Optimum Design of Fan, Queen and Pratt trusses

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Abstract - *In this study, weight optimization of 5 truss configurations like double fan, triple fan, modified queen, double Pratt and triple Pratt trusses is done with the help of SLP technique. The problem is formulated by considering stress, buckling & deflection constraints with the cross section area as the continuous design variable. While the loads on the each panel point of the truss are calculated by using the C-program developed as per latest IS codes, the axial force in each truss member due to design load is estimated using a MATLAB function. The problem is optimized with the aid of C-program based on improved move limit method of SLP. The dynamic connection is ensured between the C language & MATLAB, so as to have a real time interaction. Once the optimized cross sectional areas are got, an effort is made to understand effect of parameters like span of truss, spacing of the purlins, spacing of truss & height of truss on the process of selecting best design in the considered study area.*

Key Words: **Sequential linear programming (SLP), Optimization, Fan truss, Queen truss, Pratt truss.**

1. INTRODUCTION

Any truss design problem is a non linear problem & can have many numbers of acceptable designs, but the one which is optimum will satisfy both structural and economical needs. This process of selecting the best design under the given situations is called as optimization. For arriving at such optimum design, computer based program serves as the tool. Due to introduction of higher and efficient forms of optimization techniques, the structures are getting lighter, cheaper and stronger. Therefore this type of approach to achieve the design improvements is becoming crucial part in current engineering industry.

Optimization techniques can be broadly classified into two groups like local & global. Local algorithms such as SLP & sequential quadratic programming (SQP) are to be used in favour over global algorithms like genetic algorithm & particle swarm method for optimizing non linear problems unless it is not strictly viable to use an efficient local search method [1] & it was also suggested to use multi start approach to take care of local optimum problem in SLP. A comparative study of 11 mathematical programming codes based on two factors i.e. reliability & efficiency, showed that SLP is quite robust & efficient method with simpler implementation due to absence of any inherent round-off error which is main problem in more advanced algorithms

[2]. Another similar comparative study of the performance of 8 optimization algorithms through the development of computer code showed that for small & medium group problems involving 3 to 60 member trusses, the methods like Sequential unconstrained minimizations technique (SUMT), SQP & SLP can be satisfactorily used [3]. Whenever we are dealing with design of the steel truss one the most important factors to be looked for is buckling conditions. A 20% improvement in the results and also significant time savings is observed when local buckling is considered for optimization of truss by using SLP [4]. It is not only these geometric parameters like span, spacing, rise that effects the selection of best truss configurations, there are other factors too. It was observed that there is about 35% increase in the weight of truss when joints were treated as rigid joined instead of pinned and also the purlins at locations other than panel points causes significant increase in top chord members thus requiring heavier sections [5]. Parametric studies of Pratt roof truss configuration showed that best results can be arrived with span to height ratio as 5 & span to bays ratio as 3 [6]. Even though the study on Pratt truss is already been done, need for the present study arises from the fact that, there has been a recent amendment in the codal provisions for wind load calculation in IS 875 (Part 3)-2015.

The main objective of this work is to formulate the optimization problem & employ improved move limit SLP technique suggested by Bhavikatti and Ramkrishnan for optimization of the truss in order to carryout parametric study and come up with certain guidelines for selecting the initial geometry of different types of trusses considered. The next section presents description of the employed methodology, after which the formulation of problem and its implementation are detailed. The final section presents the conclusions.

2. METHODOLOGY

1.1 Overview of the Various Steps

The entire step is to prepare the #C program for the calculation of maximum load acting on each panel point by considering the various load combination. Any truss design primarily requires the analysis of truss hence to do that it is necessary to select an analysis tool, that can be easily called from within the #C language and it must be able to delivery axial force in the truss members and maximum nodal

deflection as the output. Thus to insure this, in the current study a MATLAB function is used.

Next step is to formulate optimization problem and to code it into a #C program. Output from such a program would be weight of the truss. Further to carryout parametric study, the comparison is made based on the value of weight per square meter of floor area. The following figure shows various phases involved.
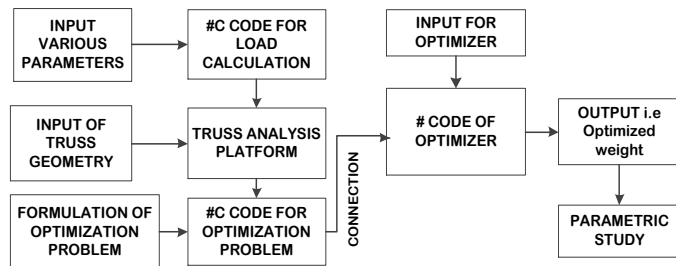

Fig-1: Various phases involved the study.

1.2 Study Area

The following data is considered for the study of all the five types of truss configuration.

- Location of the building: Dharwad.
- Basic wind speed: $33ms^{-1}$.
- Design life: 50 years.
- Terrain: Category 2.
- Maximum span: 20m.
- Sheeting Material used: AC sheets.
- Height of the building: 10m.
- Topography: θ less than 3°.
- Permeability: Medium.
- Load combinations;
  COMBO 1= 1.5(Dead Load+ Live Load)
  COMBO 2= 0.9(Dead Load) + 1.5(Wind Load)
  COMBO 3= 1.2 (Dead Load+ Live Load+ Wind Load

3. PROBLEM FORMULATION

3.1 Objective Function

Weight minimization is selected as objective function.

$$f(x) = \rho \sum_{i=1}^{n} A_i L_i \qquad (1)$$
$$f(x) = \rho * (A_1 L_1 + A_2 L_2 + \ldots + A_n L_n)$$

Where,
  A_i= Area of member;
  L_i=Length of member;
  ρ=Density of steel = 78.5kN/m³;
  n=Number of members in a truss.

The members are grouped into 4 groups because it would be an impractical situation if cross sectional area of all the members is considered as the design variable due to increased wastage of material thus sectional area corresponding to the member carrying maximum load in that particular group is selected as design variable.

Even though the cross section area in case of truss design problem is a discrete variable, in the present study it is considered as the continuous variable and AR curve (i.e. plot of area v/s radius of gyration) is used to evaluate radius of gyration corresponding to any area while designing the compression member.
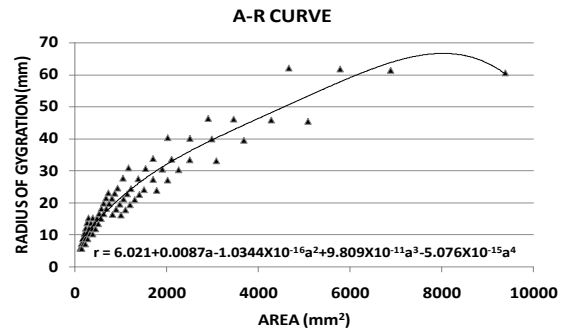

Fig-1 Plot between area along x axis & radius of gyration along y axis

3.2 Constraints

Depending upon the safety conditions the following constraints are defined and in order to avoid any discrepancy caused due the units, all constraints are represented in normalized form. Such forms of constraints are unit-less, negative quantities. It should be noted that any point which satisfies all the considered constraints is said to be a feasible point.

3.2.1 Stress Constraint

The stress in any member should not exceed the maximum permissible value. Since truss members can carry either tensile force or compressive force, this constraint is meant to take care of both the situations.

$$g_i = \frac{\sigma[i]}{\sigma[i]_{per}} - 1 \leq 0 \qquad (2)$$

Here;

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

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

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

The permissible compressive stress is calculated using equations stated as below;

$$f[i]_{cd} = \frac{(f_y/\gamma_{mo})}{\varphi[i] + [\varphi[i]^2 - \lambda[i]_e^2]^{0.5}} = f_y \chi/\gamma_{mo} \leq f_y/\gamma_{mo} \qquad (3)$$

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.

Note: IS 800-2007 suggests that when the single angle is loaded concentrically in compression, the design strength may be evaluated using Fig.8 of IS 800-2007, choosing class c curve. However, when the single angle is loaded eccentrically through one of its legs, the flexural torsion buckling strength may be evaluated using an equivalent slenderness ratio (λ_e).

Equivalent slenderness ratio=

$$\lambda_e[i] = \sqrt{k_1 + k_2 \lambda[i]_{vv}^2 + k_3 \lambda[i]_\varphi^2} \quad (4)$$

Here;

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

Here,

- L[i] = Centre-to-centre length of ith member.
- $b[i]_1$, $b[i]_2$= Width of two legs of angle for i^{th} member
- t[i] = Thickness of the leg of angle given for i^{th} member.
- $r[i]_{vv}$= Radius of gyration corresponding to area x[i] and evaluated from A-R curve as;

$$r[i]_{vv} = 6.021 + 0.0087x[i] - 1.0344 \times 10^{-6} x[i]^2 + 9.809 \times 10^{-11} x[i]^3 - 5.076 \times 10^{-15} x[i]^4$$

3.2.2 Deflection Constraints

Maximum deflection of the truss under the applied load should not be greater than the permissible deflection value.

$$g_i = \frac{U_{max}}{U_{per}} - 1 \leq 0 \quad (5)$$

Here,

U_{max} is maximum deflection taken from MATLAB function;
U_{per} is permissible deflection= Span/240;

3.2.3 Buckling Constraints

In case of compressive member if it is slender then, member undergoes sideward deflection of the member and subsequent failure at the stress levels which are well below the characteristic strength of the material. Such a failure is called as buckling failure. To keep check on such a failure buckling constraints are imposed. i.e. Maximum effective slenderness ratio of any compression member should not exceed the permissible value.

$$g_i = \frac{(kL[i]/r[i])_{prov}}{(kL[i]/r[i])_{per}} - 1 \leq 0 \quad (6)$$

Here maximum permissible slenderness ratio values are taken as per table 3 of IS 800-2007. In order to evaluate effective length cl. 7.2.4 IS 800-2007 is referred and according to that in the case of members of trusses, buckling in the plane perpendicular to the plane of the truss, the effective length, kL shall be taken as the distance between the centers of intersection.

3.2.4 Side Constraints

In the study equal angles are considered for all the member groups and sections with minimum thickness of 4 mm are been used. ISA 45x45x4 mm & ISA 200x200x25 mm are used as the smallest & largest section.
Thus,

"Optimum design of truss is formulated as finding 4 cross-sectional areas with four stress constraints, four buckling constraints & one deflection constraint"

4. RESULTS AND DISCUSSIONS

4.1 Double Fan Truss

1) For 10m span

Chart 1 shows variation of rise in case 10m double fan truss by considering all values of spacing (i.e. for 2m, 3m, 4m & 5m). The results show that the rise of 1.6m with 0.01256kN/m² weight is the least weight possible when the spacing is 2m. Similarly one can see that the rise of 1.6m, 1.7m, 1.7m gives the least value for weight when the spacings are correspondingly 3m, 4m & 5m.
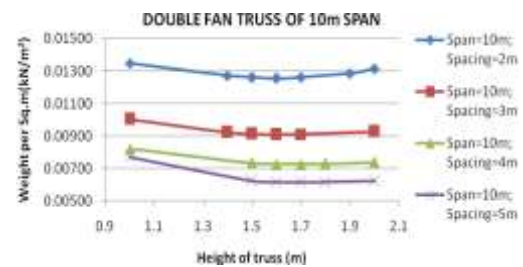

Chart 1: Plot of weight per m² v/s rise of 10m double fan

2) For 12m span

Chart 2 shows the plot of variation of rise as well as spacing v/s weight, for 12m double fan truss. The spacing considered is 2m, 3m, 4m & 5m. It can be clear observed from the graph that 1.7m rise gives lesser weight of about 0.01880kN/m² when the spacing is 2m, while the rise value of 1.9m gives lesser weight for all other spacing values.

Chart 2: Plot of weight per m² v/s rise of 12m double fan

3) For 15m span

Chart 3 shows plot of variation of rise and spacing v/s weight for 15m double fan truss. It can be seen that the rise

of 1.9m is best with least weight of 0.02911kN/m², when the spacing is 2m. Similarly the rise of 2m is found to be best for 3m spacing. Finally one can see that, in case of both 4m and 5m spacing the best rise is 2.3m.
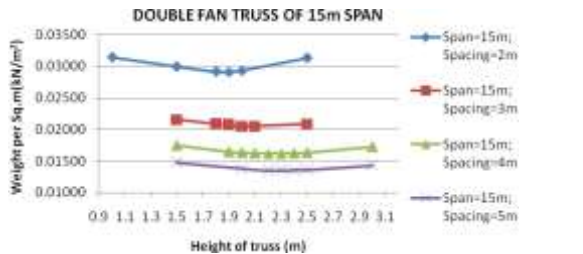

Chart 3: Plot of weight per m² v/s rise of 15m double fan

4) For 18m span

Chart 4: Plot of weight per m² v/s rise of 18m double fan

Chart 4 shows the plot of variation of rise and spacing v/s weight for the 18m double fan truss with 2m, 3m, 4m & 5m spacing. It can be observed that the rise of 2m is best because it yields a least weight of 0.04046kN/m², when the spacing is 2m. Similarly the best rises are found to be 2.5m, 2.6m, and 2.7m when the spacings are 3m, 4m & 5m respectively.

It may be inferred from the above discussion that for 10m span best rise varies from 1.6m to 1.7m for all considered spacing. Similarly it lies between 1.7m to 1.9m for 12m span, 1.9m to 2.3m for 15m span & 2m to 2.7m for 18m span.

The best spacing for the considered span can be known by comparing the total weight of truss including purlin weight and from chart 5, it may be seen that the spacing of 3m gives minimum value of weight/m² until the 15m span while 4m spacing seems be best beyond 15m span.
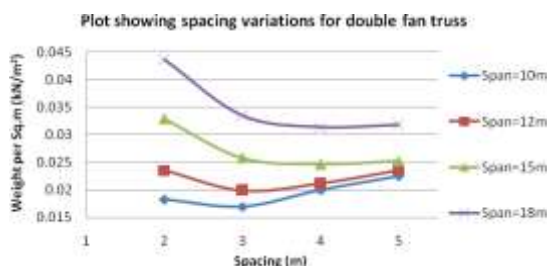

Chart 5: Plot of spacing v/s weight of double fan truss

4.2 Triple Fan Truss

1) For 12m span

Chart 6 shows the plot of variation of rise and spacing versus weight in case of 12m span triple fan truss, it helps to arrive at the best value of rise for given span and spacing. It can be seen from the results that the rise of 1.2m is found to best with weight of 0.00975kN/m², when the spacing is 2m. Similarly rise of 1.4m, 1.7m, 1.9m are best when the corresponding spacing are 3m, 4m & 5m.

Chart 6: Plot of weight per m² v/s rise of 12m triple fan

2) For 15m span

Chart 7: Plot of weight per m² v/s rise of 15m triple fan

Chart 7 shows plot of rise versus weight for 15m triple fan truss. The spacing 3m, 4m, 5m & 6m are considered here. The result shows that the rise of 1.6m leads to the least value of weight as 0.01150kN/m², when the spacing is 3m and thus 1.6m is best for 15m span and 3m spacing. Similarly the best values of rise are 1.9m, 2m, 2.1m for 4m, 5m & 6m spacing respectively.

3) For 18m span

One can arrive at the optimum rise as shown in the plot below, by varying the rise and studying the respective variation of weight/m² value. Here the spacing considered is 3m, 4m, 5m & 6m. The results shows that the rise of 1.9m, 2.1m, 2.3m, 2.4m were observed to be best for 3m, 4m, 5m & 6m spacing respectively because they yield least value of weight under given circumstances.
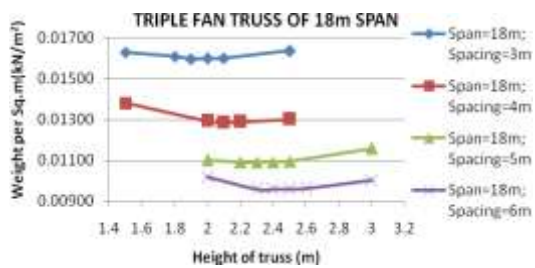
Chart 8: Plot of weight per m² v/s rise of 18m triple fan

4) For 20m span

Chart 9 shows the plot of variation of rise and corresponding variation of spacing as 3m,4m,5m & 6m in order to find a 20m triple fan truss which gives least value of weight /m² value. The result shows that the rise of 2.2m is best for 3m spacing with 0.01913kN/m² weight. Similarly 2.3m, 2.5m, 2.6m rises are best when the spacing is 4m, 5m & 6m respectively.

Chart 9: Plot of weight per m² v/s rise of 20m triple fan

Chart 10: Plot of spacing v/s weight of triple fan truss

From the above discussion it can be observed that in case of triple fan truss for 12m span, the best height varies from 1.2m to 1.9m. Similarly it varies from 1.6m to 2.1m for 15m span, 1.9m to 2.4m for 18m span & 2.2m to 2.6m for 20m span.

In order to decide the best possible spacing, the truss weight along with the weight of purlin is considered. From chart 10, it may be observed that the spacing of 3m is best until the span of 15m, as it gives minimum value of weight/m². However the spacing of 4m seems best beyond 15m span.

4.3 Modified Queen Truss

1) For 10m span

Chart 11 shows the plot of variation of rise and spacing v/s weight for 10m modified queen truss for corresponding variation of spacing of 2m, 3m, 4m & 5m. The results shows that the rise of 1.3m is observed to be best for 2m spacing as it leads to minimum weight of 0.01008kN/m², while the best rise is 1.6m for all the spacings considered.
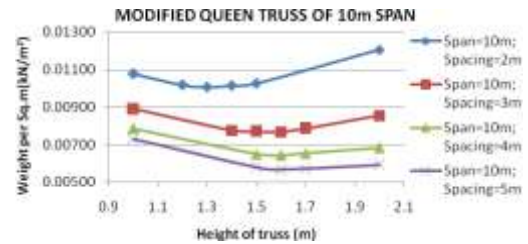

Chart 11: Plot of weight per m² v/s rise of 10m modified queen truss

2) For 12m span

In order to determine the optimum value of the rise for 12m modified queen truss. The rise of 1.4m gives the least value of weight of about 0.01486kN/m², in case of 2m spacing while the rise of 1.7m happens to be best when spacing is 3m and 4m. Finally the rise of 1.9m is observed to be best when the spacing is 5m.

Chart 12: Plot of weight per m² v/s rise of 12m modified queen truss

3) For 15m span

Chart 13: Plot of weight per m² v/s rise of 15m modified queen truss

Chart 13 shows the plot of variation of rise v/s weight, for the 15m span modified queen truss with the corresponding variation of spacing. The results observed shows that the rise of 2m is best when the spacing considered is 3m while the rise of 2.2m is found to be best

for both 5m & 6m spacing because it gives minimum weight of 0.01124kN/m² & 0.00980kN/m² respectively.

4) For 18m span

Chart 14 shows best rise value for 18m span modified queen truss. It is done by varying the rise and spacing in range of 2m to 3m & 3m to 6m respectively. The results shows that the rise of 2.4m proves to be best with the weight of 0.02260kN/m² for 3m spacing while the rise of 2.5m is found to best for the spacing of 4m and 5m. Similarly a rise of 2.6m yields the least value of weight i.e. about 0.01327kN/m² when the spacing is 6m.

From all of the above discussion it can be said that, the best rise value varies from 1.3m to 1.6m in case of 10m span modified queen truss. Similarly, it varies from 1.4m to 1.9m for 12m span, 2m to 2.2m for 15m span & 2.4m to 2.6m for 18m span.

Chart 14: Plot of weight per m² v/s rise of 18m modified queen truss

Finally in order to check for the best spacing, comparison is made based on total weight values including purlin weight. From chart 15 below, it may be seen that the spacing of 3m is best until the span of 15m. However the spacing of 4m seems best beyond 15m span.
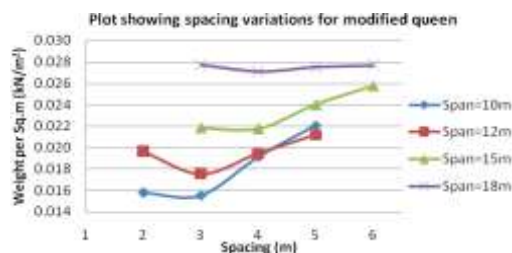

Chart 15: Plot of spacing v/s weight of modified queen truss

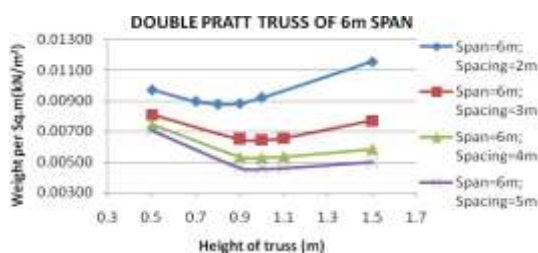**4.4 Double Pratt Truss**

1) For 6m span

Chart 16: Plot of weight per m² v/s rise of 6m double Pratt

Chart 16 shows the value of best rise for considered span and spacing for 6m double Pratt truss. The considered spacing is 2m, 3m, 4m & 5m. The results shows that the rise of 0.8m is found to best as it given a least weight of 0.00877kN/m², for the spacing of 2m while with all other spacings, the rise of 1m is found to be best.

2) For 8m span

It can be seen from chart 17 that, deciding the best rise in case of 8m double Pratt truss is done by varying the rise for fixed value of span & spacing. The spacing considered is 2m, 3m, 4m & 5m. The best value of rise is found to be 0.8m as if gives minimum weight of 0.01543kN/m², for 2m spacing. Similarly 1.1m, 1.3m, 1.4m rises are best for 3m, 4m & 5m spacing respectively.
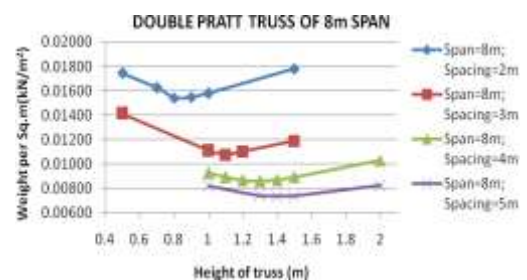

Chart 17: Plot of weight per m² v/s rise of 8m double Pratt

3) For 10m span

Chart 18 helps to decide the best rise for 10m double Pratt truss and it done by varying the rise for given span and spacing value of 3m, 4m, 5m & 6m, then choosing that rise which gives least weight. Result shows that the rise of 1.2m is best as it given the least weight of 0.01630kN/m², for 3m spacing. Similarly 1.5m rise for 4m spacing, 1.6m rise for 5m spacing and 1.8m rise for 6m spacing respectively.
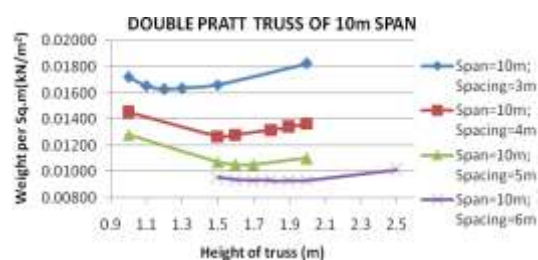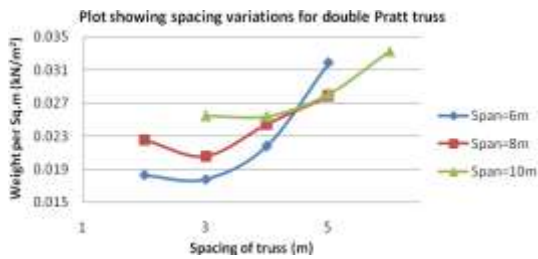

Chart 18: Plot of weight per m² v/s rise of 10m double Pratt

From the above discussion it can be inferred that, for 6m span the best height varies from 0.8m to 1m for various spacing considered for the study. Similarly, best rise varies from 0.8m to 1.4m in case of 8m span & it lies between 1.2m to 1.8m in case of 10m span.
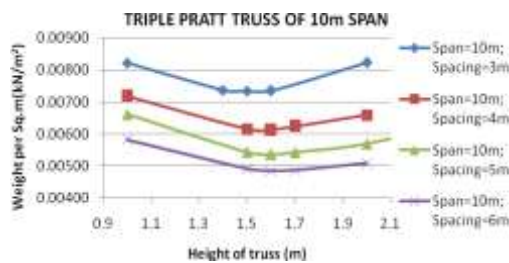
Chart 19: Plot of spacing v/s weight of double Pratt truss

In order to decide the best spacing under the given condition the total weight including the weight of purlin is to be used and chart 19 shows that the spacing of 3m is best until 10m span & spacing of 4m seems best for 10m span.
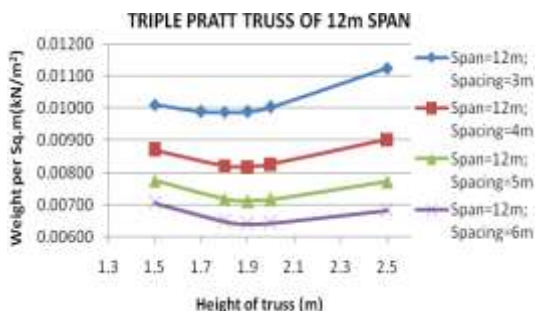
4.5 Triple Pratt Truss

1) For 10m span

Chart 20: Plot of weight per m² v/s rise of 10m triple Pratt

Above plot shows variation of height of truss or rise for 10m triple Pratt truss. The study is done by considering 3m, 4m, 5m and 6m spacing. The rise of 1.5m yields the least weight of 0.00735kN/m² of floor area, for 3m spacing. Similarly a rise of 1.6m is seen to be best in case of 4m, 5m & 6m spacing.
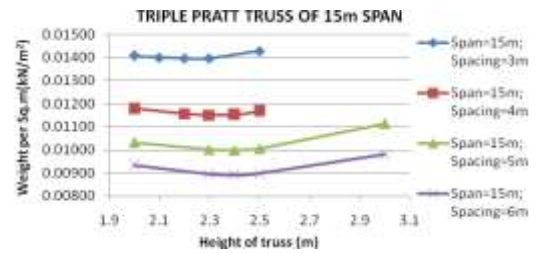
2) For 12m span

Chart 21 shows the variation of rise for 12m span triple Pratt truss. For the study 3m, 4m, 5m & 6m spacing are considered. The rise which gives least value of weight/m² of floor area for the given span and spacing is considered as best. Results show that the rise of 1.8m gives minimum weight of 0.00988kN/m², when spacing is 3m. Similarly 1.9m rise is seen to be best for all other spacing considered.

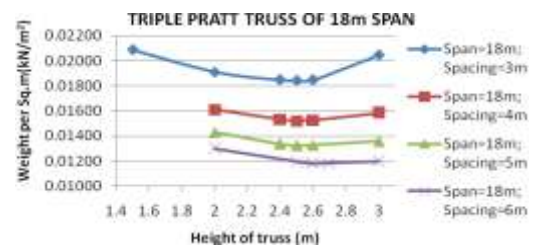**Chart 21:** Plot of weight per m² v/s rise of 12m triple Pratt

3) For 15m span

Chart 22: Plot of weight per m² v/s rise of 15m triple Pratt

Above plot shows the variation of height of truss in case of 15m span triple Pratt truss and the spacing considered for the study is 3m, 4m, 5m & 6m. Results show that, the rise of 2.2m is found to be best when spacing was 3m because it gives the minimum weight of 0.01397kN/m². Similarly 2.3m rise for 4m spacing, 2.4m rise for 5m & 6m spacing respectively.
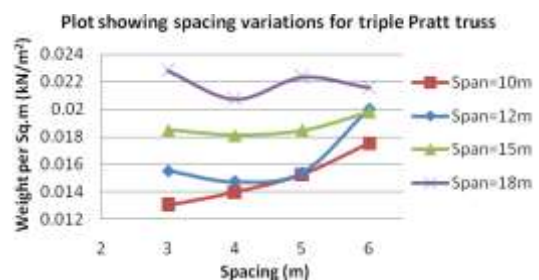
4) For 18m span

The chart 23 is used to find the best value of rise for 18m span triple Pratt truss. It is done by varying the rise and the spacing considered here are 3m, 4m, 5m & 6m. Results show that the rise of 2.5m to be best when spacing was 3m because it gives minimum weight of 0.01842kN/m². Similarly 2.5m rise for 4m spacing, 2.5m rise for 5m and 2.6m rise for 6m spacing respectively.

Chart 23: Plot of weight per m² v/s rise of 18m triple Pratt

From the above discussion one can note that, in case of triple Pratt truss, for 10m span the best value of height of the truss varies from 1.5m to 1.6m for various spacing considered for the study. Similarly, best height varies from 1.8m to 1.9m for 12m span, 2.2m to 2.4m for 15m span & it lies between 2.5m to 2.6m in case of 18m span.

Chart 24: Plot of spacing v/s weight triple Pratt truss

From chart 24 it may be seen that the spacing of 3m is best until 12m span & spacing of 4m seems best for span beyond 12m.

The following plots show the comparison between the various types of the trusses. Results shows that, for10m span, triple Pratt truss gives minimum weight of 0.0135kN/m^2 compared to other types. Hence it is considered best till 10m span. While triple fan truss gives least weight of 0.013047kN/m^2, 0.013844kN/m^2, 0.01590539kN/m^2 and 0.019899kN/m^2 for 10m, 12m, 15m and 18m span respectively. However for 20m span triple fan gives lesser weight than that given by all other types of truss for 18m only.
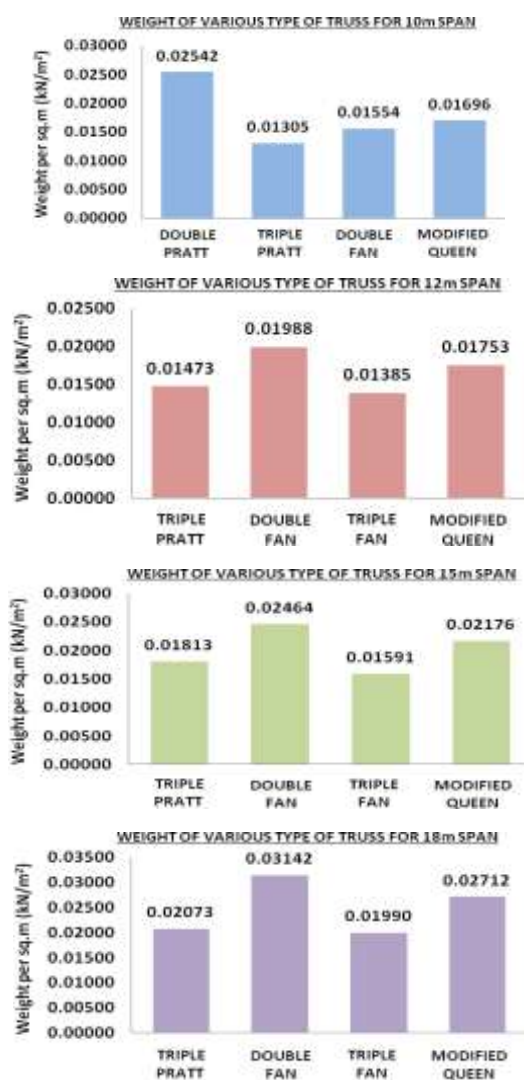

Chart 25: Plot of weight for different types of trusses for a considered span.

5. CONCLUSIONS

The followings points can be as the guidelines for selecting the initial geometry of the truss in the study area considered. i.e. for Dharwad region with basic wind speed of 33ms^{-1}, in order to increase the possibility of reaching the best and minimum weighted truss configuration.

1. Double fan truss can be used with span to height ratio of 6 to 7 and span to spacing ratio of 3 to 5 to get minimum weight design.

2. Triple fan truss can be used with span to height ratio of 7 to 9 and span to spacing ratio of 3 to 5 to get minimum weight design.

3. Modified queen truss can be used with span to height ratio of 6 to 8 and span to spacing ratio of 3 to 5 to get minimum weight design.

4. Double Pratt truss can be used with span to height ratio of 6 to 8 and span to spacing ratio of 2 to 3 to arrive at minimum weight design.

5. Triple Pratt truss can be used with span to height ratio of 5 to 7 and span to spacing ratio of 3 to 5 in order to reach optimum weight design.

However the overall comparison of the various types of the trusses leads to the following observations;

a) Triple Pratt truss is found to be more feasible compared to other type of truss configurations up to 10m span with span to spacing ratio as 4 and span to height ratio as 7.

b) Triple fan truss can be used for spans greater than 10m & can go on up to 20m with span to spacing ratio as 4 to 5 and span to height ratio as 8 to 9.

c) It is evident that irrespective of type of truss, spacing of 3m proves to be advantageous up to the span of 12m and spacing of 4m proves to be effective for spans over 12m & till 20m span.

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