A. M. Anuschenko(✉)

CKTI-Vibroseism Ltd., St. Petersburg, Russia
`AAnushchenko@cvs.spb.su`

Abstract. Lessons learned from the Turkey 2023 earthquake and other strong earthquakes in the past underlined importance of safe operation of energy facilities, such as conventional (fossil) power plants (FPP) to provide energy and heat during and after earthquake. Usually FPP consists of steel frame, steam boiler and a number of critical components, equipment and piping. Therefore, design and analysis justification of actual FPP seismic margin is associated with consideration of the complex dynamic systems "frame structure - boiler - equipment". In conventional design of the powerful FPP the boiler is suspended to the ceiling of the steel frame by special flexible and very elongated hangers in order to provide free thermal expansion of the boiler. Due to that the boiler usually has very low natural frequency that presumes big seismic displacements in the gap between boiler body and steel frame. As a result, the boiler under strong seismic impact closes the gap and all the system experiences shocks and large overloads that could lead to disruption of normal operation and even complete destruction of the boiler. The paper investigates different seismic measures and devices that could efficiently upgrade seismic capacity of FPP and provide necessary seismic margin. High efficiency is demonstrated by using of hysteresis (elastic-plastic) elements and viscous dampers, rationally distributed along the system. It is shown that using investigated approach it is possible to achieve very high seismic capacity for the new and the old one FPPs with their location in high seismic zones.

Keywords: Seismic impacts · Steel frame · Steam boiler · Hysteresis elements · Viscous dampers · Fossil power plants

1 Introduction

Ensuring the safe operation of energy facilities, such as thermal (fossil) power plants (FPP), in conditions of seismic impacts assumes trouble-free operation of technological equipment, which may be fixed on building structures.

Steam boilers are used at thermal power plants and mounted to the ceilings of steel frames on special flexible suspensions (blocks of disc or screw springs and traction) in order not to restrict thermal expansion of boilers. Therefore boilers are easy to vibrate by earthquake, so structural vibration control systems (dampers) are installed between boilers and their support structures to suppress vibration response [1, 2].

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As a rule, frame structures have sufficient cross-sections for the perception of seismic and static loads. The main problem is to ensure the permissible displacements of the boiler relative to the frame, deformations in frame elements, stresses in the suspension system. The implementation of these conditions is a criterion for the overall stability of the “frame - boiler” system.

The use of hysteresis and VD-dampers shows high efficiency. In some cases, boilers have release elements with a frame along the entire height. There may be a high level of friction in them, which is not assessed in the current codes. Therefore, the study and evaluation of equivalent damping from dry friction becomes an important task in the calculation of seismic resistance.

2 The Effect of Dry Friction on System Damping and Seismic Response

2.1 Theoretical Background

It has been experimentally established that structural damping in metal structures is quite low: it is 0.1–1% [3]. Taking this value as the damping of the structural system, many possible dissipative phenomena in the joints of structures are ignored. Analysis of regulatory documents and scientific research shows that damping in various systems made of metal structures can vary greatly and reach a value of 15% [4–12].

As a rule, damping in “frame-boiler” systems is set to 5% [8–10], considering the presence of thermal insulation, design features of screens, suspension systems, piping systems and gas ducts.

It is known that the mechanism of dissipation in real structural systems depends on many factors: imperfections of elastic properties of materials, energy dissipation in welded and bolted joints, friction in articulated parts, etc. [13, 14] The phenomenon of dry friction between structural elements and in their joints is mostly ignored, although it improves damping properties significantly.

Boiler elements consist of a large number of metal pipes that contact each other in different planes with friction. Boiler stiffness beams can have linear movable joints with screens horizontally and with frame columns vertically, where friction makes the main contribution to the damping level of the entire system, but is not regulated by norms. Generally, the work of structures occurs at elevated temperatures, when thermal expansion of materials occurs, and in the stages of dust accumulation from burning fuel and lack of lubrication. All this enhances the effects of dry friction.

2.2 Numerical Studies of the Dry Friction Effect in Joints on the Damping of Vibrations in the Frame-Boiler System

In this paper, the effect of dry friction is considered in the following elements:

- fixing the boiler stiffness beams to the frame columns, allowing only vertical movement of the boiler;
- fixing of the rigidity beams to the boiler screens, allowing only horizontal movement in a plane parallel to the screen.

In the real design scheme, friction is observed in the zones and in the directions marked with red arrows in Fig. 1 (the front (F1) and right side (F2) walls of the boiler are visible in the figure; a similar distribution of friction forces is observed along the left side and rear walls of the boiler).

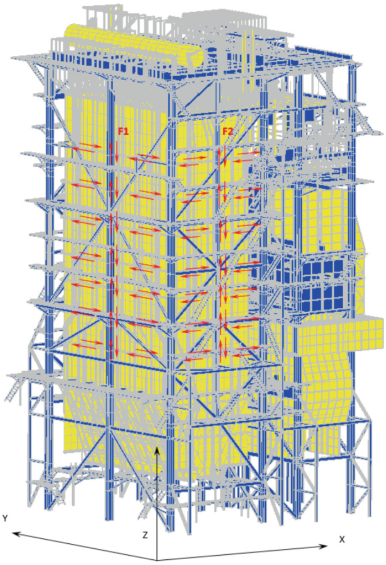


Fig. 1. "Frame-boiler" system (3D finite model) and dry friction zones

The analysis of vibrations for a mechanical system with friction in contacts in the time domain is a nonlinear problem and requires significant computational resources to solve. The real "frame-boiler" system has a large number of components and friction contacts that require detailed modeling, so the assessment of the effect of dry friction on damping is performed on equivalent simplified computational models.

Numerical analysis is carried out in the Transient Structural software package of ANSYS [15, 16]. Two equivalent simplified finite models (flat and spatial (Fig. 2)) are used. They have a similar modal response for the defining bending shape of the oscillations [12] with the real "frame-boiler" system.

The numerical analysis of the dry friction effect on the system damping is carried out as follows:

- at the first stage, calculations were carried out for a flat system without structural damping, the calculation results for a system without friction in contacts and with friction were compared;
- at the second stage, calculations were carried out for a spatial system without structural damping, the results were analyzed for the following combinations of forces: situation No. 1 - Fx: Fy: Fz = 1: 1: 0; situation No. 2 - Fx: Fy: Fz = 1: 1: 0.67;
- the cases of uneven application of horizontal loads are additionally analyzed: Fx: Fy: Fz = 1: 10: 0; Fx: Fy: Fz = 1: 0.5: 0;

- at the third stage, calculations were carried out for a spatial system with structural damping equal to 5% recommended by the norms [8–10] for a three-component effect Fx: Fy: Fz = 1: 1: 0.67, as the most appropriate ratio of forces during seismic action.

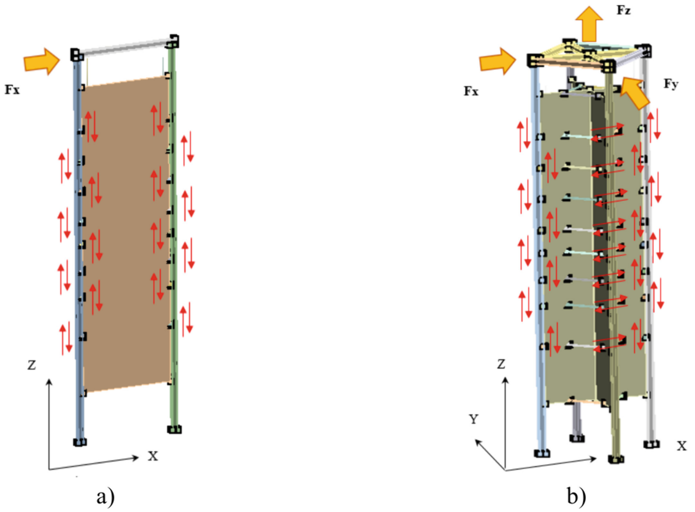


Fig. 2. Equivalent simplified models of the "frame-boiler" system for assessing the dry friction effect on damping: a) flat model; b) spatial model

Graphs of forced oscillations, the nature of which is determined by the results of numerical calculations, are constructed in relative values of displacements (the actual values of displacements are divided by the maximum amplitude of oscillations for the entire period of time). Numerical calculations were performed on a time interval of 10 s with an integration step of 0.005 s.

According to the calculation results for a flat system without friction in the contacts, undamped oscillations were shown; in the presence of friction in the contacts, the oscillation amplitudes decrease at each cycle, the decrease is mainly linear (Fig. 3). The results obtained correlate with the theoretical prerequisites, which allows us to speak about the correctness of the calculations carried out.

The calculation results for the spatial system on combinations of loads No. 1 and No. 2 are shown in Fig. 4. The amplitudes of damped oscillations decrease linearly (X direction); free oscillations without damping occur at the Y-direction. Damping occurs before the stage of oscillations with jammed friction elements.

The value of equivalent damping [17, 18] in systems with dry friction forces at different oscillation cycles varies:

- situation No. 1 – in the range of 6–10%;
- situation No. 2 – in the range of 3–7%.

Additionally, in this paper uneven horizontal loading is considered (Fig. 5).

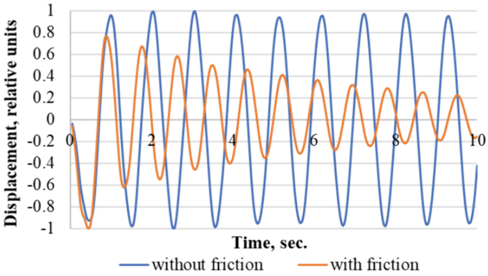
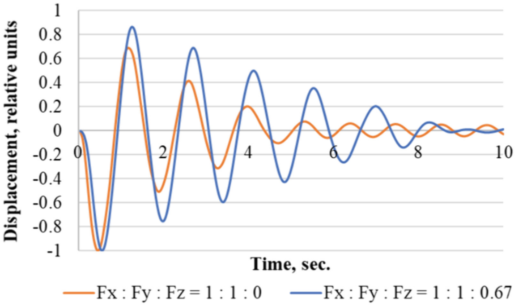
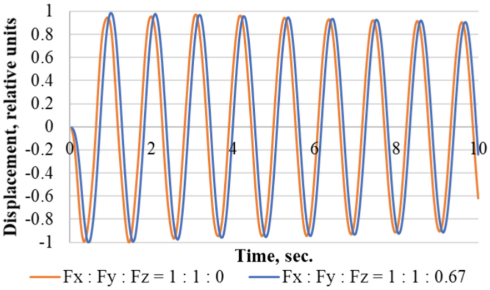


Fig. 3. Free vibrations of the flat system in the absence and presence of dry friction between elements (there is no structural damping)



a)



b)

Fig. 4. Free vibrations of the spatial system in the presence of dry friction between elements (there is no structural damping): a) for X-direction; b) for Y-direction The calculation shows that the presence of a vertical component of the impact reduces the effectiveness of damping vibrations in the horizontal plane.

When the force in the Y-direction (without friction) is significantly more (Fx: Fy = 1: 10) than the force in the X-direction (with friction), there is a weak attenuation in the X-direction with a linear decrease of amplitude to the oscillation zone with jammed friction elements. The equivalent damping value is about 0.5–2%. For a real constructive system, this case is impossible due to the design features of the arrangement of elements with dry friction.

If the force in the Y-direction decreases (Fx: Fy = 1: 0.5), the damping of vibrations in the X-direction occurs less intensively than in cases where the force ratio is 1:1, which indicates a more significant contribution to the energy dissipation in the system from elements with friction in the horizontal direction. The equivalent damping value is about 2–4%.

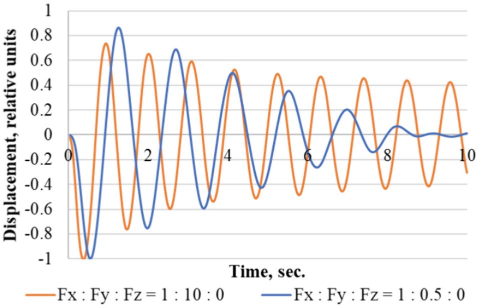


Fig. 5. Free vibrations of the spatial system in the presence of dry friction between elements and unequal horizontal loads (there is no structural damping)

Exponentially damped oscillations in the X and Y directions were adjusted according to calculation results (Fig. 6) for the spatial system with friction and structural damping 5% for a combination of forces corresponding to a three-component seismic impact (Fx: Fy: Fz = 1: 1: 0.67). Equivalent damping values are about 9.5–11.3% for X-direction (with friction), 5.5–5.6% for Y-direction (without friction).

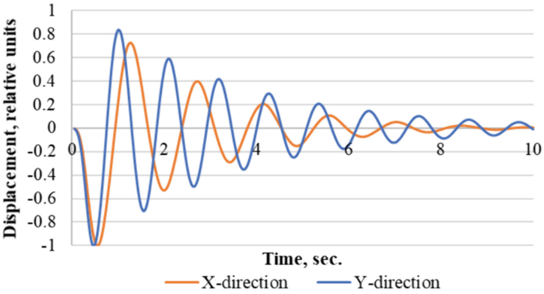


Fig. 6. Free vibrations of the spatial system with dry friction between the elements, structural damping of 5% and the ratio of forces Fx: Fy: Fz = 1: 1: 0.67

According to the results of numerical modeling, the value of damping in the structural system "frame – boiler" from the action of dry friction forces can be assumed to be equal to 5%. The total damping (structural damping + equivalent dry friction damping) is 10%.

2.3 The Damping Effect of Dry Friction on the Dynamic Response of the Frame-Boiler System

A comparison between displacements of the frame overlap under the seismic action (PGA = 0.2 g) for damping of 1% (structural in steel), 5% (from the norms for the "frame-boiler" system), 10% (with dry friction) is shown in the Fig. 7. The maximum displacement values are shown in Table 1. A comparison between the maximum forces in suspensions under the seismic action for damping 1%, 5%, 10% is shown in Table 2.

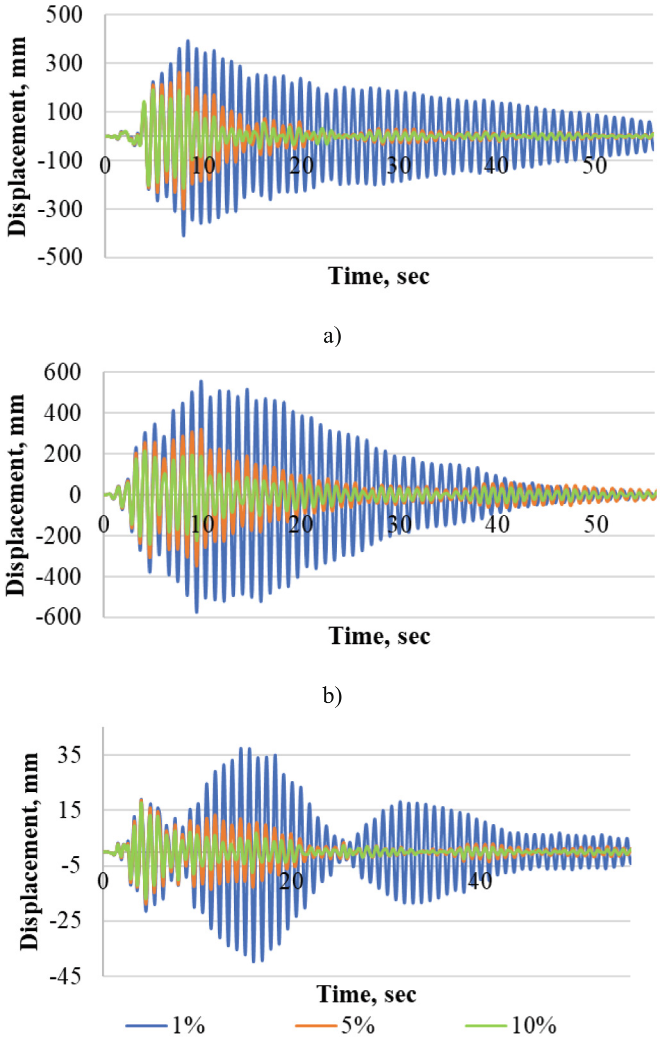
Increased damping in the system from 5 to 10% leads to decrease in horizontal displacements by 29–33% and forces in suspensions is up to 39%.

Table 1. Displacement changes of overlap for the "frame-boiler" system depending on damping

Direction	Maximum displacement, mm			Reduction of displacements, %		
	$\xi = 1\%$	$\xi = 5\%$	$\xi = 10\%$	1% → 5%	5% → 10%	1% → 10%
X	−410	−300	−215	27	29	48
	394	264	193	33	27	51
Y	−575	−349	−242	39	31	58
	557	322	216	42	33	61
Z	−40	−19	−17	53	10	57
	38	19	18	50	5	52

Table 2. Force changes in suspensions for the "frame-boiler" system depending on damping

Force/Moment	Maximum parameter			Reduction of forces/moments, %		
	$\xi = 1\%$	$\xi = 5\%$	$\xi = 10\%$	1% → 5%	5% → 10%	1% → 10%
N, kN	−1090	−640	−390	42	39	64
	870	560	430	36	23	51
M_Y, kNm	−5.5	−2.3	−1.9	58	17	65
	6.1	3.2	2.5	48	22	59
M_Z, kNm	−16.4	−9.0	−6.7	45	26	59
	12.9	8.1	5.4	37	33	58



a)

b)

c)

Fig. 7. Comparison between displacements (in time) for the "frame-boiler" system with different damping (1,5,10%): a) for X-direction; b) for Y-direction; c) for Z-direction

3 The Effectiveness of Hysteresis Dampers in Regulating Seismic Reactions in Frame-Boiler Systems

3.1 Theoretical Background

It's known that the hysteretic behavior of metal is advantageous in dissipating dynamic energy. The metallic material under loading is plasticized if the stress level exceeds the elastic limit and thereafter enters the stress hardening phase under larger stresses.

Under cyclic loadings, the elastic modulus of the metal recovers as the metal unloads. If a load is applied in the opposite direction, the material begins to yield and soften at a lower stress level than the yield stress, which is known as the Bauschinger effect. The hysteretic behavior of the material continues as long as the strain does not exceed the yield plateau and the maximum positive and negative stresses remain within the yield stress. The material follows the initial elastic stiffness even after unloading from the stresses higher than the yield plateau. The Bauschinger effect becomes more dramatic as the material reaches toward maximum strain [19, 20].

These properties of the metal were used to develop hysteresis dampers of cantilever and axial type used for seismic insulation of suspended boilers. They are characterized by nonlinear behavior and are used to change the dynamic characteristics of the structural system of a structure, introducing significant energy dissipation, which should be properly considered in nonlinear modeling for the computational analysis of structural systems, including these devices.

3.2 Damper Design

In this paper, hysteresis dampers of the console type (Fig. 8) is considered. They perceive horizontal seismic forces from the boiler through a hinge attachment to the stiffness belts, providing free movement in the axial and vertical directions. The parameters L1 and L2 are determined by the distance between the boiler and the frame. L2, b1, b2 determine the zone of plastic deformations [21, 22]. Adjustment of geometric parameters allows to obtain various "force-strain" characteristics for dampers. The force characteristic is selected in accordance with the forces in the stiffness beams that arise under the seismic action. The deformation characteristic is a parameter of permissible boiler displacements.

Experimental studies show that cantilever-type hysteresis dampers can be loaded up to 10 cycles for the maximum amplitude of deformations and up to 40 cycles for quarter of the maximum amplitude of deformations, which indicates their suitability for use in seismic conditions. A relatively simple design solution and attachment to the frame (Fig. 8c) allows the replacement of elements, if necessary, after earthquakes.

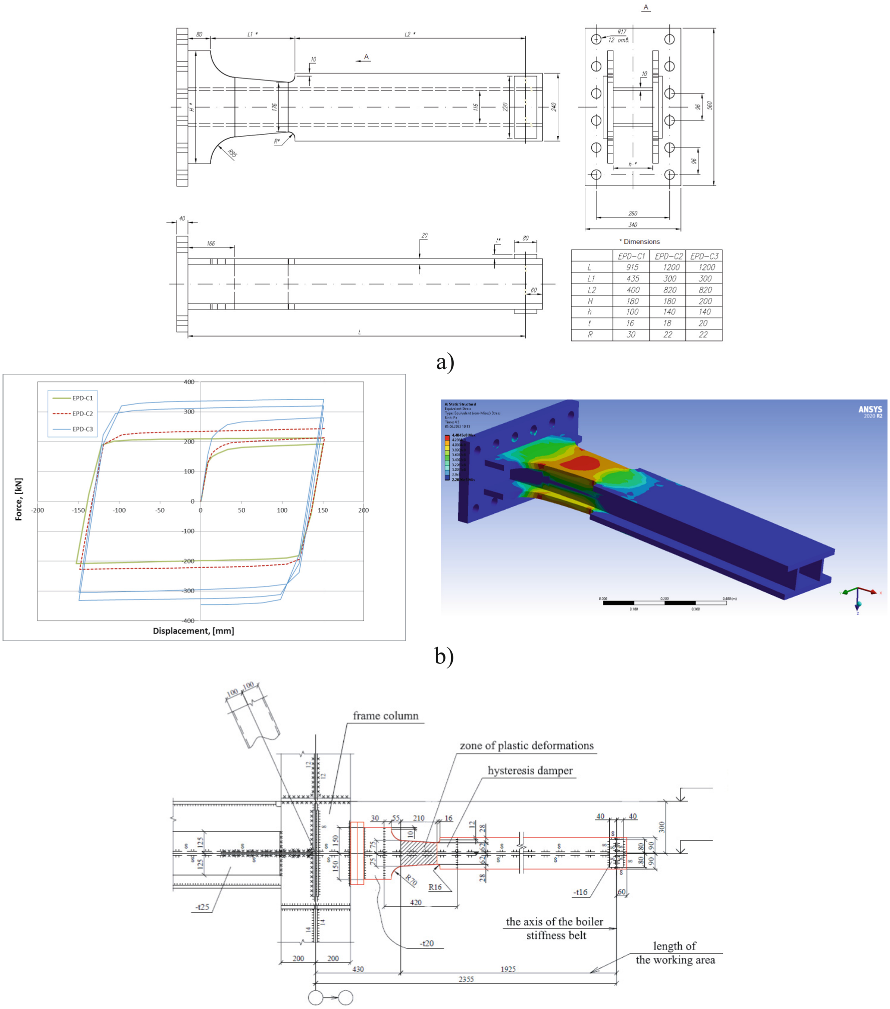
3.3 Verification of Numerical Models for Hysteresis Dampers

For numerical studies, calculation procedures and modeling methods in the ANSYS software [15, 16] were verified with the results of field tests (Fig. 9a) for samples of dampers with variable I-beam cross-section. It is established that numerical models (Fig. 9b) can be used for calculations by the finite element method (Fig. 9c).

3.4 Regulation of the Seismic Reaction by Hysteresis Dampers

Hysteresis dampers can be installed in either one or several levels of boiler stiffness beams. This is determined by the magnitude of the forces that are transmitted by the boiler to the frame during seismic action.

The article demonstrates the regulation of seismic reactions in the same "frame-boiler" system (Fig. 10) at two levels of impact: $PGA_1 = 0.1$ g, $PGA_2 = 0.2$ g.



* Dimensions

	EPD–C1	EPD–C2	EPD–C3
L	915	1200	1200
L1	435	300	300
L2	400	820	820
H	180	180	200
h	100	140	140
t	16	18	20
R	30	22	22

a)

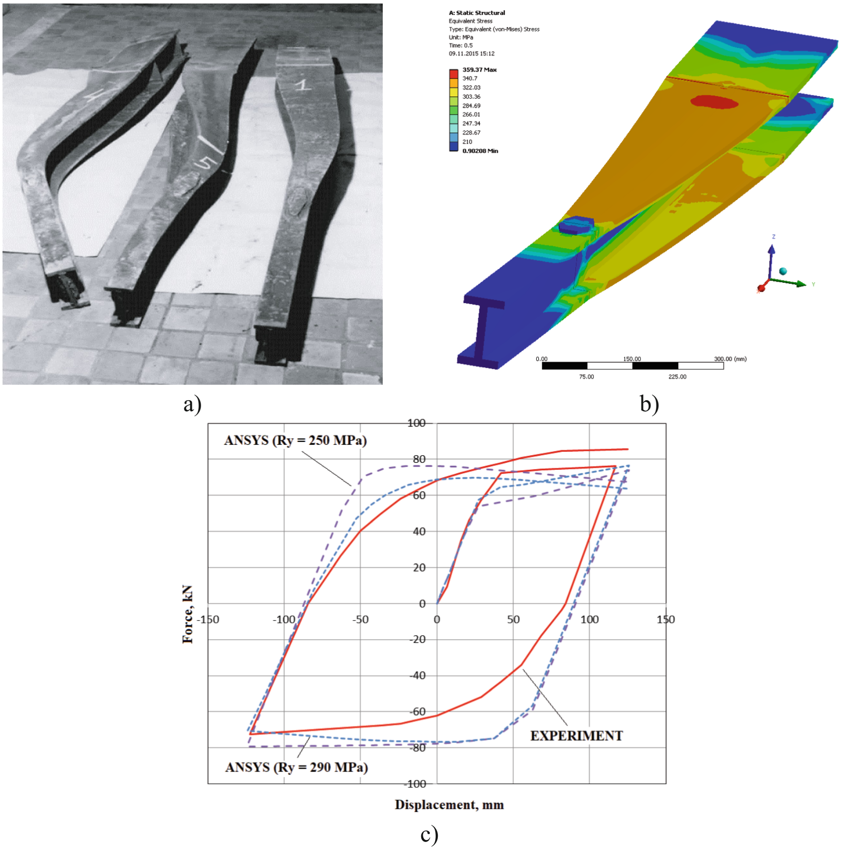
b)

c)

Fig. 8. Hysteresis damper of console type: a) shape and geometric parameters; b) "force-deformation" characteristics depending on geometric parameters and stress-strain state of finite-model; c) the assembly of the damper attachment to the frame

In the first case, dampers with a working force of 150 kN and a deformation of 100 mm are used (Fig. 11a); in the second case, dampers with a working force of 350 kN and a deformation of 140 mm are used (Fig. 11b). The deformation parameter is determined by the permissible displacements of the boiler. Parameters of dampers are determined by the results of numerical simulation in ANSYS [15, 16].

Numerical calculations of the "frame-boiler" system were carried out in the time domain on synthesized accelerograms of seismic impact.



a)

b)

c)

Fig. 9. Verification of numerical methods for modeling hysteresis dampers in ANSYS: a) full-scale samples of dampers (after tests); b) finite-element calculation; c) "force-deformation" characteristics

For $PGA_1 = 0.1$ g, force changes over time in hysteresis dampers are shown in Fig. 12, the force-displacement relationship during seismic action is shown in the Fig. 13, a comparison of boiler displacements between a system without dampers and with dampers is shown in the Fig. 14.

For $PGA_2 = 0.2$ g, force changes over time in hysteresis dampers are shown in Fig. 15, the force-displacement relationship during seismic action is shown in the Fig. 16, a comparison of boiler displacements between a system without dampers and with dampers is shown in the Fig. 17.

Comparison of boiler displacements and horizontal forces in suspension rods for different design situations are presented in Table 3. Hysteresis dampers reduce displacements of the boiler to an acceptable level. Suspension stresses are reduced by up to 60% at $PGA_1 = 0.1$ g and up to 70% at $PGA_2 = 0.2$ g.

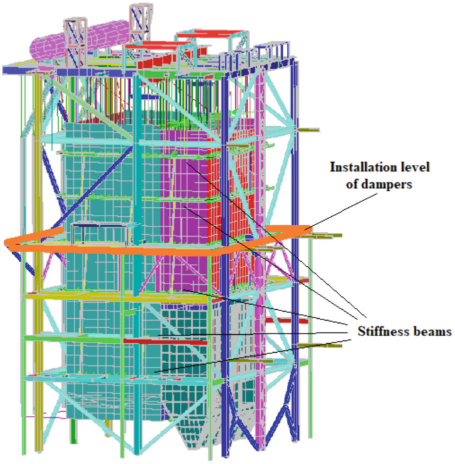
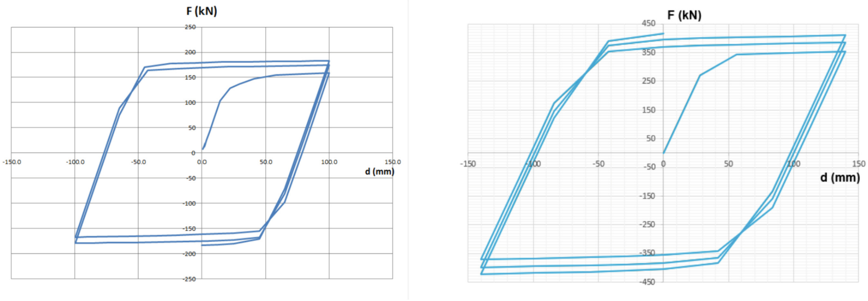


Fig. 10. "Frame-boiler" system finite-element model.



a) b)

Fig. 11. "Force-deformation" characteristics of dampers: a) force – 150 kN, deformation – 100 mm; b) force – 350 kN, deformation – 140 mm

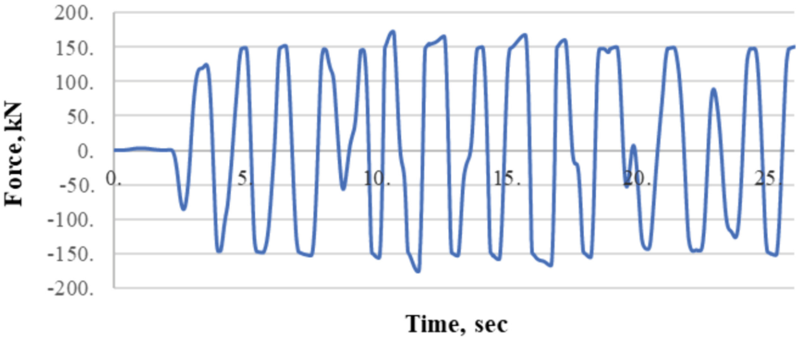


Fig. 12. Force changes over time for dampers ($PGA_1 = 0.1$ g)

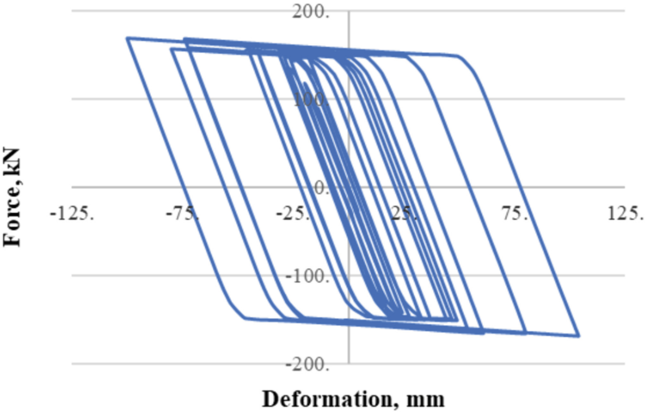


Fig. 13. Force-displacement relationship during seismic action for dampers ($PGA_1 = 0.1$ g)

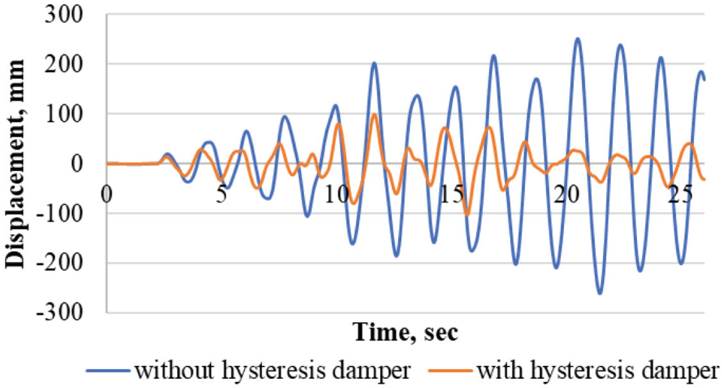


Fig. 14. Comparison of boiler displacements ($PGA_1 = 0.1$ g)

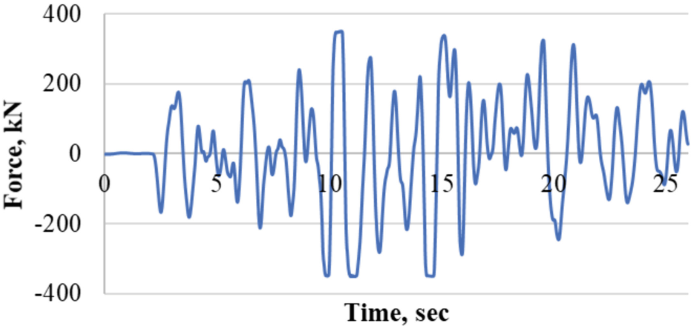


Fig. 15. Force changes over time for dampers ($PGA_2 = 0.2$ g)

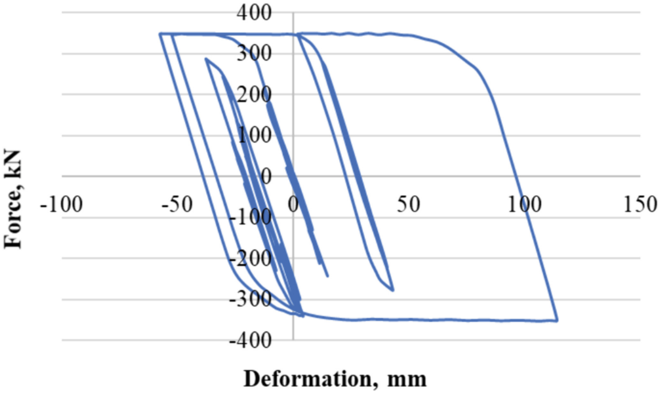


Fig. 16. Force-displacement relationship during seismic action for dampers ($PGA_2 = 0.2$ g)

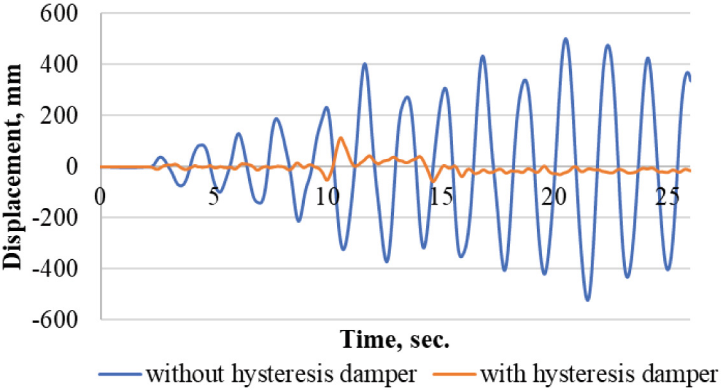


Fig. 17. Comparison of boiler displacements ($PGA_2 = 0.2$ g)

Table 3. Displacement and force changes for the system with hysteresis dampers

Parameter	$PGA_1 = 0.1$ g		$PGA_2 = 0.2$ g	
	without dampers	+ hysteresis dampers	without dampers	+ hysteresis dampers
Displacement, mm	262	104 ($\Delta = -60\%$)	523	115 ($\Delta = -78\%$)
Force, kN	6.4	2.6 ($\Delta = -59\%$)	12.8	4.1 ($\Delta = -68\%$)

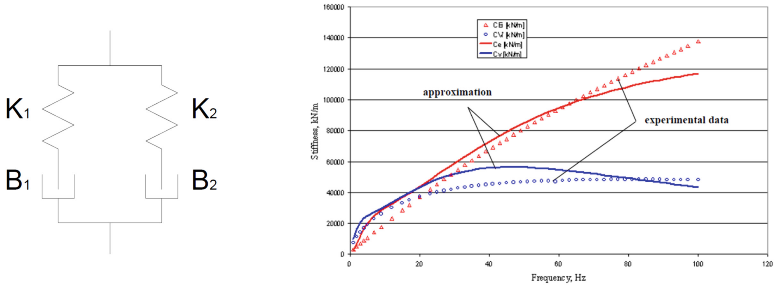
4 Combined Use of Hysteresis and Viscous Dampers to Regulate Seismic Response

Nowadays Viscous Dampers (VD) are well-known devices for providing dynamic safety for piping, components and systems at nuclear power plants, heavy industry and chemical facilities [23].

The wide spreading of VD-dampers is determined by its unique capabilities and advantages to other devices [23]:

- to reduce vibration and dynamic response of systems in all degrees of freedom;
- to react on vibration immediately without any delay;
- stability to high temperature, humid, toxic environment;
- maintenance free design and handling.

Significant peculiarity of VD-dampers is nonlinear damping and stiffness characteristics against frequency of excitation. Such dependence can be satisfactory approximated by Maxwell model (Fig. 18).



a) b)

Fig. 18. The mathematical model of VD-damper: a) The Maxwell-model (B_i – damping, K_i – stiffness); b) approximation of the test data with the Maxwell-model.

Hysteresis dampers do not regulate vertical seismic response. VD-dampers are highly effective in this case. It is advisable to use VD-dampers in addition to hysteresis dampers for “frame-boiler” systems.

Firstly, they can be installed to regulate stresses and deformations in the boiler suspension system if hysteresis dampers do not provide the required level of stresses and displacements of the suspension system. At the same time, the relative movements of the boiler and the deformation of the frame may be normal.

Secondly, they can be installed if the required type or number of hysteresis dampers cannot be installed due to the design features of the “frame-boiler” system.

VD-dampers are installed to the overlap of the frame (Fig. 19). It provides regulation of the seismic reaction in spring blocks, to which rods with a suspended boiler are attached. VD-damper can regulate seismic reactions both in one spring block and in several. In this case, the spring blocks are combined by a connecting plate.

A comparison between vertical displacements of suspensions under seismic action (PGA = 0.23 g) with two ways of seismic isolation is shown in the Fig. 20. The maximum displacement values are shown in Table 4.

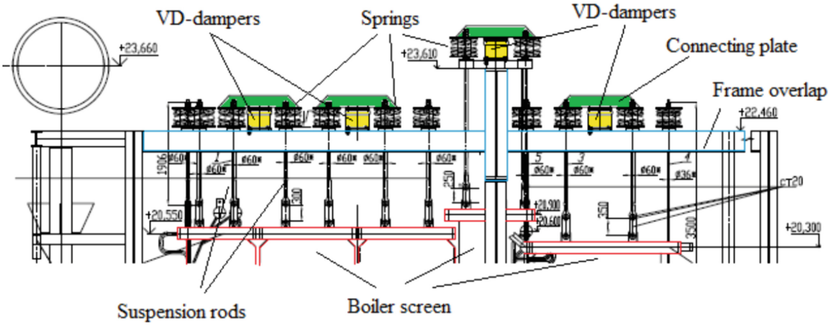


Fig. 19. Installation scheme of VD-dampers on the overlap of the frame

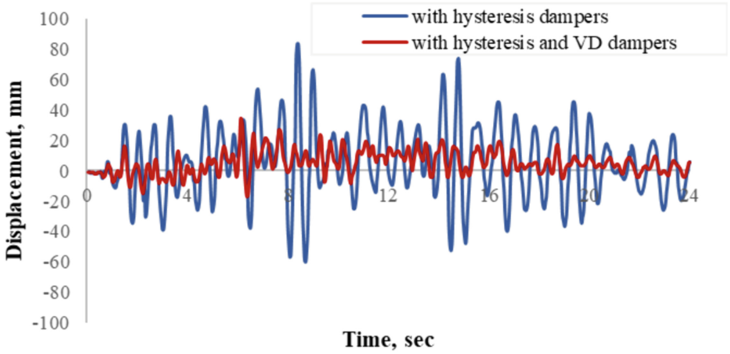


Fig. 20. Comparison between suspension displacements (in time) for the “frame-boiler” system

Table 4. Displacement changes of suspensions depending on type of seismic insulation

Parameter	Maximum value, mm		Reduction, %
	+ hysteresis dampers	+ hysteresis and VD dampers	+ VD dampers
Displacement	83	35	58
	−60	−17	72

The combined use of hysteresis and VD-dampers equalizes the vertical movements of the boiler during seismic action. This increases the safety of operation of pipelines and other equipment connected to the boiler and the frame at the same time. In addition, the stresses in the elements of the suspension system are reduced to an acceptable level. VD-dampers increase damping in the system, which generally has a positive effect on reducing seismic reactions.

5 Conclusions

1) The study of the effect of dry friction on the damping of "frame-boiler" systems is an important engineering task in the calculation of seismic resistance. Depending on the design features of the connection of the elements of the frame, boiler, equipment and pipelines, significant disruptive phenomena may be observed in the system, which it is impractical to ignore. Otherwise, there is an increase in the material capacity of the frame. Dry friction can increase damping in the system by at least 5–7% of the level of structural damping. This makes it possible to identify a reasonable reduction of stresses and deformations in the elements by up to 40%.
2) The use of hysteresis dampers of the cantilever type allows to reduce the displacement of the boiler during seismic action. Damper parameters are determined by the forces transmitted by the stiffness beams and the permissible amount of displacement. The number of dampers and their placement scheme depends on the seismic impact. The placement of dampers should be consistent with the structural solutions of the frame. Reduction of boiler displacements and suspensions stresses when using hysteresis dampers is more than 50%.
3) The combined use of hysteresis and VD-dampers helps in cases where there are design limitations on the placement of hysteresis dampers requiring parameters. VD-dampers is most effective when the vertical component of the seismic impact makes a significant contribution to the stress-strain state of the "frame-boiler" system.

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