

NUMERICAL AND EXPERIMENTAL STRENGTH ANALYSIS OF FIRE-TUBE BOILER CONSTRUCTION

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Preliminary notes

Norms, such as EN 12952-3 and EN 12953-3 handle the issues concerned with calculation of the pressurized boiler components, not however considering the influences of thermal strains that are often of vital importance for the integrity of boiler's construction. Application of FEM in boiler design in EN is suggested in calculating all components that are not covered by the norm. In this way, the calculation of thermal stress is left to the free will of designer and technical inspectorate which supervises and approves placement of a boiler into operation. This paper demonstrates that the influence of thermal stresses is great and that it must be taken into consideration when the boiler's construction is designed and its working life evaluated. It is shown that for every construction a numerical-experimental behaviour diagnostics should be conducted prior to putting it into operation. First, a numerical model must be experimentally verified and then it can be used in considering different parameters of strength diagnostics, such as distribution of membrane and bending stresses for substructures, and distribution of deformation energy. They indicate, in an optimal way, root causes of insufficiently good behaviour of the construction. Also, a dynamical calculation of natural oscillations should always be suggested.

Keywords: *deformation energy, experiment, finite element analysis, steam-boiler, stress, temperature*

Numerička i eksperimentalna analiza čvrstoće konstrukcije plameno-dimnocijevnog kotla

Prethodno priopćenje

Norme kao što su EN 12952-3 i EN 12953-3 obrađuju problematiku proračuna tlačnog dijela kotla, ali bez mehaničkoga utjecaja toplinskih deformacija koje su često puta od vitalnog značaja za integritet kotlovske konstrukcije. Primjena MKE kod projektiranja kotlova u EN se predlaže kod proračuna svih komponenti koje norma ne pokriva. Na ovaj način se proračun utjecaja toplinskih naprezanja ostavlja na slobodnu volju projektanta i tehničkog inspektorata koji nadzire i odobrava stavljanje kotla u rad. U ovom je radu pokazano da je utjecaj toplinskih naprezanja velik i da se mora uzeti u obzir pri projektiranju i procjeni vijeka trajanja kotlovske konstrukcije. Pokazano je da je za konstrukciju kotla najbolje, prije puštanja u rad, izraditi numeričko eksperimentalnu dijagnostiku. Prvo se eksperimentalno mora potvrditi numerički model, a zatim se on može koristiti za razmatranje različitih parametara dijagnostike čvrstoće kao što su raspodjela membranskih i savojnih naprezanja po podstrukturama i raspodjela energije deformiranja. Oni najbolje ukazuju na uzroke nedovoljno dobrog ponašanja konstrukcije. Također se predlaže uvijek izrada dinamičkog proračuna vlastite frekvencije vibriranja.

Ključne riječi: *analiza metodom konačnih elemenata, eksperiment, energija deformiranja, naprezanje, parni kotao, temperatura*

1 Introduction Uvod

Pressures and increased temperatures to which boiler components are exposed initiate deformations and stresses that can lead to a construction break down. So, strength calculations for most reliable boiler elements are standardized and subject to supervising inspection control. Norms such as EN 12952-3 and EN 12953-3 [1] state the allowed stresses for a given temperature and bring explicit formulas for strength calculation through determining wall thickness for pressurized elements, but do not explicitly consider the influence of thermal stresses, local concentrations of stresses and load changes.

Numerical analysis is increasingly applied in diagnosing boiler construction strength. The finite element model of the overall shell and tube waste heat recovery boiler is presented in paper [2]. The simplification of models, stress calculation of smoke tubes for boilers in elastic-plastic analysis by FEM and reforming suggestion are provided in [3]. The cause and prevention of boiler tube plate cracks are presented in [4] and [5]. Fracture mechanics study of the fire tube and the outer shell of a boiler can be obtained from a special fracture mechanics finite element program as presented in [6]. In the design of boiler components, the influence of the temperature loading does not have appropriate consideration. Temperature dilatations of some components of a steam boiler can lead to great plastic deformations [7] and to increasing of dynamic strength. Influence of fire tube geometry on behaviour of steam boiler of lower capacity [8] was examined by Gaćeša

B. In [9] a diagnostic procedure for behaviour of hot water generator is demonstrated due to previous construction compliance during the course of cold testing procedure. It was shown that calculation based on norms is not sufficiently reliable. Improvement of steam boiler plant efficiency based on results of on-line performance monitoring is provided in [10] and the application of a fuzzy logic in boiler control in [11]. Numerical analysis of strength uses FEM, analysis of calculation results and determination of the behaviour parameters. Experimental analysis encompasses the measurement of input quantities for numerical calculation and evaluation of calculation results [12].

In this paper a complete numerical-experimental strength analysis of fire-tube boiler is shown. Numerical analysis for pressure and temperature load is conducted using software package KOMIPS [13]. In the paper it is shown that the influence of thermal boiler loads is great and that it must be taken into consideration in designing and estimating operation life of boiler construction. It is shown that the best procedure for each construction is to perform numerical-experimental behaviour diagnostics. First, a numerical model must be experimentally verified after which it can be used in considering different parameters of strength diagnostics such as distribution of membrane and bending stresses and distribution of deformation energy. They indicate in a best way root causes of insufficient behaviour of construction. Also, a dynamical calculation of eigen oscillations is suggested.

A hot water flame-tube boiler (constructed strictly in accordance with norms) has been experimentally examined in boiler factory KIRKA-Suri by being fired with thatch up

to a pressure of 3 bar. A calculation model is created to simulate the behaviour of the boiler in testing conditions. Statics calculation is performed for pressure and thermal load. Model verification results have shown that the developed calculation approach that is based on FEM is capable of predicting the behaviour of boiler construction in realistic load conditions. Parameters for strength diagnostics have pointed out the causes of inadequate construction behaviour. Dynamical calculation of boiler natural oscillations has confirmed the identified static behaviour.

2 Experiment description

Opis eksperimenta

A boiler that was thermally uninsulated was filled with water and fired up with bundles of thatch. Around 10 min after the start of the experiment the boiler pressure reached 2,3 bar after which measurement of physical quantities was initiated. Measurements of boiler water pressure, outlet and inlet water temperature, temperatures of metal on selected points of boiler construction as well as deformations and stresses in one point of rear head have been conducted. After 25 min from the beginning of the experiment, another group of measurements was taken with boiler pressure being at 2,5 bar. Third group of measurements was taken after 40 min with the boiler pressure being 2,8 bar, while the fourth group of measurements was taken after 55 min when the pressure reached 3 bar.

Measurement of boiler pressure was performed with burden tube manometer, while the measurements of inlet and outlet temperature were taken with boiler thermometers that were already installed within the boiler's fine pipe fitting. Measurements of construction temperatures were taken by a non-contact laser device.



Figure 1 Measurement points along the boiler rear head
Slika 1. Mjerna mjesta na stražnjem dancu kotla

Temperature of the metal was measured in multiple points of construction that were accessible to placement of measurements, especially in the rear head (Fig. 1) and in boiler shell in which the temperature measurements were taken aside shell length and height. Deformations were measured between the bottom most edge anchor and the one above it.

Tab. 1 lists the measured values of boiler pressure (p), inlet water temperature (ϑ_{in}) and outlet water temperature (ϑ_o) as a function of time.

Stress measurements were performed using strain-gage method. On 50 mm below the lowest edge anchor of rear



Figure 2 Part of measurement equipment
Slika 2. Dio mjerne opreme

Table 1 Experimental measurements and FEM models
Tabela 1. Eksperimentalna mjerenja i FEM modeli

Time / min	p / bar	ϑ_{in} / °C	ϑ_o / °C	FEM model
10	2,3	38	60	M1
25	2,5	45	72	M2
40	2,8	60	87	M3
55	3,0	68	85	M4

head, an active strain-gage was applied in vertical direction along with foil to the cleaned metal surface. Since active and passive gages were subjected to the same load conditions, thermal strains were compensated for, so that the deformations measured were due to pressure alone. Measurement equipment has analog-digital (AD) converter and a USB communication signals to a computer.

3 Numerical analysis by finite element method

Numerička analiza metodom konačnih elemenata

3.1 Calculation model geometry

Geometrija proračunskog modela

Fig. 3 shows two projections of boiler model together with measurement points of temperatures T1-T12. Flue gas recirculation from fire tube to smoke tubes in the second pass is performed in the back chamber which is placed within boiler. Recirculation of flue gases into the tubes of third pass is performed in the front chamber. The geometry of the entire boiler supporting structure is obtained by means of addition of three substructures: A – fire tube (A1) with back recirculation chamber (A2) and inspection orifice (A3); B – boiler shell, composed of housing (B1), back (B2) and front (B3) head with front recirculation chamber (B4) and lugs (B5); C – smoke tubes (C1) and anchors (C2) with fictional beams. Substructures A and B represent the supporting elements of the construction which are loaded thermally and by surface pressure, so they are discretized using the shell elements. Substructure C presents support elements shaped as tubes and bars and is discretized with the beam finite elements. This greatly reduced the number of model elements and points thereby reducing total calculation time.

Several different meshes are analyzed and typical mesh with its substructures is shown in Fig. 4. Due to the symmetry, the model represents only one half of the actual construction. It is composed of 2873 nodes that describe 2677 plates and 507 beam elements.

In order to compare the stress and strain calculation results obtained by FEM with the measured values obtained experimentally, four options of computational model have been created (M1 to M4) for four different boiler pressures and water temperatures on inlet and outlet fittings in

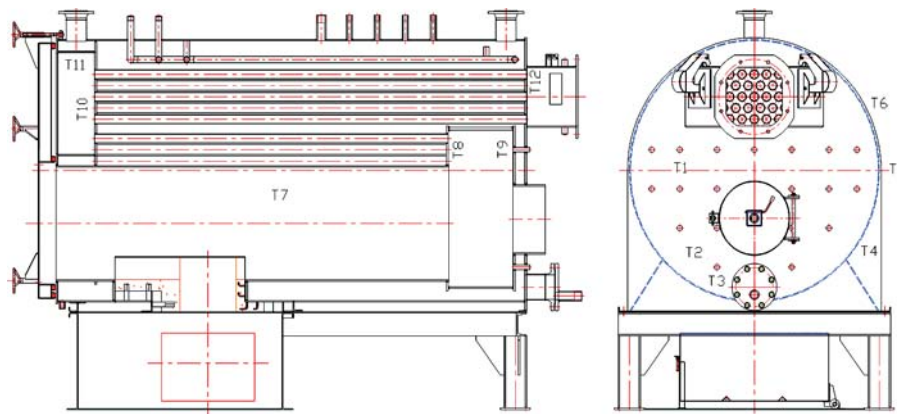


Figure 3 Geometric model of the boiler with measurement points of temperatures on construction elements that need to be defined for a FEM model
Slika 3. Geometrijski model kotla i točke mjerenja temperature elemenata konstrukcije koje treba definirati za proračun MKE

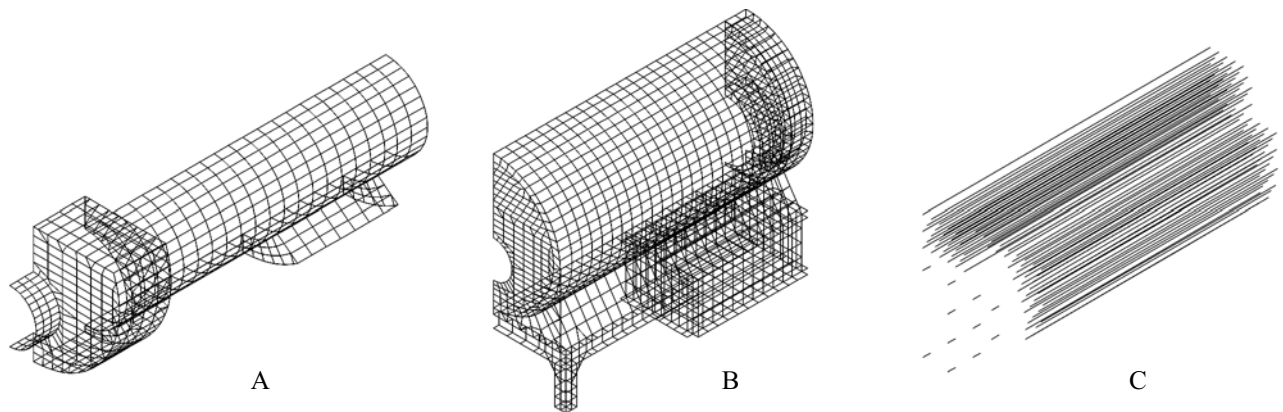


Figure 4 The boiler computational model for each structure
Slika 4. Geometrija proračunskog modela kotla po podstrukturama

accordance with Tab. 1.

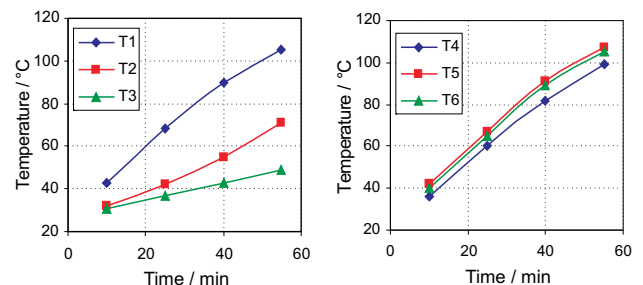
3.2 Boiler load

Opterećenje kotla

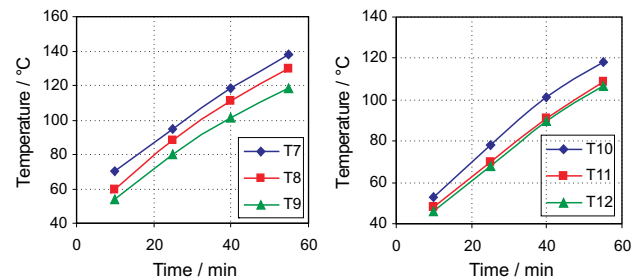
Calculation was performed for two load cases: compounded pressure and temperature load, and separated pressure load for purposes of model validation. Surface pressure load was defined for all models according to measured values. Characteristic temperatures that were measured on rear head and boiler shell are schematically shown in Fig. 5a. Temperature T1 was measured between upper anchors of the rear head, temperature T2 was measured in the point of deformation measurement, while temperature T3 was measured in the point of stress measurement. Temperatures T4, T5 and T6 were measured on various heights in the middle of boiler shell length.

According to EN computational temperature is equal to the working fluid temperature increased by a temperature addition which is created for pressurized components subjected to fire or flue gases.

Measurements of flame tube and chambers were unfeasible, as well as temperature of rear head at the boiler flue gas outlet fitting. These temperatures were, therefore, adopted on the basis of boiler water temperature values and on adopted temperature additions. Temperature load was calculated on the basis of temperature difference between elements and characteristics of the material. Adopted temperatures are shown on the diagram in Fig. 5b. On the basis of measured and assumed temperatures a temperature field for boiler construction was defined.



Slika 5a. Izmjerene temperature u funkciji vremena



Slika 5b. Pretpostavljene temperature u funkciji vremena

3.3 Results of FEM calculation

Rezultati proračuna MKE

Global image of model M4 for compounded pressure and temperature load is shown in Fig. 6. Maximum total load displacement (deformation) is 2,17 mm.

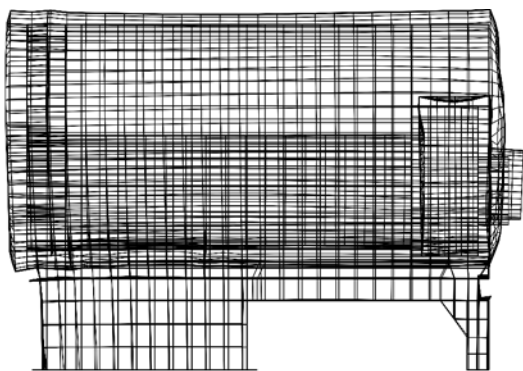


Figure 6 Total displacements (deformations)
Slika 6. Ukupni pomaci (deformacije)

Stress field of plate elements for the contours of the entire model M4 and especially for its rear head, in the range of 0-20,9 kN/cm², is shown in Fig. 8. Equivalent stresses are calculated by the Huber - von Mises hypothesis.

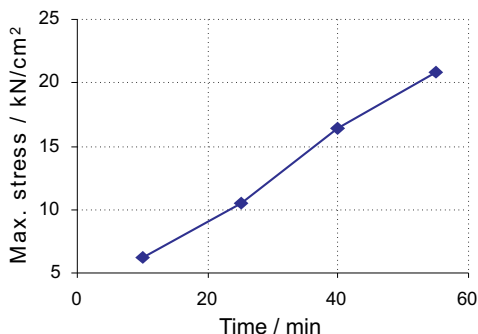


Figure 7 Maximal equivalent stresses on shell of boiler
Slika 7. Maksimalna ekvivalentna naprezanja na plaštu kotla

Maximal stresses in the construction are located in the drum housing near the location of junction with the rear head and amount to 20,9 kN/cm². Yield stress for the calculation temperature of this element and for material P265GH (EN 10028-2:2009) is 21,5 kN/cm². In the rear head somewhat lower stresses appear in the place of junction with drum housing. Calculation rendered that in some anchors high stresses are also produced.

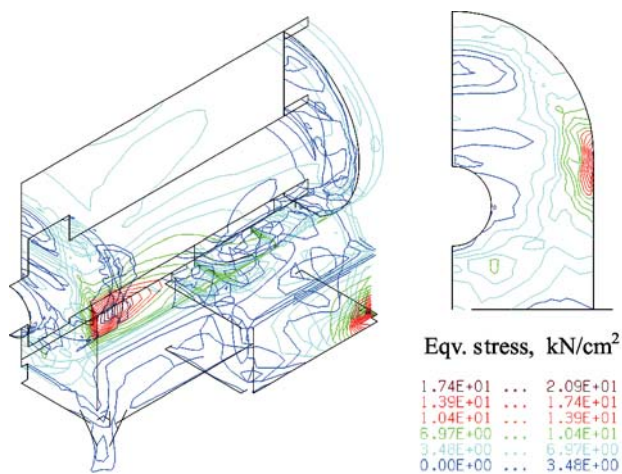


Figure 8 Stress field on shell of boiler and its rear head
Slika 8. Polje naprezanja na plaštu kotla i njegovom stražnjem dancu

Maximum stress within the construction for all models is shown on the diagram in Fig. 7. Maximum stress in the

construction is increased with load increase. The calculation using FEM is conducted after the experiment has been performed. Strain-gage was not placed on the location of maximum stress because the location was unknown at the time.

4 Comparison of experiment results and FEM calculation

Usporedba rezultata eksperimenta i proračuna MKE

Fig.s 9 and 10 show the diagrams that compare experimentally derived results - EXP and FEM derived results for stresses and strains at the measurement points. Very small deformations of rear head were measured – the lowest being 0,34 mm in the first measurement, and the largest being 1,07 mm in the last measurement. A diagram of time vs deformation (Fig. 9) shows that experimentally derived deformation values and FEM derived values differ only slightly, and are even identical for pressure values of 2,8 and 3 bar.

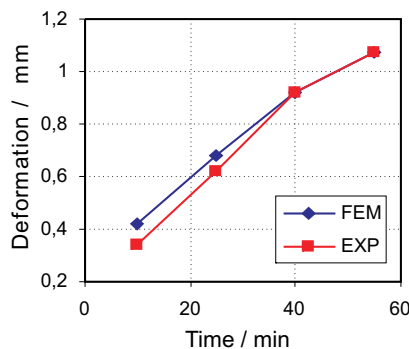


Figure 9 Deformation of the rear head
Slika 9. Deformacija stražnje podnice

Diagram in Fig. 10 shows that FEM calculation rendered somewhat higher strains than those obtained by the experiment, but also these differences are small. The most important conclusion is that FEM renders a more reliable representation of stresses and strains in realistic working conditions of boiler.

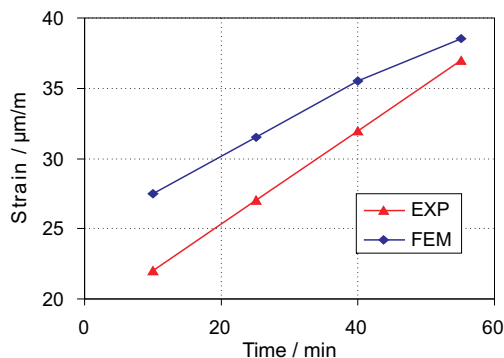


Figure 10 Strain in rear head on pressure loading
Slika 10. Relativna deformacija stražnje podnice uslijed tlaka

5 Parameters of behaviour diagnostics – elements of optimization

Parametri dijagnostike ponašanja - elementi optimizacije

The basis for defining choice parameters (a new

construction) and behaviour parameters (reconstruction or repairment of an existing construction) is standard calculation (static, thermal, dynamic) of a boiler using FEM. System KOMIPS possesses specific calculations for a closer definition of choice parameters by determining load distribution, membrane and bending stresses, deformation energy and kinetic and potential energy. This enables a very efficient state analysis and diagnosis of construction behaviour. These parameters of behaviour diagnostics – the elements for optimization suggest that changes in the construction need to be done in order to obtain better construction exploitation behaviour [12].

Efforts towards creating good exploitation behaviour of a construction include: evenly distributed stresses, strains and energy, lowered presence of stress concentration, higher resilience to crack initiation and growth, dynamical responses that are distanced from their excitations, higher first harmonic and greater distance between harmonics, lower factor of dynamical gain.

Stress analysis in model plates has shown that its highest values and concentrations are located in the boiler shell near the welded joint that connects it to rear head. Maximum equivalent stress value is as high as 20,9 kN/cm² and close to yield stress for the calculation temperature. For plates of model M4 the ratio of membrane and bending stresses was 68,5/31,5 while in the beams this ratio was 41/59. That means that the beams are dominated by bending stresses. Detailed display of membrane and bending stresses distribution, as well as energies of deformation for substructures of model M4 is given in Tab. 2. This distribution gives us the initial element for the optimization. Membrane stresses prevail significantly in the boiler shell (B1), as well as in the fire tube (A1), which is good in the sense of construction carrying capacity. Bending stresses prevail in plates of back chamber (A2) and the rear head (B2), as well as in the smoke tubes (C1) and anchors (C2). Total deformation energy distribution for substructures points to the conclusion that fire tube and smoke tubes are being mostly deformed.

Table 2 Stresses and deformation energy distribution over the boiler substructures

Tabela 2. Raspodjela naprezanja i energije deformiranja po podrstukturama kotla

Sub-structures	Stress distribution / %		Deformation energy / %
	membrane	bending	
A1	5,7	3,1	26,8
A2, A3	3,6	6,9	14,3
B1	30,3	7,0	15,9
B2	3,2	6,9	4,7
B3, B4	4,2	3,8	9,9
B5	18,4	2,1	1,9
C1	1,4	1,7	26,3
C2	0,3	1,4	0,2
Total	Σ=67,1	Σ=32,9	Σ=100,0
	Σ=100		

One of the important behaviour parameters is the distribution of the difference between kinetic and potential energy for the main oscillation modes [14]. We can see that the first three harmonics are quite high, which points to high level of system rigidity. Also, these harmonics are well separated which means that the boiler has a relatively good dynamical behaviour.

Fig. 11 shows the distribution of difference between potential and kinetic energy for the first oscillation mode.

Energy distribution expressed in percentages for each substructure and for the first three oscillation modes is shown in Tab. 3. Dynamical calculation of eigenfrequencies has confirmed the identified statical behaviour.

Table 3 Distribution of potential and kinetic energy $E_p, E_k, \%$
Tabela 3. Raspodjela potencijalne i kinetičke energije $E_p, E_k, \%$

	$f_{01}=21$ Hz		$f_{02}=33,3$ Hz		$f_{03}=45,6$ Hz	
	E_p	E_k	E_p	E_k	E_p	E_k
A1	0,8	19,2	38,6	9,0	0,6	0,8
A2, A3	0,6	7,0	34,4	73,4	1,0	1,1
B1	46,8	25,6	9,1	0,6	95,0	95,6
B2	7,2	2,4	11,5	16,4	0,8	1,0
B3, B4	0,2	16,0	2,0	0,3	1,2	0,7
B5	44,4	29,8	4,4	0,3	1,4	0,8
Total	Σ=100	Σ=100	Σ=100	Σ=100	Σ=100	Σ=100

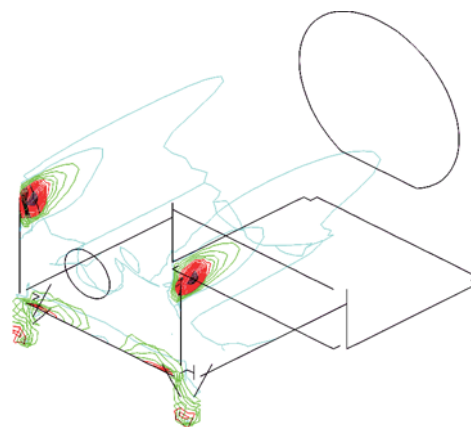


Figure 11 First main mode of oscillation $f_{01}=21$ Hz
Distribution of difference between potential and kinetic energy
Slika 11. Prvi glavni oblik oscilacija $f_{01}=21$ Hz
Raspodjela razlike između potencijalne i kinetičke energije

6 Conclusion Zaključak

In designing certain parts of boiler that are pressurized appropriate norms are used. Strength calculation using the formulas given in norms is based on the experience of the constructor with previous similar constructions. Application of norms, as well as experimentation, cannot determine the location and quantity of maximal stress due to testing or working pressure and temperature. It is not a rare case that within a relatively short period of time of operation a hazard occurs for a boiler that has been previously tested by water pressurization defined by norms. The advantages of numerical method over norms and experimentation are expressed through possibilities of determining a nearly realistic image of stresses and strains, confirming the solution choice, determining the root cause of poor behaviour (or compliance), decision making abilities regarding reconstruction or working regime changes.

In this paper a complete numerical-experimental procedure for diagnostics is shown for the construction of a fire-tube boiler fired by thatch. A FEM model is formed and static and dynamic calculation performed. Experimental measurements have verified the numerical model. On the basis of conducted static analysis it can be clearly seen that the first critical location of the boiler construction is the boiler shell in the vicinity of junction with the rear head. Boiler shell is the element that has the highest concentrations of stresses and strains, as well as great

deformation energy. The rear head is shaped as a flat plate, so transition was performed without the curvature radius, which is a feature that might be altered in new boiler designs. The plates of back chamber and rear head are dominantly loaded with bending, while for some anchors, stabilizing these elements, high stresses are present.

Therefore, the application of numerical methods (FEM, FDM, etc.) in designing boilers in EN is suggested in calculating all components not covered by norms and not analytically calculated using the theory of elasticity.

The paper shows that the influence of thermal strains is significant and that it must be taken into consideration in designing and evaluating the working time of boiler constructions. It has been shown that it is best to perform numerical and experimental diagnostics of behavior for each construction prior to putting it into operation. First, a numerical model must be experimentally verified and then used in considering various parameters for strength diagnostics, such as distribution of membrane and bending stresses for substructures as well as distribution of deformation energy. They are the best indicators of inadequate construction behavior. Also, a dynamical calculation of eigen-oscillations should always be suggested.

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Zahvale

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7

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