Optimization of Fink and Howe Trusses

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Abstract - *This work deals with weight optimization of five different truss configurations like double fink, triple fink, modified fink, double Howe and triple Howe truss. In order to achieve this, optimization problem is constituted by treating cross sectional areas as the design variable subject to stress, buckling & deflection constraints and it is solved by employing improved sequential linear programming (SLP) technique. Overall process involves usage of three main components. Initially C program is developed for load calculation by considering all the recommendations given in the relevant codes, then for the analysis of the truss, a MATLAB function is utilized. Further, an optimizer based on improved move limit SLP which is available in the form of C program is used to arrive at optimized cross sectional area. Finally, the parametric study is carried out by varying span, height and spacing of truss to get optimum truss configuration for the study area considered and the results are represented in the form of certain guidelines which serves as the preliminary reference for choosing the truss geometry so as to arrive at the most economical design.*

***Key Words*: Sequential linear programming (SLP), Optimization, Fink truss, Howe truss.**

1. INTRODUCTION

Two main responsibilities of any design engineer are to produce a safe & economical design under the action of such loads. Due to the availability of standardized method the former need is met very easily. However the economical need of the project mainly depends on the weight of the materials used. This can be kept in control by selecting the truss configuration that leads to minimum weight under the given set of conditions. The process of selecting such a design point that leads to minimum weight by satisfying all the constraints is called optimization. In addition to meeting the economical needs weight optimization also serves as a move toward better and sustainable green buildings. There are several methods available in the literature for solving such optimization problem. Optimization algorithms are broadly classified into deterministic methods like sequential linear programming (SLP), gradient based algorithms, fully constrained design (FCD), fully stressed design (FSD) and non-deterministic like genetic algorithm (GA), artificial bee colony algorithm (ABC) etc. when these are compared in terms of efficiency in the number of iterations and robustness in finding the optimal solution, it was seen that deterministic method like SLP require less number of iterations to reach optimum design but can manage problems with less than 100 variables effectively [1]. An optimization problem can either have single or multiple objective functions wherein the main purpose is finding cross-sectional area of truss members, such that both the total volume of members and the weighted mean compliance (strain energy) are minimized [2]. It was also suggested that the present multi objective problem can be transformed into an equivalent single objective optimization problem, i.e., a nonlinear programming (NLP) problem by using the Karush-Kuhn-Tucker conditions. In case of topology optimization under multiple load cases can be effectively solved by the sequential linear programming (SLP) method. However SLP performance is always more sensitive to move limits definitions on the design variables. Testing an SLP algorithm where in the move limit definition is considered based on linearization error and employing line search technique on 20 weight minimization problems of truss structures examples showed that there was a reduction in CPU time when compared to normal SLP algorithms [3]. One more such algorithm with improved move limit definition suggested that this improved method worked very well for truss problems and also number of iterations taken for convergence was found to be nearly same or even less than that of other well established methods [4]. Thus improved move limit SLP algorithm can be conveniently be applied for the optimization of truss. Since in 2015 the factor k_4 was introduced in the calculation of design wind load, a study attempted to explore the impact of the k4 factor on A-type steel trusses for different spans and with roof slopes for various building permeability conditions showed that industrial structures experiences marginal decrease of truss forces of about 1% in case of 12m span and a maximum decrease of 7% in case of 24m span [5].

The main aim of the present study is to develop a #C program for the calculation of wind load, design of purlins and to formulate the design problem and employ improved move limit SLP technique suggested by Bhavikatti and Ramkrishnan for determining the optimum cross sectional dimensions of the truss components. Finally to carryout parametric study on various truss configurations like double fink, triple fink, modified fink, double Howe and triple Howe.

2. METHODOLOGY

1.1 Technique Employed

The entire sequence of the steps being carried out primarily starts with the development of #C program for calculation of the design nodal loads by considering all the codal provisions. Once the external loads are been calculated the next step is to study about the analysis of truss and to select a suitable analysis package that can be perfectly coupled with optimizer code. In this study a MATLAB function is used as the analysis package which takes coordinates and connection details with degree of freedom as input and returns back the axial load, maximum nodal deflection and length of each member as the output. Next step would be the formulation of the optimization problem by defining suitable objective function and employ improved move limit SLP algorithm to solve that problem. Since the optimizer code is available in the form of C program and analyzer is in the form of MATLAB function, the connection between these two is ensured using the MATLAB engine API commands. Finally a parametric study is carried out by varying the rise, spacing & span for different types of truss configurations, with an aim to provide certain guidelines to design engineers which further enables them to easily answer the question- "What are the initial dimensions of the trusses to be considered so that the most economical truss configuration is obtained?"

1.2 Study Area

The following table represents the general data considered during the study.

Table -1: Parameters considered for the study

SL. No	Parameter	Considered for study
1.	Location	Dharwad
2.	Class the building	General with 50 years life
3.	Terrain	Category 2
4.	Maximum span	20m
5.	Design wind speed	$33ms^{-1}$
6.	Topography	θ less than 3^o.
7.	Permeability	Medium
8.	Sheeting	AC sheets
9.	Distance from coast	Greater than 125km
10.	Variables for study	Span; Rise; Spacing

3. ASSEMBLING THE DESIGN PROBLEM

Generally, the process of assembling any design optimization problem for any type of structure is resolved into 3 phases as mentioned below:

A) Structural modeling.
B) Optimum design modeling.
C) Optimization algorithm.

Structural modeling is the representation of the process of finding the set of design variables by using objective function and constraints. Optimum design modeling is the process of understanding the parameters involved in the design procedure, so as to decide about the design variables, objective function & constraints. These 3 phases are dealt in detail in the following section.

3.1 Structural Modeling

Before moving on further to the discussions of the assembling the optimization problem it is very much important to know the general format of the problem definition. It may be stated as follows:

Minimize f(x)
Subject to $g_j(x) \leq 0$; for j=1, 2, 3……p

Where,
f(x) is objective function &
$g_j(x)$ are inequality constraint.

3.2 Structural Modeling

3.2.1 Problem Statement

A minimum weight truss is desired, for which the conditions of safety are as follows:

- The maximum stresses developed under the action of the loads, in no case shall be more than the permissible stress.
- The maximum nodal deflection at the centre of the truss shall not be more than span/250.
- The maximum buckling under the action of compressive load shall not exceed the permissible buckling value.
- The cross sectional areas of the members must be within the following limits:
  45x45x4 ≤ Cross section ≤ 200x200x25

3.2.2 Definition of design variables

One cannot consider cross section area of all the truss members as design variable, because practically such a design would lead to much wastage of material as well as hard to assemble at the site. Thus members are grouped as shown in table below and the cross-section area corresponding to the member carrying the maximum load in that particular group is selected as design variable.

Table -2: Member groups and its designation

SL. No	Groups	Area
1	Top chord members	A1= x[1]
2	Bottom chord members	A2= x[2]
3	Vertical members	A3= x[3]
4	Diagonal members	A4= x[4]

3.2.3 Definition of Optimization Criterion

For a given problem there can be an infinite feasible designs, few of them are better than the others. Now the question arises that, how do we say that the considered point is better than others? For this, we must have a condition that associates a quantifiable term with each design. In this case minimization of weight is attributed as such condition. Weight of the truss is assembled with the equation given below;

$$f(x) = \rho \sum_{i=1}^{n} A_i L_i \qquad (1)$$

i.e. $f(x) = \rho^*(A_1L_1+ A_2L_2+........+ A_nL_n)$

Here, ρ=Density of steel = 78.5kN/m³; n=Number of members in a truss.

3.2.4 Definition of constraints

a) <u>Buckling Constraints</u>

Maximum effective slenderness ratio of any compression member should not exceed the permissible value, hence we have;

$$g[i] = \frac{(kL[i]/r[i])_{prov}}{(kL[i]/r[i])_{per}} - 1 \le 0 \qquad (2)$$

Maximum slenderness ratios are considered as per table 3 of IS 800:2007 and in the case of bolted, riveted or welded trusses and braced frames, the effective length (kL), of the compression members shall be taken as 0.7 to 1.0 times the distance between centers of connections, depending on the degree of end restraint provided.

Since design variable is considered to be continuous, even though it is discrete by nature. Hence A-R curve is used to find the values of minimum radius of gyration for any given value of area. The following equation is obtained by considering best fit of area versus radius of gyration graph;

$$r[i]_{vv} = 6.021 + 0.0087x[i] - 1.0344\times10^{-6}x[i]^2 + 9.809\times10^{-11}x[i]^3 - 5.076\times10^{-15}x[i]^4$$

b) <u>Stress Constraints</u>

Maximum stress developed in any member should not exceed the permissible limits specified in the code. Hence we have;

$$g_i = \frac{\sigma[i]}{\sigma[i]_{per}} - 1 \le 0 \qquad (3)$$

Here;

$$\sigma[i]_{act} = \frac{F[i]}{x[i]} = \text{Actual stress of } i^{th} \text{ group}$$

$$\sigma[i]_{per} = \frac{f_y}{\gamma_{mo}} = \text{Permissble axial tensile stress of } i^{th} \text{ group}$$

$$\sigma[i]_{per} = f[i]_{cd} = \text{Permissble axial compression stress of } i^{th} \text{ group}$$

Maximum permissible compressive stress;

$$f[i]_{cd} = \frac{(f_y/\gamma_{mo})}{\varphi[i] + [\varphi[i]^2 - \lambda[i]_e^2]^{0.5}} = f_y\chi/\gamma_{mo} \le f_y/\gamma_{mo} \qquad (4)$$

Where,

$$\varphi[i] = 0.5 + [1 + \alpha(\lambda[i]_e - 0.2) + \lambda[i]_e^2]$$

Here, ∝ is imperfection factor which is got from table 9 of IS 800-2007 i.e. for buckling class "c" ∝=0.49.

Equivalent slenderness ratio is given by;

$$\lambda_e[i] = \sqrt{k_1 + k_2\lambda[i]_{vv}^2 + k_3\lambda[i]_{\varphi}^2} \qquad (5)$$

$$\lambda[i]_{vv} = \frac{L[i]/r[i]_{vv}}{\varepsilon\sqrt{\frac{\pi^2 E}{250}}} \quad \text{and} \quad \lambda[i]_{\varphi} = \frac{(b[i]_1 + b[i]_2)/2t[i]}{\varepsilon\sqrt{\frac{\pi^2 E}{250}}}$$

Here,

$b[i]_1$, $b[i]_2$, $t[i]$ are the geometric properties of the section considered & corresponds to widths of the leg of angle and thickness of legs respectively. k_1, k_2, k_3 are constants depending on end conditions are taking from IS: 800-2007.

c) <u>Deflection Constraints</u>

Maximum deflection of the truss under the applied load should not be greater than the permissible deflection value, thus we have;

$$g_i = \frac{U_{max}}{U_{per}} - 1 \le 0 \qquad (6)$$

Here, the permissible deflection value may be considered as per table 6 of IS 800: 2007 and maximum nodal deflection is directly taken from MATLAB function.

3.3 Optimization Algorithm

It is based on improved move limit method of sequential linear programming, which is written in C language (which was originally written in FORTRAN language by Dr. S. S. Bhavikatti and then converted to C language by Mamatha Rao). The improvements mainly deal with the steering design vector from infeasible, to avoid oscillation problem and to carryout quadratic interpolation in an efficient manner.

4. RESULTS AND DISCUSSIONS

4.1 Simple Fink Truss

1) For 6m span

In order to decide best rise for 6m span simple fink truss, the rise is varied by considering various spacing like 2m, 3m, 4m & 5m. Results show that 0.9m rise is found to give the minimum weight of 0.00581kN/m², with 2m spacing and hence considered to be best. Similarly rise of 1.1m, 1.2m & 1.3m are observed to be best for 3m, 4m & 5m spacings respectively.

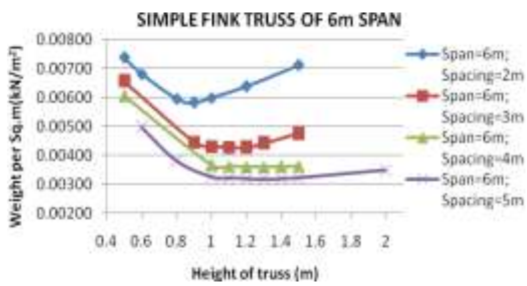


Chart 1: Graph of rise variations of 6m simple fink

2) For 8m span

Chart 2 is used to select the best rise for 8m span simple fink truss. The result shows that the rise value of 0.9m is best, as it yields a minimum weight of 0.00974kN/m² when compared to other rise values, with 2m spacing. Similarly 1.1m, 1.5m, 1.7m rises are observed to be best for 3m, 4m & 5m spacing.

Chart 2: Graph of rise variations of 8m simple fink

3) For 10m span

The following plot shows that the variations in height or rise of 10m simple fink truss. By looking at the value of weight per m² it can seen that 0.8m rise gives minimum weight of 0.01653kN/m² for 2m spacing and hence called as best. In the same manner 1.2m, 1.4m & 1.7m rises are best for the corresponding values of 3m, 4m & 5m spacings.

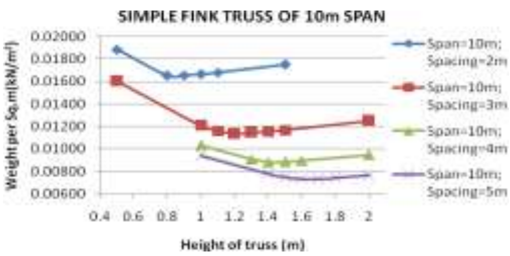


Chart 3: Graph of rise variations of 10m simple fink

4) For 12m span

Following chart 4 shows the variation of rise for 12m simple fink truss. The spacings considered here are 2m, 3m, 4m & 5m. It can be easily seen that 0.8m rise gives minimum weight of 0.02399kN/m², in case of 2m spacing, making it as the best rise. Similarly rise of 1.3m, 1.6m & 1.8m rises are best for 3m, 4m & 5m spacings respectively.

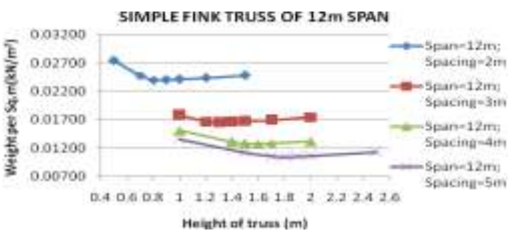


Chart 4: Graph of rise variations of 12m simple fink

From the above discussion one can note that, for 6m span simple fink truss, a rise of 0.9m to 1.3m serves the purpose, for all considered spacing. Further observing on similar line, for 8m &10m span, best height varies from 0.9m to 1.7m and for 12m span, it varies from 0.8m to 1.8m.

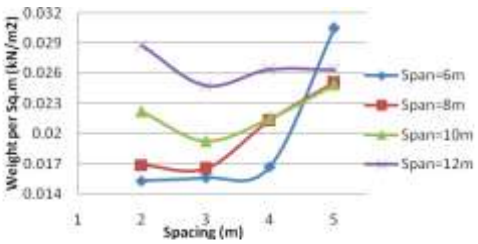


Chart 5: Graph of spacing variations of simple fink

Also it can be seen from figure 5 that, the spacing of 2m proves to be best till 8m span while 3m spacing is best for span range over 8m and up to 12m.

4.2 Double Fink Truss

1) For 10m span

Chart 6: Graph of rise variations of 10m double fink

Above plot shows the changes in height in case of 10m double fink. The various spacings checked are 2m, 3m, 4m & 5m.The results shows that the rise of 2m, 2m, 2.1m & 2.3m are best in case of 2m, 3m, 4m & 5m spacing respectively as they corresponds to minimum weight of 0.00349, 0.00277, 0.00248 & 0.00234kN/m² respectively

2) For 12m span

The following chart 7 shows the variation of height for 12m double fink truss. The spacings considered are 2m, 3m, 4m & 5m. It can be clearly seen by comparing the value of weight per m2 value that the rise of 1.9m yields 0.00443kN/m² of weight for 2m spacing. Considering in the similar manner rise 2m, 2.1m & 2.4m are best for 3m, 4m & 5m spacings respectively.

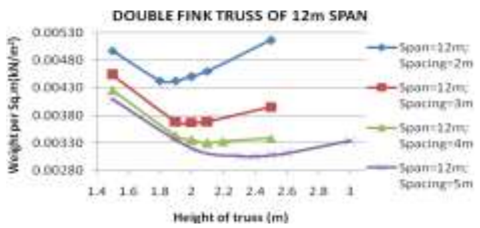


Chart 7: Graph of rise variations of 12m double fink

3) For 15m span

Chart 8 shows the variations in the rise that are being checked during the process of finding the best height for 15m double fink truss. By comparing the values of weight per m² it can be seen that the rise of 2.4m yields the minimum weight of 0.00539kN/m² for 3m spacing. Moving on the similar lines rise of 2.5m, 2.5m & 2.8m are observed to be best for 3m, 4m, 5m & 6m spacing respectively.

Chart 8: Graph of rise variations of 15m double fink

4) For 18m span

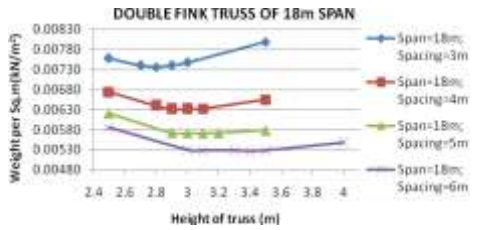


Chart 9: Graph of rise variations of 18m double fink

In order to choose the best rise for 18m double fink truss, one can observe from the following figure 9 that the rise of 2.8m, 2.9m, 3.1m & 3.4m are best in case of 3m, 4m, 5m & 6m spacings respectively as they corresponds to minimum weight of 0.00884, 0.00757, 0.00685 & 0.00632kN/m^2.

The above discussion shows that, the rise of 2m to 2.3m is found to yield minimum value of weight/m^2 for 10m span. Similarly, a rise of 1.9m to 2.4m serves as best for 12m span, while a rise of 2.4m to 2.8m for 15m span and a rise of 2.8m to 3.4m for the span of 18m.

One can also see from the above plot that the spacing of 3m is best till 15m span and beyond which a spacing of 4m is best till 18m span.

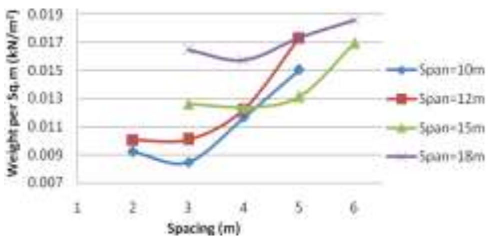


Chart 10: Graph of spacing variations of double fink truss.

4.3 Compound Fink Truss

1) For 12m span

Chart 11 shows the variation of the height of truss for 12m compound fink truss. The rise of 1.9m yields least value of weight of about 0.00545kN/m^2 and becomes best for 2m spacing. Similarly rise of 2m is best for 3m spacing while 2.3m rise is best for both 4m & 5m spacing.

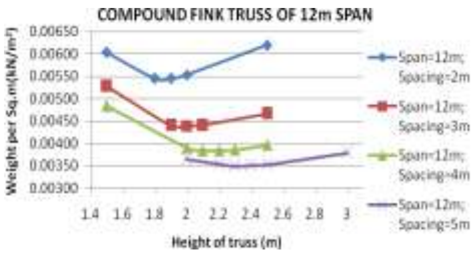


Chart 11: Graph of rise variations of 12m compound fink

2) For 15m span

In order to decide the best rise for 15m compound fink truss, the rise is varied as shown the figure below. The observations show that 2.4m rise is best for 3m spacing with the minimum weight of 0.00616kN/m^2. Similarly rise of 2.5m, 2.7m & 2.8m are best for the corresponding spacings of 4m, 5m & 6m respectively.

Chart 12: Graph of rise variations of 15m compound fink

3) For 18m span

Chart 13: Graph of rise variations of 18m compound fink

Above plot shows the variation of height for 18m compound fink truss. The spacings considered for the study are 3m, 4m, 5m & 6m. The results show that the rise of 2.9m yield least value of weight of around 0.00850kN/m^2 of floor area for 3m spacing while the rise of 3m is seen to be best for all other considered spacings

4) For 20m span

The following plot is used for choosing the best rise for 20m compound fink truss. The spacings considered are 3m, 4m, 5m & 6m.One can easily see that the rise of 3.1m is best for both 3m and 4m spacing as it gives minimum weight of 0.01100 kN/m^2 and 0.00892kN/m^2. While the rise of 3.4m and 3.6m are best for 5m & 6m spacing respectively.

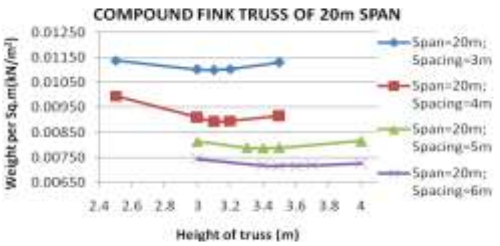


Chart 14: Graph of rise variations of 20m compound fink

From above discussions it can be observed that, height of 1.9m to 2.3m is found to be best for 12m span while 2.4m to 2.8m rise is found to be best for 15m span. Further it can be seen that the height of 2.9m to 3m seems to be best for 18m span and height of 3.1m to 3.6m serves best for 20m span.

One can also observe from figure that, the spacing of 3m is best for spans up to 15m while a spacing of 4m is best a for spans beyond 15m.

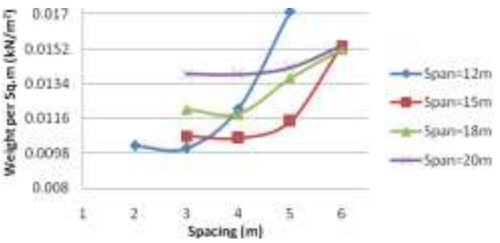


Chart 15: Graph of spacing variations of double fink truss

4.4 Double Howe Truss

1) For 6m span

Chart 16 shows the variation of the rise in case of 6m double Howe truss. By comparing value of weight per m^2 one can see that the rise of 0.9m, 1m, 1.1m, 1.2m are best for the corresponding spacings of 2m, 3m, 4m & 5m respectively as they yield the minimum weight of 0.00679, 0.00500, 0.00418 and 0.00366kN/m^2 respectively.

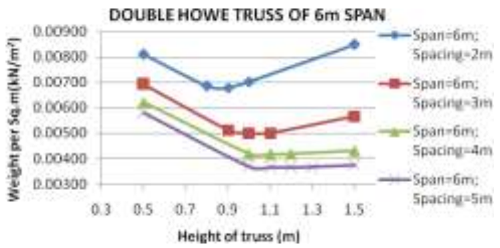


Chart 16: Graph of rise variations of 6m double Howe

2) For 8m span

Following is the plot showing the changes in height that are considered for 8m double Howe truss in order to choose the best rise. Result shows that the rise of 0.9m yields least value of weight of about 0.0100kN/m^2 of floor area. Similarly rise of 1.1m, 1.3m & 1.5m are observed to be best for 2m, 3m, 4m & 5m spacings respectively.

Chart 17: Graph of rise variations of 8m double Howe

3) For 10m span

Chart 18 shows the variations of rise that are being checked in case of 10m double Howe truss. For this the various spacings considered are 3m, 4m, 5m & 6m. The results show that rise of 1.2m gives the least value of weight of about 0.01048kN/m^2, for 3m spacing. Similarly rise of 1.5m, 1.6m & 1.7m are found to be best for 4m, 5m & 6m spacings respectively.

Chart 18: Graph of rise variations of 10m double Howe

It can be observed from the previous discussion that, the rise of 0.9m to 1.2m serves best for 6m span, while it varies from 0.9m to 1.5m for 8m span. Similarly the height value of 1.2m to 1.7m is found to be best for 10m span.

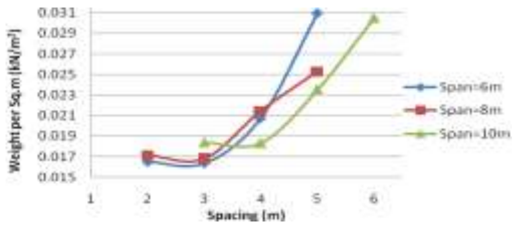


Chart 19: Graph of spacing variations of double Howe

From above chart, one can also observe that the spacing of 3m is best for spans up to 10m while beyond that 4m spacing proves to be best at 10m span.

4.5 Triple Howe Truss

1) For 10m span

Following is the figure that shows the variations in height that are being considered for the study in case of 10m span triple Howe truss. The results indicate that the rise value of 1.7m seems best because of giving minimum weight of 0.00485kN/m^2, when the spacing is 3m. However rise value of 1.9m seems best for all other three spacings those are 4m, 5m & 6m.

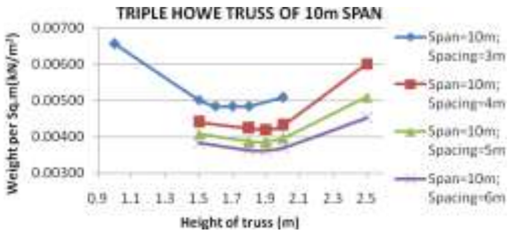


Chart 20: Graph of rise variations of 10m triple Howe

2) For 12m span

Chart 21: Graph of rise variations of 12m triple Howe

Chart 21 shows the variation of rise and spacing in case of 12m triple Howe truss. This table is used to find the best rise for the given span and spacing values. The various spacings considered here are 3m, 4m, 5m & 6m. The result shows that the best rise in case of all considered spacings is 1.9m as it yields minimum weight of 0.00636, 0.00561, 0.00514 & 0.00480kN/m².

3) For 15m span

The rise of the truss is varied in order to choose the best rise for given span and spacing as shown in the figure. It shows the rise variations for 15m triple Howe truss. The results shows that the rise of 2.2m yield minimum weight of 0.00968kN/m² for 3m spacing while rise of 2.3m seems best in case of 4m spacing. Similarly the rise of 2.4m is best for both 5m & 6m spacings.

Chart 22: Graph of rise variations of 15m triple Howe

4) For 18m span

Chart 23: Graph of rise variations of 18m triple Howe

Chart 23 is used in order to choose the best rise in case of 18m triple Howe truss. The various spacing considered here are 3m, 4m, 5m & 6m. the results clearly shows that with minimum weight per m² value the rise of 2.4m appears to be best with minimum weight of 0.01325kN/m², when spacing is 3m. Similarly the best rises are 2.6m, 2.7m & 2.8m in case of 4m, 5m & 6m spacings respectively.

It can be inferred from above discussions that the height of 1.7m to 1.9m is found to be optimum for 10m triple Howe truss. Similarly height of 1.9m is best for 12m span for all considered spacing values. Rise of 2.2m to 2.4m is observed to be best for 15m span while a rise of 2.4m to 2.8m is found to be best in case of 18m span.

It is also observed from chart 24 that, the spacing of 3m proves to be best till 15m span while 4m spacing proves best for spans between 15m to 18m.

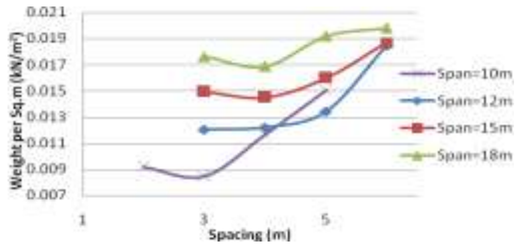
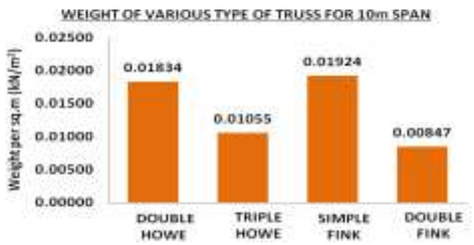


Chart 24: Graph of spacing variations of triple Howe

For 6m span, out of simple fink truss and double Howe truss, simple fink truss gives least weight of 0.0153112kN/m² and proves to be best. In case of 8m span simple fink truss gives lesser weight of 0.01652kN/m² when compared to double Howe truss. From the following diagram one can see that in case of 10m span double fink truss gives the least weight of 0.008468kN/m².Hence from 8m to 10m one can use double fink truss and from 12m span till 20m span compound fink truss gives the least weight of 0.01006kN/m², 0.01059kN/m² and 0.0118364kN/m² for 12m, 15m and 18m span respectively.



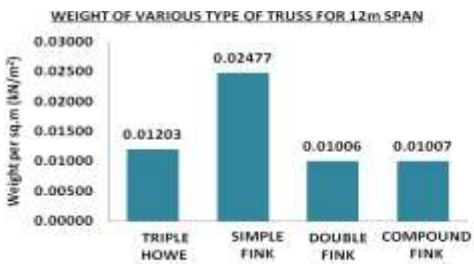


Chart 25: Graph showing weight of different types of truss for a given span.

5. CONCLUSIONS

The following are certain guidelines which are based on the discussion done so far, for selecting the truss geometry in the considered study area in order to get the minimum weight design, which indirectly helps to achieve economy.

- In case of simple fink truss, in order to reach optimum design of cross sectional area, one can use span to spacing ratio of 3 to 4 and span to height ratio as 6 to 9.
- In case of double fink truss configuration, one can use span to spacing ratio of 3 to 5 and span to rise ratio of 5 to 7 to get minimum weight truss for given value of span.
- In case of compound fink, it is favourable to use span to spacing ratio of 4 to 5 & span to rise ratio of 6 to 7, so as to reach best and minimum weight truss.
- In case of double Howe truss one can use span to spacing ratio of 2 to 3 and a span to rise ratio of 6 to have a optimum design of cross sectional area.
- In case of triple Howe truss, one can use a span to spacing ratio of 3 to 5 and a span to rise ratio of 5 to 7 to get minimum weight optimized design.

The important points that are observed during the process of comparison between different types of trusses for a considered span are mentioned as follows;

i. Triple for 6m span among simple fink truss and double Howe truss, one can use simple fink truss with span to spacing ratio of 3 and span to rise ratio of 7.

ii. For 8m span among simple fink truss and double Howe truss, one can use simple fink truss with span to spacing ratio of 3 and span to rise ratio of 8.

iii. Up to 12m span one can use double fink truss with span to spacing ratio of 4 and span to rise ratio of 5.

iv. From 12m to 18m one can use compound fink truss with span to spacing ratio of 4 to 5 & span to rise ratio of 6.

v. It can be observed that, the spacing of 3m is best up to 12m span while spacing of 4m for the spans over 12m span.

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