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Cal-Reliability Assessment of Failure of Industrial Structural Steel Roof Truss Systems

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Abstract: This research investigated the reliability of a newly designed steel roof truss system of an industrial building to be constructed in one of the major cities in Nigeria. The probabilistic analysis technique was done with the aid of CalREL, a general-purpose structural reliability analysis software program. The longest span truss element (consisting of 73 members), is the most critical in the system, was selected and first analysed using SAP2000 Advanced 12.0.0 finite element analysis (FEA) software program in order to obtain the forces in the steel truss members; this forms part of the inputs required in CalREL. Four load variations (referred to as load ratios in the study) were tested on the selected truss. The strengths of the truss members and other properties were determined as specified in BS 5950-1: 2000. Limit state equations were derived for the calculation of the probability of failure of the individual members of the truss system. A reliability index as a measure of structural performance and related to the probability of failure was developed for all the elements of the truss. The results showed that compression members displayed a noticeable violation of the ultimate limit state requirement, while tension members showed a negligible violation. Sensitivity factors that reflect the relative importance of the individual variables in the design of roof trusses were also presented. The estimated reliability indices also revealed structural members that require immediate redesign; though they appear satisfactory in the level of deterministic design. A probabilistic approach for the reappraisal of new and existing civil structures is well supported by the findings of this investigation.

Keywords: CalREL Software, SAP2000, Probabilistic, Truss, Limit State Equations, Reliability Index, Sensitivity Factors

1. Introduction

Trusses, in general, are triangular frameworks in which the members are subjected to essentially axial forces due to externally applied loads. The axial forces can either be tension or compression. They may be plane trusses, wherein the external load and the members lie in the same plane or space trusses, in which members are oriented in three dimensions in space and loads may also act in any direction. Steel members subjected to axial forces are generally more efficient than members in flexure since the cross section is nearly uniformly stressed [1]. Steel trusses are extensively used to span long lengths in the place of solid web girders. They are used in roofs of single storey industrial buildings (the focus of this research), long span floors, and roofs of multi-storey buildings, to resist gravity loads. They are also used in multi-storey buildings and walls and horizontal planes of industrial buildings to resist lateral loads and give lateral stability. Trusses are also used in long span bridges to carry gravity and lateral loads. Trusses act like deep beams - a beam becomes stronger and stiffer as its depth increases. However, when a deep beam carries a light load over a long span, a lot of material may be wasted supporting predominantly the self-weight of the beam [2].

Loads are generally assumed to be applied at the intersection point of the members, so that they are principally subjected to direct stresses. To simplify the analysis, the weights of the truss members are assumed to be apportioned to the top and bottom chord panel points and the truss members are assumed to be pinned at their ends. Normally, chords are continuous and the connections are either welded or contain multiple bolts; such joints tend to restrict relative rotations of the members at the nodes and end moments develop [3]. However, in light building trusses, secondary stresses are negligible and are often ignored.

Engineering systems, components, and devices are not perfect. A perfect design is one that remains operational and attains system's objective without failure during a preselected life. This is the deterministic view of an engineering system. This view is idealistic, and may not always be satisfactory [4-6]. All potential failures in a design are generally not known or well understood. Accordingly, the prediction of failures is inherently a probabilistic problem [7-8]. This is embedded in the field of Engineering known as Reliability. Reliability is the ability of an item to perform its intended function under stated operation conditions for a given period of time [3, 5]. Reliability, in a more precise definition, is the probabilistic assessment of the likelihood of the adequate performance of a system for a specified period of time under proposed operating conditions. The acceptance level of reliability must be viewed within the context of possible costs, risks, and associated social benefits [9].

The structural integrity of trusses is usually evaluated by using deterministic analysis techniques and applying appropriate load and safety factors. In spite of applied factors of safety, cases of collapse of roof trusses are reported [10]. In this regard, the factors of safety can actually be referred to as "factors of ignorance" [11].

2. Methods of Structural Reliability Analysis

Structural reliability analyses involve the development of accurate and efficient methods for computing multi – dimensional probability integrals. Two classes of methods are widely used to compute structural reliability or its complement, the probability of failure [12-17]. The first class consists of first and second-order reliability methods (FORM and SORM), [18], which search for most probable point of failure (MPP) or the reliability index 'β', for well-behaved limit state functions. The second class consists of simulation methods, such as the widely used Monte-Carlo simulation for ill-behaved or difficult to capture responses, including importance sampling methods (one of the various reduction techniques, VRT), which are of higher degree of accuracy and more computational effort than FORM and SORM. FORM and SORM methods are applied to the classical reliability integral as in equation 1,

$$I = \int_F p(\theta)d\theta \tag{1}$$

where F is the failure domain generally defined by the function g (X) < 0.

The First-order reliability method (FORM) was adopted and presented. The general problem to which FORM provides an approximate solution [19-21]. The state of a system is a function of many variables some of which are uncertain. These uncertain variables are random with joint distribution function:

$$F_x(x) = P(\cap_{i=1}^{n}\{X_i \le x_i\}) \tag{2}$$

Equations 2 defines the stochastic model. for FORM, it is required that F_x (x), is at least locally continuously differentiable; i.e., that probability densities exist. The random variables $X = (X_1,\ldots, X_n)^T$ are called basic variables. The locally sufficiently smooth (at least once differentiable) state function is denoted by g (X). It is defined such that g (X) > 0 corresponds to favourable (safe, intact, acceptable) state. g (X) = 0 denotes the so-called limit state or the failure boundary. Therefore, g (X) < 0 (sometimes also g (X) ≤ 0) defines the failure (unacceptable, adverse) domain, F. The probability of failure, P_f, and the reliability or safety index, β, can be related using information obtained from FORM as given by equation (3).

$$P_f = P(X \in F) = P(\mathrm{g(X)} \le 0) = \int_{\mathrm{g}(x)\le 0} dF_x(x) = \emptyset(-\beta) \tag{3}$$

3. Methodology

The design data of a proposed industrial building was used for the research. A 15.6 m monopitch Howe roof truss with some modifications, consisting of 73 members of welded double angle steel sections, being the longest span, was selected for this probabilistic study as shown in figures (1) to (3). SAP2000 Advanced 12.0.0 was first used to obtain the forces in the truss members due to the applied design load. Four load variations (referred to as load ratios λ = 0.25, 0.55, 1.0, and 1.5) were tested using the ratio (dead to imposed load) of the most critical load combination considered. The strengths of the truss members and other properties were determined as specified in BS 5950-1: 2000. The probabilistic testing was done with the aid of CalREL program. Limit state equations were derived for this testing as given in equations (4) and (5): for all compression members,

$$P_f = P[G = (\sigma_c - \frac{F_c}{2(L_1T_1+L_2T_2)}) \le 0] \tag{4}$$

and for tension members:

$$P_f = P[G = (\rho_y - \frac{F_t}{2(L_1T_1+L_2T_2)}) \le 0] \tag{5}$$

where

P_f is the probability of failure;
P is the probability
G is the truss under investigation
σ_c is the compressive strength of truss member i;
ρ_y is the design strength of truss member i;
F_c is the compressive force in member i;
F_t is the tensile force in member i;
L_1, L_2 are the leg lengths of the member cross section
T_1, T_2 are the thicknesses of the member cross section; and
i is the truss member i

Writing the gross area A_g of member cross section as, A_g =

2 (L_1 T_1 + L_2 T_2), equations (4) and (5) become equations (6) and (7):

$$P_f = P[G = (\sigma_c - \frac{F_c}{A_g}) \leq 0] \tag{6}$$

$$P_f = P[G = (\rho_y - \frac{F_t}{A_g}) \leq 0] \tag{7}$$

On the basis of practical statistical information on all relevant variables, normal and lognormal probability distributions were adopted.

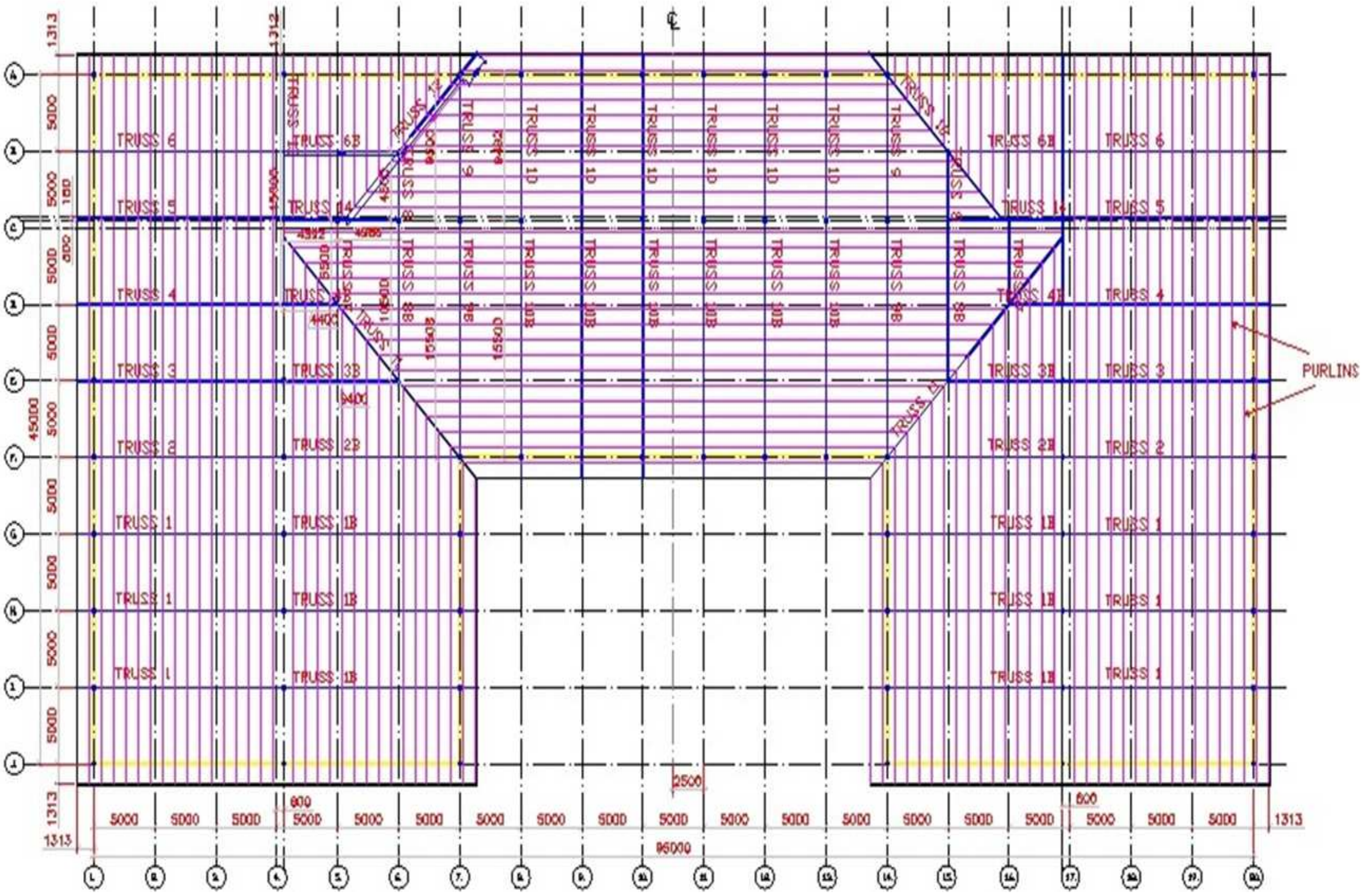

Figure 1. *Steel Roof Truss Layout (All dimensions in mm).*

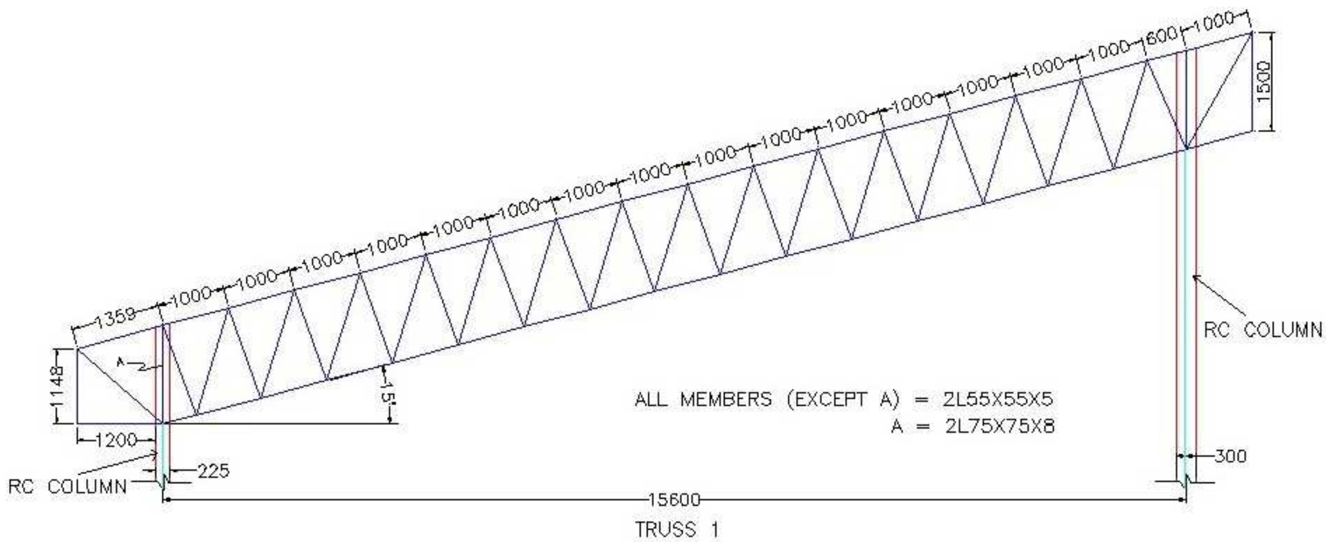

Figure 2. *Selected Truss Showing Member Sections and Dimensions (mm).*

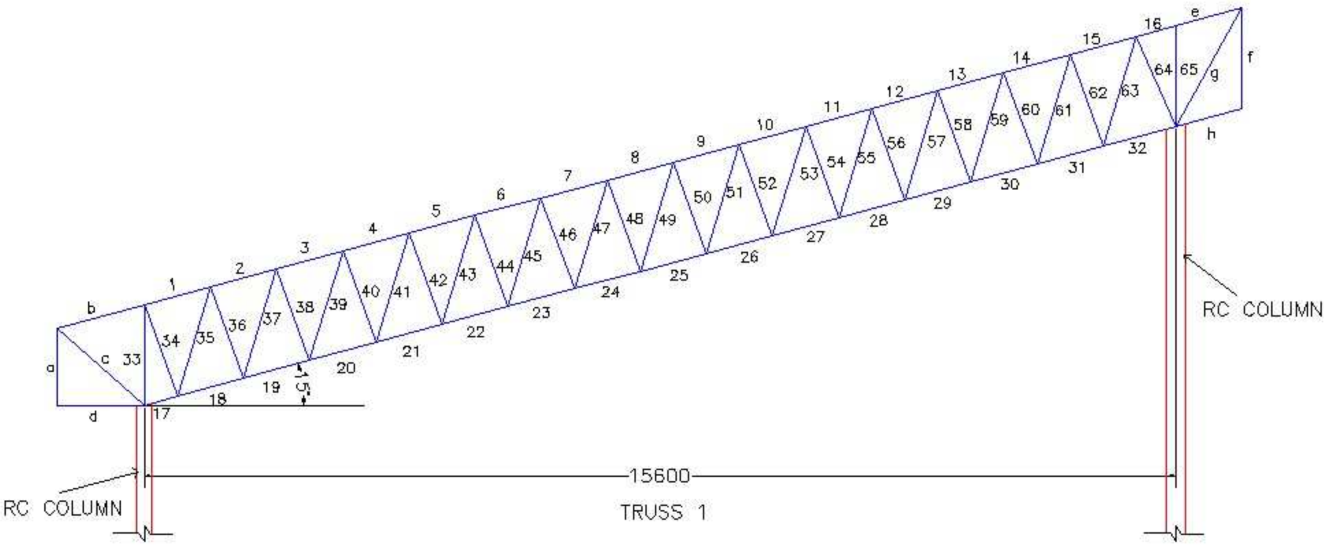

Figure 3. *Selected Truss Showing Numbering of Members (65 chord and web members; and 8 eaves members).*

4. Results and Discussions

Truss member forces obtained from SAP2000 analyses and plotted using AutoCAD 2014 are presented in figures 4 to 7.

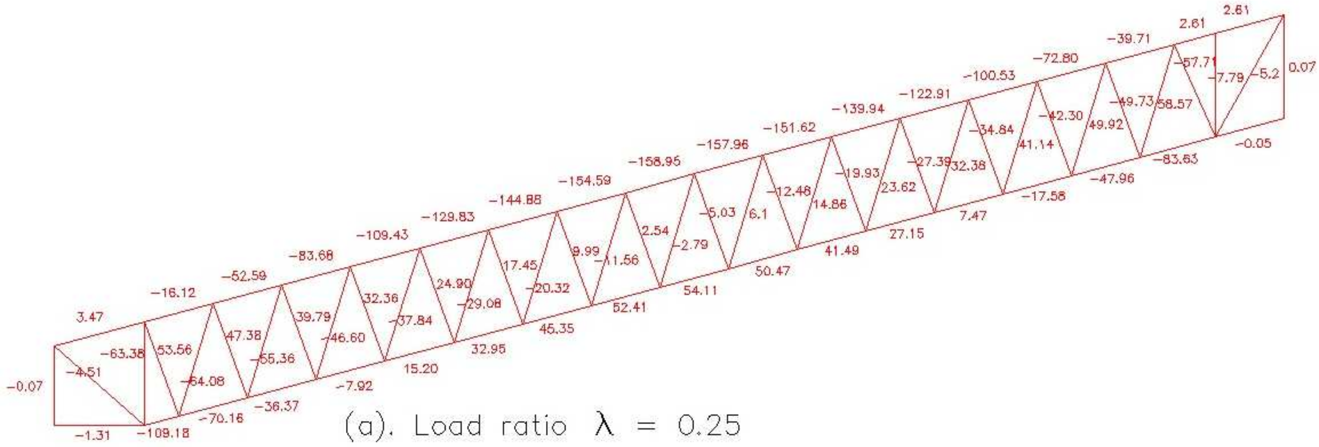

Figure 4. *Truss Member Forces (kN) for Load Ratio 0.25. Negative Values Show Compression.*

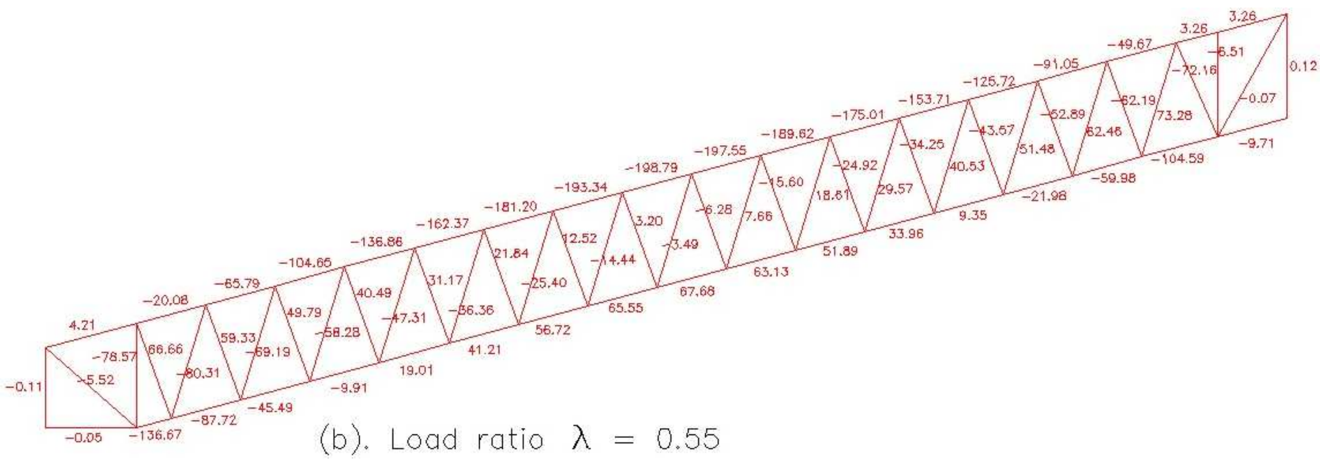

Figure 5. *Truss Member Forces (kN) for Load Ratios 0.55 Negative Values Show Compression.*

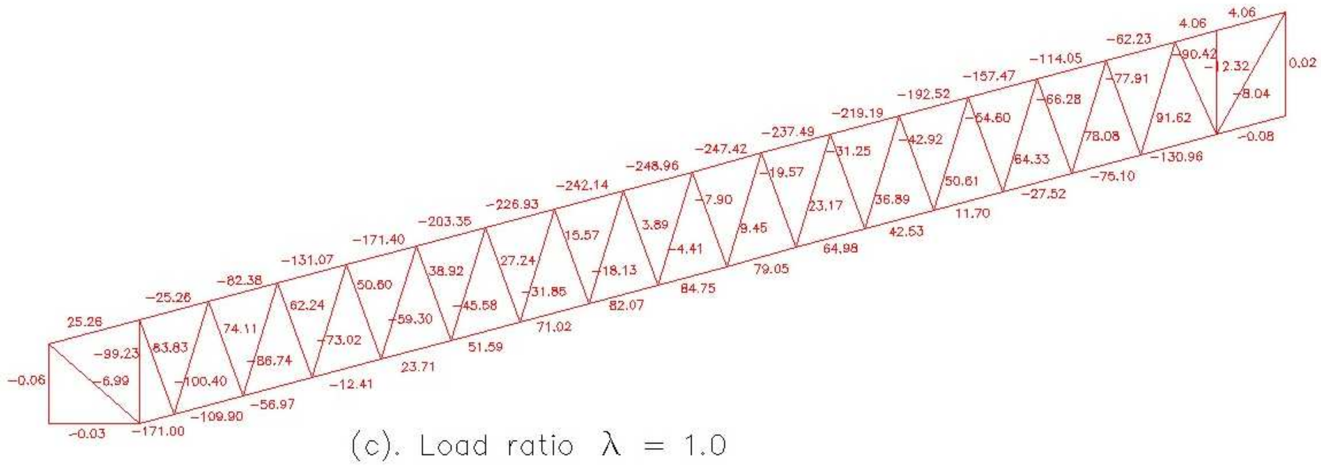

Figure 6. *Truss Member Forces (kN) for Load Ratios 1.0. Negative Values Show Compression.*

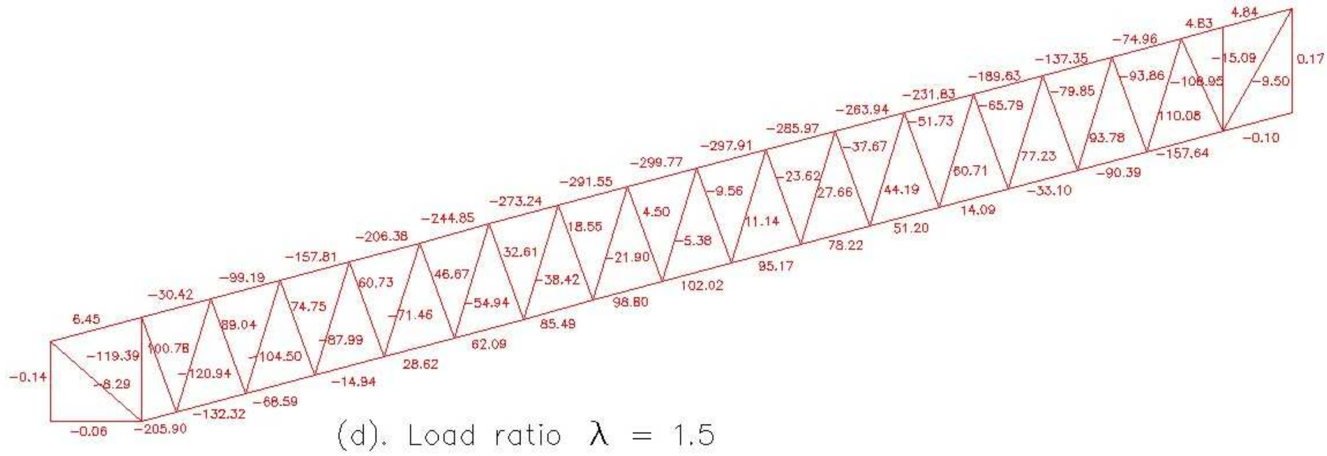

Figure 7. *Truss Member Forces (kN) for Load Ratio 1.5. Negative Values Show Compression.*

4.1. Probabilistic Results

Results from the first-order reliability analysis (FORM) done using CalREL are presented in tables (1) to (8). Sensitivity factors α, ϒ, δ, and η, with respect to the variables for each truss member are given. Also the reliability index, 'β'; number of iterations, i; and the probability of failure, P_f, are presented. It should be noted that in the presentation,

α is the sensitivity of β with respect to x (the coordinates of design point in original space);

ϒ is the scaled and normalized sensitivity of β with respect to x;

δ is the scaled sensitivity of β with respect to the mean, μ, of each basic random variable, given in equation (8):

$$\delta = \sigma_i \frac{\partial \beta}{\partial \mu_i} \tag{8}$$

η is the scaled sensitivity of β with respect to the standard deviation, σ, of each basic random variable, expressed in equation (9) as:

$$\eta = \sigma_i \frac{\partial \beta}{\partial \sigma_i} \tag{9}$$

The variables σ_c / ρ_y, P $=F_c$ / F_t, L_1, L_2, T_1 and T_2 are as defined earlier.

Note: P = F_c (compression), or F_t (tension), as the case may be

Table 1. *Sensitivity Factors with β, i, And P_f - Member 1 (Compressive) (λ = 0.25).*

Variable	Sensitivity Factor			
	α	ϒ	δ	η
σ_c	.0002	.0002	-.0002	.0001
P	.9280	.9280	-.0215	-3.0895
L_1	-.3726	-.3726	.3726	-.5637
T_1	.0000	.0000	.0000	.0000
L_2	.0000	.0000	.0000	.0000
T_2	.0000	.0000	.0000	.0000

β = 4.06, i = 8, $P_f = 2.447 \times 10^{-5}$.

Table 2. *Sensitivity Factors with β, i, And P_f – Member 16 (Tensile) (λ = 0.25).*

Variable	Sensitivity Factor			
	α	ϒ	δ	η
ρ_y	.0003	.0003	-.0003	.0001
P	.9501	.9501	-1.3669	1.3199
L_1	-.3119	-.3119	.3119	.1184
T_1	.0000	.0000	.0000	.0000
L_2	.0000	.0000	.0000	.0000
T_2	.0000	.0000	.0000	.0000

β = -1.22, i = 4, $P_f = 8.882 \times 10^{-1}$.

Table 3. *Sensitivity Factors with β, i, And P_f – Member1 (compressive) (λ = 0.55).*

Variable	Sensitivity Factor			
	α	ϒ	δ	η
σ_c	s-.6854	-.6854	1.2961	-1.9854
P	. 6854	.6854	-.2206	-1.5997
L_1	-.1283	-.1283	.1283	-.0656
T_1	-.1283	-.1283	.1283	-.0656
L_2	-.1172	-.1172	.1172	-.0547
T_2	-.1172	-.1172	.1172	-.0547

β = 3.98, i = 6, P_f = 3.413 x 10^{-5}.

Table 4. *Sensitivity Factors with β, i, And P_f – Member16 (Tensile) (λ = 0.55).*

Variable	Sensitivity Factor			
	α	ϒ	δ	η
ρ_y	-.6808	-.6808	2.1459	-4.8341
P	.6808	.6808	.6396	-4.511
L_1	-.1406	-.1406	.1406	-.2066
T_1	-1406	-.1406	.1406	.2066
L_2	-.1295	-.1295	.1295	-.1754
T_2	-.1295	-.1295	.1295	-.1754

β = 10.455, i = 11, P_f = 1.000 x 10^{-10}.

Table 5. *Sensitivity Factors with β, i, And P_f – Member 1 (Compressive) (λ = 1.0).*

Variable	Sensitivity Factor			
	α	ϒ	δ	η
σ_c	-.6857	-.6857	1.2244	-1.7456
P	.6857	.6857	-.2928	-1.3597
L_1	-.1275	-.1275	.1275	-.0560
T_1	-.1275	-.1275	.1275	-.0560
L_2	-.1164	-.1164	.1164	-.0467
T_2	-.1164	-.1164	.1164	-.0467

β = 3.44, i = 6, P_f = 2.842 x 10^{-4}.

Table 6. *Sensitivity Factors with β, i, And P_f – Member 16 (Tensile) (λ = 1.0).*

Variable	Sensitivity Factor			
	α	ϒ	δ	η
ρ_y	-.6854	-.6854	1.3021	-2.0055
P	.6854	.6854	-.2145	-1.6197
L_1	-.1284	-.1284	.1284	-.0664
T_1	-.1284	-.1284	.1284	-.0664
L_2	-.1173	-.1173	.1173	-.0554
T_2	-.1173	-.1173	.1173	-.0554

β = 4.03, i = 6, P_f = 2.823 x 10^{-5}.

Table 7. *Sensitivity Factors with β, i, And P_f – Member 1 (Compressive) (λ = 1.5).*

Variable	Sensitivity Factor			
	α	ϒ	δ	η
σ_c	-.6859	-.6859	1.1663	-1.5509
P	.6859	.6859	-.3515	-1.1649
L_1	-.1268	-.1268	.1268	-.0484
T_1	-.1268	-.1268	.1268	-.0484
L_2	-.1157	-.1157	.1157	-.0403
T_2	-.1157	-.1157	.1157	-.0403

β = 3.01, i = 6, P_f = 1.297 x 10^{-3}

Table 8. *Sensitivity Factors with β, i, And P_f – Member 16 (Tensile) (λ = 1.5).*

Variable	Sensitivity Factor			
	α	ϒ	δ	η
ρ_v	-.6816	-.6816	2.0283	-4.4393
P	. 6816	.6816	-.5202	-4.0558
L_1	-.1385	-.1385	.1385	-.1831
T_1	-.1385	-.1385	.1385	-.1831
L_2	-.1275	-.1275	.1275	-.1550
T_2	-.1275	-.1275	.1275	-.1550

β = 9.54, i = 11, P_f = 2.823 x 10^{-10}.

4.2. Probability of Failure and Reliability Index

Attempt was made to get a clear interpretation, using table 9, which shows members with negative values of reliability index, β, corresponding to specific load ratio, λ. The percentage of truss members, already classified as struts or ties, with negative reliability index is also computed.

Table 9. *Number and Percentage of Negative Reliability Index, β.*

λ		Negative β	%
0.25	C	17	37.78
	T	1	3.57
0.55	C	8	17.78
	T	0	0.00
1.0	C	12	26.67
	T	0	0.00
1.5	C	16	35.56
	T	0	0.00

C = Compression, T = Tension.

The information in table 3 was further used to plot total violation of the limit state in the study. It must be noted that negative value of β implies total violation of the limit state being investigated.

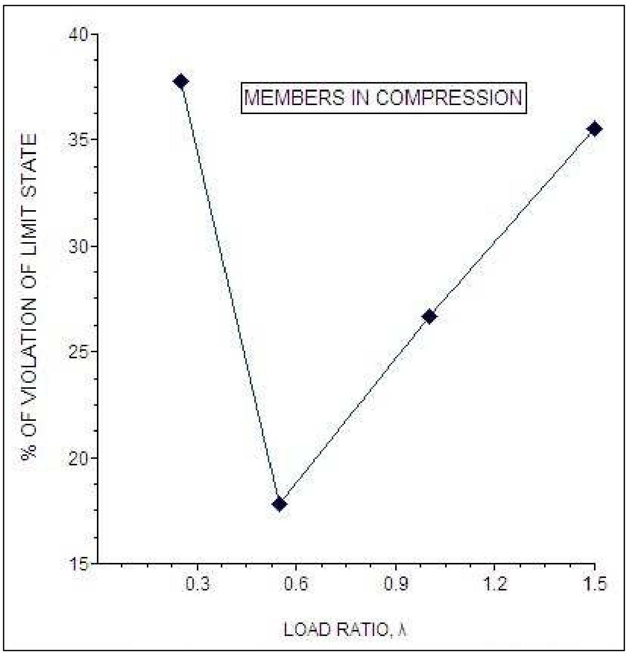

Figure 8. *Percentage of Limit State Violation of Members at Varying Load Ratio – Members in Compression.*

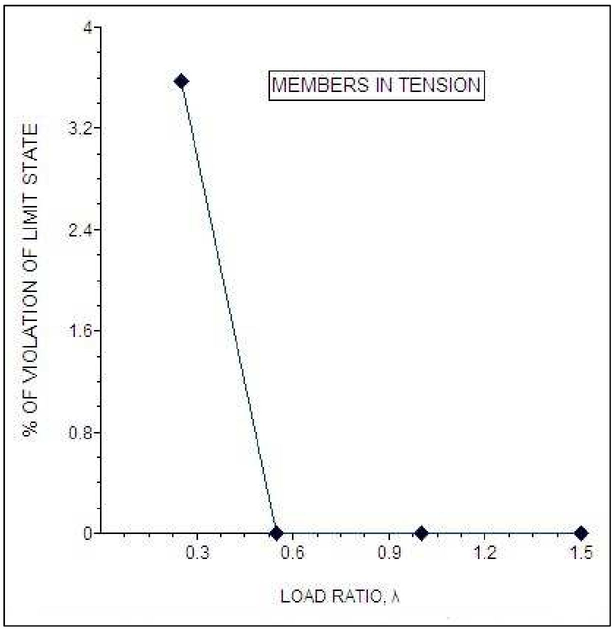

Figure 9. *Percentage of Limit State Violation of Members at Varying Load Ratio – Members in Tension.*

4.3. Sensitivity Factors

It must be noted that all input random variables do not have equal influence on the statistics (like mean and standard deviation) of the output. Hence, the use of sensitivity factors in determination of reliability index to account for the importance of each random variable.

The plots of the sensitivity factors against the load ratios considered have been presented. It can be seen from figures 7 to 15 that the sensitivity factor, δ, gives a positive plot for all load ratios except for the compressive force member 1 (Figure 11) and tensile force member 16 at load ratio 1.0 (Figure 15). These are due to the effect of the applied load ratios being higher than the capacities/strength of these members. Furthermore, the effect of the sensitivity factors α and ϒ is minimal on the compressive force member 1 and tensile force member 16 as shown in Figures 11 and 15, because of the capacities of the members that are greater than the applied load ratios. However, the effect of the remaining sensitivity factors, α, ϒ, and η, on the reliability index, β, produced negative plots as presented.

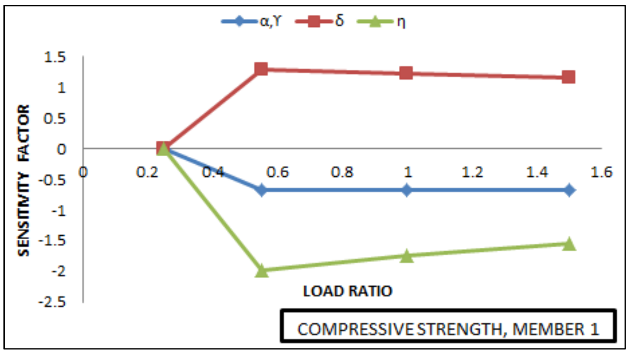

Figure 10. *Sensitivity Factors against Load Ratio for Compressive Strength (Member 1).*

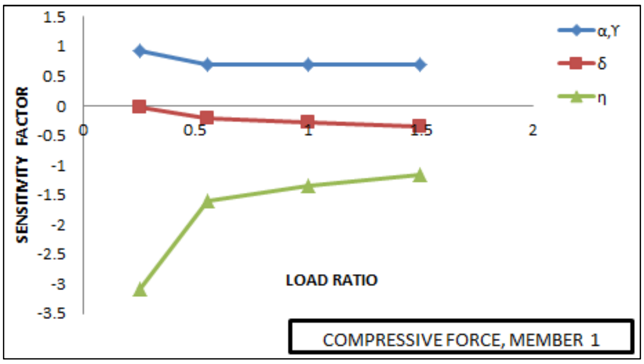

Figure 11. *Sensitivity Factors against Load Ratio for Compressive Force (Member 1).*

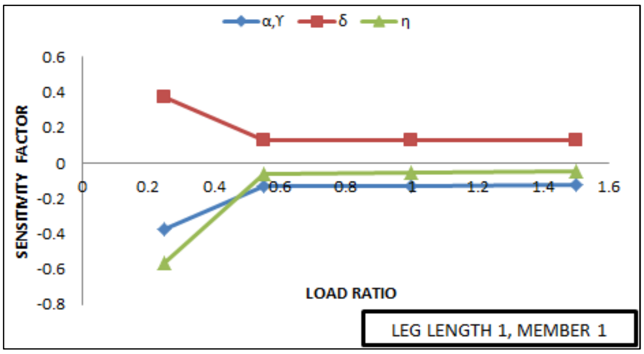

Figure 12. *Sensitivity Factors against Load Ratio for Leg Length 1 (Member 1).*

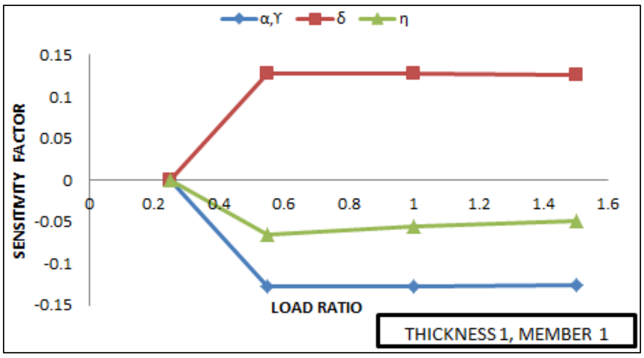

Figure 13. *Sensitivity Factors against Load Ratio for Thickness 1 (Member 1).*

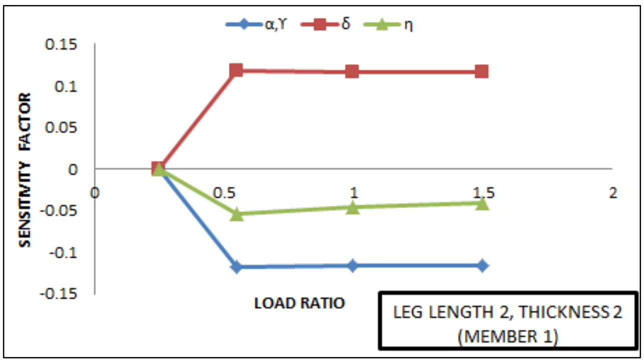

Figure 14. *Sensitivity Factors against Load Ratio for Leg Length 2 and Thickness 2 (Member 1).*

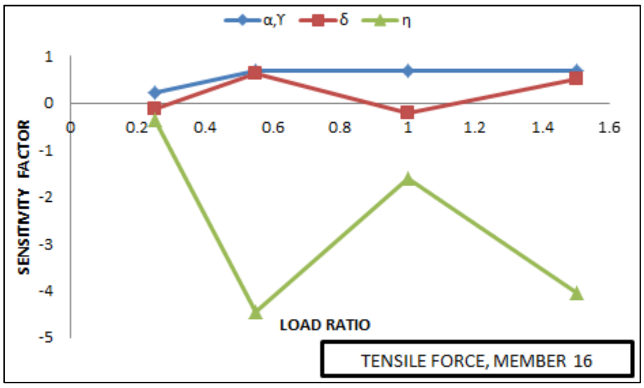

Figure 15. *Sensitivity Factors against Load Ratio for Tensile Force (Member 16).*

5. Conclusion

From this research on structural steel roof truss systems, the limit state function has been shown and defined as a function of many variables (load components, resistance parameters, material properties, dimensions, and analysis factors) which are uncertain. However, these uncertain variables have been treated as random variables using reliability-based approach.

From the result obtained on the selected truss element investigated in the study, for the newly designed steel roof truss system, it must be noted that struts showed more concern than ties (table 9 and figures 8 and 9); i.e., struts displayed total violation of the limit state function (equations 4 to 7) than ties. Negative value of β implies total violation of the limit state being investigated. Ties showed negligible violation.

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