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# An Investigative approach to design of trussless roof by Indian codes & FEM

S.Prakash [1], Dr. Sachin Mulay[2]
[1]- Mtech Structures Student , Department of Civil engineering, Sandip University, Nashik
[2]- Associate Professor, Department of Civil Engineering, Sandip University, Nashik

**Abstract**: Trussless roofing being a relatively new construction technology, there are very few codal and reference guidelines available for designing such systems. Owing to lack of scientific research and literature, many companies are exploiting the system for commercial benefit. Few unscientific practices that can be seen in designs of suppliers who provide trussless roofing systems are no seismic considerations and wind force calculations by using foreign codes with incorrect the factors of safety and combinations. Scope of this paper is to establish a design method for such structures with Indian codes and do a comparative study with FEM analysis and publish the results.

**Keywords:** Trussless roof, Self-supporting Roofing structure, arch roofing systems

## 1. INTRODUCTION

Self-supported roofs or Trussless roofs were initially used for small industrial buildings of up to 20m width. These roofing systems gained popularity due to aesthetically pleasing curved look, low cost and faster erection. Major industries where these are used are storage buildings or factories where cranes or any other collateral loads like false ceiling ductings were not required. However with booming warehousing industries in India, trussless roofs provided the right fit of lower cost of projects and faster erection, resulting in faster ROI for owners.

The Components of these structures are manufactured directly on site by a mobile truck where standing seam sheets are first roll formed into a profile and then bent to achieve curved shape by means of a bending machine Fig.1. These sheets are bent in a single piece without any joints in one single span of sheet. The Profiles are then joined by a cold seaming process first at ground level and then at roof after lifting and placing it over column supports.

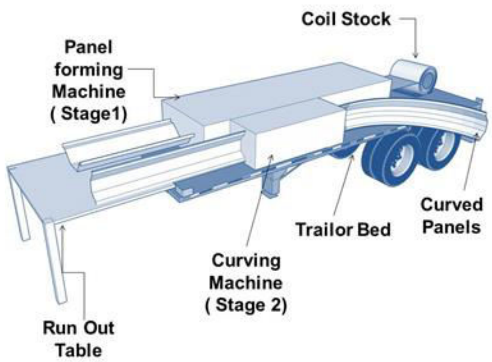


Fig.1 Process of making Curved Panel at site

The structural mechanics of a trussless roof or Self supported roof has its root in the theory of two hinged arches Fig.2. An arch is a pure compression form [1]. It spans a large area by distributing forces by means of internal compressive stresses, and thereby eliminating tensile stresses. This is called the arch action. As the forces in the arch are transferred to its base, the arch pushes outward at its base, denoted as “thrust” [2]. As the rise i.e the height of the arch decreases the outward thrust increases. In order to preserve arch action and prevent collapse of the arch, the thrust must be restrained by columns and beams framing arrangements[3].

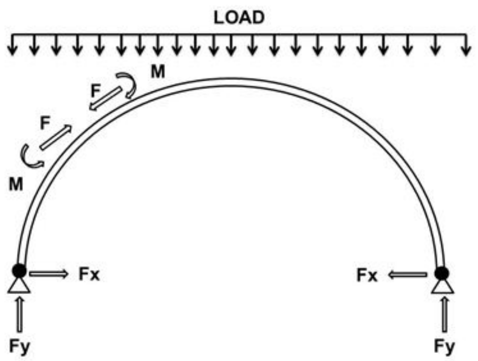


Fig.2 Diagram of Loadings and Supports of two Hinged Arch

2. MATERIAL & INSTALLATIONS

The Main Material used for roofing is Galvalume Steel. Galvalume is a trademark invented in 1972 by Bethlehem Steel.Galvalume is a high quality, high grade pre-coated material having thicknesses of 0.8 to 1.6mm used as trussless roofing material. It is aluminum-zinc alloy-coated steel sheets with 55% aluminum, 43.5% zinc and 1.5% silicon coating. Detailed specification has been given in table 1.

Table 1 technical Specifications of galvalume Steel

| | |
|---|---|
| Base Metal | Cold Rolled Structural Quality Steel In Coil Form, Coil Width: 1250 Max +/-0.5mm |
| Steel Grade | 350/550MPA |
| Thickness of Material used | 0.7 to 2.0mm ( Base metal thickness) |
| Coating Details | AZ 150, 150 Gms./Sq. M. Alu-Zinc-silicon Coating ( 55% Al , 43.5% Zn, 1.5% Si) |
| Coating Grade | AZ150 /AZ200 |
| Standards | ASTM A792 D |

The plane Sheet from the roll is passed through a Hydraulic Profile machine (MIC Machine) as shown in stage 1 of fig.1 to give it the Trapezoidal shape as shown in fig.3. The machine is basically a roll forming machine where the sheets are formed into a shape by a cold pressing process and then cut to the required length by a press cutter fitted at the end of the machine. After the profiling, these panels are passed through another Hydraulic machine as shown in stage 2 of fig.3 for Pre Curving as per the design. This process is also called crimp curving of the sheet which curves the sheet as per required radius.

Every Three such panels after curving are then placed at ground and joined together with the help of Seaming machine (fig.3). This is done to achieve better quality control and to avoid seaming done at height and also this helps in stability during lifting and erections.

A variety of roof seaming machines are available in the market, but they play an important role in joining sheets. A small error leads to heavy scratches and removal of coatings at joints. Machines are small and portable and are easy to handle by operator.

Seaming is like 'zipping up' rolled metal panels together using a Mechanical

Seaming machine. Panels are free from holes, nuts/bolts, overlaps and sealants which ensure almost zero maintenance.

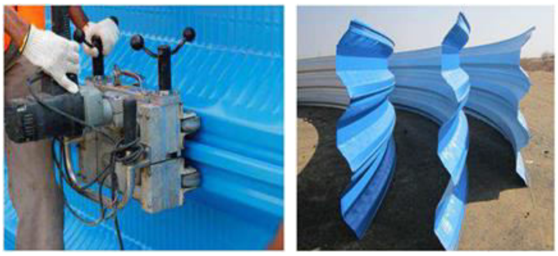

Fig.3 Mechanical Seaming & Grouping of three members at Ground

Precurved Sheets seamed in a set of three will be lifted by Cranes and placed over supporting structure. Once placed the group of three members are then seamed at roof top with the help of the same roof seamer. Alignments and plumbs are checked and corrected during this phase. After placing the sheets on the supporting structure, it is then fixed by mechanical Anchors of 3 or 4 Nos .

Supporting structure can be of RCC or steel as per customer or Architects requirements as shown in Fig.4. A continuous member with sloping edge and gutter provision is needed in both the systems. Sheets will rest on these continuous members. The columns should withstand the lateral Deflection caused due to horizontal thrust by arch roofs.

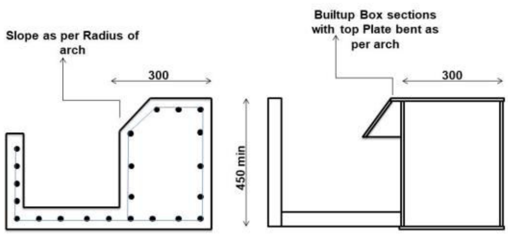


Fig.4 RCC & Steel Continuous Beam Support for Trussless Roof

3. STRUCTURAL CONFIGURATION

| | |
|---|---|
| Location of Structure | Pune ( India) |
| Width ( Span of Buildings) | 18m |
| Column Height | 4m |
| Arch height at center | 8m from Ground level |
| Length of Buildings | 60m |
| Column Spacings | 7.5m |
| Wind Speed | 39m/s |
| Seismic Zone | Zone III |

4. LOAD CALCULATIONS

Dead Loads on trussless roof are generally its self-weight and other miscellaneous items like turbo ventilators and skylights arrangements. Since we are modeling this structure in staad and FEM , only self-weight is considered.

| | |
|---|---|
| Sheeting Weight | 1.2mm Thick Sheets Considered 12kg/m2 |

| | |
|---|---|
| As per IS 875- Part 2-2015 | 0.75Kn/m2 |
| Bay Spacing | =0.6m<br>=0.6 X0.75Kn/m2<br>= 0.45Kn/m |

Wind calculations are considered per IS 875-3 -2015, where for columns table no 6 of code is considered and for roof table no 18 has been considered. All considered parameters are mentioned in Table no. 4 below:

| | |
|---|---|
| Basic wind speed (Vb) | 39m/s |
| Risk Coefficient ( K1) (Clause 6.3.1) | 1 |
| Terrain category ( Clause 6.3.2.1) | 2 |
| Terrain Height Factor (K2) | 1 |
| Topography Factor ( K3) | 1 |
| Importance Factor for Cyclonic Region( K4) | 1 ( All other Structures) |
| Design Wind speed ( Vz) | = Vb X k1 X k2 X k3 X k4<br>= 39 X 1 X 1 X 1 X 1<br>= 39m/s |
| Design Wind Pressure Pz at height z ( Clause 7.2) | = 0.6 X Vz^2<br>= 0.6X 39X39<br>= 912.60 N/m2<br>= 0.91 Kn/m2 |
| If H < 10 m multiply Pz with 0.8 (20 % reduction) clause 6.3 Note | = 0.91 X 0.8<br>= 0.73 Kn/m2 |
| Wind directionality factor (Kd) Clause 7.2.1 | 1 |
| Area Averaging Factor ( Ka) Clause 7.2.2 | 1 |
| Combination Factor (Kc) Clause 7.3.13 | 0.9 |
| Design Wind Pressure Pd | = Kd X Ka X Kc X Pz |
| | = 1 X 1 X 0.9 X 0.91Kn/m2<br>**= 0.66 Kn/m2** |
| Cpi | 0.2 |

Seismic Loadings applied as below:

| | |
|---|---|
| Code | IS1893-2016 ( Part 1) |
| Zone | 0.16 |
| Response reduction Factor | 3 |
| Importance Factor | 1 |
| Rock and soil site factor | 2 |
| Type of structure | 5 |
| Damping ratio | 0.05 |

| | |
|---|---|
| Period in X direction | 0.085 Seconds |
| Period in Z Direction | 0.045 Seconds |

## 5. STAAD MODELLING & FEM

Column is used of size ISMB 600 and the continuous member on which the trussless roof will rest is considered as Builtup tubular Member of size 300x300x8m thick of grade 250 mpa. Bracings have been considered as IS 100x100x10 back to back sections in the first and last bay.

Curved Member has been added at a spacing of 600mm for a length of 60m in a curve of 18m span as shown in Figure No.5. A dummy horizontal member has been added along the length to provide longitudinal stability to structure as in actual all sheets will be connected with each other.

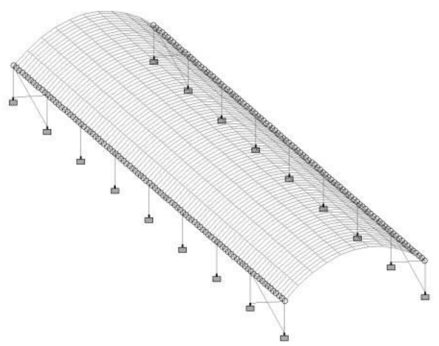

Fig. No 5 Staad Wire frame model

Trussless members, which is a C section modified with new properties, has been modelled as a curved member and released in My & Mz direction at Continuous member where it will rest. This way it will not transfer any moments to Continuous Beam. Channel members have been rotated by 90 degrees to place in a similar way trussless roofs will be placed. The 3d Rendered view is shown in figure no.6

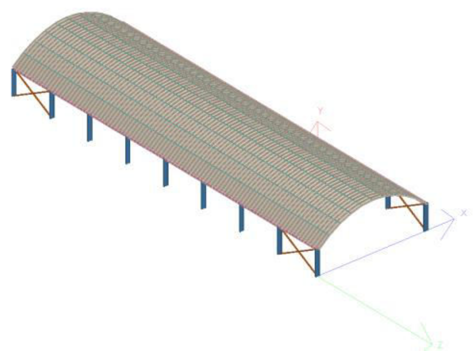

Fig No. 6 3d Rendered Model

Analysis performed using two codes i.e IS 800 (working stress method) for column and Built Up Box Beam and IS-801 for trussless roof Sections. Results of typical members are listed below for references. ISMB 600 are passing for columns, whereas Builtup Box sections of 300x300x8 mm are passing as continuous beams . 1.8mm thick trussless members are passing as per IS 801-code.

```
                    STAAD.PRO CODE CHECKING - (     IS-800:1984)   v1.1
                    *********************************************

|--------------------------------------------------------------------------|
|                                                       Y        PROPERTIES |
|*************                                          |        IN  CM  UNIT |
|             *  |=============================|    ===|===      ------------ |
|MEMBER 101   *  |  INDIAN SECTIONS            |       |        AX =  154.0  |
|             *  | ST  ISMB600                 |       |   --Z  AY =   72.0  |
|DESIGN CODE  *  |                             |       |        AZ =   56.8  |
|  IS-800     *  ==============================    ===|===      SY =  245.1  |
|             *                                                 SZ = 3008.7  |
|             *  |<---LENGTH (ME=    4.00 --->|                 RY =    4.1  |
|*************                                                  RZ =   24.2  |
|                                                                            |
|                327.9( KN-METR)                                             |
|PARAMETER       |L103                                          STRESSES    |
|IN   NEWT  MM   |   L103                                       IN   NEWT  MM|
|--------------- +       L103L103                               ------------|
| KL/R-Y=   36.7 |               L103                             FA  =  191.9 |
| KL/R-Z=   16.5 +                                                fa  =    5.7 |
| UNL   = 4000.0 |                   L103L103                     FCZ =  152.2 |
| C     =  400.0 +                                                FTZ =  231.0 |
| CMY   =   0.40 |                           L103                 FCY =  231.0 |
| CMZ   =   0.60 +                               L103L103         FTY =  231.0 |
| FYLD  =  350.0 |                                       L105fbz =  109.0 |
| NSF   =    1.0 +---+---+---+---+---+---+---+---+---+---|        fby =    0.3 |
| DFF   =    0.0 -18.2                                            FV  =  140.0 |
| dff   =    0.0              ABSOLUTE MZ ENVELOPE                fv  =   11.4 |
|                                (WITH LOAD NO.)                             |
|                                                                            |
|                   MAX FORCE/ MOMENT SUMMARY ( KN-METR)                     |
|                   -------------------------                                |
|                                                                            |
|                AXIAL     SHEAR-Y    SHEAR-Z    MOMENT-Y    MOMENT-Z        |
|                                                                            |
|       VALUE    90.1       82.0        0.1         0.2        327.9         |
|     LOCATION    0.0        0.0        0.0         4.0          0.0         |
|      LOADING   111        103        104         104          103          |
|                                                                            |
|****************************************************************************|
|*                                                                          *|
|*                       DESIGN SUMMARY ( KN-METR)                          *|
|*                       --------------                                     *|
|*                                                                          *|
|*       RESULT/     CRITICAL COND/     RATIO/         LOADING/             *|
|         FX              MY             MZ            LOCATION              |
|        =======================================================            |
|          PASS        IS-7.1.1(A)       0.747           103                 |
|         88.54 C          -0.1          327.9           0.00                |
|*                                                                          *|
|****************************************************************************|
|                                                                            |
|----------------------------------------------------------------------------|
```

```
                    STAAD.PRO CODE CHECKING - (     IS-800:1984)   v1.1
                    ********************************************

|--------------------------------------------------------------------------|
|                                                          Y       PROPERTIES |
|*************                                             |       IN  CM  UNIT |
|            *  |===============================|   |=====|       ----------- |
|MEMBER 112  *  |  BRITISH SECTIONS             |   |     |       AX =   92.8 |
|            *  | ST  TUB3003008.0              |   |     |--Z    AY =   48.0 |
|DESIGN CODE *  |                               |   |     |       AZ =   48.0 |
|  IS-800    *  ===============================    |=====|       SY =  875.3 |
|            *                                                    SZ =  875.3 |
|            *  |<---LENGTH (ME=     0.63 --->|                    RY =   11.9 |
|*************                                                    RZ =   11.9 |
|                                                                             |
|                  51.9( KN-METR)                                             |
|PARAMETER        |L107                                        STRESSES     |
|IN   NEWT  MM    |   L107                                     IN   NEWT  MM|
|---------------  +       L107L107                             -------------|
| KL/R-Y=   63.1  |               L107                         FA  =  119.0 |
| KL/R-Z=   63.1  +                                            fa  =    0.4 |
| UNL   =  625.0  |                   L107L107                 FCZ =  164.9 |
| C     =  400.0  +                                            FTZ =  165.0 |
| CMY   =   0.81  |                           L107             FCY =  165.0 |
| CMZ   =   0.81  +                               L107L107     FTY =  165.0 |
| FYLD  =  249.9  |                                       L107fbz =   58.0 |
| NSF   =    1.0  +---+---+---+---+---+---+---+---+---+---|   fby =   55.9 |
| DFF   =    0.0  26.4                                         FV  =  100.0 |
| dff   =    0.0              ABSOLUTE MZ ENVELOPE             fv  =    7.9 |
|                               (WITH LOAD NO.)                              |
|                                                                             |
|                   MAX FORCE/ MOMENT SUMMARY ( KN-METR)                      |
|                   -------------------------                                 |
|                                                                             |
|               AXIAL      SHEAR-Y    SHEAR-Z    MOMENT-Y    MOMENT-Z        |
|                                                                             |
|      VALUE     4.2        38.9       36.9        48.9        51.9          |
|   LOCATION     0.0         0.0        0.0         0.0         0.0          |
|    LOADING     105         107        102         102         107          |
|                                                                             |
|****************************************************************************|
|*                                                                          *|
|*                      DESIGN SUMMARY ( KN-METR)                           *|
|*                      --------------                                      *|
|*                                                                          *|
|*      RESULT/     CRITICAL COND/     RATIO/        LOADING/               *|
|        FX             MY              MZ          LOCATION                |
|       =======================================================             |
|         PASS       IS-7.1.1(A)      0.694           102                   |
|         3.64 C       -48.9          50.8            0.00                  |
|*                                                                          *|
|****************************************************************************|
|
```

```
                    STAAD.Pro CODE CHECKING - ( IS:801 )   v3.0
                    ***********************
 ALL UNITS ARE IN - METE  KN   (U.N.O.)
|--------------------------------------------------------------------------|
| MEMBER:   475 SECTION: 600CS169X1.8          LEN:    2.120   LOC:   1.237 |
| STATUS: PASS    RATIO:   0.495               REF: 6.4.3       LC:    111 |
|--------------------------------------------------------------------------|
| DESIGN FORCES:                                                           |
|  Fx:(C)        7.699       Fy:        -0.034         Fz:       -0.014    |
|  Mx:          -0.000       My:         2.405         Mz:        0.218    |
|--------------------------------------------------------------------------|
| SECTION PROPERTIES:                                        (Unit:   CM)  |
|  Ag:     1.69600E+01     Az: 6.08400E+00         Ay: 1.40904E+01         |
|  Cz:     2.60000E+00     Cy: 3.00000E+01         ZO: 8.80000E+00         |
|  Iz:     6.03100E+03     Iy: 8.56000E+02          J: 1.90000E+00         |
|  Sz:     1.97000E+02     Sy: 7.75000E+01                                 |
|  Rz:     1.88574E+01     Ry: 7.10434E+00         Cw: 1.93500E+04         |
|--------------------------------------------------------------------------|
| MATERIAL INFO:                                             (Unit: MPa)   |
|  Fy:   350.025       Fu:   450.032      E: 203404.356      G:  77968.401 |
|  Fya(compression):   350.025            Fya(bending):   350.025          |
|--------------------------------------------------------------------------|
| DESIGN PROPERTIES:                                                       |
|  Member Length:     2.120      Lz:    20.000 Ly:     0.600 Lb:     2.120 |
| DESIGN PARAMETERS:                                                       |
|  Kz:   1.000     Ky:   1.000   NSF:  1.000   Cb:   0.000                 |
|--------------------------------------------------------------------------|
| CRITICAL SLENDERNESS:                                                    |
|  Actual:     106.059      Allowable:     200.000      Ratio:   0.530     |
|--------------------------------------------------------------------------|
| CHECKS:                                |      Stresses       |                |
|              | Loc. | Demand |  L/C | Actual   | Allow    |Ratio | Ref CL     |
|              |(MET) |(KN-MET)|      | (MPa)    | (MPa)    |      |            |
|--------------|------|--------|------|----------|----------|------|------------|
| Tension      | 2.120|   -1.99|   116|    1.176 |  210.015 | 0.006| 6.1        |
| Compression  | 0.000|    9.26|   103|    5.458 |   47.078 | 0.116| 6.6.1.1    |
| BendZComp    | 2.120|    0.51|   105|    3.457 |  210.015 | 0.016| 6.3        |
| BendZTens    | 2.120|    0.51|   105|    2.887 |  210.015 | 0.014| 6.3        |
| BendUnbraced | 2.120|    0.51|   105|    3.457 |  210.015 | 0.016| 6.3 LTB    |
| BendYComp    | 1.237|    2.40|   111|   35.619 |  210.015 | 0.170| 6.3        |
| BendYTens    | 1.237|    2.40|   111|   14.941 |   88.095 | 0.170| 6.3        |
| Bend Web     | 1.237|    2.41|   111|   16.177 |   32.661 | 0.495| 6.4.2      |
| Shear Z      | 0.000|    0.96|   111|    1.570 |  140.010 | 0.011| 6.4.1      |
| Shear Y      | 0.000|   -0.11|   105|    0.078 |    5.226 | 0.015| 6.4.1      |
| Axial+Bend   | 1.237|   -    |   111|    -     |    -     | 0.259| 6.7.2(a)2  |
| Bend+Shear   | 1.237|   -    |   111|    -     |    -     | 0.495| 6.4.3      |
|--------------------------------------------------------------------------|
| Effective Section Properties:(cm)                                        |
|  Ae:   5.130 SzTop: 174.955 SzBot: 146.122 SyLeft: 160.952 SyRight:  67.514 |
| Intermediate Results:  Cb =  1.000                                       |
|--------------------------------------------------------------------------|
```

To identify the actual stresses and to find correlation between the staad model and actual site practices, FEM model of the same building has been performed on staad itself. For ease of calculation, columns and continuous beams have been excluded from the scope of FEM. FEM Method is a powerful technique originally developed for numerical solution of complex structural mechanics problems [16]. The FEM method also helps to analyze the behavior of seamed joints, which is difficult to understand in other conventional calculations.

In finite element analysis, Structural system is modelled by a set of finite elements modelled by nodes interconnected.

Methods of FEM in staad are as per below steps:

- Node Modeling as per shape of structures as shown in Fig no. 7 &7a
- Generate mesh as per Quadrilateral meshing of appropriate sizes.
- Supports definitions
- Plate properties , thickness, grades and material types for all plates
- Loadings & Load Combinations
- Result analysis as shown in fig. no.9

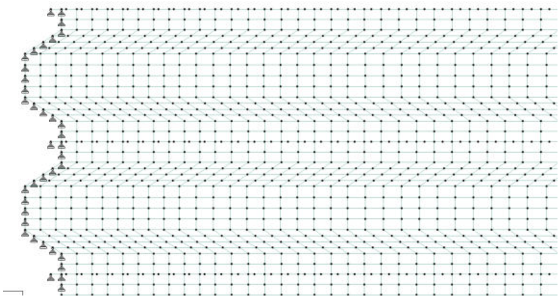

Fig No. 7 Quadrilateral meshing

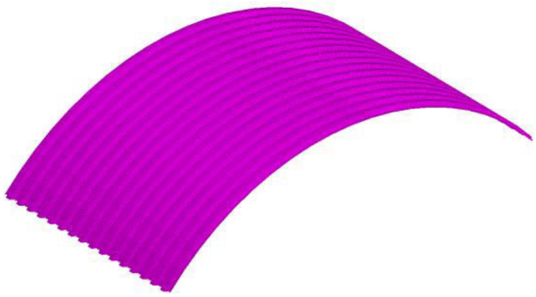

Fig No. 7a Rendered Model

Loads and load combinations can be applied the same as per codal methods, however one can also check for critical Combinations. There is no need to define any codes or design parameters in staad for FEM. Post analysis one can review various type of stresses as listed below:

- Max Absolute
- Tau Max
- Von Mis
- Max tresca
- Global Moment
- Global Stress
- Base pressures
- Sx
- Sy

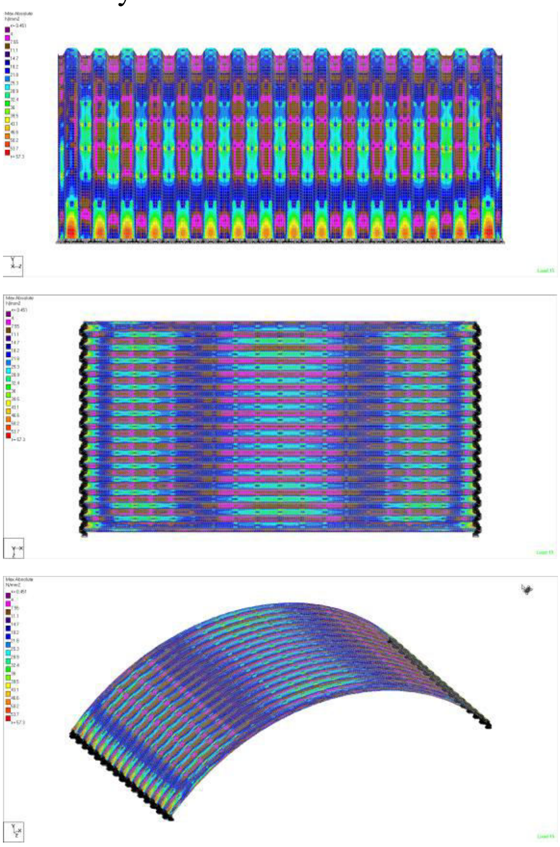

Fig.No. 9 Absolute Stress Results

The other results like reactions, displacement can also be obtained for every load case and combinations and results can be interpreted.

6. RESULTS & DISCUSSION

A span of 18m trussless roof on 4m steel column has been designed using Indian & American codes. The same has also been analysed by FEM methods. Section sizes received in all the three methods have already been given in above chapters. Various results have been summarized in this chapter .

| | |
|---|---|
| Column Sizes | ISMB600 |
| Continuous Beam Size | Built Up Box 300x300x8mm |
| Trussless Sheet thickness | IS 801 ( Staad ) - 1.8mm<br>RSG CFC - 0.8mm<br>FEM method- 0.8mm |
| Maximum vertical Deflections | 36mm- ( Dead + Live + Wind load ) |
| Maximum Reactions ( for Connection design of trussless with Continuous members ) | Vertical Downward Forces= 5.2Kn<br>Horizontal Force= 4.145Kn<br>Uplift= -7.2Kn |
| Maximum reaction for Foundation Design | Vertical Reaction = 99.Kn<br>Horizontal reaction = 89.35Kn |

| | |
|---|---|
| | Moment= 352.3knm |

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