Stress Distribution as a Cause of Industrial Steel Chimney Root Section Failure

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This paper has studied failure initiation of the root section of 60 m tall industrial steel chimney. Cracks that occurred in steel wall of the wind shield have significantly influenced integrity of the structure. Analytical and numerical analysis of failure occurrence was performed. Location of extreme stress values in the steel structure were identified numerically by finite element method. Identified locations coincided with the location of the cracks initiation. The results of analysis identified causes of the failure initiation and allowed expression of the recommendation for root redesign and further maintenance procedures.

Keywords: *steel chimney, finite element analysis, stress analysis.*

1. INTRODUCTION

Crack occurrence in steel structures is well documented and not unusual. Depending on the structure or component purpose, different causes can initiate cracks in material structure. Corrosion [1], fatigue [2,3], stress concentrations due to inappropriate design [4,5], welding [6,7], or vibrations [8] are most common causes of crack initiation but it is usually a combination of several or all of these factors that initiate cracks in material structure [9,10].

Tall and slender steel structures are susceptible to wind action which is in general critical to their design [11,12]. Besides common failure causes for these types of structures, such as wind load, foundation settlement and earthquakes, chimneys are subject to high chemical loads, temperature loads, vortex shedding and ring oscillation ovalling [13].

Diverse loading of the chimney makes it prone to numerous different modes of failure [14-16], such as mechanical overload, force or temperature induced elastic yielding, fatigue, corrosion, stress concentration, buckling, wear, vibration etc.

Steel chimney, that operates as a part of auxiliary boiler facility in TENT ‘B’ power plant, Fig. 1 is in use for nearly 30 years. During visual inspection, three cracks were discovered in root section of the chimney. After removal of flue duct thermal insulation, additional three cracks were discovered. All discovered cracks are initiated on the upper corners of flue duct openings. Chimney’s flanges were also inspected in detail but there were no signs of damage on them and all bolts were at place and properly tightened.

The aim of this paper study is to investigate possible causes of failure occurrence.

The paper presents results of finite element method analysis of chimney’s root structure stress state under static wind loading. The aim of linear static stress analysis is to obtain stress field distribution and to identify stress concentration as the main cause of occurred failures. Based on the results of analysis, corrective actions that will ensure safe exploitation of chimney structure are proposed.

Figure 1. Industrial steel chimney of auxiliary boiler facility in TENT ‘B’ power plant

Received: October 2008, Accepted: November 2008
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2. BASIC FACTS ABOUT CHIMNEY AND ITS OPERATION

Basic dimensions of double skin industrial steel chimney, which is studied, are given in Table 1. with corresponding sketch in Figure 2.

Chimney construction consists of windshield (outer wall of the chimney) and separate flue duct inside windshield (inner wall) that carries flue gases to the atmosphere. Chimney walls are made of welded steel plates forming sections. Windshield sections are flanged together, while flue duct sections lean onto each other. Thickness of windshield plates is getting thinner along chimney to reduce weight.

Three unreinforced rectangular openings are made near the bottom of the windshield to allow flue ducts to enter inner flue. Additional rectangular access door for cleaning and inspection is located at the ground level.

The observed chimney possesses six trapesodial base ribs to increase bending stiffness of its root. Bottom windshield plates are welded to the steel base plate anchored to the foundations. Twelve anchor bolts are used to secure connection with concrete foundation.

Access to the top of the chimney and visual inspection of chimney is provided by ladders mounted on the windshield and platform located on the top of the chimney.

The steel chimney at TENT ‘B’ power plant is not operational permanently because the auxiliary boiler is in the function only during maintenance or failure of primary boiler facility. Nevertheless, the chimney is subject to wind loads throughout whole year.

The chimney is exposed to wind actions at both high and low temperatures, and has to respond to wind loads while being prestressed with temperature loads. Stochastic behaviour of wind loads makes certain components of steel chimney structure prone to fatigue.

Condensation of the stack gases on the inner side of chimney causes formation of acid droplets resulting in high corrosion. The ambient atmosphere surrounding the chimney also caused additional corrosion because of worn surface coating.

Table 1. Chimney basic data

Height (H)	60000 mm
Flue duct outer diameter (D_f)	3000 mm
Windshield outer diameter (D_w)	3300 mm
Base plate diameter (D_b)	4470 mm
Thickness of windshield (δ_w)	13.9 – 3.7 mm
Thickness of flue stack (δ_f)	5.3 – 4.1 mm
Stiffening ribs height (H_s)	5000 mm
Material S235JRG2	R_{eh} = 235 MPa R_m = 340 – 470 MPa

Combination of mechanical, chemical and thermal loads can cause various types of damage that can endanger the integrity of steel chimney structure.

Performing of regular maintenance activities is therefore required.

3. VISUAL INSPECTION OF THE CHIMNEY

To make all cracks clearly visible, root section of chimney was sanded. After detailed visual inspection of chimney [17] it was found that:

- A total of six cracks are initiated at root segment of chimney structure;
- All cracks are initiated on the upper corners of flue duct entries;
- Two cracks are longer than 400 mm with varying propagation direction at outer wall;
- Four cracks are shorter than 100 mm with vertical propagation direction at the outer wall.

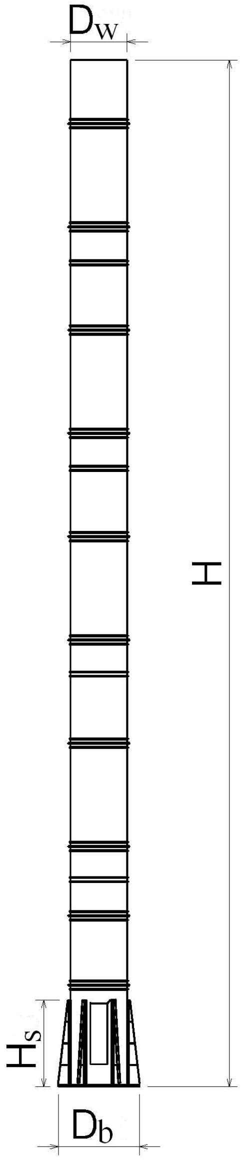

Figure 2. Basic dimensions of the chimney

Largest crack (A_1) is initiated at the upper right corner of flue duct entry located on the left side of the climbing ladders, Figs. 4 and 5. From its origin it propagates first upward, following the welding seam, and then making a sharp turn toward the stiffening rib top, where it continued to propagate above and beyond it. At the time of visual inspection this crack measured 650 mm.

Figure 6 shows the crack (C_2). It is initiated at the upper left corner of flue duct entry located on the right side of the climbing ladders, Fig. 4. From its origin it propagates toward the stiffening rib top ending just before it. At the time of visual inspection this crack measured 410 mm.

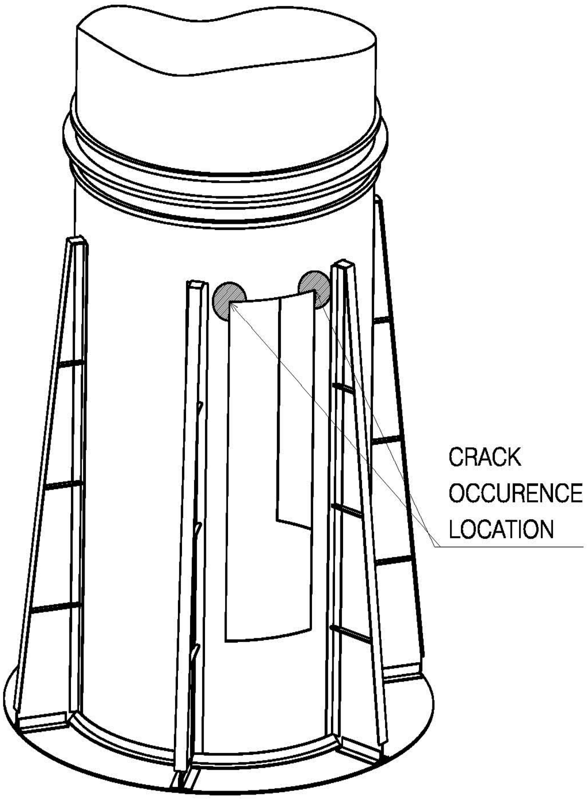

Figure 3. Chimney's root section

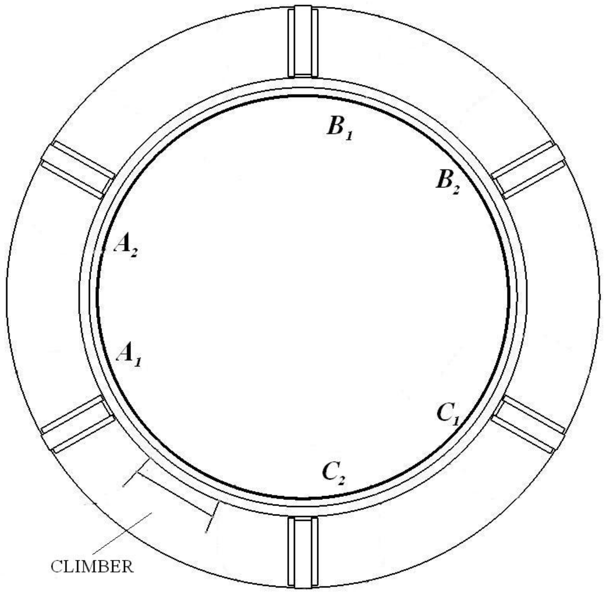

Figure 4. Top view of cracks dispositions

Figure 5. Crack A_1

Figure 6. Crack C_2

Four cracks are initiated at the remaining top corners of flue duct entries. These four cracks are similar to each other and Figure 7 shows crack (A_2) as their typical representative. From initiation point, these cracks propagate upwards following the welding seams. All of these four cracks are less than 100 mm long.

Propagation of all six cracks also continued on the other side from their initiation points over corresponding edges of flue ducts which are not considered as the part of the outer wall structure, Figs. 5, 6 and 7.

Figure 7. Crack A_2

4. LOADING OF THE STEEL CHIMNEY

Major loads acting on the chimney are [11]:

- dead load (self weight),
- wind loads (static and dynamic),
- seismic loads,
- temperature loads and
- chemical loads.

The key engineering concerns, associated with chimneys, include accurate determination of wind forces, distribution of wind forces in time and space, vibration forces due to earthquake, and fluctuating wind velocities at or near the chimney's natural frequencies.

Also, special care has to be taken when designing a chimney, since the operation condition can consider significant thermal loads of the structure.

5. ANALYTICAL AND NUMERICAL CALCULATION OF THE CHIMNEY'S STRESS STATE

The chimney can be considered as cantilever beam with annular cross section. Loading of steel chimney structure includes self-weight and wind loadings in accordance [11]. Sudden change in structure's axial moment of inertia at the level of upper edge of flue duct entries is present. The absence of flue duct openings reinforcement causes abrupt change in stress state of the chimney structure [18]. The moment of inertia is reduced by 21 % at this level. This is even further reduced taking into account the existence of the cracks propagating in the horizontal direction.

The existence of horizontal cracks, besides further reducing of cross-section area at the most loaded part of the structure, has as a consequence significantly higher stress states at their tip points [19].

The identification of the industrial steel chimney stress state is done by applying linear finite element analysis.

5.1 FEM model

By the synthesis of 3D model of all structural parts, the 3D model of the chimney is set up and presented in Figure 8. The structure thickness is varying along the structure height. Thickness is modelled in accordance with the ultrasonic measurement of sheet metal thickness [17].

Figure 8. 3D Model of chimney

3D CAD model of the structure was a starting point in creating finite element model. The model presents the continuum discretized by the 10-node parabolic tetrahedron elements [20,21] in order to create FEM model. FEM model of the chimney structure consists of 174,948 nodes. Figures 9 and 10 show details of the root section finite element model [22]. The size of the elements varies depending on the local geometry of the structure.

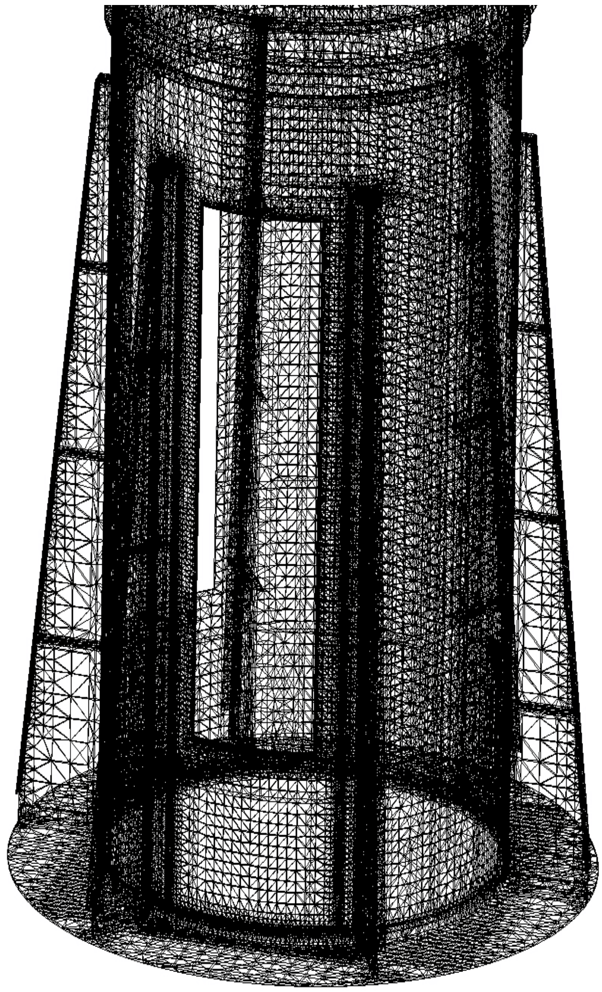

Figure 9. FEM Model of chimney's root section

5.2 External load

The load analysis of the chimney is carried out according to the rules given in the international codes. Modelling of external loads and anchor connection between steel structure and concrete foundation simulated realistic boundary conditions of the structure of the chimney.

5.3 Stress state of the structure

The uniaxial stress field obtained according to the Huber-Hencky-Von Mises hypothesis for the root section of the chimney is shown in Figure 11 and for the rest of the chimney structure.

Maximum values of uniaxial stress are obtained at the chimney's root section in the zones next to the upper corners of the flue duct entries, Fig. 12. High values of uniaxial stress are obtained at the outer wall just above the stiffening ribs.

Chimney sections above the root section have evenly distributed uniaxial stress field without stress concentration locations.

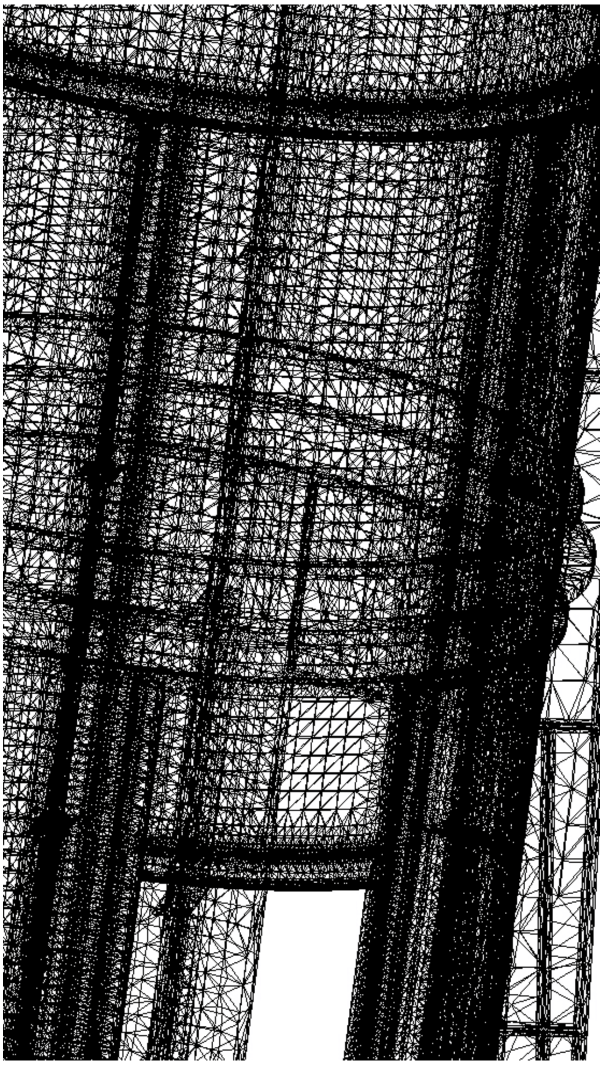

Figure 10. Detail of the mesh in the failure zone

5.4 Discussion of FEM analysis results

Results of the linear finite element method analysis of the industrial steel chimney structure indicate clearly that:

- The stress state levels in the regions around the upper corners of flue duct entry opening and in the regions around the top of the stiffening ribs are very high;
- These values of uniaxial stresses are exceeding the yield stress of the material;
- Maximum stress value calculated using linear FEM analysis indicates that the stress concentration factor is 6.2 in the vicinity of the flue duct entry opening upper corners;
- Zones of high stresses values in the region around the upper corners of flue duct entry opening and the top of the stiffening ribs are adjacent;
- Calculated uniaxial stress field indicates considerably lower stress state levels in the rest of the chimney's root.

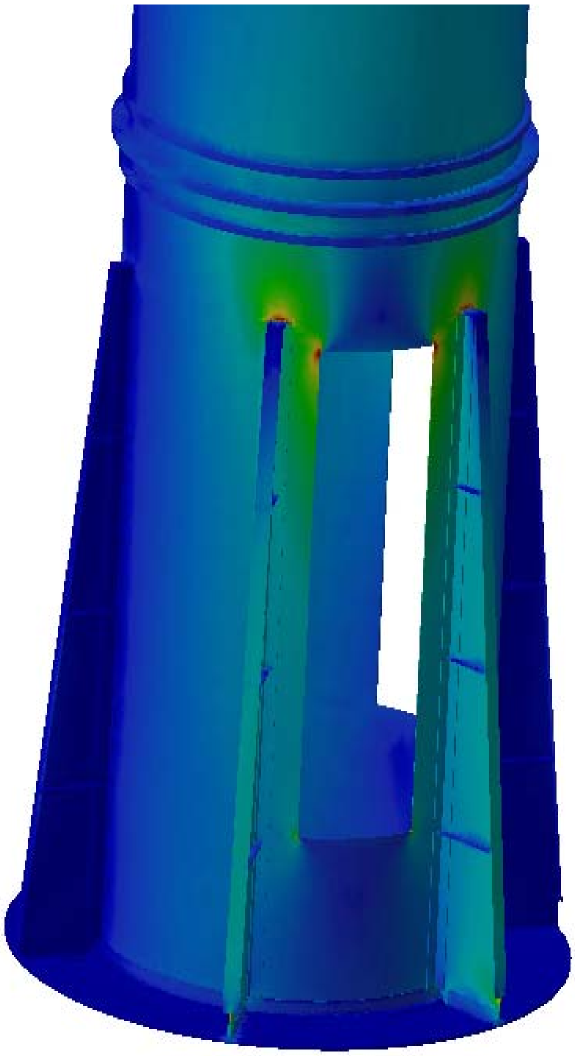

Figure 11. Uniaxial stress field on the chimney's root segment

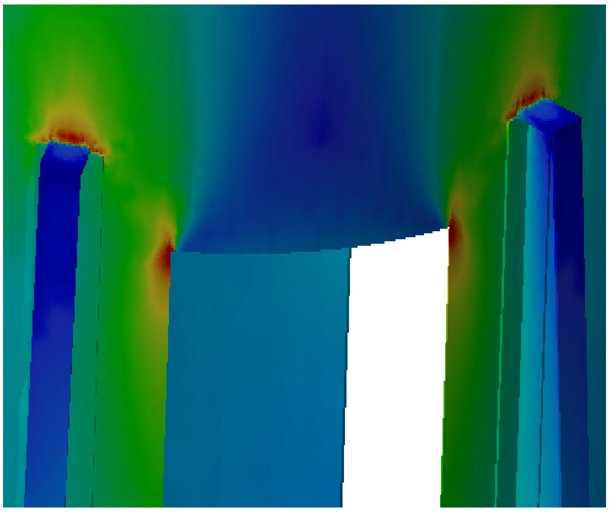

Figure 12. Distribution of the uniaxial stress at the zone of flue duct upper corners

6. CONCLUSION

Industrial steel chimneys are exposed to various harmful mechanical – chemical – thermal actions. Complex loads can cause various types of damage influencing the structure integrity.

As a section with maximum loads, geometrical discontinuities, duct flue openings and manufacturing flaws, root sections of the industrial steel chimney are subject to failures occurrences.

Based on the visual inspection and presented results, it is clear that failure initiation of windshield was brought about by cumulative influence of the factors that have affected the local distribution of stresses such as:

- Influence of the significant reduction of moment of inertia at the root section of the chimney structure;
- Absence of the flue duct opening edge reinforcements;
- Influence of prompt incursion of the stiffening rib in the chimney structure;
- Negative influence of the welding seams ending at the flue duct opening upper edges;
- Influence of corrosion in the corners of flue duct entries in windshield;
- Influence of the proximity of stiffening rib top and the flue duct opening upper corners.

These factors have caused highly uneven stress distribution in the two cross-sections of the chimney. Prompt incursions of the stiffening rib have as a consequence high stress level state just above them. Sharp corners of the flue duct openings without reinforcements along their edges, result in stress concentration at top corners.

The identified high level stress zones conjugated with detrimental effects of the welding seams ending at the top corners are principal causes of the structure failure occurrence.

6.1 Recommendation

Visual inspection, existing cracks and performed analysis impose the need for redesign of the chimney root section.

In order to secure safe operation of the chimney, steel plates containing cracks should be replaced prior to redesign.

Redesign should result in:

- elimination of the high stress concentration zones,
- even redistribution of stress field in the root section of the chimney,
- reinforcement of the flue duct openings at the outer wall,
- significant reduction of stress level in the proximity of welding seams, and
- enhanced protection against corrosion.

Installing of the flue duct opening reinforcement should eliminate high stress concentration zones from the vicinity of the opening corners, therefore dislocating higher stress concentration zones further from welding seams ends. Redesign solution should reconfigure chimney structure near the level of the top of the stiffening ribs to achieve evenly distributed uniaxial stress field in their vicinity. Maintenance procedures should be conducted on regular basis.

ACKNOWLEDGEMENTS

The research reported in this paper is a part of the project 006373 supported by Serbian Ministry of Science.

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РАСПОДЕЛА НАПОНА КАО УЗРОК ОТКАЗА КОРЕНОГ ДЕЛА ИНДУСТРИЈСКОГ ЧЕЛИЧНОГ ДИМЊАКА

Александар Симоновић, Слободан Ступар, Огњен Пековић

Овај рад разматра иницирање отказа корене секције индустријског челичног димњака висине 60 m. Прслине настале у челичној структури спољашњег плашта димњака значајно су утицале на интегритет структуре. Извршена је аналитичка и нумеричка анализа појаве прслина. Анализа методом коначних елемената указала је на постојање зона са високом концентрацијом напона. Идентификоване зоне поклопиле су се са местима на којима је дошло до иницирања прслина. Резултати анализе разјаснили су узроке отказа и омогућили израду програма санације и даље мере одржавања димњака.