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An Assessment of the Severity of a Metal Loss Defect Detected on the Steam Boiler Drum of a Thermoelectric Power Plant and the Development of a Repair Technology

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Abstract

In this paper we present an assessment procedure consistent with the level 3 methods recommended by API 579 / ASME FFS-1, of a local metal loss defect detected on the outer surface of the steam boiler drum mantle of a thermoelectric power plant. We analyze several solutions for corrective maintenance work to restore and re-commission the drum mantle. In selecting the optimal solution conforming to the requirements of the ISCIR PT C1-2003 and C4/2-2003 Technical Prescriptions we employed criteria addressing mainly the welding suitability and the behavior of the materials involved, during and after welding.

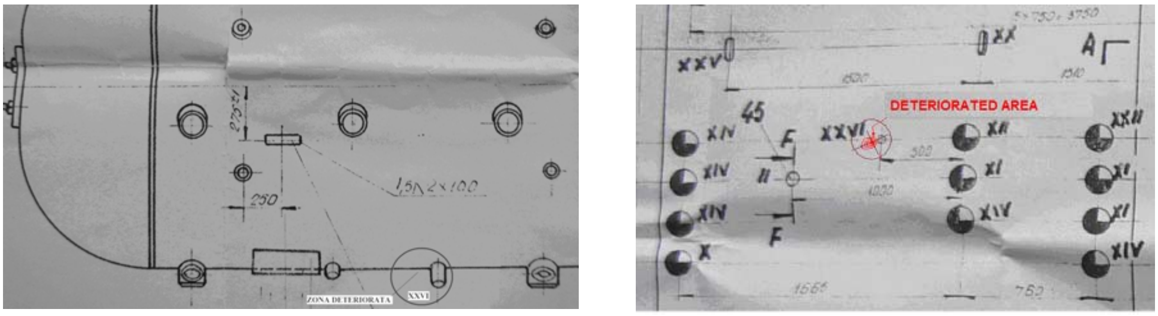
Key words: *defect, local metal loss, corrective maintenance, weld, Finite Element Method, API 579.*

Introduction

In this paper we present the methodology and the techniques used to evaluate and subsequently repair a loss of material defect detected on the outer surface of the steam boiler drum mantle of a thermoelectric power plant. The device in question is a horizontal cylindrical vessel having total length L = 10350 mm, diameter D_i = 1600 mm and mantle wall thickness s_l = 60 mm. The technological operating parameters are: maximum pressure p_i = 11,5 MPa, temperature t_i = 340 °C and service life τ_s = 76 000 h. The base material of the drum mantle is *AMMO 65*, symbol *14 MNDV 5*, standard *AFNOR NF 36-210(83).*

The defect was discovered during an accidental boiler shutdown. Careful inspection of the boiler drum revealed a crack that had penetrated the weld on the exterior plug of a pipe connector. The damaged test connector Dn20, denoted by XXVI Ø25x20x4 on the blueprints in figure 1, is located at 600 mm from the saddle-type support and at 500 mm from the pool of input/output pipe connectors labelled XI, XII, XIV, 3Ø133x20x4. The geometry of a suitable region enclosing the defect and relevant neighbouring elements on the drum mantle is presented in Figures 1 and 2.

Purging of the feed water (at p_i = 11.5 MPa and t_i = 340 °C) through the hole in the welding seam of the Dn20 pipe connector, as a stream shooting at the drum mantle nearby, created in time, through erosion, a loss of material defect on the outer surface of the drum. The shape and size of the material loss are determined by photometric analysis of a cast, sampled at the site, as presented in Figures 3. The defect is elliptical in shape (Figure 3a), extending longitudinally over s_p = 95.2 mm (defined as the defect length) and transversely over c_p = 62 mm (the defect width). The maximum depth of the loss of material, as measured on the cast in Figure 3b, is d_{max} = 33 mm.



a. **b.**

Fig. 1. The positioning of the deteriorated area: a. in section with longitudinal view; b. drum unfolded image with a view from outside according to the project in the deteriorated area

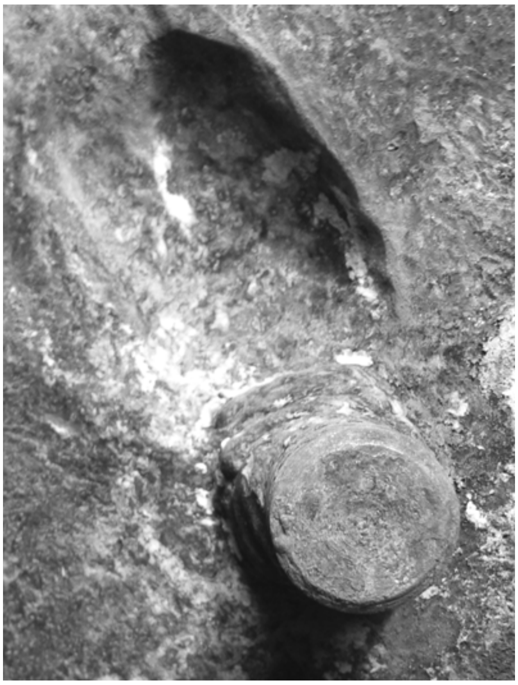
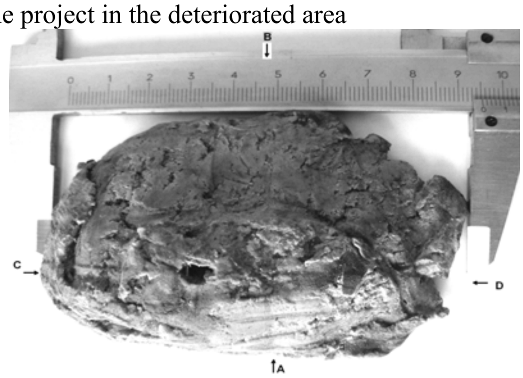
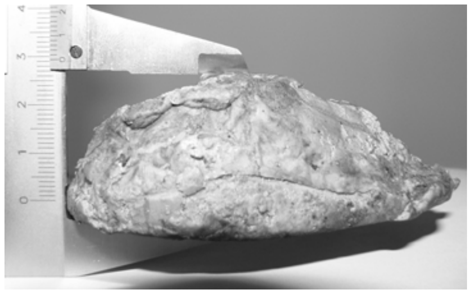


Fig. 2. Processing of the photo outlines



a.



b.

Fig. 3. Cast projection: **a.** on a horizontal plane; **b.** on a vertical plane, lateral view from A

The goal of this study is to provide reliable documentation for the assessment and repair of this equipment, in accordance to the requirements of the ISCIR PT C1-2003 and C4/2-2003 Technical Prescriptions.

Drum Fitness-for-Service Assessment Using the API 579 Procedure

The preliminary stage of the analysis involved evaluating the possibility of continuing to operate the drum despite the defect identified in situ, that is, without repairing it. This approach was suggested by the smooth quality of the defect surface - free of asperities, folds or ridges - as it was generated by fluid purging through the hole in the weld line of the Dn20 pressure gauge connector.

In this respect, for establishing the severity of the anomaly and its integration in the category of imperfections or in the category of defects it was necessary the application of a procedure of *assessment of the functioning aptitude*, namely a methodology through which the anomalies and the work technical conditions of the technological equipment are evaluated for establishing its integrity and to decide its maintaining in function (procedure known in technic as *Fitness-for-service assesment*: (1) a methodology whereby flaws and conditions contained within a structure are assessed in order to determine the integrity of the structure for continued service [2], (2) a methodology whereby flaws contained within a structure are assessed in order to determine the adequacy of the structure for continued service without failure [1]).

In case of the area type „ metal loss", detected on the steamboiler drum which is the subject of the present work, first it has been occured the assessment on 1 and 2 levels according to the procedure from Section 5 (assessment of local metal loss) from *API Standard 579/ASME FFS-1[1].*Thus it has been established that there are fulfilled the conditions from stages (steps) 1...4, and passed on to step 5 from Stage II which has the following content: It is carried out the assessment of the functioning aptitude of the equipment , checking if the following conditions are respected:

$$R_t \geq 0.20;\ t_{mm} - FCA \geq 2.5 \text{ mm};\ L_{msd} \geq 1{,}8\sqrt{Dt_c}\ ; \quad (1)$$

If the conditions are accepted it passes on to the next stage, otherwise it is considered that the anomaly cannot be accepted (it is qualified as being a defect). The significances of the values involved in the conditions previously formulated are: t_{mm} is the minimum measured thickness of the wall in the area of the anomaly on the equipment which is assessed (t_{mm} =30mm), a value which results from figure 5 where it is represented the critical profile of the thicknesses in the anomaly area processed in figure 4; t_c is the wall thickness which is considered on the assessment of the device: $t_c = (t_n - t_{LOSS}) - FCA = t - FCA$, t_n being the nominal thickness (of the project) of the equipment body, t- the effective thickness(measured) of the equipment wall in the neighbouring area of the anomaly place; t_{LOSS} – the decreasing of the thickness of the wall due to the uniform corrosion while using the equipment and FCA – the allowable decreasing of the wall thickness due to the future corrosion, namely while the functioning of the equipment after the moment when the assessment of the detected anomaly is carried out (it was considered $t_n = t = 60$ mm, t_{LOSS} =0 mm, $FCA = 0$ mm, and $t_c = t = 60$ mm), D is the internal diameter of the equipment; L_{msd} is the minimum distance from the anomaly and to the nearest structural major discontinuityon the equipment body which is assessed (because in close vicinity of the anomaly of type metal loss on the drum body there is the welded connection XXVI, the distance L_{msd} = 2...2.5 mm) and R_t is the ratio of available thicknesses, analytical defined by the relation:

$$R_t = \frac{t_{mm} - FCA}{t_c}. \quad (2)$$

It has been found that the first two criteria previously mentioned are fulfilled while the third criterion is not, as the distnce $L_{msd} \cong 2.0$ mm, is much lower than the distance at which the anomaly should be as to be accepted as imperfection $1{,}8\sqrt{Dt_c} = 558$ mm.

Consequently, based on the assessment with procedure from Section 5 of API Standard 579, the anomaly type local metal loss detected on the outer surface of the cylindric drum body of the steam boiler has been qualified as being a defect (an imperfection that does not respect the specified allowable criteria). In these circumstances, the only pertinent decision is to establish a proper technology and to schedule the maintenance service for repairing this defect. The change of this decision and the rigurous integration of the anomaly type local material loss in the imperfections category or in the defect category is possible according to the API Standard 579 prescriptions if it is carried out a re-assessment of the drum at its upper level, level 3 respectively, achieving the numeric analysis and operatin with finite element method (FEA) of the mechanical tensions and strains generated in the drum wall in the anomaly area due to mechanical stresses, that is subjected during the operation, with fair consideration of configuration and anomaly sizes and of the interaction effects of anomaly with discontinuity represented by the welded connection located in its vicinity.

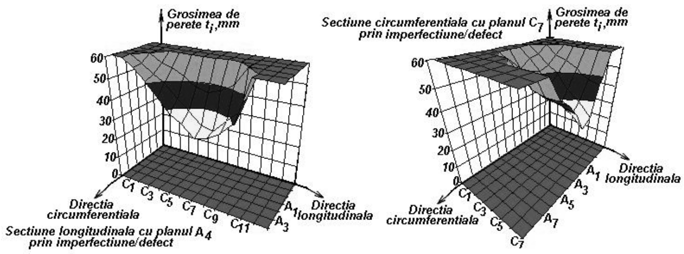
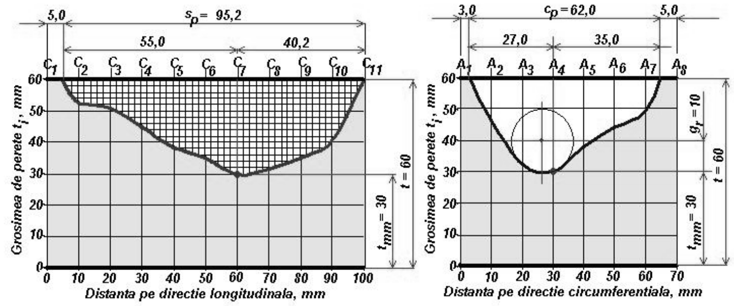


Fig. 4. The graphical processing of the wall thickness measurement results in the imperfection/defect area



a. **b.**

Fig. 5. The thickness critical profile – *PCG* – in the imperfection/defect area:
a.on longitudinal direction; b.on circumferential direction

Finite Element Analysis of the Barrel Shell-Defect-Nozzle Coupled System

The numerical results are presented concisely and suggestively in Table 1 using various post-processing techniques involving the equivalent/comparison stress in the Third Resistance Theory tabulated in the combination [$p^{11,5MPA}+ t_C^{340C}$], according to several models of the "material loss" anomaly that were considered and analysed.

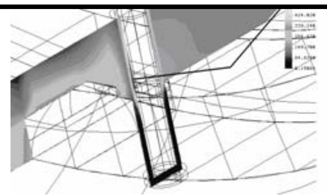
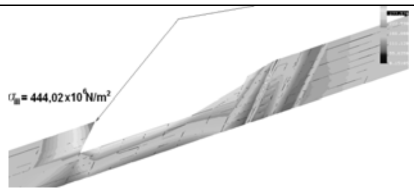
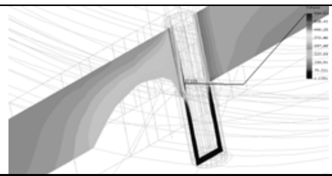
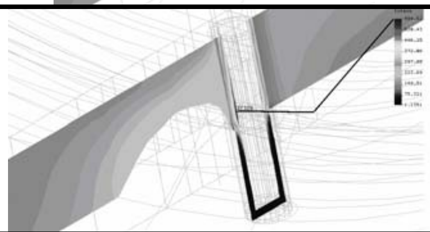
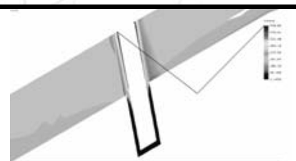
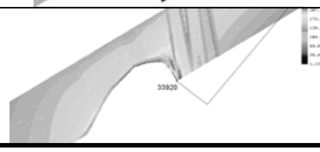
The FEM analysis [3,4,5] incorporating the exact configuration of the anomaly – quasi-eliptical niche defined in the photometric survey (Figures 1 and 2) and by the geometry of the cast in Figure 3 – and taking into account the effects generated by the interaction of the defect with the nearby joint (coupled interacting system *Barrel Shell-defect-joint* processed in Figure 6) shows that te maximum comparison stress in the Third Theory of Resistance/Strength T_τ [6,7] at the limit service state (*SLS*) in the characteristic combination [$p^{11,5MPA}+ t_C^{340C}$] does/do not exceed the Yield Strength limit of the drum mantle material at the operating temperature $t_m = 340^0$C,

$$\max \sigma_{III}^{SLS} = 532{,}2 < R_{p0,2}^{340} = 547 MPa, \text{ see row 4 in Table 1.} \quad (3)$$

Moreover, as indicated by the tension distribution maps in Figure 6, the local values of the mechanical stresses are significantly larger than the allowable stress of the drum mantle material, at the operating temperature $t_m = 340°C$, computed according to the ***ISCIR PT C1-2003*** and ***PT C4/2-2003 Technical Prescriptions***, namely:

$$\max \sigma_{III}^{SLS} = 532{,}2 > \sigma_a = \min\left[\frac{R_{p0,2}^{340}}{1{,}5};\frac{R_m^{20}}{2{,}4}\right] = \min\left[\frac{547}{1{,}5};\frac{700}{2{,}4}\right] = 291{,}7 MPa. \quad (4)$$

Table 1. FEM analyzed defect models and the resulting maximal mechanical tensions (in The III-rd Theory of Strength T_τ) corresponding to the service limit state (SLS) for the $[p_i + t_C^{340°C}]$ load configuration.

Nr.	Defect Type	FEM Analysis Model	Maximum Stress $max\sigma_{III}$, N/mm^2
1	*Rectangular niche with steps connection on the front side with connecting nozzle (pipe connection) XXVIØ28x20x4*		679.3
2	*Rectangular niche with steps connection generated from previous variant by removing the connecting piece XXVI and filling Dn20 opening*		444.0
3	*Niche with quasi-cylindrical bilateral connection*		594.6
4	***Quasi-elliptical niche identified in situ according to the photo mappings and mold geometry***		**537.2**
5	*Initial-nominal variant without defect*		430.0
6	*Quasi- elliptic niche without connecting piece*		275.8

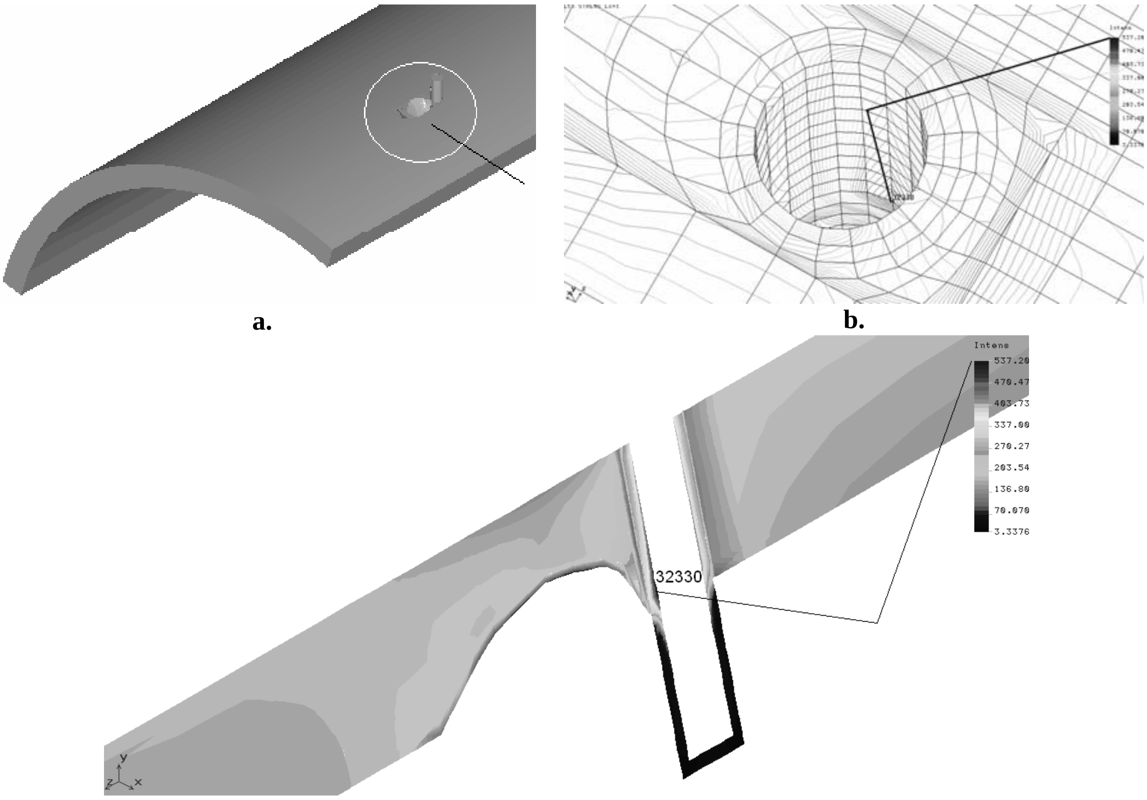
Consequently, following the level 3 assessement by numerical simulation FEM it results that anomaly type „ local metal loss", detected on the outer cylindrical body of the steamboiler drum is qualified as being a **defect.** In this situation, ***for a safety drum operation it is necessary to remedy this defect.***

Development and Analysis of Drum Remedy Solutions

We develop and analyze four possible repair solutions for the CET boiler drum and classify them according to their potential load bearing capacity (strength) as indicated in Table 2. In choosing the optimal solution that is also compliant with the ***ISCIR PT C1-2003*** and ***PT C4/2-2003 Technical Prescriptions***, we considered the following requirements:

- ✓ Maximizing the load bearing capacity in the repaired zone under limit operating conditions;

- ✓ Using an accredited remediation procedure that is quasi-universal for this type of vessel;
- ✓ Use of a mechanic procedure of cutting the cylindric carrot for removing the defect that cannot produce the local heating of the material; it is recommended practice of multiple adjacent holes made by a drilling machine fixed on the mantle and further, application of a proper technology for the welded edges.



c.

Fig. 6. Graphical processing of the equivalent mechanical stresses in The Third Strength Theory T_τ corresponding to the *service limit state (SLS)* defined by parameters *[*p_i + $t_C^{340°C}$*]* assuming a *quasi-elliptical niche* model of the erosion: **a.** meshing of the FEM model using *12-15* solid finite elements distributed of the Barrel Shell thickness; **b.** FEM post-processing showing the stress iso-liness plot; **c.** contour plot of the stress over a longitudinal section through the niche and the *XXVI* nozzle, revealing a stress concentration at the *32330* node, on the inner surface of the *d_i=20 mm* recess, having magnitude $\boldsymbol{max\sigma_{III} = 537.2 \times 10^6\ N/m^2}$.

Considering the criteria stated above and the FEA results presented in Table 2, we conclude that the optimal repair solution corresponds to row 3.4 in Table 2, processed in figures 7, 8 and involves the following steps: 1) cutting out a cylindrical core of diameter *D* = 145 mm that encloses – and therefore removes – the metal loss defect; 2) welding of a thick metal *plug* with dimensions *160x130x(60+15) mm,* featuring a *15 mm* high offset on its exterior surface and made of the same alloy as the drum mantle – AMMO 65 alloy; 3) connecting the plug (starting at the top of the offset) to the drum exterior surface through a concave fillet weld and grinding the exposed, concave surface of the weld to a depth of 3 mm.

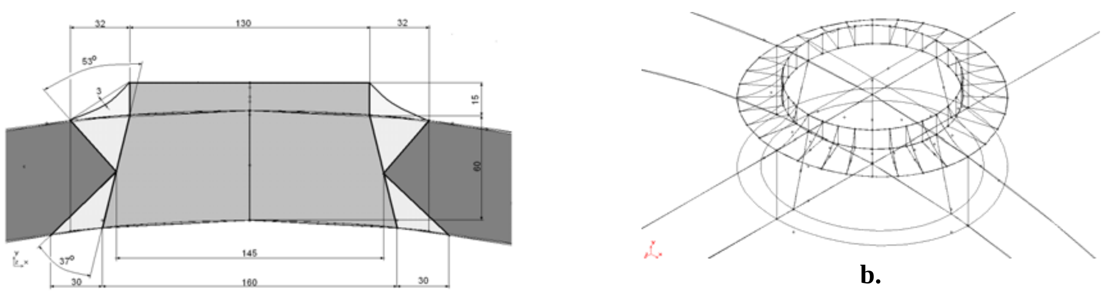
Conclusions

In the case of the repair solution processed in Figures 7 and 8, the maximum equivalent mechanical stresses according to The III-rd Strength Theory T_τ over the ZIT section of the repair panel comprising *the 160x130x(60+15) plug-offset-welding ring-chamfer-ZIT structure* are much smaller than the allowable stress of the mantle base material at the operating temperature t_m = *340°C*. This holds true for both limit states that were analyzed, *ULS* and *SLS* respectively, $max\sigma_{III}^{ULS} = 182.7 < \sigma_a = 291.7$ *MPa*, $max\sigma_{III}^{SLS} = 172.14 < \sigma_a = 291.7$ *MPa*. Satisfying these conditions is an express requirement of the ISCIR technical standard *PT C1-2003 (pct. 3.2.2.3 Metode de calcul lit. b) Rezistenta),* and therefore it reinforces and validates our choice of repair solution from the four possible candidates that were analyzed.

Table 2. FEM analyzed repair solutions and the resulting maximum mechanical stresses (in The III-rd Theory of Strength) corresponding to the factorized load effects in the *service limit state (SLS)* and the *ultimate limit state (ULS)* on the regime stage in appropriate repair formation

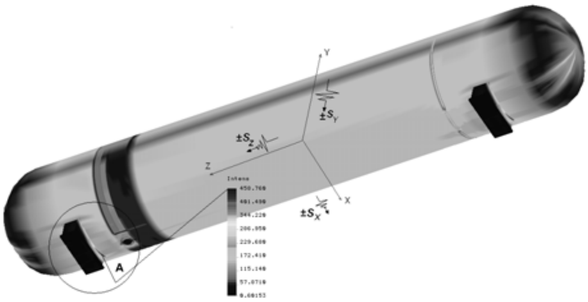
<table>
<tr><th>Nr.</th><th colspan="2">Repair Solution</th><th>$max\sigma_{III}$, MPa</th></tr>
<tr><td>1</td><td colspan="2">Filling of the metal loss with suitable weld material, without initial cutting/processing the defect surfaces (temper bead weld repair and weld temper bead reinforcement)</td><td>430</td></tr>
<tr><td>2</td><td colspan="2">Cutting out a cylindrical core normal to the drum wall and welding of a nozzle with outer diameter D_e and wall thickness s_{nozzle}= 14...18 mm s_{stut} / D_e</td><td>425.6 … 563.3</td></tr>
<tr><td>3.1</td><td rowspan="3">Cutting out a defect-enclosing cylindrical core with diameter D=145 mm, normal to the drum wall, followed by welding a thick metal plug with dimensions 160x130x(60+15) mm</td><td>Plug with exterior offset relative to the mantle surface</td><td>306.2</td></tr>
<tr><td>3.2</td><td>Plug with exterior offset and connecting weld</td><td>252.7</td></tr>
<tr><td>3.3</td><td>Plug flush with the mantle surface</td><td>221.4</td></tr>
<tr><td rowspan="2">3.4</td><td colspan="2" rowspan="2">Full FEM model of the coupled, interactive system comprising the Barrel Shell -supports-repair assembly, corresponding to repair by cutting out a defect-enclosing cylindrical core with diameter D=145 mm, followed by welding of a thick metal plug with dimensions 160x130x(60+15) mm</td><td>182.7[1]</td></tr>
<tr><td>172.14[2]</td></tr>
<tr><td>4</td><td colspan="2">Cutting out a cylindrical core and welding of a metal plug made up of eight stacked sheet metal pieces of thickness s=7,5mm each</td><td>178.6</td></tr>
</table>

[1] *Equivalent mechanical stresses (according to The III-rd Theory of Strength* T_τ*) computed in the service limit state SLS, under the* $[1{,}0g^n_p + 1{,}0p_i^{11,5MPa} + 1{,}0t_i^{340°C}]$ *factorized load configuration applied to the* ***full analysis model*** *(see Figure 8).*
[2] *Equivalent mechanical stresses (according to The III-rd Theory of Strength* T_τ*) computed in the ultimate limit state SLS, under the* $[1{,}0g^n_p + 1{,}0p_i^{11,5MPa} + 1{,}0\,t_i^{340°C} + 1{,}0S_X + 0{,}3S_Z + 0{,}3S_Y]$ *factorized load configuration applied to the* ***full analysis model*** *(see Figure 8).*



a. **b.**

Fig. 7. Analysis model corresponding to repair by cutting out a defect enclosing cylindrical core with diameter *D = 145 mm*, followed by welding of a thick metal patch of size *160 x 130 x (60+15) mm*: **a.** Cross-section through a sector of the mantle showing the 2D geometry and size of the *cut-plug-weld* assembly; **b.** 3D view of the FEA solid element generating surfaces at the defect.



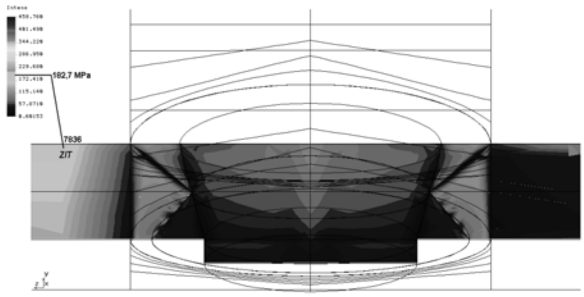


Fig. 8. Drum thermo-mechanical analysis by modeling the full *Barrel Shell-supports-repair panel* coupled system corresponding to the repair solution detailed in Figure 7, in the *ultimate limit state (ULS)* and subject to the $[1.0g^n_p+1.0p_i^{11,5MPa}+1.0t_i^{340°C}+1.0S_X + 0.3S_Z+0.3S_Y]$ factorized grouping of load effects in this state: **a.** the full analysis model and the stress concentrator with magnitude $\boldsymbol{max\sigma_{III} = 458.756}$ ***MPa*** identified in the fix support in the fillet weld of the saddle gusset; **b.** detail of the ZIT section of the repair panel comprising the *160x130x(60+15) plug-outer offset-welding ring-chamfer-ZIT structure,* where the stress has the maximum value $\boldsymbol{\sigma_{III} = 182.7}$ ***MPa*** at node *7836*.

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Evaluarea gravităţii unui defect de tip lipsă de material depistat pe tamburul unei centrale termoenergetice şi elaborarea tehnologiei de reparare a acestuia

Rezumat

În lucrare se prezintă modul de evaluare, cu metodele de nivelul 3 recomandate de API 579 / ASME FFS-1, a unui defect de tip lipsă de material depistat pe suprafaţa exterioară a mantalei tamburului cazanului de abur al unei centrale termoenergetice. Sunt analizate mai multe soluţii de realizare a lucrărilor de mentenanţă corectivă pentru recondiţionarea mantalei tamburului şi repunerea sa în funcţiune, pentru selectarea soluţiei recomandate (prin prisma cerinţelor din Prescriptiile tehnice ISCIR PT C1-2003 si PT C4/2-2003) fiind utilizate criterii vizând în principal sudabilitatea materialelor şi comportarea (metalurgică, tehnologică şi în construcţia sudată) la sudare a acestora.