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MAKING USE OF THE PRINCIPLE OF ENERGY DISSIPATION IN THE SEISMIC DESIGN OF A STEEL STRUCTURE OF A STEAM BOILER

VYUŽITÍ PRINCIPU DISIPACE PŘI SEISMICKÉM NÁVRHU OCELOVÉ KONSTRUKCE PARNÍHO KOTLE

Abstract

For structural design of steel structures under seismic action there are two possible approaches of global analysis. In global analysis we can consider the structure to behave in linear elastic way or in post-elastic way with developing of plastic hinges during seismic situation. The second method is based on principle of seismic energy transformation into thermal energy. Both design methods are defined in Eurocodes but the post-elastic way is only rarely used because of design complexity. Application of this design method is presented in the entry on an example of a steam power plant boiler structure.

Keywords

Seismicity, earthquake, energy dissipation, critical zones, ductility, behaviour factor.

Abstrakt

Při návrhu nosné konstrukce vystavené účinkům zemětřesení je možné analyzovat konstrukci pomocí lineárně jako lineárně pružnou nebo jako konstrukci s plastickými klouby, které se rozvinou během seismické situace. Oba způsoby analýzy konstrukcí jsou definovány v evropských normách navrhování, ovšem druhý způsob vycházející z principu přeměny seismické energie v teplo v plastických kloubech je z důvodu náročnosti průkazu bezpečnosti, využíván minimálně. Aplikace principů toho přístupu je prezentována v příspěvku na příkladu konstrukce parního elektrárenského kotle.

Klíčová slova

Seismicita, zemětřesení, disipace energie, disipativní zóna., duktilita, součinitel duktility.

1 INTRODUCTION

Designing structures exposed to seismic action involves a lot of aspects that need to be taken into account. It is essential to ensure a specified level of design reliability in the course of its projected lifetime. It is necessary to take into account the fact that any precisely made mathematical global analysis of the structure is burdened with a certain level of uncertainty resulting from an inaccurate estimate of the size and types causing the earthquakes, as well as uncertainties resulting from simplification of the real structure on a dynamic model. One also needs to keep in mind that

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when designing dynamically loaded structures, strengthening the structure does not need to lead to a safer design.

The analysis of the structure dimensioned for earthquake effects can be carried out as a linear elastic analysis. The second option is a dimensioned structure that corresponds to seismic excitation in a post-elastic way. This option is called a dissipative concept, because it assumes that the earthquake energy acting on the structure can be dissipated in plastic hinges, which means converted into heat during the plasticization of projected areas (further reffered to as "critical zones"). The design of dissipative structures, however, adds to the above-mentioned uncertainties others resulting from statistical straggling of the value of yield point of applied elements and the change in dynamic behaviour of non-linear structures. Application of this concept will be further presented on the design of a dissipative structure of a steam boiler. Furthermore, the results of a study on efficiency of the dissipative concept compared to a “classic” elastic concept will be presented, outlining the problematic aspects of the method.

2 THEORETICAL BACKGROUND OF SOLVING THE SEISMIC DESIGN OF STRUCTURES

Earth's crust is formed by earth plates moving towards each other. The individual plates prevent each other from moving by friction-induced forces in the area of their mutual contact. Seismic impulse originates by a sudden release of accumulated energy of internal forces at the edge of one of the earth plates. Such energy then spreads through the earth massif in the form of different types of waves [1]. Seismic actions on structures can thus be considered as steady harmonic excitation in construction support. Seismic load for a specific construction is stated by the value of reference ground acceleration, which is specified in seismic maps and corresponds to the size of the earthquake with a return period of 475 years.

Nowadays, the most common way of analysis of structures exposed to seismicity is an elastic response spectrum method of the ground for the construction site with the harmonic analysis of a structure with the development to its natural shapes. This method converts the reference acceleration of the ground to a spectrum of several accelerations operating with an oscillation period close to zero, until the period of oscillation equals to 4 seconds. This method allows to take into account the influence of dampening by internal dampening of the construction, and combines effects of natural multiple shapes of oscillation.

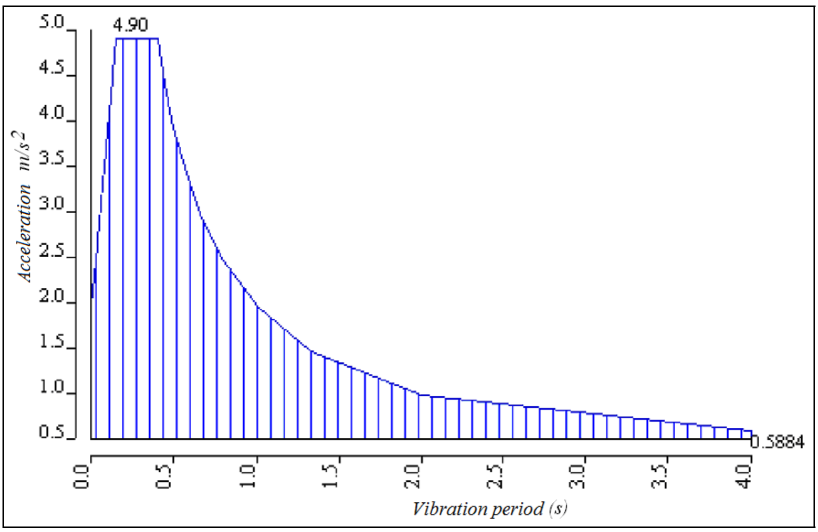

Fig. 1: The design of elastic response spectrum of the ground used for the analysed structures – non-dissipative variations

3 THEORETICAL BACKGROUND OF DISSIPATIVE DESIGN OF STRUCTURES

Dissipative design is based on application of the principles of plasticity theory, the principles of the second law of thermodynamics and theoretical work of I. Prigogine [2] and H. Ziegler [3]. Exceeding the value of yield stress of the material in certain details leads to irreversible thermodynamic phenomenon - the energy of external forces is converted into heat, the entropy of the system increases, and - in accordance with the dynamic material model – this leads to changes in the structure of the material.

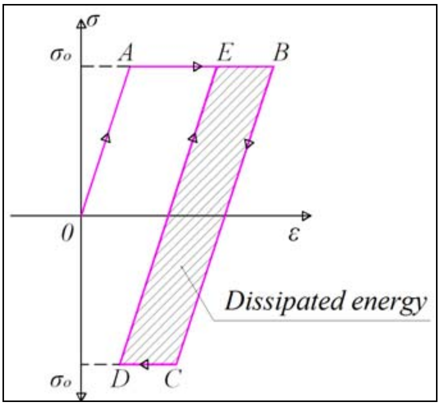

Fig. 2: Stress-strain diagram of steel in critical zones of the structures [4]

N.M. Newmark [4] demonstrated that the structure which remains elastic has approximately the same final demonstration as the structure with the development of plastic zones occuring. This finding shows that the dissipative structure can be designed using the linear elastic analysis.

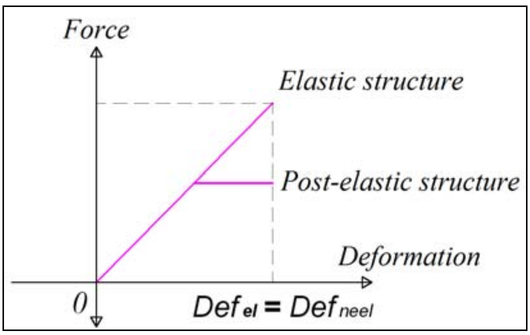

Fig. 3: The principle of identical deformations [4]

The potential of a structure to dissipate energy is expressed by a behaviour factor. In other words, the behaviour factor quantifies the level of construction reserve as a whole in the post-elastic area. This factor is determined by the designer according to expected energy dissipation in critical zones and the level of static redundancy of the structure. The behaviour factor may reach the values from one to six or more in compliance with EN standards [6]. The earthquake force effects on the structures and the effects of the structures on the bottom of the construction are divided by this number, so it is a factor which affects the final design to a great extent.

The core of the dissipative structure design is the distribution of critical zones in the structure in a way that the development of plastic deformation in all zones occurs evenly. Critical zones are to be evenly distributed along the height and the ground plan in order not to change their regularity or symmetry because of plasticization. They can be designed into the elements of frame cross beams, bracing or connections of these elements to other structures.

4 DESCRIPTION OF THE EXAMINED CONSTRUCTION TYPE

Application of dissipative design concept will be presented on an example of a supporting steel structure of a plant vertical heat recovery steam generator (further referred to as “vertical boiler”). The basic purpose of a steam boiler is to convert water into steam needed for steam turbines.

Vertical boilers are formed by a boiler casing used to conduct flue gas from the combustion turbine to the stack. Inside the casing, i.e. in the area where the flue gas flows, there are piping systems, inside which there is water heating, evaporating and overheating of output steam going on. The combustion pipe and piping system are hung on the supporting structure of the ceiling and dilate downwards. The boiler coating is attached to the supporting structure via a sliding vertical line, which ensures the position of the boiler and transfers horizontal forces to the ground.

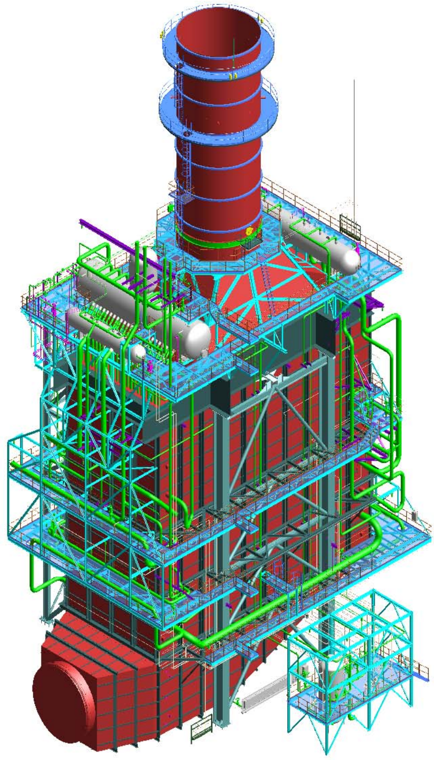

Fig. 4: 3D view of the model of vertical boiler in PDMS programme (project Krasnodar, Russia)

The supporting structure of a vertical boiler consists of a spatial frame on one side of the boiler, a plane frame on the other side of the boiler and ceiling beams. The ceiling beams ensure the position of a plane frame and the whole boiler is hung on them (meaning both the casing and all the piping systems). Most of the static burden is transmitted to the ceiling by ceiling beams and operates in the head of the columns. In terms of dynamic action, the mass in the construction is concentrated mainly in piping systems. Pipeline bundles (further referred to as "modules") are hung to each other and everything is suspended over the topmost module in the ceiling beams. Sliding vertical guiding of modules is on several levels but not at the level of each single module. Examining the dynamic behaviour of the entire piping system will be the subject of further scientific work. For the purposes of this study the mass was divided in a conservative way into the guiding points.

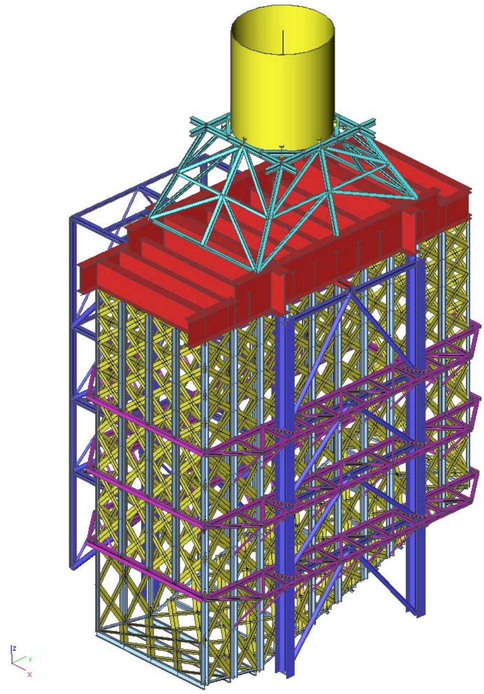

Fig. 5: 3D view of the static model of the vertical boiler in SCIA programme (project Krasnodar, Russia)

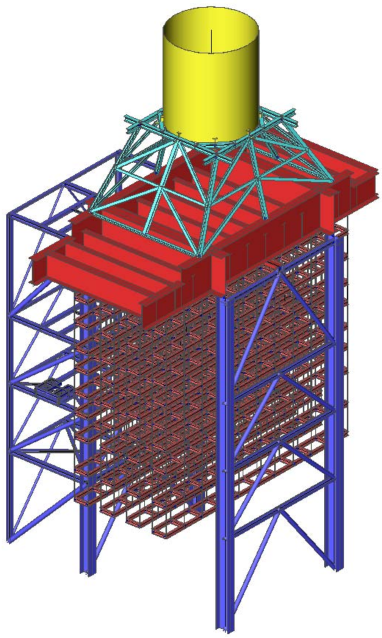

Fig. 6: 3D view of the static model of the vertical boiler in SCIA programme - simulation of pipe bundles hanging (project Krasnodar, Russia)

5 DISSIPATIVE CONSTRUCTION DESIGN OF A VERTICAL BOILER

The transfer of horizontal forces in structures of vertical boilers is ensured by vertical bracing of columns in the shape of an "A" and the flexural rigidity of the columns. Crtitical zones in this type of design can be solved by compression diagonals of bracing, bending of frame cross beams or in seismic elements of eccentric bracing. For further work we have chosen a variant with vertical seismic elements. Their advantage is that after a seismic event, they can be easily removed and replaced by new elements.

To determine the value of the behaviour factor it was necessary to rank the construction into a corresponding ductility class according to EN 1998 standards [6]. The choice of a ductility class depends on the classes of cross-sections used for primary seismic elements, as classified by EN 1993-1-1 standards [7]. The dimension of profiles determined at boiler designs on the effects of static loads are usually class 1 and 2, so the structure was included in the ductility class M with the maximum value of the behaviour factor 4. Structures of vertical boilers generally does not meet the criteria of regularity defined by EN 1998 standards[6], therefore it is not appropriate to use the maximum allowable values listed in table 1. The value of a behaviour factor for a dissipative structural design of vertical boiler was set to 3.2.

Tab. 1: Limitation of classes of a section according to the ductility class of a structure

Ductility class	Concept of designing	Maximum class of a section	Maximum behaviour factor
L - low	non-dissipative	4	1,5
M - medium	dissipative	3	2
	dissipative	2	4
H - high	dissipative	1	> 4

6 COMPARISON OF DISSIPATIVE AND NON-DISSIPATIVE STRUCTURAL DESIGN

For the purpose of this study we examined the structure of a vertical boiler implemented by Babcock Borsig Steinmüller CZ, Ltd. (further referred to as "BBS") in 2011 in Krasnodar, Russia. The structure was designed as non-dissipative on seismicity effects defined by reference acceleration of the ground of 0.2 g, magnified by an importance factor of the structure to 0.3 g. From the spatial structure, which is depicted in pictures 5 and 6, there was a 2D structure isolated, bearing half of the ceiling, which is half of the determinative boiler load. Simplifying the complete solution to a limited part led to reduction of labour-intensity and increased the predictive value of the final weight comparison of both variants. Random effects of the torsion of structure as a whole will be taken into account by increasing the internal forces in accordance with EN 1998 standards [6]. The dissipation factor of a non-dissipative structure was determined in accordance with EN 1998 standards [6] to 1.5.

The structural design carried out through dissipative concept requested several conceptual changes of the static model. In a non-dissipative option, all frame cross beam connections to columns were modelled as hinged, neglecting rotational toughness of joints. At dissipative design, it was necessary to increase the redundancy of the structure, so the hinged connections of frames were replaced by flexural-rigid connections. Another major change was the insertion of seismic elements between vertical bracing joints and frame cross beams. With regard to the practical aspects of easy dismantling, short vertical seismic articles of different lengths were chosen. The length was chosen in order to meet the requirement of the even overloading of all critical zones, with the maximum overload factor of the most loaded article from the least loaded article differing by not more than 25%.

The dynamic analysis of structures in both variants was performed in the programme Scia Engineer 2011.1 for the first ten natural frequencies of the structure. To calculate the eigenmodes, the subspace iteration method was chosen. The effects of eigenmodes were combined using the complete quadratic combination, considering the dumping decrement 0.05 specified for the entire spectrum of natural frequencies. Changing the dampening characteristics in the plastic hinges of the dissipative structure was neglected and its exact determination will be the subject of further work. Given that the amount of mass in the individual eigenmodes exceeded 99% in both directions examined, only the participating mass was considered in the calculation.

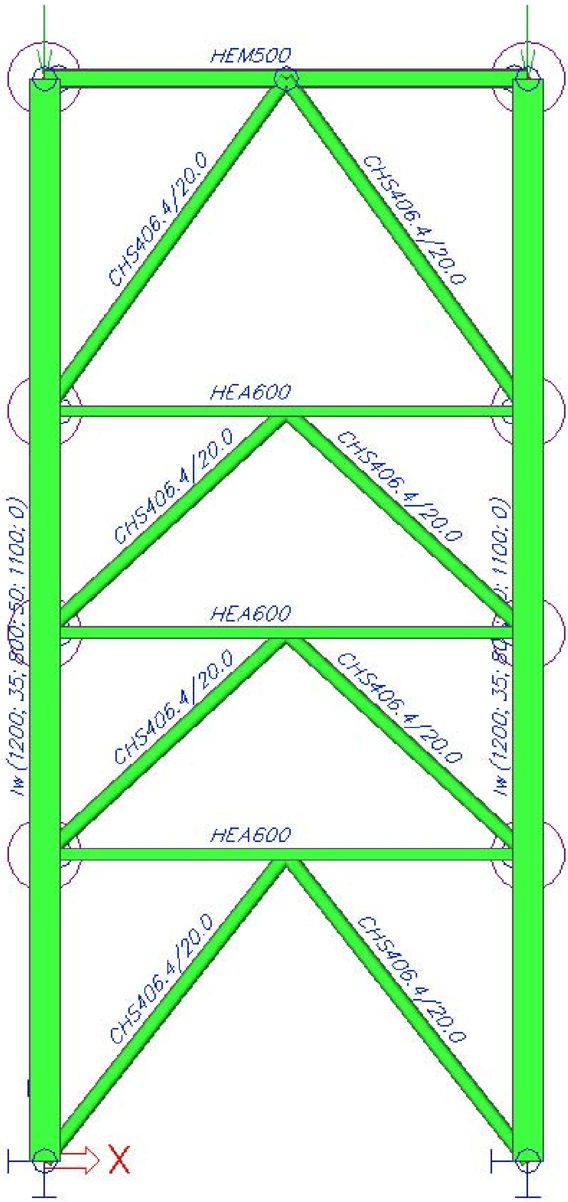

Fig. 7: 3D view of the static model of a structural segment of a vertical boiler in the programme SCIA – non-dissipative design (distribution of acting loads and mass shown symbolically).

Determinative natural frequency of non-dissipative structure was 1.074 Hz for X direction and 0.637 Hz for Y direction. The stated frequencies corresponded to a simple natural shape with one wave.

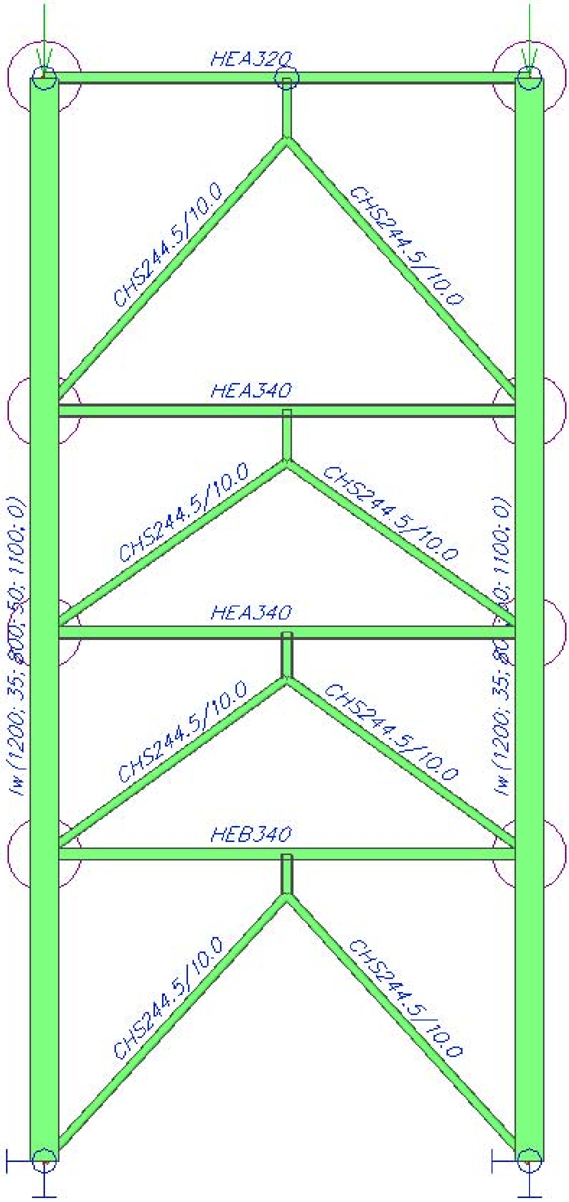

Fig. 8: 3D view of the static model of structural segment of a vertical boiler in SCIA programme - dissipative design distribution of acting loads and mass shown symbolically).

The crucial natural frequency of the dissipative structure was 0.299 Hz for X direction and 0.639 Hz for the direction Y. The stated frequencies corresponded to a natural simple shape with one wave.

Designing of dimensions of dissipative articles was carried out on the effects of the earthquake reduced by dividing the behaviour factor. Connections of articles, frame cross beams and columns were verified by a capacity design. It was necessary to prove that the elements attached to the articles safely resist to forces equal to plastic resistance of articles magnified by factors expressing the statistical struggling of the yield point of the material. Another verification was to demonstrate that all elements outside the critical zones securely transmit force effects resulting from a special combination:

$$R_{dJ} \geq \gamma * \frac{R_{dI}}{E_{dI}} * E_{dJ} + S_{dJ,G} \quad (1)$$

where:

R_{dJ} – resistence of element outside the critical zones (N, M, V)

γ – safety factor

R_{dI} – seismic resistance of the article (N, M, V)

E_{dI} – loading effect in an article caused by seismic loads (N, M, V)

E_{dJ} – loading effect in the elements outside the critical zones caused by seismic loads (N, M, V)

$S_{dJ,G}$ – loading effects from non-seismic loading cases, which occur in the seismic combination in the elements outside the critical zones (N, M, V)

7 COMPARISON OF DISSIPATIVE AND NON-DISSIPATIVE STRUCTURES FROM THE ECONOMICAL POINT OF VIEW

The difference in the dimensions of the examined variants was observed mainly in the stiffening system of the structures and the dimensions of frame cross beams. The weight proportion of each type of the structure from the total structure of a vertical boiler and the difference of the weight fractions are summarized in the following table.

Tab. 2: The structural weights specified for the model variants (kg)

Type of structure	Columns	Frame cross beams	Articles	Bracing	Total
Non-dissipative structure	54511	10544	0	15058	80113
Dissipative structure	54511	5789	593	4127	65020

Tab. 3: Percentage distribution of weight structures budgeted for the entire construction project of a vertical boiler Krasnodar (%)

Type of structure	Columns	Frame cross beams	Articles	Bracing	Boiler ceiling	Total
Non-dissipative structure	31.3	6.4	0	6.1	53.4	100
Dissipative structure	31.3	3.5 – 6.4	1	1.7 - 4	53.4	93.7–98.9

Tab. 4: Structural response to the foundation of the structure (kN)

Type of structure	R_x	R_y	R_z	M_x	M_y	M_z
Non-dissipative structure	3449	715	24915	0	0	0
Dissipative structure	1545	345	14078	0	0	0

8 CONCLUSION

Designing dissipative structures leads to more economical designing of structures. In case of the supporting structure of a vertical steam boiler, the dissipative designing concept leads to savings in the design worth percents. Savings can be expected in the design of cross-sections of vertical bracing and frame cross beams. Significant savings can also be achieved when designing foundation, since at dissipative design, the effects of structure on the foundation are inversely proportionally smaller than the values obtained at non-dissipative design, in relation to the used behaviour factor.

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