DIAGNOSIS OF EXISTING STATE AND STRENGTHENING SOLUTION FOR 180 M HIGH REINFORCED CONCRETE CHIMNEY

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ABSTRACT:
The present paper deals with the procedure for diagnosis of the existing conditions of the bearing structure and a solution for strengthening and repair of 180 m. high reinforced concrete chimney of the thermal power plant Oslomej, Republic of Macedonia.
Diagnosis of the bearing structure of the chimney has been done by: (1) osculating particularly the zones of observed cracks; (2) using nondestructive methods for obtaining the strength characteristics of the built-in materials and definition of the position of the built-in bearing reinforcement; and (3) experimental "in situ" definition of mode shapes and periods of natural vibrations by using the ambient vibration method. With the performed investigations, a complete insight into the conditions of the structure, i.e., the general stability of the bearing structure of the chimney has been obtained.
Given the results from the diagnosis of the bearing structure, analytical investigation of the conditions of the chimney structure was carried out. With the performed static and dynamic analyses using defined mathematical models and the obtained results (dynamic characteristics, displacements and static quantities), the need and the effects from strengthening and repair of the structure have been defined.
Based on the knowledge acquired through all the previous investigations and the defined design criteria, the performed analyses of the structure involving analysis of bearing and deformability capacity, analysis of the stress-strain state and dynamic analyses for expected earthquake intensities, a solution for repair and strengthening of the structure of the reinforced concrete chimney of the thermal power plant Oslomej has been proposed.

Keywords: non-destructive methods, repair and strengthening, ambient vibration methods, chimney

1. INTRODUCTION

A procedure for diagnosis of the existing conditions of the bearing structure of a 180 m high reinforced concrete chimney of the thermal power plant "Oslomej" in Oslomej, Republic of Macedonia, has been defined. Analytical study of the conditions of the chimney has been performed as well as the needs and the effects from strengthening and repair of the structure have been presented. The chimney of the thermal power plant "Oslomej" represents a reinforced-concrete structure with a circular cross-section, variable thickness and a height of 180 metres, Fig. 1.

Based on the knowledge acquired from all the previous investigations and the defined design criteria, analysis of the stress and deformability state as well as dynamic analyses for expected intensities of earthquake effects, a solution for repair and strengthening of the reinforced concrete chimney structure of the thermal power plant Oslomej has been proposed.

The procedure for diagnosis, experimental and analytical investigations as well as the proposed solution for repair and strengthening of the bearing structure of the reinforced concrete chimney of the thermal plant "Oslomej" are given in the subsequent text.

2. DIAGNOSIS OF THE BEARING STRUCTURE OF THE CHIMNEY

The methodology of defining the present state and providing diagnosis of the bearing structure of the Chimney of the thermal power plant Oslomej consists of the following consecutive entities:

- Osculation of the structure, particularly the zones where cracks are observed;
- Non-destructive methods for obtaining the strength characteristics of the built-in material and definition of the position of the bult-in bearing reinforcement;
- Experimental “in situ” definition of the mode shapes and periods of natural vibrations of the chimney structure by use of the ambient vibration method.

The performed investigations enabled getting an insight into the conditions of the structure, i.e., the general stability of the bearing structure of the chimney.

2.1. Detection of Damage to Chimney Structure by Osculation

The complete osculation of the structure showed existence of a large number of micro-cracks in horizontal and vertical direction as well as mesh like cracks. The cracks were observed and their dimensions were defined at a distance of about 2 meters. The opening of the cracks is visible and ranges from 0.1 mm to maximal values of 1-2 mm. At several places, open caverns with blowing ash coming from inside, are observed.

Figure 1. View of the chimney along height

Figure 2. Vertical and horizontal cracks in the external wall at level + 90,00

The damages in the form of cracks extend from the height of 90 m to the highest point of the chimney. The cracks are the most pronounced (per length and width, Fig. 2) in the middle of the chimney, at the height of 85 to 95 meters. With the performed osculation of the lower part of the chimney structure up to the height of 85 meters, no damage or important cracks were observed on the external wall.

2.2. Non-Destructive Methods

2.2.1. Obtaining of Strength Characteristics of Built-in Material

To obtain the strength of the concrete built-in the chimney of the thermal power plant Oslomej, measurements were performed by use of a non-destructive method and DIGISCHMIDT instrument. At 10 measuring points, with a defined procedure, the strength characteristics of the concrete were obtained at two levels (platform 1 and base). The results obtained from the measurements are presented graphically. Fig. 3 shows an example of graphic results (instrument output) at a defined point.

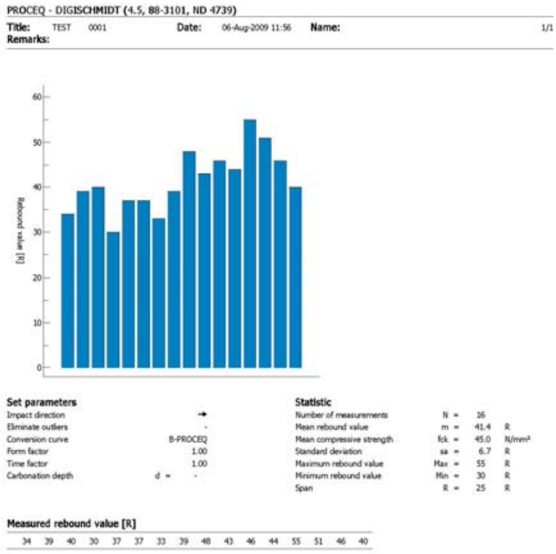

Figure 3. Graphic output for the strength at a given point

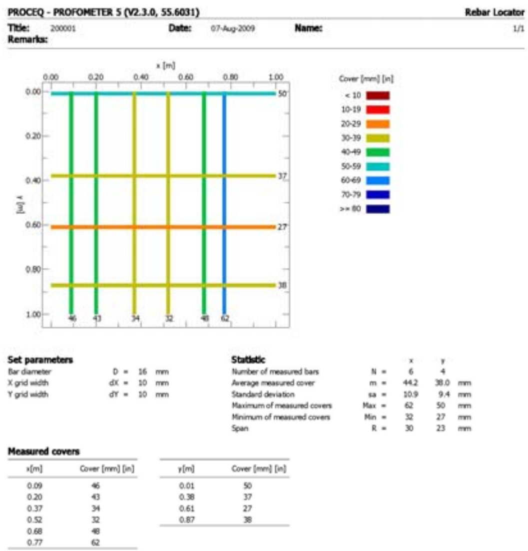

Figure 4. Graphic presentation of built-in bearing reinforcement at a defined measuring point

Elasticity moduli were computed according to PBAB 87 at the selected 10 measuring points using the values for the concrete strength obtained with the DIGISCHMIDT instrument. Using the formula, the following was obtained:

$$E_b = 9.25 * \sqrt[3]{f_{bk} + 10} \qquad \text{fb (MPa)} = \text{MB}$$

The obtained values for the strength characteristics were taken in the analytical computations within the project for repair and strengthening of the chimney of the thermal power plant Oslomej.

2.2.2. Definition of Position of Built-in Bearing Reinforcement

Simultaneously, nondestructive tests were performed by use of the PROFMETER 5 instrument for location of the position of the reinforcement and its protective layers. The measurements were performed at the first platform of the chimney, at the height of h = 41,5 m and at the base. Fig. 4 shows an example of the graphic results from the measurements (instrument output) at the defined measureing point.

From the performed investigations, it can be concluded that the distribution of the reinforcement, the number of built-in iron bars as well as the distance and the protective layers measured in situ correspond to the designed ones. These were used in the computations of the cracks at the characteristic cross-section.

2.3. Experimental Definition of Dynamic Characteristics of the Chimney of Thermal Power Plant Oslomej

To define the dynamic characteristics of the chimney of the thermal power plant Oslomej, the natural frequencies, the mode shapes and the damping coefficients, the ambient vibrations of the chimney were measured at defined points and at several levels. The obtained results will be the basis for making the mathematical model of the chimney more accurate and corresponding evaluation of its seismic stability, resulting finally in recommendations regarding the need for possible repair.

To define the dynamic characteristics of the chimney, the ambient vibration method was used. This is a widely applied and popular experimental method for in situ testing of full scale structures. It is based on measurement of micro-vibrations of the structure caused by the ambient – wind, traffic, operation of machines and alike and the main assumption is that the excitation forces are stationary, with an acceptably flat frequency spectrum, whereat the structure vibrates and its response contains all its normal modes. The equipment used for measurement of the ambient vibrations of the chimney consists of the following:

- Seismometers, type Ranger SS-1, produced by Kinemetrics, USA;
- Signal Conditioner, also produced by Kinemetrics;
- Fourier Analyzer, for fast checking and analysis of signals in frequency domain and obtaining of Fourier amplitude spectra;
- Fast data acquisition system that transforms the analog into digital signals;
- Personal computer with a special software for on-line processing of data and plotting of time histories and Fourier amplitude spectra at each measuring point.

To process the data and analyze the recorded vibrations at all the measuring points on the chimney, the ARTeMIS programme was used. This programme package is based on the peak picking technique and decomposition in a frequency domain and offers excellent opportunities for graphic presentation of the results.The measurements of the chimney vibrations were carried out at 5 points along height whereat the radial components were measured. The point at the level of the fourth platform – point R was the referent one during the measurements. The length of each record lasted 50 seconds while the sampling frequency was 200 samples/per second. Figure 5 shows the distribution of the measuring points on the chimney geometry generated with the ARTeMIS programme.

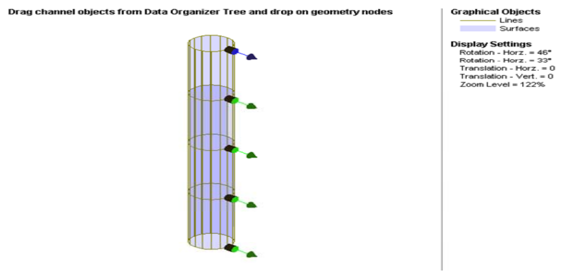

Figure 5. Distribution of measuring points on the chimney

Fig. 6 shows the dominant frequencies for the chimney in the range of up to 10 Hz and the coefficients of viscous damping obtained by processing using the ARTeMIS programme. Frequency f = 0,29 Hz is the first natural frequency of the chimney, freqiency f = 1.07 Hz belongs to the second mode, while frequencies f = 2.44 Hz and f = 4.49 Hz belong to the third and the fourth mode of vibrations.The damping coefficients have quite high values and range around 10% (Tab.1). Such high values are most probably the result of the existing degree of damage to the chimney.

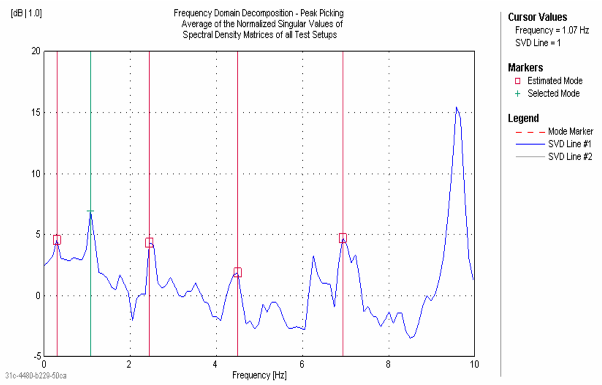

Figure 6. Dominant frequencies and viscous damping coefficients

Table 1. Dominant frequencies and the damping coefficients

Mode	fr(Hz)	Damping coefficients (%)
1	0.293	9.6
2	1.074	6.4
3	2.441	10.2
4	4.492	9.4

The mode shapes of vibration for the corresponding natural frequencies are shown in Fig. 7 and Fig. 8 - spatial and linear presentation. In this way, a clear insight into the vibration modes of the chimney is obtained and used as a basis for concluding the following:

- The vibration shape at the first natural frequency of the chimney f = 0.29 Hz points to deviations from the usual and expected shape of the first mode for such type of structures – high and slender RC chimneys, i.e., that there is a certain discontinuity in stiffness at the level above the second platform. This is also pointed out by the amplitudes of the mode shapes that are considerably high at the level of the third and the fourth platform, i.e., the upper part of the structure, expressing in this way, the so called " whip effect";
- Although there is expected distribution of zero points along vertical line in the vibration shapes at the second, the third and the fourth mode, the "whip effect" still clearly points that, above the second platform, the chimney has increased amplitudes of vibration that most probably result from the existing and visible cracks in that part of the structural height as well as crushing of concrete and penetration of aggressive gasses that pass through the chimney, which was observed in some zones of the upper height, between the third and the fourth platform.
- To confirm the above statement, analytical simulation of a model with an incorporated plastic hinge at the level above the second platform was performed. The analytically obtained mode shapes compared with the experimentally defined ones show good agreement, which points out that the assumption about the existence of such a hinge is realistic.

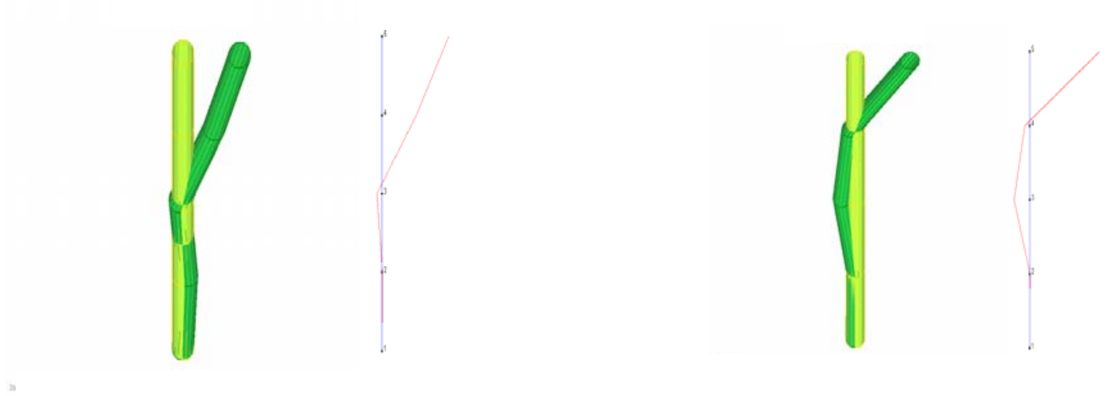

Figure 7. Vibration shape at f = 0.29 Hz and f =1,07 - experimental

Figure 8. Vibration shape at f = 2.44 Hz and f = 4.49 Hz - experimental

3. ANALYTICAL INVESTIGATION OF THE CONDITIONS OF THE CHIMNEY

To be able to round off the procedure for diagnosis of the bearing structure of the chimney, we had to perform several analyses by which we intended to get an insight into the need for and the effects from strengthening and repair through analysis of the obtained results (dynamic characteristics, displacements and static quantities).

For that purpose, three different mathematical models have conceptually been defined and analyses of three different states of the bearing structure were performed as follows:

- Model-1 of the designed chimney (main design);
- Model-2 of the damaged chimney
- Model-3 of the strengthened and repaired chimney.

Three 3D mathematical models with stiffness and deformation characteristics were defined as follows:

- Model-1 – DESIGN, with stiffness and deformation characteristics taken from the main design;
- Model-2 – DAMAGED, for which modeling of larger cracks was performed by partial hinged joints, which means that, with this mathematical model, a damaged model verified by experimental in situ measurements was modeled, and,
- Model – 3 – STRENGTHENED, for which a mathematical model for the strengthened and repaired chimney was defined with mathematical modeling of the strengthening elements.

For such defined mathematical models, complete static and dynamic analysis was performed and the main dynamic characteristics, static quantities and deformations were obtained. The periods and the mode shapes of vibrations, the static quantities due to serviceability loads (dead weight + wind) and the random (earthquakes etc.) effects and so on.

3.1. Discussion on Obtained Analytical Results

Table 2 shows the characteristic results from the performed analyses for the three mathematical models (design, damaged and strengthened).

Table 2. Comparison of the results obtained from the analyses of the three mathematical models

MODEL	**Comparison of the analiticaly obtained fudamental periods**				**Horizontal displacements Xp at the top**		**Tensile stress σ_1 (MPa) at a critical cross section**	
	Periods				*Effects*		*Effects*	
	T_1 *(s)*	T_2 *(s)*	T_3 *(sec)*	T_4 *(s)*	*Wind comb.8 Xp (cm)*	*Seismic comb..10 Xp (cm)*	*Wind comb.8 Xp (cm)*	*Seismic comb.10 Xp (cm)*
1	2,989	0,799	0,342	0,188	43,2	23,4	1,41	0,41
2	3,451	0,892	0,372	0,194	58,4	31,7	2,82	1,48
3	2,910	0,777	0,333	0,185	40,8	22,0	1,71	0,67

By comparison of the results obtained from the analyses of the three mathematical models, the following main statements can be given as follows:

- In case of modeled cracks in the mathematical model – damaged, increased fundamental periods, displacements and tensile stresses at the critical cross section in respect to the design mathematical model are obtained.
- A more referent combination in the analyses of all the mathematical models is the combination with wind in respect to the combination with seismic effect. The tensile stress at the critical cross section under the effects of dead loads and wind exceeds the ultimate tensile stress $\sigma_1 = 2{,}4\ MPa$.
- Due to the occurred damage under the effect of stronger winds, larger displacements may take place in the upper part of the chimney by which its general stability could be endangered.
- In the case of the mathematical model of the chimney modeled as strengthened and repaired, considerable reduction of fundamental periods, displacements and tensile stresses is obtained in respect to the damaged model.
- In this way, with the proposed strengthening and repair, the chimney could be restored to the design level, i.e., the obtained fundamental periods, displacements and stresses at the critical cross-section are at the level of the designed ones.

Based on the performed field and analytical investigations and the detected discontinuity of mode shapes in the zone around the middle of the structure (90 m) where there are also visible vertical and horizontal cracks, we can recommend strengthening and repair of the 180 m high chimney of the thermal power plant Oslomej. As a result of all the previous investigations, a solution for repair and strengthening of the 180m high reinforced concrete chimney is proposed.

4. PROPOSED SOLUTION FOR REPAIR AND STRENGTHENING OF THE CHIMNEY STRUCTURE

Based on the knowledge obtained from all the previous investigations and the defined design criteria, the performed analyses of the structure including analysis of the stress and deformation state and dynamic analyses for expected intensities of earthquake effect, a solution for repair and strengthening of the reinforced concrete chimney structure of the thermal power plant Oslomej is proposed.

Based on the results from the performed analyses that are completely presented in IZIIS Report – 2009/18, the proposed solution for *repair and strengthening* of the structure of the RC chimney of TE Oslomey anticipates repair of all the damaged nonstructural and structural elements, while structural strengthening is aimed at retrofitting of the bearing and deformability capacity of the structure to the design level.

4.1. Proposed Repair of the Chimney

With the repair of the structure, injection of all the observed cracks is anticipated to be carried out by injection mixtures based on cement mortar with additives for fluidity, increased strength characteristics and adhesion with the base. The same can be done also by filling the cracks with epoxy resins. The designed strength characteristics of the injection mixture have to be proved by testing of trial prisms proportioned 40 mm x 40 mm x 160 mm. The injection should be done in all the detected cracks, particularly in the zones starting from 85 metres to the top of the chimney.
With the injection, a compact connection is achieved between the concrete and the mixtures so that good strength and deformability characteristics are achieved at the well injected places of the structure.

4.2. Proposed Strengthening of the Chimney

The proposed solution for strengthening of the structure consists of formation of horizontal belts of polymer wrap strengthened by carbon fibers with bearing capacity in both orthogonal directions **(CFRP WRAP Hex-103C)** along height of the chimney. The carbon fiber fabric is wrapped around the perimeter of the chimney with a corresponding width to provide complete coverage of the zone where tensile stresses and cracks occur in accordance with the performed analyses. With the formation of the horizontal belts along the entire height of the chimney, confinement of the cross-sections is achieved and "opening" of the existing and occurrence of new cracks in the reinforced concrete bearing structure of the chimney is prevented. The realization of the technical solution of strengthening of the structure of the reinforced-concrete chimney is necessary to be carried out in accordance with the enclosed details and according to the following chronology:

1. Application and drying of a layer for fixation of the entire area where placement of carbon wrap is planned;
2. Application of a layer for connection of the fixation layer and the epoxy glue
3. Application of a corresponding layer (3-4 mm) of epoxy glue;
4. Gluing of the CFRP wrap around the perimeter of the chimney in the epoxy glue layer and its impregnation by means of rollers;
5. Application of a thinner layer (1-2 mm) of epoxy glue and rolling of the entire surface again.

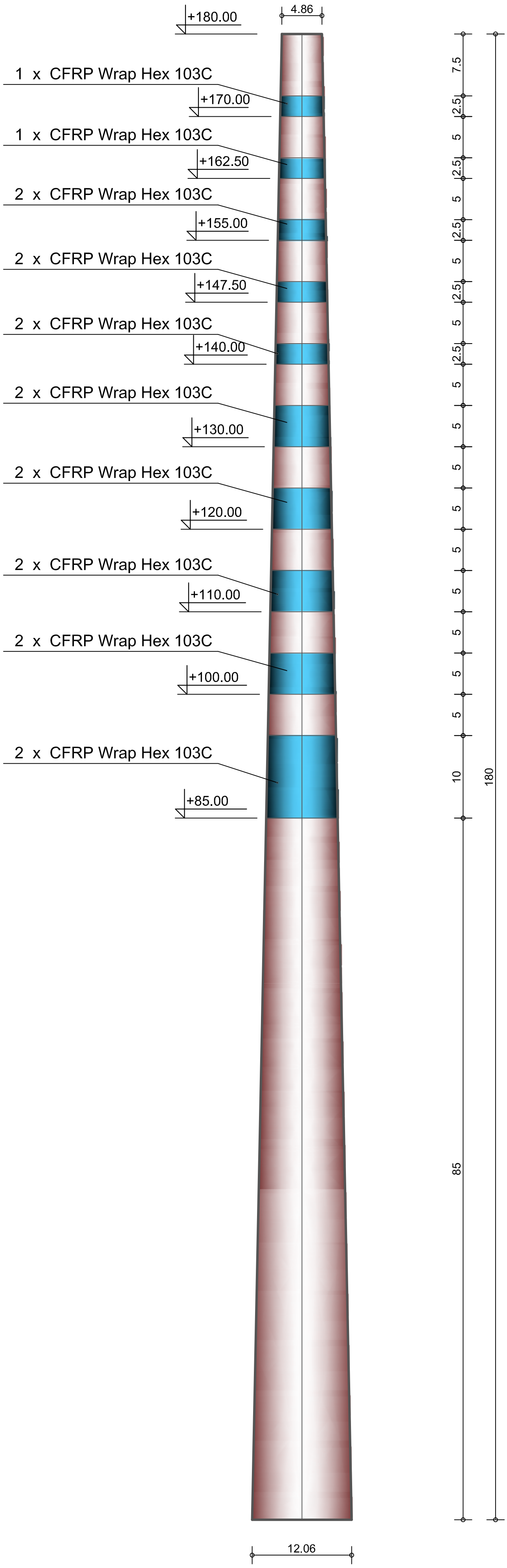

Figure 9. Proposed solution for strengthening of chimney structure of thermal power plant Oslomej

Figure 9. shows the scheme of the proposed solution for strengthening of the chimney structure in thermal power plant Oslomej “strengthening of RC chimney – thermal power plant Oslomej”. A computation has been done regarding the type of wrap and its thickness, i.e., the necessary layers that have to be applied to provide confinement of the entire cross-section, using the software received from the producer (SIKA). With the computations, carbon fiber wrap type **CFRP Wrap Hex 103 C** was adopted.

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