Comparative Analysis of the Reliability of Steel Structure with Pinned and Rigid Nodes Subjected to Fire

Katarzyna Kubicka 1, Urszula Radoń 1, Waldemar Szaniec 1, Urszula Pawlak1
1 Kielce University of Technology, Poland

ksuckert@tu.kielce.pl

Abstract. The paper concerns the reliability analysis of steel structures subjected to high temperatures of fire gases. Two types of spatial structures were analysed, namely with pinned and rigid nodes. The fire analysis was carried out according to prescriptions of Eurocode. The static-strength analysis was conducted using the finite element method (FEM). The MES3D program, developed by Szaniec (Kielce University of Technology, Poland), was used for this purpose. The results received from MES3D made it possible to carry out the reliability analysis using the Numpress Explore program that was developed at the Institute of Fundamental Technological Research of the Polish Academy of Sciences [9]. The measurement of reliability of structures is the Hasofer-Lind reliability index (β). The reliability analysis was carried out according to approximation (FORM, SORM) and simulation (Importance Sampling, Monte Carlo) methods. As the fire progresses, the value of reliability index decreases. The analysis conducted for the study made it possible to evaluate the impact of node types on those changes. In real structures, it is often difficult to define correctly types of nodes, so some simplifications are made. The presented analysis contributes to the recognition of consequences of such assumptions for the safety of structures, subjected to fire.

1. Introduction
In the design of spatial steel structures, it is important how nodes are modelled. The approach adopted to node modelling is closely related to the solutions used for connecting individual structural elements together. Many of the currently used systems were developed as long as decades ago. The popular solutions include Oktoplatte [1] and SDC [2] welded connections. Bolted connections can be used in many systems, e.g. Unibat [3], Tridimatec [3], Nodus [4] and Mero [5]. Figure 1 shows the diagrams of SDC and Mero connections, which are identified as rigid and pinned ones, respectively.

![Figure 1. Connection systems: a) SDC [6], b) Mero [7]](image-url)
In the SDC system, steel tubes are the working elements, and the connection technique involves the welding of all components. The node is composed of two lightweight cast steel shells into which the tubes are inserted and then fixed.

The MERO node system developed by Dr Max Mengeringhausen over seventy years ago is still in use. The node basic component is a solid hot-pressed steel ball that has flat facets and threaded holes. Members are tubular bars with cone-shaped steel forgings welded at the ends which accommodate connecting hexagonal bolts. Up to 18 members can be connected at a joint without eccentricity. Nodes are manufactured in different sizes with the diameter ranging from 46.5 do 350mm, and the corresponding bolts vary in size from M12 to M64, with the maximum permissible force of 1413 kN.

2. Method of analysis

The analysis was conducted for a steel spatial structure shown in Figs. 2. It was assumed that the structure was made from circular S235 hollow sections. The members constituting the top and lower chords were made from CHS 20x3.2 profiles, and bracing elements from CHS 30x3.2. The fire proofing insulation material was sprayed-on vermiculite coating having increased density and a thickness of 3 cm. The material had the following thermal characteristics: specific heat \( c_p = 1100 \) J/(kgK), density \( \rho_p = 550 \) kg/m\(^3\) and thermal conductivity \( \lambda = 0.12 \) W/(mK).

![Element's number and Profiles](image)

| Element's number | Profiles |
|------------------|----------|
| 1-16             | CHS      |
| 17-32            | CHS      |

![Node's number and blocked direction of translation](image)

| Node's number | x [m] | y [m] | z [m] | blocked direction of translation |
|---------------|-------|-------|-------|----------------------------------|
| 1             | 0.00  | 0.00  | 0.00  | x,y,z                            |
| 2             | 3.00  | 0.00  | 0.15  | y,z                              |
| 3             | 0.00  | -3.00 | 0.00  | z                                 |
| 4             | 3.00  | -3.00 | 0.15  | z                                 |
| 5             | 1.50  | 1.50  | 1.50  | (-)                              |
| 6             | 4.50  | 1.50  | 1.65  | (-)                              |
| 7             | 1.50  | -1.50 | 1.50  | (-)                              |
| 8             | 4.50  | -1.50 | 1.65  | (-)                              |
| 9             | -     | 1.50  | 1.35  | (-)                              |
| 10            | -     | -1.50 | 1.35  | (-)                              |
| 11            | 1.50  | -4.50 | 1.50  | (-)                              |
| 12            | -     | -4.50 | 1.35  | (-)                              |
| 13            | 4.50  | -4.50 | 1.65  | (-)                              |

Figure 2. Analyzed spatial structure
Table 1. Effect of action for the structure with pinned (a) and rigid (b) connections

| Element's number | Effect of actions [kN] | Axial forces [kN] | Bending moment My [kNm] | Bending moment Mz [kNm] |
|------------------|------------------------|-------------------|------------------------|------------------------|
| 1-4              | -0.02                  | 0                 | 0.009771               | 0.000017               |
| 5,7,9,11,13-16   | 2.00                   | 1.98              | 0.011101               | 0.000007               |
| 6,8,10,12        | 3.98                   | 3.96              | 0.0111290              | 0                      |
| 17,30            | -3.42                  | 7                 | 0.0111036              | 0.000124               |
| 18,21,26,29      | -3.44                  | 8                 | 0.011199               | 0.000002               |
| 19,32            | -3.35                  | 9,13              | 0.010907               | 0.00029                |
| 20,23,28,31      | -3.33                  | 10                | 3.96                   | 0.011132               |
| 22, 25-          | -3.46                  | 11,14             | 1.98                   | 0.010942               |
| most stressed elements |                  | 12                | 3.95                   | 0.0111199              |
| 24,27            | -3.32                  | 15                | 1.98                   | 0.0110360              |
|                  |                        | 16                | 1.98                   | 0.007231               |
|                  |                        | 17,30             | -3.44                  | 0.009793               |
|                  |                        | 18,29             | -3.45                  | 0.016207               |
|                  |                        | 19,32             | -3.34                  | 0.021237               |
|                  |                        | 20,31             | -3.34                  | 0.001462               |
|                  |                        | 21, 26-          | -3.45                  | 0.016178               |
|                  |                        | most stressed elements |              | 0.005648               |
|                  |                        | 22, 25           | -3.45                  | 0.021268               |
|                  |                        | 23,28            | -3.34                  | 0.016149               |
|                  |                        | 24,27            | -3.33                  | 0.009687               |

A two-stage analysis was performed for the study. The first stage involved static and thermal computations for fire conditions. That was done using the MES3D program developed by Szaniec [8]. The results received from MES3D made it possible to carry out the reliability analysis with the Numpress Explore program developed at the Institute of Fundamental Technological Research of the Polish Academy of Sciences [9]. The measurement of the reliability of structures was the Hasofer-Lind reliability index (β). The reliability analysis was carried out according to approximation (FORM, SORM) and simulation (Importance Sampling, Monte Carlo) methods [10,11,12,13]. In this group of methods single elements of structure are consider in contrast to system reliability analysis [14] and methods connected with spectral analysis of stiffness matrix [15-17].

As the fire progresses, the value of reliability index decreases. The analysis conducted for the study made it possible to evaluate the impact of node types on those changes. In the study two types of nodes were analyzed, namely pinned and rigid ones. In real structures, it is often difficult to define correctly types of nodes, so some simplifications are made. The presented analysis contributes to the recognition of consequences of such assumptions for the safety of structures subjected to fire.

As regards the analysis of spatial truss with pinned connections, principal focus was given to compressed elements, as their bearing capacity is lower compared with tension elements. In the basic design situation, treated as equivalent to fire duration "t=0", load bearing capacity analysis was carried
out according the PN-EN 1993-1-1 standard. The resistance of the elements in compression in accidental fire situation was computed, acc to Eurocode PN-EN 1993-1-2, from the following formula:

\[ N_{h,f,\theta} = \chi_{\beta} A k_{y,\theta} f_y \]  

(1)

where \( k_{y,\theta} \) – reduction factor for yield strength, depending on the temperature of the element (defined in Table 3.1 PN-EN 1993-1-2), \( A \) - cross-sectional area, \( f_y \) - yield strength, \( \chi_{\beta} \) - flexural buckling coefficient in the fire design situation, computed as for the regular design situation, with non-dimensional slenderness reduced acc. the formula below:

\[ \lambda_0 = \left[ \frac{k_{y,\theta}}{k_{E,\theta}} \right]^{0.5} \]  

(2)

where:

\( \lambda_0 \) - non-dimensional slenderness in the basic design situation, \( k_{y,\theta}, k_{E,\theta} \) - the reduction factor for the yield strength and the reduction factor for the linear elastic range of steel at temperature \( \theta_a \), respectively, determined in accordance with Table 3.1 PN-EN 1993-1-2.

When the structure is analysed as a spatial with rigid nodes, it is necessary to account for the interaction of compression and bending of individual elements. For the regular design situation, the computations were made according PN-EN 1993-1-1. For the fire situation, the stability condition was checked due to flexural buckling, which was done according the formula below:

\[ \frac{N_{\beta}}{\chi_{\min,\beta} A k_{y,\theta} f_y} + \frac{k_y M_{y,\beta}}{W_{pl,y} k_{y,\theta} f_y} + \frac{k_z M_{z,\beta}}{W_{pl,z} k_{y,\theta} f_y} \leq 1 \]  

(3)

where \( N_{\beta}, M_{y,\beta}, M_{z,\beta} \) – respective cross-sectional forces under fire conditions (for the structure of concern, they remain constant), \( \chi_{\min,\beta} \) - minimum value of buckling coefficients about y and z axes (in the case under analysis, those values were equal), \( W_{pl,y}, W_{pl,z} \) – sectional modulus. Factors \( k_y \) and \( k_z \) were defined as follows:

\[ k_y = 1 - \frac{\mu_y N_{\beta}}{\chi_{y,\beta} A k_{y,\theta} f_y} \leq 3 \]  

(4a)

\[ k_z = 1 - \frac{\mu_z N_{\beta}}{\chi_{z,\beta} A k_{y,\theta} f_y} \leq 3 \]  

(4b)

where:

\[ \mu_y = \left( 2 \beta_{M,z} - 5 \right) \bar{\beta}_{z,\theta} + 0.44 \beta_{M,z} - 0.29 \leq 0.8 \]  

(5a)

\[ \mu_z = \left( 2 \beta_{M,z} - 5 \right) \bar{\beta}_{z,\theta} + 0.44 \beta_{M,z} - 0.29 \leq 0.8 \]  

(5b)

In the above equation, \( \beta_{M,z} \) is the equivalent uniform moment factor, defined in accordance with PN-EN 1993-1-2.

3. Results and discussion

When the structure was analysed as a spatial truss with pinned nodes, the limit state function was defined as follows:

\[ g_{h,basic} = 1 - \frac{N}{\chi A f_y} \]  

(6a)
\[ g_{h,\text{fire}} = 1 - \frac{N}{\chi_{\text{fi}} \cdot A \cdot f_y} \]  

(6b)

where \( g_{h,\text{basic}}, g_{h,\text{fire}} \) - the limit state function for pinned structure in the basic and fire design situations, 
\( \chi, \chi_{\text{fi}} \) - the reduction factors for flexural buckling about the weaker axis in the basic and fire situations. This parameter was assumed as deterministic, others as probabilistic with the characteristics listed in table 2.

**Table 2.** Probabilistic characteristics of random variables for structure with pinned connections

| Name of parameter          | Symbol | Expected value | Coefficient of variation | Standard deviation |
|---------------------------|--------|----------------|--------------------------|--------------------|
| Effect of actions         | N      | 3.46 kN        | 10%                      | 0.346 kN           |
| Cross-sectional area      | A      | 0.000269 m²    | 6%                       | 0.00001614 m²      |
| Yield strength            | f_y    | 235 MPa        | 8%                       | 18.8 MPa           |

The results of the reliability analysis for structure with pinned connection are presented in the table 3.

**Table 3.** Monitoring the reliability index of structure with pinned connections in successive minutes of the fire duration

| Fire duration [min] | Temperature of the element [°C] | \( \chi_{\text{fi}} \) | Reliability index \( \beta \) |
|---------------------|---------------------------------|-------------------------|------------------------------|
|                     |                                 |                         | FORM | SORM | Monte Carlo | Importance Sampling |
| 0                   | 20                              | 0.11043                 | 4.86283 | 4.83967 | 4.46518 | 4.77768 |
| 5                   | 22                              | 0.095218                | 3.90137 | 3.88999 | 3.9444 | 3.83731 |
| 10                  | 46                              | 0.095218                | 3.90137 | 3.88999 | 3.9444 | 3.83731 |
| 15                  | 79                              | 0.095218                | 3.90137 | 3.88999 | 3.9444 | 3.83731 |
| 20                  | 116                             | 0.093872                | 3.80448 | 3.79406 | 3.80817 | 3.72294 |
| 25                  | 154                             | 0.090657                | 3.56596 | 3.55761 | 3.29053 | 3.49985 |
| 30                  | 191                             | 0.087502                | 3.32171 | 3.31508 | 3.2388 | 3.26131 |
| 35                  | 227                             | 0.08441                 | 3.07193 | 3.068 | 2.98888 | 3.01972 |
| 40                  | 263                             | 0.081295                | 2.80922 | 2.80602 | 2.82016 | 2.74206 |
| 45                  | 297                             | 0.078331                | 2.54826 | 2.54561 | 2.5427 | 2.48524 |
| 50                  | 330                             | 0.075433                | 2.28211 | 2.27988 | 2.24217 | 2.22541 |
| 55                  | 362                             | 0.072604                | 2.01116 | 2.00878 | 1.98196 | 1.93624 |
| 60                  | 392                             | 0.069933                | 1.74466 | 1.74271 | 1.72617 | 1.66013 |
For the structure with rigid nodes, for basic \((g_{r,\text{basic}})\) and fire \((g_{r,\text{fire}})\) situations, limit states functions are defined as follows:

\[
g_{r,\text{basic}} = 1 - \frac{N}{\chi \cdot A \cdot f_y} - k_y \frac{M_y}{\chi_{LT} \cdot M_{y,Rk}} - k_z \frac{M_z}{M_{z,Rk}}
\]

\[
g_{r,\text{fire}} = 1 - \frac{N}{\chi f_y} - k_y \frac{M_y}{W_{pl,y} \cdot f_y} - k_z \frac{M_z}{W_{pl,z} \cdot f_y}
\]

The probabilistic characteristic of random variables of the structure with rigid connections are shown in the table 4.

**Table 4.** Probabilistic characteristics of random variables for structure with rigid connections

| Name of parameter          | Symbol | Expected value | Coefficient of variation | Standard deviation |
|---------------------------|--------|----------------|--------------------------|--------------------|
| Effect of actions         | N      | 3.45 kN        | 10%                      | 0.345 kN           |
| (elements 21,26)          | My     | 0.016178 kNm   | 10%                      | 0.0016178 kNm      |
|                           | Mz     | 0.005648 kNm   | 10%                      | 0.0005648 kNm      |
| Cross-sectional area      | A      | 0.000269m²     | 6%                       | 0.00001614 m²      |
| Yield strength            | f_y    | 235 MPa        | 8%                       | 18.8 MPa           |
| Sectional modulus         | W_{pl,y}=W_{pl,z} | 0.00000231m³ | 6%                       | 0.0000001386m³     |

The results of the reliability analysis for structure with rigid connections are shown in table 5.

**Table 5.** Monitoring the reliability index of structure with rigid connections in successive minutes of the fire

| Fire duration [min] | Temperature of the element [°C] | \(\chi_f\) | \(k_y\) | \(k_z\) | Reliability index \(\beta\) |
|---------------------|---------------------------------|------------|--------|--------|---------------------------|
|                     |                                 |            |        |        | FORM                      | SORM     | Monte Carlo | Importance Sampling |
| 0                   | 20                              | 0.11043    | not applicable |        | 4.6459 | 4.63345 | 4.67082 | 4.655 |
| 5                   | 22                              | 0.095218   | 2.01   | 0.91  | 3.31011 | 3.30443 | 3.23888 | 3.32656 |
| 10                  | 46                              | 0.095218   | 2.01   | 0.91  | 3.31011 | 3.30443 | 3.23888 | 3.32656 |
| 15                  | 79                              | 0.095218   | 2.01   | 0.91  | 3.31011 | 3.30443 | 3.23888 | 3.32656 |
| 20                  | 116                             | 0.093872   | 2.05   | 0.91  | 3.20563 | 3.20044 | 3.22816 | 3.15591 |
| 25                  | 154                             | 0.090657   | 2.12   | 0.9   | 2.95715 | 2.95376 | 2.8943  | 2.97746 |
| 30                  | 191                             | 0.087502   | 2.19   | 0.9   | 2.70256 | 2.69968 | 2.74198 | 2.70648 |
| 35                  | 227                             | 0.08441    | 2.28   | 0.9   | 2.43787 | 2.43538 | 2.48399 | 2.40438 |
| 40                  | 263                             | 0.081295   | 2.36   | 0.89  | 2.16459 | 2.1624  | 2.20883 | 2.08837 |
| 45                  | 297                             | 0.078331   | 2.46   | 0.89  | 1.88761 | 1.88537 | 1.94289 | 1.83882 |
| 50                  | 330                             | 0.075433   | 2.56   | 0.89  | 1.60627 | 1.60433 | 1.65394 | 1.56206 |
| 55                  | 362                             | 0.072604   | 2.67   | 0.88  | 1.31943 | 1.31767 | 1.33138 | 1.2356 |
| 60                  | 392                             | 0.069933   | 2.77   | 0.87  | 1.04    | 1.03836 | 1.0517  | 1.002 |
In the figure 3, the comparison of the reliability index (according to FORM method) for the structure with rigid and pinned nodes is presented. The dotted line indicates the required reliability index, which for fire situation is equal to 1.34 [18].

![Reliability index according to FORM method](image)

**Figure 3.** Spatial structure analyzed as a frame (rigid nodes) and as a truss (pinned nodes)

In this paper, approximation (FORM, SORM) and simulation (Importance Sampling, Monte Carlo) methods were used. The simulation methods are more time-consuming, especially the Monte Carlo method, because it may need a big sample size, where the reliability index is high. The time of analysis according to different methods is presented in Table 6.

| Fire duration [min] | FORM/SORM rigid/pinned nodes | Monte Carlo pinned nodes | Monte Carlo rigid nodes | Importance Sampling pinned nodes | Importance Sampling rigid nodes |
|---------------------|-------------------------------|--------------------------|------------------------|----------------------------------|-------------------------------|
|                     | time                          | sample size              | time                   | sample size                      | time                          | sample size                      | time                          | sample size                      |
| 0                   | 306s                          | 1 000 000                | 3879s                  | $10^7$                          | 2s                            | 10 000                        | 2s                            | 10 000                        |
| 5                   | 29s                           | 100 000                  | 36s                    | $10^5$                          | 1s                            | 10 000                        | 1s                            | 10 000                        |
| 10                  | 29s                           | 100 000                  | 36s                    | $10^5$                          | 1s                            | 10 000                        | 1s                            | 10 000                        |
| 15                  | 29s                           | 100 000                  | 36s                    | $10^5$                          | 1s                            | 10 000                        | 1s                            | 10 000                        |
| 20                  | 45s                           | 100 000                  | 5s                     | 10 000                          | 2s                            | 10 000                        | 1s                            | 10 000                        |
| 25                  | <=1s                          | 6s                       | 10 000                 | 7s                              | 10 000                        | 2s                            | 10 000                        | <1s                           | 10 000                        |
| 30                  | 5s                            | 10 000                   | 4s                     | 10 000                          | 1s                            | 10 000                        | 2s                            | 10 000                        |
| 35                  | 5s                            | 10 000                   | 8s                     | 10 000                          | 1s                            | 10 000                        | 1s                            | 10 000                        |
| 40                  | 5s                            | 10 000                   | 5s                     | 10 000                          | 1s                            | 10 000                        | 1s                            | 10 000                        |
| 45                  | 7s                            | 10 000                   | 6s                     | 10 000                          | <1s                           | 10 000                        | 1s                            | 10 000                        |
| 50                  | 4s                            | 10 000                   | 5s                     | 10 000                          | 1s                            | 10 000                        | 1s                            | 10 000                        |
| 55                  | 4s                            | 10 000                   | 5s                     | 10 000                          | 1s                            | 10 000                        | 1s                            | 10 000                        |
| 60                  | 3s                            | 10 000                   | 2s                     | 10 000                          | 1s                            | 10 000                        | 1s                            | 10 000                        |

**Table 6.** Computational effort in the reliability analysis
4. Conclusions

The reliability of steel structure with SDC nodes is lower than that with MERO nodes. In the basic design situation, i.e. when fire duration is $t=0$, computations performed for the spatial frame with rigid nodes (SDC) produce the reliability index that is approx. 5% lower than for the same structure with pinned nodes (MERO). In the first minutes of the fire, when the reliability index starts falling, the differences amount to several percent. That is caused by a sharp increase in factor $k_y$, which enhances stress on the element. Factor $k_y$ increase is caused by a fall in coefficient $\chi_f$ as the fire progresses, which means that compressed elements become more prone to buckling as the temperature grows. The differences become more apparent as the fire duration increases, and thus the reliability index becomes lower. The analysis revealed a particularly dangerous phenomenon observed in the 55th and 60th minutes of the fire (Figure 3). Then, for the truss structure, the computations produce the reliability index that is higher than the required one. Conversely, when the structure is modelled as a frame, the index is lower than the necessary one. The structure computed as a truss is assigned R60 fire resistance class, whereas the structure computed as a frame is categorised as the one having R45 fire resistance class.

It should be noted that the values of the reliability index obtained with the approximation methods (FORM, SORM) are slightly overestimated (Tables 3, 5) when compared with the results received using the simulation methods (Monte Carlo, Importance Sampling). However, the advantage offered by approximation methods include their effectiveness and a short time of computations. When simple limit functions were analysed, FORM or SORM method produced the results within 1s or less than that. The application of simulation methods prolongs the time of computations (Table 6). It takes only slightly longer when the Importance Sampling is used, whereas with the Monte Carlo method, substantial differences can be observed. For high reliability indexes, the sampling size needs to be increased, which additionally intensifies the computational effort. For the basic design situation when the reliability index was very high, the use of the Monte Carlo method with a larger number of samples resulted in the unacceptably long duration of the analysis.

References

[1] J. Frohlich, "Oktolplatte in Rorhkonstruktionen." Der Stahlbau, 9/1959.
[2] S. Du Chateu, "Structures spatielles." Cahiers du Centre d'Etudes Architecturales, 1967.
[3] S. Du Chateu, "Les tridimensionnelles industrialisées." Technique et Architecture, 5/1969.
[4] M. Mengeringhausen, "Raumfachwerke aus Stäben und Knoten." Bauverlag GmbH, Wiesbaden and Berlin, 1975.
[5] "Nodus Space Frame Grids." Parts 1-3. British Steel Corporation. London, 1971.
[6] L. Chodor, "Roof covering of halls and galeries. XXXI Polish nationwide workshops of structural designer's work", Szczyrk 24-27.02.2016 (in Polish)
[7] www.signs.pl
[8] W. Szaniec, K. Zieleńska, "Harmonic analysis of the wind-loaded bar dome at the satellite services in Psary", Archives of Civil Engineering, vol.62, issue 1, pp. 37-50, 2016.
[9] numpress.ippt.pan.pl, access> 05/2017.
[10] R. E. Melchers,. "Structural reliability analysis and predictions." 2nd Ed. Wiley, 1999.
[11] U. Radoń, "Numerical aspects of application of FORM in node snapping truss structures", Archives of Civil and Mechanical Engineering, vol.15, Issue 1, pp.262-271, 2015.
[12] U. Radoń, "Reliability analysis of Mises truss." Archives of civil and mechanical engineering, vol.11, issue 3,pp.723-738, 2011.
[13] A. Dudzik, U. Radoń, "The reliability assessment for steel industrial building", Advances in Mechanics: Theoretical, Computational and Interdisciplinary Issues, pp.163-166.
[14] K. Kubicka, U. Radoń, "Proposal for the assessment of steel truss reliability under fire conditions", Archives of Civil Engineering, vol. 61, issue 4, pp.141-154,2015.
[15] P. Obara, W. Gilewski, and J. Klosowska, “Applications of tensegrity structures in civil engineering,” Procedia Engineering, XXIV R-S-P seminar, Theoretical Foundation of Civil
Engineering (24RSP) (TFoCE 2015), vol. 111, pp. 242–248, 2015.

[16] P. Obara, W. Gilewski, and J. Kłosowska, “Verification of Tensegrity Properties of Kono Structure and Blur Building,” XXV Polish - Russian - Slovak Seminar - Theoretical Foundation of Civil Engineering, vol. 153, pp. 173–179, 2016.

[17] P. Obara, W. Gilewski, “Dynamic stability of moderately thick beams and frames with the use of harmonic balance and perturbation methods,” Bulletin of The Polish Academy of Sciences: Technical Sciences, vol. 64(4), pp. 739–750, 2016.

[18] M. Maślak, "Assessment of the fire safety level ensured by a steel load-bearing structure when subjected to a fire." Eighth international conference on advances in steel structures, Lisbon, Portugal, July 22-24, 2015 (conference materials, pen-drive, 15 pages).