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Serviceability Limit Verification for Structural Elements of Steel Hall

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Abstract. In recent years, the importance of assessing structural reliability has increased significantly. This is confirmed by the recommendations of the PN-EN 1990 standard. This standard gives the principles and requirements to ensure the safety, serviceability and durability of the structure. It sets out the basis for calculation and verification of the structure and provides guidance to ensure their reliability. Reliability of structure is its ability to meet specific design requirements, taking into account the planned period of use. The planned period of use should be understood as a time period approved in the project, in which the structure or part of it is to be used for their intended purpose, without the need for major repairs. Typically, reliability is expressed by probabilistic measures as indicator of reliability or probability of failure. The aim of this study is to present the results of of roof girder deflection surveying and modeling their reliability. A general algorithm for determining the value of the reliability indicator for the bending steel beam with FORM method will be presented. Verification of the differences between the indicator of reliability obtained by simplified probabilistic methods and compare them with the values recommended in the Eurocode 0 standard will be also shown. For the analyzed steel beam the serviceability limit states were considered.

Keywords: serviceability limit, reliability of structure, roof girder deflection surveying.

Conference topic: Technologies of geodesy and cadastre.

Introduction

The PN-EN 1990:2004 standard gives the rules and requirements to ensure the safety, serviceability and durability of the structure. It sets out the basis for calculation and verification of structure design and provides guidance to ensure their reliability. Reliability is defined as the ability of a structure or its component to meet the specific requirements of the resistance, and durability during the planned service life, which is usually expressed in probabilistic measure. A similar definition used in ISO 2394 standard (PN-ISO 2394:2000), where additionally an elementary reliability (of a single structural element) and the reliability of the system composed of more than one element is distinguished.

The methods of structures calculation that allow a quantitative assessment of the probability of exceeding limit states in the proposed service life is among the probabilistic methods. If simplification and reduction used in the calculations are precisely defined, the methods are classified as a simplified probabilistic methods, or methods of level II (Melchers 1987; Nowak, Collins 2000; Woliński, Wróbel 2001; Benjamin, Cornell 1970). In this study, considerations are limited to the PN-EN 1990:2004 and ISO 2394 (PN-ISO 2394:2000) standards recommended method of β reliability index, which belongs to the analytical methods of FORM – First Order Reliability Method (Tichy 1993; Gulvanessian, Holicky 1996; Faber *et al.* 2007; Skrzypczak *et al.* 2016). It is assumed that all the random variables of X_i state are defined by two parameters of the normal distribution mean value – $\overline{X}$ and standard deviation – σ_X or equivalent to normal.

A standardized random variable expressing a condition of limit state $g = R - E = 0$ (where R is the resistance and E the effect of actions) is called as reliability indicator β (1):

$$\beta = \left|(0 - \overline{Z}) / \sigma_Z\right| = \overline{Z} / \sigma_Z = 1 / v_Z , \tag{1}$$

where: $\overline{Z}$ – mean value of g; σ_Z – standard deviation of g; v_Z – variation coefficient.

A β measure of reliability is associated with the probability of failure – P_f (exceeding of limit state) of the element or structure by Equation (2):

$$P_f = \Phi(-\beta) = P(Z \le 0) = P(Z \le \overline{Z} - \beta\sigma_Z) , \tag{2}$$

where: Φ(.) – Laplace function; P(.) – probabilty.

Equation (2) is formally correct if the variable g has a normal distribution $N(\overline{Z}, \sigma_Z)$. For other distributions of g the reliability indicator β is only a conventional measure of the reliability $P_s = 1 - P_f$ (Ps – survival probability). The construction may be regarded as a reliable if the value of reliability indicator is not less than the target value.

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Annex C of PN-EN 1990:2004 standard describes the recommended minimum (target) values of the reliability indicator β_{lim} for components of class RC2 (Table 1).

Table 1. Recommended β_{lim} values for RC2 class components

Limit state of:	β_{lim} / P_f for 1 year recerence period	β_{lim} / P_f for 50 years recerence period
load bearing capacity	4.7 / 1.30E-06	3.8 / 7.23E-05
fatigue of structure	–	1.5÷3.8 / 6.68E-02÷7.23E-05
serviceability	2.9 / 1.87E-03	1.5 / 6.68E-02

Due to the various recommendations for the analysis of the structure and its components to evaluate the reliability with respect to limit state of serviceability the deterministic and simplified probabilistic methods were used. Considering serviceability limit states only for computing effects of impacts the target value of reliability index for a limit states have to be multiplied by the coefficient of sensitivity to the effects of interactions – $\alpha_E = 0.7$. So the 1.05 target value of reliability index was taken for analyzes.

In this study object of analysis is a over 40 m long roof girder made of steel beam. It is one of the components of steel hall structure, its dimentions and schematic drawing are shown in Figure 1. The construction of the hall are the steel frames made of steel profiles S355J2G3 (18G2A). They are one nave, rigid frames and hingedly based on the footings (Kochańczyk, Kopczyk 2015).

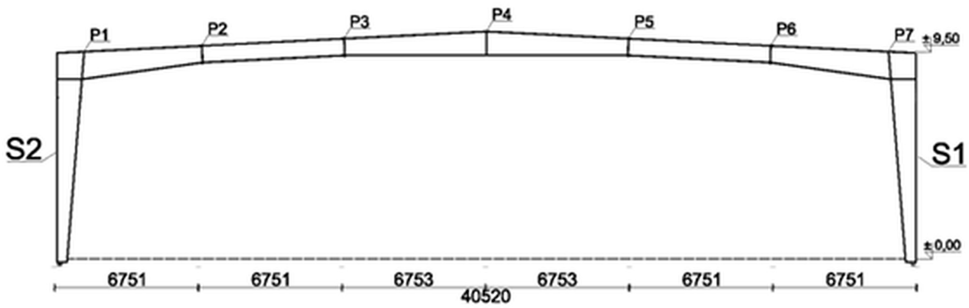

Fig. 1. Schematic drawing of the study structure

Geodetic survey of roof girder

To measure the girder's deflection in vertical plane the Total Station instrument (South NTS-362R) was used. Basic specification of the instrument are listed in Table 2. A method of trigonometric levelling, based on reflectorless mode of distance measurements was applied. Reflectorless mode has enabled quick measurements with no need of access to highly-placed measured points. seven explicit, recurring points on the top shelf of the girder was adopted to avoid gross errors in measurement results. Instrument was placed at a distance of about 25 m away from the girder. While aiming each point a slope distance and zenith angle was read from the device. The measurement procedure is schematically shown in Figure 2 (Kochańczyk, Kopczyk 2015).

Table 2. Basic specification of the South NTS-362R

Feature	South NTS-362R
Accuracy of angle measurement	2"
Accuracy of reflectorless distance measurement	±(5 + 2ppm ×D) mm
Range of reflectorless distance measurement	300 m
Plate vial	30" / 2mm
Circular vial	8' / 2mm
Minimal Focus dictance	1 m
Auto compensator	Dual axis, Liquid-electric
Working range of compensator	±3'
Accuracy of compensator	3"

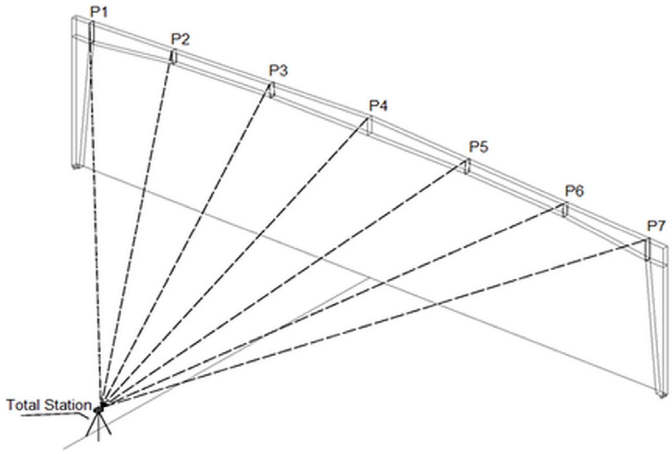

Fig. 2. Schematic drawing of measurement procedure

On the basis of the observations the height of all the points in a local reference system according to well known formula (3) were determined. The beginning of the reference system was the point of geometric intersection of the vertical rotation axis of the instrument, the horizontal axis of telescope rotation and the line of sight of the telescope.

$$H = S \cdot cos\,V, \tag{3}$$

where: H – height of point in a local reference system; S – slope distance; V – zenith angle.

With the law of propagation of measurements uncertainties formula (4) for the height of the point uncertainty can be derived (Baran 1987; Preweda 2013):

$$m_H = \sqrt{(cosV \cdot m_S)^2 + (S \cdot sinV \cdot m_V)^2}, \tag{4}$$

where: m_H – height of the point uncertainty; m_S – accuracy of reflectorless distance measurement; m_V – accuracy of angle measurement.

While the girders vertical deflection uncertainty, understood as the difference of coordinates (heights in local reference system) can be written as (5):

$$m_D = m_H\sqrt{2}, \tag{5}$$

where: m_D – vertical deflection uncertainty.

On assumption of average measurement conditions for the girders points heights determination and taking into account the accuracy of the observations, which are compatible with the specifications of the instrument, uncertainty of the height of the point will be 1.8 mm and the uncertainty of the girder vertical deflection will be 2.5 mm. The final vertical deflections of the steel girder obtained on the basis of discussed measurements are summarized in Table 3.

Table 3. The final vertical deflections of the steel girder

Number of steel girders point (according to Fig. 2)	Vertical deflection [mm]
P1	0
P2	38
P3	69
P4	68
P5	30
P6	27
P7	0

As recommended by the EN 1993-1-1 Eurocode 3 sandard (PN-EN 1993-3-1:2008), serviceability limit state check is a comparison of the actual measured vertical deflection with defined acceptable deflection (6):

$$D < D_{lim} = L/250, \tag{6}$$

where: D – actual measured vertical deflection; D_{lim} – defined acceptable deflection; L – span of girder.

In discussed case maximum actual measured vertical deflection is D = 69 mm, according to Figure 1 span of the girder is L = 40 520 mm, and defined acceptable deflection is D_{lim} = 40 520 / 250 = 163 mm. Hence the conclusion that the serviceability limit state is not exceeded.

Probabilistic analysis

In the PN-EN 1990:2004 standard reliability is defined as ability of a structure or a structural member to fulfil the specified requirements, including the design working life, for which it has been designed. Reliability is usually expressed in probabilistic terms. The design working life is understood as assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary. Therefore reliability is called the probability that the construction will not fail in assumed time of her life. Failure is a term related to situation in which the variables defining the structure exceed certain criteria set up by the designer. Reliability of building structures depends on many factors of which the most important are: quality and characteristics of used materials, manufacturing accuracy of construction and the type and values of influences taken into account. In this study, considerations are limited to recommended in PN-EN 1990:2004 and ISO 2394:2000 standards method of reliability index, which belongs to the analytical FORM (First Order Reliability Method) methods. Standardized random variable expressing condition of limit state due to the not exceeding the acceptable vertical deflection of steel girder can be described by the following formulas (7, 8):

$$Z = D_{lim} - D; \tag{7}$$

$$Z = D_{lim} - (H_i - H_j), \tag{8}$$

where: Z – standardized random variable of limit state; H_i, H_j – height of appropriate measurement points in a local reference system.

Analysis of reliability for a serviceability limit state

In analyzed example input data, for calculating the reliability index, were adopted in accordance with Table 4.

Table 4. Input data for probabilistic analyze

Feature	H_i	H_j	D_{lim}
Distribution	Normal	Normal	Defined value
Mean	8302 mm	8233 mm	163 mm
Standard deviation	1.8 mm	1.8 mm	–

The resulting value of the reliability index β is 42.30. Probabilistic analysis results are given in Table 5 and in Figure 3 from a to c.

Table 5. Results of the probabilistic analysis

Feature	Z function characteristics
Distribution	Normal
Mean	93.59 mm
Standard deviation	2.21 mm
Reliability index β	42.30

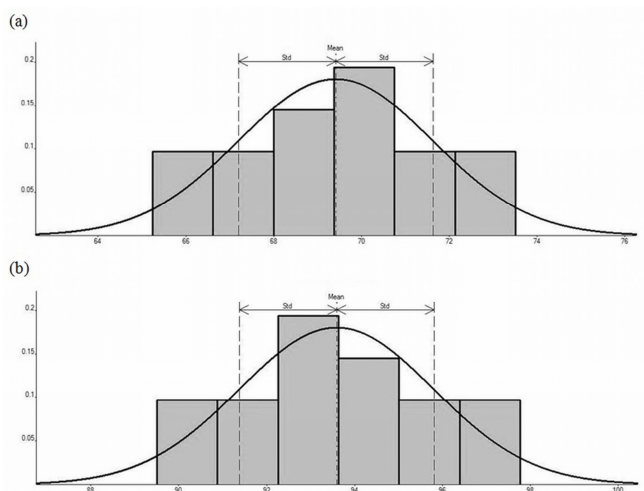

Fig. 3. Density function for: (a) – measured vertical deflection D; (b) – limit state function Z

The resulting value of the reliability index meets the minimum rate of reliability. Steel girder must be regarded as reliable, because the reliability index value is larger than the target value: $\beta = 42.30 > \beta_{lim} = 1.05$ (Table 2) (Nowak, Collins 2000; Woliński, Wróbel 2001; PN-EN 1993-3-1:2008). Analyzed steel girder meets design requirements with respect to reliability requirements for serviceability limit states.

Conclusions

It should be noted that the structure designed in a deterministic phase with a relatively low safety (reliability) margin, respectively, for the wide dispersion of input random variables may be considered as improperly designed. Therefore, before proceeding to inventory surveys, it is advisable to specify the measurement accuracy and determine the uncertainty of the final result. It is very important to apply the appropriate method of measurements. In case of conventional geodetic methods of surveying problems associated with measuring points arrangement along the structure are significant. Measured points should be clearly identifiable and clearly visible targets which arrangement should result from the analysis of the construction work and the rules of searching for the most vulnerable places (parts, elements) of the structure.

Application of higher-order methods, recommended in Eurocode 0, in the analysis of structures allows more accurate assessment of the work of construction and efficient management of reliability, durability, quality and safety of the structure.

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