PROBABILITY ANALYSIS OF REINFORCED CONCRETE STRUCTURE CONSIDERING NONLINEAR BEHAVIOUR AND DEGRADATION EFFECTS

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Abstract

This paper describes the reliability analysis of reinforced concrete structure of the containment and emergency tank under high internal overpressure. There is showed summary of calculation models and calculation methods for the probability analysis of the structural integrity in the case of the loss of coolant accident (LOCA). The uncertainties of the loads level (long-time temperature and dead loads), the material properties (concrete cracking and crushing, reinforcement, and liner), degradation effects and other influences following the inaccuracy of the calculated model and numerical methods were taking in the account in the $10^6$ direct MONTE CARLO simulations.

1 Introduction

The task of probabilistic analysis of the concrete structure failure using nonlinear capacity of the concrete structures under extreme overpressure was defined in the framework of safety check of the NPP structures in the case of accident. The concrete structures of hermetic zone were analyzed for number of situations, such as a LOCA (Loss of Coolant Accident) or a HELB (High Energy Line Break) or a SBLA (Steam Line Break Accident) on the different primary loop piping system.

For a complex analysis of the concrete containment for various loads, ANSYS 7.0 software and the program CRACK [6, 7] (created by Králik) were used. The building of the power block was idealized with a discrete model consisting of 26 923 elements with 325 036 DOF. The accident scenario was defined by SIEMENS KWU, VÚEZ Tlmače and VÚJE Tnava within the Phare program and “The NPP V1 Reconstruction Project”

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The overpressure loads in the tank 800m³ was taking with value 33kPa and in the hermetic zone various from level 40kPa to 300kPa. The long time effect of temperature (considered of the concrete creep and shrinkage after 20 years), the dead loads from structures and technology were taking constant for nonlinear analysis.

2 Degradation of reinforced concrete structure

The safety of nuclear power plants could be affected by the age related degradation structures if it is not detected prior to loss of functional capability and if timely corrective action is not taken. The loss or even a reduction of functional capability of the principal plant components reduces plant safety. Mild steel reinforcing bars are provided to control the extent of cracking and the width of cracks at operating temperatures, to resist tensile stresses and computed compressive stresses for elastic design, and to provide structural reinforcement where required. Potential causes of degradation of the reinforcing steel would be corrosion, exposure to elevated temperatures and irradiation.

The corrosion effects of the reinforcement in the concrete failure were considered according to Faraday’s law indicates the uniform corrosion penetration (of 11.6 µm/year)

\[
\Delta D(T) = 0.0232 \int_{T_0}^{T} i_{corr}(t) \, dt,
\]

where \( \Delta D(T) \) is reduction diameter of reinforcing bar at time \( T \) in mm, \( T \) is the actual time in years, \( T_0 \) is the initial time of corrosion.

The net cross-sectional area of a reinforcing bar, \( A_r \), at time \( T \), is then equal to

\[
A_r(T) = \begin{cases} 
\frac{\pi D_o^2}{4}, & T \leq T_0 \\
\frac{\pi [D_o - \Delta D(T)]^2}{4}, & T > T_0 
\end{cases}
\]

General corrosion also affects the bond between the concrete and reinforcement. According to available experimental data, after the initiation of corrosion the bond strength initially increases slightly (before cracking occurs), but then decreases as the corrosion propagates.

Typical relationships between the bond strength, \( \tau_{bu} \), and the percentage of corrosion, \( c\% \), obtained from pullout tests are shown in Fig.3, where \( c\% \) represents the percentage...
loss of reinforcement weight.

The bond strength at time \( T \) can be estimated as

\[
\tau_{bu}(T) = \begin{cases} 
\tau_{bu,0} & c\% (T) \leq c\%, \\
\tau_{bu,0} \left[ 1 - (1 - \beta_T) \frac{c\% (T) - c\%_1}{c\%_2 - c\%_1} \right] & c\%_1 < c\% (T) \leq c\%_2, \\
\beta_T \tau_{bu,0} & c\%_2 < c\% (T) \end{cases}
\]

where \( \tau_{bu,0} \) is the initial bond strength, and \( c\% (T) \) can be found from \( \Delta D(T) \) as

\[
c\% (T) = 100 \left[ 1 - \left( 1 - \frac{\Delta D(T)}{D_0} \right)^2 \right],
\]

Uniaxial stress-strain diagrams for the concrete and reinforcing steel are adopted according to [3]. A nonlinear relationship between average bond stress, \( \tau_b \), and slip, \( s \), for the interface element is defined as

\[
\tau_b = \begin{cases} 
\frac{k_s s}{1 + \left[ \frac{s}{s_u} / \tau_{bu}(T) \right] - 2 \left( s / s_u \right)} & s \leq s_u \\
\beta_T \tau_{bu}(T) & s > s_u
\end{cases}
\]

where \( k_s \) is an initial stiffness, and \( s_u \) is the slip at \( \tau_{bu} \). The initial bond strength, \( \tau_{bu,0} \) can be estimated by the Tepfers formula

\[
\tau_{bu,0} = \frac{C_c + D_o / 2}{1.664 D_o}.
\]

where \( C_c \) is the concrete cover.

For localized corrosion, the maximum penetration of potting, \( P_{max} \), normally exceeds the average penetration, \( P_{av} \), calculated solely from \( i_{corr} \) values. The experimental results shows that the ratio between \( P_{max} \) and \( P_{av} \) is equal 4 to 8 (by Gonzales) or 4 to 10 (by Tuutti) in the case of repeated periods of wetting (in chloride environment). Generally, pits may be of different forms. For simplicity, a hemispherical form of pits is assumed (see fig.4). The radius of the pit, \( p \), at time \( T \), can be estimated (in mm) as

\[
p(T) = 0.0116 (T - T_i) i_{corr} P_{max} / P_{av}.
\]

The net cross/section area of a corroded bar (the added area in Fig.4) at time \( T > T_o \), is the calculated as

\[
A_r(T) = \begin{cases} 
\frac{\pi D_o^2}{4} - A_1 - A_2 & p(T) \leq \frac{\sqrt{2}}{2} D_o \\
A_1 - A_2 & \frac{\sqrt{2}}{2} D_o < p(T) \leq D_o \\
0 & p(T) > D_o
\end{cases}
\]

where

\[
A_1 = \frac{1}{2} \left[ \theta_1 \left( \frac{D_o}{2} \right)^2 - \alpha \left( \frac{D_o}{2} - \frac{p(T)}{D_o} \right)^2 \right] \\
A_2 = \frac{1}{2} \left[ \theta_2 \left( \frac{p(T)}{D_o} \right)^2 - \alpha \frac{p(T)^2}{D_o} \right]
\]
\[ \alpha = 2 p(T) \sqrt{1 - \left( \frac{p(T)}{D_o} \right)^2}, \quad \theta_1 = 2 \arcsin \left( \frac{\alpha}{D_o} \right), \quad \theta_2 = \arcsin \left( \frac{\alpha}{2 p(T)} \right) \]

Localized corrosion produces an oxide of iron different from the common rust produced in general corrosion, with lower volume per unit mass. Localized corrosion often does not cause disruption of the concrete cover. The partial reduction of the bond strength around pits has an insignificant influence on structural behavior. The yield stress, the modulus of elasticity and ultimate tensile strength of reinforcing are unaffected by corrosion.

### 3 Structural model

For the membrane and bending deformation of the reinforced concrete shell structure, we have chosen the SHELL91 layered shell element, on which we propose a plane state of stress on every single layer.

The stiffness matrix of reinforced concrete for the layer \(^{\text{ith}}\) can be written in the following form

\[
[D_t^{LR}] = [T_c] [D_c] [T_c] + \sum_{j=1}^{n} [T_s] [D_s] [T_s],
\]

where \([T_c], [T_s]\) are the transformation matrices for concrete and reinforcement separately and \([D_c], [D_s]\) are stiffness matrix

The stiffness matrix of equivalent steel layer is diagonal \((\mu_{ij}=0)\) and intermediate layer shear modulus is defined using the relation from stress-slip relations as

\[ G_{ij} = \partial \tau_{ij} / \partial s \]

The reduction of steel in accordance of corrosion effect will be considered as reduction of layer depth or layer stiffness.

### 4 Nonlinear analysis

The presented model of corrosion was implemented to the calculation model of the concrete nonlinear layered shell element created by Kralik [6].

![Fig.6 Failure during operating loads](image1.png)

![Fig.7 Steel corrosion depending on time](image2.png)
This calculation model was used for nonlinear analysis of the reliability of NPP concrete structure. On bottom of the concrete plate of the emergency tank was monitoring the cracking face of concrete.

The influence of these cracks and corrosion effect of steel reinforcement to safety of emergency tank and containment structure was considered after 10 and 20 years in next probabilistic study.

Following the experimental results a new concrete cracking layered finite shell element was developed and incorporated into the ANSYS system. One concrete layer was considered as orthotropic material for which the direction of a crack is the same as the direction of a principal strain. The failure function of the concrete was defined follow

\[ F_u^l = F_u^l(\varepsilon_p^u, \varepsilon_u^p, \xi) = 0, \quad F_u^l = \sqrt{\alpha_u \left(\frac{\varepsilon_p^u}{\varepsilon_1}\right)^2 + \left(\frac{\varepsilon_u^p}{\varepsilon_2}\right)^2} - \varepsilon_u^p = 0; \quad \frac{2}{3} \leq \alpha_u \leq 1 \]  

(10)

where \( \xi = 1 \) in compression \( \xi, = \left(\frac{\varepsilon_p^u}{\varepsilon_u^p}\right) \) in tension.

On base of nonlinear analysis providing the monotone increases of overpressure in CTMT were defined critical point in structure. These critical places correspond to concentration of singular tension forces after high bending deformation of wall at line “10” or “V” and the enfeeblement plate by hole of cell and near assembly cover.

5 Probabilistic analysis

The probability of loss integrity of reinforced concrete structure hence it will calculated from the probability of no accomplishment condition of reliability SF,

\[ P_f = P(S_F < 0), \quad SF = R_d - E_d \geq 0, \]  

(11)

where SF is the reliability condition defined by [7], \( R_d \) is design capacity of structure, \( E_d \) design load effect. In the case of calculus the resistance of reinforced concrete structure leads off the condition of section integrity (7). The probabilistic analysis of the condition integrity of containment was realized by simulation of design check using the direct method MONTE CARLO under system ANSYS. The distribution function of containment failure probability for normal distribution of input data obtains from nonlinear analysis with 2D failure criterion for mean properties values and overpressure 260,5kPa go out the presented consideration. For this case of probability distribution is the error factor equal to value 1,31.
6 Conclusion

This paper deals with the problem of the complex analysis of the buildings of nuclear power plants from the point of view of their resistance to possible accidents [6, 7]. The probability analysis of the concrete structure integrity were considered for the overpressure loads from 40kPa to 300kPa using the iterative stiffness of structure and mean properties of materials [7]. The probability of the containment failure (without degradation effects) using the normal distribution of the input parameters is equal to $8.10^{-6}$ (or $9.31.10^{-6}$) for overpressure 200kPa taking the 2D criteria of the structure failure (9). The results of the probability analysis of the containment failure under high overpressure show that in the case of the LOCA accident at 122,7kPa is probability lesser then required $10^{-4}$.

Acknowledgements

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7 References


