Stress and stability calculation of the third pass module of the steam boiler during lifting

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Abstract: *This paper presents the calculation of the stress and stability of a third-cycle module of a steam boiler during the lifting process. A steam boiler is a key element of a cogeneration plant, so all calculations are performed according to prescribed standards. Before the numerical analysis of the steam boiler, the characteristics, components and function of the boiler are described, as well as the required standards. The 3D model of the boiler was created using the Abaqus/CAE 2016 program package according to the manufacturer's technical documentation. Using the finite element method, the stresses and stability during lifting of the boiler from the horizontal and vertical positions were calculated and presented. It was found that when lifting from a horizontal position, the structural stress values of the main elements do not exceed the allowable values. On the other hand, when lifting from a vertical position, the stresses exceed the allowable values. In this case, the connection point between the lug and the profile was checked and analytically dimensioned. The obtained values of the stability analysis of the boiler module are satisfactorily defined and there is no risk of buckling in both cases of lifting. The boiler conforms with the standard and fulfils the requirements handed over to the engineer.*
***Keywords**: STEAM BOILER, STRESS, STABILITY, FINITE ELEMENT METHOD*

1. Introduction

In a conventional context, a steam boiler is a closed vessel and it allows the transfer of combustion heat to the working medium until it is boiling and becomes steam. It could be stated that a steam boiler is an exchanger of heat between water and fire. It is the part of a steam generated power plant process that and as a result produces the heat. That generated steam can then be utilized to pass the heat to a process that and transforms it to work [1].

The main components of a cogeneration plant are: Steam Boiler, Steam Turbine and Electricity Generator. Fuel and air are supplied to the steam boiler to produce high pressure steam through the combustion process. The high-pressure steam is fed into the steam turbine, where the expansion of the steam converts some of the heat energy into mechanical energy of rotor rotation. The rotor of the electric generator is attached to the steam turbine rotor, and the mechanical energy is converted into electricity. Depending on the needs, the steam exiting the turbine is used for technological processes or for heating. If the thermal energy of the output steam is not fully used, it is directed to the condenser and released to the ambient air or water. The energy efficiency of this type of equipment ranges from 0,7 to 0,8 [2].

A cogeneration plant that uses biomass as a fuel source becomes more environmentally friendly by using waste materials from the wood industry and more competitive in the marketplace by having a more acceptable price and locally available fuel sourcing [3-7]. In the following chapters, the characteristics, components, and functions of combined heat and power plants and steam boilers are described in more detail. The calculation of the stresses and stability of the module of the third pass of the steam boiler during lifting is performed using the Abaqus/CAE 2016 program package. The cases of lifting from the horizontal and vertical position are considered, all stages of the analysis are described in detail. It is essential for a designer to engineer and calculate a steam boiler that provides security, durability and usability to the customer. Completing that task requires a great understanding of the design specifications, especially geometry of the pressure vessel, which has to be reviewed to abide with the standards for the design [8]. For that reason, various studies have been conducted and performed to describe the design and calculations of steam boilers [9-12].

This paper presents the results of the stress and stability calculation of the third pass module of the boiler during the lift. The 3D model of the steam boiler was designed using the Abaqus/CAE 2016 program package [13] based on the technical documentation of company Đuro Đaković Termoenergetska Postrojenja d.o.o. [14]. Using the finite element method, the stresses and stability in the course of lifting the boiler from the horizontal and vertical positions were calculated and described.

2. Problem description

The lifting and positioning of the boiler to a certain height is done with an overhead crane using trusses, pulleys and ropes. A truck with a trailer is positioned under the lifted boiler, which is lowered onto the trailer and transported to the cogeneration plant construction site. The process is shown in Figure 1.

***Fig. 1** Steam boiler module transport*

At the construction site, the boiler module must be lifted from the trailer and installed in a supporting steel structure (Figure 2). The boiler is lifted by two cranes, and its rotation is performed in the air. The supporting steel structure is a spatial metal structure used for fastening, supporting and suspending heating surfaces, walls, smoke ducts, piping and other elements belonging to the boiler. Due to significant thermal expansions, the structure is a very responsible part of the boiler. The design of the steel structure depends on the steam boiler, because the design solutions of boilers can be very different.

Fig. 2 *Supporting steel structure*

The steel support structure consists of the main columns mounted on concrete foundations and steel feet. The main columns are connected by cross beams, and the areas between them are filled with auxiliary frames and struts. They are most commonly used for supporting brackets for studs and sheet metal boiler formwork. In this paper, two cases of lifting are considered: from a horizontal and a vertical position.

Lifting from a horizontal position is done in such a way that the first crane is connected to the first lifting beam, lifting beam 1 is attached with ropes to the auxiliary lifting beam, which is connected to lugs no. 1 and 2. The second crane is connected to the second lifting beam, two pulleys are connected to beam 2, a rope is passed through them and attached to lugs no. 3 and 5 and no. 4 and 6 respectively. In this way, the load is evenly distributed to all four lugs, as can be seen in Figure 3. The first and the second crane simultaneously lift the boiler module to the required height in relation to the trailer. After that, the first crane maintains the position reached, while the second crane continues its rotation to the final vertical position.

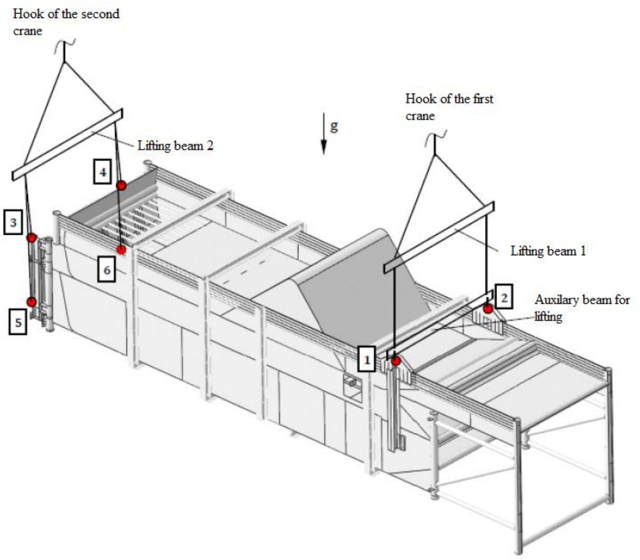

Fig. 3 *The display of lifting the module from the horizontal position*

After the boiler module is rotated to the vertical position, it is lifted and inserted into the supporting structure. Figure 4 shows the process of fixing the boiler module to the cranes, its lifting, rotation and insertion into the supporting steel structure.

Fig. 4 *Attaching the boiler module to cranes, its lifting, rotation and placement in the load-bearing steel structure.*

3. Numerical analysis of the boiler module

The boiler module is bounded by the back and side walls of the first, second, and third boiler passages. The 3D model shown in Figure 5 was created using Abaqus software [13]. The geometric model is discretized mainly with finite shell elements. Around the walls of the boiler module, there are bandages enclosed in a support ring, which help to stiffen the membrane walls (defined as an orthotropic plates) to maintain stability during lifting and placement of the module. Supporting profiles and bandages are defined by beam elements to which the required properties are assigned. The 3D model was created according to the technical documentation [14].

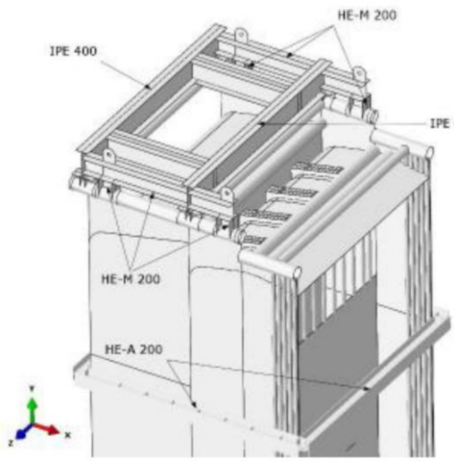

Fig. 5 *Display of loading profiles and bandages*

The numerical calculation of the boiler module is performed for the cases of lifting from horizontal and from vertical position. The first step is to create and define the properties of all materials used. The material 16Mo3 is applied to the side and rear walls of the passage, bandages, supporting profiles and chamber. The material S235JR+N / S355J2+N is defined for lugs and reinforcements, the yield strengths of the mentioned materials are defined by standards [15-17], as shown in Table 1.

Table 1 *Properties of defined materials [15-17]*

Material	Thickness, t, mm	Yield strength, $R_{p0,2}$, MPa	Norm
16Mo3	$t \leq 16$	280	EN 10216
	$16 < t \leq 40$	270	
16Mo3	$t \leq 16$	275	EN 10028-2
	$16 < t \leq 40$	270	
S235JR+N	$t \leq 16$	235	EN 10025-2
	$16 < t \leq 40$	225	
S355J2+N	$t \leq 16$	335	EN 10025-2
	$16 < t \leq 40$	345	

The membrane wall of a steam boiler can be approximated by an equivalent orthotropic plate that has the same elastic properties as a true membrane wall. Using Kirchhoff-Love shell theory, the constitutive equation of an equivalent orthotropic plate can be written:

$$\sigma = D \cdot \epsilon \qquad (1)$$

Where σ is the vector of internal forces, D is the elasticity matrix, ε is the deformation vector. The matrix expression (1) represents the six constitutive equations of the membrane wall as a structurally orthotropic plate or an equivalent orthotropic plate, which connect the internal forces with the corresponding deformations. The next step of the numerical calculation is to define the stiffness matrix for each wall (back wall and side walls of the first, second and third pass).

To obtain the desired results, the model is assigned the material properties of the above-mentioned materials. For lifting from the horizontal position, a global model is created using a coarse mesh with a finite element mesh size of 40 mm, and an element size of 5 mm is specified at the locations of the structural elements that are important for the lifting conditions. Four boundary conditions are applied. The first boundary condition is located on lug no. 1, with restricted *x*-direction. The second boundary condition applies to the lug No. 2, with restricted *x*-direction. The third boundary condition is on lug no.3, with both the *x* and *y* directions constrained. The fourth boundary condition is applied to lug no. 4, with both the *x* and *y* directions constrained. For lifting from the vertical position, a global model is also created with a coarse mesh, but with a finite element mesh size of 50 mm. An element size of 5 mm is specified at the locations of the structural elements that are important for the lifting conditions. The same boundary conditions apply as for lifting from the horizontal position. Figure 6 shows the model with a fine mesh of the lug.

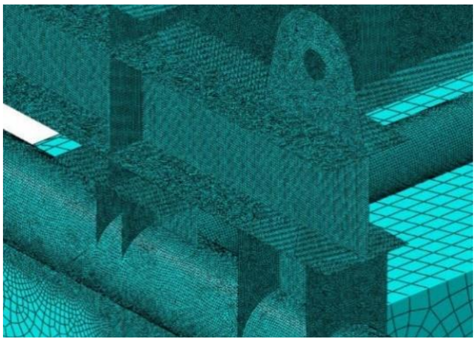

Fig. 6 *Model with fine mesh of the lug*

4. Results analysis

All material and test pressure data previously given were used to obtain results for lifting from horizontal and vertical positions. The stresses that occur at the top of the module when lifted from a horizontal position are shown in Figure 7. The maximum stress according to von Mises is 98 MPa.

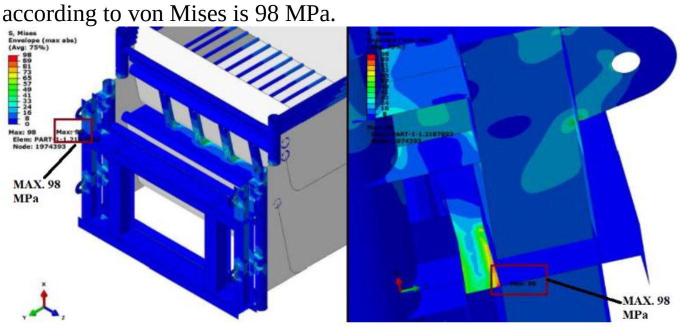

Fig. 7 *Distribution of the equivalent von Mises stress in conditions of lifting from a horizontal position*

The stresses occurring in the lower part of the boiler module are highest in the area of lugs 1 and 2, more precisely near lug 2, where the maximum stress according to von Mises is 125 MPa (Figure 8). The highest stress according to von Mises is at lugs 1 and 2, it is 43 MPa and is shown in Figure 9.

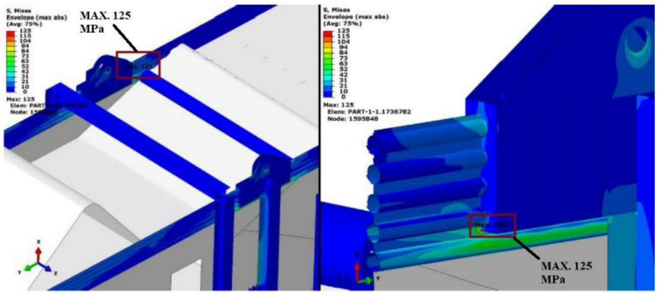

Fig. 8 *Distribution of the equivalent von Mises stress of the lower part of the module*

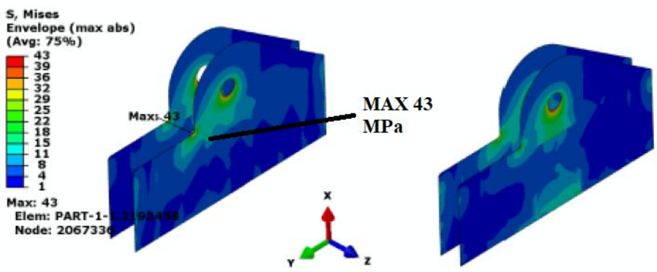

Fig. 9 *Distribution of the equivalent von Mises stress of the lugs 1 and 2*

The calculation of the stress on the structure in the conditions of lifting from a horizontal position was carried out under the load of its own weight. The yield strength of the lug material is $R_{p0,2}$ = 225 MPa [17], the safety factor is equal to S_F = 1,35 and the dynamic factor is equal to S_{din} = 1,2 [18]. According to the given data, the allowable stress is:

$$\sigma_{all} = \frac{R_{p0,2}}{S_F \cdot S_{din}} = \frac{225}{1{,}35 \cdot 1{,}2} = 138{,}8 \text{ MPa} \qquad (2)$$

Since the maximum stress is 125 MPa, it does not exceed the allowable values, and it is not necessary to analytically check the joint between the lug and the profile HEM 200.

The stresses that occur on the upper part of the module when it is lifted from a vertical position are shown in Figure 10. The maximum stress according to von Mises is 217 MPa at the junction of the lug no. 6 and the profile HEM 200. The highest stress according to von Mises is at the lugs 1 and 2, it is 43 MPa and is shown in Figure 11.

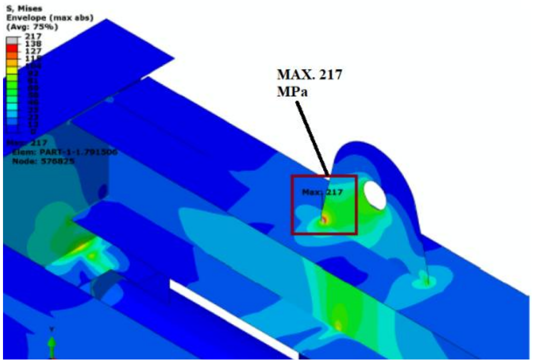

Fig. 10 *Distribution of the equivalent von Mises stress in conditions of lifting from a vertical position*

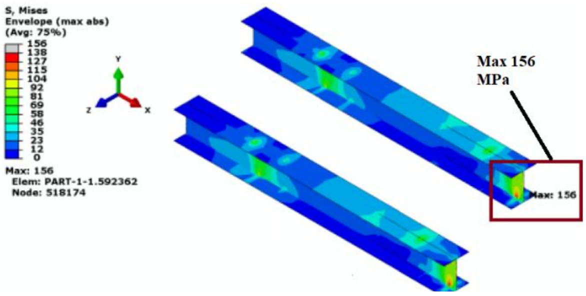

Fig. 11 *Distribution of the equivalent von Mises stress of the HEM profile*

The stress calculation of the structure under the conditions of lifting from a vertical position was carried out under the load of its own weight. Yield strength, safety factor and dynamic factor have the same values as in the case of lifting from a horizontal position. Since the highest stress occurs in the lugs, which are made of the same material, the allowable stress is equal to 138,8 MPa like in expression 2. Since the highest stress is 217 MPa, which exceeds the allowable values, it is necessary to check the connection point between the lug and the profile and dimension the lug. With this analytical calculation, the link plate, whose maximum stress is 105 MPa, is sized so that it does not exceed the allowable value and meets the prescribed condition.

4. Conclusions

This paper presents the results of stress and stability calculation of the third pass module of the steam boiler during the lift. The cases of lifting from a horizontal and vertical position are considered, and the work was carried out according to the technical documentation of the company ĐĐ TEP. In the work, the module is tested as described in the standard. Based on the obtained results of the numerical analysis, an analytical calculation of the lug was performed. The numerical analysis of the problem was performed using the Abaqus/CAE 2016 program package. The stress and stability results during lifting of the boiler module in two cases are presented.

It was found that when lifting from a horizontal position, the stress values of the structurally important elements do not exceed the allowable values and it is not necessary to analytically check the location of the connection of the lug and the profile. On the other hand, when lifting from a vertical position, the stresses occur in the upper part of the module, i.e. at the point of connection of lug no. 6 and the profile HE -M 200, exceed the permissible values. In this case, the position of the connection between the lug and the profile was checked and the required lug was analytically dimensioned. The boiler module conforms with the standard and fulfils the requirements handed over to the engineer in the construction of steam boilers.

5. References

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