INTERACTIVE DESIGN OF STEEL ROOF SYSTEM ON MICROCOMPUTERS

(A Reliability Approach)

Thesis submitted to the Post-Graduate School Ahmadu Bello University Zaria, in partial fulfillment of the requirement for the award of Master in Science degree in Structural Engineering.

By

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CERTIFICATION

This is to certify that this thesis write up titled **'*Interactive Design of Steel Roof System on Microcomputers*'** presented by Abubakar Sadiq Usman meets the regulation governing the award of Master in Science Degree in Civil Engineering. It has been supervised and approved for its contribution to knowledge.

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DEDICATION

I dedicate this research to my dear parents

Alh. Magaji Dambatta (OFR) and Hajia Sa'adatu Dambatta.

ACKNOWLEDGEMENT

All praise be to Allah, most gracious, most merciful for seeing me get through with this programme successfully.

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ABSTRACT

FORTRAN programs are presented for the design of a Howe steel roof system in accordance with BS5950 (1985) at a constant reliability level. The concept of the design was built upon the First-Order Reliability Method (FORM) and System Reliability (SYSREL).

The reliability indices of components making the truss system were observed to vary as the dead/live load ratio increases. The overall safety index of the system is lower than the safety indices of the individual components and joints. The reliability program developed iteratively selects optimum sectional properties which offer a target reliability level when inherent uncertainties in the design variables are systematically considered.

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NOTATIONS

A	Angle length
A_e, AE	Effective Area
A_g, AG	Gross Area
B	Flange width
d	Section depth
D_L	Dead Load
E	Young's Modulus
F	Member force, Joint force
I_L	Imposed (live) load
L	Weld effective length
L_e	Effective length of member
M_b	Bucking moment
M_{cx}	Moment capacity of section about x – x axis
M_{cy}	Moment capacity of section about y – y axis
M_X	Applied moment in x – x axis
M_y	Applied moment in y – y axis
P_{cc}	Compressive Capacity
P_{cs}	Compressive Strength
P_f	Probability of Failure
P_t	Tensile strength
P_w	Design strength of weld
P_{wc}	Weld Capacity

P_y,PY	Design Strength
q	Dynamic pressure
Q	Design load
r	Root radius
r_x	Radius of gyration about x-axis
r_y	Radius of gyration about y – y axis
r_1	Root Radius
r_2	Toe radius
R	Resistance
S	Weld leg length, Load effect
S1	Topography factor
S2	Roughness, size & height factor
S3	Statistical factor
S4	Directional factor
t	Leg thickness
t_w, t	Web thickness
T	Flange thickness
v	Basic wind speed
V_s	Design wind speed
W_L	Wind load
Z_y	Elastic modulus about y – y axis
$\propto$	Alfa = dead – live load ratio
β	Beta = safety index

β_T	Target Beta = Target Safety Index
ε	Epsilon = level of acceptance of design points
π	Pi = 3.142

Chapter 1

INTRODUCTION

1.1 STRUCTURAL STEEL

Structural steel products are manufactured to conform to BS4360 (1990): Weldable structural steels. Steel is composed of about 98% Iron with the main alloying elements; carbon, silicon and manganese.

It is produced in strength grades 43, 50 and 55. The important properties are strength, ductility, impact resistance and weldability. The most common members used in structures are single and double angles, tees, channels and structural hollow sections. I, H, Compound and built–up members are used in heavy trusses, certainly hot – rolled sections.

1.2 ROOF SYSTEMS

Roof systems are structures comprising several member components or elements connected by joints to form a series of triangles, commonly known as *' trusses'*.

In other words, trusses are framed elements resisting in-plane loading by axial forces either in tension or compression in the individual members. The elements are typically assumed to be joined at their intersections with pinned connections so that all loads and reactions occur only at these joints.

The primary function of trusses in buildings is to provide support to roofs, floors and such internal load as services and suspended ceilings. There are many types and forms of trusses according to their application. The most widely used trusses in buildings are pitched–roof trusses such as Pratt, Howe, or Fink, the Mansard, the Warren, and Saw tooth or butterfly truss. The type of truss adopted in design is governed by architectural and client requirements, carried in details by dimensional and economic factors. Other applications include Bridges.

The Howe truss can be advantageous for very lightly loaded roofs in which reversal of load due to wind will occur.

The Fink truss offers greater economy in terms of steel weight for long span high-pitched roofs as the members are divided into shorter elements.

The Mansard truss has the advantage of reducing unusable roof space and so reducing the running cost of the building. Its disadvantage is that forces in the top and bottom chords are increased due to the smaller span – depth ratio.

The Warren truss having equal length of compression and tension web members, result in a net saving in steel weight for smaller spans.

1.3 RELIABILITY APPROACH

The study of structural reliability is concerned with the calculation and prediction of the probability of limit state violation for engineered structures at any stage during their life. The term *'reliability'* is commonly defined as the complement of the probability of failure but more appropriately is the probability of safety of structure over a given period of time (Melchers, 1987).

The assurance of structural safety and reliability is an important objective in engineering design. Indeed the evaluation of safety and reliability of a proposed system is one of the purposes of structural analysis and is necessary in the development of proper criteria for design.

Engineering designs, however are normally formulated under conditions of uncertainty – the loading processes and structural properties are usually random. In the face of such uncertainties, absolute assurance of safety and reliability would ordinarily be difficult to achieve. Realistically, safety and reliability may be assured only with a tolerable risk or probability of failure. Uncertainty has traditionally been treated implicitly i.e the significance of uncertainty is presumed to be allowed for through a factor of safety.

1.4 PROBLEM STATEMENT AND JUSTIFICATION OF STUDY

There are numerous difficulties in structural reliability design because of limited data and the need for small allowable failure probabilities. This makes the common notion of statistical confidence difficult to apply. The choice of distribution parameters has a great effect on failure probability, then the statistical dependence between failure modes, and so the utility of accurate computations may be lost due to incorrect approaches. This subject certainly warrants much further thought and investigation.

1.5 RESEARCH AIM AND OBJECTIVES

This research is aimed at producing a program for designing a steel roof system using the first-order reliability method (FORM) and SYSREL to meet a certain safety reliability level.

The Objectives include;

(a) Identifying the modes of failure of members in a steel roof system.

(b) Computing the probabilities of failure and their associated safety indices.

(c) Conducting a system reliability analysis to determine the system safety index.

(d) Designing a roof system to meet an established target safety index

1.6 SCOPE OF RESEARCH

The scope of this research is limited to the analysis and design of a Howe steel roof system on a microcomputer in accordance with BS5950 (1985) to meet a specified target safety level.

1.7 METHODOLOGY

This study is basically a library research. The steps involved in achieving the aim and objectives of this study were generated from books, journals, and manuals. FORM was used to generate safety levels of members based on the system analysis. The results obtained were then utilised in the SYSREL program to determine the safety level of the roof system. Finally a program is written in FORTRAN language to meet a specified target safety level.

Chapter 2

LITERATURE REVIEW

2.1 STRUCTURAL SYSTEM

Most structures are often made up of several members. Such composition is termed *'structural system'* (Melchers, 1987). Thoft – Christensen and Baker (1982) classified systems into 2 fundamental types.

1. The series system: one that failure is said to have occurred when any of its elements attain its limit state. Such system is also called a weakest-link system (Moses, 1974).
2. The parallel system: when the elements on the system are so interconnected that the reaching of limit state in any one or more elements does not necessarily mean failure of the whole system, such is termed a *'parallel'* or '*Redundant system*'.

The safety and reliability of a structure clearly depends on the reliabilities of its components. Because information is seldom available for complete structures, any evaluation of the safety of a structural system usually must rely on deductive analysis based on the information available for its components. The reliability analysis of redundant systems, however is complicated, and remains a subject for

further study (Melchers, 1987). Nevertheless, the only basis in which the relationship between the safety level of a structural system and those of its components can be systematically derived and analysed is the reliability approach.

2.2 SYSTEM RELIABILITY.

(Melchers, 1987) proposed that a rational criterion for the safety of a structure is its reliability or probability of survival. Statistical frequency distribution for loads and strengths must be considered in determining the reliability. Due to reliability computational difficulties, safety factors are used to provide structural safety. A safety factor, however, relates to the failure of a single member under a single load condition and a constant safety factor cannot be used to ensure the overall reliability of a structure.

Structural failure modes which consist of the combined effects of two or more member or material failure events, are of particular interest in system reliability. If all failure modes for the system have been identified, then the various events contributing to these failure modes may be systematically enumerated using the '*fault –tree'* concept.

For the reliability of multi-membered structures, two complementary approaches can be adopted (Bennett and Ang, 1983).

(1) failure modes approach

(2) survival modes approach

The failure modes approach is based on identification of all possible failure modes for a structure. Each mode of failure for the structure will consist of a sequence of member 'failures' sufficient to cause the structure to reach a limit state. This can be represented by an 'event – tree' or as a 'failure graph'. The survival modes approach is based on identifying various states (or modes) under which the structure survives. For each survival mode, the structure has partially failed but is statically and geometrically stable.

2.3 THE BASIC RELIABILITY PROBLEM

The basic structural reliability problem considers only one load effect **S** resisted by one resistance **R**. Each of **S** and **R** is described by a known probability density function, f_s ( ) and f_R ( ) respectively.

For convenience, but without loss of generality, only the safety of a structural element will be considered. The probability of failure of a structural element can be stated in any of the following ways:

$$P_f = P(R \leq S) \text{ ----------(2.1a)}$$

$$= P (R - S \leq 0) \text{ ----------(2.1b)}$$

$$= P (R/S \leq 1) \text{ ----------(2.1c)}$$

$$= P (\mathit{ln}\ R - \mathit{ln}\ S \leq 1) \text{ ----------(2.1d)}$$

Or in general,

$$= P [G (R,S) \leq 0] \text{ ----------(2.1e)}$$

Where G ( ) = the 'limit state function' and the probability of failure is equivalent to the probability of limit state violation.

For any infinitesimal element (Δr. Δs) the probability of failure can be expressed in terms of (marginal) density functions f_R and f_S such as:

$$P_f = P\ (R - S \leq 0) = \int_D \int f_{RS}\ (r,s)\ \partial r.\partial s \quad \text{----------(2.2)}$$

When R and S are independent, $f_{RS}(r,s)=f_R(r).f_S(s)$ so that (2.2) becomes

$$P_f = P\ (R - S \leq 0) = \int_{-\infty}^{\infty} \int_{-\infty}^{s \geq r} f_R(r).\ f_S(s)\ \partial r.\partial s \quad \text{----------(2.3)}$$

For any random variable ***X***, the cumulative distribution $F_{\mathbf{x}}$ (x) is given by

$$F_{\mathbf{x}}\ (x) = P\ (X) \leq x = \int_{-\infty}^{x} f_{\mathbf{x}}\ (y)\ dy$$

provided that $x \geq y$.

It follows that for the common, but special case when R and S are independent, equation (2.3) can be written in the form

$$P_f = P\ (R - S \leq 0) = \int_{-\infty}^{\infty} F_R\ (x)\ f_S\ (x)\ dx \quad \text{----------(2.4)}$$

This integral is also known as a '*convolution integral'.*

$F_R(x)$ is the probability that $R \leq x$

An alternative to equation (2.4) is

$$P_f = \int_{-\infty}^{\infty} [1 - F_S\ (x)]\ f_R\ (x)\ dx \quad \text{----------(2.5)}$$

which is simply the sum over all the cases of resistance for which the load exceeds the resistance.

2.4 RELIABILITY ANALYSIS

The reliability analysis of structures is mainly concerned with the determination of the overall probability of failure of structures whose failure mechanism is expressed as a linear combination of several structural resistances and loadings.

The moment resistance and load variables in reliability analysis are described by 3 quantities; mean value, standard deviation and statistical distribution function. This description differs with deterministic analysis where only mean values are considered explicitly while safety factors compensate for undefined standard deviations and distribution functions. In the analysis, all variables are assumed to be independent continuous random variables with known mean, standard deviation and probability density function (Stevenson and Moses, 1970).

Realistically, engineering designs cannot be developed without a measure of permissible risk or failure probability. Traditionally, the design load, **Q** is specified as some nominal 'maximum' load, whereas the required resistance **R** is defined as some nominal 'minimum' value. Note that the strength **S** may be obtained from the applied loading **Q** through structural analysis.

2.5 FORMULATION OF RELIABILITY- BASED DESIGN

Special case: Normal Random variables

Consider S and R as normal random variables with means μ_R and μ_S and variances σ^2_R and σ^2_S respectively.

The safety margin **Z = R - S** then has a mean and variance given by:

$$\mu_Z = \mu_R - \mu_S \text{ ----------(2.6a)}$$

$$\sigma^2_Z = \sigma^2_R + \sigma^2_S \text{ ----------(2.6b)}$$

Recall $P_f = P(R - S \leq 0)$

Hence $P_f = P(Z \leq 0) = \Phi\{(0 - \mu) / \sigma_Z\}$ ----------(2.7)

where the standard normal distribution function N (0,1) is extensively tabulated in statistics texts.

The random variable Z =R-S is shown in Fig. 2.1 in which the failure region $\mathbf{Z \leq 0}$ is shaded.

Fig. 2.1 : Distribution of safety margin

Using equations (2.6) and (2.7) it follows that [Cornell, 1969]

$$P_f = \Phi [- (\mu_R - \mu_S)/(\sigma^2_R + \sigma^2_S)^{1/2}] \text{ ----------(2.8)}$$

$$= \Phi (- \beta)$$

where $\beta = \mu_Z/\sigma_z$ = 'safety index'

For practical purpose, equation (2.8) may be used as the basis for the development of design criteria based on specified measures of permissible risk. The safety index may be used as a measure of reliability without reference to the probability of failure (Ang, 1973). For the purpose of code development, a reliability -based design format can be calibrated to existing codes through an appropriate choice of the safety index value.

The same strategy, however, can be employed by calibrating on the basis of the implied risk of present designs as illustrated by Ellingwood and Ang (1974). By explicitly relating the safety index to the reliability measure, it will serve to enhance the recognition of the need for and advantages of probability concepts. In other words, the safety index is a statistical consistent indicator of reliability. It should be recognized as an intermediate measure of safety and does not posses the theoretical or operational properties of failure (and survival) probability.

Chapter 3

FUNDAMENTALS OF FORM AND SYSREL

3.1 RELIABILITY ASSESSMENT

As probability denotes the chance that a particular predefined event occurs, classically the probability of such event occurrences was considered to be obtainable only from many repeated observations of the process which led to the event; the so called objective definition. This is not necessarily the case. Probability estimates could be based on no previous data or experience of any sort to express degree of belief (Melchers, 1987).

Structural failure is considered to be the occurrence of one or more types of undesirable structural response including the violation of predefined limit states. When real structures fail in a serious manner, it is often due to causes not directly related to the predefined nominal loading or strength probability distributions. Imaginable events such as human error, negligence, poor workmanship or neglected loadings are most often involved (Melchers, 1987). However, not all possible reasons for structural failure are always imaginable. To carry out a reliability analysis for imaginable events, it will be necessary to consider the various types of uncertainty. These include environmental conditions, workmanship and human error, and prediction of future events.

3.2 PROBABILITY THEORY

3.2.1 Variance and Standard Deviation

Mean or expected value is a 'weighted average' of all the values that a random variable may take. That is,

$$E(x) = \mu_x = \int_{-\infty}^{\infty} x f_X(x) \partial x \quad \text{----------(3.1)}$$

The variance of a random variable is a measure of the degree of randomness about the mean.

$$E(x-\mu_x)^2 = Var(x) = \int_{-\infty}^{\infty} (x-\mu_x)^2 f_x(x)\, \partial x$$

$$= E(x^2) - (\mu_x)^2 \quad \text{----------(3.2)}$$

The standard deviation is

$$\sigma = \sqrt{var(x)} \quad \text{----------(3.3)}$$

The co-efficient of variation is:

$$V_x = \sigma_x/\mu_x \quad \text{----------(3.4)}$$

3.2.2 Co-variance and Correlation

In a joint distribution involving two or more random variable X_1 and X_2, the covariance is

$$Cov(X_1,X_2) = E[(X_1 - \mu_{x1})(X_2 - \mu_{X2})] \quad \text{----------(3.5)}$$

The correlated coefficient given as

$$\rho_{X1X2} = Cov[(X_1,X_2)/\sigma_{x1},\sigma_{x2}] \quad \text{----------(3.6)}$$

is a measure of linear dependence between two random variable. If $\rho_{X1X2} = 0$, it follows only that X_1, X_2 are not linearly related.

No correlation exists between any pair of random variables if the matrix turns out a diagonal matrix.

3.5 THE TRANSFORMATION OR FIRST-ORDER RELIABILITY METHO

3.5.1 Simple Transformation

Extra information might be incorporated in the reliability analysis by transforming non–normal distributions into equivalent normal distributions (Paloheimo and Hannus, 1974). Let X be log–normally distributed with mean μ_X and variance $\sigma^2 x$, the transformation to an equivalent variable U is given by U = *ln* X with $U_X \approx ln\ U_x$ and $\sigma^2_v \approx V^2_x$. If U is then converted to the standardized normal random variable Y, then

$$Y = (U - \mu_u) / \sigma_u \quad \text{----------(3.7)}$$

which is approximated by

$$ln\ (X / \mu_x) / V_x \quad \text{----------(3.8)}$$

It follows that the original variable X can be represented in terms of the standard normal variable Y and the first two moments μ_x and σ_X as

$$X \approx \mu_u \exp (YV_X) \quad \text{----------(3.9)}$$

This can be done for other non-normal random variables as well. In addition, the limit state function G (x) = 0 must be transformed to the y-space, yielding a non linear g(y)=0 function.

3.3.2 Transformation of non-normal basic variables

Non-normal basic variables are practically normalised by matching point wise, the density functions and distribution functions of the original distribution with the standard normal distribution (Gollwiter *et al*, 1988).

$$f_i(x_i) = \frac{1}{\sigma_{N,i}} \phi \left\{ \frac{x_i - \mu_{N,I}}{\sigma_{N,i}} \right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.10)$$

$$F_i(x_i) = \phi \left\{ \frac{x_i - \mu_{N,I}}{\sigma_{N,i}} \right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.11)$$

where $\mu_{N,i}$ and $\sigma_{N,I}$ are the mean and standard deviation of the equivalent normal distribution respectively, evaluated from equations (3.10) and (3.11) as

$$\mu_{N,I} = x_i - \sigma_{N,i}\, \phi^{-1}[f_i(x_i)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.12)$$

and

$$\sigma_{N,i} = \frac{\phi[\Phi^{-1}(F(x_i))]}{f_i(x_i)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.13)$$

3.6 DETERMINATION OF RELIABILITY INDEX

When G(X) is linear and uncorrelated in the basic variables X_i, the following steps are required to evaluate the reliability index β

1. Adopt a reduced, normally distributed variable expression for each variate

   Let $x = x_1, x_2, \ldots\ldots\ldots\ldots x_n$

   Then the reduced variate

   $x'_1 = x'_1, x'_2, \ldots\ldots\ldots\ldots x'_n$

   where $x'_i = \frac{x_i - \mu_{xi}}{\sigma_{xi}}$ .....(i)

such that $x_i = \sigma_{xi} x'_i + \mu_{xi}$ .....(ii)

2. Develop an expression for the limit state function with the reduced variate

$G(x) = G(\sigma_{Xl} x'_l + \mu_{xi}, \sigma_{x2} x'_2 + \mu_{x2}, \ldots \sigma_{xn} x'_n + \mu_{xn}) = 0$…… (iii)

3. Find an expression of the distance from the failure surface to the origin of the reduced variate space

Let the distance in question be D.

Then $D = \sqrt{(x'_1)^2 + (x'_2)^2 + \ldots + (x'_n)^2}$ ……..…….....(iv)

4. This expression is minimised, subject to G(X)=0 using Lagrange's method.

$L = D + \lambda G(x_i)$ ……..(v)

where λ = Lagrange multiplier

Hence $\frac{\partial L}{\partial x'_i} = x'_i + \lambda \frac{\partial G(x_i)}{D \, \partial x'_l} = 0$ ……..……..…….(vi)

and $\frac{\partial L}{\partial \lambda} = G(x_i) = 0$ ……..…(vii)

The solution of equations (vi) and (vii) gives the most likely minimum distance point x* from the origin.

5. The minimum distance is obtained by introducing the gradient vector

$$G' = \frac{\partial G}{\partial x'_i} \quad \text{……..……..(viii)}$$

coupled with appropriate matrix representation of D. Equation (vi) is manoeuvred into the expression for

$G(x_1, x_{2\ldots,} x_n) = G(x_1^*, x_2^{*\ldots,} x_n^*) + \sum^{n} (x_i - x_i^*) \partial G(x_i)$…….... (ix)

$$\sum_{i=1} \frac{}{\partial x_i}$$

but the failure surface $G(x_i^*) = 0$

Therefore ,

$$G(x_1, x_{2....,} x_n) = \sum_{i=1}^{n} (x_i - x_i^*) \frac{\partial G(x_i)}{\partial x_i} \quad \text{.....(x)}$$

In terms of reduced variate

$$G(x) = \sum_{i=1}^{n} (x_i^{/} - x_i^{*/}) \frac{\partial G(x_i)}{\partial x_i^{/}} \quad \text{.....(xi)}$$

Noting the parameter of $x_i^{/}$ are N(0, 1)

$$\mu_G = -\sum_{i=1}^{n} x^{*/} \frac{\partial G}{\partial x_i^{/}} \quad \textbf{and} \quad \sigma_G \approx \sum_{i=1}^{n} \sigma_{xi}^2 \left\{\frac{\partial G}{\partial x_i^{/}}\right\}^2 = \sum_{i=1}^{n} \left\{\frac{\partial G}{\partial x_i}\right\} \quad \text{.....(xii)}$$

Thus, the ratio

$$\frac{\mu_G}{\sigma_G} = -\frac{\sum_{i=1}^{n} x^{*/}_i \left\{\frac{\partial G}{\partial x_i^{/}}\right\}}{\sum_{i=1} \left\{\frac{\partial G}{\partial x_i^{/}}\right\}^2} = \beta \quad \text{.....(xiii)}$$

In equation (xiii) where basic variables are assumed to be normally distributed and uncorrelated, the Taylor's expansions of G(X) about the mean yields quite accurate estimates of β. However, G(X) may contain non-normal distribution and often correlated variable, the accuracy of the estimates heavily depends on the choice of the point of linearization.

FORM5 solves this problem by introducing appropriate transformations, converting all variables into correlated normal variables, subsequently linearising the emergent non-linear function G(X) about a suitable

point X* selected through an optimisation procedure. Hence a probability of failure is evaluated using standard normal integral.

3.5 INTRODUCTION TO FORM

FORM (First-Order Reliability Method) has been designed for the approximate computation of general probability integrals over given domain with locally smooth boundaries, but especially for probability integrals occurring in structural reliability. FORM5 is an updated version of FORM.

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. $F_{\underline{X}}(\underline{x})$ defining the *stochastic model*. It is required that $F_{\underline{X}}(\underline{x})$ is at least locally continuously differentiable. The random variables $\underline{X}$ $(X_1,\ldots\ldots\ldots\ldots\ldots\ldots..X_n)^T$ are called *basic variables*. The locally sufficiently smooth state function is denoted by $g(\underline{X})$. $g(\underline{X})>0$ denotes favourable state, whereas $g(\underline{X})=0$ denoted the so called *limit state* or the *failure boundary*. Therefore $g(\underline{X})<0$ defines the *failure domain* F. $g(\underline{X})$ can also be defined as an analytic function or an algorithm.

FORM (written in FORTRAN language) requires the easy use of input parameters, the state function as a subroutine and the stochastic model in terms of the distribution function type together with its distribution parameter. The state function must be written as a subroutine (DOUBLE PRECISION). Running FORM5 is either directly via a main

program or interactively via the program EFORM (Gollwitzer *et al,* 1988).

3.6 COMPONENTAL FIRST – ORDER PROBABILITY ESTIMATES

Basic Formulation

Let $\underline{U} = (U_1, U_2, \ldots U_n)^T$ be an independent standard normal vector and $g(\underline{U})$ the differentiable state of function of a system component. Then a first order approximation to $P_f = P(\underline{U} \in F) = P(g(\underline{U}) \leq U)$ is

$$P_f \approx \Phi(-\beta) \quad \ldots\ldots (3.14)$$

where Φ (.) = standard normal integral and

β = so called geometric safety index defined as

$$\beta = \min \{\| \underline{U} \|\} \text{ for } \{\underline{u}: g(\underline{u}) \leq U\} \quad \ldots\ldots (3.15)$$

Approximation of equation. (3.14) rests on a linearization of $g(\underline{u}) = 0$ by

$$\iota(\underline{u}) = \underline{\alpha}^T \underline{u} + \beta \quad \ldots\ldots (3.16)$$

where $\beta = -\underline{\alpha}^T \underline{u}^* = \| \underline{u}^* \|$

and $\underline{\alpha} = \dfrac{\text{grad } g(u^*)}{\| \text{grad } g(\underline{u}^*) \|}$

The normalised gradient of $g(\underline{u}) = 0$ at $\underline{u} = \underline{u}^*$, the solution point of equation (3.15). This point can be found by a modified projected gradient algorithm.

3.7 INTRODUCTION TO SYSREL

3.7.1 Theoretical Background

SYSREL (system reliability) computes the probabilities of arbitrary logical representation of sets in multidimensional uncertainty spaces as occurring in the probabilistic analysis of technical systems, event trees, networks and the like. It is based on the so-called equivalent plane concept. The results of FORM in terms of equivalent hyperplane representation of the component are particularly used as input in SYSREL. SYSREL can also produce a minimal cut set representation out of an arbitrary logical representation of a system by the program library CUTALG. SYSREL computes system probabilities, sensitivity measures for the uncertain variables and its importance measures for components and systems (Gollwitzer and Rackwitz, 1988)

SYSREL comes as a library of FORTRAN-based programs with subroutines which can be run via a main program or interactively via program ESYS.

3.7.2 Minimal Cut-Set Representation

SYSREL requires the logical structure to be either a *minimal cut-set* or a *disjoint cut-set* of componental domains. Originally, the logical structure of a system might not be given in the form of a minimal or disjoint cut-set. It is therefore necessary to produce such sets of failure events using one of the well known algorithms. A special case for the

formation of a minimal cut-set out of a classical fault tree representation of the system is included in the program **CUTALG.**

Cut–Set: A cut-set is a combination of component failures that ensure system failure.

Fault Tree: A fault tree is a tree-like structure that shows all the possible combinations of faults that may give rise to a failure in a system. It is usually illustrated by the use of symbols to represent events and logical gates.

3.7.3 Formation Of Minimal Cut-Set

Assume the logical connections of a system are given by a fault- tree using **"and - gates", "or-gates"** and **"basic events**". Further assume that the fault tree is a coherent tree. Then any system can be given as an arbitrary combination of unions and intersections of individual events E_K and the primary task is to re-arrange these combinations such that the event of interest can be given as $E = \cup\cap E_{ij}$

and is minimal in the sense that no combined sets contains another as genuine subset. The formation of such a set can always be achieved by the systematic application of the distributive (expansion) rules of set algebra ie. by

$$E_i \cap (E_j \cup E_K) = (E_i \cap E_j) \cup (E_i \cap E_K)$$

$$E_i \cup (E_j \cap E_K) = (E_i \cup E_j) \cap (E_i \cup E_K)$$

and the absorption rules. In particular if $E_i \subset E_j$ and $E_K \subset E_j$ then

$$(E_j \cup E_K) \subset E_j \quad \text{and} \quad (E_i \cap E_K) \subset E_j$$

The minimal cut set is obtained by the absorption rules. Since these operations on arbitrary systems are straight forward but can be quite cumbersome for larger system, the algorithms ‘CUTALG’ performs these expansions and absorption automatically.

Chapter 4

ANALYSIS, DESIGN AND RELIABILITY ESTIMATE

4.1 LOAD, ANALYSIS AND MEMBER FORCES

The analysis and design of the roof system shall focus on Howe steel truss (see Fig 4.1) which is commonly used in workshops, stores and warehouses.

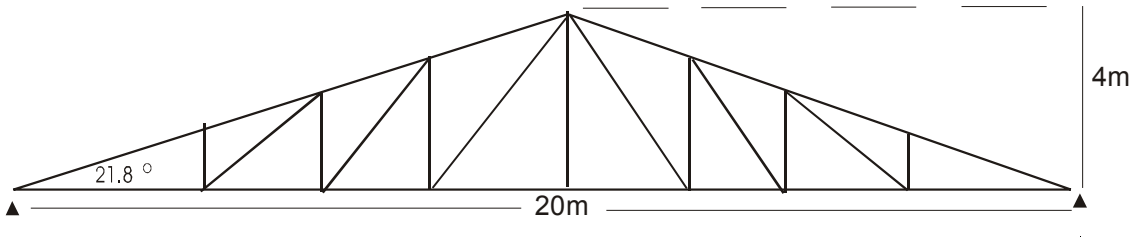


Fig. 4.1: Typical Howe Truss configuration

ROOF SYSTEM DATA

Plan dimension:	45m x 20m
Height to eaves:	10m
Rise of roof:	4m
Pitch of roof:	21.8^{O}
Spacing of truss:	5m
Steel grade:	43
Roofing material:	Aluminum

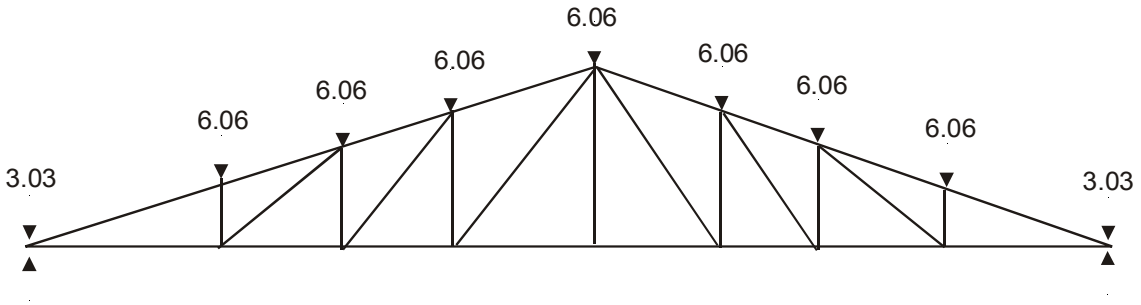
a. Dead Load, D_L

Measured on slope length

Sheeting + Insulation board	= 0.25 kN/m^2
Purlin	= 0.10 kN/m^2
Truss	= 0.10 kN/m^2
	0.45 kN/m^2

Total dead load = 0.45 x (21.54 x 5) = 48.465 kN

Nodal load = 48.465 / 8 = 6.06 kN



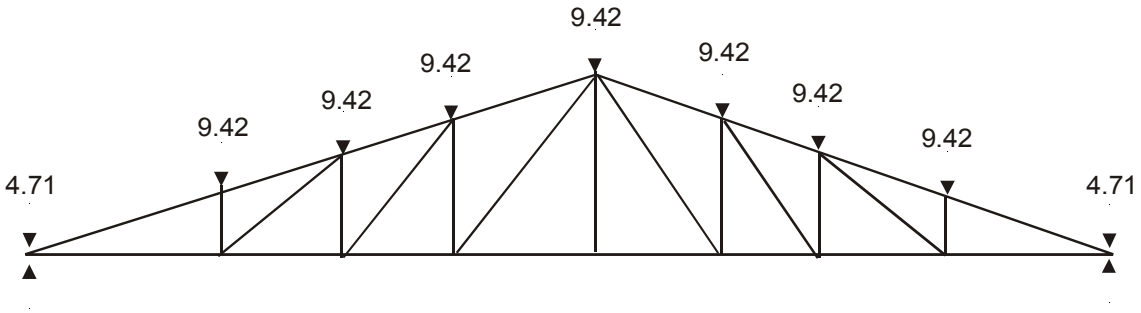
b. Imposed Load, I_L

Measured on plan = 0.75 kN/m^2 (No access)

Measured on slope = 0.75 x (10 / 10.77) = 0.7 kN/m^2

Total imposed load = 0.7 x (21.54 x 5) = 75.39 kN

Nodal load = 75.39 / 8 = 9.42 kN



c. Wind Load, W_L

Wind Loads in accordance with CP3: Chapter V Part 2: 1972

Location : Kano

Basic wind speed v = 45m/s

Building dimension :

Greater horizontal dimension , L = 45m

Lesser horizontal dimension , W = 20m

Height of structure H = 10m

Topography factor: The average slope of the ground does not exceed 0.05. Within a kilometre radius of the site the terrain is taken as level and hence in accordance with clause 5.1, CP3: Chapter V Part 2: 1972, topography factor **S1** = 1.0

Cladding and building size : class B

All structures where neither the greatest horizontal dimension nor the greatest vertical dimension exceeds 50m,

Roughness, size and height factor, **S2** = 0.74 (for H = 10m)

Statistical factor, **S3** = 1.0

Directional factor, **S4** = 1.0

Design wind speed, $V_s = V \times S1 \times S2 \times S3 \times S4$

$= 45 \times 1 \times 0.74 \times 1 \times 1$

$= 33.3 m/s$

Dynamic pressure $q = 0.613 Vs^2 / 1000$

$= 0.613 \times 33.3^2 / 1000$

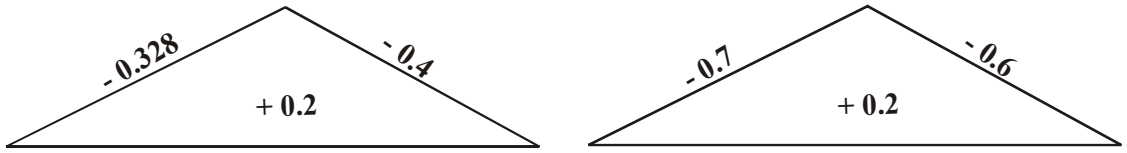
$= 0.6798 kN/m^2$

Building – Height Ratio, H/W = 10/20 = 0.5

Building plan Ratio, L/W = 45/20 = 2.25

Coefficient of internal pressure, Cpi = 0.2 (CP3, 1972)

Wind Angle (α – degrees)	**Cpe values for Roof**			
	longer side		**shorter side**	
0	-0.328	-0.4	*	*
90	*	*	-0.7	-0.6



$\alpha = 0^0$ $\alpha = 90^0$

Wind Load on inclined area

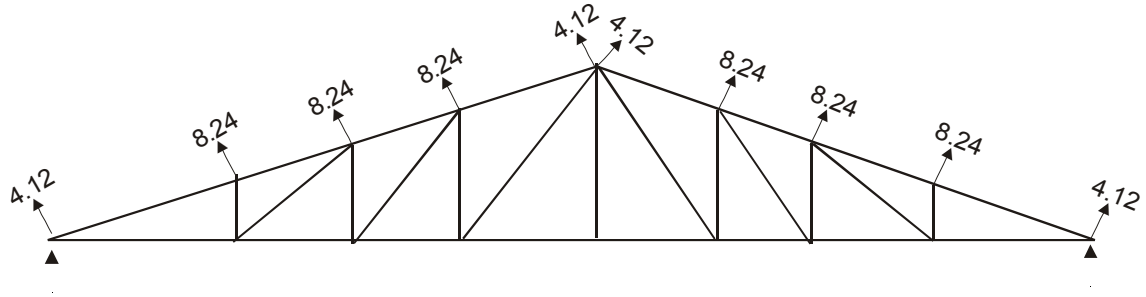
Total wind load = qA (Cpe – Cpi)

= 0.68 (21.54 x 5) (-0.7 –0.2) max

= 0.68 x 107.7 x (-0.9)

= -65.91 kN

Nodal Load = -65.91/ 4= -8.24 kN



The Design Load

The magnitude of the partial load factor is dependent on the load type, the load combination and limit state under consideration. The following approach used in deriving the critical load combinations in each truss member.

1. The member forces were calculated for each unfactored load type (dead, imposed, wind) using an appropriate method of analysis.
2. Load combinations are identified and the appropriate load factors for each combination applied for the ultimate or serviceability limit state.
3. The critical load at each joint and for each element was extracted and used for design.

In this study , the force diagram method was used to determine the forces in members due to gravity loads and wind loads. As the truss system is symmetrical, only one- half of the system was considered for analysis and design.

The load combinations considered were:

a. Dead load only
b. Dead load + Imposed load ($1.4D_L + 1.6\ I_L$)
c. Dead load + Wind Load ($D_L + 1.4\ W_L$)
d. Dead load + Imposed load + Wind load 1.2 ($D_L + I_L + W_L$)

The load combination due to (b) gave the critical values, hence applied in the design. Forces in each member under the critical load combination are as in Table 4.1 with reference to Fig. 4.2.

Table 4.1 Member forces obtained from load combination force Diagram.

Member	Dead Load D_L (N)	Imposed Load I_L (N)	Wind Load W_L (N)	1.4 D_L + 1.6I_L (N)	MEMBER FORCE MULTIPLIER
a	- 57.17	- 76.10	- 99.43	- 222.04	15.08
b	- 57.17	- 76.10	-96.14	-222.04	15.08
c	-65.36	-88.78	-82.32	-253.76	17.24
d	-68.14	-93.00	-83.55	-264.33	17.95
p	53.08	70.66	94.00	206.16	14.00
q	60.65	82.44	84.16	235.18	15.97
r	63.19	86.36	88.49	245.00	16.64
s	65.73	90.29	80.76	254.79	17.31
e	-6.06	-9.42	7.65	-23.56	1.6
f	-3.04	-4.71	5.20	-11.78	0.8
g	-4.06	-6.28	12.39	-15.65	1.06
k	-9.70	-15.08	12.34	-37.71	2.56
m	-3.96	-6.13	-6.77	-15.34	1.04
n	-4.79	- 7.41	14.58	-18.46	1.25

4.2 DESIGN OF TRUSS MEMBERS AND JOINTS

(i) Top Chord Members

Purlin loads are applied at the nodes. The top chord therefore acts as a continuous beam. It is designed to meet clause 4.8.3.2 of BS5950 (1985) part 1. Generally the member is certified adequate if it satisfies the following conditions;

a. Local capacity check where $F/(A_gP_y) + M_x/M_{cx} + M_y/M_{cy} \leq 1$

b. Overall buckling check where $F/(A_gP_c) + mM_x/M_b + mM_y/(P_yZ_y) \leq 1$

Bottom Chord Members

Clause 4.6.1 of BS 5950 (1985) part 1 states that its member force should not exceed its tensile capacity for the bottom chord to be considered satisfactory, that is, $\mathbf{P_t > F}$.

(ii) Internal Members

Internal members are designed not to exceed the capacities as stipulated in clauses 4.6.1 and 4.7.1 depending on whether the member is a tie (carrying tensile force) or a strut (carrying compressive force), that is,

$\mathbf{P_t > F}$…….. ties

$\mathbf{P_c > F}$…….struts

However all internal members were analysed and found to be struts.

(iii) Joints

Joints are designed to conform with clause 6.6.5 of BS 5950 (1985) part 1 – fillet weld, and clause 6.6.6 for butt welds. Clause 6.6.5 states that the vector sum of the design stresses due to all forces and moment transmitted by the weld should not exceed the design strength of the fillet weld, that is, $\mathbf{P_{wc} > F}$

DESIGN SECTIONS

Members and joints were designed to meet the conditions as stipulated above and the following sections were adopted.

Table 4.2: Adopted sections and sizes.

Member	Section	Serial Size
Top Chord	T – section	102 x 102 x 12 kg/m
Bottom Chord	T – section	102 x 89 x 10 kg/m
Internal Struts		
e	L – section	40 x 40 x 6 kg/m
f	L – section	40 x 40 x 6 kg/m
g	L – section	60 x 60 x 6 kg/m
k	L – section	70 x 70 x 8 Kg/m
m	L – section	70 x 70 x 8 Kg/m
n	L – section	70 x 70 x 8 Kg/m

4.3 RELIABILITY ESTIMATE

This section comprises the componental reliability analysis and the system reliability analysis.

4.3.1 Component Reliability Analysis

This involves the estimation of the safety levels of individuals members and joint making the truss system.

4.3.1.1 Limit State Equation

The limit state equations for members are derived as follows:

Top Chord Members

Limit state equation of a top chord member is given as

$$G(x) = 1 - \left\{ \frac{F}{A_g P_y} + \frac{M_x}{M_{cx}} \right\}$$

where F = member force
A_g = Gross Area (mm^2)
P_y = Design Strength (N/mm^2)
M_x = Applied moment in x – x axis (Nmm)
M_{cx} = Moment capacity of section about x – x axis (Nmm)

Since purlin loads are applied at the nodes, the second term in bracket was omitted.

The top chord is a T-section with its geometric properties shown in Fig. 4.4

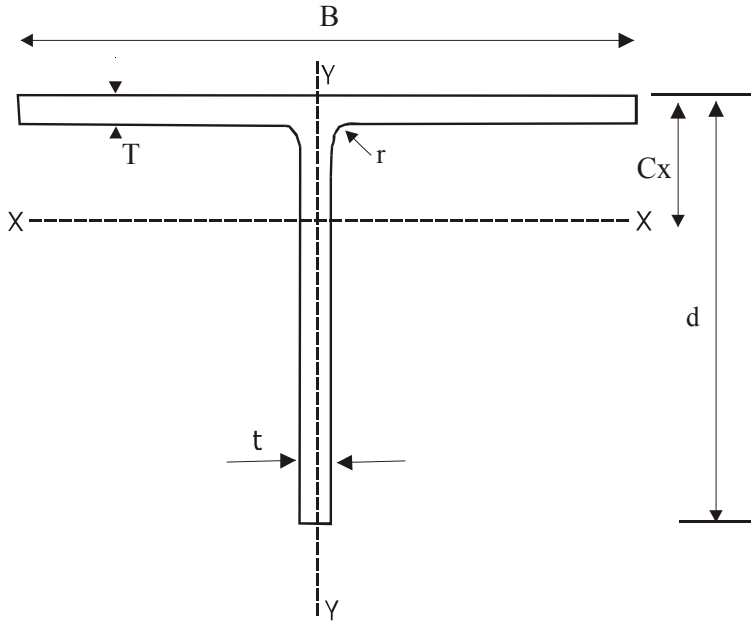


Fig 4.4: T- Section.

"F" is a function of the dead and live load. Dead load varies with constant live load depending on the roof pitch or truss span. As such, the member forces shall be expressed as a function of dead to live load ratio.

Take member 'a' for example:

$F = 1.4D_L + 1.6\ I_L$

where D_L = Dead load

and I_L = Imposed load

$$F = 1.6\ I_L \left(\frac{1.4\ D_L}{1.6\ I_L} + 1\right)$$

$F = 1.6\ [I_L\ (0.875\ \alpha + 1)]$

But $I_L = 9.42$ and $\alpha = 0.643$, $F = 222.04$

$222.04 = 1.6 \times [14.72]$

$$\frac{222.04}{14.72} = 15.08$$

$F = 15.08\ I_L\ (0.875\ \alpha + 1)$……..…… (4.1)

where I_L = live load (N)

α = Dead to live load ratio

All member forces are expressed in the form of equation (4.1).

Bottom Chord Members

Limit state equation for bottom chord members is as follows:

$G(x) = P_t - F$

where P_t = Tensile force = $A_e P_y$

and A_e = Effective Area (mm^2)

P_y = Design Strength (N/mm^2)

F = Member force expressed in terms of dead to live load ratio .

The effective area is defined as

$$A_e = BT + (d - T)\, t + ((4-\pi)/4)\, 2r^2$$

Internal Strut Members

Limit state equation of a strut member is given as

$$G(x) = P_{cc} - F$$

where P_{cc} = Compressive Capacity = $A_g . P_{cs}$

P_{cs} = Compressive Strength (N/mm^2)

A_g = Gross Area (mm^2)

F = Member force expressed in terms of dead to live load ratio .

Internal strut members have an L-section. Fig (4.5) shows an L- section with its geometric properties.

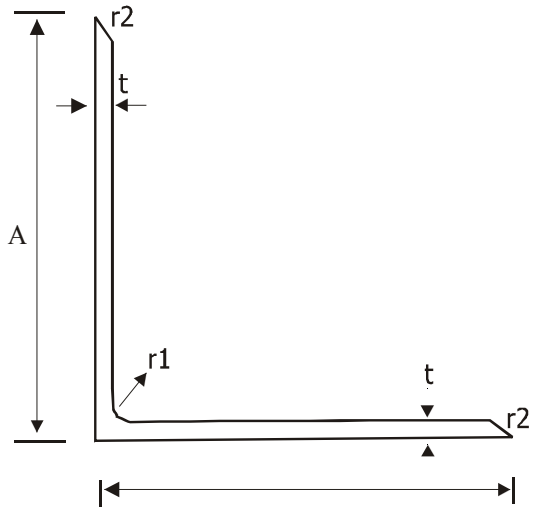


Fig 4.5 : Equal L - Section.

The gross sectional area is

$$A_g = 2At - t^2 - ((4-\pi)/4) (2r_2^2 - r_1^2)$$

Joints

Limit state equation for a joint can be expressed as

$G(x) = P_{wc} - F$

where P_{wc} = Weld capacity = $0.7SLP_w$

S = Leg length (mm)

L = Effective length (mm)

P_w = Design strength of weld (N/mm^2)

F = Joint force, expressed in terms of dead to live load ratio

4.3.1.2 Statistical Characters of Relevant Design Parameters

Design codes often quote upper and lower limit values but generally they use conservative values to ensure that their design values fall within the safe range. The probability distribution of basic variables or design parameters can be obtained either from observed data or by subjective assessment or by both. In practice, employing the direct inference method is rarely possible due to insufficient data. In this study, the relevant sectional properties used as basic variables are tabulated accordingly in tables (4.3) – (4.6).

Note that VAR = $S[X_i] / E[X_i]$

where $E[X_i]$ = Mean Values

and $S[X_i]$ = Standard deviation values

TABLE 4.3: Statistical Values of Design Parameters for Top Chord Member (102 x 102 x 12 Kg/m)

	Variables	Dist. Type	#	$E[X_i]$	$S[X_i]$	VAR
X1	Design strength, P_y-N/mm^2	Log normal	3	275	19.25	0.07
X2	Imposed load, I_L -N	Gamma	5	9420	2826	0.30
X3	Flange width, B - mm	Normal	2	101.6	3.048	0.03
X4	Section depth, d - mm	Normal	2	101.6	3.048	0.03
X5	Web thickness, t - mm	Normal	2	5.2	0.312	0.06
X6	Flange thickness, T - mm	Normal	2	9.3	0.558	0.06
X7	Root radius, r - mm	Normal	2	7.6	0.4560.	0.06

TABLE 4.4: Statistical Values of Design Parameters for Bottom Chord Member (102 x 89 x 10 Kg/m)

	Variables	Dist. Type	#	$E[X_i]$	$S[X_i]$	VAR
X1	Design strength, P_y -N/mm^2	Log normal	3	275	19.25	0.07
X2	Imposed load, I_L -N	Gamma	5	9420	2826	0.30
X3	Flange width, B - mm	Normal	2	101.6	3.048	0.03
X4	Section depth, d - mm	Normal	2	88.9	2.667	0.03
X5	Web thickness, t - mm	Normal	2	4.7	0.282	0.06
X6	Flange thickness, T - mm	Normal	2	7.9	0.474	0.06
X7	Root radius, r - mm	Normal	2	7.6	0.456	0.06

TABLE 4.5: Statistical Values of Design Parameters for Strut Member (40 x 40 x 6 Kg/m)

	Variables	#	$E[X_i]$	$S[X_i]$	VAR
X1	Compressive strength, P_{cs} -N/mm^2	3	110	7.7	0.07
X2	Imposed load, I_L -N	5	9420	2826	0.30
X3	Angle Length, A - mm	2	40	1.2	0.03
X4	Leg thickness, t - mm	3	6	0.36	0.06
X5	Root Radius r_1 - mm	3	6	0.36	0.06
X6	Toe Radius r_2 - mm	3	2.4	0.144	0.06

TABLE 4.6: Statistical Values of Design Parameters for Joints

	Variables	#	$E[X_i]$	$S[X_i]$	VAR
X1	Design strength of fillet weld, P_w N/mm^2	3	215	3.225	0.015
X2	Imposed load, I_L -N	5	9420	2826	0.3
X3	Leg thickness, S - mm	3	4	0.12	0.03
X4	Effective length, L - mm	2	56	1.68	0.03

* Steel grade 43 to BS 4360

Electrode strength to BS 639, E43 = 215 N/mm^2

4.3.1.3 Componental Reliability Results

Computation to determine the safety indices, β for members and joints and their corresponding probabilities of failure, P_f was carried out using FORM.

The results are obtained by compiling and linking programs. Such programs are presented in Appendix 2. The dead to live load ratio, $\propto$ was varied from 0.40–0.80 with a computation interval of 0.1. The results are in tables 4.7 and 4.8. From the tables, the following observations can be deduced:

i. the safety indices, β ranged from 3.267 to 0.408 for members;

ii. the safety indices ranged from 2.919 to 0.044 for joints;

iii. the probability of failure increases with an increase in load ratio, $\propto$.

iv. most members exhibit a higher β - values than for joints at a particular load ratio. This indicates that failure will be initiated at the joints before extending to members.

v. failure of members is in the ascending order: bottom chord members, struts, followed by top chord members having the highest safety level.

TABLE 4.7: Safety Indices, β and their corresponding Probabilities of Failure in truss members

Members	∝ = 0.40		∝ = 0.50		∝ = 0.643		∝ = 0.70		∝ = 0.80	
Top Chord	β	P_f	β	P_f	β	P_f	β	P_f	β	P_f
a	2.691	0.357 E – 20	2.445	0.723 E – 02	2.126	0.167 E – 01	2.008	0.223 E – 01	1.811	0.350 E - 01
b	2.691	0.357 E – 20	2.445	0.723 E – 02	2.126	0.167 E – 01	2.008	0.223 E – 01	1.811	0.350 E - 01
c	2.173	0.49 E – 01	1.937	0.264 E – 01	1.630	0.516 E – 01	1.576	0.648 E – 01	1.327	0.923 E – 01
d	2.021	0.216 E – 01	1.788	0.369 E – 01	1.484	0.689 E – 01	1.371	0.851 E – 01	1.184	1.18 E - 01
Bottom Chord										
p	2.271	0.116 E – 01	2.033	0.210 E – 01	1.724	0.424 E – 01	1.609	0.538 E – 01	1.419	0.780 E - 01
q	1.778	0.377 E – 01	1.549	0.607 E – 01	1.251	1.06 E - 01	1.140	1.27 E – 01	0.957	1.69 E - 01
r	1.617	0.518 E –01	1.401	0.806 E – 01	1.106	1.34 E – 01	0.997	1.59 E - 01	0.816	2.07 E - 01
s	1.485	0.69 E - 01	1.261	1.04 E - 01	0.970	1.66 E - 01	0.862	1.94 E - 01	0.683	2.47 E - 01
Strut										
e	3.267	0.543 E – 03	3.017	0.128 E – 02	2.690	0.357 E – 02	2.569	0.511 E – 02	2.367	0.896 E – 02
f	1.553	0.602 E – 01	1.331	0.917 E – 01	1.041	1.49 E –01	0.934	1.75 E –01	0.755	2.25 E –01
g	2.243	0.124 E – 01	2.009	0.222 E – 01	1.705	0.441 E- 01	1.592	0.557 E – 01	1.404	1.801 E – 01
k	1.183	1.18 E - 01	0.967	1.67 E –01	0.686	2.46 E –01	0.581	2.80 E –01	0.408	3.42 E –01
m	3.212	0.660 E – 03	2.962	0.153 E 0 02	2.637	0.418 E – 02	2.516	0.593 E – 02	2.316	0.103 E –01
n	1.207	1.14 E - 01	0.991	1.61 E –01	0.709	2.39 E –01	0.605	2.73 E –01	0.431	3.33 E –01

TABLE 4.8 Safety Indices, β and their corresponding Probabilities of Failure in Welded Joints.

Joints	Members	∝ = 0.40		∝ = 0.50		∝ = 0.643		∝ = 0.70		∝ = 0.70	
		β	P_f	β	P_f	β	P_f	β	P_f	β	P_f
	e	1.901	0.287 E – 01	1.660	0.485 E – 01	1.347	3.73 E – 01	1.232	1.09 E – 01	1.040	1.49 E – 01
2	k	0.826	2.04 E – 01	0.607	2.72 E – 01	0.323	0.373 E – 01	0.218	4.14 E – 01	0.044	4.82 E – 01
	f	2.919	0.176 E – 02	2.656	0.395 E – 02	2.316	0.103 E – 01	2.190	0.143 E – 01	1.982	0.237 E – 01
3	m	2.566	0.515 E – 02	2.311	0.104 E – 01	1.90	2.238 E – 01	1.858	0.316 E – 01	1.656	0.489 E – 01
	g	2.488	0.642 E – 02	2.235	0.127 E – 01	1.906	0.283 E – 01	1.785	0.371 E – 01	1.584	0.566 E - 01
4	n	2.182	0.145 E – 01	1.935	0.265 E – 01	1.615	0.531 E – 01	1.497	0.672 E – 01	1.301	0.967 E – 01
6	n	2.182	0.145 E – 01	1.935	0.265 E – 01	1.615	0.531 E – 01	1.497	0.672 E – 01	1.301	0.967 E – 01
	m	2.566	0.515 E – 02	2.311	0.104 E – 01	1.90	2.238 E – 01	1.858	0.316 E – 01	1.656	0.489 E – 01
7	g	2.488	0.642 E – 02	2.235	0.127 E – 01	1.906	0.283 E – 01	1.785	0.371 E – 01	1.584	0.566 E - 01
	k	0.826	2.04 E – 01	0.607	2.72 E – 01	0.323	3.73 E – 01	0.218	4.14 E – 01	0.044	4.82 E – 01
8	f	2.919	0.176 E – 02	2.656	0.395 E – 02	2.316	0.103 E – 01	2.190	0.143 E – 01	1.982	0.237 E – 01
9	e	1.901	0.287 E – 01	1.660	0.485 E – 01	1.347	0.889 E – 01	1.232	1.09 E – 01	1.040	1.49 E – 01

4.3.2 System Reliability Analysis

4.3.2.1 Fault – tree Analysis

The fault tree of a Howe truss system is shown in Fig. 4.6. SYSREL requires the logical structure of the system to be a minimal cut-set. For simplification, the fault-tree is hereby divided into *members fault-tree,* Fig. 4.7 and *joints fault-tree,* Fig. 4.8 to form a minimal cut-set by the program 'CUTALG'.

4.3.2.2 Input Data to CUTALG

Running CUTALG requires the numbering of all gates and basic events in the fault tree. The **r-th** gate is denoted by **r**. The **s-th** basic event is denoted by the number followed by a **B** i.e. **sB.**

The input to YCUT (main administration routine in CUTALG) has to specify the following parameters in the first line of the input file.

KN = number of gates

KB = number of basic events

MEB = number of subset – checks during expansion.

This line is followed by exactly KN lines defining the logical connection below the gate under question. Each line starts with the gate number followed by "**=**"

An 'or –gate' is denoted by "+"

An 'and-gate' is denoted by "*"

If the successor is a basic event, the event number must be followed by a **'B'**. An **'E'** at the end of the line which is not admissible at the first and last line calls for a subset check operation. Commata has successive gate or basic event. The syntax of the input for Figs. 4.7 and 4.8 are presented below.

Input to YCUT (Fig. 4.7)

4, 14, 0

1 = +, 2 ,3, 4

2 = +, 1B, 2B, 3B, 4B

3 = +, 5B, 6B, 7B, 8B,

4 = +, 9B, 10B, 11B, 12B, 13B, 14B

Input to YCUT (Fig. 4.8)

6, 12, 0

1 = +, 2, 3, 4, 7B, 5, 6, 12B

2 = +, 1B, 2B

3 = +, 3B, 4B

4 = +, 5B, 6B

5 = +, 8B, 9B

6 = +, 10B, 11B

Note that these input data are written on separate files.

Input Data to ESYS

The input to SYSREL is either created interactively or read from two files. If from files then,

File 1: This file being the output file from CUTALG operation contained M,K, and KMAT in a format to be used by ESYS as input.

File 2: In this file, ALFMAT (collecting α - Vectors) and BETVEC (collecting β - values) are written in a sequence and format readily acceptable as input to ESYS. However, input to SYSREL was carried out at different load ratios.

SYSREL Analysis Result

Running CUTALG/SYSREL packages yielded unfavourable results for members and joints as presented in Table 4.9. The results show that only a single joint was successful at a load ratio of 0.40. All members have failed at the given load ratio range. Negative safety index indicates failure of any component. This interprets an overall system failure, although the initial values of the design variables meet the BS5950 (1985) requirements.

This observation is an indication to the fact that the current partial safety factors in the code have not adequately compensated for inherent variabilities.

TABLE 4.9: Safety Indices, β and their corresponding probabilities of failure in Members and Joints.

	MEMBERS		JOINTS		SYSTEM	
ALFA	β	P*f*	β	P*f*	β	P*f*
0.40	- 0.049	0.520	0.820	0.206	-	-
0.50	- 0.800	0.788	-0.668	0.748	-	-
0.643	-36.564	1.285	-36.564	1.156	-	-
0.70	-36.564	1.157	-36.564	1.346	-	-
0.80	-36.564	1.987	-36.564	1.715	-	-

4.4 TARGET SAFETY INDEX

NKB report No. 36 (1978) recommended that for all types of failure whether less serious, serious or very serious, the target safety level, β_T should range from 3- 5 for ultimate limit state. For serviceability limit state on the other hand, β_T should range from 1 – 2. This indicates that the system safety indices are out of range. In line with this, a conservative target safety index is chosen to satisfy both limit state cases. The idea is that if each component is designed to meet a target safety index β_T, the system safety index β_s will automatically meet the required safety level.

Chapter 5

SAFETY DESIGN PROGRAM

5.1 GENERAL

The work of design involves the provision of a structure with an established safety level at a minimum cost. The steps are as follows:

i. Determination of design loads

ii. Determination of the strength of structure

iii. Determination of a quantitative value for safety.

The methods of specifying structural safety are; engineering methods, ratio methods and the probability method. The latter was found to be the most efficient method and provides the safest result (Brown, 1960).

The use of computer in structural design makes possible the selection of a number of alternate sections, all of which have been subjected to comprehensive checks to ensure that they meet the relevant requirements. It enables alternate sections to be checked giving the designer a wider choice than would be possible manually (McGinley and Ang, 1990).

In this chapter, reliability-based design program is developed using FORTRAN programming language. The program modules are based on BS5950 (1985) design procedures and the concept of First-Order

Reliability Method (FORM). Such programs design and check the reliability of the structure during its expected life span.

5.2 PROGRAM FLOW CHART

This provides a schematic diagram of the steps involved in the development of the reliability-based design programs. The diagram is as presented in fig. 5.1.

5.3 DESIGN CRITERION

The reliability-based design is considered satisfactory if the following condition is satisfied.

$$(\beta - \beta_T)^2 \leq \varepsilon$$

where β = Computed safety index as obtained from the reliability program.

β_T = target safety index

ε = epsilon, the level of acceptance of the design points.

If the condition is not satisfied, the program re-designs using new set of variables. The process continues until the condition is satisfied.

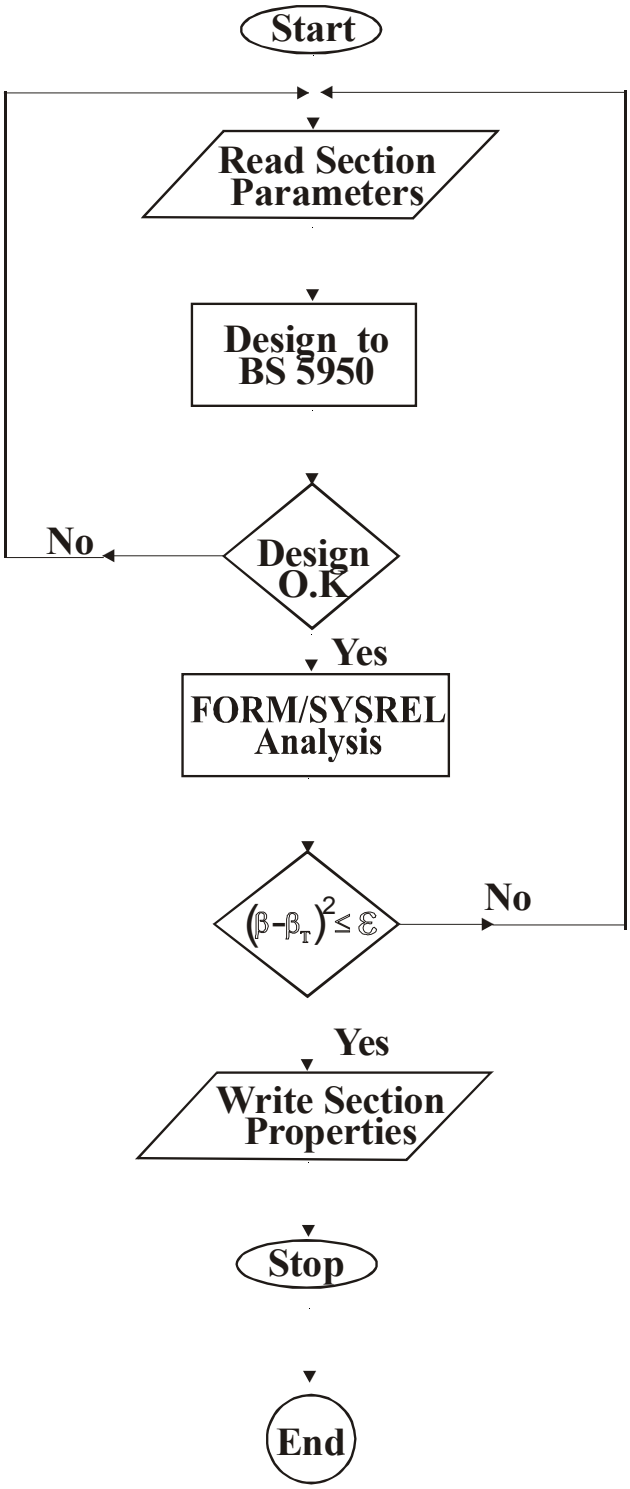


Fig. 9 Reliability based Design program Flow chart .

5.4 PROGRAM DESCRIPTION

5.4.1 FORM5

There are 2 principal ways of running FORM5. Either via user defined main program or interactively via EFORM. The stochastic model is defined in the main program or EFORM, and the state subroutine are all declared external in the main subroutine. Each main program has main subroutine defining the statistical characters of all basic variables which in turn calls FORM5 subroutine.

Input into the main subroutine are section parameters. Input into the state subroutine are the values of the basic variables. The state subroutine returns the value of the state function and possible error messages to FORM5. FORM5 then returns the solution and possible error messages to the main program.

5.4.2 SYSREL/ CUTALG

These are packages of programs, subprograms and subroutines for the computation of system probabilities and related measures.

There are in principle, 2 ways to run the system reliability package:

1. **Interactively**:

   The program ESYS runs SYSREL interactively. ESYS is most suitable for individuals runs for not too large systems.

   The program CUTALG runs CUTALG

2. **Via a user defined main program**:

   A main program to run SYSREL is supplied as a sources code on the file SYSTE.FOR.

   A main program to run CUTALG is supplied as a source code on the file CUT.FOR.

If the logic representation of a system is not a minimal cut set, the package CUTALG with its main subroutine YOUT performs the task. SYSREL with its main subroutine FORSYS requires the component to be represented by (equivalent) hyperplanes in the standard space. These hyperplanes have to be produced separately by FORM where the necessary transformation have to be carried out.

In structural reliability applications, FORSYS or other subroutines in SYSREL will most frequently be called by a user defined main program.

5.5 PROGRAM STRUCTURE

5.5.1 Program RELOTOP

This is a reliability-based program for the design of the top chord member in a truss system. It has a main subroutine called BARAX1. FORM5 is a subroutine within the main subroutine. The state subroutine TOMAX is declared external to the main subroutine.

5.5.2 Program RELOBOT

This is a reliability-based program for the design of the bottom chord member in a truss system. it has a main subroutine called BARAX2 with

FORM5 as a subroutine to it. The state subroutine BOMAX is declared external to the main subroutine.

5.5.3 Program RELOSTRUT

This is a reliability-based program for the design of internal strut members in a truss system. It has a main subroutine called BARAX3 and another subroutine AMY. FORM5 is as well a subroutine to BARAX3. The state subroutine STRUTMAX is declared external to BARAX3.

5.5.4 Program RELOWELD

This is a reliability-based program for the design of wielded joints in a truss system. It has a main subroutine called BARAX4. FORM5 is a subroutine called by the main subroutine. The state subroutine WELMAX is declared external to the main subroutine.

5.6 PROGRAM STATEMENTS

The programs developed for the design of top, bottom chords, struts and welded joints in a truss system are presented in Appendix 2.

5.7 PROGRAM RESULTS

Results for individual components and joints of the Howe truss system were generated at a target safety index of 2.8. Initially the numerical value of the geometric parameters of 'adopted' sections were read from an input file. The program checks the adequacy of that section in accordance with BS5950 (1985). If section is 'inadequate' the program

returns and asks for new parameters value. If section is 'adequate' the reliability design (FORM5), is called and proceeds by checking 'epsilon' i.e. the level of acceptance of design points. If epsilon is out of range, the program prompts '*target not met'* and returns for a new section parameters input. If epsilon is within range, then 'target beta' is satisfied. The geometric section properties are hence printed in the result file.

Results were obtained at a load ratio of 0.40 – 0.80. It is worth noting that the epsilon value of the top chord members was fixed uniform for an identical group and so also the value differs for other groups. Steel section that proved satisfactory in both cases (i.e. ultimate and serviceability) are shown in Tables 5.1 through 5.8.

5.8 COMPARISON OF RESULT AND DISCUSSION

Comparing adopted sections in Table 4.2 with sections adopted in the program, it was observed that both sections were adequate in terms of ultimate limit state but the latter sections were preferable as they were found to be satisfactory at a reliability level of 2.8. Despite the fact that a uniform adopted T-section (102 x 102 x 12) proved adequate for all top chord members, the program selected a T- section (102 x 127 x 13) from the profile table to be a reliable one for members **a** and **b,** size (102 x 127 x 14) for member **c** while size (142 x 127 x 16) for member **d** at a reliability level = 2.8 and load ratio of 0.40 – 0.80.

The same applies to the bottom chord members. T- section size (102 x 127 x11) for member **p** and size (102 x 127 x 13) for members **q, r** and **s** were selected by the program to be more reliable than a single uniform size section of (102 x 89 x 10). Same applied for struts as there has been a general increment in section size before members proved reliable. Speaking of fillet weld joint, the weld length was increased or decreased accordingly at a constant weld thickness of 5mm in order to maintain the target reliability level at an load ratio of 0.40 – 0.80.

It is a little time consuming to design a truss system comprising of steel sections from the profile table that will meet the target beta value of 2.8 while keeping epsilon very low (i.e. close to zero) and uniform within a load ratio of 0.40 – 0.80. To meet such condition implies manipulating and/or interpolating some or all of the section properties of a particular component.

TABLE 5.1: Reliable sectional design parameters for the reliability design of top chord members at target beta = 2.8

Member	Section	Section Width B(mm)	Section Depth d(mm)	Web Thickness t(mm)	Flange Thickness T (mm)	Root Radius r(mm)	Gross Area $A_g(mm^2)$
a	102 x 127 x 13	101.9	128.5	6.1	8.4	7.6	161
b	102 x 127 x 13	101.9	128.5	6.1	8.4	7.6	161
c	102 x 127 x 14	102.1	130.2	6.4	10.0	7.6	182
d	146 x 127 x 16	146.1	125.7	6.1	8.6	7.6	20

TABLE 5.2: β - values from reliability design of top chord members at load ratio range 0.40 – 0.80, target beta = 2.8

ALFA / MEMBER	0.40	0.50	0.643	0.70	0.80
	β - VALUES				
a	3.12	2.87	2.54	2.42	2.22
b	3.12	2.87	2.54	2.42	2.22
c	3.06	2.81	2.48	2.36	2.15
d	3.28	3.02	2.69	2.56	2.36

TABLE 5.3: Reliable sectional design parameters for the reliability design of bottom chord

members at target beta = 2.8

Member	Section	Section Width B(mm)	Section Depth d(mm)	Web Thickness t(mm)	Flange Thickness T (mm)	Root Radius r(mm)	Effective Arc Ae (mm^2)
p	102 x 127 x 11	101.6	127.0	5.8	6.8	7.6	14100
q	102 x 127 x 13	101.9	128.5	6.1	8.4	7.6	16100
r	102 x 127 x 13	101.9	128.5	6.1	8.4	7.6	16100
s	146 x 127 x 13	101.9	128.5	6.1	8.4	7.6	16100

TABLE 5.4: β - values from reliability design of bottom chord members at load ratio range 0.40 – 0.80, target beta = 2.8

Alfa / Member	0.40	0.50	0.643	0.70	0.80
	β - VALUES				
p	3.22	2.96	2.63	2.51	2.30
q	3.54	3.28	2.94	2.81	2.60
r	3.37	3.11	2.77	2.65	2.44
s	3.20	2.95	2.62	2.50	2.29

TABLE 5.5: Reliable sectional design parameters for the reliability design of strut members at target beta = 2.8

Member	Section	Leg.	Thickness	Root	Toe	Gross	Radiius

		Length A(mm)	t(mm)	Radius r1(mm)	Radius r2(m)	Area Ag (mm^2)	of Gyration rx = ry (mm)
e	30 x 30 x 5	30	5	5.0	2.4	278	8.83
f	40 x 40 x 4	40	4	6.0	2.4	309	12.10
g	50 X 50 X 8	50	8	7.0	2.4	744	14.90
k	70 x70 x 6	70	6	9.0	2.4	819	21.50
m	60 x 60 x 8	60	8	8.0	2.4	907	18.00
n	70 x 70 x 8	70	8	9.0	2.4	1070	21.20

TABLE 5.6: β - values from reliability design of strut members at load ratio range 0.40 – 0.80, target beta = 2.8

Alfa / Member	0.40	0.50	0.643	0.70	0.80
	β - VALUES				
e	2.86	2.61	2.29	2.17	1.97
f	3.04	2.78	2.46	2.33	2.13
g	3.07	2.81	2.48	2.36	2.16
k	3.15	2.90	2.37	2.44	2.24
m	3.48	3.22	2.88	2.76	2.55
n	3.25	2.99	2.66	2.53	2.33

TABLE 5.7: Reliable design parameters for the reliability design of fillet welded joints, target beta = 2.8

Joint	Member	Weld thickness	Weld thickness

		S (mm)	L (mm)
2	e	5	62
	K	5	100
3	f	5	31
	m	5	41
4	g	5	41
	n	5	49
6	n	5	49
7	m	5	41
	g	5	41
8	k	5	100
	f	5	31
9	e	5	62

TABLE 5.8 β - values from reliability design of fillet welded joints at load ratio range 0.40–0.80, target beta = 2.8

Joint	Alfa / Member	0.40	0.50	0.643	0.70	0.80
		β - values				
2	e	3.23	2.96	2.62	2.49	2.27
	k	3.27	3.00	2.65	2.52	2.31
3	f	3.23	2.96	2.62	2.49	2.27
	m	3.31	3.04	2.69	2.56	2.34
4	g	3.23	2.96	2.61	2.48	2.27
	n	3.28	3.01	2.66	2.53	2.32
6	n	3.28	3.01	2.66	2.53	2.32
7	m	3.31	3.04	2.69	2.56	2.34
	g	3.23	2.96	2.61	2.48	2.27
8	k	3.27	3.00	2.65	2.52	2.31
	f	3.23	2.96	2.62	2.49	2.27
9	e	3.23	2.96	2.62	2.49	2.27

Chapter 6

CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

The previous chapters have been describing the reliability-based design of a Howe truss system on micro-computers. The concept of the design was built upon the First-Order Reliability method (FORM) and System Reliability (SYSREL) programs. These are programs written for the purpose of probabilistic analysis. For a typical truss, the overall truss system failed when subjected to probabilistic analysis, even though it was proved to be safe at ultimate limit state using BS 5950 (1985) requirement. Results show that the safety index of individual components and joints are higher than when functioning as a system, an indication that the BS 5950 (1985) requirement has not sufficiently accommodated uncertainties in the design of truss systems.

Results are generated at a constant reliability level. Section properties are manipulated to meet the target safety level of the reliability design. A section was then matched with a section in the steel profile table with the closest but slightly higher property values. Such section is assured to have satisfied the safety index format hence, considered reliable.

6.2 RECOMMENDATION

A thorough research into reliability application on micro-computer is highly recommended .The design of statically indeterminate complex

trusses need to be looked into. In steel trusses, there is the need to compare developed program section properties with the profile table section properties to determine the percentage difference and ascertain how economical the section in question is. This may lead to the incorporation of new steel sectional sizes in the designers manual.

I therefore recommend reliability theory as a unified analytical tool for the systematic analysis of risk and safety under conditions of uncertainty.

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APPENDIX 1

LIST OF PARAMETERS IN FORM5

PARAMETER	TYPE	DESCRIPTION
N	(INTEGER)	number of uncertain variables and dimension of the vectors EX, SX, X and U
IV	(INTEGER)	matrix of dimension (2,N) whose 1st element in the i-th column assigns the probability distribution type J to the variable X (i) and whose 2nd element defines the type of input for the distribution parameters
EX	(REAL)	vector of mean values of uncertain variables
SX	(REAL)	vector of standard deviations of uncertain variables
VP	(REAL)	matrix with 10 rows and N columns
IRHO	(INTEGER)	correlation control parameter IRHO = O : no correlations between X - variables IRHO = 1 : correlations permitted
COV	(REAL)	matrix with NC rows and NC columns For IRHO = O ,COV will not be used For IRHO = 1 user has to give the correlation coefficients in the matrix. Only the lower triangle is used.
NC	(INTEGER)	dimension of the matrix COV For IRHO = O, NC must be >1 For IRHO = 1, NC must be > N
EIVEC	(REAL)	matrix with NE rows and NE columns, an auxillary matrix to stop the Eigenvectors which are on EIVEC on output of FORM5 for correlation cases.
NE	(INTEGER)	dimension of EIVEC For IRHO = O, NE must be >1 For IRHO = 1, NE must be > N
V1	(REAL)	control parameter for iteration. Usually it suffices to set V1 =1.0 In case of non-convergence for V1 = 1, try V1 < 1.0.

PARAMETER	TYPE	DESCRIPTION
NAUS	(INTEGER)	print control and unit number parameter. For NAUS > 99 or < 0, all prints suppressed. For 0< NAUS < 98, print to the unit # NAUS
BETA	(REAL)	on input : for BETA = 0 the starting solution on X is set FORM5 to X(i) = EX(i) for BETA > 0 a starting solution is expected on X(i), = 1, N on output : safety index = (// u-*//)
X	(REAL)	vector of dimension N on input : Possibly initial solution vector on output : coordinates of the checking point in X – space.
U	(REAL)	vector of dimension N on output : coordinates of the checking point in U – space.
ZES	(REAL)	vector of dimension 3. Contains the values ZES (1) = value of the uncertain variable Z ZES (2) = mean of Z ZES (3) = standard deviation of Z Z is the linearisation of g(X) at the checking point
IER	(INTEGER)	error indicator IER = O no error IER > O six digit number on output. The first 3 digits are used to locate the error and its cause. The last 3 digits are used to pass a value IER > O set by the user within the state subroutine in case of an error.

LIST OF PARAMETERS IN FORSYS

I – P / V / M : Input / Vector / Matrix
O – P / V / M : output / Vector / Matrix

PARAMETER	TYPE	DESCRIPTION
M	I – P	Defines number of cuts.
K	I – P	Total number of different components in the system.
N	I – P	Dimension of U – space i.e. number of all U- variables of the system
MMAX 1	I – P	MMAX1 $\geq$ M+1 defines first dimension of KMAT.
KMAX	I – P	KMAX > K defines second dimension (number of columns) of KMAT and ALFMAT and dimension of BETVEC.
NMAX	I – P	NMAX > N defines first dimension of ALFMAT Note: NMAX1, KMAX, NMAX must give the dimensions as defined by the user (statistically) in the calling.
KMAT	I – M	KMAT (MMAX1, KMAX) contains all α - vectors of the system components stored as column vectors. The α - vectors must be normalised i.e. $11\underline{\alpha}11 = 1.0$.
BETVEC	I – V	BETVEC (KMAX) contains the β - values of the K components.
ISTEU	I – P	Controls how FORSYS evaluates P_{fsys} etc.
IPAR	I – P	Controls accuracy of the multinormal integral routine YNORH1
NAUS	I – P	Number of output file, has to be specified for IPRI >0
ICRT	I – P	Channel (unit) for screen monitoring (eg ICRT = O for MS – FORTRAN)

PARAMETER	TYPE	DESCRIPTION
IPRI	I – P	Print parameter For IPRI = 0, no print For IPRI = 1,2,3, increasing amount of print, also depending on ISTEU.
TOL	I – P	FORSYS tries to reduce the numerical effort for TOL>0 on input.
DLOB	O – P	Lower bound to P_{fSYS} for ISTEU=0, else it is set to Zero.
BETALO	O – P	BETALO = - Φ^{-1} (DLOB) FOR ISTEU=0, else it is set to CNORM.
DUB	O – P	Upper bound to P_{fSYS} for ISTEU=0, else it is set to 1.0.
BETAUP	O – P	BETAUP = - Φ^{-1} (DUB) for ISTEU=0, else it is set to – CNORM
PBETA	O – P	Approximation to P_{fSYS} for ISTEU $\neq$ 0, else it is set to 1.0.
BETA	O – P	BETA = -Φ^{-1} (PBETA) for ISTEU $\neq$ O, else it is set to – CNORM **Note**: CNORM is a machine dependent constant defining the numerical range of Φ (u).
MRED	O – P	MRED $\leq$ M on output. It gives the number of cuts FORSYS has actually worked with.
IER	O – P	For IER = O on output no error (fatal or informative) was encountered in FORSYS).
A	_	Working array. An output, a contains further results depending on ISTEU.
IDIM	I – P	IDIM is the dimension of the working array A as declared statistically in the calling program. It must be: a. IDIM $\geq$ (2*K+8) * K+M * (M + K + 3) for ISTEU = - 1 and ISTEU = 0. b. IDIM $\geq$ (3*ID+9) * ID + (N+K+2) + NMAX +

PARAMETER	TYPE	DESCRIPTION
		KMAX with ID=MAX (M,K) for ISTEU >O.