

Juraj KRÁLIK¹**NONLINEAR ANALYSIS OF THE HERMETIC POSTAMENT SAFETY DURING TECHNOLOGY ACCIDENT IN THE NUCLEAR POWER PLANT****Abstract**

This paper describes the nonlinear analysis of the nuclear power plant (NPP) postament safety under a high internal overpressure and temperature. The scenario of the hard accident in NPP and the methodology of the calculation of the safety of the technology segments are presented. The elastoplastic behavior of steel material dependent on temperature was considered in software ANSYS. The safety analysis of the original and upgraded postament structure is described here.

Keywords

Nuclear Power Plant, Postament, Nonlinearity, Safety, ANSYS.

1 INTRODUCTION

The new IAEA safety documents initiate the requirements to verify the hermetic structures of NPP loaded by two combinations of the extreme actions. These requirements are defined in the document “Stress tests of NPP”. First extreme loads is considered for the probability of exceedance 10^{-4} by year and second for 10^{-2} by year.

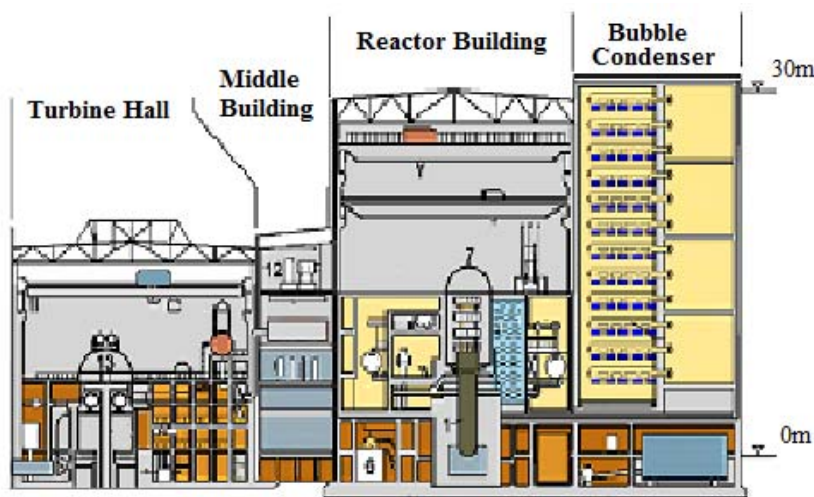


Fig.1: Section plane of the NPP with reactor VVER440/213

Other action effects are considered as the characteristic loads during the accident. In the case of the loss-of-coolant accident (LOCA) the steam pressure expand from the reactor hall to the bubble condenser [10 and 11]. The reactor and the bubble condenser reinforced structures with steel liner are

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the critical structures of the NPP hermetic zone [10]. Next, one from the critical technology structures is the reactor postament. In the case of the hard accident the overpressure can be increased linearly and the internal and external temperature are constant. Three types of the scenarios were considered (Tab.1).

The critical was the accident during 7 days with the overpressure 250kPa, internal temperature 150°C and external temperature -28°C. The duct system O-141 is the part of the hermetic zone for the system 3KLA11, 3KLA11BR cooling system for the reactor shaft (Fig.2-4) [13].

Tab.1: The assumed scenarios of the accidents in the hermetic zone

| Type | Duration | Overpressure in Hz [kPa] | Internal temperature [°C] |
|------|----------------|--------------------------|---------------------------|
| I. | 1hour - 1day | 150 | 127 |
| II. | 2hours - 7days | 250 | 150 |
| III. | 1year | - | 80 - 120 |

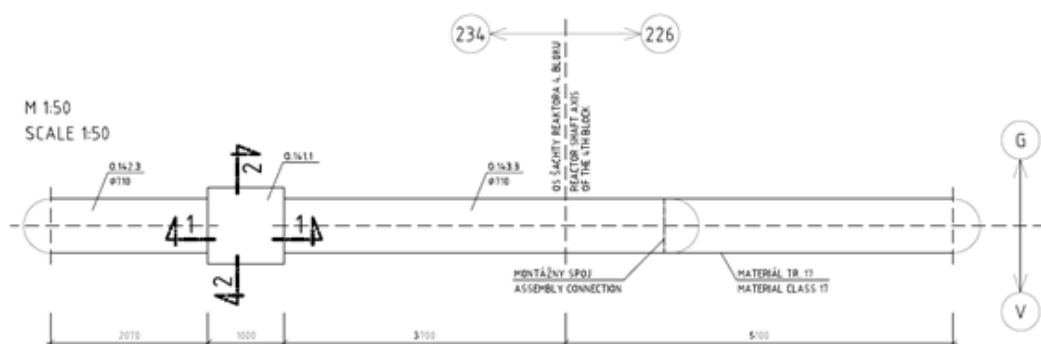


Fig.2: Original pipeline - pipe hermetising 0-141 [D5]

The critical structure is the steel rectangular box 1000x1000x1200mm from the steel plates with the thickness 4mm between the steel pipes Ø710 coincident with this box (Fig.2 and 3). The original structure of postament was not satisfied under extreme overpressure and temperature [13].

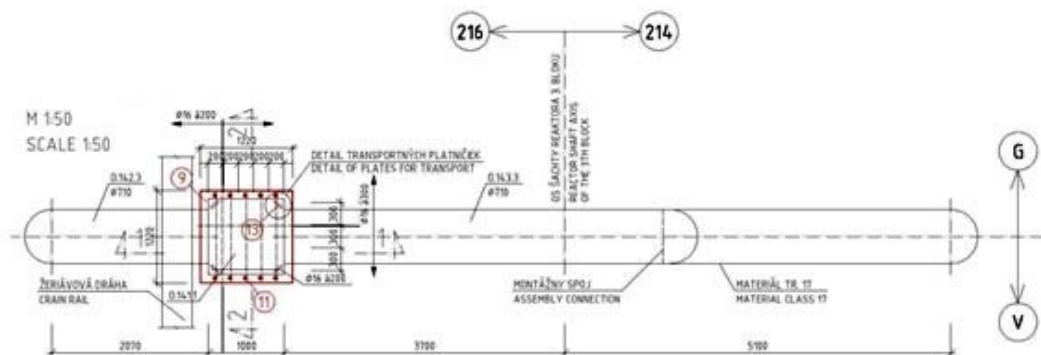


Fig.3: Section 1-1 of upgraded steel box by steel plate 50mm - pipe hermetising 0-141 [13]

Two alternatives of the upgrading were proposed (Fig.4):

1. Using the steel plate 1220x1220x50mm at top of box and anchored to the concrete.
2. Making the new steel box from the steel plate with the thickness 10mm and 20mm.

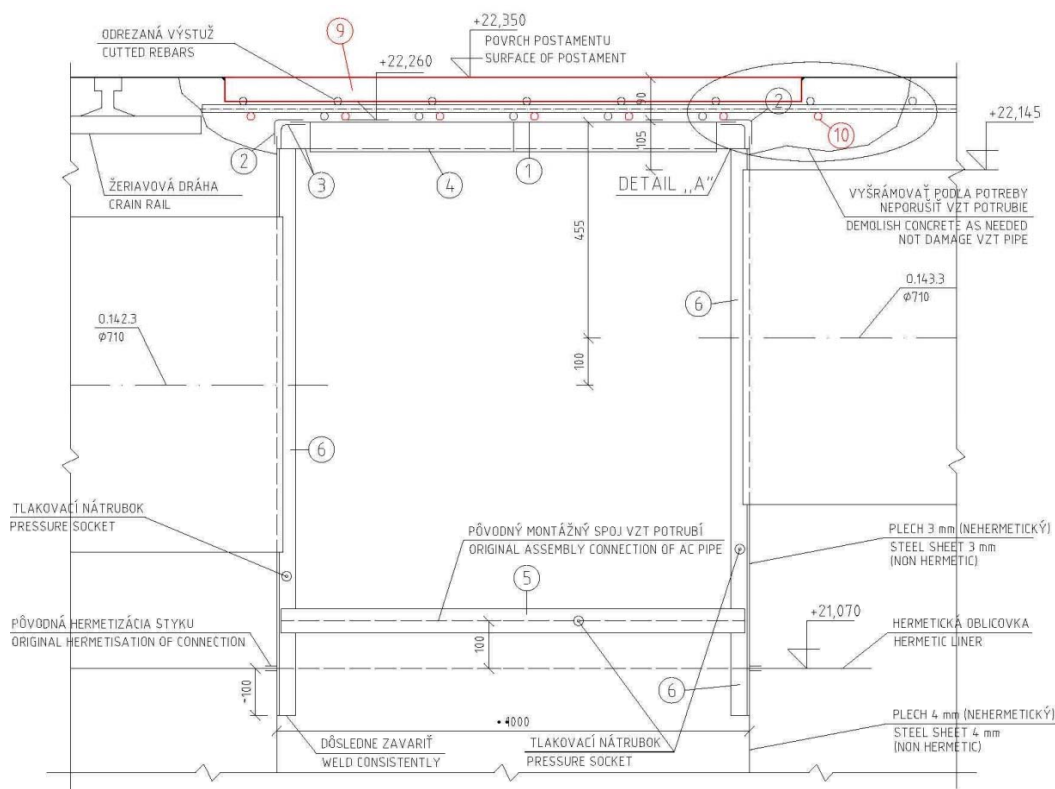


Fig.4: Original pipeline - pipe hermetising 0-141 [13]

2 FE MODEL OF ORIGINAL AND UPGRADED POSTAMENT

The critical structure of the power duct system is the steel rectangular box 1000x1000x1200mm (Fig. 2) from the steel plates with the thickness 4mm between the steel pipes Ø710 (Fig. 3) coincident with this box [13].

We considered the resistance of the following linear and nonlinear models:

1. Models 4W/4WL - these models (4W-nonlinear, 4WL-linear) assume that the concrete layer on the top of duct is damaged. This technology segment is not in contact with the concrete structures. The stiffness of this concrete plate is neglected.
2. Models 5W/5WL - these upgraded models (5W-nonlinear, 5WL-linear) assume that the concrete channel wall under the level 18.9m is in contact with the concrete in direction perpendicular to Y axis. The steel plate 1220x1220x50mm is update at top of box and anchored with the 10 bolts welded with reinforcements Ø16mm in accordance with documentations [13].
3. Models 5WF/5WFL - these upgraded models (5WF-nonlinear, 5WFL-linear) assume that the concrete channel wall under the level 18.9m is in contact with the concrete in direction perpendicular to X and Y axis. The steel plate 1220x1220x50mm is update at top of box and anchored with the 10 bolts welded with reinforcements Ø16mm in accordance with documentations [13].
4. Models 6W/6WL - these alternative upgraded models (6W-nonlinear, 6WL-linear) assume that the concrete channel wall under the level 18.9m is in contact with the concrete in direction

perpendicular to Y axis, the top plate is upgraded with the steel plate (thickness of 10mm) and steel welded plates 1000x100x10 in form X.

5. Models 6WF/6WFL - these alternative upgraded models (6WF-nonlinear, 6WFL-linear) assume that the concrete channel wall under the level 18.9m is in contact with the concrete in direction perpendicular to X and Y axis, the top plate is upgraded with the steel plate (thickness of 10mm) and steel welded plates 1000x100x10 in form X.

The FE model from the shell element SHELL181 considering membrane, bending and shear stiffness was taken for the mechanical analysis in software ANSYS. The reduced stiffness of the shaft concrete structure was modelled using SURF154 [8].

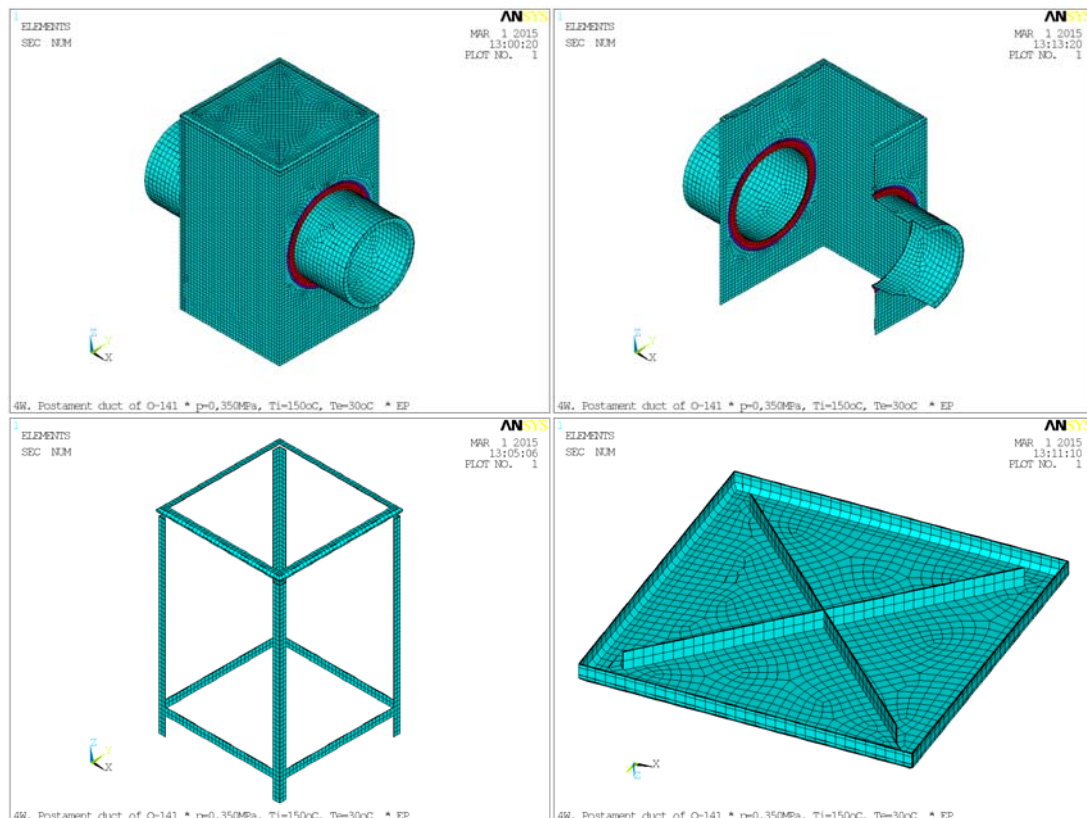


Fig.5: FE model of the steel box with the steel pipes - Duct O141/5W

The design check of these technology segments is based on comparison of the maximum stress intensity with the limited values in accordance with requirements [13] in case of the linear analysis. On the contrary in case of the nonlinear analysis the design check is based on comparison of the maximum values of the strain intensity with the limited values. The nonlinear analysis represents a more realistic verification and gives a more convincing indications that the technology segments will not be damaged in case of the extreme situation due to accident in hermetic zone.

The resistance of these upgraded structures is acceptable in accordance with the international safety requirements [1, 6, 11].

3 ACCEPTANCE CRITERIA

In the case of the nonlinear analysis the thermal dependent material properties are used the input data for material 08CH18N10T defined in standard CSN 413240, CSN 411700, CSN 413230, CSN 413240 and NTD SAI Section II. The criterion for the max. stress values is limited by the H-M-

H plastic potential [8]. The failure of the steel structure is limited by the max. strain values and the stability of the nonlinear solution [10].

The standard EN 1993 1-2 [5] define following characteristic values of the strain for the structural steel :

- yield strain $\varepsilon_{ay,\theta} = 0.02$
- ultimate strain $\varepsilon_{au,\theta} = 0.15$
- max. allowed strain $\varepsilon_{ae,\theta} = 0.20$

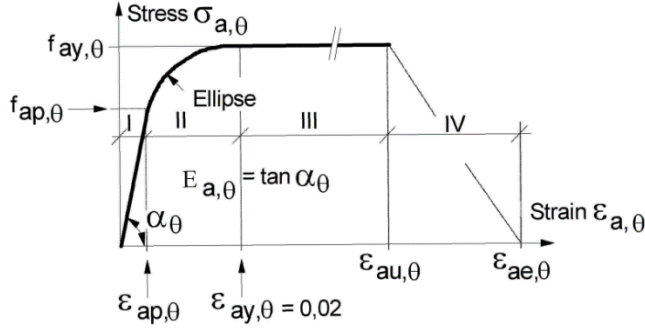


Fig.6: Stress-strain relationship of the steel dependent on temperature

The stress-strain relationship for the steel (Fig.6) are considered in accordance with Eurocode [5] on dependency of temperature level θ for heating rates between 2 and 50K/min. In the case of the steel the stress-strain diagram is divided into four regions.

The stress-strain relation $\sigma_{a,\theta} \approx \varepsilon_{a,\theta}$ are defined in following form in region I:

$$\sigma_{a,\theta} = E_{a,\theta} \varepsilon_{a,\theta}, \quad E_{a,\theta} = k_{E,\theta} E_a \quad (1)$$

where the reduction factor $k_{E,\theta}$ can be chosen according to [5].

In region II :

$$\sigma_{a,\theta} = (f_{ay} - c) + \frac{b}{a} \sqrt{a^2 - (\varepsilon_{ay,\theta} - \varepsilon_{a,\theta})^2}, \quad a^2 = (\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta})(\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta} + c/E_{a,\theta}),$$

$$b^2 = E_{a,\theta} (\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta}) c + c^2, \quad c = \frac{(f_{ay,\theta} - f_{ap,\theta})^2}{E_{a,\theta} (\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta}) - 2(f_{ay,\theta} - f_{ap,\theta})} \quad (2)$$

and in region III :

$$\sigma_{a,\theta} = f_{ay,\theta} \quad (3)$$

4 NONLINEAR ANALYSIS

The nonlinear analysis based on potential theory considering the isotropic material properties was made for the layered shell elements SHELL181 in the FE model. The steel is typical isotropic material. The elastic-plastic behavior of the isotropic materials is described by the HMH yield criterion [8].

Consequently the stress-strain relations are obtained from the following relations

$$\{d\sigma\} = [D_{el}]\left(\{d\varepsilon\} - \{d\varepsilon^{pl}\}\right) = [D_{el}]\left(\{d\varepsilon\} - d\lambda \left\{\frac{\partial Q}{\partial \sigma}\right\}\right) \quad (4)$$

or

$$\{d\sigma\} = [D_{ep}] \{d\varepsilon\} \quad (5)$$

where $[D_{ep}]$ is elastic-plastic matrix in the form

$$[D_{ep}] = [D_e] - \frac{[D_e] \left\{ \frac{\partial Q}{\partial \sigma} \right\} \left\{ \frac{\partial F}{\partial \sigma} \right\}^T [D_e]}{A + \left\{ \frac{\partial F}{\partial \sigma} \right\}^T [D_e] \left\{ \frac{\partial Q}{\partial \sigma} \right\}} \quad (6)$$

The hardening parameter A depends on the yield function and model of hardening (isotropic or kinematic). Huber-Mises-Hencky (HMH) define the yield function in the form

$$\sigma_{eq} = \sigma_T(\kappa), \quad (7)$$

where σ_{eq} is equivalent stress in the point and $\sigma_o(\kappa)$ is yield stress dependent on the hardening.

In the case of kinematic hardening by Prager (versus Ziegler) and the ideal Bauschinger's effect is given

$$A = \frac{2}{9E} \sigma_r^2 H' \quad (8)$$

The hardening modulus H' for this material is defined in the form

$$H' = \frac{d\sigma_{eq}}{d\varepsilon_{eq}^p} = \frac{d\sigma_T}{d\varepsilon_{eq}^p} \quad (9)$$

When this criterion is used with the isotropic hardening option, the yield function is given by:

$$F(\sigma) = \sqrt{\{\sigma\}^T [M] \{\sigma\}} - \sigma_o(\varepsilon_{ep}) = 0 \quad (10)$$

where $\sigma_o(\varepsilon_{ep})$ is the reference yield stress, ε_{ep} is the equivalent plastic strain and the matrix $[M]$ is as follows

$$[M] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 \end{bmatrix} \quad (11)$$

On the base of the elastic-plastic theory and the HMH function of plasticity the extreme strain and stress of the reactor cover for the accident scenario type II are presented in the Tab. 3

The nonlinear analysis of the technology segments is based on HILL potential theory considering the temperature dependent nonlinear material properties. The model of concrete structures of the hermetic zone was investigated for the smeared crack model of the layered reinforced concrete shell element in the software CRACK and ANSYS [10].

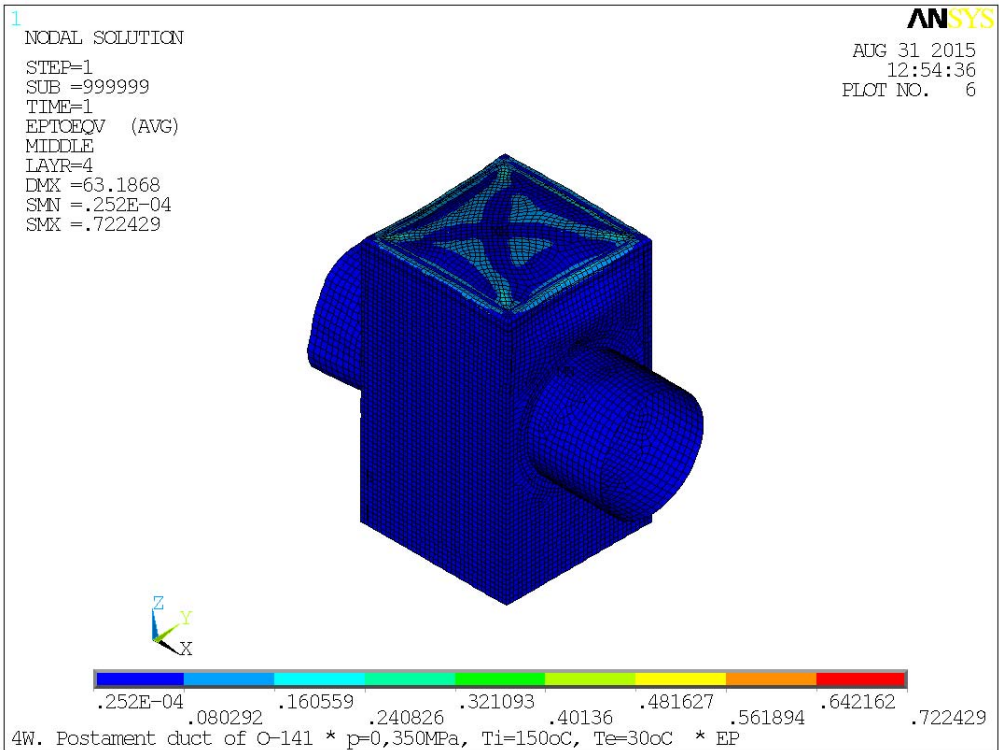


Fig.7: The stress-strain intensity of FE model O141/4W

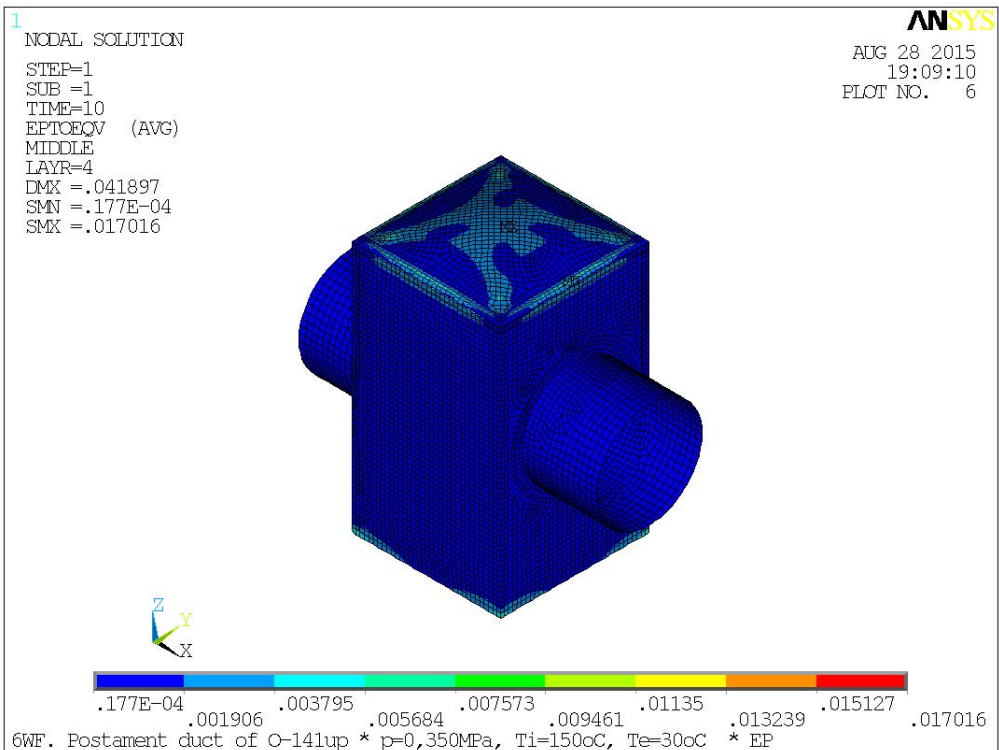


Fig.8: The stress-strain intensity of FE model O141/6WF

The safety level of the original structure was exceeded more than 17.87 time in linear model 4WL and 7.92 time in nonlinear model 4W too [13]. On the contrary, the stiffening models 5WF and 6WF, which are embedded in the concrete structures, those models present the high resistance of these structures from the point of the damage of the steel structure in case of the extreme loads.

Tab.2: Recapitulation of capacity check of steel box of duct O-141

| Model | Analysis | Stress intensity [MPa] | | Ratio | Strain intensity | | Ratio |
|-------|-----------|------------------------|----------|-------|------------------|----------|-------|
| | | Action | Capacity | | Action | Capacity | |
| 4WL | Linear | 3726.8 | 148.6 | 16.88 | 0.0229 | - | - |
| 4W | Nonlinear | 6308.7 | - | - | 1.1881 | 0.15 | 7.92 |
| 5WFL | Linear | 412.14 | 148.6 | 1.87 | 0.00268 | - | - |
| 5WF | Nonlinear | 230.99 | - | - | 0.00307 | 0.15 | 0.02 |
| 6WFL | Linear | 607.45 | 148.6 | 2.75 | 0.00395 | - | - |
| 6WF | Nonlinear | 264.06 | - | - | 0.0256 | 0.15 | 0.17 |

Tab.3: Recapitulation of capacity check of steel frame of duct O-141 [13]

| Model | Analysis | Min/Max Stress [MPa] | | Ratio | Strain intensity | | Ratio |
|-------|-----------|----------------------|----------|-------|------------------|----------|-------|
| | | Action | Capacity | | Action | Capacity | |
| 4WL | Linear | 3946.7 | 148.6 | 17.87 | 0.0243 | - | - |
| 4W | Nonlinear | 16838 | - | - | 1.1881 | 0.15 | 7.92 |
| 5WFL | Linear | 677.67 | 148.6 | 3.07 | 0.00443 | - | - |
| 5WF | Nonlinear | 247.84 | - | - | 0.0118 | 0.15 | 0.08 |
| 6WFL | Linear | 639.02 | 148.6 | 2.89 | 0.00418 | - | - |
| 6WF | Nonlinear | 264.45 | - | - | 0.0256 | 0.15 | 0.17 |

5 CONCLUSIONS

The recapitulation of the capacity check of five models of duct system O-141 show us that this system is not acceptable without the strengthening. Two acceptable upgrading are proposed here:

1. **Model 5WF** - this upgraded model assume that the concrete channel wall under the level 18.9m is in contact with the concrete in direction perpendicular to X and Y axis. The steel plate 1220x1220x50mm is update at top of box and anchored with the 10 bolts welded with reinforcements Ø16mm in accordance with documentations [5]
2. **Model 6WF** - this alternative upgraded models assume that the concrete channel wall under the level 18.9m is in contact with the concrete in direction perpendicular to X and Y axis, the top plate is upgraded with the steel plate (thickness of 10mm) and steel welded plates 1000x100x10 in form X [5].

The methodology of these analyses is based on requirements IAEA [6] and NEA [1, 19], experiences from the similar analysis NPP in abroad [3, 11-13], new finding from the nonlinear analysis of structures [8, 10-16, 19], the methodology of the reliability analysis in case of the extreme loads [2, 4, 5, 7, 9, 10, 12, 14, 15, 17, 18, 20, 21] and our experiences from the previous analysis [10-13]. This contribution is based on methodology of the deterministic nonlinear analysis of the NPP technology segment collapse during the hard accident in the hermetic zone [10].

These analyses are based on the previous results of the monitoring of material properties and structures NPP Mochovce, as well as from the results of the resistance analysis of the important

structural components from the point of the initiated accidents. The structures were analysed on impact of the extreme loads situation defined in the scenarios of the internal accidents [6, 11].

According to the nonlinear deterministic analysis were defined the most critical structural components for which the values of the failure pressure of the accident are determined on base of the best estimation [13].

The standard EN 1993 1-2 [5] defines the following characteristic values of the strain for the structural steel - yield strain $\varepsilon_{ay,\theta} = 0.02$ and ultimate strain $\varepsilon_{au,\theta} = 0.15$.

The recapitulations of the capacity check based on deterministic linear and nonlinear analysis is presented in Tables 2 and 3. The capacity check of the FE original models of duct system O-141 in the cable canal without the contact with the concrete structures reveals that the original duct system is not satisfied [13]. The safety level was exceeded more than 17.87 times in linear model 4WL and 7.92 times in nonlinear model 4W too.

On the contrary, the stiffening models 5WF and 6WF, which are embedded in the concrete structures, those models present the high resistance of these structures (see Tables 2 and 3) from the point of the damage of the steel structure in case of the extreme loads. This paper presented the effectiveness of the nonlinear analysis due to extreme overpressure and temperatures considering the elastic and plastic deformations and the temperature dependent material properties. In the case of the linear analysis the design criteria are not satisfied but the nonlinear analysis give us a proof the safety of the critical technology segments in accordance with the international level of safety [6, 10] and experimental tests of material resistance under the high temperature [5, 16, 17].

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