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RESISTANCE OF STEEL FASTENERS SUBJECTED TO SHEAR AT PUBLIC ARENAS IN NORMAL AND FIRE TEMPERATURES – PROBABILISTIC APPROACH

The buildings with great grandstands are the public places where consequences of failure are very high. For this reason, according to EN 1990 they belong to CC3 class consequence of failure. The reliability class RC3 is associated with the consequences class CC3 [7, 8] and is defined by the $\beta = 4.3$ reliability index with probability of failure $p_f \approx 8.54 \cdot 10^{-6}$. Shear connections have to transfer forces between structural members – steel body and bolts with adequate degree of safety. The load-carrying mechanism of bolted shear connections is complex and analytical methods for predicting the shear resistance are not applicable. Instead the resistance of the connections may be determined using empirical formulas. The distributions of horizontal and shear resistance within steel body – bolts will be described depending on material characteristics of steel body and bolts components. The characteristic resistance of steel shear connection is obtained as minimum of two variables: bolds resistance and steel body resistance. Probability function of this minima will be defined and described in this paper. Laboratory tests provide the only practicable basis for specifying safety margins for ultimate strength connections. The determination of partial safety factors within shear connections will be presented according to EN1990. Design value of such resistance is specified as suitable fractile of log- normal probability distribution, calculated with the assumption that the acceptable probability of down-crossing is not greater than $p_{f,ult} \approx 2.91 \cdot 10^{-4}$. It means that the target reliability index, defined for the resistance, is taken as $\beta_{R,req}$ = 3.44, in accordance with the European recommendations (EN 1990***).***

Keywords: steel structures, structural safety, steel bolt connections, fire safety

1. Introduction

The empirical formulas related to bolted steel connection resistance are presented in EN1993-1-8 [2], [5]. The design shear resistance bearing type A; F_{Rd} per bolt should be determined as minimum of:

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$$F_{Rd} = \min(F_{v,Rd}, F_{b,Rd}) \tag{1}$$

Where $F_{v,Rd}$ is the design steel bolt resistance per shear plane and $F_{b,Rd}$ is the design bearing resistance of the steel body defined for reliability class RC3, as follows [9]:

$$F_{v,Rd} = \frac{\alpha_v f_{ub} A}{\gamma_{M2} K_{FI}} \qquad F_{b,Rd} = \frac{k_1 a_b f_u dt}{\gamma_{M2} K_{FI}} \tag{2}$$

where:
α_v, k_1, a_b, d, t – design parameters,
f_{ub} – characteristic strength of the steel bolts,
f_u – characteristic strength of the steel body,
$\gamma_{M2} = 1.25$ partial safety factor for connections,
$K_{FI} = 1.10$ for RC3 - partial safety factor usually associated with actions.

Partial safety factor for connections in structures of reliability class RC3 according to EN1990 is equal:

$$\gamma_{MRC3,EC} = \gamma_{M2} K_{FI} = 1.375 \tag{3}$$

2. Probabilistic analysis of shear bolted connection resistance

Let's assume that $X = F_{v,Rd}$ is the random variable of steel bolt shear resistance, $Y = F_{b,Rd}$ - random variable of bearing resistance of the steel body and define new random variable of bolted capacity $Z = F_R$

$$Z = \min(X, Y) \tag{4}$$

Cumulative distribution function of variable Z bolted shear resistance $F_Z(z)$ is defined as [1],[2],[3], [4]:

$$F_Z(z) = P(Z \le z) = P[\min(X,Y) \le z] = 1 - P[\min(X,Y) > z] = \\ = 1 - \int_z^\infty \int_z^\infty f_{XY}(x,y)\,dxdy. \tag{5}$$

where: P(x) and f(x) are probability and density functions of random variable *x*.

Assuming that random variables *X* and *Y* are independent density function $f_Z(Z)$ of variable Z can be obtained from:

$$f_Z(z) = f_X(z) + f_Y(z) - f_X(z)F_Y(z) - f_Y(z)F_X(z) \tag{6}$$

- Probabilistic moments of random variable Z.

The probability density function $f_Z(Z)$ of shear stud resistance is known, then it is easy to obtain first two probabilistic moments of variable Z using classical methods as follows:

- Mean value $\mu_Z = E(Z)$ as the first moment:

$$\mu_Z = \int_{-\infty}^{\infty} z f_Z(z) dz \tag{7}$$

- Variance $\sigma_Z^2 = \mathrm{var}(Z)$ as the second moment:

$$\sigma_Z^2 = \int_{-\infty}^{\infty} f_Z(z)\left(z - \mu_Z^2\right) dz \tag{8}$$

3. Characteristic and design values of shear bolted connection resistance in normal temperatures

Safety condition is defined, for standardized random value *Z* $\ln(\breve{Z}/z)/\nu_Z = \ln(\breve{\mu}_Z/z)/\nu_Z$,by using the following formula: ($\breve{Z}$ – median value, ν_Z - coefficient of variation) [2], [5]:

$$\beta_R = \frac{\ln(\breve{Z}/z)}{\nu_Z} \geq \beta_{R,req} = \alpha_R \beta_{req} \tag{9}$$

β_R is a partial reliability index, $\beta_{R,req}$ is target reliability index for resistance of shear stud connection. Index $\beta_{R,req} = \alpha_R \beta_{req}$ is the part of global target reliability index β_{req} defined in EN 1990 [6]. The value $\beta_{req} = 4,3$ for high consequence for loss of human life and considerable social, environmental consequences. According to EN1990 $\alpha_R = 0.8$ then $\alpha_R \beta_{req} = 0.8 \cdot 4.3 = 3.44$.

Design value of shear connection resistance is defined as:

$$Z_d = \breve{Z} \exp\left(-\alpha_R \beta_{req} \nu_Z\right) = \breve{Z} \exp\left(-3{,}44\nu_Z - \frac{\sigma^2_{\ln Z}}{2}\right) \tag{10}$$

Characteristic value of *Z* is defined as 5% fractile of log-normal distribution as follows:

$$Z_k = \breve{Z}\exp\left(-1{,}645\nu_Z\right) = \breve{Z}\exp\left(-1{,}645\nu_Z - \frac{\sigma^2_{\ln Z}}{2}\right) \tag{11}$$

Based on the fact that Z_d and Z_k are known, we can estimate minimum partial safety coefficient for shear connection resistance *Z* in RC3 class as:

$$\gamma_{MRC3.\min} = \frac{Z_k}{Z_d} = \exp\left[\left(3.44 - 1.645\right)\nu_Z\right] = \exp\left(1.795\nu_Z\right) \tag{12}$$

As shown in Figure 1, $\gamma_{MRC3,\min}$ is the variable for different value of coefficient variation ν_Z. It is necessary to mention, assuming $\gamma_{MRC3,\min}$ =1.375, that the required level of safety can not be guaranteed for value of ν_Z >0.18.

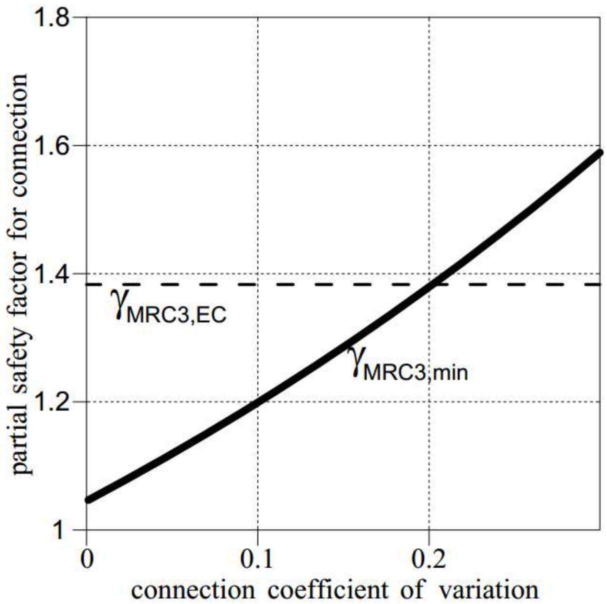

Fig. 1. Partial safety factor for steel shear connection resistance Z

Example 1.

Let's consider the shear bolted connections with steel bolt classes 4.6, 5.6, 6.8, 8.8 with accordingly – ultimate strength of the bolts f_{ub}=400 MPa, 500 MPa, 600 MPa, 800 MPa, diameter of the shank of the bolt d=20 mm. The connectionjoins two steel plates of steel *S*275, f_u= 430 MPa, thickness t = 7 mm. The coefficient of variation of ultimate strength for steel body is v_{fu}= 0.10 and for bolt steel is v_{fub}= 0.05. Table 1 presents results of calculations of connection resistance, using methods according to EC recommendations and probabilistic approach.

Table 1. Resistance for individual fasteners subjected to shear

Bolt classes	4.6	5.6	6.8	8.8
Median value of bolt ultimate strength $\breve{f}_{ub}$ [MPa]	434	543	651	868
Median value of fastener resistance $\breve{Z}$ [kN]	81.74	101.03	111.61	113.39
Standard deviation of fastener resistance σ_Z [kN]	4.08	5.43	9.345	13.31
Coefficient of variation of fastener resistance v_Z	0.050	0.054	0.084	0.100
Design value of fastener resistance (EC) P_{Rd} [kN]	54.81	68.51	70.02	70.02
Design value of fastener resistance (Probabilistic approach) Z_d [kN]	68.84	83.96	83.68	80.39

4. Steel shear connection capacity in fire temperatures

4.1. Design value of ultimate strength in fire temperatures

The ultimate strength $f_{u,k}$ decreases when fire temperatures Θ grow:

$$f_{u,k,\Theta} = k_{u,\Theta} f_{u,k,20} \tag{13}$$

$$f_{y,k,20} = \breve{f}_u \exp(-1.645 v_{fu,20} - 0.5 v_{fu,20}{}^2) \tag{14}$$

Where; $\breve{f}_u, v_{fu,20}$ are the median and log-normal coefficient of variation of the steel ultimate strength in temperature $\Theta = 20\,^oC$. It has been assumed that applied value of characteristic strength $f_{u,k,20}$ is described in normal – room temperature $\Theta = 20\,^oC$. The reduction coefficient $k_{u,\Theta} = k_{y,\Theta}$ for $\Theta \geq 400\,^oC$. For different fire temperatures Θ is presented in standard EN 1993-1-2 [10]. This relation is described as:

$$Z_{k,\Theta} = k_{u,\Theta} Z_{k,20} \tag{15}$$

The Z_{Θ} is the random variable described by log-normal probability distribution function $\mathrm{LN}\left(\breve{Z}_{\Theta}, \nu_Z\right)$ – where: $\breve{Z}_{\Theta}$ is the median value and ν_Z is the log-normal coefficient of variation. Reduction coefficient $k_{u,\Theta}$ is defined for different fire temperatures Θ.Temperature Θ will be treated as no-random in this analysis. The relation is as follows :

$$\nu_{Z,\Theta} = \nu_{Z,20} = const \text{ and } \nu_{fu,\Theta} = \nu_{fu,20} = const \tag{16}$$

It has been assumed that log – normal coefficient of variation ν_R does not depend on temperature Θ.

4.2. Standard deviation σ and coefficient of variation *V* of the steel ultimate strength in fire temperatures

Now, it is necessary to test hypothesis H_o- equality of variances :σ_k^2 = var (Y_k) in fire temperature. The null hypothesis H_o is: $\sigma_1^2 = \sigma_2^2 = \ldots = \sigma_k^2$ against alternative hypothesis H_1: $\sigma_1^2 \neq \sigma_2^2 \neq \ldots \neq \sigma_k^2$ for all fire temperatures $\Theta(k)$ and adequately $V_k^2 = \sigma_{ln,k}^2$ the null hypothesis H_o: $\sigma_{\ln,1}^2 = \sigma_{\ln,2}^2 = \ldots = \sigma_{\ln,k}^2$ against alternative hypothesis H_1: $\sigma_{\ln 1}^2 \neq \sigma_{\ln 2}^2 \neq . \sigma_{\ln k}^2$.

The above hypothesis will be verified by using Bartlett's test which is based upon the following statistic[6]:

$$b = \frac{\left(\prod_{i=1}^{k} \sigma_i^2\right)^{n/(N-k)}}{\sigma_p^2} \tag{17}$$

where: n – sample quantity, n=24, i=1…k=4, N =k n = 96.

$$\sigma_p^2 = \mathrm{n} \sum_{i=1}^{k} \sigma_i^2 \,/(N\text{-}k) \tag{18}$$

We accept hypothesis H_0 at the α level of significance when it's true for the following:

$$b < b_k(\alpha; n) \tag{19}$$

where: $b_k(\alpha;n)$ – critical value for Bartlett's test ,k –number of populations in fire temperatures =4, α – level of significance =0.01 ,n – sample quantity = 24.

The Bartlett's statistic b_{fe} (b) to verify hypothesis about equality of yield point standard deviation in fire temperatures $\sigma_1^2 = \sigma_2^2 = \dots = \sigma_k^2$ was estimated as follows;

$$b_{fe}=1.171 > b_4(0.01\ ,\ 24) = 0.882 \tag{20}$$

then hypothesis H_0 ($\sigma_1^2 = \sigma_2^2 = \dots = \sigma_k^2$) is rejected,

σ_k^2 – variance of the ultimate strength in fire temperature.

Consistently ,the Bartlett's statistic b_{lnfe} to verify hypothesis about equality of ultimate tensile strength coefficient of variations in fire temperatures
$V_1^2 = V_2^2 = \dots = V_k^2$ was estimated;
b_{lnfe} 0.247 < b_4(0.01 , 24) = 0.882.

In this case we accept hypothesis H_0: $V_1^2 = V_2^2 = \dots = V_k^2$=const, and $v_{fu,\Theta} = v_{fu,20} = const$.

V_k^2 – coefficient of variation of the ultimate strength in fire temperatures.

5. Conclusions

The shear design resistance of connections in sport arena structures should be calculated as fractile (at level $p_{f,ult} \approx 8.54 \cdot 10^{-6}$) of shear resistance probability density function. The shear resistance density functions can be obtained using the formulas presented in this paper. For steel fasteners it is necessary to verify the values of partial safety factors of shear connectors in fire temperatures. More research is needed on the steel ultimate variance parameters in fire temperatures assuming, that the distribution of shear resistance is lognormal.

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