Reliability analysis for tension and compression designs of steel truss elements using Vietnamese codes.

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Abstract. This study performs a reliability analysis to assess the probabilistic safety levels of the truss members designed by Vietnamese design codes. Based on the investigations, the suitability of the load and the resistance factors currently specified in the design codes are examined. For this purpose, two truss structures are first designed using the load and actions code (TCVN 2737-2020) and the current design code for steel structures (TCVN 5575-2012). Monte Carlo simulations are then carried out for the design solutions. The results disclose that the reliability indexes estimated for the strength limit states are relatively close to the target value of 3.8, which is recommended in Eurocode. The compression designs seem to be overestimated when using the national codes. The compression bars are then redesigned with modified resistance factors of 0.95. The reliability analyses are again performed, and the results reveal that the resistance factor of 0.95 is more reasonably applied.

Keywords: Limit state design, TCVN 2737-2020, TCVN 5575-2012, reliability analysis, Monte Carlo simulation, truss structure.

1 Introduction

Recently, limit state design (LSD) codes are prevailingly performed for most structure design fields. The LSD approach helps to provide uniform and consistent design solutions in terms of probabilistic results [1,2]. Since the direct evaluations of probabilistic terms such as the probability of failure or reliability index are complicated, the partial safety factor (PSF) codes or load and resistance factors design (LRFD) codes are commonly applied in Europe [3,4] and North America [5–8] respectively. The same concept of these design codes is the factors prescribed in the codes are determined by probabilistic frameworks. In the probabilistic frameworks, uncertainties inherently involved in load and resistance components are accounted for. Thus, the design solutions tend to be close to a given target safety level. This concept makes the LSD superior to the allowable strength design approach [2,9,10].

Since 2005, when the bridge design code 22 TCN 272-05 was specified, the LSD has been used to design bridge structures in Vietnam. Notably, 22TCN 272-05 leans on the bridge design code widely employed in America, i.e., AASHTO 2004. In the design codes, the uncertainty models for loads and strength components, including structural and geotechnical terms are referred to many previous studies [1,11]. On the other hand, conventional methods of allowable strength design are commonly used for different design fields, such as buildings and harbour facilities. For example, the load and actions are specified in TCVN 2737 -1995. Noticeably, the term TCVN stands for Vietnamese design codes in this work. Recently, an updated version of TCVN 2737-1995, i.e., TCVN 2737 – 2020 [12] is proposed. It is worth noting that the limit state design is recommended in the new version. Accordingly, the load factors and associated load combinations are provided. It is seen that the new version (TCVN 2737 - 2020) only focuses on the load side, hence, the resistances are estimated using specific strength design codes such as the steel structure design standard (TCVN 5575-2012) [13] and reinforced concrete structures design standard (TCVN 5574-2018). However, the target reliability or target failure probability are not mentioned in the design standards. Furthermore, the consistency between the factors specified in the two design standards (one for load, which is new, and one for resistance) becomes questionable.

This study investigates the probabilistic safety levels of the truss structures, which are designed following the current design codes. Namely, the load effects are determined from TCVN 2737 – 2020, and the sections are designed following TCVN 5575 – 2012. For this purpose, two planar truss structures are examined in this study. First, the tension and compression chords are designed to reach the strength limit states. The buckling conditions required in the steel design standard are also accounted. Since the deterministic design solutions are obtained, fully probabilistic analyses, i.e., Monte Carlo simulations are performed to assess the probability of failure and the associated reliability indexes of the design solutions. Because the reliability indexes are intertwined with the load and resistance factors, the reliability indexes estimated for the design solutions help to provide insight into the load and resistance factors employed. The limit state design selects several feasible sections, and their probabilistic safety levels are also considered.

2 Method

2.1 Strength limit state designs using national codes of TCVNs

In TCVN 2737 – 2020, there are two limit states, i.e., the first limit state and the second limit state. It seems that the first limit state is for the strength design, and the second limit state is for the service limit state where the unity load factors are used. This study focuses on the first limit state, and only one temporary load is considered. Therefore, the design equation can be written as Equation (1) below. In the design equation, D and γ_L denotes the permanent load and its factor. Similarly, L and γ_L denotes the temporary load and its combination factor. The right-hand side is the factored resistance of the members. γ_R is the resistance factor and γ_M is the material factor. Notably, this equation is employed for designing both tension and compression behaviors, hence, R_c denotes the corresponding characteristic resistances.

$$\gamma_D D + \gamma_L L \leq \gamma_R \frac{R_c}{\gamma_M} \tag{1}$$

The load factors are taken from TCVN 2737 – 2020. Accordingly, values of 1.35 and 1.50 are used for γ_D and γ_L, respectively. Contrastingly, the material and the resistance factor are taken from TCVN 5575-2012. Thus, the resistance factor of 0.95 and 0.9 is specified for tension and compression members, respectively. Particularly, the same material factor of 1.1 is recommended for designing the two behaviors.

In the design process presented above, the equal sign in Equation (1) indicates the limit state. However, in design practices, it is difficult to accurately achieve the equal sign because the truss members are commonly taken from given sets of steel structure products. In this study, the sections are chosen such that the redundancy capacity of strength is not higher than 5%.

2.2 Probabilistic assessment

Since the deterministic design process in Subsection 2.1 is obtained, the probabilistic terms of the design process are examined. This study performed MCS for evaluating the outcome probability of failure and reliability indexes.

It should be noted that the load and resistance factors or the partial safety factors provided in the LSD codes are commonly assessed using the approximation method such as the first-order second-moment method or the first-order reliability method. Since the standards need to cover most of the design situations, the two approximation reliability methods are reasonably applicable although they include some limitations. In this work, the axial forces in the truss members are solved using the finite element methods. That means the load effects in the truss members are determined through the implicit process so that MCS is the most suitable approach for assessing the failure probability. The limit state equation is defined in Equation (2) below for MCS.

$$g = R - Q \tag{2}$$

In the equation, R is the resistance components and Q is the load effects obtained from MCS. g is the performance function.

The procedure for performing MCSs is well presented in the literature [9,10] and applied to numerous problems [14,15]. The application of MCS is briefly summarized as follows.

Step 1. Defining the uncertainty models involved in the problem at hand.

Step 2. Justifying the feasible size for MCS, i.e., N_{MCS}.

Step 3. Generating a sampling set of all uncertain variables using the uncertainty models defined in Step 1.

Step 4. Evaluating the load and resistance components and determining the performance function for each sample using Equation (2).

Step 5. Recording the failure events obtained from the MCS, i.e., counting N^{Fail}.

Step 6. Evaluating the failure probability (P_f) and the associated reliability index (β) using Equations (3) and (4), respectively. In Equation (4), Φ is the cumulative probability density of the standard normal distribution.

$$P_f = \frac{N^{Fail}}{N_{MCS}} \tag{3}$$

$$\beta = \Phi^{-1}\left(1 - P_f\right) \tag{4}$$

The feasible size of the MCS in Step 2 can be determined based on the coefficient of variation of the anticipated P_f as shown in Equation (5). The equation implies that the larger the MCS size, the more accurate P_f estimated. A limit value of 30% for COV_{Pf} is recommended in the previous studies [16,17]. Based on the expected reliability index of 4.0, the size of MCS is chosen as two millions to obtain the COV_{Pf} is not higher than 13%.

$$N_{MCS} = \frac{1-P_f}{P_f COV_{Pf}^2} \tag{4}$$

The load effect, i.e., the axial forces in truss bars for each sample of MCS is determined based on the finite element methods. Thus, the *FEM-Truss* program [18], which was developed using MATLAB platform is used in this study.

3 Numerical examples

3.1 Two planar truss examples

In this section, the two truss structures, i.e., a simply supported truss presented in Fig. 1 (Example 1) and a cantilever truss shown in Fig. 2 (Example 2) are examined. In Example 1, a 24m length and 2m height truss is investigated. The permanent load *D* and temporary load *L* apply are considered in two examples. A ratio between the temporary and permanent load of 3.0 is recommended in [] and is employed in this work. A total factored load of 100kN is applied to the truss. That means the unfactored loads of 17.1kN and 51.3kN are used for D and L, respectively. For the second example, the span length and height of the truss are 15m and 2m, respectively. the factored load effect of 45 kN is utilized. Thus, the unfactored loads of 7.7 kN and 23.1 kN are applied for Example 2. The FEM-Truss program is carried out to evaluate the axial forces in the truss members. After that, the square hollow sections provided by SSAB Domex Tube (available on www.ssab.com) are used for designing tension and compression members. The yield strength of 350 MPa and Young's modulus of 200,000 MPa are utilized for steel structures.

The results of the sections designed are reported in Table 1 for Example 1 and Table 2 for Example 2. Notably, the trusses are statistically determinate, and the chord bars are critical members, hence, they are focused on this study. Moreover, the buckling conditions are also examined during the design for compression bars as recommended in Subsection 7.6 of TCVN 5575-2012. In each table, three design solutions are chosen for tension bars and two sections are designed for compression members. Generally, compression behaviors require bigger sections compared to the tensions.

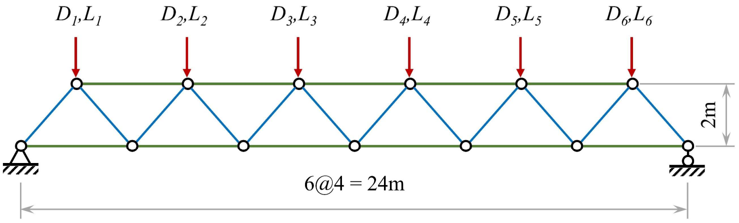

Fig. 1. Example 1, a simply supported truss structure.

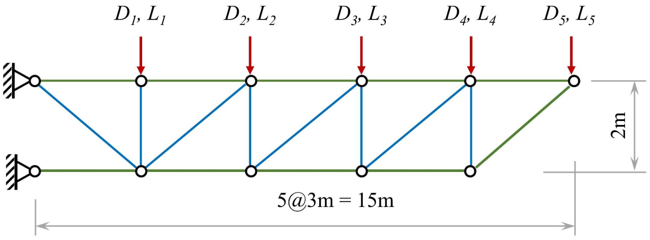

Fig. 2. Example 2, a cantilever truss

Table 1. Results of limit state design for Example 1

No	Behavior	Section (in mm)	Redundant capacity	RI
1	Lower bars	120 × 120 × 7.1	1.9%	3.75
2	Lower bars	140 × 140 × 6	4.9%	3.89
3	Lower bars	160 × 160 × 5	2.0%	3.76
4	Upper bars	150 × 150 × 8	2.3%	4.34
5	Upper bars	160 × 160 × 7.1	2.4%	4.33

Table 2. Results of limit state design for Example 2

No	Behavior	Section (in mm)	Redundant capacity	RI
1	Lower bars	150 × 150 × 10	1.2%	4.03
2	Lower bars	180 × 180 × 8	4.5%	4.22
3	Upper bars	120 × 120 × 7.1	1.9%	3.57
4	Upper bars	140 × 140 × 6	4.9%	3.72
5	Upper bars	160 × 160 × 5	2.0%	3.58

The uncertainties involved in the steel truss structures are taken from previous studies and summarized in Table 3. The uncertainties are depicted by their bias factors, i.e., the mean μ and coefficient of variation COV. Namely, the load models are recommended in [19,20] and used to derive the load factors specified in ASCE/SEI 7 – 16 [6]. The steel properties, i.e., Young's modulus, the yield strength; and the section variability (represented by the thickness of sections) are taken from the previous studies [20–22].

Table 3. Uncertainty models used in the examples.

No	Variable	Symbol	μ	COV	Distribution
1	Ten. bar thickness	t_t	0.964	0.04	Normal
2	Comp. bar thickness	t_c	0.964	0.04	Normal
3	Web bar thickness	t_w	0.964	0.04	Normal
4	Young's modulus	E	1.00	0.06	Normal
5	Yield strength	F_y	1.10	0.10	Normal
6	Permanent load	D	1.05	0.10	Normal
7	Temporary load	L	1.00	0.25	Extreme type 1

The MCSs presented in Section 2 are then executed for assessing the probabilistic outcomes of the solutions designed following the codes. Results of MCSs are reported in Fig. 3 for Example 1 and Fig. 4 for Example 2 for illustrations. The reliability indexes estimated for each design solution are summarized in Table 1 and Table 2. It is seen in the tables that the safety levels are quite similar for each behavior of tension or compression. Furthermore, the reliability indexes for tension designs are generally obtained lower than those for compression bars although they are all designed at the limit states. That means failures tend to occur more frequently in tension bars than the compression members. In other words, the resistance factor specified for the compression designs seems to be more conservative than that for tensions.

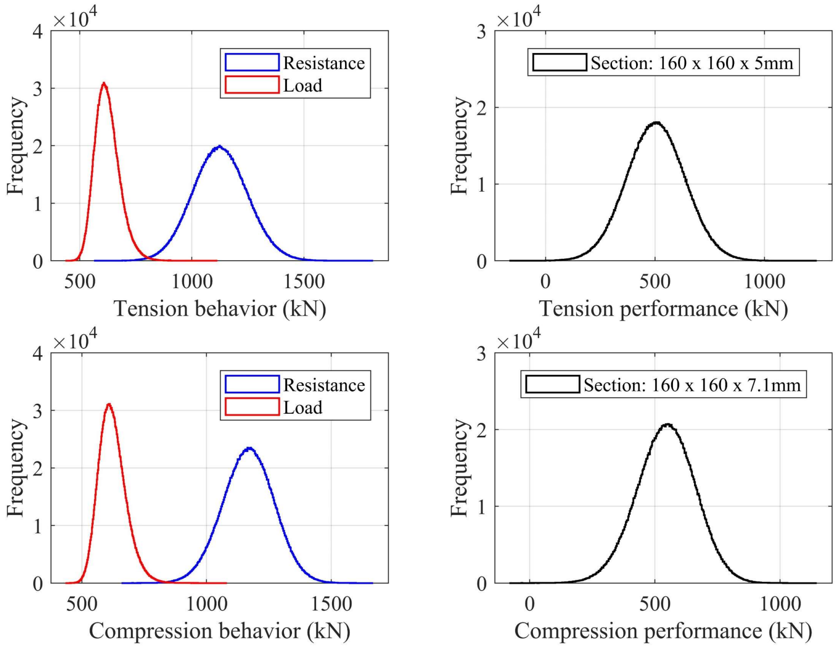

Fig. 3. An illustration of MCS results for Example 1.

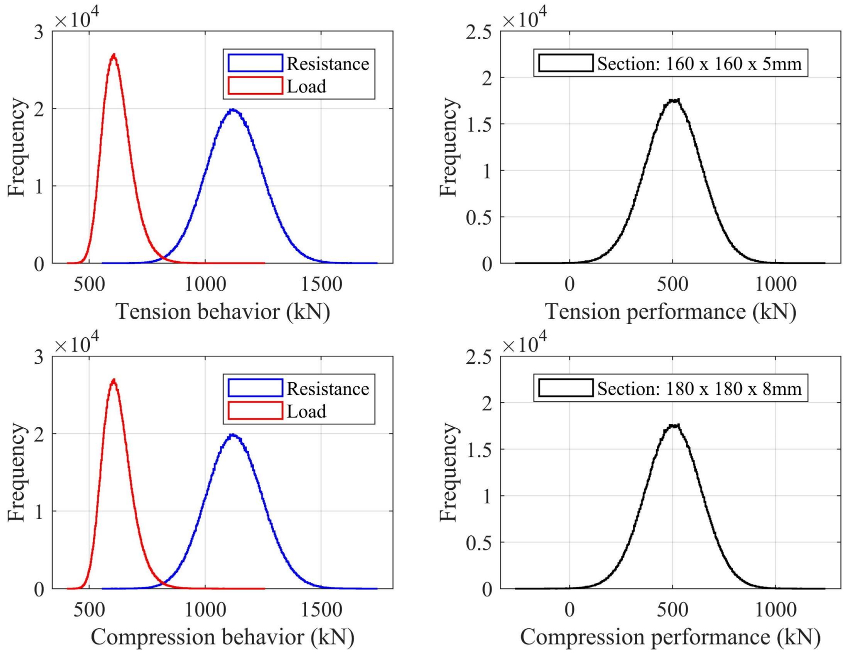

Fig. 4. An illustration of MCS results for Example 2.

Because the design codes do not mention the target reliability index used for developing the codes, the target reliability index of 3.0 specified in American specifications [6,7] and 3.8 in Eurocodes [3,4] are referred to in this work. It is seen that the outcome reliability index is close to the target value used in Eurocodes. Namely, the reliability indexes for tension members are slightly lower than 3.8, and those for compression behaviors are higher than 3.8. Here, it can be stated that the compression bars are designed with more redundancy capacity in terms of reliability indexes.

3.2 Redesign for the truss structures

In the limit state designs, it is expected that the design solutions will achieve a uniform and consistent safety level. Therefore, the more redundant designs of the compression bars are redesigned in this work. To do that, the resistance factor for compression design of 0.9 initially specified in TCVN 5575-2012 is increased to 0.95 to redesign the compression members. Then, MCSs are again performed to estimate the probabilistic results of the two examples. The results of the redesign process are summarized in Table 4 for the two examples. It is observed in the table that the lower reliability index of 3.84 is desired for the target 3.8 and also higher than the reliability indexes for tension behaviors reported in Tables 1 and 2. Therefore, it is recommended that the resistance factor for designing compression behaviors can be increased from 0.90 to 0.95 to make the design solutions become more consistent and help to reduce the cost investment.

Table 4. Results of redesign process of compression bars.

No	Case	Section (in mm)	Redundant capacity	RI
1	Example 1	140 × 140 × 8.8	1.5%	4.14
2	Example 2	160 × 160 × 8.8	3.9%	3.84

4 Conclusion

This study performs reliability analyses for truss structures that are designed following national design codes of TCVN 2737- 2020 and TCVN 5575 – 2012. Two planar trusses are examined. The main conclusions are derived as follows.

Although the limit state design solutions are satisfied for the two strength conditions, the reliability indexes for tension behaviors are obtained lower than those for compressions. Therefore, the failures tend to be occurred more frequently in the tension members compared to the compression bars.

The outcome reliability indexes of the truss structures designed following the national design standards are closer to the target value specified in the Eurocode than that defined in the American specification.

Using a resistance factor of 0.9 for compression design, which initially is defined in TCVN 5575-2012 results in overestimate designs. Based on the redesign process, a resistance factor of 0.95 is recommended to make the design solutions more uniform and consistent since the reliability indexes of the redesigned bars desire the target value of 3.8.

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