Advanced Modeling Approaches for Reliability Analysis of Steel Structures

ABAYOMI OMISHORE
Department of Structural Mechanics
Brno University of Technology, Faculty of Civil Engineering
Veveří Str. 95, Brno
CZECH REPUBLIC
omishore.a@fce.vutbr.cz; http://www.vutbr.cz

Abstract: One important approach in the identification of uncertainty is sensitivity analysis. The sensitivity analysis is crucial for building, understanding and applying complex mathematical models to reliability problems of building structures. Attainment of limit state is generally a random event, which is studied in the reliability theory by means of the probability theory and mathematical statistics. Methodology based on ANOVA variance-based techniques is used for the sensitivity analysis. The sensitivity indices were evaluated applying the Monte Carlo method. Sensitivity analysis is used to identify the dominant input random quantities and their higher order interaction effects. The imperfections which interact and may thus generate extreme values of resistance capacity have been identified. The results obtained may be utilized in standards for design.

Key-Words: Reliability, Frame, Column, Structure, Sensitivity, Safety.

1 Introduction

The identification and representation of uncertainty is recognized as an essential component in model applications [1]. The sensitivity analysis is a fundamental tool in the building and understanding of mathematical models as it provides information on the behavior of the underlying simulated system [1]. The sensitivity analysis evaluates how the variations in the model output can be apportioned to variations in model parameters [2]. Nowadays, many sensitivity analysis techniques are available [3]. In the case of simple mathematical models, Taylor series expansion can be used to approximate the model, and the analytical differential sensitivity index can be derived [1]. However, it would be difficult to use the Taylor series approximation for complex models; there are needed more advanced techniques [1]. The sensitivity analysis of steel frame structures is aimed at safety and serviceability assessment in the limit state methods.

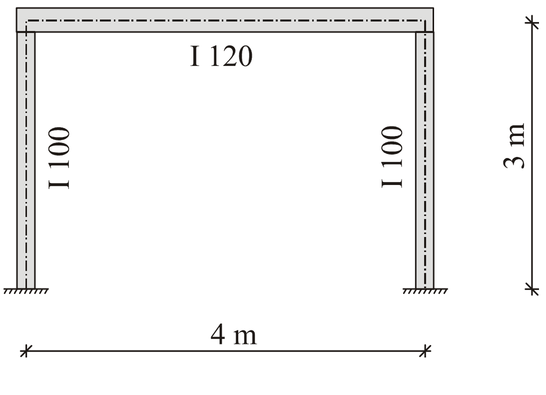

Fig.1 Steel plane frame geometry

The system response is understood as the ultimate resistance capacity and maximal deformation of structure. The present paper is aimed at the sensitivity analysis of the ultimate resistance capacity of a steel plane frame, see Figure 1. It is focused on the application of such sensitivities to obtain new modeling approaches for problems of steel structures. This information can be used to support the development of optimal design and the reduction or simplification of existing ones. Sensitivity analysis is often carried out to identify the most relevant material and geometrical characteristics, on which of them it is therefore reasonable to concentrate the efforts during the calibration activity.

2 Sensitivity and Statistical Analysis

The sensitivity analysis evaluates how the variations in the model output can be apportioned to variations in model parameters [3]. In the presented article, the sensitivity analysis is applied to the study of the influence of initial imperfections on the resistance capacity. The sensitivity analysis can be generally divided into two groups: (i) deterministic sensitivity analysis and (ii) stochastic sensitivity analysis [4-13]. The variance-based techniques are sometimes called ANOVA techniques for ANalysis Of VAriance [14]. With regard to the limit states of structures, the ultimate or fatigue resistance and deflection are frequently considered to be the output quantities [15-21]. Stochastic methods are based upon various assumptions, and it is difficult to compare the results. However, each of the methods has its informative capability of a different type.

2.1 Input Random Quantities

Experimentally obtained material and geometrical characteristics of steel products made by a dominant Czech producer, see [22, 23] were applied to the problem solved. Input quantities X_i of left column are yield point f_{y1}, cross-sectional height h_1, cross-sectional width b_1, web thickness t_{w1}, flange thickness t_{f1} and Young modulus E_1. Input quantities of right column are f_{y2}, h_2, b_2, t_{w2}, t_{f2}, E_2. Input quantities of cross beam are f_{y0}, h_0, b_0, t_{w0}, t_{f0}, E_0. All the input parameters X_i, given synoptically in Table 1, are statistically independent of one another.

Table 1: Statistic characteristics of the input quantities

No.	Member	Symbol	Mean value	Std. deviation
1.	Left Column	h_1 *	100.09 mm	0.44 mm
2.		b_1 *	49.6 mm	0.49 mm
3.		t_{w1} *	4.74 mm	0.18 mm
4.		t_{f1} *	6.75 mm	0.31 mm
6.		f_{y1} *	297.3 MPa	16.8 MPa
7.	Cross Beam	h_0 *	120.11 mm	0.53 mm
8.		b_0 *	58.81 mm	0.57 mm
9.		t_{w0} *	5.37 mm	0.2 mm
10.		t_{f0} *	7.64 mm	0.35 mm
12.		f_{y0} *	297.3 MPa	16.8 MPa
13.	Right Column	h_2 *	100.09 mm	0.44 mm
14.		b_2 *	49.6 mm	0.49 mm
15.		t_{w2} *	4.74 mm	0.18 mm
16.		t_{f2} *	6.75 mm	0.31 mm
18.		f_{y2} *	297.3 MPa	16.8 MPa

* Histogram

2.2 Sensitivity Indices

The description of Sobol' decomposition theory is listed, e.g., in [24]. The Sobol' first order sensitivity indices may be written in the form:

$$S_i = \frac{V\left(E\left(Y|X_i\right)\right)}{V\left(Y\right)} \qquad (1)$$

Sobol' proposed an alternate definition $S_{\mathrm{i}} = corr\left(Y, E\left(Y|X_{\mathrm{i}}\right)\right)$ based on the evaluation of the correlation between output random value Y and the conditional random arithmetical mean $E\left(Y|X_{\mathrm{i}}\right)$. Analogously, we can write the second order sensitivity indices:

$$S_{ij} = \frac{V\left(E\left(Y|X_i, X_j\right)\right)}{V\left(Y\right)} - S_i - S_j \qquad (2)$$

Sensitivity index S_{ij} expresses the effect of doubles on the monitored output. Other Sobol' sensitivity indices enabling the quantification of higher order interactions may be expressed similarly.

$$\sum_i S_i + \sum_i \sum_{j>i} S_{ij} + \sum_i \sum_{j>i} \sum_{k>j} S_{ijk} + \ldots + S_{123\ldots M} = 1 \qquad (3)$$

The number of members in (13) is 2^M-1, i.e., for M=3, we obtain 7 sensitivity indices S_1, S_2, S_3, S_{12}, S_{23}, S_{13}, S_{123}; for M=18, we obtain 262143 sensitivity indices; it is excessively large for practical usage. The computational demand represents the main limitation in the determination of all members of (3).

2.3 Results of Sensitivity Analysis

The Monte Carlo method was employed for the calculation of sensitivity indices. The model output Y is the resistance of the column under tension calculated in each simulation run of the Monte Carlo method. Resistance of column is yield point multiplied by cross section area. Resistance of frame is minimum of resistance of left and right columns. Nine thousand simulation runs were applied in our study. Results of sensitivity analysis depicted in Figure 2 illustrate that the variance of yield point of both columns has the greatest effect on the variance of ultimate resistance. A further dominant quantity is the flange thickness of both columns of the I profile. The sum of higher-order sensitivity indices is approximately 0.25. It means that the interactions of higher orders between input random quantities also have a significant effect.

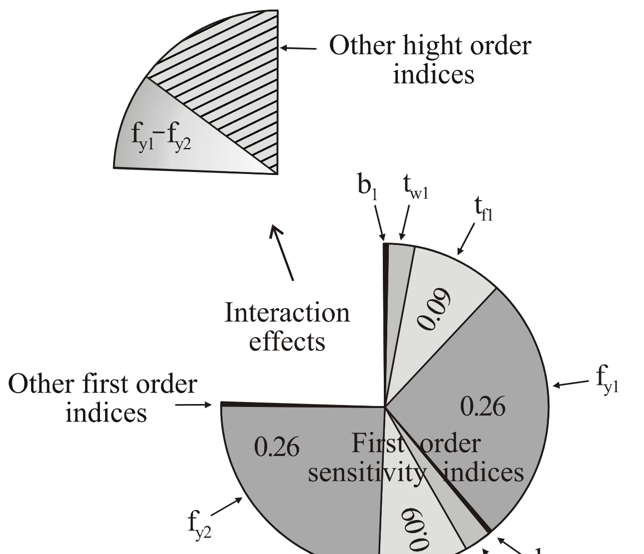

Fig.2 Sensitivity analysis results

2.4 Statistical Analysis

In Fig. 3, there are presented simulations runs of the Monte Carlo method. All the input quantities from Table 1 were considered to be random characteristics. The arithmetic mean of resistance capacity is 313.85 kN; the standard deviation is 17.18 kN; standard skewness is -0.097; standard kurtosis is 3.08. Taking low values of standard skewness and of standard kurtosis into consideration, it can be supposed that the runs of Monte Carlo method can be approximated by the Gauss probability density function. This assumption was confirmed by three distribution tests carried out independently from each other, namely by Chi-square test, Kolmogorov-Smirnov test and Anderson-Darling test. The findings that the hypothesis of Gauss stochastic model of resistance capacity should not be rejected were the conclusions of every test.

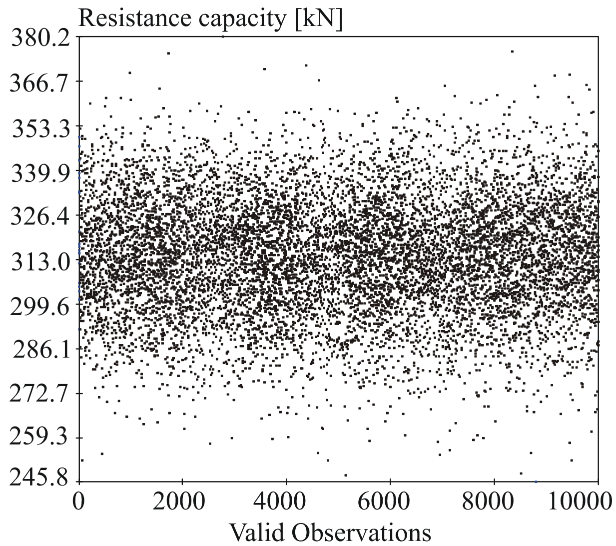

Fig.3 Monte Carlo runs of resistance capacity

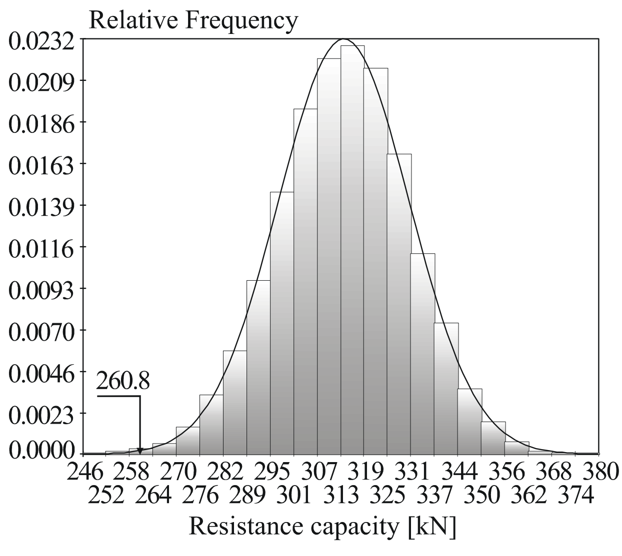

Fig.4 Histogram and design value of resistance capacity

These conclusions are of great importance for the calculation of the design value of resistance capacity. The design value can be calculated, according to the standard EN1990, as 0.1 percentile by the value 260.8 kN, see Fig. 4. The design value calculated according to the EUROCODE 3 is 249.1 kN. The design value 260.8 kN is higher than 249.1 kN; it means that the design according to the EUROCODE 3 is safe. From the practical point of view, the differences between both values are, however, very small.

2.5 Limit States Methods

What is the connection among the results of sensitivity analysis, statistical analysis and reliability of design like? The reliability of steel structures can be increased by decreasing the variance of input geometrical and material parameters which are of random character in general. An objection can be made saying that it is not sufficient to focus the attention only to the variance, nevertheless, with exception of yield strength, the majority of mean values are approximately equal to characteristics values. The sensitivity analysis supplies us the information for which of parameters the decrease of variance will have the largest effect on the decrease of the random ultimate resistance. The presented analyses can be applied analogously also to the serviceability limit state problems, e.g., when evaluating the maximum deflections of bridges. Also the deformation of struts in structural system can be significant from the point of view of the serviceability limit state; it is one of the problems which is paid relatively low attention in the field of the reliability of steel structures.

3 Conclusion

The past 33 years have witnessed the advent of numerous computer models in different application areas including physics, chemistry, environmental sciences, and ecology [1]. At the beginning, the structures of models were relatively simple and the outputs of models were assumed to be error free. Today, more and more complex models have been developed, and at the same time, the uncertainty influence analysis methods enabling the identification of sophisticated model dependences [3] are getting improved [25]. One important distinction between Sobol' and classical sensitivity is that the Sobol' sensitivity analysis detects interactions of input quantities through the second and higher order terms, while classical sensitivity methods give only derivatives with respect to single quantities.

The imperfections which interact and may thus generate extreme values of resistance capacity have been

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identified. In the frame with columns under tension, the yield point of the left column, yield point of the right column and the mutual interaction of these quantities had a significant effect on the ultimate resistance as corroborated by the second order sensitivity index (2). the flange thickness of the left and the right columns is next in order. The other input random quantities influence the resistance capacity only little.

It is evident that the implementation of probabilistic methods in reliability assessment presents a number of problems. With the development of the algorithms optimizing problems of structures, these procedures can contribute to a qualitative improvement of the safety and reliability analysis of structures [26-32]. In order for the mathematical models employed for reliability analysis to provide realistic information on the reliability of real steel structures, it is necessary that input random quantities are obtained from experimental research on ample samples. Many new measurements of noncommercially aimed research are available for model parameters, and therefore the probability functions or at least the variances of the parameters are known.

The input random parameters may be generally divided into two basic groups [3]. The first group includes those variables whose statistical characteristics can be positively influenced during production (yield strength, geometric characteristics) and those that are not sufficiently sensitive to changes in production technology (e.g. variability of Young's modulus E). The first group of quantities may be further subdivided into two subgroups: (i) quantities for which mean value and standard deviation can be changed by improving production quality [3]. Examples of such variables include Young's modulus; (ii) variables, the mean value of which cannot be significantly changed, because it should approximately correspond to the nominal value, for e.g. geometric characteristics of profile dimensions.

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