ISSN 1392-3730 / eISSN 1822-3605

VILNIUS TECH
Vilnius Gediminas Technical University

JOURNAL of CIVIL ENGINEERING and MANAGEMENT

2024
Volume 30
Issue 1
Pages 85–98
https://doi.org/10.3846/jcem.2024.19783

SEISMIC PERFORMANCE SENSITIVITY ANALYSIS TO RANDOM VARIABLES FOR CABLE TRAY SYSTEM

Zhaoyang FU[1], Siyuan WU[1,2,3]✉

[1]*Department of Civil Engineering, Dalian University of Technology, Dalian, China*
[2]*China Construction Eighth Engineering Division Co., Ltd., Shanghai, China*
[3]*Zhixing Technology Nantong Co., Ltd., Nantong, China*

Article History:
- received 6 March 2022
- accepted accepted 31 May 2023

Abstract. Random variables introduced in modelling of seismic engineering are often the result of cognitive limitations and the unpredictability of structures, leading to uncertainties in the field. A practical method for dealing with them is to develop sensitivity analysis in the framework of data and probability statistics. Of existing non-structural components, cable tray systems are characterized by a number of uncertainties which may influence their bearing capacity drastically. In this research, the main characteristics of material, geometry, member layout along with the connection stiffness in cable tray are considered as random variables using global sensitivity analysis, with their results relative importance of these potential uncertainties on the seismic performance of cable tray. The sensitivity analysis method developed especially for cable tray under seismic excitation is constructed based on modal analysis and equivalent inertia force method combined with the Latin hypercube sampling method. The final results demonstrate the need to consider the effects of random variables in modeling assumption in seismic performance analyses of cable tray and can be further used in optimization design.

Keywords: cable tray, sensitivity analysis, modeling uncertainty, seismic engineering.

✉Corresponding author. E-mail: *siyuan_wu1992@163.com*

1. Introduction

Cable tray system is firstly used in industrial plants such as nuclear power plants (NPPs), thermal power plants and chemical plants and has been introduced to modern architecture as a typical non-structural component in recent years. It is suspended from the ceiling or mounted on the floor to support heavy electric cables (Figure 1), which usually considered as "lifeline engineering" since the essential role in connecting the external power and ensuring normal operation of building in seismic hazards. As characterized by the long distributed, generally multi-span and large mass of cable tray system, it is more vulnerable to damage and even fall during earthquakes, which has been reported by failure incidents worldwide (e.g., Chile Earthquake (Miranda et al., 2012), Anchorage Earthquake (Qu et al., 2019)).

Thus, several research efforts and contributions have stemmed from the above-reported context and the increased awareness of analysts in assessment of seismic performance and seismic design for cable tray system, allowing several issues in failure mechanism, design and performance quantification using theoretical and numerical analysis (Matsuda & Kasai, 2017; Shahin et al., 1978; Pearce et al., 1984; Desmond & Dermitzakis, 1987; Hu et al., 2016) or, to other extent, by experimental testing of structural components and full-scale structures (Hatago & Reimer, 1979; Masoni et al., 1989; Reigles et al., 2016; Huang et al., 2017; Wu & Huang, 2022; Matsuda et al., 2020). It is particularly noteworthy that the seismic performance of cable tray system accurate estimation of the seismic demand of cable tray system using performance-based earthquake engineering (PBEE) methodology has been attempted by Huang (2021). Nonetheless, the critical foundation for seismic performance assessment, which is the basis of structure optimization, of the cable tray system is still questionable on account of limited analytical or experimental studies (Eder & Yanev, 1988; Smith et al., 1990).

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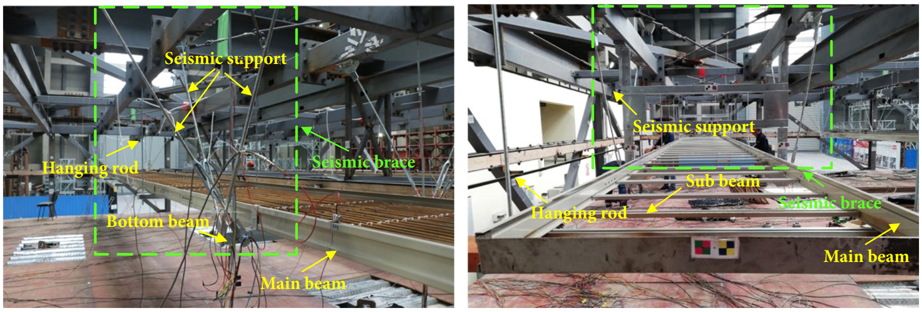


Figure 1. Typical cable tray system

With the improvement of seismic design requirements and advances in the computational resources available, more attention has been devoted so far in accurately evaluating the seismic performance assessments of structures (Martins et al., 2019). It is a challenging task owing to the large number of physical and geometric parameters involved (epistemic parameters) and the large amount of information that arises from considering several load cases, time-dependent and geometrically nonlinear effects (aleatory randomness) which all make big contributions in affecting the seismic risk assessment of structural systems. Consequently, a fixed model structure will probably provide sufficient predictive performance, but might still not be adequate for many other applications. To the author's best knowledge, unfortunately, overwhelming majority of the past and recent researches for cable tray system were based on computational frameworks of deterministic or parametric without reflecting the effects of epistemic parameters, to small scope considering random times and regions of earthquakes (Huang, 2021).

In reality, an effective method is to assess the sensitivity of the seismic demand in the framework of probabilistic to varying parameters in a range of structural systems (Martins et al., 2019; Padgett & DesRoches, 2007; Yu et al., 2017; Rodríguez et al., 2021; Alembagheri & Seyedkazemi, 2014). Sensitivity analysis has been proved to be a useful method in determining how changes in model input random variables (epistemic parameters) or assumptions affect the model outputs based on probabilistic methods and sufficient information from experiments (Kala, 2016). It can excavate random variables which have important influence on the seismic performance of structures and explore their corresponding variation, further, for structural optimization design.

In light of the above, this study assesses the influence of independent action of random variables in material, geometry, member layout and bolted connection on the overall vibration response of the structure. Besides, the correlation between random variables when a special random variable changes in the actual definition domain is also investigated. The results obtained in this study, could be used towards seismic risk assessment studies and seismic optimization design of cable tray system, hence, could be of some interest to this field.

2. Research methodology

2.1. Study framework

For the aim of propagating the uncertainty in the input factors to access the uncertainty in the output, it is essential to repeatedly running the model using different values for the uncertain inputs within their plausible ranges then characterizing the output distribution and extracting their summary statistics. This constitutes uncertainty analysis using Monte Carlo simulation (Rubinstein & Kroese, 1981; Baker & Cornell, 2008), First-Order Second-Moment Method (FOSM) (Le & Mosalam, 2005; Baker & Cornell, 2008) and Response surface methodology (RSM) (Liel et al., 2009). Once this is done, sensitivity analysis could be used to assign this uncertainty to the input random variables. Sensitivity analysis problems are essentially different, hence different methods have been proposed for their solutions (Saltelli et al., 2004) (e.g., reliability analysis for geotechnical tasks (Marčić et al., 2013), different forms of structures (Sousa et al., 2015; Yang, 2007; Kala, 2011) or sustainable building assessments (Šiožinytė & Antuchevičienė, 2013; Prasad et al., 2015; Antucheviciene et al., 2015)). The use of sensitivity analysis in this paper will focus on identifying which input random variables contribute the most to model uncertainty and random variables in very little contributions and can potentially be fixed.

The main steps involved in the procedure and the adopted research methodology for sensitivity analysis presented in this paper has been summarized in Figure 2. Further basic considerations and pivotal assumptions underlying the implemented framework are provided hereafter.

2.2. Latin hypercube sampling simulation

Monte Carlo method was widely used among a variety of uncertainty analysis method by sampling N times from the parameter distributions, this procedure creates a population of N possible instances of the structure. Therefore, the seismic response of structure can be reliably predicted assuming sufficient sampled structures. However, it is also the most time-consuming method since every structure needs to be analyzed.

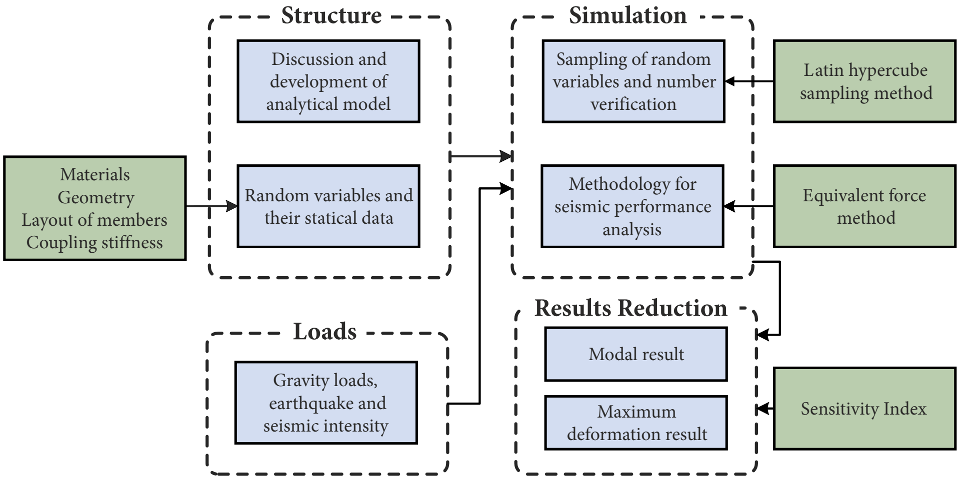


Figure 2. Flowchart of the sensitivity analysis framework

Hence, the Monte Carlo simulation can be further improved by replacing the classic direct sampling of the population with Latin hypercube sampling (LHS). The LHS is a statistical method for generating a sample of plausible collections of parameter values from a multidimensional distribution which firstly described by McKay et al. (1979). It has an advantage of "memory" function, which can avoid the repeated sampling caused by the concentration of data points in the direct sampling method, thus improving the sampling efficiency and saving 20–40% of the structure analysis. Consequently, in recent years, Latin hypercube sampling has become a popular tool for sensitivity analysis (Dolsek, 2009; Helton & Davis, 2003). The mainly implementation of LHS includes the following steps.

Assuming that the needed number of samples size is N and the types of random variables number considered in the sampling process is K, that is the sampling space dimension. The $N \times K$ dimensional matrix P is obtained, and N natural numbers from 1 to N in each column of matrix P are set for random arrangement. A matrix R with the same dimensions as P is also established, where all elements are uniformly distributed: $U(0,1)$. The cumulative distribution probability value corresponding to each element in the sample space $S_{(N,K)}$ can be obtained using Eqn (1):

$$S_{(N,K)} = \frac{P-R}{N}. \quad (1)$$

Finally, the inverse method is used to calculate the original sample value:

$$x_{ij} = F_{x_j}^{-1}\left(s_{i,j}\right) \quad (2)$$

in which i = 1, 2, ..., N; j = 1, 2, ..., K, $X = \left[x_{ij}\right]$ is the sample space matrix from LHS, $F_{x_j}^{-1}$ is the inverse function of the cumulative distribution function of parameter j; $s_{i,j}$ is the element of matrix S in column j of line i in the sample space.

2.3. Sensitivity analysis

A global sensitivity approach is requisite to performing an effective sensitivity analysis when model fractures nonlinearities in virtue of its extension of uncertainty propagation: it informs analyst about how much each input random variable contributes to the output variance including the effect of interactions among factors (Box et al., 2005). Global sensitivity analysis methods mainly include regression-based or correlation-based methods (e.g., Regression coefficients, Pearson correlation coefficient and spearman correlation coefficient (Heijungs & Lenzen, 2014; Chen & Corson, 2014; Geisler et al., 2005)), variance-based methods (e.g., Sobol method (Sobol, 2001)), and fourier amplitude sensitivity test (Koning et al., 2010). In addition, for more complicated failure surfaces, a new efficient and robust method was presented by Vořechovský (2022). Study of Groen et al. (2016) has proved that Spearman correlation coefficient and Sobol method have better stability and multi-parameter processing ability than other analytical methods. Hence, the squared Spearman correlation coefficient (SCC) was employed in this paper to calculate the linear dependence between the input and output parameters. The Spearman correlation coefficient can be calculated as follows:

$$r_i^{SCC} = \frac{\sum_i \left(x_{ij} - \bar{x}_i\right)\left(y_j - \bar{y}\right)}{\sqrt{\sum_i \left(x_{ij} - \bar{x}_i\right)^2 \sum_i \left(y_j - \bar{y}\right)^2}}, \quad (3)$$

where, x_{ij} is value of the i^{th} random variable in the j^{th} sample and $\bar{x}_i$ is the mean value of i^{th} random variable; y_j represents the output seismic performance analysis result of the j^{th} sample, while $\bar{y}$ refers to the mean value of all seismic performance analysis results; i = 1, 2, ..., N; j = 1, 2, ..., K. The sensitivity index using in SCC is equal to:

$$S_i^{SCC} = \left(r_i^{SCC}\right)^2. \quad (4)$$

The above process can be completed by the PDS module in the finite element software ANSYS.

3. Case-study information and analytical modeling

3.1. System description and Finite element (FE) model

As shown in Figure 1, a typical cable tray is suspended on the top floor or ceiling through threaded rods and steel struts. The main body is a lattice frame composed of main beams and sub beams through welding connection, and also includes other components such as splice plates, conduits, connections, insert plates with embeds and cable ties. According to the requirements of Code for seismic design of buildings GB 50011-2010 (Ministry of Housing and Urban-Rural Development and the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2010), seismic design is needed for areas over 6 seismic fortification intensity, meanwhile, non-structural components in seismic design should also be connected to the main structure, which indicates that seismic braces are needed in protecting cable tray system form seismic hazards. Hence, this section will concentrate on seeking structure forms of cable tray with balanced economy and safety as well as the details in developing FE model.

3.1.1. System discussion

For purpose of searching a safety and economically rational layout of seismic brace when the cable tray system is installed in modern buildings, attention will be fixed on influence of the layout spacing of seismic brace (or seismic layout spacing) on the installation price and structural response of the cable tray system in this section.

Maximum displacement ratio, which has been chosen as the seismic response index here, can be defined as:

$$r_{d,i} = \frac{d_{\max,i}}{d_{\max,60}}, \tag{5}$$

where $d_{\max}$ is the maximum displacement of the cable tray and i indicates the seismic layout spacing in Eqns (5) and (6). Installation price ratio is:

$$r_{p,i} = \frac{p_i}{p_4} \tag{6}$$

in which p is the installation price.

It is noteworthy that the maximum displacement response of cable tray is obtained by nonlinear time history analysis of Sweep wave under different peak ground accelerations (0.05 g, 0.1 g, 0.15 g and 0.2 g); the installation price is determined by the cable tray of 60 m length. The variation of the maximum displacement ratio and installation price ratio of cable tray with seismic layout spacing are shown in Figure 3.

The curves demonstrate that with the increase of the seismic layout spacing, the price and displacement tend to be stable, and the intersection of the maximum displacement ratio and the price ratio occurs when the seismic layout spacing is close as 12 m, which indicates the optimization of vibration reduction and economy can be better realized by using seismic brace, when the seismic layout spacing is 12 m. Besides, it is interesting to find that 12 m is also the maximum permitted seismic layout spacing in seismic design code (China Architectural Design Institute, 2014; Building Center of Japan, 2014). Furthermore, 53% of the maximum displacement was reduced when the seismic layout spacing is 12 m, which increased with decrease of seismic layout spacing. By comparison, the seismic brace almost lost its damping efforts when the seismic layout spacing is more than 24 m. On another track, from economic aspect, the installation price decreases as the increases of seismic layout spacing, e.g., compared with the 4 m, the installation price of 12 m seismic layout spacing is reduced by 40%. As the seismic layout spacing is greater than 24 m, the price tends to be stable gradually.

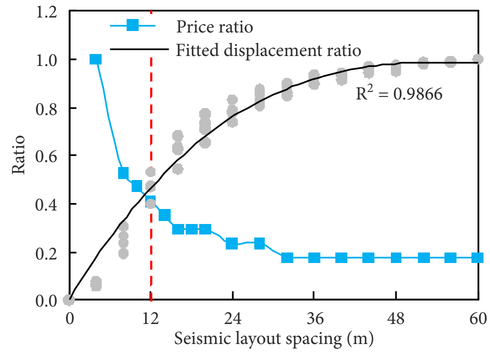


Figure 3. Variety of maximum displacement ratio and installation price ratio of cable tray with seismic layout spacing

For the sake of balancing seismic design and economic requirements, 4 m, 8 m and 12 m seismic layout spacing are selected in the following analysis respectively.

3.1.2. Development of Finite element (FE) model

Three kinds of numerical models mentioned in Section 3.1.1 are established with the aid of the commercial software ANSYS, as depicted in Figure 4. The X, Y and Z Cartesian coordinate axes represent the transverse, axial and vertical directions, respectively. The element Beam 188 is adopted to model beams and hanging rods. A bilinear stress-strain relationship with 3% kinematic hardening is adopted to simulate the mechanical property of the steel. A hysteretic model for Main to sub beam joints (MSBJs) is utilized in this study, which takes damage evolution of welded joint into consideration and reflects the characteristics of hysteretic behavior of the joint. More detailed information about the hysteretic model for MSBJs can be referred in Wu (2022). The mass of components (e.g., beams and hanging rods) are reflected in the FE model by changing the density, while the cable mass is realized by adding mass units on sub beams. It is assumed that the top of hanging rod is fixed to the ceiling to simulate the real state of hanging rods and structure more accurately.

With respect to the seismic input in nonlinear time history analysis, the horizontal acceleration component is chosen as the transverse (Y direction in Figure 4) directional ground motion input, while there is no seismic input in axial (X direction) and vertical (Z direction) directions.

3.2. Seismic information and equivalent inertia force method

Nonlinear time history analysis is still a calculation consuming task, although Latin hypercube sampling reduces the required sample size to a great extent. For the aim of improving the calculation efficiency, fundamental frequency based on modal analysis and maximum deformation based on equivalent inertia force method, which is an alternate method of analysis that allows a simpler technique in return for similar result, are utilized in the following part.

The equivalent inertia force imposed on main beams, which can be expressed as follows:

$$F_j = \eta m_j S_a, \tag{7}$$

where η represents static coefficient, a conservative value of 1.5 is taken here; m_j represents the distributed cable mass on the j^{th} sub beam; S_a represents the absolute maximum peak ground accelerations (0.05 g, 0.10 g, 0.15 g, and 0.20 g) of cable tray under Sweep wave.

The seismic artificially wave, Sweep wave, in this paper is a kind of frequency conversion sine wave, which is used to study seismic failure mechanism of non-structural components. Figure 5 shows the acceleration-time history curve and acceleration response spectrum of Sweep wave with PGA = 0.15 g, duration 100 s, frequency varies between 5 Hz and 0.5 Hz and rate of change in frequency is –1.744 octave/min. From Figure 5, it can be found that the fundamental frequency of cable tray corresponds to the dominant frequency of Sweep wave.

3.3. Uncertain modelling variables and corresponding properties statistic

3.3.1. Material

The random variables of material mainly affect the nonlinear hysteretic response of cable tray under earthquake, mainly including the yield strength (f_{y_Q235}), elastic modulus (E), Poisson's ratio (ν) and density (ρ) of steel.

It is worth noting that the cable mass, which ought to be the uncertainty of loads for the cable tray, is added to the cable tray in the form of mass units. However, essentially, the cable mass belongs to the category of the material uncertainty, so it is classified as random variables of material in this paper. It should be noted that the damping ratio is set to a constant value and realized by Rayleigh damping model here, which is obtained from full-scale shaking table test (Wu & Huang, 2022).

Uncertainty of material properties with their corresponding probability properties statistics were shown in Table 1 (Wu, 2022; Porter et al., 2002; Joint Committee on Structural Safety, 2001).

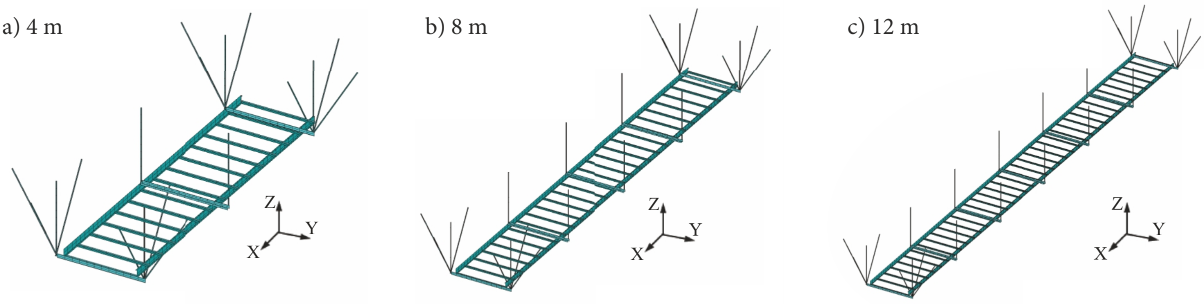


Figure 4. Finite element model of cable tray with different seismic layout spacing

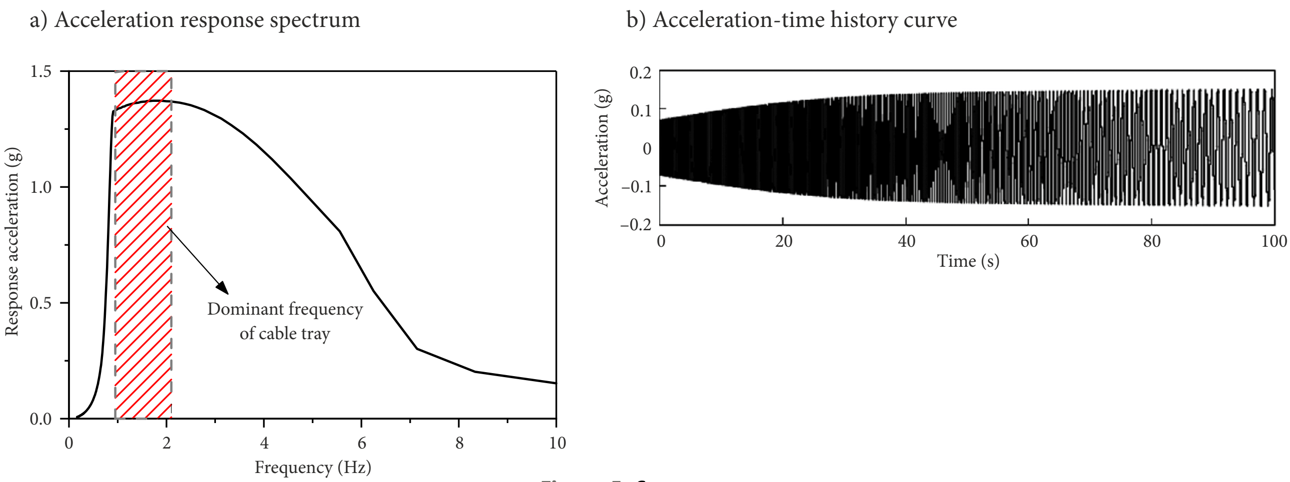


Figure 5. Sweep wave

Table 1. Probability distributions of the material properties random variables

Uncertain parameters	Random variable (unit)	Probability mode	Probability parameter	
			Mean	Coefficient of variation (%)
Damping	ξ	Deterministic	0.06	0
Q235 yield strength	f_{y_Q235} (MPa)	Normal	268.05	0.08
Cable mass	m (kg/m)	Normal	97.2	0.03
Density	ρ (kg/m^3)	Normal	7800	0.03
Elastic modulus	E (GPa)	Lognormal	206	0.03
Poisson's ratio	ν	Lognormal	0.3	0.03

3.3.2. Geometry

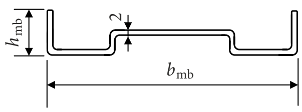
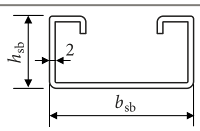
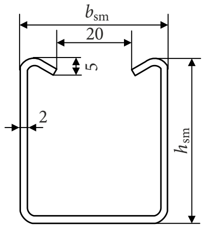
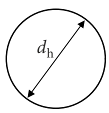
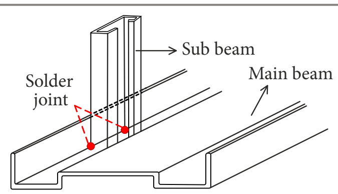
Due to the complexity of the construction site and the random errors in the process and installation of components, there are differences between design and actual geometric dimension for cable tray, which will affect its mass distributions and stiffness characteristics. Thus, the random variables of geometrical uncertainty assumed in this paper are cross sections (height and width of beams and bottom support or diameter of hanging rod) and initial stiffness of MSBJs.

According to Ellingwood et al. (1980), the coefficient of variation of geometric dimensions is 0.05 and the initial stiffness of MSBJs should be defined as:

$$r_{MSBJ} = \frac{k_{MSBJ,i}}{k_0}, \tag{8}$$

where k_0 and $k_{MSBJ,i}$ represent initial stiffness of welded joint and simulation stiffness of MSBJ, i is the number of connection joint. In which r_{MSBJ} equal to 1 indicates joint free of damage. While the change of joint stiffness will be realized by adjusting the initial stiffness ratio in simulation. Normal and lognormal distributions are assumed for the majority of the random variables of geometrical uncertainty in this article following previous studies (Ellingwood et al., 1980; Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2018) with their property statistics summarized in Table 2.

Table 2. Probability distributions of the geometrical size random variables

Members	Size	Uncertain parameters	Random variable (unit)	Probability mode	Probability parameter	
					Mean	Coefficient of variation (%)
Main beam		Height	h_{mb} (mm)	Normal	20	0.05
		Width	b_{mb} (mm)	Normal	100	0.05
Sub beam		Height	h_{sb} (mm)	Normal	20	0.05
		Width	b_{sb} (mm)	Normal	40	0.05
Bottom support		Height	h_{sm} (mm)	Normal	45	0.05
		Width	b_{sm} (mm)	Normal	40	0.05
Hanging rod		Diameter	d_h (mm)	Normal	14	0.05
Main to sub beam joint		Initial stiffness of MSBJ	r_{MSBJ}*k_0 (kN/mm)	Lognormal	1.15*k_0	0.15

3.3.3. Member layout

Across classes of cable trays, the configuration of members can be different. Although all of cable trays addressed by this paper are typical cable trays suspended on the ceiling, their length of sub beams and hanging rods as well as span of hanging rods may differ. As recommended in Technique specifical for steel cable supporting system engineering T/CECS 31-2017 (China Association for Engineering Construction Standardization, 2017) Codes 4.6.1 and 3.5.6, the length of brace should be between 60 mm and 1000 mm while the length of sub beam should be less than 2 m which all depend on loads. As regards the span of hanging rod, its statistical parameters are taken from the literature (Oterkus & Jung, 2020). All random variables are uniformly distributed and their statistical characteristics are presented in Table 3.

3.3.4. Connection stiffness between hanging rod and structure

In engineering practice, bolted connections of hanging rod and main structure are affected by construction errors during installation or low cycle fatigue under earthquakes, resulting in loosening or even shedding of bolts. Accordingly, the importance of bolted stiffness of different connections, as shown in Figure 6, is evaluated to ulteriorly inferring its influence of damage on seismic performance of cable tray. Here we set the bolted stiffness ratio:

$$r_{b,i} = \frac{E_{b,i}}{E_{hb}}, \tag{9}$$

where E_b indicates the elastic modulus of bolted stiffness of connections; E_{hb} is the elastic modulus of hanging rod; different positions are represented by i; r_b = 1 illustrates

Table 3. Probability distributions of the member layout

Layout members	Uncertain parameters	Random variable (unit)	Probability mode	Characteristic parameter	
				Lower level	Upper level
Sub beam	Length	l_{sb} (mm)	Uniform distribution	150	1000
Hanging rod	Length	l_h (m)	Uniform distribution	0.5	2
	Span	l_{sh} (m)	Uniform distribution	1.5	3

a) Experiment diagram
b) 4 m seismic layout spacing

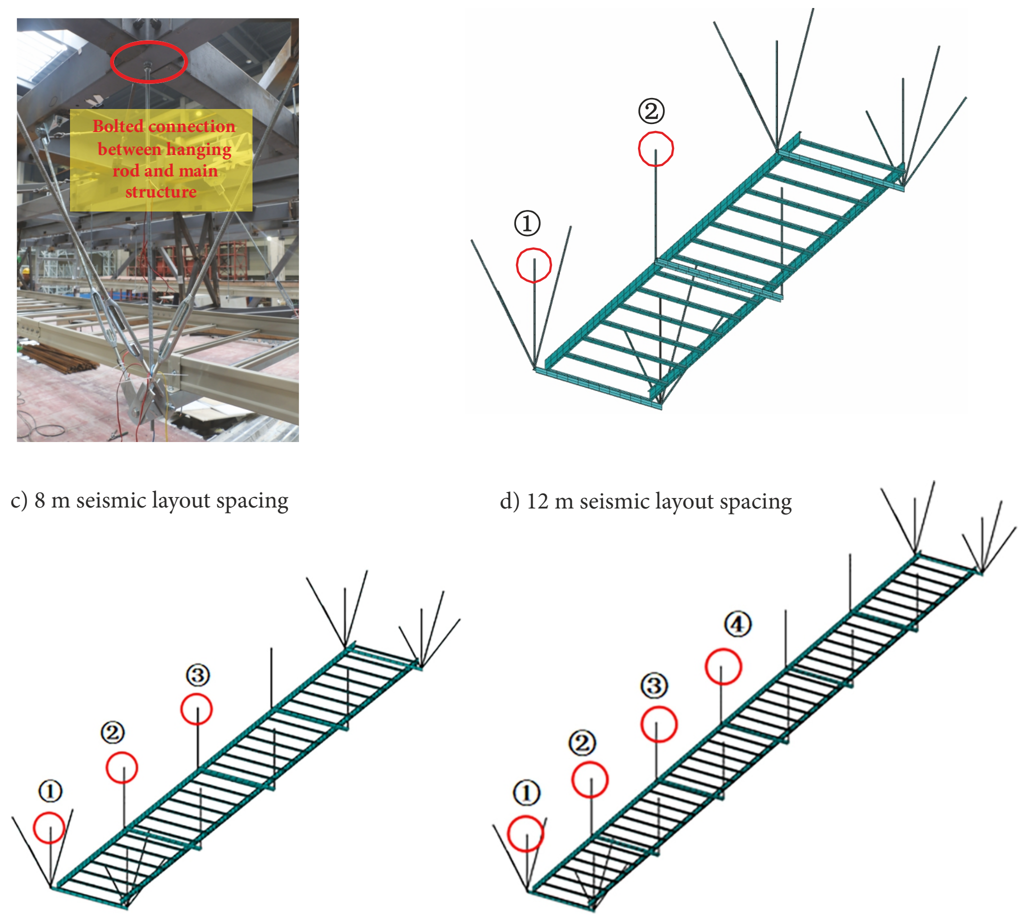


Figure 6. Bolted connections

Table 4. Probability distributions of stiffness of bolted connection

Uncertain parameters	Random variable (unit)	Probability mode	Probability parameter	
			Mean	Coefficient of variation (%)
Stiffness of bolted connection ①	$r_{b,1}*E_{hb}$ (Pa)	Lognormal	$1.25*E_{hb}$	0.15
Stiffness of bolted connection ②	$r_{b,2}*E_{hb}$ (Pa)	Lognormal	$1.25*E_{hb}$	0.15
Stiffness of bolted connection ③	$r_{b,3}*E_{hb}$ (Pa)	Lognormal	$1.25*E_{hb}$	0.15
Stiffness of bolted connection ④	$r_{b,4}*E_{hb}$ (Pa)	Lognormal	$1.25*E_{hb}$	0.15

no looseness in bolted connection. Stiffness of connections change with the variation of elastic modulus of the end region, which is 10% total length of hanging rod, of hanging rod connected to main structure in simulation procession. Probability distributions of bolted stiffness of different connections (Ellingwood et al., 1980) are shown in Table 4.

3.4. Latin hypercube sampling and verification

The accuracy of the sampling results of each random variable should be verified before conducting analysis. Taking elastic modulus (E), height of main beam (h_{mb}), length of hanging rod (l_h) and Stiffness of bolted connection ④ ($r_{b,4}\times E_{hb}$) for examples, their probability distribution histogram corresponding to the values of the uncertainty parameters of different samples extracted by LHS is also presented in Figure 7 when seismic layout spacing is 12 m. It shows precise fits between the random samples and corresponding target distributions. What needs special attention is that some random variables (e.g., elastic modulus, Poisson's ratio and initial stiffness of MSBJ), which should be subject to lognormal distribution, show normal distribution in their sample result. This is because the statistical characteristics of random variables subject to lognormal distribution are converted into normal distribution in advance when using Latin hypercube sampling.

Besides, LHS simulation samples N times from the parameter distributions, this procedure creates N possible instances of the cable tray, each of them needs to be analyzed. The reliable seismic response of the cable tray can be predicted more accurately by means of acquiring a large enough number of sampled structures. Therefore, the demand to balance the calculation cost and accuracy should also be taken into account. Structural models with different sample sizes were created here aims at studying the influence of sample size (N) on the seismic response of cable tray to seek a rational sample size. Figure 8 shows displacement response of 12 m seismic layout spacing whose equivalent static load is 0.15 g, of which mean

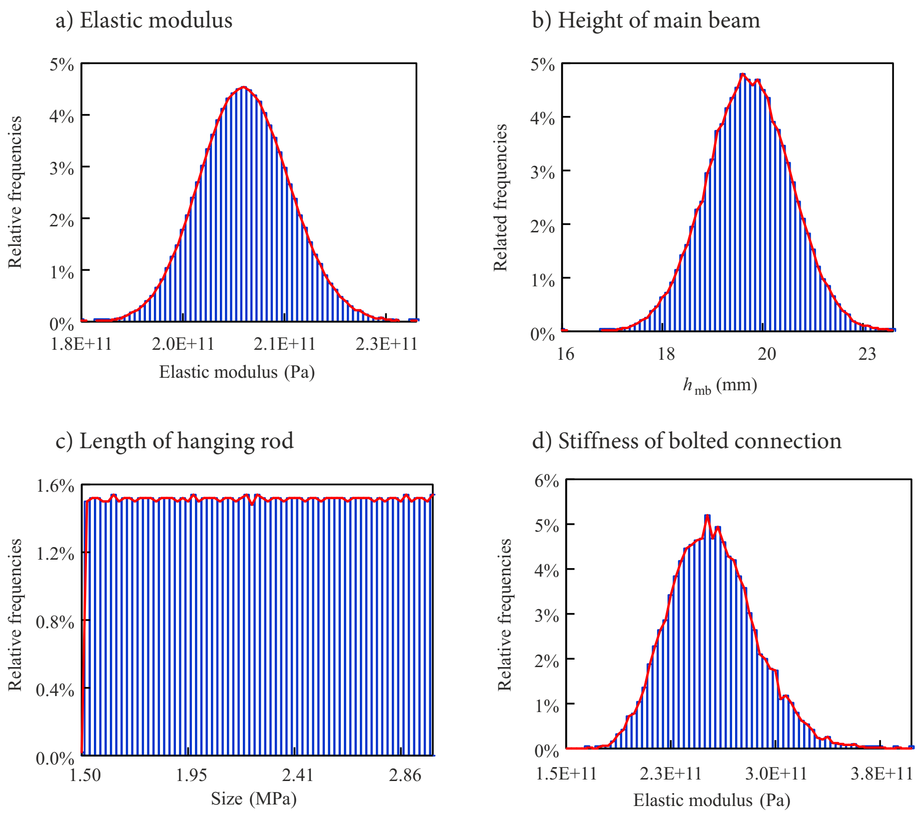


Figure 7. Frequency distribution histogram of different random variables

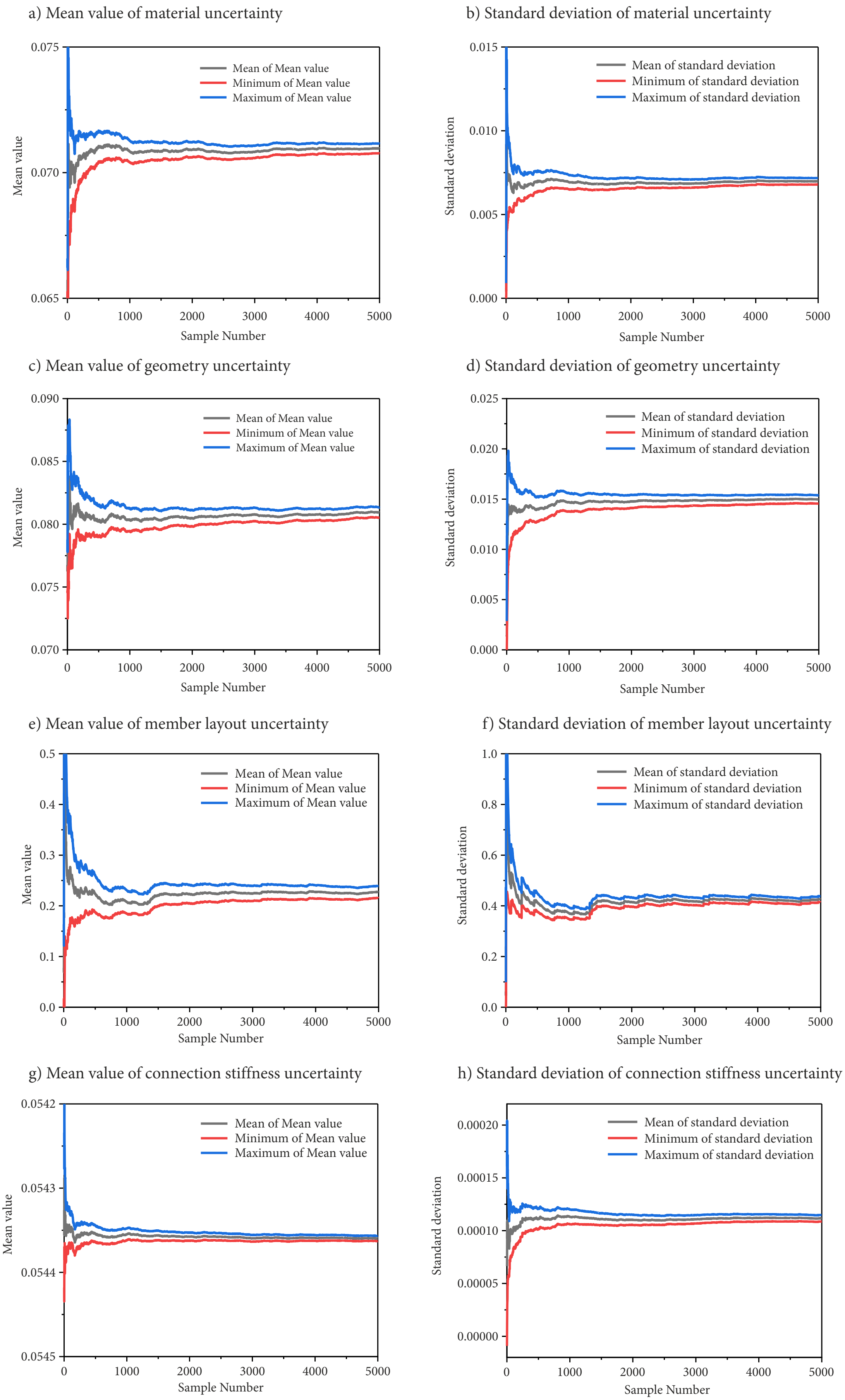


Figure 8. Displacement response changes with sample size

value and standard deviation are selected as indices to quantify the constant of sample result. As shown in Figure 8, the LHS used 5000 samples in actual practice, while the mean value and standard deviation of displacement response tends to stabilize when the number of samples reaches 2000 for all kinds of random variables. Note that for different examples, the selected size (N = 2000) of the set of structural models may not be appropriate.

4. Sensitivity analysis results and discussion

Sensitivity analysis based on structural frequency and maximum deformation of cable tray was conducted on the basis of principles and assumptions proposed in the above sections. It is noteworthy that different types of random variables are analyzed separately rather than considering all random variables at same time. Therefore, the sensitivity analysis in this paper contains four different types of random variables (material, geometry, member layout and stiffness of bolted connection) under three different seismic layout spacing (4 m, 8 m and 12 m) of seismic brace, with its result summarized in this section.

4.1. Sensitivity analysis based on modal

Figure 9 indicates sensitivity indexes of different seismic layout spacing of 4 m, 8 m and 12 m. For sensitivity to material, the main material random variables affecting the fundamental frequency of the cable tray are cable mass (m), elastic modulus (E) and material density (ρ) in turn, and the influence of seismic layout spacing is faint, while the fundamental frequency is not sensitive to Poisson's ratio (ν). Diameter of hanging rod (d_h), initial stiffness of MSBJ ($r_{MSBJ}*k_0$), height of main beam (h_{mb}), width of sub beam (b_{sb}) are found to be the geometry random variables which have the maximum impact on the fundamental frequency of cable tray. Specially, with the increase of seismic layout spacing, the influence of diameter of hanging rod (d_h) increases significantly while that of other geometries have reverse trend, which indicates the influence of stiffness of hanging rod on the fundamental frequency of cable tray significantly higher with the increase of seismic layout spacing. The remaining geometry random variables have a negligible effect on the fundamental frequency of cable tray. Intuitively, the length of hanging rod (l_h) always has the most critical impact on the sensitivity of member layout. Influence degree of length of hanging rod (l_h) gradually apparent while reduce for its span (l_{sh}), with the increase of seismic layout spacing. When the seismic layout spacing is 12 m, the influence of sub beam length (l_{sb}) is slightly larger than that of span of hanging rod (l_{sh}). When comes to connection stiffness, the influence of other connecting position of hanging rods are relatively significant, in addition to the location of the hanging rod (①), with peak value appeared at mid-span.

4.2. Sensitivity analysis based on maximum deformation

In addition to the modal analyses, equivalent inertia force analyses were performed for each of the investigated cable trays, in order to estimate the sensitivity of maximum deformation at the mid-span of cable tray to the input random variables, with its results visually displayed in Figures 10–12.

It is clear that mass of cable tray (m), yield strength (f_{y_Q235}), elastic modulus (E) and density (ρ) are the main material random variables have higher impact on seismic response. Furthermore, with the increase of seismic layout spacing and the equivalent inertia force, the influence

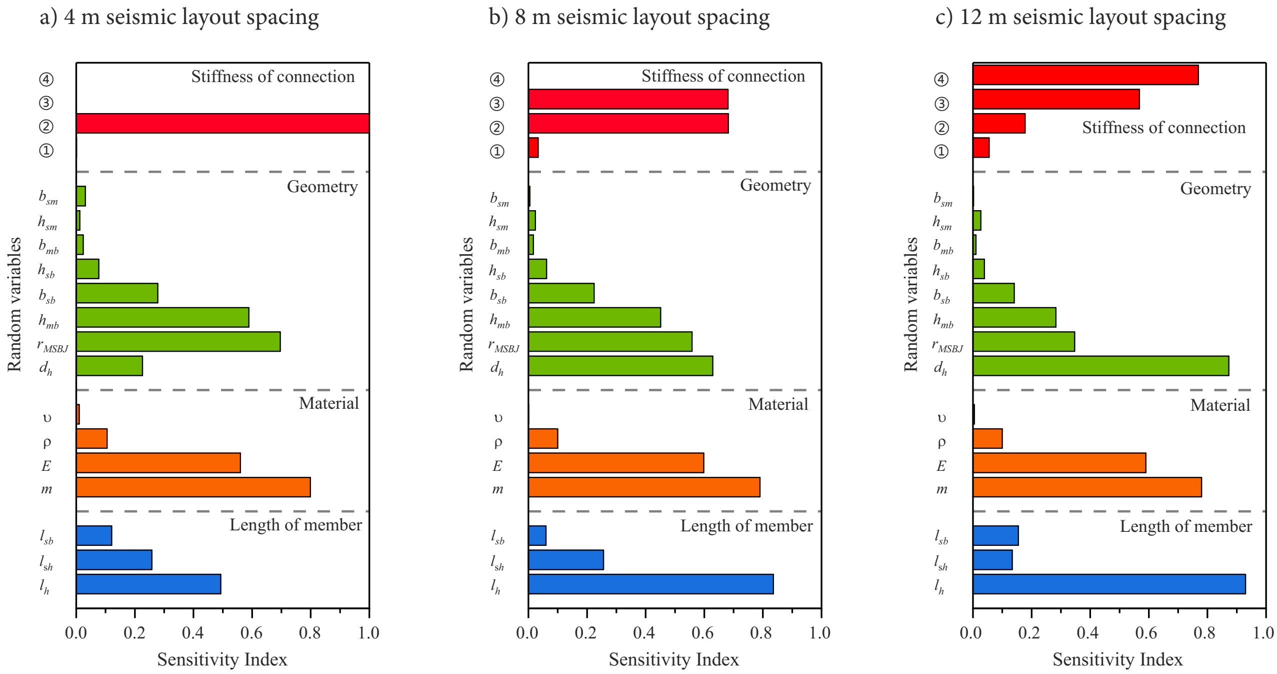


Figure 9. Fundamental frequency sensitivity

of the yield strength increases, while cable mass, elastic modulus and material density show less impact. Similar result to fundamental frequency sensitivity analysis is that Poisson's ratio remains the minimum influential material random variables. It also can be observed that diameter of hanging rod (d_h), initial stiffness of MSBJs ($r_{MSBJ}*k_0$), height of main beam (h_{mb}), width of sub beam (b_{sb}) are parameters have a quite high impact on maximum deformation of cable tray, whereas the effect of the other random variables on geometry uncertainty are only minor. Specifically, the initial stiffness of the MSBJ maintains greater effect as the variation of seismic layout spacing and equivalent inertia force while the influence of diameter of the hanging rod increases significantly and other geometry random variables decrease accordingly. This means that when the seismic layout spacing is larger, the stiffness of the hanging

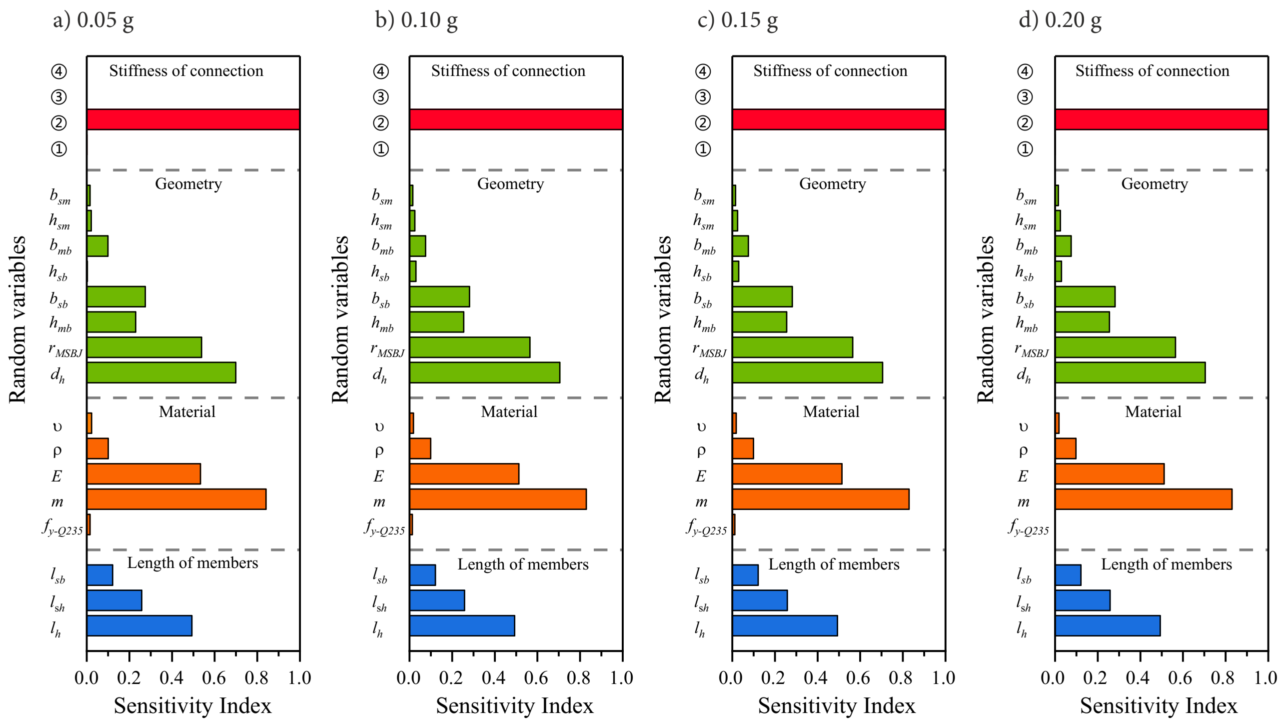


Figure 10. Maximum deformation sensitivity of 4 m seismic layout spacing

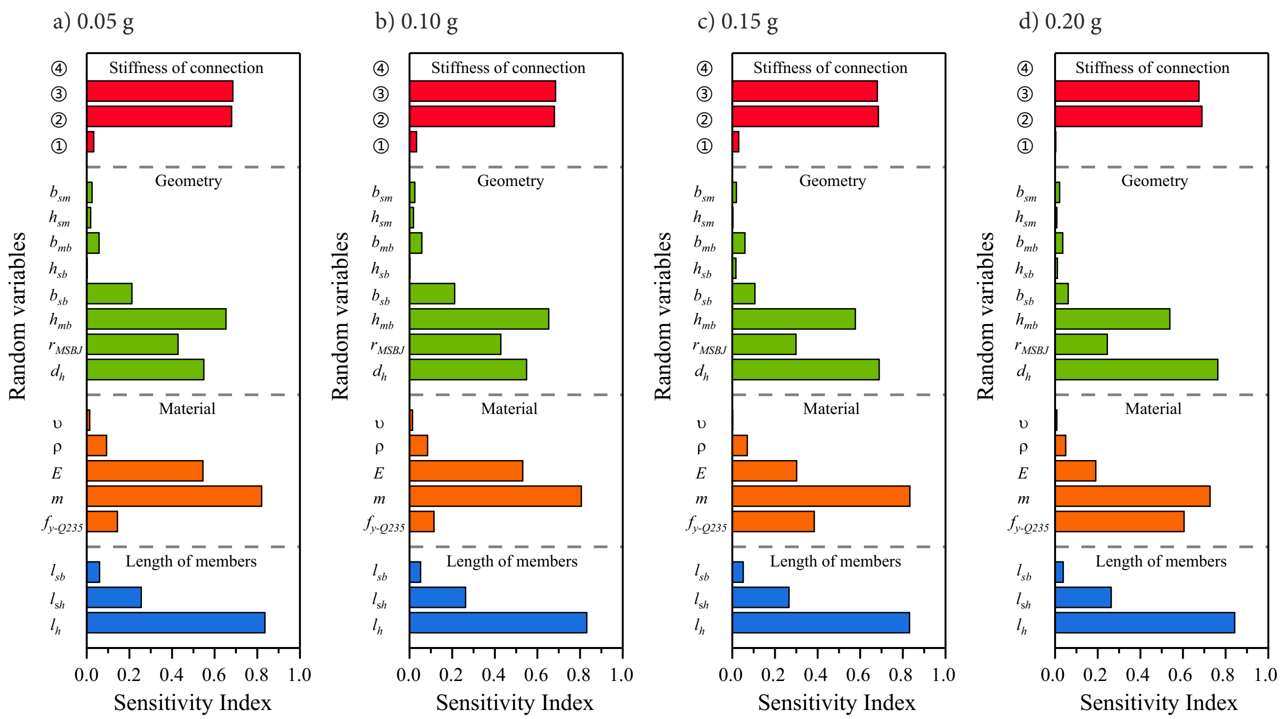


Figure 11. Maximum deformation sensitivity of 8 m seismic layout spacing

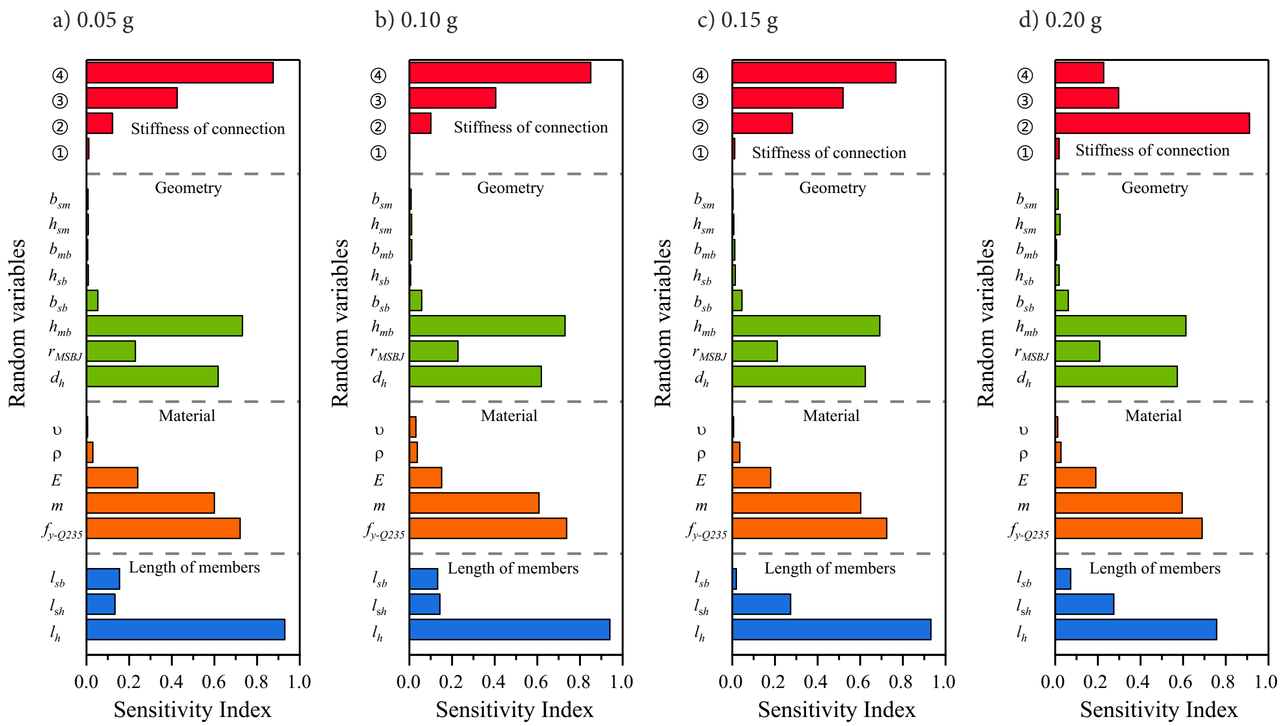


Figure 12. Maximum deformation sensitivity of 12 m seismic layout spacing

rod has a more significant impact on the deformation of the cable tray. The observation of member layout random variables' influence on seismic response more or less coincides with the results of fundamental frequency. Specially, the variation in span of hanging rod (l_{sh}) is found to be significant for seismic response, however, the impact of length of hanging rod (l_h) is reduced by setting a greater equivalent inertia force. When comes to connection stiffness, all bolted connections expect ①, have a significant impact on the deformation sensitivity of the cable tray. The influence of the hanging rod to the mid-span is greater when the equivalent inertia force is small, while this influence changed inversely as the increase of equivalent inertia force.

5. Conclusions

In this paper, the fundamental frequency and seismic performance sensitivity analysis, which is conducted within the framework of modal and equivalent inertia force analysis combined with LHS method, is performed selecting a typical cable tray as case study. Its obtained results point out the imperfections the random variables of which can have an effect on the reliability of the structure and can be further used in optimization design of cable tray. The main findings of the study are:

(1) The applicability of the sensitivity analysis has been demonstrated. It was shown that the accuracy of the results obtained by using the proposed method depends on the size of the set of structural models (N), which has to be defined prior to their determination. For the cable tray in this paper, N should be greater than 2000.

(2) The frequency and deformation of cable tray system are closely related to the change of seismic intensity and seismic layout spacing.

(3) Generally, mass, yield strength, elastic modulus and density of material random variables; the diameter of the hanging rod, the initial stiffness of the MSBJ, the height of main beam and the width of the sub beam of 4 m seismic layout spacing for geometry random variables; the length and span of hanging rod of member layout random variables are important random variables that have considerable impacts on the seismic response. While, in terms of connection performance, the connection stiffness in different positions is greatly affected by the seismic intensity. In contrast, the influences of the other random variables are only minor.

Acknowledgements

The authors thank Prof. Jiang Huanjun for his kind cooperation.

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