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RESEARCH ARTICLE

Nonlinear Analytical Models of the Seismically Isolated "Frame-Boiler" System with Cantilever-Type Hysteresis Dampers

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ABSTRACT

This study shows results of development of the "frame-boiler" system with hysteresis dampers analytical model. Hysteresis dampers are used as boiler antiseismic bracing. It is noted that simplified analytical models are necessary at the stage of preliminary iterative calculations, when a CAE-modeling is impractical due to significant time costs. The authors have proposed 2 options of analytical models: 2-mass model and 3-mass model. The differential equations of motion for each model are written below. The results of the calculation for seismic impacts are compared with the finite element model. It is shown that 3-mass model gives good match of results both in terms of displacement values and in terms of accelerations: the average discrepancy is less 5%. This model is proposed to use at the stage of preliminary calculations, including selection optimal parameters of dampers and their number.

Keywords: Frame-boiler system, Thermal power plant, Seismic resistance, Hysteresis damper, Bouk-Wen model

1. Introduction

The seismic resistance of energy facilities, such as thermal power plants, is an important engineering task. On the one hand, it is necessary to ensure an uninterrupted supply of energy resources to the population in an emergency situation. On the other hand, emergency situations with a large number of victims and environmental risk should not be allowed [1–5].

The boiler is a suspended mass that can oscillate with significant amplitude under seismic influence (Fig. 1). This can cause the boiler to hit the frame and the subsequent collapse of the frame structures, deformation of the boiler screen, circulation disruption of liquid or steam in the screen, breakage of pipelines, etc. Any of these cases is an emergency and is not acceptable [2, 3, 6, 7].

At the same time, the mass of the boiler cannot be rigidly connected to the frame due to technological features. Firstly, the operation of the boiler is associated with high temperatures. This causes thermal deformations, displacements and expansions, which should be free. Secondly, the boiler screens have a small cross section of pipes with low load-bearing capacity. They are unable to perceive high-intensity seismic forces. In addition, the weight of the boiler is significant. It usually exceeds the mass of the frame and has a high level of seismic acceleration, respectively. The ratios between the masses of metal structures of frames and boilers are shown in Table 1.

Therefore, to ensure the seismic safety of these objects, the amplitude of the boiler oscillations is regulated. This is provided by means of boiler antiseismic bracing elements with a high level of energy dissipation (dampers) [7].

Both hysteresis dampers and hydraulic devices with viscous damping can be used to release the boiler and the frame [7–9]. As a rule, viscous dampers work in

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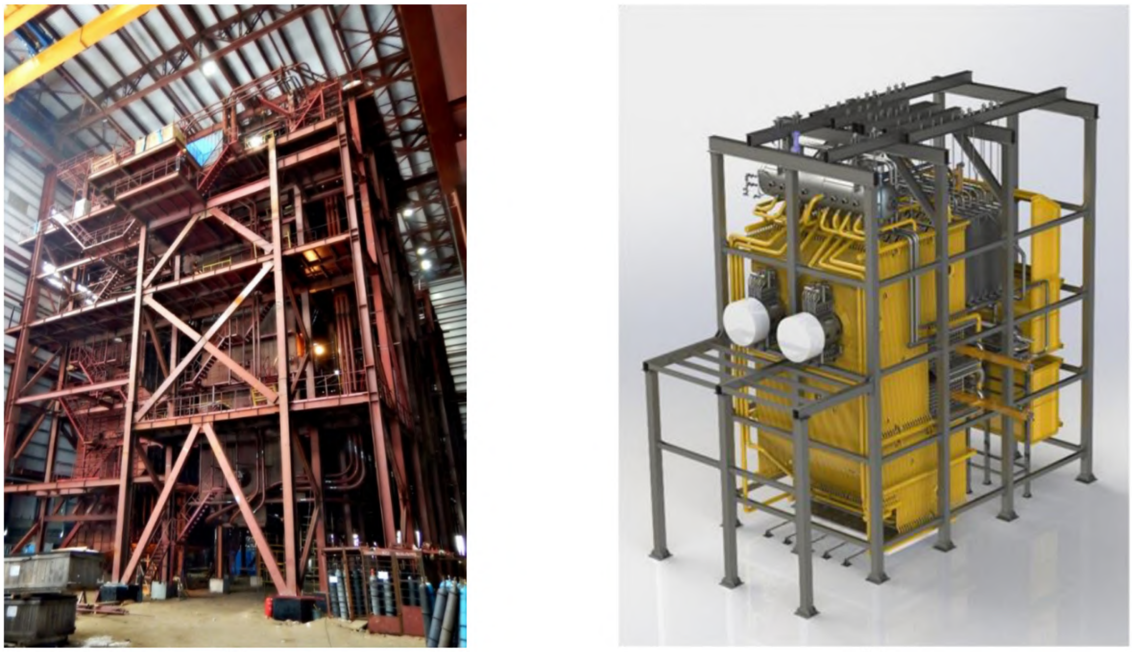


(a) (b)

Fig. 1. General view of the frame with suspended steam boiler: (a) photo, (b) 3D model.

one direction and provide a rigid connection of the boiler to the frame in other directions. Therefore, they are practically not used for bracing. Hysteresis dampers have a large number of implementation options and are well researched at the moment [10, 11].

In this study, a cantilever-type hysteresis damper (Fig. 2-a) is considered. It's a metal beam with welded box section and a short section of the plastic deformation zone. This section prevents buckling. Damper is fixed rigidly to the frame structures and pivotally to the boiler stiffness beams through a special connector (Fig. 2-b). During an earthquake, damper experiences transverse bending in one of the horizontal directions, it does not perceive axial and vertical forces due to the hinge attachment. Damper dimensions are consistent with the gap between the frame and the boiler, the cross section of supporting structures. The attachment point to the frame is similar to the nodes of building structures. Numerical simulation reproduces the hysteresis character of deformations obtained from the test results (Fig. 2-c) [6].

The main advantages of this type of dampers are:

- ease of manufacture (this is also possible on the construction site, during installation work, specialized production is not required);
- versatility (the structure can be designed individually depending on the distance between the boiler and the frame, the cross sections of the elements for mounting, etc.);
- no additional installation space is required;
- comparative compactness; no need for specialized maintenance;
  a significant number of workload cycles before destruction (more than 40–50).

The main disadvantage is the need to replace dampers after an earthquake and work in the plastic

Table 1. Examples of objects and their characteristics.

Object, country	ZPGA, g	Height, m	Weight, kN	
			Boiler	Frame
FPP «BAR», India	0.24	103.8	170000	72000
FPP «LONG PHU», Vietnam	0.06	83.58	108090	47900
FPP «SOFIA», Bulgaria	0.23	22.46	7870	1983
FPP «SOVIET GAVAN», Russia	0.20	35.55	13580	4700
NEVINNOMYSSK FPP, Russia	0.10	28.3	10120	2722

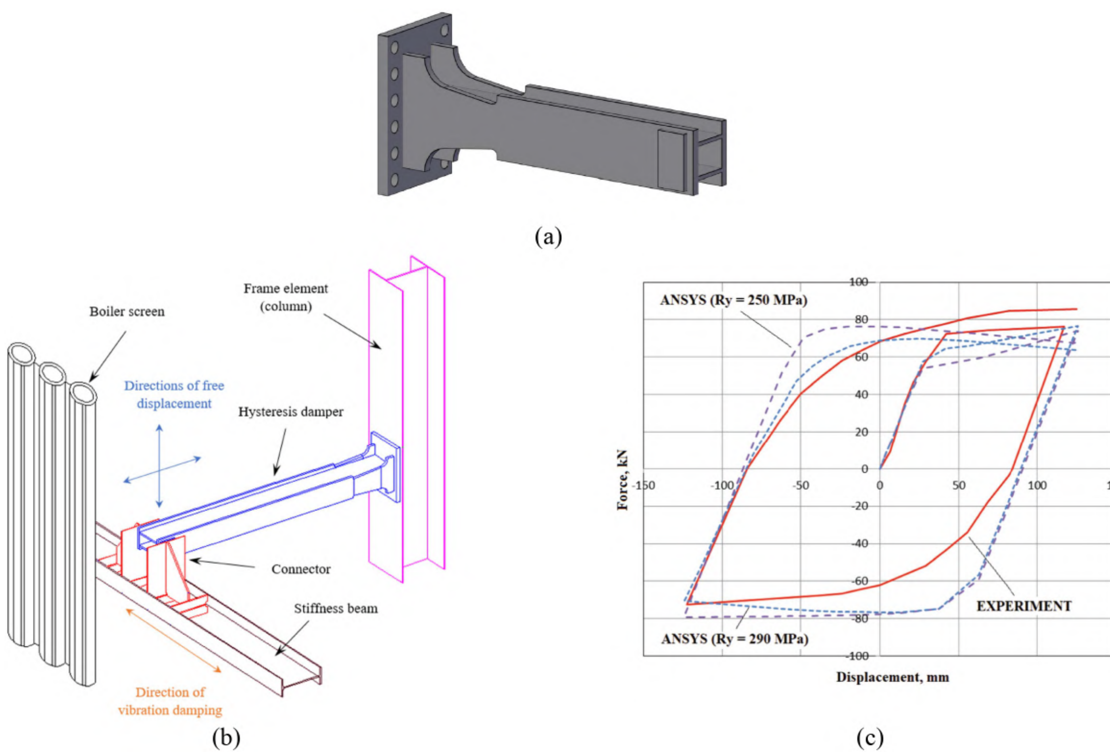


Fig. 2. Cantilever-type hysteresis damper: (a) 3D model, (b) installation scheme, (c) CAE-modelling verification results.

zone, but their low cost with a low probability of seismic occurrence compensates for this disadvantage.

The efficiency of hysteresis dampers for reduction of boiler displacement and regulating of frame stress-strain state was demonstrated in [6]. The use of a different number of elements, varying installation levels, and stiffness parameters allows for high efficiency at different intensity of seismic impact [12].

Ensuring the seismic stability of the frame-boiler systems is associated with numerical modeling of structures and their dynamic behavior during seismic impact. Finite element models include stiffness and loads similar to real ones, describe features of element joints, are designed for a detailed stress-strain state analysis mechanical systems, structures and connections nodes. Despite their undeniable merits, they require significant computing power and time resources, especially in cases where it is necessary to consider the geometrically or physically nonlinear nature of the materials, conduct direct dynamic analysis, etc. In this regard, the use of such models in the process of designing frame structures, choosing optimal geometric and mechanical parameters, as well as the number of hysteresis release elements (dampers) is inefficient and impractical. It is required to develop simplified analytical dynamic models of frame-boiler system, which can allow to do some iterative calculations quickly.

2. Development of nonlinear analytical models for the "frame-boiler" system with hysteresis dampers

2.1. Idealization of multi-mass systems with suspended masses

The structural system "frame-boiler" includes a large number of structural elements and groups of elements:

- building structures forming the frame;
- suspension system and bracing elements connecting the boiler equipment to the frame;
- elements of the boiler equipment.

It is advisable to allocate a primary system – a frame interacting with the base, and a number of secondary systems fixed to the main one, which are a suspended boiler, suspended convective and screen superheaters, economizers and others. Such differentiation makes it possible to assess the need to include primary and secondary systems in the design finite element model and exclude unnecessary elements that do not significantly affect the dynamic response of the system when assessing seismic resistance [13, 14].

ASCE 4–16 specifies different criteria which provide details on the type of model to be adopted, based

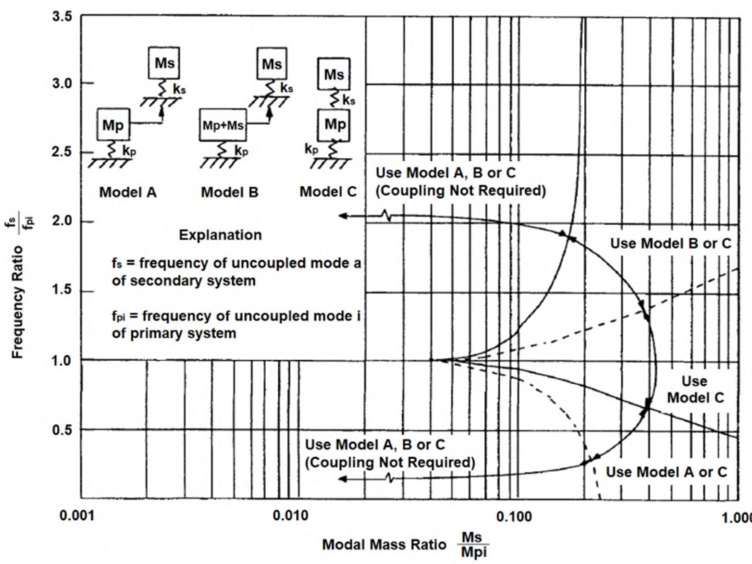


Fig. 3. Decoupling criteria in ASCE 4-16.

on mass and frequency ratios (Fig. 3). In the ASN guide 2006, CEA 2008, ETC-C 2012 criteria are available for the mass and fundamental vibration frequencies ratio between the secondary and the primary structure [15]:

- to neglect the coupling if the mass ratio is less than 1%;
- to take it into account if the mass ratio is greater than 10%;
- to take it into account, for mass ratios ranging between 1 and 10%, if the frequency ratio is between 0.8 and 1.25.

Dynamic response features and characteristics of metal frames and steam boilers are well studied [2, 3, 6–8]:

- the first natural oscillation frequencies of the frames are in the range of 1–2 Hz,
- the first natural oscillation frequencies of suspended boilers are in the range of 0.1–0.5 Hz,
- the modal mass of the first natural frequency for the frame is 60–80%,
- the torsional forms of natural oscillations are of little importance,
- the ratios between the frame mass (M_f) and boiler mass (M_b) are shown in Table 1, as a rule, the ratio of M_f / M_b = 1/4 is observed.
- suspended convective and screen superheaters have masses of up to 1% of the mass of the frame,
- economizers are rigid bodies with high first oscillation frequencies, they are considered as a concentrated mass.

Thus, the steam boiler mass cannot be excluded from the calculation. It is necessary to consider the nature of its attachment to the frame structures.

Aida, Nishida et al. [16, 17] have carried out the most extensive studies of "frame-boiler" systems in Japan. They proposed several options for schematization of "frame-boiler" systems (Fig. 4):

- formation of multi-mass models with concentrated masses of frame and boiler parts on frame floors and on bracing levels (seismic ties);
- approximation of multi-mass models to two-mass models (m1 – frame mass m2 – boiler mass).

Initially, the rigidity of the suspension system was ignored, only bracing elements (seismic ties) were considered. It has been shown that this approach is

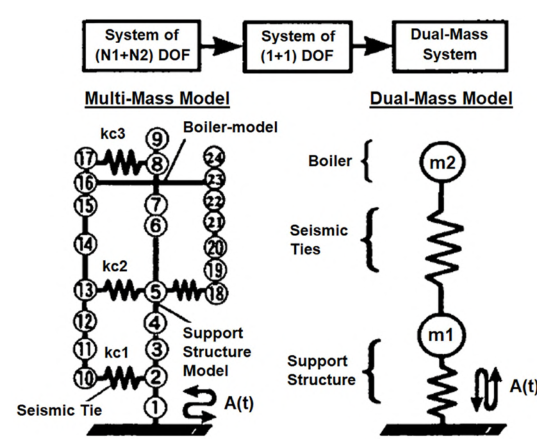


Fig. 4. Multi-mass and dual-mass model of the "frame-boiler" system [16, 17].

incorrect. After introducing the stiffness parameter of the suspension system, it was shown that the dual-mass model correctly describes the seismic response of the system with elastic nature of the work for structures and bracing elements. The nonlinear nature of the work has not been investigated.

2.2. The Bouk-Wen model for nonlinear operation of hysteresis dampers

Structures can exhibit pronounced inelastic behavior under intense cyclic loads caused by earthquakes. Inelastic behavior often manifests itself in the hysteresis loop form. Despite the widespread distribution of hysteresis in devices and equipment used in mechanical engineering and civil engineering, a fundamental and comprehensive theory of hysteresis has not been developed. Phenomenological hysteresis models are often used to solve practical problems in modern design and analysis of structures [18].

One of the most widely accepted models is a differential model Bouk-Wen [19, 20]. In this model, the restoring force and deformation are related by a nonlinear first-order differential equation containing a number of parameters that refine the shape of hysteresis loops in accordance with experimental data [21–24].

According to [23, 24], an element with hysteresis (Fig. 5) can be represented in the form of elastic postyielding spring (F^{el}) and hysteretic spring (Z), giving in total a full restoring force ($F_{u,Z}$):

$$F_{u,Z} = F^{el} + Z. \tag{1}$$

The hysteresis force Z is expressed by a nonlinear differential equation according to the Bouk-Wen model as

$$\frac{dZ}{dt} = \left\{ Ak_d - \left[\gamma + \beta sign\left(Z\frac{du}{dt} \right) \right] |Z|^n \right\} \frac{du}{dt}, \tag{2}$$

where, u: Displacement, t: Time, A: Parameter regulating the duration of plastic deformations, β, γ: Parameters regulating the shape of the hysteresis loop, n: Parameter regulating the sharpness of the transition from the elastic to the plastic stage of deformation,

$$k_d = k_i - k_f. \tag{3}$$

Parameters A, β, γ, n are determined individually for each designed device with hysteresis according to experimental or calculated graphs of material deformation for one full cycle of operation, based on the solution of the equation system of motion for a simple oscillator, considering the hysteresis according to Eq. (2).

The parameters A, β, γ and n regulate and control the scale and general shape of the hysteresis loop. Due to the lack of an analytical description for the hysteresis loop, many studies [25–28] have used numerical simulation to understand the influence of these parameters. Simulations have been done by fixing three parameters and varying one.

The effect of changing model parameters can be summarized as follows [21–28]:

- parameter n defines the degree of smoothness of the transition from the elastic to post-elastic branches;
- if n → ∞, then the hysteresis reduces to a bilinear diagram;

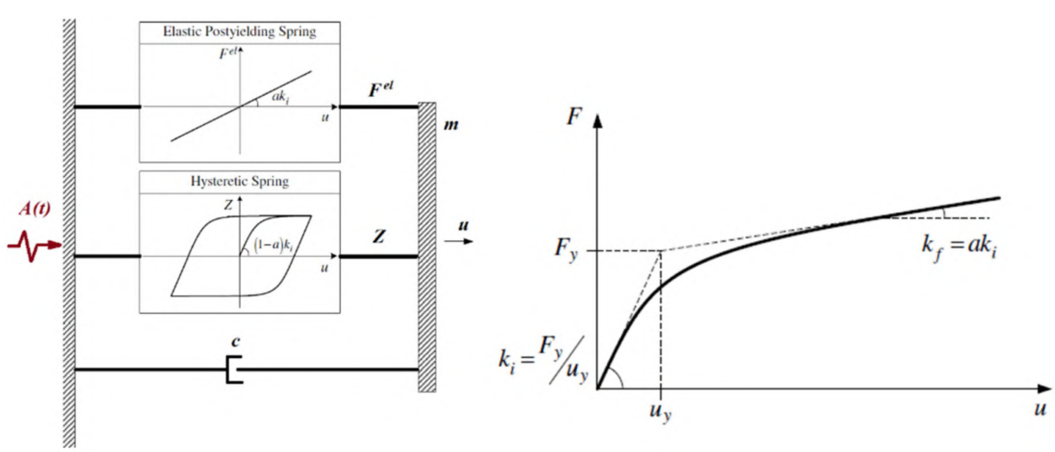


Fig. 5. Parameters for Bouk-Wen model [23].

- if n ≈ 2.0, then the hysteresis is smoothed;
- when the amplitude of the excitation is small, the frequency response of the system is quasilinear hysteretic system, while the system exhibits a large multivalued frequency region as the amplitude of the excitation increases;
- parameter γ tunes the extent of the restoring force loop;
- as the parameter γ varies from negative value to positive one, the system frequency response curves gradually vary from hardening character to a quasilinear character and then to soft character;
- when β is increased, the response amplitude is decreased;
- hardening and softening behaviors are shown to be related to the sign of $\beta + \gamma$;
- sum $(\beta + \gamma)$ affects the maximum value of the hysteretic force, while their ratio γ/β controls the shape of the cycles and, consequently, the dissipative capacity;
- the maximum loop area, and therefore, the maximum energy dissipation is obtained when $\gamma = \beta$;
- increasing A parameter increases the system natural frequency, the resonant frequency and reduces the resonant peak;
- increasing A and n parameters makes the hysteresis loop narrower.

The relationships between β and γ and their effects on hysteresis are shown in Fig. 6.

Considering the hysteresis characteristics of the cantilever type dampers (Fig. 2) [6], it is recommended to take a fixed value of the parameter $n = 2$ to smooth the transition from the elastic to the plastic branch of deformation, γ and β parameters are assumed to be equal. In general, the coordination of the design schedule of the damper with the Bouk-Wen model is carried out by varying two numbers (parameter A and $\gamma = \beta$ parameters).

2.3. Proposed nonlinear mathematical models and differential equations

When designing, it is assumed that frame load-bearing elements work in the elastic stage exclusively, even under seismic impacts. This is due to the fact that inelastic deformations can be significant and lead to the failure of working equipment. For example, suspension loads are redistributed sharply after an inelastic increase in the deflection of the overlap beam, which causes the breakage of overloaded suspensions and the collapse of the entire boiler unit. Therefore, the mathematical model of the frame can be considered as an oscillator with elastic bonds. Dampers are not load-bearing structures, so the non-linear nature of their operation does not contradict the design principles. At the same time, energy dissipation due to the development of plastic deformations can be very high. The hysteresis nature of dampers connecting the frame and the boiler provides nonlinear dependencies in the change of accelerations and displacements of the system elements. The nonlinear nature of the damper operation is described using the Bouk-Wen model.

Based on the researches [13–17], it is proposed to use a two-mass model of the “frame-boiler” system (Fig. 4). The dual mass approximation method transfers the real object into a dual mass of which seismic response is equivalent. The first mass (m1) with elastic bonds (k1) to the support approximates the frame, the second mass (m2) with elastic bonds (k2) to the first mass approximates the suspended boiler. Additionally, an inelastic hysteresis connection is introduced between masses m1 and m2, simulating the operation of N pieces of dampers. The damping of the frame and suspension system is described by the corresponding parameters c1 and c2. This approximation of the frame-boiler system is a 2DOF system (Fig. 7-a).

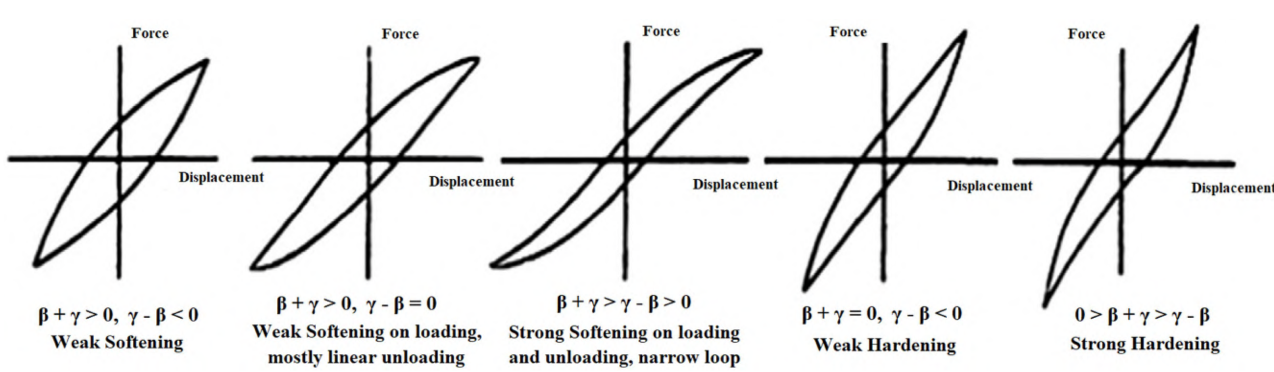


Fig. 6. Possible hysteresis shapes according Bouk-Wen model.

In articles [13–17], it was also proposed to consider a multi-mass approximation of a real object, where each horizontal level of the frame with rigidity trusses and adjacent vertical structures was considered as a separate mass. In this case, the boiler was divided into the number of masses corresponding to the number of bracing levels. This approximation method is not universal, since for each new model of the frame-boiler system it is necessary to form systems of differential equations individually. The solution of such systems is difficult, since in reality the number of bracing levels and stiffness trusses can reach several dozen. This approximation method was abandoned when the two-mass approximation provided a sufficient level of calculation accuracy. In this paper, it is proposed to partially use this experience. Here, the vertical load-bearing structures of the frame and the overlap are divided into two masses (m1 – vertical load-bearing structures mass and m2 – overlap mass) in order to more physically describe the elastic coupling between the boiler (m3) and the overlap (m2) and the elasto-plastic coupling between the boiler (m3) and the vertical load-bearing structures (m1). This approximation of the frame-boiler system is a 3DOF system (Fig. 7-b). The accepted designations in Fig. 7 are explained below in the text.

The two-mass model (2DOF) has the following parameters:

- the reduced mass of the frame (m_1), describing the inertial characteristic of the frame:

$$m_1 = 0.25m_v + m_p, \tag{4}$$

where, m_v: Mass of vertical frame structures, m_p: Mass of the frame overlap;
- the mass of the boiler (m_2), describing the inertial characteristic of the boiler;
- stiffness coefficient of the frame structure (k_1), which determines the first natural oscillation frequency;
- stiffness coefficient of the suspension system (k_2);
- damping parameters for frame (c_1) and boiler (c_2) structures:

$$c_i = 2\xi m_i \sqrt{\frac{k_i}{m_i}}, \tag{5}$$

where, ξ: Damping ratio, i: Mass number;
- ground acceleration – $y''(t)$;
- mass displacements – x_i ($i = 1, 2$).

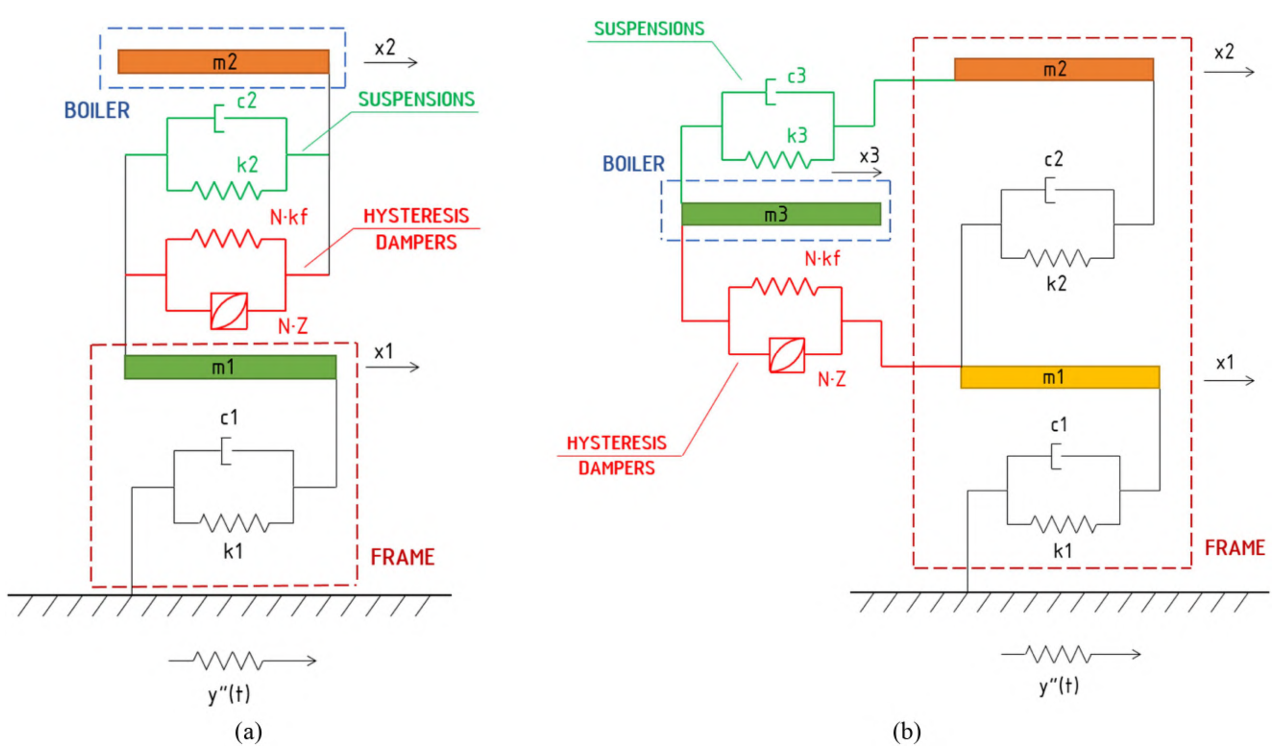


Fig. 7. 2DOF (a) and 3DOF (b) analytical models of the “frame-boiler” system with hysteresis dampers.

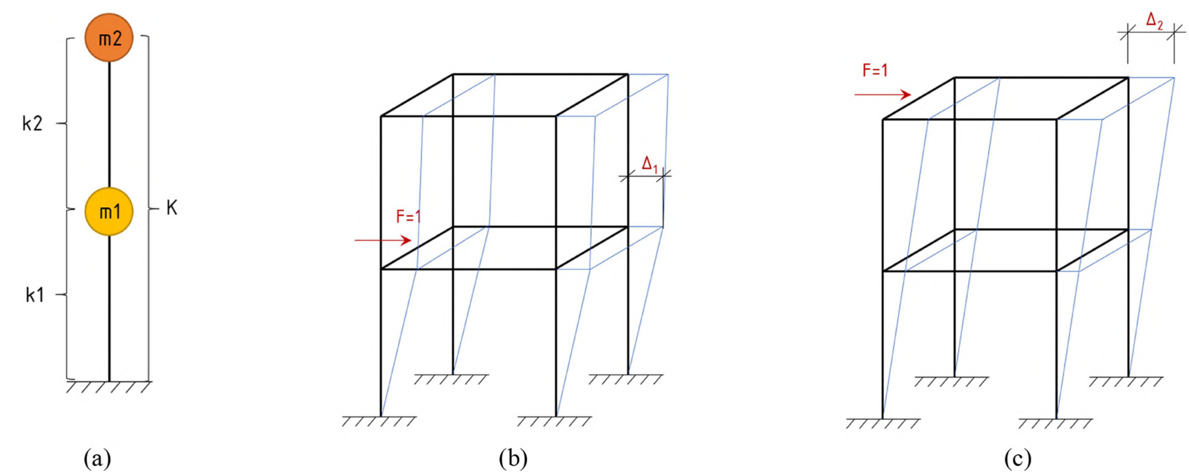


Fig. 8. Schemes for determining stiffness coefficients using finite element models of the frame: (a) 2DOF-system without dampers; (b) k_1 parameter evaluation; (c) k_2 parameter evaluation.

The system of differential equations of motion for two-mass model (Fig. 7-a):

$$\begin{cases} m_1\frac{d^2x_1}{dt^2}+c_1\frac{dx_1}{dt}+k_1x_1-c_2\frac{d(x_2-x_1)}{dt}-k_2(x_2-x_1) \\ \quad -Nk_f(x_2-x_1)-NZ=-m_1y''(t) \\ m_2\frac{d^2x_2}{dt^2}+c_2\frac{d(x_2-x_1)}{dt}+k_2(x_2-x_1)+Nk_f(x_2-x_1). \\ \quad +NZ=-m_2y''(t) \\ \frac{dZ}{dt}=\left\{Ak_d-\left[\gamma+\beta sign\left(Z\frac{d(x_2-x_1)}{dt}\right)\right]|Z|^n\right\}\frac{d(x_2-x_1)}{dt} \end{cases} \quad (6)$$

The three-mass model (3DOF) has the following parameters:

- the mass of vertical load-bearing structures up to the level of the mass center of the boiler (m_1);
- the mass of the overlap with adjacent vertical structures up to the level of the mass center of the boiler (m_2);
- the mass of the boiler (m_3),
- stiffness coefficients of the frame structure (k_1, k_2):

$$k_1=\frac{F}{\Delta_1},\ K=\frac{F}{\Delta_2},\ k_2=\frac{k_1K}{k_1-K}, \quad (7)$$

where, F: Single force, K: Total stiffness coefficient, Δ_1, Δ_2: Single displacements (Fig. 8).
- stiffness coefficient of the suspension system (k_3);
- damping parameters for frame (c_1, c_2) and boiler (c_3) structures;
- ground acceleration – $y''(t)$;
- mass displacements – x_i (i = 1, 2, 3).

The system of differential equations of motion for three-mass model (Fig. 7-b):

$$\begin{cases} m_1\frac{d^2x_1}{dt^2}+c_1\frac{dx_1}{dt}+k_1x_1-c_2\frac{d(x_2-x_1)}{dt}-k_2(x_2-x_1) \\ \quad -Nk_f(x_3-x_1)-NZ=-m_1y''(t) \\ m_2\frac{d^2x_2}{dt^2}+c_2\frac{d(x_2-x_1)}{dt}+k_2(x_2-x_1)-c_3\frac{d(x_3-x_2)}{dt} \\ \quad -k_3(x_3-x_2)=-m_2y''(t) \\ m_3\frac{d^2x_3}{dt^2}+c_3\frac{d(x_3-x_2)}{dt}+k_3(x_3-x_2)+Nk_f(x_3-x_1) \\ \quad +NZ=-m_3y''(t) \\ \frac{dZ}{dt}=\left\{Ak_d-\left[\gamma+\beta sign\left(Z\frac{d(x_3-x_1)}{dt}\right)\right]|Z|^n\right\}\frac{d(x_3-x_1)}{dt} \end{cases}. \quad (8)$$

3. Results and discussion

3.1. Modelling procedures and parameters

The "frame-boiler" system was adopted as the object for research:

- with the arrangement of hysteresis dampers in one level (the center of mass of the boiler) with 2 bracing elements,
- with the arrangement of hysteresis dampers in three levels (evenly along the height of the boiler and symmetrically relative to the center of mass) with 6 bracing elements.

The finite element model (Fig. 9) was calculated in ANSYS. The systems of (Eq. (6)) and (Eq. (8)) were solved in the MathCAD program.

Characteristics of the object:

- the first natural frequency – f = 1.25 Hz;
- the total horizontal stiffness of the suspension system – 2202000 N/m;

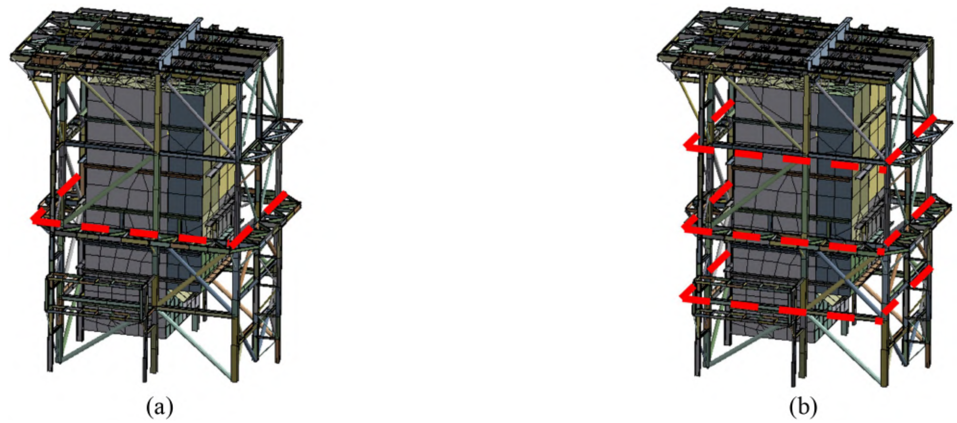


Fig. 9. Finite element models of the "frame-boiler" system with hysteresis dampers in 1 level (a) and 3 level (b).

- the frame mass – 1053138.1 N·s^2/m;
- the overlap mass – 401355.7 N·s^2/m;
- the frame mass below the level of the mass center of the boiler – 513720.2 N·s^2/m;
- the boiler mass – 921238.4 N·s^2/m.

Parameters for 2DOF-model:

- $m_1 = 564300$ N·s^2/m, $k_1 = 34810000$ N/m, $c_1 = 443200$ N·s/m;
- $m_2 = 921238.4$ N·s^2/m, $k_2 = 2202000$ N/m, $c_2 = 142400$ N·s/m.

Parameters for 3DOF-model:

- $m_1 = 513720.2$ N·s^2/m, $k_1 = 95238095$ N/m, $c_1 = 699500$ N·s/m;
- $m_2 = 539417.9$ N·s^2/m, $k_2 = 81300812$ N/m, $c_2 = 662200$ N·s/m;
- $m_3 = 921238.4$ N·s^2/m, $k_3 = 2202000$ N/m, $c_3 = 142400$ N·s/m.

Characteristics of hysteresis damper (Fig. 10): $k_i = 4.24{\cdot}106$ N/m, $k_f = 1.27{\cdot}105$ N/m.

Based on recommendations of [23, 24] parameters for the Bouk-Wen model have been clarified, ensuring high-quality coordination of deformation and cycle energy for dampers:

$$\gamma = \beta = 0.00013\ \text{N}^{-1}/\text{m},\ n = 2.0,\ A = 1.45.$$

Calculations were made for a single-component seismic impact in the horizontal direction. Seven seismic impact spectra (Fig. 11) were used:

- №1 – the low-frequency spectrum (Bukharest, 1977) with maximum response in the range below 0.5 Hz (characteristic range of the main vibrations of boilers);
- №2 – the high-frequency spectrum (Valparaiso, 1985) with maximum response in the range of 2...10 Hz (characteristic range of frame vibrations in higher forms);
- №3 – the medium-frequency synthesized spectrum with maximum response in the range of 1...2 Hz (characteristic range of the main vibrations of frames);

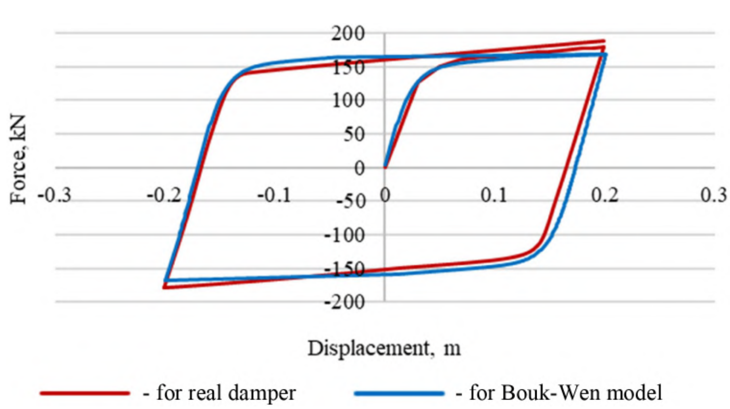


Fig. 10. Comparison of cyclic operation schedules of the damper for finite element calculation and Bouk-Wen model.

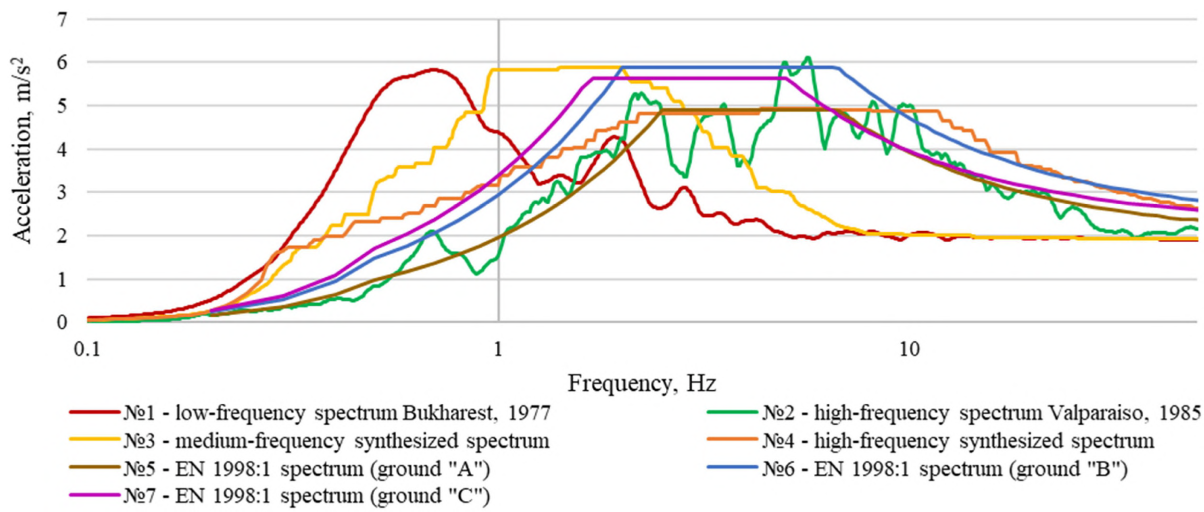


Fig. 11. Seismic impact spectra.

- №4 – the high-frequency synthesized spectrum according Russian Building Code [29];
- №5, №6, №7 – regulatory spectra for durable soils of type A, B, C according to EN 1998:1 [30].

Performing series of calculations for different spectra makes it possible to execute statistical data processing and draw reasonable conclusions about the acceptability of using models for a preliminary analysis (pre-design work, selection of the damper section and an approximate estimate of possible efficiency). A data is said to follow a normal distribution when values are dispersed evenly around one representative value. A normal distribution is a necessary condition for a parametric statistical analysis. The mean (M) in a normally distributed data represents the central tendency of the values of the data. However, the mean (M) alone is not sufficient when attempting to explain the shape of the distribution; therefore, the standard deviation (SD) and the standard error of the mean (SEM) along with the mean are used to report statistical analysis results [31]. These parameters are analyzed for all obtained results.

3.2. Results for 2DOF-model

The calculation results of the finite element model (CAE) and the analytical two-mass model (2DOF) are compared in Table 2. Statistical processing of the results (for error (Δ, %) in comparison with the finite element model) is presented in Table 3. Fig. 12 shows a graphical comparison of the results using numerical and analytical models for the calculation with the maximum seismic response for frame displacements (as one of the most important regulatory criteria for the overall sustainability of the system) from the series.

Based on the results, the following conclusions were made:

- the hysteresis nature of the damper operation is reproduced qualitatively and quantitatively;
- the pattern of boiler displacements in models is well coordinated;
- values of displacements and accelerations of frame overlap, which determine the stability of the system and the forces in the frame structures, differ significantly; the maximum discrepancy exceeds 50%;
- the average discrepancy between the results of analytical and numerical calculations for frame displacements and accelerations is in the range from 26 to 35%.

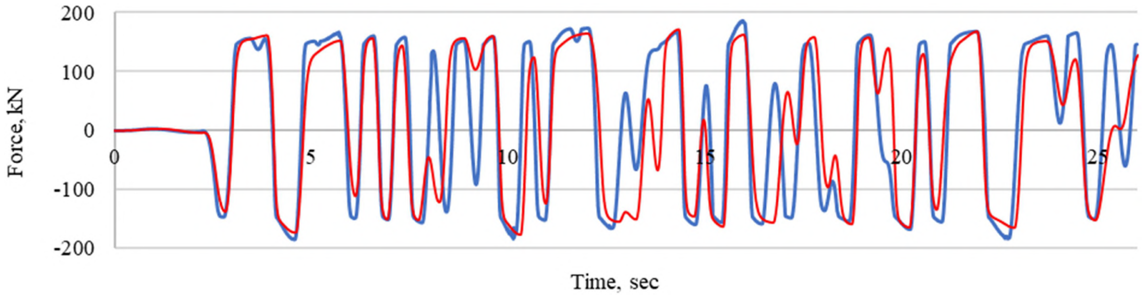
The significant difference between the results of the analytical and numerical models is explained by the peculiarities of schematization of the connections between the boiler and the frame. In the analytical model, elastic and hysteresis connections are at the same level, which is completely different from a real object, where the suspension system is attached to the ceiling (the frame top), and hysteresis dampers is attached to columns at various levels below (starting from the mass center level). Considering the fact that a good agreement of results was obtained for boiler displacements, and in general the mass of the boiler is significantly higher than the mass of the frame, it can be assumed that displacements and accelerations of mass (m1) modeling the frame correspond to the values at the level of the center of mass of the

Table 2. Comparison of calculation results for 2DOF-model.

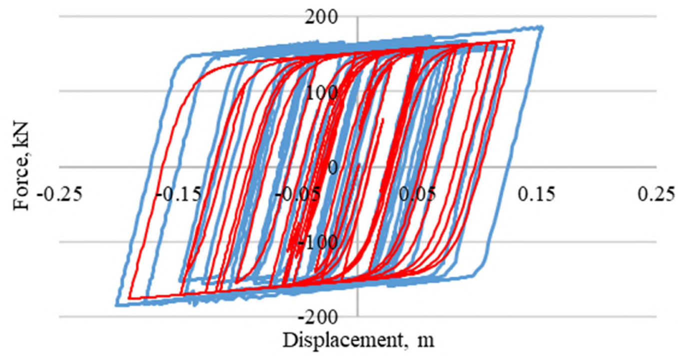
Spectrum type																				
№1			№2			№3			№4			№5			№6			№7		
CAE	2DOF	Δ, %	CAE	2DOF	Δ, %	CAE	2DOF	Δ, %	CAE	2DOF	Δ, %	CAE	2DOF	Δ, %	CAE	2DOF	Δ, %	CAE	2DOF	Δ, %
1 bracing level (level of the boiler mass center)																				
Maximum force in damper, kN (res. 1)																				
180	176	**–2.2**	175	173	**–1.1**	186	177	**–4.8**	179	173	**–3.4**	175	172	**–1.7**	179	178	**–0.6**	180	176	**–2.2**
Maximum displacement of the frame top, m (res. 2)																				
0.061	0.044	**–27.2**	0.039	0.026	**–33.4**	0.092	0.044	**–52.0**	0.056	0.041	**–26.8**	0.035	0.024	**–31.6**	0.054	0.034	**–37.5**	0.061	0.042	**–31.1**
Maximum boiler displacement, m (res. 3)																				
0.337	0.331	**–1.8**	0.061	0.063	**+3.5**	0.202	0.200	**–1.0**	0.159	0.167	**+5.0**	0.062	0.060	**–3.5**	0.098	0.098	**–0.2**	0.114	0.117	**+2.3**
Maximum acceleration of the frame top, m/sec^2 (res. 4)																				
4.06	2.59	**–36.2**	2.60	1.58	**–39.2**	6.13	3.78	**–38.3**	4.52	3.14	**–30.5**	2.33	1.63	**–30.0**	3.58	2.32	**–35.2**	4.07	2.68	**–34.2**
3 bracing levels (symmetrically relative to the boiler mass center)																				
Maximum force in damper, kN (res. 1)																				
174	170	**–2.4**	195	189	**–2.9**	180	170	**–5.6**	199	189	**–5.0**	195	192	**–1.3**	199	195	**–2.0**	200	193	**–3.6**
Maximum displacement of the frame top, m (res. 2)																				
0.053	0.042	**–21.5**	0.059	0.041	**–30.5**	0.080	0.075	**–6.3**	0.085	0.056	**–34.1**	0.053	0.038	**–27.7**	0.082	0.050	**–38.7**	0.093	0.068	**–27.1**
Maximum boiler displacement, m (res. 3)																				
0.293	0.272	**–7.2**	0.082	0.090	**+9.5**	0.179	0.166	**–7.3**	0.214	0.216	**+0.9**	0.084	0.088	**+5.1**	0.132	0.129	**–2.5**	0.154	0.163	**+5.9**
Maximum acceleration of the frame top, m/sec^2 (res. 4)																				
3.53	2.69	**–23.9**	3.43	2.31	**–32.7**	6.69	3.06	**–54.3**	6.00	3.83	**–36.2**	3.08	2.01	**–34.8**	4.73	3.31	**–29.9**	5.37	3.68	**–31.5**

Table 3. Statistical analysis for errors between 2DOF-model results and CAE results.

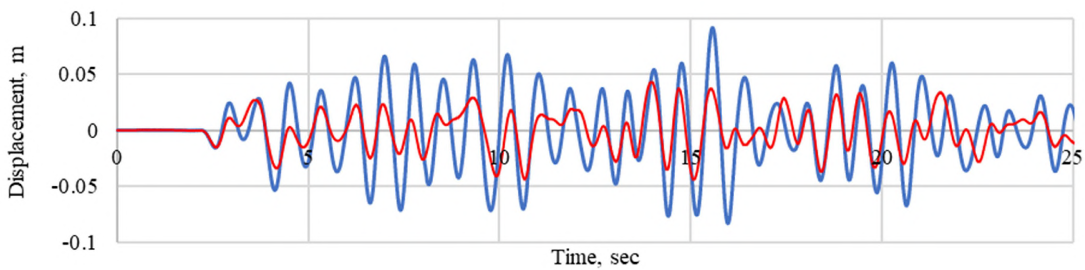
	Spectrum type									
Result	№1	№2	№3	№4	№5	№6	№7	**M**	**SD**	**SEM**
1 bracing level (level of the boiler mass center)										
1	–2.2	–1.1	–4.8	–3.4	–1.7	–0.6	–2.2	**–2.3**	**1.43**	**0.54**
2	–27.2	–33.4	–52.0	–26.8	–31.6	–37.5	–31.1	**–34.3**	**8.71**	**3.29**
3	–1.8	+3.5	–1.0	+5.0	–3.5	–0.2	+2.3	**0.6**	**3.07**	**1.16**
4	–36.2	–39.2	–38.3	–30.5	–30.0	–35.2	–34.2	**–34.8**	**3.55**	**1.34**
3 bracing levels (symmetrically relative to the boiler mass center)										
1	–2.4	–2.9	–5.6	–5.0	–1.3	–2.0	–3.6	**–3.2**	**1.57**	**0.59**
2	–21.5	–30.5	–6.3	–34.1	–27.7	–38.7	–27.1	**–26.6**	**10.48**	**3.96**
3	–7.2	+9.5	–7.3	+0.9	+5.1	–2.5	+5.9	**0.6**	**6.59**	**2.49**
4	–23.9	–32.7	–54.3	–36.2	–34.8	–29.9	–31.5	**–34.7**	**9.48**	**3.58**



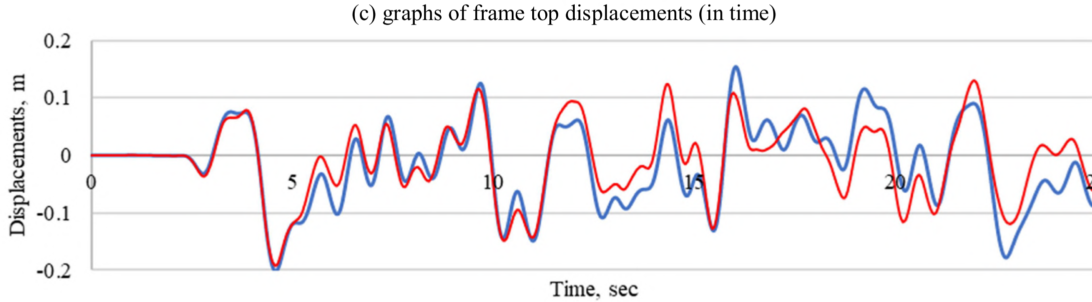
(a) force change graphs in the damper (in time)



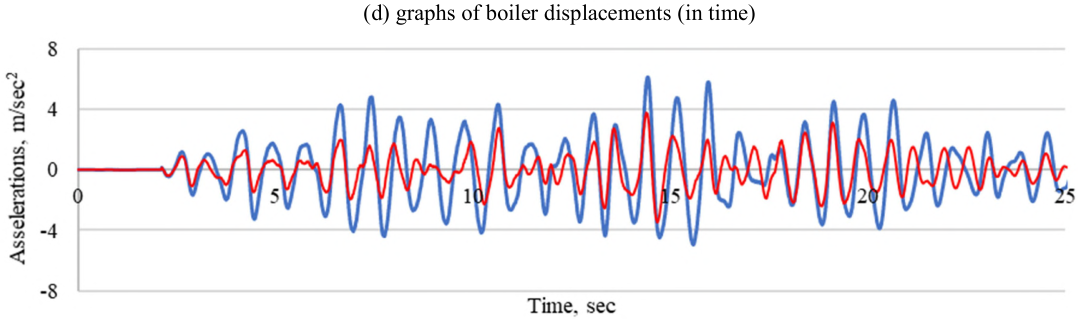
(b) cycles of hysteresis operation of the damper



(c) graphs of frame top displacements (in time)



(d) graphs of boiler displacements (in time)



(e) graphs of frame top accelerations (in time)

ANSYS 2DOF model (MathCAD)

Fig. 12. Graphical comparison of calculation results for 2DOF and numerical models (using the example of calculation No. 3).

Table 4. Additional study of the frame displacements at the level of the boiler mass center.

Spectrum type																				
№1			№2			№3			№4			№5			№6			№7		
CAE	2DOF	Δ, %	CAE	2DOF	Δ, %	CAE	2DOF	Δ, %	CAE	2DOF	Δ, %	CAE	2DOF	Δ, %	CAE	2DOF	Δ, %	CAE	2DOF	Δ, %
1 bracing level (level of the boiler mass center) Maximum displacement of the frame in level of the boiler mass center, m (res. 1)																				
0.053	0.044	–17.0	0.021	0.026	+23.8	0.056	0.044	–21.4	0.032	0.041	+28.1	0.019	0.024	+26.3	0.038	0.034	–10.5	0.056	0.042	–25.0
3 bracing levels (symmetrically relative to the boiler mass center) Maximum displacement of the frame in level of the boiler mass center, m (res. 1)																				
0.048	0.042	–12.5	0.035	0.041	+17.1	0.080	0.075	–6.3	0.050	0.056	+12.0	0.041	0.038	–7.3	0.056	0.050	–10.7	0.059	0.068	+15.3

Table 5. Statistical analysis for errors in additional study.

Result	Spectrum type							M	SD	SEM
	№1	№2	№3	№4	№5	№6	№7			
1 bracing level (boiler center of mass level)										
1	–17.0	+23.8	–21.4	+28.1	+26.3	–10.5	–25.0	**0.6**	**24.26**	**9.17**
3 bracing levels (symmetrically relative to the center of mass of the boiler)										
1	–12.5	+17.1	–6.3	+12.0	–7.3	–10.7	+15.3	**1.1**	**13.07**	**4.94**

boiler. Additionally, an analysis of these values was carried out, recorded in the nodes of the numerical model at the level of the center of mass of the boiler (Tables 4 and 5).

Hypothesis testing has shown that the error between the results of the analytical and numerical models is decreasing, and the average error (M) value is approaching 1%. However, the value of the standard deviation (SD) shows a significant variation in the values obtained, which does not allow using these results in preliminary calculations. The reasons for such a significant variation in the results may lie in the fact that it may be necessary to consider the frame nodes at different levels (not the frame top and not the area of the boiler mass center).

3.3. Results for 3DOF-model

The calculation results of the finite element model (CAE) and the analytical three-mass model (3DOF) are compared in Table 6. Statistical processing of the results (for error (Δ, %) in comparison with the finite element model) is presented in Table 7. Fig. 13 shows a graphical comparison of results using numerical and analytical models for the calculation with the maximum seismic response (as one of the most important regulatory criteria for the overall sustainability of the system) from the series.

Based on the results, the following conclusions were made:

- the hysteresis nature of the damper operation is reproduced qualitatively and quantitatively;
- the pattern of boiler displacements in models is well coordinated;
- the frequency composition of the oscillations for the analytical and numerical models is the same;
- values of displacements and accelerations of the frame overlap, which determine the stability of the system and the forces in the frame structures, have a qualitative and quantitative correspondence;
- the maximum discrepancy between the results does not exceed 12%;
- the average discrepancy between the results of analytical and numerical calculations is less than 5%.

3.4. General conclusions

A normally distributed statistical model can be achieved by examining values of mean and SD data: approximately 68.7% of the observed values are placed within 1SD from the mean, approximately 95.4% of the observed values are arranged within 2SD from the mean, and about 99.7% of the

Table 6. Comparison of calculation results for 3DOF-model.

Spectrum type																				
№1			№2			№3			№4			№5			№6			№7		
CAE	3DOF	Δ, %	CAE	3DOF	Δ, %	CAE	3DOF	Δ, %	CAE	3DOF	Δ, %	CAE	3DOF	Δ, %	CAE	3DOF	Δ, %	CAE	3DOF	Δ, %
1 bracing level (level of the boiler mass center)																				
Maximum force in damper, kN (res. 1)																				
180	178	**–1.1**	175	172	**–1.7**	186	176	**–5.4**	179	173	**–3.4**	175	176	**+0.6**	179	173	**–3.4**	180	175	**–2.8**
Maximum displacement of the frame top, m (res. 2)																				
0.061	0.058	**–4.7**	0.039	0.038	**–2.1**	0.092	0.085	**–7.6**	0.056	0.054	**–3.6**	0.035	0.034	**–3.2**	0.054	0.049	**–8.8**	0.061	0.058	**–4.5**
Maximum boiler displacement, m (res. 3)																				
0.337	0.323	**–4.2**	0.061	0.058	**–4.4**	0.202	0.192	**–5.0**	0.159	0.170	**+6.9**	0.062	0.058	**–6.3**	0.098	0.093	**–5.2**	0.114	0.107	**–6.4**
Maximum acceleration of the frame top, m/sec^2 (res. 4)																				
4.06	3.87	**–4.6**	2.60	2.48	**–4.7**	6.13	6.35	**+3.6**	4.52	4.90	**+8.4**	2.33	2.25	**–3.5**	3.58	3.35	**–6.5**	4.07	3.78	**–7.2**
3 bracing levels (symmetrically relative to the boiler mass center)																				
Maximum force in damper, kN (res. 1)																				
174	172	**–1.3**	195	189	**–2.9**	180	173	**–3.9**	199	181	**–9.0**	195	192	**–1.3**	199	190	**–4.5**	200	189	**–5.6**
Maximum displacement of the frame top, m (res. 2)																				
0.053	0.052	**–1.8**	0.059	0.061	**+2.3**	0.080	0.071	**–11.3**	0.085	0.085	**0.0**	0.053	0.051	**–4.6**	0.082	0.079	**–3.4**	0.091	0.089	**–2.1**
Maximum boiler displacement, m (res. 3)																				
0.293	0.279	**–4.7**	0.082	0.081	**–2.1**	0.179	0.167	**–6.7**	0.214	0.231	**+7.9**	0.084	0.081	**–3.2**	0.132	0.121	**–8.8**	0.154	0.157	**+2.0**
Maximum acceleration of the frame top, m/sec^2 (res. 4)																				
3.53	3.38	**–4.2**	3.43	3.28	**–4.4**	6.69	6.28	**–6.1**	6.00	6.44	**+7.3**	3.08	2.88	**–6.3**	4.73	4.84	**+2.4**	5.37	5.03	**–6.4**

Table 7. Statistical analysis for errors between 3DOF-model results and CAE results.

Result	Spectrum type									
	№1	№2	№3	№4	№5	№6	№7	**M**	**SD**	**SEM**
1 bracing level (level of boiler mass center)										
1	–1.1	–1.7	–5.4	–3.4	+0.6	–3.4	–2.8	**–2.4**	**1.90**	**0.72**
2	–4.7	–2.1	–7.6	–3.6	–3.2	–8.8	–4.5	**–4.9**	**2.42**	**0.92**
3	–4.2	–4.4	–5.0	+6.9	–6.3	–5.2	–6.4	**–3.5**	**4.67**	**1.77**
4	–4.6	–4.7	+3.6	+8.4	–3.5	–6.5	–7.2	**–2.1**	**5.82**	**2.20**
3 bracing levels (symmetrically relative to the boiler mass center)										
1	–1.3	–2.9	–3.9	–9.0	–1.3	–4.5	–5.6	**–4.1**	**2.71**	**1.02**
2	–1.8	+2.3	–11.3	0.0	–4.6	–3.4	–2.1	**–3.0**	**4.28**	**1.62**
3	–4.7	–2.1	–6.7	+7.9	–3.2	–8.8	+2.0	**–2.2**	**5.65**	**2.13**
4	–4.2	–4.4	–6.1	+7.3	–6.3	+2.4	–6.4	**–2.5**	**5.33**	**2.01**

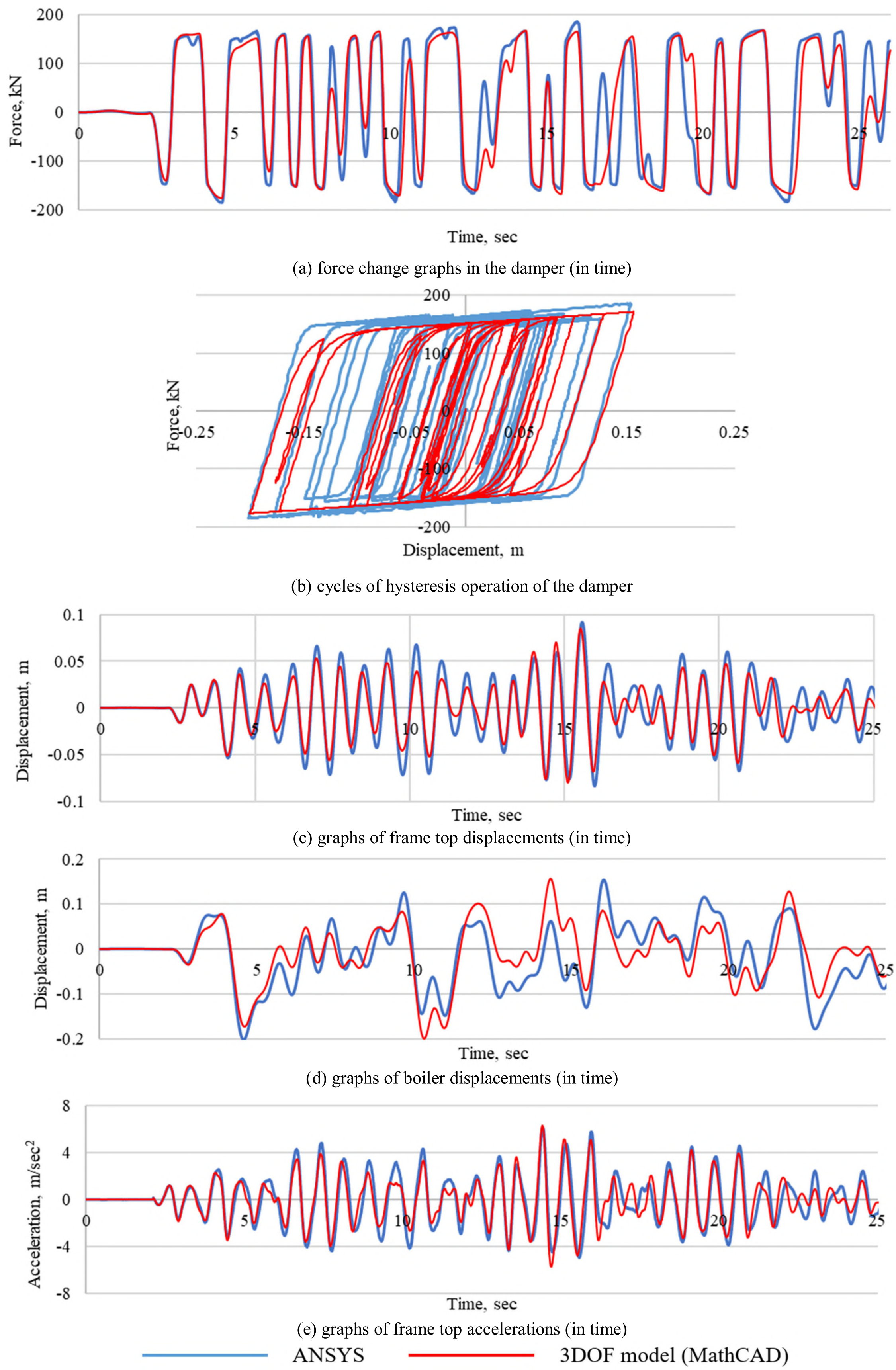


Fig. 13. Graphical comparison of calculation results for 3DOF and numerical models (using the example of calculation No. 3).

Table 8. 95% confidence intervals for analytical model errors.

2DOF model		3DOF model	
M – 1.96·SEM	M + 1.96·SEM	M – 1.96·SEM	M + 1.96·SEM
1 bracing level (level of the boiler mass center)			
Maximum force in damper, kN			
–3.4%	–1.2%	–3.9%	–1.0%
Maximum displacement of the frame top, m			
–40.7%	–27.8%	–6.7%	–3.1%
Maximum boiler displacement, m			
–1.7%	+2.9%	–7.0%	0.0%
Maximum acceleration of the frame top, m/sec^2			
–37.4%	–32.2%	–6.4%	+2.2%
3 bracing levels (symmetrically relative to the boiler mass center)			
Maximum force in damper, kN			
–4.4%	–2.1%	–6.1%	–2.1%
Maximum displacement of the frame top, m			
–34.3%	–18.8%	–6.2%	+0.2%
Maximum boiler displacement, m			
–4.2%	+5.5%	–6.4%	+2.0
Maximum acceleration of the frame top, m/sec^2			
–41.8%	–27.7%	–6.5%	+1.4%

observed values are positioned within 3SDs from the mean [31]. As we can see from obtained results (Tables 2 and 6), differences between all quantities (accelerations, displacements) calculated according to analytical models and finite element models have a normal distribution.

A confidence interval is set to illustrate the value mean intuitively and is determined from the SEM. A 95% confidence interval is the most common [31]. It's calculated as (M – 1.96·SEM) for left border of the confidence interval, (M + 1.96·SEM) for right border of the confidence interval.

According to the calculation results (Tables 3 and 5), 95% confidence intervals for error of analytical models are shown in the Table 8.

The main conclusions that can be drawn from the analysis of calculations of analytical and numerical models:

- both models reproduce the nature of the operation of the "frame-boiler" system qualitatively;
- 2DOF model has a lower quantification of results than 3DOF model;
- in most cases, analytical models show values of calculated values (displacements, accelerations) lower than in finite element models;
- in 95% of cases, when using the 3DOF model, the maximum discrepancy with the results of the numerical model will be less than 7%;
- in 95% of cases, when using the 2DOF model, the results for the frame top will differ by up to 42% from the numerical model.

Researches by Aida, Nishida et al. [16], where a dual-mass approximation of the "frame-boiler" system with elastic bonds was proposed for the first time, does not contain a statistical analysis of the calculation results for a two-mass model and a multi-mass model. The graphical data indicate a difference in the results for frame elements of less than 11%, for elastic bonds - less than 7%. With the complication of the two-mass model (the introduction of additional hysteresis coupling), there is a significant decrease in the accuracy of the calculation. This is shown in the present work. 2DOF model provides results that differ significantly from the numerical model. Considering the additional study in Section 3-2, it can be assumed that a high level of result agreement can be observed for the unexplored levels of the frame height. However, there is no information in the regulatory documentation on the permissible displacements and accelerations even for the level of the boiler mass center, which was additionally accepted for consideration. The main normative indicators are given for the upper level of the framework, for which the results of the analytical and numerical models differ too much. This means that the model cannot be used in engineering practice.

Given the low level of inconsistency between the results of the 3DOF model and the numerical model, it can be recommended for preliminary calculations of the frame-boiler system (when searching for optimal damper parameters, estimating overall deformability, etc.). Such an analytical model does not require large time and computational resources, which is its main advantage.

Conflict of interest

The authors declare that they have no conflict of interest.

Data availability statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

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Author contribution

Anushchenko Aleksandr Mikhailovich developed the basic concept, prepared finite element models, performed calculations, wrote systems of differential equations, performed programming for solving systems of differential equations, analyzed the results, and prepared the text of the article.

Bondarev Dmitrii Evgenievich developed the basic concept, assisted in programming the algorithm for calculating the system of differential equations, edited the text of the article.

Schukin Aleksandr Yurievich developed the basic concept, edited the text of the article.

Ethics

There are no ethical issues with the publication of this manuscript.

Use of AI for writing assistance

Not declared.

Peer-review

Externally peer-reviewed.

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