http://dx.doi.org/10.14311/asfe.2015.045

Proceedings of the International Conference in Dubrovnik, 15-16 October 2015

RELIABILITY OF TIMBER STRUCTURES EXPOSED TO FIRE

Mislav Stepinac, Vlatka Rajčić

University of Zagreb, Faculty of Civil Engineering, Zagreb, Croatia

Abstract

Until recently, the fire resistance of buildings was based on the ISO standard curve. ISO standard curve used by the current norm is too simple, unrealistic and lead to uneconomic situations with no guarantee of security proportional to the invested money. Unlike the fire design of the steel, concrete or composite structures, methods for fire design of timber structures have been greatly simplified. Generally, it is not necessary to check the reduction of strength in the residual section because each increase of temperature is considered small and it is ignored. Global fire safety concept of timber structures is presented according to the recommendations from Eurocode norms. Special attention was given to natural fire design with two different methods of parametric exposure which are given in EN1995-1-2.

This paper presents reliability analysis of a glulam beam in a case of fire. The limit-state functions for maximum bending stress of glulam beam in fire conditions are formed. Reliability indexes are obtained from the limit state of the beam exposed to 30 min fire. Reliability index in the Eurocodes (reliability class RC2) compared to the calculated reliability indexes obtained by the methods of reduced strength and effective section were described.

Keywords: fire design, reliability, Eurocode 5, timber structure, glulam beam

1 INTRODUCTION

Until recently, the fire resistance of buildings was based on the ISO standard curve. ISO Standard curve used by the current standards is too simple, unrealistic and lead to uneconomic situations with no guarantee of security proportional to the invested money. A new approach called “Global Fire Safety Concept” considers the following steps:

- takes into account characteristics of structures important to the spread of fire: fire scenario, fire load, charring rate, type of barriers, ventilation conditions,
- quantifies the risk of fire starting activities, the size of considered fire compartments and their occupancy and the impact of active firefighting measures; risk analysis is based on existing statistical data of real fires and probabilistic methods,
- determines the design heating curve of the design fire load,
- simulates the global behaviour of structures subject to the design heating curve in combination with a static load in case of fire,
- determines the fire resistance time,
- verifies the safety of the structure by comparing the calculation fire resistance time with the time of the evacuation and the consequences of the failure.

Fig. 1 The sequence of events in the structure in the occurrence of fire

The new engineering approach is trying to solve the problem of fire protection with numerical procedure. Selection and identification of fire scenarios is a beginning of the reliability concept for structures with natural fire.

2 FIRE FROM THE ASPECT OF THE RELIABILITY ASSESSMENT

Reliability is defined as the ability of a structure or a structural element to fulfil certain requirements, including the estimated lifespan; it is expressed through probabilistic expressions, and includes safety, serviceability and durability (Androić et al. 2008). In order to ensure sufficient reliability, it is necessary that failure occurs with a very small probability which is measured by the reliability index β. The failure value given in EN 1990 is 7.25×10^{-5} for the structure lifetime, which corresponds to the value of 3.8 for reliability index β. However, fire action is accidental, so the target value of probability, p_t, must be less than or equal to the product of the targeted failure value in case of fire, p_{fi}, and the probability of occurrence of fire, $p_{t,fi}$:

$$p_{t,fi} \cdot \leq \frac{p_t}{p_{fi}} \tag{1}$$

In that case, reliability index β is no longer the fixed value 3.8. Knowing the probability of occurrence of fire that engulfs the cross section, and depending on the size of the cross section, current level of active measures for protection, the reliability index β can be determined through the following equation:

$$_{fi} = \Phi^{-1}\left(\frac{p_t}{p_{fi}}\right) = \Phi^{-1}\left(\frac{7{,}25\times10^{-5}}{p_{fi}}\right) \tag{2}$$

The probability of occurrence of fire p_{fi} is determined with the equation:

$$p_{fi} = p_1 \times p_2 \times p_3 \times p_4 \times A_{fi} \tag{3}$$

where:

- p_1 probability of occurrence of a fully developed fire, including the effects of the interventions of users and fire brigade (for 1 m^2 of the layout of the construction and for one year),
- p_2 reduction factor dependent on the type of the fire department and the passage of time from the onset of the alarm to the arrival of the firefighters,
- p_3 reduction factor in case of the automatic fire notification (through smoke or heat detection),
- p_4 probability of the sprinkler system failure (if they exist),
- A_{fi} area of the fire sector.

3 FIRE IN TIMBER STRUCTURES

Unlike the fire design of the steel, concrete or composite structures, methods of design of fire in timber structures have been greatly simplified. Generally, it is not necessary to check the reduction of strength in the residual section, because each increase of temperature is consider small and is ignored. Method of design according to EN 1995-1-2 is a two stage process, the calculation of charring depth and then determination of the strength of the residual section.

3.1 Real fire

Unlike the standard fire where the charring rate is constant, in real fires, characteristics of the room (surface openings, floors, walls and partitions), fire load density, and physical characteristics of the timber element are taken into account for the charring rate. The procedure from the EN 1995-1-2, Annex A is as follows:

$$d_{char,n} = \beta_{par} \times t \qquad \text{for } 0 \leq t \leq t_0 \tag{4}$$

$$d_{char,n} = \beta_{par} \times (1{,}5t_0 - t^2/4t_0 - t_0/4) \qquad \text{for } t_0 \leq t \leq 3t_0 \tag{5}$$

$$d_{char,n} = 2\beta_{par} \times t_0 \qquad \text{for } 3t_0 \leq t \leq 5t_0 \tag{6}$$

where t time in minutes,

t_0 time period with a constant charring rate,

$q_{t,d}$ design fire load density [MJ/m^2],

O opening factor [$m^{0,5}$],

A_v	total area of vertical openings of fire compartment,
A_t	total area of floors, walls and ceilings that enclose the fire compartment,
h_{eq}	the average height of vertical openings.

Strength and stiffness properties for the fire limit states cannot be calculated for the usual 5% fractile but for 20% fractile. Design values of strength f_k and stiffness S_{05} are multiplied by a factor k_{fi} which has a value of 1.25 for hardwood and 1.15 for the laminated.

The first calculation method uses the increased charring depth to allow for potential strength loss in the core and is known as "effective section method". Effective depth d_{ef} is given as the sum of $d_{char,n}$ and additional factor k_0d_0:

$$d_{ef} = d_{char,n} + k_0d_0, \tag{7}$$

where d_0 *7mm,*

k_0 *t/20 (k_0 = 1 for t >20 min)*

$\gamma_{M,fi}$ *1.0.*

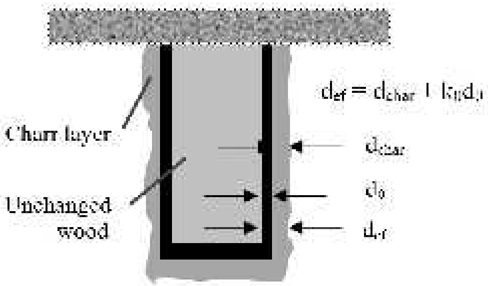

Fig. 2 Effective depth d_{ef}

The second method takes only a reduction in cross section as a result of combustion and is known as "reduced strength and stiffness method". The strength and modulus of elasticity are reduced by modification factor $k_{mod,fi}$ which is given for each strength, respectively, bending strength, compressive strength, tension strength and modulus of elasticity.

For t > 20 min, $k_{mod,fi}$ for bending strength:

$$k_{mod,fi} = 1{,}0 - \frac{1}{200} * \frac{p}{A_r} \tag{8}$$

where p perimeter of the fire exposed residual cross-section,

A_r area of residual cross-section.

4 CALCULATION OF RELIABILITY OF GLULAM BEAM EXPOSED TO REAL FIRE

The statics system is a simply supported beam. The glulam beam is a part of the roof frame system, and it is affected by dead load and snow. The value of the dead load is 0.45 kN/m^2 (beams own weight is not taken into account), and the snow load of 2.74 kN/m^2. Distance between the main beams is 3.3 m. Timber class GL24k was used. The beam was designed according to the ultimate limit state for bending affected by the real fire (reduced strength and stiffness method). The most critical cross section was analyzed.

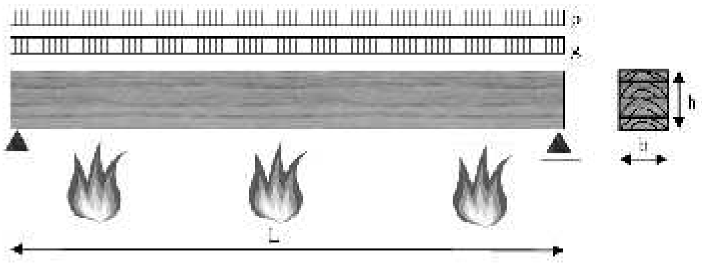

Fig. 3 Effective depth d_{ef} reduction in effective cross-section

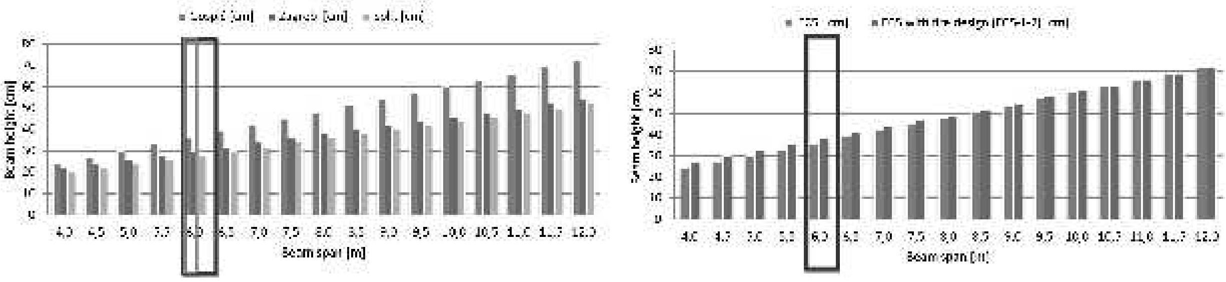

Fig. 4 Comparison of the necessary cross section height for the given beam in three different areas in the Republic of Croatia (depending on the snow load), without fire design; Comparison of the necessary cross-section height for the given beam with fire design and without fire design (EC5)

Total action is calculated according to:

$$M_{y,d} = M_{Ed,fi} = \frac{G+P}{8} \times L^2 \tag{9}$$

where $M_{Ed,fi}$ design action in fire,

G characteristic value of permanent load per m’,

P characteristic value of live load per m’,

L beam span in m.

Total resistance in case of fire is:

$$M_{Rd,fi} = W_{ef} \times f_{20} \times k_{\text{mod},fi} \tag{10}$$

$$b_{ef} = b - \left[d_0 + {}_{par}(1{,}5 \times t_0 - \frac{t^2}{4t_0} - \frac{t_0}{4} \right] \tag{11}$$

$$f_{20} = k_{fi} \times f_{m,k} \tag{12}$$

where $M_{Rd,fi}$ design capacity of components in case of fire,

W_{ef} reduced section modulus after exposure to fire,

b_{ef} reduced cross-section width,

f_{20} 20% fractile strength at normal temperature.

4.1 Forming the limit state function

The reliability analysis is done for a beam with dimensions b/h = 20/36 cm and a span of 6 meters. Reliability analysis was made with software VAP. Variant methods were examined (FORM, Monte Carlo method) which have, due to the simplicity of the specific problem, resulted in a very similar results. The limit state function is formed for the maximum bending stress.

$$Z = X1 \times R - X2 \times E = 0 \tag{13}$$

where $X1$ model uncertainty for designed resistance in fire,

R designed resistance of the material,

$X2$ model uncertainty for actions on the structure,

E action on the structure.

The limit state function for the maximum bending stress in fire situation is:

$$Z = X1 \times \frac{b_{ef} \times h_{ef}^2}{6} \times f_{m,k} - 1{,}2 \times \left(\frac{G+P}{8} \times L^2 \right) = 0 \tag{14}$$

where $X1$ model uncertainty for designed resistance in fire,

b_{ef} reduced beam width,

h_{ef} reduced beam height,

$f_{m,k}$ bending strength,

$X2$ model uncertainty for actions on structure,

G permanent load,

P live load,
L beam span (6m).

Upon defining limit states basic equations were designed. The probability of failure as a function of coefficient of variation of strength is shown in Figure 5. As recommended in literature (*Profil Arbed Research, Handbook 5 – design of buildings for the fire situations*) variation coefficients for strength of 0,15 and variation coefficient of model uncertainty for designed resistance with value of 0,15 were taken into account.

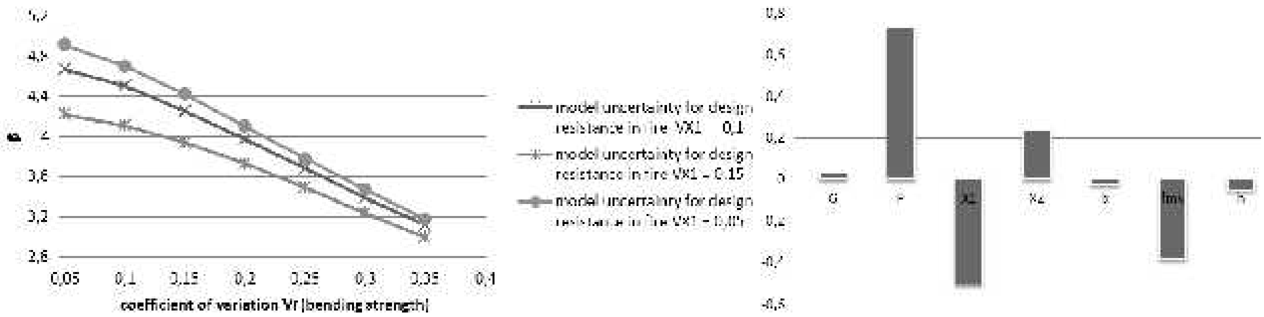

Fig. 5 Effective depth d_{ef} reduction in effective cross-section; Weighning factors (bending with fire)

Recommendations for distributions and remaining variation coefficients were taken from Toratti et al., 2007 and Androić et al., 2008.

Table 1 Basic variable and related distributions, mean values, standard deviation and coefficients of variation.

Basic variable	Distribution N – normal L – lognormal G – Gumbel's	Mean X_i	Standard deviation σ_i	coefficient of variation V_i
G [kN/m']	N	1,5	0,15	0,1
P [kN/m']	G	5,8	1,73	0,3
b [cm]	N	15.8	0,158	0,01
$q_{t,d}$ [MJ/m^3]	const.	285	-	-
h [cm]	N	33.9	0.3339	0,01
$f_{m,k}$ [N/mm^2]	L	31,02	4,65	0,15
X1	N	1	0,15	0,15
X2	N	1	0,1	0,1
$\sqrt{\rho c \lambda}$ [J/m^{2}s$^{1/2}$K]	const.	1160	-	-
O [m$^{1/2}$]	const.	0,026	-	-
L [m]	const.	6	-	-

Figure 6 presents failure probability in time. It can be noticed that with effective section method greater failure probabilities were achieved.

Table 2 Calculated and standardized reliability indexes with the corresponding failure probabilities

Limit state- Resistance to bending in the fire (30min)	Calculated indexes of reliability	Standardized reliability index for 50 years (RC2) for a surface area of 2500 m^2 β_{fi}
Effective section method	2.69	3,03
Reduced strength and stiffness method	3,04	3,03

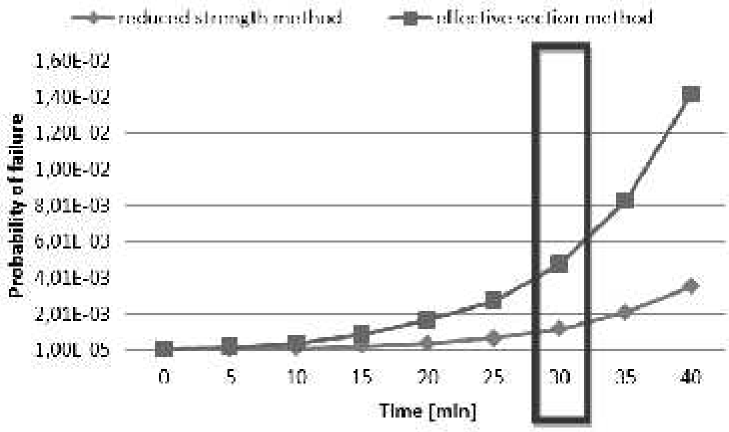

Fig. 6 Comparison of reduced strength method and effective section method in terms of given values of probability of failure

4 CONCLUSIONS

Reliability of glulam beams in case of fire has been analysed and basic hypotheses about timber structures in fire are shown. A special attention is given to the design of the real fire and the two representative methods for design of timber structures in case of fire. Comparison between level I (Eurocode) and level II (FORM) was made. Reliability indexes were obtained from computational analysis of beams exposed to 30 minute fire. The calculated values are based on the span of the beam from 4 -12 m. Figure 5.10. shows the reliability index in the Eurocode (reliability class RC2) compared to the reliability indexes obtained by the methods of reduced strength and effective section. The reduced strength method gives a higher value of reliability.

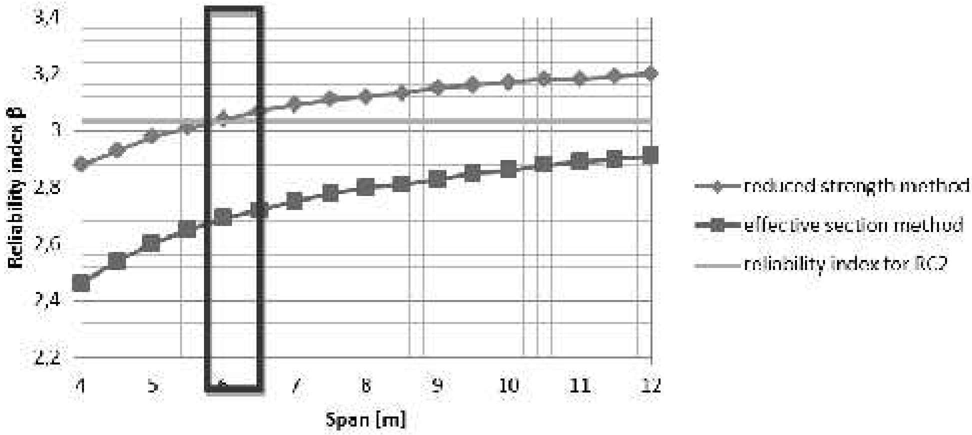

Fig. 7 Reliability index for different spans in a 30-minute fire

REFERENCES

EN 1990: *Eurocode – Basis of structural design*, European Committee for standardization, Brussels, 2001.

EN 1991-1-2: *Actions on structures – Actions on structures exposed to fire*, European Committee for standardization, Brussels, 2002.

EN 1995: *Eurocode – Design of timber structures: Common rules and rules for buildings*, European committee for standardization, Brussels, 2003.

Profil ARBED – Research: *Competitive steel buildings through natural fire safety concept*, 1999.

Leonardo Da Vinci Pilot Project: *Handbook 5 – Design of buildings for the fire situations*, 2005.

Toratti, T., Schnabl, S., Turk, G. 2007., *Reliability analysis of a glulam beam, Probabilistic Concepts in the Design of Timber Structures, Structural safety*, pp. 279-293., 2007.

Androić, B., Čizmar, D., Rajčić V. 2008., *Analiza pouzdanosti drvenih lameliranih nosača, Građevinar 60,* ***,*** *6*, Zagreb, p. 513-518