Structural integrity assessment of thermal power plant superheater collector

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Abstract

Thermal power plants (TPPs) belong to the important objects, the failure of which can cause accidents with severe consequences. A large portion of Ukrainian TPP has exceeded its design life, which is determined by the main elements of steam power systems. Therefore, the main task is to assess correctly the superheaters collectors limit state using modern approaches and taking into account the service degradation of material.

TPP superheater collectors operate in the steamy environment under the pressure of 15.5 MPa at temperature 545 °C. As a result of combined action of prolonged thermo-mechanical stresses, corrosive and hydrogen environment and slow deformation, fatigue cracks emerge in these components on the inner collector surface.

The limit state of boiler steam superheater collector model was assessed using failure assessment diagram (FAD). The FADs were built for $K_{mat} = K_{Ic}$ and $K_{mat} = K_f$ taking into account safety factors for plastic collapse and for brittle fracture mechanisms for the collector model with part circumferential internal surface crack for various ratio of crack length $l$ to depth $a$.

The critical sizes of the inner surface defect, that is perpendicular to the axis of the cylinder, considering fracture toughness of 12Cr1MoV steel for static and cyclic loading, were assessed.

It was found out, that the increase of $l/a$ ratio decreases the minimum crack depth that is critical for structural element.

Keywords: superheater collector, 12Cr1MoV steel, fracture toughness, failure assessment diagrams, R6

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1. Introduction.

Thermal power stations belong to important facilities, failure of which can cause accidents with severe consequences. A large portion of thermal power plants in Ukraine has exceeded its designed service life, which depends on the basic elements of steam power systems Dmytrakh et al. (2005) that have considerable operating damage Yasniy, V. et al., (2013). Therefore, an important task is the reliable estimation of superheaters collectors strength, taking into account the operational degradation of the material.

Superheaters collectors operate in the steamy environment under pressure 15.5 MPa at operating temperature of 545 °C. Prolonged thermomechanical stresses, corrosive hydrogenated environment and slow deformation of these structural elements cause the appearance of fatigue cracks on the inner surface of the collector. Cracks originate mainly along the grain boundaries weakened by pores and carbides precipitations Yasniy, O. et al. (2013). As a result of collectors exploitation, material mechanical properties change. Periodic stop and starts destroy the protective film at crack tip, accelerating collector hydrogen cracking. Usually cracks propagate between the nozzle holes.

In the exploited material of collector together with multiple cracking when the length of most cracks is less than 2 mm, a significant localized damage was found in the form of part circumferential crack with length 149 mm on the inner surface and maximum depth 37.8 mm, which crosses all mounting nozzles holes Yasniy, V. et al. (2013). Cracks of such sizes can cause a sudden failure of collector. Therefore, an important task is to evaluate the possibility of further operation of the collector with existing defects.

R6 procedure is used to evaluate the strength of structural elements R6 (2003), that is based on the two-parameters failure criteria of bodies with cracks – failure assessment diagram (FAD), which takes into account the plasticity of the material in the crack tip.

The input data to verify the failure of structural elements is geometric parameters of structure and crack; operational parameters of the loading, the mechanical properties of the material.

The calculated coordinates of points in FAD were determined from the formula Milne et al. (1988):

\[
K_I = \frac{K_{Ie}}{K_{mat}} + \frac{K_{Ir}}{K_{mat}} + \rho, \quad L_r = \frac{P}{P_L} = \frac{\sigma_{ref}}{\sigma_{0.2}},
\]

where \(K_{Ie}\) and \(K_{Ir}\) — stress intensity factors (SIF) for applied and residual stresses, respectively; \(K_{mat}\) (\(K_{lc}\)) — material fracture toughness under static loading; \(\rho\) — correction for plasticity; \(P\) (either \(\sigma_{ref}\)) — applied load (stress); \(P_L\) (or limit yield \(\sigma_{0.2}\)) — yield stress (load) in a weakened cross-section of the specimen. The limit curve of failure assessment diagram \(K_r = f_{R6}(L_r)\), that separates the safe area from the failure area, was determine by tests results of specimens with cracks on fracture toughness R6 (2003).

The aim of the study is to investigate the influence of defect size on limit state of the operational superheater collector

2. Results and discussion.

The limit state of the "hot collector" was estimated. The collector was dismounted after 179 thousand exploitation hours of boiler. The collector is made of 12Cr1MoV steel.

Mechanical properties of 12Cr1MoV steel for the static tension test are given in Table 1.

<table>
<thead>
<tr>
<th>(t) (ºC)</th>
<th>(\sigma_{0.2}) (MPa)</th>
<th>(\sigma_U) (MPa)</th>
<th>(\delta) (%)</th>
<th>(\psi) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>364</td>
<td>478</td>
<td>19.7</td>
<td>72.6</td>
</tr>
</tbody>
</table>

The fracture toughness was determined by the non-central tension of compact specimens with thickness 12 mm on servohydraulic testing machine STM-10 according to the standards ASTM E1820 (2001), ASTM E647 (2000).
Static fracture toughness of material collector superheater at the temperature \(20 \, ^\circ\text{C}\) \(K_I = 82.2\) MPa\(\sqrt{\text{m}}\), cyclic \(K_{ic} = 32.0\) MPa\(\sqrt{\text{m}}\) Yasniy et al. (2012).

The superheater collector was considered in the form of thick-walled cylinder, covered at the ends with part circumferential surface crack on the inner wall. The cylinder is under loading caused by internal pressure.

The scheme of part circumferential crack on the inner wall of the thermal collector is shown in Figure 1.

![Fig. 1. Scheme of part circumferential internal surface crack on the inner wall of the collector; \(a\) — defect depth, \(l\) — length of the defect on the surface, \(NA\) — neutral axis Delfin (1997).](image)

The wall thickness of the cylinder \(t = 50\) mm, inner radius \(R_i = 112.5\) mm, inner pressure \(p = 15.5\) MPa. Since the inequality \(t > 0.1(2R_i + t)/2\) holds, the cylinder was considered as a thick-walled. Due to the axial symmetry of the cylinder and of the loading, the current stresses and corresponding strains were also symmetric with respect to its axis. Tangential \(\sigma_t\), radial \(\sigma_r\) and axial \(\sigma_a\) stresses were equal to Timoshenko (1940):

\[
\begin{align*}
\sigma_t &= \frac{r^2}{R^2 - r^2} (1 + \frac{R^2}{r^2}) p; \\
\sigma_r &= \frac{r^2}{R^2 - r^2} (1 - \frac{R^2}{r^2}) p; \\
\sigma_a &= \frac{pr^2}{R^2 - r^2},
\end{align*}
\]

where \(p\) — inner pressure, \(r = R_i\) — inner radius; \(R = R_i + t\) — outer radius, \(r_s\) — variable radius, for which the stress was calculated \((R_i \leq r_s \leq R_i + t)\).

Radial displacement was determined by the Lame formulas Timoshenko (1940)

\[
\begin{align*}
u &= \frac{1 - \mu}{E} \frac{pr^2}{R^2 - r^2} r_s + \frac{1 + \mu}{E} \frac{pR^2 r^2}{R^2 - r^2} \frac{1}{r_s},
\end{align*}
\]

where \(E\) i \(\mu\) — the elastic modulus and Poisson's ratio, respectively.

Stress \(\sigma_t\) in the cylinder wall is compressing, and \(\sigma_r\), \(\sigma_a\) are stretching; radial displacement increases with the increase of the radius \(r_s\).

The equivalent stress in the wall of the cylinder was calculated by the formula

\[
\sigma = \sqrt{\frac{1}{2} [(\sigma_t - \sigma_r)^2 + (\sigma_t - \sigma_a)^2 + (\sigma_a - \sigma_r)^2]}.
\]

For the studied geometry of superheater collector the stress distribution in the cylinder wall without openings, calculated by formulas (2) and (4) and pressure, equal to 15.5 MPa, are shown in Fig. 2.
Stress intensity factor (SIF) for points A and B of the crack front (fig. 1) was calculated by the formula Delfin (1997):

\[ K_i = \sqrt{\pi a} \left( \sum_{j=1}^{3} \sigma_j f_j \left( \frac{a}{t}, \frac{l}{a}, R_i, t \right) + \sigma_{bg} f_{bg} \left( \frac{a}{t}, \frac{l}{a}, R_i, t \right) \right), \]  

where \( \sigma_j \) (\( j = 0, 1, 2, 3 \)) - polynomial coefficients derived from the approximation of stress distribution in the cylinder wall without cracks by 3rd degree polynomial using formula:

\[ \sigma = \sigma(u) = \sum_{j=0}^{3} \sigma_j \left( \frac{u}{a} \right)^j \text{ when } 0 \leq u \leq a, \]

where \( \sigma_{bg} \) is bending stress, in the test case it is equal to zero; \( f_j, f_{bg} \) are the geometry functions for points A and B (intermediate values found by linear interpolation).

The parameter \( L_r \) for the cylinder with an inner surface defect, perpendicular to its axis, was calculated by the formula Chapuliot et al. (1998):

\[ L_r = \sqrt{\left( \frac{\sigma_m}{S_m} \right)^2 + \left( \frac{\sigma_{bg}}{S_{bg}} \right)^2}, \]

where the parameters \( S_m, S_m^*, S_{bg} \) and \( S_{bg}^* \) were obtained from the system of equations Delfin (1997).

To assess the failure, the values of \( L_r \) and \( K_c \) were calculated. The acceptable area is bounded by the limit curve according to R6 procedure R6, (2003), Milne et al. (1988) and is defined by the equation:

\[ K_c \leq f_{R6} = (1 - 0.14L_r^* \left[ 0.3 + 0.7 \exp(-0.65L_r^*) \right]). \]
If the points are located on the acceptable area, the failure does not occur. Otherwise, the crack size is critical. The results of calculations are presented on diagrams (Fig. 3)

Five ratios of crack length along the inner surface $l$ to its depth $a$ were analyzed. In each analyzed case, these cracks are acceptable, except of defects with $l/a = 8$, depth $a \geq 48.06$ mm and $l/a = 16$, depth $a \geq 41.75$ mm ($K_{\text{mat}} = K_{f}\ell = 32.0$ MPa$\sqrt{m}$) and $l/a = 8$, depth $a \geq 48.10$ mm and $l/a = 16$ and depth $a \geq 44.03$ mm ($K_{\text{mat}} = K_{c} = 82.2$ MPa$\sqrt{m}$).

The acceptable damage was also assessed using the approach described in Dillstroem et al. (2008), which introduces safety factors for the parameters $L_r$ and $K_c$,

$$
\frac{K_1}{K_{cr}} + \frac{\rho}{\sqrt{SF_j}} \leq \frac{f_{\text{int}}(L_r)}{\sqrt{SF_j}},
$$

(9)

$$
L_r \leq \frac{L^\text{max}_r}{SF_L},
$$

(10)

where $SF_j$ is the safety factor for the mechanism of brittle fracture, $SF_L$ is the safety factor for the mechanism of plastic collapse, $K_{cr}$ is fracture toughness.

For the pipe material of ferritic structure $SF_j = 10.0$, $SF_L = 2.22$ Dillstroem et al. (2008).

Taking into account the mentioned above considerations, FAD with the acceptable region defined by the safety factors was built.

Fig. 3 a shows the FAD of superheater collector model at 20 °C and $K_{\text{mat}} = K_{f}\ell$. The cracks depth $a = 5, 10, ..., 50$ mm, $l/a = 2 (2), 4 (3), 8 (4), 16 (5), 32 (6)$. The defects with crack length greater than $2\pi R = 706.86$ mm were not considered.

Fig. 3 b shows FAD model of superheater collector at 20 °C, $K_{\text{mat}} = K_{f}\ell$. The crack depth are the same as in FAD for $K_{\text{mat}} = K_{c}$.

![Fig. 3. a) FAD of collector model at 20 °C, $K_{\text{mat}} = K_{f}\ell$, $a = 5, 10, ..., 50$ mm, limit curve $f_{\text{int}}(1)$, $l/a = 2 (2), 4 (3), 8 (4), 16 (5), 32 (6)$, limit curve according to safety factor (7). b) FAD of collector model at 20 °C, $K_{\text{mat}} = K_{f}\ell$, $a = 5, 10, ..., 50$ mm, limit curve $f_{\text{int}}(1)$ $l/a = 2 (2), 4 (3), 8 (4), 16 (5), 32 (6)$, limit curve according to safety factor (7).](image)

The smallest crack sizes, that are critical for the structure operation, for $K_{\text{mat}} = K_{f}\ell$ and $K_{\text{mat}} = K_{c}$ taking into account the safety factors without taking them into account are given in Table 2.
Table 2. The critical crack sizes based on safety factors and without taking them into consideration.

| $K_{mat} = K_{fc}$ | 32.0 MPa$\sqrt{m}$ | $K_{mat} = K_{f_c}$ | 82.2 MPa$\sqrt{m}$ |
|-------------------|----------------------|----------------------|
| $a$, mm           | with safety factors   | without safety factors| with safety factors   | without safety factors |
| 2                 | 25.40                | —                    | —                    | —                    |
| 4                 | 23.00                | —                    | —                    | —                    |
| 8                 | 15.14                | 48.06                | 44.00                | 49.49                |
| 16                | 12.77                | 41.41                | 36.66                | 43.88                |
| 32                | 11.90                | —                    | —                    | —                    |

It was found out, that the minimum critical crack depth $a$ decreases with the $l/a$ ratio increase. For example, with $l/a$ increase from 2 to 16 and taking into account the safety factor for $K_{mat} = K_{f_c}$ the minimum depth of the defect decreases from 25.40 mm to 12.77 mm.

3. Conclusions.

- The influence of internal surface crack that is perpendicular to the cylinder axis on the residual structural integrity of thermal power plant superheater collector has been studied.
- The failure assessment diagrams were built taking into account the fracture toughness of 12Cr1MoV steel after 179 thousand operation hours for static and cyclic loading and, also, the safety factors for the brittle fracture mechanism and plastic collapse.
- The critical sizes of the inner surface defect, that is perpendicular to the axis of the cylinder, considering fracture toughness of 12Cr1MoV steel for static and cyclic loading, were assessed.
- It was found out, that with the increase of $l/a$ ratio decreases the minimum crack depth that is critical for structural element.

References