Effectiveness and Shape Design of CFRP Structural Sections in Roof Trusses

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Abstract

Roof trusses have always been constructed using traditional materials such as timber and steel which have been used in industrial, agricultural and residential structures. This study aims at obtaining further effectiveness which can be attained when Carbon Fibre Reinforced Plastic (CFRP) is used as the structural section materials of a roof truss. A CFRP truss section is compared with the same 350W (AISC 2005) steel truss section subjected to same loading conditions. Results indicate that the steel truss withstand deflections more than the CFRP truss in both linear and non-linear analysis. The CFRP truss was 77% lighter than the steel truss. It was also concluded that the shape of sections used in steel can be adopted for CFRP structures.

Keywords: CFRP; Roof trusses; FEM and reliability; Structural section; Optimization

Introduction

The roof is the first line of defence between any building and the element, and a good working roof is crucial to the survival of a historic building. However, despite its importance, a roof can be the most neglected part of a building. Many owners never make it to roof level to carry out even the most basic maintenance inspections of the roof fabric and the rain water drainage system. This is usually very unfair unless the builders were certain about the quality of material used for the roofing.

Carbon Fibre Reinforced Polymer (CFRP) is currently used to retrofit and repair structurally deficient infrastructures such as bridges, buildings and roof trusses. These composite materials are gaining recognition in civil engineering as a viable alternative to traditional material. The migration from customary automotive, marine, aerospace and military industries into civil engineering has continued to gain momentum over the last three decades as new civil engineering develops [1].

The main impetus for development of carbon fibres has come from the aerospace industry with its need for a material with combination of high strength, high stiffness and low weight. Recently, civil engineers and construction industries have begun to realize that this material (CFRP) has potential to provide remedies for many problems associated with deterioration and strengthening of infrastructure. Effective use of carbon fibre reinforced polymer could significantly increase the life of structures, minimizing the maintenance requirements [1]. Carbon fibre composites provide an alternative to conventional materials, for example steel, aluminum and fiberglass; for the construction of light weight truss and frame structures which is particularly considered in this study. A steel truss section is compared with CFRP section materials and various advantages of the CFRP were deduced.

Generally, as obtained from various studies and researches, properties and advantages of the characteristic property of Carbon Fibre Reinforced Plastics over conventional materials in structure includes [2]:

a) Corrosion resistance in highly acidic environments
b) Thermal and electrical non conductivity
c) Lightweight (weighs about 80% less than steel)
d) High strength to weight ratio
e) Dimension stability
f) Low maintenance and
g) Custom colours.

Further properties are [1]:

i) Short curing times. This saves time in its application in structures.
ii) High fatigue resistance and generally non bio-degradable.
iii) Non-magnetic
iv) Alkali resistant
v) Displays appreciable bond characteristics in reinforced concrete application.
However, steel is found to be deficient in most of the above listed advantages of CFRP. Some of those deficiencies that must be considered in using steel sections for roof truss in particular are:

a) Installation complexity: steel is less forgiving of installation errors than traditional materials when used for roofing. Leaks are possible if panel joint are not watertight or if the panel screws are not in the correct place

b) Proximity to corrosion in high acidic environment

c) Thermal and electric conductivity which can pose unnecessary danger during unusual lightning and thunder storms. Also in the case of fire, heat can easily be transmitted via the steel material.

d) Heavy weight of steel material.

In all the above listed factors, the replacement of the steel material in roof truss with Carbon Fibre Reinforced Plastic (CFRP) can be conceived as resourceful idea. This is the main justification of this research.

**Scope, Aim and Objectives**

The scope of this study covers the effectiveness of Carbon Fibre Reinforced Plastic (CFRP) as a better replacement material for steel in roof trusses. The study highlights the various properties of both materials.

Finite element method using PROKON v2.4 software [3] will be used in running analysis on two designed truss structure built with steel and CFRP. Both trusses assume same section sizes and loading conditions but different materials. Results will be drawn out and comparisons and conclusions would be made.

**Limitations of the Study**

This topic of effectiveness of CFRP roof truss section over steel is one that cannot be exhausted. There are several parameters and methods which can be used to compare the effectiveness which is not discussed in this study due to limited resources. Also, practical tests were not conducted to know the properties of both materials in order to validate the values we obtained and adopted from literatures and theories. The sources of the values used are properly referenced. Below are some other limitations.

a) There are no much literature on the study of CFRP materials and its application as a roofing material.

b) CFRP materials are quite expensive and therefore, it discourages possibility of practical in research projects.

c) Due to the non-availability of CFRP, high precision and accurate results that can be adopted for real life practicality cannot be guaranteed from this study. This research only probes into the possibility of CFRP as a roof section material and its effectiveness. It is therefore open for development and further research.

CFRP is just a stem out of the whole FRP family. Others include Aramid fibre reinforced plastic (AFRP) and Glass fibre reinforced plastic (GFRP). The difference between them is their fibre material. In CFRP, the reinforcing fibre is carbon fibre. Determining the strength of FRPs has been a bit of argument. This is because fibre/resin combination is what determines the strength (tensile, yield, young’s modulus, etc) of the final FRP product which is dependent on the taste of the manufacturer. So there are no specifications yet for the grade of the material. All that is still available is the range of strength that can be adopted for research study. This also is a limitation.

**Methodology**

**PROKON**

PROKON is a structural analysis and design suite useful for solving everyday building design problems. The PROKON has two main components with distinct but supplementary functions [3]

The **calcpad**: This is the main module from where you launch the analysis and design modules. You can use calcpad to build calcsheets with design notes, drawings and equations.

The **analysis and design modules**: These individual modules can be used to analyse and design typical structural and geotechnical elements. Design output can be sent to calcpad and appended to your calcsheet.

**Frame analysis**

Frame can be used for the analysis of 2D and 3D structures. By selecting the domain, frame input can be limited or expanded to include various degrees of freedom:

a) Plane Frame: Analysis of a frame in a vertical (X - Y) plane.

b) Grillage: Analysis of a structure in a horizontal (X - Z) plane.

c) Space Frame: Analysis of three-dimensional structures made up of beam and/or shell elements and design of concrete shells.

d) Space Truss: Analysis of three-dimensional trusses where only axial forces are considered.

**Finite element analysis**

Frame allows one to use finite shell elements and solid elements alongside normal beam elements. Shell elements enable one to model the combination of plate bending and membrane action in 3D, and solid elements provide for complex 3D stress analysis. For easy modelling of plate bending in concrete slabs, one may prefer using the Finite Element Slab Design module instead.

**Linking with design**

Frame analysis results can be post-processed using many steel and concrete design modules. One can fast-track the design of a steel portal frame, its connections and concrete footings from within Frame.

**Analysis modes**

The following types of analysis are possible in PROKON:
**Linear analysis:** Basic linear elastic analysis. A linear analysis is normally sufficient for the static analysis of a frame or truss with negligible sway. This analysis mode in particular is the one considered for the study.

**Second order analysis:** Choose this mode to include p-delta effects in the analysis. This option is recommended for structures where sway may have a marked effect on the member forces, e.g., portal frames. The second order analysis is an iterative procedure. The total strain energy of the frame is calculated after each iteration. The analysis is deemed to have converged once the total strain energy of two sequential iterations differs by less than the specified tolerance. If convergence was not possible, e.g., structural instability due to buckling of critical members, a message to that effect will be displayed.

**Non linear analysis:** Choose this mode where non-linear effects and large deflections may be expected or where second order analysis might not provide sufficient accuracy. Loading is applied in a series of steps and an iterative analysis is carried out at each step so that the forces in the deflected structure at that point balance with the applied loading.

**Modal analysis:** For calculating the natural modes of vibration. The modal analysis is an iterative procedure during which several sets of trial vectors are selected and evaluated. The process takes relatively long to complete and it is therefore recommended that the structure size be limited to a few hundred nodes. One can specify the number of mode shapes to be calculated and other dynamic analysis parameters.

**Harmonic analysis:** Choose harmonic analysis to determine the response of the frame to harmonic loading. Load amplitudes are entered exactly like static nodal and element loads. One can enter a load frequency and phase angle for each harmonic load case. The first step of a harmonic analysis is the calculation of the frame’s natural modes of vibration. Therefore, if preceded by a modal analysis, the results of that analysis are re-used and only the harmonic response calculated. The harmonic response is taken as the sum of the square (SSRS) of the maximum modal responses, a method that is considered fundamentally sound when modal frequencies are well separated. When frequencies of major contributing modes are very close together, the SSRS method can give poor results.

**Earthquake analysis:** Use this option to calculate the response of the frame to the specified seismic acceleration parameters. Nodal and element loads entered are treated as static loads. The analysis procedure starts by calculating the frame’s natural modes of vibration. Therefore, if preceded by a modal analysis, the results of the modal analysis are re-used and only the seismic response calculated.

**Buckling analysis:** Use this option to determine the buckling load factors and mode shapes for each load case or combination. Being the critical case, the first buckling mode shape is normally the only one of interest.

For the scope of this study, we will be concentrating on linear and modal analysis.

**The PROKON Interface**

The figure below shows the sample of the subdivided warren roof truss as it is in the PROKON software interface during input. The tables below give a brief of some of the inputs made into the software before analysis (Figure 1 and Table 1 & 2).

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**Table 1:** Configuration.

| Span (m)      | 18  |
|--------------|-----|
| Eaves Height (m) | 2   |
| No. of Panels | 8   |
| Fixity Left (XYZxyz) |       |
| Fixity Right (XYZxyz) |       |
| No. of Truss in Line | 1   |
| No. of Bays | 1   |
| Bay Spacing (m) | 1   |

| Truss End Depth (m) | 5   |
|---------------------|-----|
| Material            | Steel 350W/CFRP |

**Table 2:** Designation.

| Top Chord | 100x100x8 |
| Bottom Chord | 90x90x8 |
| Vertical   | 70x70x6  |
| Diagonal   | 60x60x6  |
Examples, Analysis and Results

In this chapter the results obtained from the finite element analysis using PROKON is attached. Several variations between the steel section materials and the CFRP section materials were observed. From each of the categories of the result, several differences were obtained between the results of CFRP structural sections and steel structural section material in roof truss. The details of the geometry, type of truss considered, loading conditions and all necessary structural section inputs are given in the PROKON (FEM) result attached to this chapter.

The research is based on several assumptions which are stated in the section above. The results obtained from both materials were different and comparable because of the variation of the basic intrinsic properties of both materials edited into the PROKON section table (refer to PROKON INTERFACE AND TABLES), even though both structures were subjected to the same loading conditions.

Results

Figure 2-24 and Table 3
**Figure 3:**

**Figure 4:**
Figure 5:

![Figure 5 Image]

Figure 6:

![Figure 6 Image]
Figure 7:

Figure 8:
Figure 13:

Figure 14:
Figure 15:

![Figure 15](image1)

Figure 16:

![Figure 16](image2)
Table 1: Summary of Static Analysis Results

| Section   | Mode Shape | Load Case | Load | Displacement (mm) |
|-----------|------------|-----------|------|-------------------|
| Main Beam | 1          | Line Load | 1    | 0.123             |
|           | 2          | Line Load | 2    | 0.134             |

Figure 19:

Figure 20:
Figure 23:

Figure 24:
**Table 3:** Properties of steel and CFRP.

| Designation | E (kPa) | Poisson | Density kN/m² | Exp. Coeff |
|-------------|---------|---------|---------------|------------|
| STEEL 350W  | 200.0E⁶ | 0.3     | 77.00         | 11.70E⁶    |
| CFRP        | 135.0E⁶ | 0.77    | 17.65         | 2.160E⁶    |

**Discussion of Result**

From the results obtained from Finite Element Analysis using PROKON software, there are several differences but the pronounced difference is obtained from the section weights outlined below (Table 4).

**Table 4:** This gives 77% weight saving for steel when CFRP is used. This shows that the steel truss is about five times heavier than the CFRP truss.

| Section Designation | WT (Steel) | WT(CFRP) |
|---------------------|------------|----------|
| T chord 100×100×8   | 226.7kg    | 52.0kg   |
| A1                  |            |          |
| B chord 90×90×8     | 196.4kg    | 45.0kg   |
| A1                  |            |          |
| Vertical 70×70×6     | 176.4kg    | 40.4kg   |
| A1                  |            |          |
| Diagonal 60×60×6    | 171.4kg    | 39.3kg   |
| A1                  |            |          |
|                      | 770.9kg    | 176.7kg  |

**For Linear Analysis**

In the FEM analysis using PROKON software, the steel truss was found to withstand deflection more than the CFRP. In modal analysis, it was obtained that the steel truss vibrate more than the CFRP truss with an average of 0.0244/s and 0.0142/s respectively. This gives an average of 41.8% of vibration saved when CFRP is used instead of steel (Table 5).

**Table 5:**

| Steel               | CFRP                        |
|---------------------|-----------------------------|
| · Max Deflection for DEAD LOAD case | · Max Deflection for DEAD LOAD case |
| X = -0.18mm at node 14 | X = -0.20mm at node 14 |
| Y = -1.34mm at node 12 | Y = -1.5mm at node 12 |

**Conclusion and Recommendations**

The aim of this study is to show the effectiveness of CFRP as a material for the structural sections of a roof truss is achieved as the results obtained from the Finite Element Analysis using PROKON reveals its effectiveness and deficiency as well; depending on the aim and focus of the design. For instance, where the weight of the structure is the subject of consideration in the design, CFRP proves to be more economical by a large percentage from this study. Also, we can deduce that even where strength of the structure is of essence, CFRP can still be considered over steel because the steel truss withstands deflections more than CFRP only with a small difference.

**References**

1. Gunter E (2006) Designing with plastics. Trans Martin Thompson. Hanser Publishers, Munich, Germany.
2. Gopal M (2011).
3. PROKON: version 2.4 Software Consultant (Pty) Ltd.