Design Of A Composite Truss System In A Multistorey Building

S. A. Raji
Department of Civil Engineering
University of Ilorin, Ilorin, Nigeria
saraji@gmail.com

K. K. Abdulraheem
Department of Civil Engineering
University of Ilorin, Ilorin, Nigeria
kehinde_olaitan56@yahoo.com

R. O. Rahmon
Department of Civil Engineering
University of Ilorin, Ilorin, Nigeria
rorahmon2222@gmail.com

A. A. Adelowo
Department of Civil Engineering
University of Ilorin, Ilorin, Nigeria
adelowoadeyinka@gmail.com

Abstract—The design specifications of composite trusses are only partially included in Euro code standards. However, this construction system can be considered as one of the most economical for building and bridge structures. The composite trusses can be used for greater spans up to 30 m, which allows better use of internal space without restricting the columns. They are appropriate also to meet the requirements for building height limitation as well as the need to run complex installation systems. To create the interaction between steel and concrete, it is necessary to prevent the relative slip at the steel and concrete interface using the shear connectors. Whereas the local effects of a concentrated longitudinal force and the distribution of the shear force between the steel section and the concrete slab, as special task, should be appropriately examined. In this research, composite truss of 10m span is considered. The finite element analysis using ROBOT and STAADPRO software packages was used to investigate and compare numerically to determine the structural system behaviour. The total deflection results obtained in the manual and software design satisfy permissible deflection which must be < l/365. This shows that composite truss system provides the best solution in the range of 10m span with a least steel weight.

Keywords—Composite truss, shear connection, numerical study, ROBOT and STADPRO.

INTRODUCTION

Composite steel-concrete trusses can be considered as one of the most economical systems for building, especially for greater spans, commonly to the 20 m. The continuous structural elements of this composite type can be used for even greater spans up to the 30 m, which allows better use of internal space without restricting columns [1]. The trusses are appropriate also to meet the requirements for building height limitation as well as the need to run complex electrical, heating, ventilating, and communication systems. Also composite steel bridges, whose carriageway deck is supported on a filigree steel truss structure and slim piers, are particularly preferable especially to ordinary concrete bridges. Primarily considering the technical and architectural aspects as well as compromise between protections of the landscape on the one hand and hard transports necessities on the other. Thus a composite truss bridge, with its speedy assembly engineering can be a structural type which is both economically and aesthetically attractive. To create the interaction between steel parts and concrete, it is necessary to prevent the relative slip at the steel-concrete interface using the shear connectors. But the local effects of a concentrated longitudinal force and the distribution of the shear force between steel section and concrete slab, as special task, should be appropriately examined. The finite element analyses can be used to investigate numerically this structural system behavior, exploiting several computer procedures [2]. In multi-story buildings, the composite truss systems also reduce the total height of the building, by accommodating the services (heating, ventilation, lighting and telecommunication ducts) within the depth of the truss, thus integrating structural,
mechanical and electrical systems within the floor space. This minimizes the inter-floor height. Considering functional and structural efficiency and economy, it is only natural that composite steel-concrete trusses are a popular choice for long span and high-rise construction.

1.2 Structural Framing of Composite truss
Experiences abroad have shown that trusses are economically viable for spans greater than 20m. Composite truss system are most often used with composite slabs comprising steel decking which act as a main reinforcement and permanent shuttering. Other system such as pre-cast planks or cast in situ slab can be used but are usually less cost effective.

1.3 Truss shear connections
In Euro code, there is no particular recommendation for the design of composite truss, except the formulas in EC 4 [1], clause 6.6.2.3 for the local effect of a concentrated longitudinal force and the distribution of the longitudinal shear force into local shear flow between steel section and concrete slab. In the case of a composite truss, the longitudinal forces are introduced into the concrete slab similarly only locally in the nodes, where the web members are connected to the compressed chord.

1.4 Shear connection Properties
First of all the influence of the connectors size considering numerous theoretical values of shank diameter varying on truss beam stiffness. These values represent the progression of the degree of shear stud connection in the truss from no connection to full interaction. It was recognized that the usual diameter of 19 mm is quite sufficient to obtain a full connection. Moreover, the composite effect obtained by the shear connector diameter variation can increase even twice the stiffness of the truss with no connection in comparison to the composite truss beam with full connection.

In case of very long span length pitched roof, trusses having trapezoidal configuration, with depth at the ends are used. This configuration reduces the axial forces in the chord members adjacent to the supports. The secondary bending effects in these members are also reduced. The trapezoidal configurations having the sloping bottom chord can be economical in very long span trusses (spans > 30 m), since they tend to reduce the web member length and the chord members tend to have nearly constant forces over the span length. It has been found that bottom chord slope equal to nearly half as much as the rafter slope tends to give close to optimum design.

2.0 METHODOLOGY
To determine the basic component like displacement and base shear, this design has been carried out using manual design of composite truss system as well as finite elements software packages such as ROBOT and STAADPRO V8I and comparing both results for the design purpose.

2.1 Building Modeling
In this building model composite truss of multistory structures is considered. The building models, properties of the considered composite trusses models are detailed below here.

2.2 Material Properties
The materials used for design of composite truss models construction is reinforced concrete with M-25 grade of concrete and fc-415 grade of steel and the stress-strain relationship is used as per Euro code 4.
2.3 Section Properties

Table 2: Section properties

<table>
<thead>
<tr>
<th>Prop</th>
<th>Section</th>
<th>Area (cm²)</th>
<th>Ixx (cm⁴)</th>
<th>Iyy (cm⁴)</th>
<th>J (cm⁴)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>GA1300X1300X10</td>
<td>59.360</td>
<td>1.01E3</td>
<td>262.146</td>
<td>9.833</td>
<td>STEEL</td>
</tr>
<tr>
<td>3</td>
<td>GA1000X600X65</td>
<td>8.130</td>
<td>58.931</td>
<td>15.698</td>
<td>0.950</td>
<td>STEEL</td>
</tr>
</tbody>
</table>

2.4 MODEL

Three dimensional models considered for the design purpose of composite truss system.

3.0 RESULTS

3.1 Manual results

PROBLEM:
Design a composite truss of span 10.0 m with following data:

DATA:
Span = l = 10.0 m
Truss spacing = 3.0 m
Slab thickness = Ds = 175 mm
Profile depth = Dp = 75.0 mm
Self weight of deck slab = 3.0 kN/m²

Maximum laterally un-restrained length in top chord is 1.5 m.
Grade of concrete, M25 = (fck)cu = 25 MPa

Loading:

<table>
<thead>
<tr>
<th>Factored Load (kN/m²)</th>
<th>kN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deck slab weight</td>
<td>3.0</td>
</tr>
<tr>
<td>3.0*1.5 = 4.50</td>
<td></td>
</tr>
<tr>
<td>Truss weight (assumed)</td>
<td>0.4</td>
</tr>
<tr>
<td>0.4*1.5 = 0.60</td>
<td></td>
</tr>
<tr>
<td>Ceiling, floor finish and Services</td>
<td>1.0</td>
</tr>
<tr>
<td>1.0*1.5 = 1.5</td>
<td></td>
</tr>
<tr>
<td>Construction Load</td>
<td>1.0</td>
</tr>
<tr>
<td>1.0*1.5 = 1.5</td>
<td></td>
</tr>
<tr>
<td>Superimposed live load</td>
<td>5.0</td>
</tr>
<tr>
<td>5.0*1.5 = 7.5</td>
<td></td>
</tr>
</tbody>
</table>

PRE-COMPOSITE STAGE:

Total factored load = 6.60 kN/m²

Choose depth of truss = Span/20
= 10000/20
= 500 mm

Total factored load = 6.60 * 3
= 19.8 kN/m

Maximum bending moment = w²/8 = 19.8
*10²/8 = 247.5 kN-m

Maximum shear = wL/2 = 19.8*10/2
= 99.0 kN
Depth of truss (centre to centre distance of chords) = 0.5 m

Maximum axial compressive force in top chord = \( \frac{247.5}{0.5} = 495.0 \text{ kN} \)

\[ D_t = 500 + x_t + x_b \]

**Truss configuration:** Choose the following truss configuration

Top chord design:

Try ISNT 150 X 150 X 10 mm @ 0.228 kN/m

**Sectional properties:**

Area of cross-section = \( A_t = 2908 \text{ mm}^2 \)

Depth of section = 150 mm

Width of section, \( b = 2b_t = 150 \text{ mm} \)

Thickness of flange = \( T = 10.0 \text{ mm} \)

Thickness of web = \( t = 10.0 \text{ mm} \)

Centre of gravity = \( x_t = 39.5 \text{ mm} \)

\[ r_{xx} = 45.6 \text{ mm} \]

\[ r_{yy} = 30.3 \text{ mm} \]

**Section classification:**

\[ \varepsilon = \left( \frac{250}{f_y} \right)^{0.5} = \left( \frac{250}{250} \right)^{0.5} = 1.0 \]

**Flange:**

\[ b/T = 75/10 = 7.5 < 8.9 \varepsilon \text{ Flange is plastic} \]

**Web:**

\[ d/t = 140/10 = 14 \text{ ( >9.98\varepsilon and < 19.95\varepsilon ) Web is semi-compact} \]

As no member in the section is slender, there is no need of adopting reduction factor (Yielding govern).

Given, maximum un-restrained length of top chord is 1.5 m during construction stage.

Maximum unrestrained length = \( l_s = 1500 \text{ mm} \)

\[ l_s = 0.85*1500 = 1275 \text{ mm} \]

\[ r_{xx} = 45.6 \text{ mm} \]

\[ r_{yy} = 30.3 \text{ mm} \]

\[ \lambda_{xx} = 1275/45.6 = 28 \]

\[ \lambda_{yy} = 1500/30.3 = 49.5 \]

Then, \( \delta_c = 202.8 \text{ N/mm}^2 \) [From Table - 3 of Chapter on axially compressed Columns]

Axial capacity = \( (202.8/1.15)^{2.908}/1000 = 512.8 \text{ kN} \)

Axial capacity = \( (202.8/1.11)^{2.908}/1000 = 536.13 \text{ kN} \)

Hence, section is safe against axial compression at construction stage.

[Other member design is governed by composite loading]

**COMPOSITE STATE:**

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</tr>
<tr>
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<td></td>
</tr>
</tbody>
</table>

Total factored load = \( (4.5+0.6+1.5+7.5)*3 = 14.1*3 = 42.3 \text{ kN/m} \)

Maximum bending moment \( (M_z) = w^2\ell/8 = 42.3*10^2/8 = 528.75 \text{ kN-m} \)

Maximum shear \( = wl/2 = 42.3*10/2 = 211.5 \text{ kN} \)

**Bottom chord design:**

Force in bottom chord, \( R_{b,req} \) is given by: [See Fig. of the text]

\[ R_{b,req} = (D + x_t + D_c)/(D_c - D_p)/2 = M_z \]

[Assume NA is in the concrete slab]

\[ R_{b,req} = (500 + 39.5 + (175-50)/1000 = 528.75 \text{ kN-m} \]

\[ R_{b,req} = 528.75/0.6645 = 795719 \text{ kN} \]

Area required = \( 795.71*1000/(f_y/1.1) = 795.71*1000/(250/1.1) = 3501.124 \text{ mm}^2 \)

**Trial-1 Trying ISHT 150 @ 0.294kN/m**
Sectional properties:
A = 3742 mm$^2$; \( x_b \) = Centre of gravity = 26.6 mm
Width of the section, \( b = 2b = 250 \) mm
Axial tension capacity of the selected section (\( R_b \)):
\[
R_b = (250/1.1) \times 3742/1000 = 850.46 \text{kN} > 795.71 \text{kN}
\]
Hence, O.K.

Capacity of Composite Section in Compression:
Capacity of concrete slab, \( R_c \), is given by
\[
R_c = 0.45 \times (f_{ck})_{cu} \times b_{eff} \times (D_s - D_p)
\]
Effective width of the slab, \( b_{eff} \): [See the chapter Composite beams – II]
\[
b_{eff} = \frac{D_s - D_p}{4} = \frac{10000}{4} = 2500 \text{ mm}
\]
Then, maximum moment it can carry
\[
M_{u, \text{design}} = 850.46(0.566 + 0.15 - 0.5 \times 0.0302 - 0.0266)
\]
\[
= 573.47 \text{kN-m} > 527.85 \text{kN-m}
\]
Hence, the slab and chord members are designed.

Web members:
\[
F_{AB} = V(1.414) = 211.5(1.414) = 299.06 \text{kN}
\]
(tension)
\[
F_{BC} = (V - 0.5 \times 39.5) \frac{(500+750)0.5}{500} = 345.68 \text{kN}
\]
(compression)
\[
F_{CD} = (V - 2.0 \times 39.5) \frac{(500+750)0.5}{500} = 238.87 \text{kN}
\]
(tension)
Hence, maximum tensile force in bracing members = 299.06 kN
Maximum compressive force in bracing members = 345.68 kN

Design of tension members:
\[
\text{Trial gross area required} = 299.06 \times 10^2/(250/1.1) = 1315.86 \text{ mm}^2
\]
Trying 2 – ISA 70 X 70 X 0.6 @ 0.126 kN/m

Design of compression members:
Maximum compressive load = 320 kN
Trying 2 – ISA 80 X 80 X 6.0 @ 0.146 kN/m
\[
A = 1858 \text{ mm}^2
\]
\[
r_{xx} = 24.6 \text{ mm}
\]
\[
r_{uu} = 34.9 \text{ mm}
\]

Section classification:
\( b/t = 80/6 = 13.3 < 15.75 \)
Hence, the section is not slender and no need to apply any reduction factor.

Slenderness ratio is taken as the greater of
Length of member = \( (750^2 + 500^2)^{0.5} = 901 \text{ mm} \)
\[
r_{xx} = 0.85 \times 901/24.6 = 31.1
\]
\[
r_{xx} = 1.0 \times 901/34.9 = 25.8
\]
Design buckling strength = 231.2 Mpa [Table – 3 of chapter on axially compressed columns]
Design compressive strength = \( 1858 \times (231.2/1.1)/10 = 390.52 \text{ kN} > 335.86 \text{ kN} \)
Hence the 2 – ISA 80 X 80 X 6.0 are adequate for the web members
(The web members away from the support would have lesser axial force and can be redesigned, if so desired. Preferably use the same section for all web members)
## Weight Schedule:

<table>
<thead>
<tr>
<th>Description</th>
<th>Section mm X mm</th>
<th>Weight kN/m</th>
<th>Number</th>
<th>Length h (m)</th>
<th>Total Length h (m)</th>
<th>Weight kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Chord</td>
<td>ISNT 150x150</td>
<td>0.22</td>
<td>1</td>
<td>10.0</td>
<td>10.0</td>
<td>2.28</td>
</tr>
<tr>
<td>Bottom Chord</td>
<td>ISHT 70X70</td>
<td>0.29</td>
<td>4</td>
<td>1.00</td>
<td>10.0</td>
<td>2.94</td>
</tr>
<tr>
<td>Bracing Members</td>
<td>2-ISA 70X70</td>
<td>0.12</td>
<td>6</td>
<td>0.71</td>
<td>0.71</td>
<td>0.18</td>
</tr>
<tr>
<td>Tension Members</td>
<td>2-ISA 80X80</td>
<td>0.14</td>
<td>6</td>
<td>0.90</td>
<td>0.90</td>
<td>0.79</td>
</tr>
</tbody>
</table>

| Allow 2.5% Extras | 6.87 |

Average weight per unit area of floor = 7.04 = 0.23 kN/m² - 0.4 kN/m² (Assumed)  
Hence, O.K.

### Deflection:

**Pre-composite stage:**

The second moment of area of the steel truss, I, can be calculated from the following equation.

Where,

- $A_b$ - Cross-sectional area of bottom chord.
- $A_t$ - Cross-sectional area of top chord.

In this problem,

- $A_b = 3742 \text{ mm}^2$
- $x_b = 26.6 \text{ mm}$
- $A_t = 2908 \text{ mm}^2$
- $x_t = 39.5 \text{ mm}$
- $D_t = 566 \text{ mm}$

$$I_r = \frac{3742 \times 2908}{(3742 + 2908)} \left[566 - 26.6 - 39.5\right]^2 = 409 \times 10^6 \text{ mm}^4$$

**Loading:**

- Deck slab weight: 3.0 kN/m²
- Truss weight: 0.23 kN/m
- Construction load: 1.00 kN/m

**Total Load** = 4.23 kN/m

Deflection at pre composite state is given by

$$\delta_0 = \frac{(5*126.9*10000)/(384*200*409*10^4)}{20.19 \text{ mm}}$$

**Deflection at composite state due to dead load** = $\delta_1 = (3.03/4.23)*20.19$

= 14.46 mm

[For composite stage construction load has to be removed for calculating deflections]

**Deflection - Composite stage:**

The second moment of area, $I_c$, of a composite truss can be calculated from the following equation

$$I_c = \frac{A_b A_t / m}{(A_b + A_t / m)} \left[D_t + (D_z + D_p) / 2 - x_b\right]^2$$

Where,

- $A_c$ = Cross-sectional area of the concrete in the effective breadth of slab
- $D_t = (D_t - D_p) b_{eff}$
- $m = \text{modular ratio}$

In this problem,

- $A_b = 3742 \text{ mm}^2$; $b_{eff} = 2500 \text{ mm}$
- $A_c = (175 - 75)*2500 = 2500*10^4 \text{ mm}^2$
- $m = 15$ (light weight concrete)
- $D_t = 566 \text{ mm}$
- $x_b = 26.6 \text{ mm}$

$$I_c = \frac{3742 \times 1875 \times 10^4 / 15}{(3742 + 1875 \times 10^4 / 15)} \left[566 + 225 / 2 - 26.6\right]^2 = 1298.67 \times 10^6 \text{ mm}^4$$

**Loading:**

- Super Imposed load = 5.0 kN/m²
- Total Load = 5.0*3*10 = 150 kN

Deflection at composite state due to superimposed load is given by

$$\delta_2 = (5*150*10000)/((384*200*1298.67*10^4)) = 7.52 \text{ mm}$$

10% allowance is given

Then, $\delta_2 = 8.27 \text{ mm} < V/360 = 10000/360 = 28 \text{ mm}$

Hence, design is O.K.

### 3.2 Staad Pro Results

The figure 3 and 4 shows structural displacement and maximum bending diagram. The results of the support reaction, Principal and Von mis stress as well as shear membrane and bending are shown in table 2, 3 and 4 respectively. Figure 5 and 6 shows graphs for moment and shear force.
Fig 3: Structural displacement diagram

Fig 4: Maximum bending along z-direction

Fig 5: Beam Graph (Moment) of Beam 243

The maximum deflection obtained is 21.25mm.

3.3 Robot Software

The stress and bending along the three directions (x, y, and z) are shown in figure 6 using robot software. The maximum normal stress obtained is 131.43 N/mm² while the minimum is 21.99 N/mm². Maximum axial forces are 21.99 N/mm² while the minimum is 20.07 N/mm². The maximum deflection obtained is 30.40mm.
The support reaction is shown in figure 7 and the value obtained is shown in the diagram for the two end support.

Figure 7: Support Reaction

4.0 Validation of Results
In order to validate the results obtained, the maximum deflection result obtained from ROBOT software is compared with the results obtained using STAADPRO. It can be seen that maximum deflection obtained for the two results is close (20.40mm and 21.40mm) which satisfy the permissible deflection (l/325 i.e. 30.76mm). Hence, the two results are adjudged to be satisfactory.

5.0 Conclusion
It can be seen from the manual and software design using ROBOT and STAADPRO that composite truss system provide the best solution in the range of 10m span and it has a least steel weight. The total deflection obtained for both manual and software design satisfy permissible deflection for truss system which must be < L/365. However, the analysis and design of the composite truss is depends upon the class of the compression flange and web. The truss system can facilitate the concentration of material at the structurally most efficient locations for transfer of force. Hence theoretically, composite truss can provide the least steel weight of any steel framing system.

REFERENCES
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