Reliability of simple space truss structure

Sang Toga Sitompul, Pariatmono Pariatmono

Master of Civil Engineering, Universitas Mercu Buana Jakarta, INDONESIA
E-mail: sangtogas@gmail.com

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ABSTRACT

Structural analysis has been widely applied in civil engineering. This analysis based on probability theory. Structural analysis was carried out to calculate the probability of failure and reliability of the structure. There are many cases of construction failure caused by uncertain environmental and human activities, including improper load in the external design process. In the process of designing a structure in Indonesia, complicated analysis is rarely carried out because of the complexity and impracticality of the analysis. Engineers and developers need to understand the behavior of the space truss structure and procedures in structural reliability analysis, Therefore it is necessary to simplify the structure in the analysis of the structure. This paper has carried out a structural reliability analysis using simple space truss modeling to understand its structural behavior and the principles of structural analysis under indeterministic load with simplified methods to make it more practical. A comparison of struktural analysis was carried out on 3 methods of structural analysis, manual calculation, ETABS v9.7.4, and MStower V6.20.1.11. The results of the three methods have the same value so that the structural analysis using MStower is reliable. In the loading approach, the load that is developed into a population of possible loads that can occur. Monte Carlo simulation is used by generate a sample of the load population that can represent the number of possible loads so as to reduce the number of analyzes. Random value generation methods were compared to get a more effective and practical method. The failure criteria are determined to obtain the limit state function of the structure so that the probability of failure and the reliability of the structure can be calculated. In this study, the limit state function was obtained in compression member with a 67% probability of failure and 33% reliability of the structure.

Keywords: structure reliability; probability; simple space truss; monte carlo; failure criteria.

INTRODUCTION

Infrastructure is a necessity that can support the economy of the country. Currently, infrastructure construction continues to increase along with the growth of a country. Infrastructure development cannot be separated from design work. In the design work determining the loading on the structure is an important thing to calculate the capacity of the structure.

The structure is designed for loads that are influenced by uncertain environmental, mechanical and human activities (Okasha 2016). However, there are many cases of structural failure. There is always a very small risk that a building will collapse (Dewi et al. 2018). Therefore, structural reliability analysis needs to be applied to the design and evaluation process.

A structure can collapse completely due to various things, including improper determination of external loads. Determination of the load in the design refers to the regulated standards. There are many variations of load in designing a structure. Standards that have been regulated have defined deterministic load but cannot be used in a probabilistic approach due to the many variations in load symptoms that can occur. There are many natural conditions and structural components that have the potential as loads, but this load is not available in detail and monitoring data are in fact generally insufficient due to limited equipment with cost consideration (Fang, Tan, and Zhang 2020) so these loads can be considered as uncertain loads.

The truss structure is important in civil engineering, generally used in antenna towers, architectural towers, transmission towers, chimney towers, light towers, viewing towers, or water towers (Mochocki, Obara, and Radoń 2018). This paper will explain how the behavior of a simple space truss structure with a comparison of each method and procedure of structural reliability analysis with a deterministic structural capacity and an indeterministic load.

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In another study, structural reliability analysis was carried out on the effect of loads under wind load conditions, one of which was using structural analysis software such as SAP2000 (Gao and Wang 2018), Autodesk ROBOT Structural Analysis (Szafran, Juszczyk, and Kamiński 2020), ANSYS (Zheng and Fan 2018), experimental modeling with compressive load (Zhang and Xie 2018), experimental modeling of wind loads using the wind tunnel method (Zhang et al. 2015). These methods can be simulated on the MStower software. MStower has features that make it easy to model the loads, in special condition wind loads that can be applied from any angle to the section of the structure. The application of MStower software in this study is expected to be applied to various types of other structures. Before using MStower, this study made a comparison between softwares and manual calculations.

The results from manual calculations are used to validate the results of structural analysis using MStower. In carrying out an indeterministic load approach, random variables are generated to represent the population of the load data, a Monte Carlo simulation is carried out so that there is no need for structural analysis on every possible load that can occur.

RESEARCH METHODS

Simple structure will make it easier to analyze the behavior of the structure and its load. The results of the structural analysis can determine the failure criteria to find the limits of the structural capacity such as the compressive, tension and displacement limit of the structure. Simple space truss model (see Figure 1) was used in this analysis to validate the results of the structural analysis using ETABS v9.7.4 and MStower V6.20.1.11 and compared the results.

The development of load data can be estimated with a small range of values so that it can determine the possible combination of loads that can occur. The load combination data is simulated on the structure, then the capacity of the structure in each combination is obtained so that the probability of failure and the reliability of the structure is obtained as a reference in data sampling.

Monte Carlo simulation is used to reduce the number of structural analyzes. Random value generator is used to determine the sample that can represent the population value of the structure capacity. In determining the method of generating random values, a comparison of methods is carried out between normal distributed generators of normally distributed random values and generators of random values using Microsoft Excel. The comparison results obtained using excel are simpler and easier so that the analysis is continued using this method. The calculation of the probability of failure and the reliability of the structure is carried out with the results of sampling data using a random value generator. This research method is concluded in the flow chart in Figure 2.

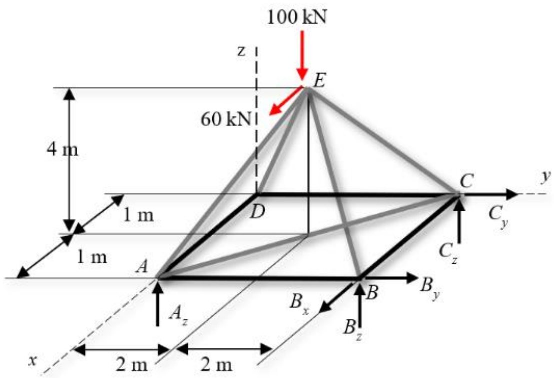


Figure 1. Simple Space Truss Structure (Adapted from Kassimali, 2011)

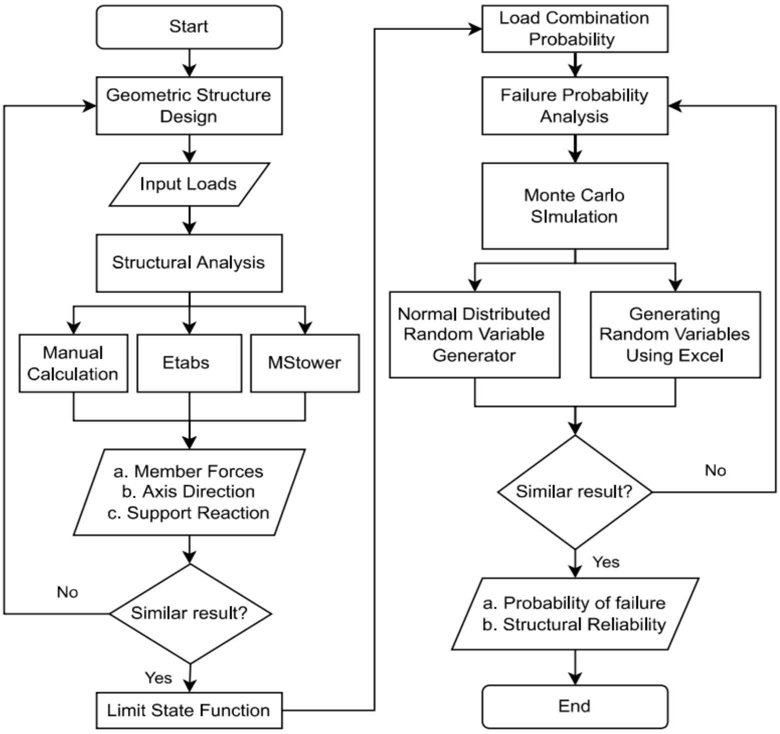


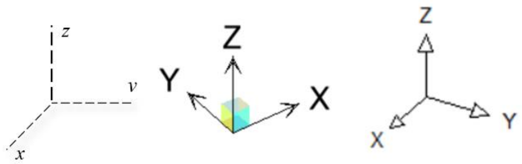
Figure 2. Structural Reliability Analysis Flow Chart

The results showed that the 3 methods of structural analysis obtained the same value for the member force and the support reaction.

Table 1. Member force result from manual calculation and software

Member	**Member Force (kN)**		
	Manual	**ETABS**	**MStower**
AB	0.000	0.000	0.000
BC	-30.000	-30.000	-30.000
CD	0.000	0.000	0.000
AD	0.000	0.000	0.000
AC	27.951	27.950	27.951
AE	-57.282	-57.280	-57.282
BE	-137.477	-137.480	-137.477
CE	80.195	80.200	80.195
DE	0.000	0.000	0.000

The difference in the direction of the axis (see Figure 3) is explained by the comparison of the direction of the axis in Table 2.



(a) (b) (c)

Figure 3. Axis Direction in Manual (a), ETABS (b) and MStower (c)

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Table 2. Comparison of axis direction between manual calculation and software analysis

Manual	ETABS	MStower
X	-X	X
Y	-Y	Y
Z	Z	Z

Another parameter that is considered is the support reaction in the three structural analysis methods, the results of the comparison of structural analysis have the same value. The results of the support reaction are summarized in Table 3.

Table 3. Comparison of support reaction for manual calculation and software analysis

Node	Support Reaction (kN)								
	Manual			ETABS			MStower		
	Fx (kN)	Fy (kN)	Fz (kN)	Fx (kN)	Fy (kN)	Fz (kN)	Fx (kN)	Fy (kN)	Fz (kN)
A	0	0	50	0	0	50	0	0	50
B	-60	-60	120	60	60	120	-60	-60	120
C	0	60	-70	0	-60	-70	0	60	-70

The reliability of a structure is its ability to meet design objectives for a certain period (Thoft-Christensen and Murotsu 1986). Structural reliability analysis can be started by defining the limit state function in a structural system. In determining the failure criteria, this study refers to ASCE/SEI 10-15 (ASCE 2015). The limit state function can be seen from the failure mode of the structure, there are many modes of structural failure as in Tian's (2020) study, it was found that structural failure in buckling so that the parameter under consideration was flexural deformation (Tian, Zhang, and Fu 2020). In another study, simulations were carried out by reducing the capacity of the structural model and reviewing the dependencies between components to assess structural failure (Luque and Straub 2016). Based on the results of structural analysis in this study, the compressive and tension stress ratio of the members (see Table 4) with failure in the BE member were obtained. The reliability model for this structure is a serial system. It should be noted that for such a system, failure of one element is equivalent to failure of the whole structure (Mochocki, Obara, and Radoń 2020). In previous studies, the evaluation of structural failure in single elements is an important area of research. The analysis of failed single elements can be carried out for structural safety assessment (Mochocki and Radoń 2019). Structural failure is defined if one component fails in a structural system so that the structure cannot function properly or cannot be used.

Table 4. Compression and tension stress ratio

Member	KL/r	F (N/mm^2)	Fa (N/mm^2)	Ratio
AB	203.05	0.00	47.83	0.00
BC	101.52	19.39	164.73	0.12
CD	203.05	0.00	47.83	0.00
AD	101.52	0.00	164.73	0.00
AC	227.01	18.07	240.00	0.08
AE	193.85	-22.55	52.48	0.43
BE	**193.85**	**-54.12**	**52.48**	**1.03**
CE	193.85	31.57	240.00	0.13
DE	193.85	0.00	240.00	0.00

Based on the results of structural analysis using MStower software, the maximum displacement results are 0.007 m. Displacement analysis refers to ANSI/AISC 360-16, with limits H/400. Considering these conditions, the truss structure modeling is within safe limits with a maximum displacement value of 0.01 m, so it is not analyzed in this study.

In the first simulation, the load consists of a value in each direction of the load as shown in Figure 1. Adapting from Fu's research (2019), which is to develop loads to estimate the probability of failure with different load levels (Fu et al. 2019), and Cai's research (2019) which is modeling wind loading with 3 parameters, the magnitude of the load, the direction of the load and the span between structures (Cai et al. 2019), so the load value in this modeling is 100 kN with a direction on the z-axis and 60 kN with a direction on the x-axis as a reference in estimating possible loads that will occur (see Table 5).

Table 5. Possibility load that will occur

Number	FZ (kN)	FX (kN)
1	105	65
2	104	64
3	103	63
4	102	62
5	101	61
6	99	59
7	98	58
8	97	57
9	96	56
10	95	55
Average	100	60

The load values in Table 5 are then processed into a combination of loads probability. The combination of loads probability is applied to the structure and analyzed in each combination so the stress value that occurs is obtained.

The possible load data that will occur can be combined into 100 load combinations which are load population data. The combined load probability data will be applied to a simple structural example and analyzed using MStower software. The results of the analysis obtained the stress that will be used as a stress population

RESULTS AND DISCUSSION

Failure probability analysis can be carried out using data from the member stresses at 100 load combinations using the equation (1).

$$P_f = \frac{\mathrm{n}}{\mathrm{N}} \times 100\% \tag{1}$$

Notes:

P_f = Probability of failure
n = Probability
N = Amount of data

So,

$$60\% = \frac{60}{100} \times 100$$

The reliability of the structure is denoted by R [11] and can be calculated by the equation (2).

$$R = 1 - Pf(\%) \tag{2}$$

Notes:

R = Structural reliability

So,

$$40\% = 1 - 60\%$$

Based on the calculation of probability and reliability using equations (1) and (2), it can be concluded that the probability of failure on the member BE is 60% and the structural reliability is 40%.
In previous studies, several types of case conditions were taken into account, for example in the Kubicka’s study four cases were simulated into a loading condition scheme (Kubicka et al. 2019), in the Çeribaşı’s study, the load was simulated into 3 conditions, slight, moderate and severe (Çeribaşı 2020). In this journal, 100 cases of loading condition schemes are carried out to approach

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the analysis results more precisely. To reduce the number of analyzes, the Monte Carlo simulation is used.

The first step is to generate random numbers to represent the data population. There are 2 random generator methods that are experimented with, generators of normally distributed random variables and generators of random variables using Microsoft excel. The results of the comparison of the two methods are the same, but the random variable generator using Microsoft excel has a simpler process so that it is easier to apply. Simulation using Microsoft Excel software has been carried out sampling experiments to determine the number of samples that can represent the data population. The sampling experiment was carried out 10 times with a total sample of 5, 10, 20, 30, 40, 50, 60, 70, 80, and 90 (see table 5) with the results of taking 30 samples that could represent the possible risks that occur to members.

Table 6. Comparison of sampling

SAMPLE	5	10	20	30	40	50	60	70	80	90
AVE (N/mm^2)	54.85	55.57	53.67	54.27	53.79	54.413	53.85	54.01	54.28	54.04
STD DEV (N/mm^2)	2.58	2.09	3.25	2.78	2.93	3.138	3.01	2.90	3.07	3.00
CoV	4.71%	3.76%	6.06%	5.13%	5.45%	5.77%	5.59%	5.36%	5.65%	5.54%
ERROR	1.33%	2.67%	0.83%	0.28%	0.62%	0.53%	0.50%	0.21%	0.29%	0.15%
PF	80%	90%	55%	66%	57%	60%	56%	57.%	66%	60%
R	20%	10%	45%	33%	42%	40%	43%	43%	34%	40%

The data is statistically processed so the average result, standard deviation, coefficient of variation, error, failure probability, and structural reliability are obtained (see Table 6).

Table 7. The results of the Monte Carlo simulation data processing

AVERAGE	54.27	kN
STD DEV	2.78	kN
CoV	5	%
ERROR	0.278	%
PF	67	%
RELIABILITY	33	%

CONCLUSION

Based on the comparison of the three structural analysis methods, the results of the parameters reviewed obtained the same value so the analysis using ETABS and MStower is reliable. Based on the two trials of the random variable generation method, the probability results of both are close to the actual value so a simpler method is chosen, the generation of random numbers using features in Microsoft excel. In general, the procedure for structural reliability analysis is the determination of the failure criteria, in other words, the load-bearing capacity limit of the structure and the load data to be supported by the structure so that it can be used as a reference in analyzing the probability of failure and the reliability of the structure.

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