
JURAJ KRÁLIK

Abstract: This paper presents the methodology of the reliability analysis of the fire resistance of the steel structure of the cable way in NPP. The elastic and plastic solution of the steel structure under fire loads is discussed. The deterministic and probability analysis of the fire resistance of the steel structures are considered. The executed fire resistance analysis of the steel structures is investigated as the influence of temperature, permanent and variable loads. The Response Surface Method (RSM) for the nonlinear analysis of the fire structure reliability was used on program ANSYS. The advantages and disadvantages of the deterministic and probabilistic analysis of the fire safety are discussed.

Keywords: ANSYS, RSM, Fire, Probability, Nonlinearity, Safety, Reliability

1 Introduction

In consequence of the economic and life lost due to fire accident the new regulation was created in European countries [1, 3 and 4]. Those regulations specified:

- the escape ways by prescribing the number of emergency exits, the characteristics of the exit signs, the number of staircases and the width of the doors,
- the prevention of fire spread by referring to the concepts of “fire resistance” and “reaction to fire ”,
- the fire resistance of the structure in terms of ISO-fire resistance period, R30, 60, 90, or 120,
- the conditions for smoke and heat exhaust,
- the implementation of active fire fighting measures such as the number of hand extinguishers, smoke detectors and sprinklers,
- the access conditions for the fire brigade.

Each country defined its regulations generally based on its own perception of the fire safety problems [3, 4].

The objective of this paper is to describe a performance based more realistic and credible approach to the analysis of structural safety in case of fire, which takes also account of structural models, which should be as realistic as possible.

The objective of this paper is to describe a performance based more realistic and credible approach to the analysis of structural safety in case of fire, which takes also account of structural models, which should be as realistic as possible. The behavior of a structure in the fire situation may be performed either as a global structural analysis dealing with the entire structure, which should take into account the relevant failure mode under fire, the temperature dependent material properties, or as an analysis of parts of the structure, or as a member analysis (see fig.1). In the case also the support and restraint conditions of the member, applicable at time \( t=0 \), may generally by assumed to remain unchanged throughout the fire exposure. According to EN1992-1-2, EN1993-1-2 and EN...
1994-1-2 the assessment of structural behavior in a fire design situation shall be based on one of the following permitted design procedures:

- recognized design situations on the base of the tabulated data,
- simple calculation models for specific type of structural members,
- advanced calculation models able to deal with any kind of the structural model.

2 Safety assessment of fire resistance

Experiences from fire cases and their consequences are the main reasons for the developing of the fire safety standards [1, 2, 3, 4, 5, 7, 13, 14 and 17]. A list of codes, standards, and other legal documents being used to achieve this aim are based on the simple numerical methods. However, it is possible to solve fire resistance in another way [4]. This paper particularly shows the possibility of solution the fire resistance problem. The fire resistance of the structure could be verified by simplified or exact computational model [4, 9, 10 and 11]. This paper particularly shows the possibility of solution the fire resistance problem.

The fire resistance of the structure could be verified by simplified or exact computational model [4, 11 and 17]. From the structural behavior point of view we consider elastic or a plastic computational model. While using the elastic model, the static consideration is made of the linear elastic model and the critical intersection is tested with bending moment. Usage of the plastic model investigates the fire safety resistance of the structure until collapse. Fire safety of the structures can be solved by the deterministic or probabilistic method.

Simplified computational methods along with empirical formulations are widely used in daily design work [4]. Their main advantage is the simple formulation of critical temperature in the basis of which the stress of the structure is considered. The definition of the material properties, as well as the load condition, can be defined by deterministic or probabilistic access. In the case of deterministic access the conditions are established by the factors of load and structure resistance. In the case of probabilistic access the conditions are established by variable load factors and material properties of the structure [3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 16]. The probabilistic method describes the load and material property by histograms [4 and 11]. Fire resistance of the structure is evaluated by discrete histogram obtained from the probabilistic analysis.

3 Reliability of structures

Most problems concerning the reliability of building structures are defined today as a comparison of two stochastic values, action effects $E$ and the resistance $R$, depending on the variable material and geometric characteristics of the structural element [11]. The deterministic definition of the reliability condition depend on design values of action effect $E_d$ and resistance $R_d$ in form

$$R_d \geq E_d \quad (1)$$

and in the case of the probabilistic approach, it has the form

$$RF = R - E \geq 0 \quad (2)$$

where $RF$ is the reliability function, which can be expressed generally as a function of the stochastic parameters $X_1, X_2$ to $X_n$, used in the calculation of $R$ and $E$.

$$RF = g(X_1, X_2, ..., X_n) \quad (3)$$

The failure function $g(X)$ represents the condition (reserve) of the reliability, which can either be an explicit or implicit function of the stochastic parameters and can be single
(defined on one cross-section) or complex (defined on several cross-sections, e.g., on a complex finite element model).

Table 1 Target values for the reliability index βd and probability of failure pd by Eurocode 1990

<table>
<thead>
<tr>
<th>Limit state</th>
<th>Life time - 55 years</th>
<th>For 1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>βd</td>
<td>pd</td>
</tr>
<tr>
<td>Structural safety</td>
<td>3.8</td>
<td>7.23.10^-3</td>
</tr>
<tr>
<td>Serviceability</td>
<td>1.5</td>
<td>6.70.10^-2</td>
</tr>
</tbody>
</table>

The most general form of the probabilistic reliability condition is given as follows:

\[ p_f = P(R - E < 0) = P(RF < 0) < p_d \]  (4)

where \( p_d \) is the so-called design ("allowed" or "acceptable") value of the probability of failure. The reliability criteria are defined in the Eurocode [3] in dependency on reliability index \( \beta \), what is adequate to target level of failure probability (Table 1). In the case of the stochastic approach, various forms of analyses (statistical analysis, sensitivity analysis, probabilistic analysis) can be performed considering the probabilistic procedures, Eurocode 1990 recommends a 3-level reliability analysis. The approximation methods [11] - RSM was applied with nonlinear solution of fire response. Roux W.J. at 1998 has defined this method as follow : „Response surface method is a method for constructing global approximations to system behavior based on results calculated at various points in the design space“.

\[ Y = c_o + \sum_{i=1}^{N} c_i X_i + \sum_{i=1}^{N} c_i X_i^2 + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} c_{ij} X_i X_j \]  (5)

where \( c_o \) is the index of the constant member; \( c_i \) are the indices of the linear member and \( c_{ij} \) the indices of the quadratic member, which are given for predetermined schemes for the optimal distribution of the variables or for using regression analysis after calculating the response [11]. The concept of this method is described in fig.1. Approximate polynomial coefficients are given from the condition of the error minimum, usually by the "Central Composite Design Sampling" (CCD) method.

http://aum.svsfem.cz
4 Fire resistance of the electrical cable way structures

On a base of the requirements of the IAEA [5], US NRC [14], Eurocodes [3, 4] and national standards [15] the fire resistance of electrical cable way structures in nuclear power plants were considered. These structures are made from the steel perforate plate placed on steel console of U8 profile and fixed on ceiling with hanger of U8 profile and steel bar. There are analyzed four type of cable troughs - RSU 60.100 OV, RSU 60.200 OV, RSU 60.300 OV, RSU 60.400 OV and the cable shaft RDV 100, 200, 300, 400 with various width (100, 200, 300 and 400mm). The modulus of support is equal 1500mm. The fire resistance of the cable way supported structures RSU without the shaft was established by experiment in the laboratory TU Braunschweig [13]. The aim of the numerical analysis was to prove the fire resistance of the cable way supported structures with the shat RDV.

![Image of fire and cables](image)

Figure 2 Experimental test of the cable way structures in TU laboratory Braunschweig [13]

The calculation model of the electrical cable way support system (fig.2) was made from the shell elements SHELL43, beam elements BEAM181 and link elements LINK8 in program ANSYS. Four models were created – RSU130, RSU230, RSU330 and RSU430 for various widths of cable troughs (100, 200, 300 and 400mm).

The consider structures are exposed to next loading inputs: permanent load (G), variable load (Q) involves the load of the electrical cables, the uniform value of the temperature (T) and the characteristic value of the material properties reduced due to fire action. Those values are specified in codes and standards.

In the deterministic analysis there is the design value of effect of actions $E_d$ and resistance $R_d$ defined in accordance with the Eurocode (EN 1991-1-1. 2002) follow

$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot Q_k + \gamma_T \cdot T_k$  
and  
$R_d = f_{yk} / \gamma_M$

where $\gamma_G$, $\gamma_Q$, $\gamma_T$ are the partial factors of actions ($\gamma_G=\gamma_Q=\gamma_T=\gamma_M=1$), $G_k$, $Q_k$, $T_k$ are the characteristic values of the defined actions and $f_{yk}$.

In the probabilistic analysis there is the value of effect of actions $E$ defined in accordance with the JCSS code [7] (EN 1991-1-1. 2002) follow

http://aum.svsfem.cz
\[ E = e_{var}(g_{var}G_k + q_{var}Q_k + t_{var}T_k) \quad \text{and} \quad R = r_{var}k_{var}f_{var}f_{yk} \] (7)

where \( e_{var} \), \( g_{var} \), \( q_{var} \), \( t_{var} \), \( r_{var} \), \( k_{var} \), \( f_{var} \) are the variable functions defined in form of histogram.

Figure 3 FEM model of cable way structure RS430 (RSU 60.400 OV and RDV400)

5 Temperature loading

The fire load depends on fire scenario and the requirements of standards [2 and 3] to the fire safety of the electrical cable ways in NPP. There are defined the temperature-time curves and reduction factors for material properties. The temperature-time curve (Fig.5) for the electrical cable ways in the NPP was defined from the experimental test in fire chamber (table 2). The standards for the NPP structures [5] require the fire resistance of the cable way equal to 30min (F30).

Figure 4 The stress-strain relationships for the steel by EN 1993-1-2
The critical temperature for the time 30min is defined on the base of the temperature curve. The reduced coefficients for the strength and Young modulus is obtained from the EN 1993-1-2 [2] as follow (fig.4) –

\[
\begin{align*}
T_1 &= 841.8 \degree C \\
E_{30} &= 0.081 \quad E_\theta = 16,925GPa \\
k_{p,\theta} &= 0.045 \quad f_{ap,\theta} = 10,522MPa \\
k_{y,\theta} &= 0.089 \quad f_{ay,\theta} = 20,939MPa
\end{align*}
\]

Table 2 The temperature values versus time determined by experiment in fire chamber

<table>
<thead>
<tr>
<th>Time</th>
<th>Td1</th>
<th>Td2</th>
<th>Td3</th>
<th>Td4</th>
<th>Td5</th>
<th>Td6</th>
<th>Td7</th>
<th>Td8</th>
<th>Tave</th>
<th>Tn</th>
<th>To</th>
<th>Variation (d_t(%))</th>
<th>Pres [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>35.1</td>
<td>49.8</td>
<td>45.8</td>
<td>52.3</td>
<td>35.2</td>
<td>46.2</td>
<td>46.3</td>
<td>51.0</td>
<td>45.2</td>
<td>20.0</td>
<td>19.3</td>
<td>0.0</td>
<td>5.6</td>
</tr>
<tr>
<td>5</td>
<td>503.0</td>
<td>597.1</td>
<td>626.4</td>
<td>565.8</td>
<td>517.2</td>
<td>582.0</td>
<td>596.8</td>
<td>576.1</td>
<td>568.5</td>
<td>576.4</td>
<td>18.3</td>
<td>-13.9</td>
<td>13.4</td>
</tr>
<tr>
<td>10</td>
<td>671.9</td>
<td>883.4</td>
<td>686.0</td>
<td>667.2</td>
<td>648.4</td>
<td>677.0</td>
<td>686.3</td>
<td>664.4</td>
<td>677.1</td>
<td>678.4</td>
<td>19.4</td>
<td>-5.2</td>
<td>14.3</td>
</tr>
<tr>
<td>15</td>
<td>731.8</td>
<td>745.5</td>
<td>744.1</td>
<td>713.5</td>
<td>706.2</td>
<td>733.3</td>
<td>726.6</td>
<td>713.0</td>
<td>726.5</td>
<td>736.6</td>
<td>19.4</td>
<td>-3.6</td>
<td>14.1</td>
</tr>
<tr>
<td>20</td>
<td>791.0</td>
<td>740.5</td>
<td>767.3</td>
<td>745.0</td>
<td>738.1</td>
<td>748.6</td>
<td>749.7</td>
<td>762.9</td>
<td>747.5</td>
<td>781.4</td>
<td>19.4</td>
<td>-4.1</td>
<td>14.5</td>
</tr>
<tr>
<td>25</td>
<td>767.3</td>
<td>763.4</td>
<td>787.7</td>
<td>763.9</td>
<td>774.5</td>
<td>782.7</td>
<td>794.2</td>
<td>808.3</td>
<td>781.5</td>
<td>814.6</td>
<td>19.4</td>
<td>-3.9</td>
<td>17.7</td>
</tr>
<tr>
<td>30</td>
<td>802.8</td>
<td>828.5</td>
<td>856.5</td>
<td>838.6</td>
<td>812.3</td>
<td>943.6</td>
<td>852.5</td>
<td>852.0</td>
<td>836.8</td>
<td>841.8</td>
<td>18.8</td>
<td>-3.7</td>
<td>17.1</td>
</tr>
<tr>
<td>35</td>
<td>816.9</td>
<td>838.3</td>
<td>867.8</td>
<td>856.8</td>
<td>828.9</td>
<td>862.7</td>
<td>869.1</td>
<td>860.1</td>
<td>852.6</td>
<td>864.8</td>
<td>18.8</td>
<td>-3.1</td>
<td>17.4</td>
</tr>
<tr>
<td>40</td>
<td>855.2</td>
<td>876.3</td>
<td>900.9</td>
<td>875.0</td>
<td>866.4</td>
<td>906.2</td>
<td>918.0</td>
<td>911.0</td>
<td>856.6</td>
<td>884.7</td>
<td>19.0</td>
<td>-2.6</td>
<td>18.4</td>
</tr>
<tr>
<td>45</td>
<td>877.0</td>
<td>905.5</td>
<td>924.0</td>
<td>905.8</td>
<td>901.3</td>
<td>924.4</td>
<td>924.9</td>
<td>934.8</td>
<td>909.6</td>
<td>902.3</td>
<td>18.1</td>
<td>-2.2</td>
<td>17.7</td>
</tr>
<tr>
<td>50</td>
<td>897.4</td>
<td>916.1</td>
<td>948.0</td>
<td>925.4</td>
<td>912.6</td>
<td>942.9</td>
<td>940.3</td>
<td>950.1</td>
<td>929.6</td>
<td>918.1</td>
<td>19.4</td>
<td>-1.8</td>
<td>18.3</td>
</tr>
<tr>
<td>55</td>
<td>915.4</td>
<td>932.9</td>
<td>962.4</td>
<td>948.0</td>
<td>928.7</td>
<td>956.2</td>
<td>954.9</td>
<td>955.3</td>
<td>954.1</td>
<td>953.2</td>
<td>19.8</td>
<td>-1.5</td>
<td>17.5</td>
</tr>
<tr>
<td>60</td>
<td>924.4</td>
<td>946.8</td>
<td>970.1</td>
<td>955.7</td>
<td>946.4</td>
<td>972.4</td>
<td>987.7</td>
<td>968.3</td>
<td>956.4</td>
<td>945.3</td>
<td>19.9</td>
<td>-1.2</td>
<td>17.2</td>
</tr>
<tr>
<td>65</td>
<td>941.3</td>
<td>964.7</td>
<td>973.3</td>
<td>962.4</td>
<td>946.9</td>
<td>965.5</td>
<td>963.9</td>
<td>967.8</td>
<td>958.3</td>
<td>957.3</td>
<td>20.2</td>
<td>-1.0</td>
<td>15.9</td>
</tr>
<tr>
<td>70</td>
<td>945.5</td>
<td>945.5</td>
<td>973.4</td>
<td>960.4</td>
<td>957.5</td>
<td>970.2</td>
<td>965.0</td>
<td>970.2</td>
<td>965.4</td>
<td>958.4</td>
<td>20.6</td>
<td>-1.0</td>
<td>15.4</td>
</tr>
<tr>
<td>75</td>
<td>955.4</td>
<td>955.1</td>
<td>985.1</td>
<td>960.5</td>
<td>959.8</td>
<td>977.0</td>
<td>973.6</td>
<td>1000.0</td>
<td>973.3</td>
<td>976.7</td>
<td>20.7</td>
<td>-0.9</td>
<td>18.1</td>
</tr>
<tr>
<td>80</td>
<td>983.5</td>
<td>984.6</td>
<td>989.2</td>
<td>985.9</td>
<td>972.1</td>
<td>991.3</td>
<td>994.0</td>
<td>1000.0</td>
<td>982.1</td>
<td>988.4</td>
<td>20.9</td>
<td>-0.9</td>
<td>15.5</td>
</tr>
<tr>
<td>85</td>
<td>995.2</td>
<td>997.5</td>
<td>1002.0</td>
<td>1000.0</td>
<td>986.0</td>
<td>1001.0</td>
<td>996.3</td>
<td>1000.0</td>
<td>995.7</td>
<td>997.4</td>
<td>21.3</td>
<td>-0.9</td>
<td>14.8</td>
</tr>
<tr>
<td>90</td>
<td>999.6</td>
<td>999.7</td>
<td>1015.0</td>
<td>1017.0</td>
<td>998.3</td>
<td>1012.0</td>
<td>1005.0</td>
<td>1000.0</td>
<td>1009.3</td>
<td>1005.9</td>
<td>21.1</td>
<td>-0.8</td>
<td>15.7</td>
</tr>
<tr>
<td>95</td>
<td>1001.0</td>
<td>992.7</td>
<td>1016.0</td>
<td>1016.0</td>
<td>1000.0</td>
<td>1017.0</td>
<td>1012.0</td>
<td>1012.0</td>
<td>1013.0</td>
<td>1017.0</td>
<td>21.2</td>
<td>-0.8</td>
<td>14.5</td>
</tr>
<tr>
<td>100</td>
<td>1003.0</td>
<td>985.3</td>
<td>1017.0</td>
<td>1019.0</td>
<td>1002.0</td>
<td>1016.0</td>
<td>1012.0</td>
<td>1012.0</td>
<td>1012.0</td>
<td>1018.2</td>
<td>21.3</td>
<td>-0.8</td>
<td>15.7</td>
</tr>
</tbody>
</table>

![Figure 5 The thermal curve for the electrical support structures by laboratory test](http://aum.svsfem.cz)

6 Nonlinear material and geometric solution

The action of the high temperature due to fire effect can be analyzed using elastic or elastic-plastic solution. The elastic solution gives us the conservative results in comparison with the experimental results in the fire laboratory [17]. The elastic-plastic solution of the high temperature effect lead on to more real results. The plastic deformation of the structure results to the large strain. These deformations can no longer
be neglected. The solution of the nonlinear (geometric and material) equations is solved on the base of the Newton-Raphson method \[11\] in the increment of the displacement

\[
\{du\} = [N]\{dr\},
\]

(8)

where \(\{du\}\) the vector of increment of displacement on element is, \([N]\) is the matrix of shape functions, \(\{dr\}\) is the increment of unknown nodal displacement parameters. The increment vector of large strain \(\{dr\}\) is defined following

\[
\{d\varepsilon\} = \left([B_e] + [B_{NL}]\right)\{dr\},
\]

(9)

where \([B_e]\) (resp. \([B_{NL}]\)) is the vector of linear (resp. nonlinear) deformation shape. The material equations for the incremental theory of plasticity is defined in form

\[
\{d\sigma\} = [D_{\sigma p}]\{d\varepsilon\}, \quad [D_{\sigma p}]=[D_e] - \frac{[D_e]\left\{\frac{\partial g(\sigma)}{\partial \{\sigma\}}\right\}^T[D_e]}{H + \left\{\frac{\partial g(\sigma)}{\partial \{\sigma\}}\right\}^T[D_e]^{-1}\left\{\frac{\partial g(\sigma)}{\partial \{\sigma\}}\right\},
\]

(10)

where \(\{d\varepsilon\}\) is the strain vector increment, \(\{d\sigma\}\) is the stress vector increment, \(g(\sigma)\) is the yield function, who is considered by Von Mises for the isotropic theory of plasticity in form

\[
g(\sigma) = 1 - \frac{\sigma_{ef,E}}{\sigma_{uy,R}} \geq 0, \quad \sigma_{ef} = \left(1 - \frac{1}{2}\left[\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2\right]\right)^{\frac{1}{2}},
\]

(11)

where \(\sigma_{ef,E}\) is the effective (equivalent) stress, \(\sigma_{uy,R}\) is the ultimate value of the stress depended on temperature due to fire.

On the base of the Lagrangian formulation in FEM the equilibrium equation for the \(i^{th}\) step and the increment vector of forces \(\{\Delta F_i\}\) is following

\[
[K_T]\{\Delta r_i\} = \{\Delta F_i\} - \{F_{iNR}\},
\]

(12)

where the tangent matrix has the form

\[
[K_T] = [K_{EP,i}] + [K_{Gi}],
\]

(13)

\([K_{EP,i}]\) is the elastic-plastic stiffness matrix

\[
[K_{EP,i}] = \int_B [B_i][D_{EP,i}][B_i]d\Omega,
\]

(14)

where \([B_i]\) is the strain-displacement matrix in terms of current geometry and the current elastic-plastic material matrix \([D_{EP,i}]\)

\([K_{Gi}]\) is the geometric stiffness (stress stiffness) contribution

\[
[K_{Gi}] = \int_B [B_{Gi}][S_i][B_{Gi}]d\Omega,
\]

(15)

http://aum.svsfem.cz
where $[S_i]$ is a matrix of the current Cauchy (true) stresses $\{\sigma_i\}$ in the global Cartesian system. The Newton-Raphson restoring force vector is:

$$ \{F^{NR}_i\} = \int [B_i]^T \{\sigma_i\} d\Omega $$

(16)

![Figure 6 The Newton-Raphson method](image)

The Newton-Raphson method is the most rapidly convergent process for solutions of problems in which only one evaluation of $\{F^{NR}_i\}$ is made in each iteration. Of course, this assumes that the initial solution is within the zone of attraction and, thus, divergence does not occur. Indeed, the Newton-Raphson method is the only process described here in which the asymptotic rate of convergence is quadratic. The method is sometimes simply called Newton’s method but it appears to have been simultaneously derived by Raphson, and the interesting history of its origins is given in [11].

7 Uncertainties of input variables

Reality is more complex than deterministic design situation, as the number of variables as well on the side of actions as on the side of resistance is often quite large.

### Table 3 Probabilistic model of input parameters [6]

<table>
<thead>
<tr>
<th>Name</th>
<th>Quantity</th>
<th>Character. value</th>
<th>Variable paramet.</th>
<th>Histogram</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Min.</th>
<th>Max. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Young’s modulus</td>
<td>$E_k$</td>
<td>$m_{var}$</td>
<td>Lognormal</td>
<td>1.100</td>
<td>0.066</td>
<td>0.000</td>
<td>1.299</td>
</tr>
<tr>
<td>Stress yield</td>
<td>$f_{y_k}$</td>
<td>$k_{var}$</td>
<td>Lognormal</td>
<td>1.100</td>
<td>0.066</td>
<td>0.000</td>
<td>1.299</td>
<td></td>
</tr>
<tr>
<td>Reduction factor</td>
<td>$r_k$</td>
<td>$k_{var}$</td>
<td>Lognormal</td>
<td>1.000</td>
<td>0.050</td>
<td>0.000</td>
<td>1.149</td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>Permanent</td>
<td>$G_k$</td>
<td>$g_{var}$</td>
<td>Normal</td>
<td>1.000</td>
<td>0.030</td>
<td>0.916</td>
<td>1.084</td>
</tr>
<tr>
<td>Variable</td>
<td>$Q_k$</td>
<td>$q_{var}$</td>
<td>Gama T.I</td>
<td>0.600</td>
<td>0.215</td>
<td>0.000</td>
<td>1.378</td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>Fire-temperature</td>
<td>$T_k$</td>
<td>$t_{var}$</td>
<td>Gama T.I</td>
<td>0.822</td>
<td>0.246</td>
<td>0.000</td>
<td>1.684</td>
</tr>
<tr>
<td>Model</td>
<td>Model uncertainties</td>
<td>$c_E$</td>
<td>$o_{var}$</td>
<td>Lognormal</td>
<td>1.000</td>
<td>0.050</td>
<td>0.000</td>
<td>1.149</td>
</tr>
<tr>
<td>Resistance uncertain.</td>
<td>$c_R$</td>
<td>$o_{var}$</td>
<td>Lognormal</td>
<td>1.000</td>
<td>0.050</td>
<td>0.000</td>
<td>1.149</td>
<td></td>
</tr>
</tbody>
</table>

Hence the use of probabilistic procedures gets very quickly time consuming for everyday’s practical engineering. The variability of input parameters are described in table 3 on the base of the literature requirements [4, 7 and 11].

8 Reliability criteria for fire resistance

Reliability of the foundation structures is analyzed in accordance of national and Eurocode standard requirements [3 and 4] for serviceability and ultimate limit state. The
serviceability of structure is limited by equivalent strain and the ultimate limit state by equivalent stress in dependency on fire temperature.

The failure function of the equivalent strain and stress is defined in the form

\[ g(\varepsilon) = 1 - \frac{\varepsilon_{ef}}{\varepsilon_{ayR}} \geq 0, \quad g(\sigma) = 1 - \frac{\sigma_{ef}}{\sigma_{ayR}} \geq 0 \]  

(17)

where \( \varepsilon_{ef} \) and \( \sigma_{ef} \) is the equivalent strain and stress of action and \( \varepsilon_{ayR} \) and \( \sigma_{ayR} \) are the ultimate strain and stress depending on fire temperature.

9 Sensitivity analysis

Sensitivity analysis of the influence of the variable input parameters to the reliability of the structures depends on the statistical independency between input and output parameters.

\[
s_{ij} = \frac{1}{n-1} \sum_{i=1}^{n} (R_i - \bar{R})(E_i - \bar{E})
\]

\[
r_S = \frac{n \sum (R_i \bar{R})(E_i \bar{E})}{\sqrt{\sum (R_i \bar{R})^2} \sqrt{\sum (E_i \bar{E})^2}}
\]

(18)

Figure 7 Sensitivity analysis of the equivalent strain and stress versus input variables

Figure 8 Sensitivity analysis of the reliability functions RE and RS versus input variables

http://aum.svsfem.cz
where $R_i$ is rank of input parameters within the set of observations $[x]^T$, $E_i$ is rank of output parameters within the set of observations $[y]^T$, $\bar{R}$, $\bar{E}$ are average ranks of the parameters $R_i$ and $E_i$ respectively.

The variability of three input quantities (variable load, model and resistance uncertainties) is important to the equivalent strain and stress of cable way structures.

10 Comparison of deterministic and probabilistic analyses

The probabilistic part of the assessment is performed by the software ANSYS. The task is to consider the members of the cable way structures exposed to permanent, variable and temperature load due to fire effect (probability of fire is $P_{\text{fire}} = 0.002$).

![Figure 9](image.jpg)

Figure 9 The equivalent strain and stress of the cable way structure

![Figure 10](image.jpg)

Figure 10 The deflection and Mises strain of the cable way structure – RSU 100, 200, 300 and 400

The deflection and the Mises strain of the cable way structures for various widths of cable troughs (100, 200, 300 and 400mm) and fire resistance (30, 60 and 90 min) is compared in fig.10.

<table>
<thead>
<tr>
<th>Model</th>
<th>Equivalent strain (Von Mises)</th>
<th>Equivalent stress (Von Mises) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fractile 5%</td>
<td>Mean 50%</td>
</tr>
<tr>
<td>RS130</td>
<td>-0.0009980</td>
<td>0.0014791</td>
</tr>
<tr>
<td>RS230</td>
<td>0.0001994</td>
<td>0.0008968</td>
</tr>
<tr>
<td>RS330</td>
<td>0.0002112</td>
<td>0.0005266</td>
</tr>
<tr>
<td>RS430</td>
<td>0.0006762</td>
<td>0.0007590</td>
</tr>
</tbody>
</table>

http://aum.svsfem.cz
Table 5 Results of deterministic analyses of the cable way structures

<table>
<thead>
<tr>
<th>Model</th>
<th>Equivalent strain (Von Mises)</th>
<th>Equivalent stress (Von Mises)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum action</td>
<td>Resistance</td>
</tr>
<tr>
<td>RS130</td>
<td>0.0077235</td>
<td>38.618</td>
</tr>
<tr>
<td>RS230</td>
<td>0.0022362</td>
<td>11.181</td>
</tr>
<tr>
<td>RS330</td>
<td>0.0009144</td>
<td>4.457</td>
</tr>
<tr>
<td>RS430</td>
<td>0.0008993</td>
<td>4.497</td>
</tr>
</tbody>
</table>

Reliability of the foundation structures is analyzed in accordance of national and Eurocode standard requirements [3 and 4] for serviceability and ultimate limit state. The serviceability of structure is limited by equivalent strain and the ultimate limit state by equivalent stress in dependency on fire temperature.

The comparison of deterministic and probabilistic solution of the safety and reliability of the fire resistance of cable way structures is documented in the table 4 and 5. The histogram of reliability function $RF(\varepsilon)$ (failure function of the equivalent strain) are presented in fig.11. The differences between deter-ministic and probabilistic results are equal about to 2.3-45.9% (or 2.3-19.1%) for 95% equivalent strain fractile (or stress fractile) values.

11 Conclusions

This paper deals with the possibility of the deterministic and probabilistic analysis of the reliability of the cable way support structures depending on variability of the load, material and model characteristics. The analysis of the fire resistance of four types of cable way structures by deterministic as well as probabilistic calculation is shown in this paper. The fire resistance of the cable way structures are limited by the ultimate Mises strain $\varepsilon_u = 0.02$. The 49 simulations using approximate method RSM for four cases were calculated in the real time on PC (max $CPU = 728$ sec). The nonlinear solution was running in max 191 steps. The output quantities were determined from $10^6$ Monte Carlo simulations. The probabilistic method shows that the probability of the failure of all structures is less than target probability $p_d = 7.23.10^{-5}$. However, the probabilistic calculation provides us with possibility of sensibility analysis, on the base of which the extreme load conditions on the cable way structures can be identified or also modified.

References


**Acknowledgement**

The project was realized with the financial support of the Grant Agency of the Slovak Republic (VEGA). The project registration number is VEGA 1/1039/12.

http://aum.svsfem.cz
Contact address:
Juraj Kráľ, prof.Ing.CSc.,
Faculty of Civil Engineering STU Bratislava, Radlinského 11, Bratislava 813 68, Slovakia,
e-mail: juraj.kralik@stuba.sk