Stochastic Analysis of Wire-Connected Round Timber Trusses

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Abstract

Round timber, as a by-product of forest thinning, can be used for construction of innovative and attractive wooden structures. It forms an inexpensive source of construction material for agricultural structures in developing countries. Several methods of connecting round timber have been proposed and investigated world-wide. This paper considers a method that uses flitch plate and wire lacing connections to achieve stable, low-cost and durable round timber structures. For the structural designer, however, it is also necessary to have methods for structural analysis of such structures.

This paper discusses a stochastic finite element analysis procedure that was developed and used to analyse round timber trusses made from eucalyptus poles. Static load versus displacement characteristics of the trusses were investigated using full-scale trusses. In the deterministic analysis, the wire-connected joints developed for the purpose were modelled using semi-rigid connection elements. The effects of slip at the joints, and the effects of creep and joint movement over a long time were incorporated in the analysis. In the experimental set-up, only the deflection of the mid-point of the bottom chord of the truss was measured. It was observed that the results from the deterministic analysis compared well to full-scale truss tests.

Keywords: Timber structures, round timber, stochastic analysis, limit states design.

1. Introduction

Round timber has been shown to be an excellent construction material[1,2,3,4]. One advantage of using timber in the round is that the cost and wastage of sawing is eliminated. Another advantage is that round timber possesses a very high proportion of the basic strength of its species, because knots have less effect on the strength of naturally round timber compared with sawn timber. However, consideration of the difficulty of jointing elements of round timber to form structural systems such as roof trusses has tended to dictate the use of sawn timber. The connections should be able to cope with variations in pole diameter and ideally allow members to be connected in the same plane. This paper considers a method that uses flitch plate and wire lacing connections to achieve stable, low-cost and durable round timber structures. The jointing method was adapted from a technique developed at the University of Delft called the steel binding method. Fig. 1 shows a typical end construction for round timber truss joints.

Wire lacings were used to connect the various members into a truss. Bolts were used at the apex and the heel joints to complete the construction of a truss as shown in Fig. 2. The configuration of the full-scale trusses tested in this study is shown in Fig. 3.

The loading experiments described in this paper were conducted to evaluate the short term to medium term load-displacement performance of trusses constructed using Zambian grown *Eucalyptus Grandis* species. Three trusses were tested in this study. The tests were conducted in order to check their behaviour, establish a proven load capacity and provide a degree of assurance for their future use. Furthermore, the designed structure was analysed using probability-based limits-states criteria. The results from the theoretical finite elements analysis were compared with the results of the full-scale truss tests.

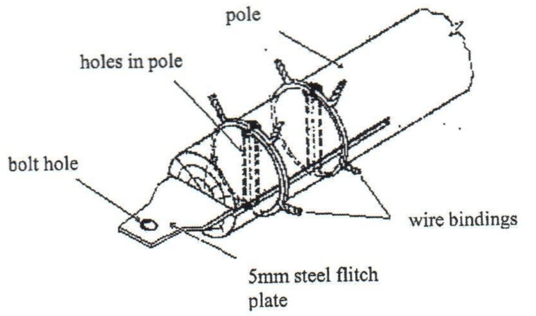

Figure 1: Flitch plate joint with wire lacing

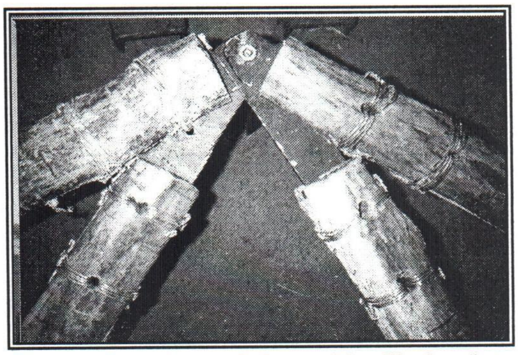

Figure 2: Apex joint with flitch plates and wire lacings

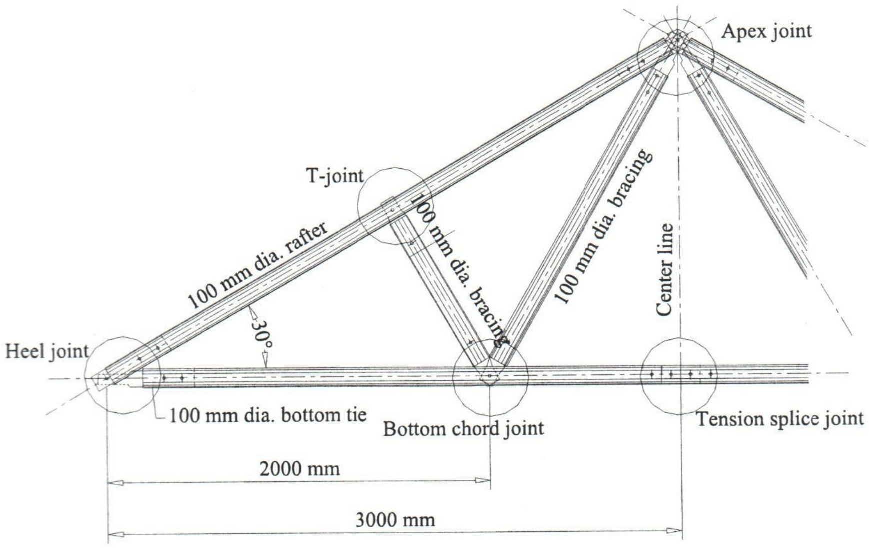

Figure 3: Full-scale round timber truss used for load tests

2. Probability-Based Limits-States Criteria

The trend in modern structural design codes is toward probability-based limits-states criteria using the load and resistance factor design (LRFD) format[5]. In this approach, there is a need to perform probabilistic analyses of structural systems. The limit states design method involves checking the performance of a structure against various limiting conditions at appropriate load levels. The limiting conditions to be checked are ultimate limit states (collapse) and serviceability limit states (deflection). Equation (1) was used as the basic equation for checking the ultimate limit state condition[6]:

$$\varphi R_n = \sum \lambda_i Q_{ni} \qquad (1)$$

Where φ = resistance factor; R_n = nominal resistance; λ_i = load factors; and Q_{ni} = nominal loads applied on the structure.

The current design code for structural use of locally grown timber in Zambia[7] is based largely on the old British Standard for structural timber and does not apply the limit states philosophy.

However, advances in computational capabilities have now made it possible to analyse the behaviour of wood structures using finite element models. Furthermore, recent advances in load modelling and reliability analysis[8,9] allow the system in its entirety to be considered, including stochastic loading and variable material properties.

3. Analysis under Variable Material Properties and Stochastic Loading

3.1 Deterministic Analysis Model

A necessary requirement for a stochastic analysis is an adequate deterministic procedure. Such a procedure is the finite element method (FEM). A FEM computer program was used to analyse the truss. The effects of slip at the joints, the effects of creep and joint movement over a long period of time were accounted for. The basic equations used in this analysis are:

$$KD = P \tag{2}$$

Where K = the structure stiffness matrix; D = the structure nodal displacement matrix in global co-ordinates; and P = the structure nodal load matrix.

Equation (2) can be solved for the unknown nodal displacements, D. In general, each of the terms in Equation (2) is a function of random variables, that is, material properties, section properties, and the loading. The estimates of the mean displacements were determined by solving the equations, evaluated at the mean values of the random variables.

3.2 Strength Properties

The wood properties for the analysis were obtained from ZS 032 (1989)[7] and Lusambo and Mulenga (2004)[10] . The left-hand side of equation (1), the resistance side, includes a resistance factor that is multiplied with the nominal strength values, R. The resistance factor was not available since it is not incorporated in the design code. In order to reflect the inherent variability in strength and consequences of failure, the design strength in LRFD criteria should include such a resistance factor. However, this study was concerned with the right hand side of equation (1). In order to evaluate loads, the mean values of the wood properties used were as follows: mean elastic modulus, $E_m = 11.0 \times 10^3$ N/mm^2 and mean density, $\rho = 540$ kg/m^3.

3.3 Sectional Properties

It is also necessary to use statistical analyses when dealing with sectional properties of timber supplied for construction purposes. This is so because of the variability of sizes supplied on the market which is even greater for roundwood. For example, the major supplier of poles in Zambia quotes pole sizes in groups of a range of "close" diameters. The poles used in this study were considered to have a nominal (average) diameter of 100mm but actually had sizes ranging from 75mm to 120mm with the following statistics: mean diameter = 98.04mm; standard deviation = 9.866; coefficient of variation = 0.101.

3.4 Loading

A structural load is considered to be random process, that is, a function that varies randomly in time. The loading on timber roof trusses includes the dead load, the live load and the wind load. The dead load, D_n, was assumed to be random in intensity but invariant in time, and was modelled simply by a normal variable[8]. The time behaviour of a live load, L_n, on a roof can be considered to be in two parts: a sustained load and an extraordinary (or transient) load. The lifetime maximum sustained live load, L_s, is modelled as the maximum of the various sustained loads a given roof truss supports in its lifetime. Because of the time-dependent nature of the structural behaviour of wood structures, a stochastic model of the entire load process is required[8]. In a reliability-based design code, however, different load factors and combinations may be used for the various load components in considering ultimate and serviceability limit states. It is proposed here that the design of round timber roof trusses be governed by Equation (1) where the factors on the right hand side are as follows[6].

$$\varphi R_n = 1.4D_n + 1.6L_n \qquad (3)$$

Where φ = resistance factor; R_n = nominal resistance; D_n = nominal dead load; L_n = nominal live load.

Having decided on the load components of Equation (3), the design loading was evaluated and was equal to 11.612kN. In undertaking the load calculations, the following design parameters were assumed: (i) roofing materials are asbestos cement sheets weighing $0.16kN/m^3$, (ii) purlins are *E. grandis* with a mean diameter of 100mm, (iii) trusses are spaced at 1200mm centres, and (iv) nominal live load on a plan area is $0.25kN/m^2$ as specified in ZS 016[11].

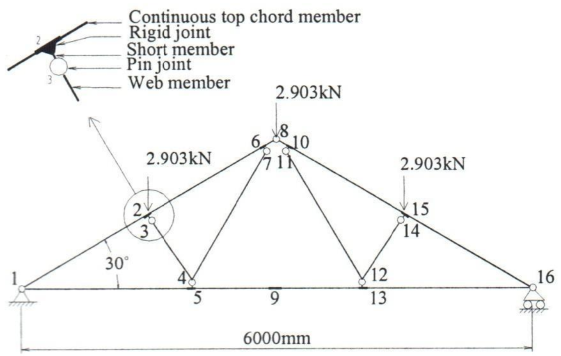

Figure 4: Truss configuration and loading used in the analysis

The truss configuration used in the tests and analysis included top chord and bottom chord members which were continuous at the panel points as shown in Fig. 3. In order to simulate continuity of the members at the panel points labelled 2 and 15 for the top chords, and 5 and 13 for the bottom chord, rigid joints were used. To this were connected stubs or very short members (very short members have very high axial and bending stiffness).

The internal web members were connected to the stubs using pin joints as shown in Fig. 4. The heel joints were simulated using pin joints as was the joint at the apex of the truss.

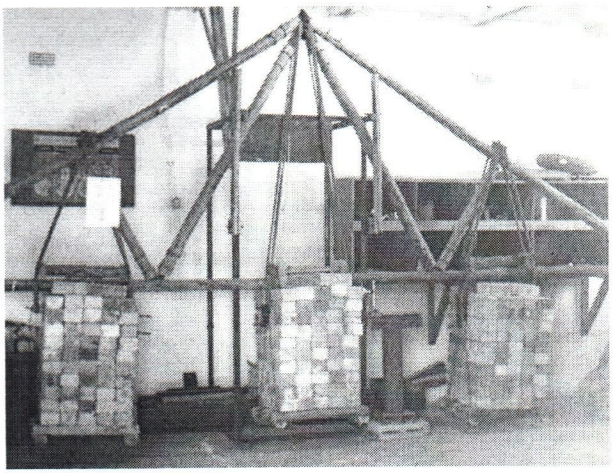

Figure 5: Rig for full-scale loading tests

The loading tests on the trusses were carried out over a period of 4 months in which the vertical displacements of the bottom chords were monitored on a daily basis. Only one truss configuration was considered, that is, the Fink truss. The loading on the truss was applied at the top chord joints using cables and loading platforms as shown in Fig. 5. The trusses were loaded when the average moisture content of the wood was 15.8%. This was close to the moisture content the trusses would attain in service, estimated at 15 per cent.

4.0 Results

4.1 Experimental Study

The deflections at the mid-span of the bottom chords of the trusses were plotted against time as shown in Fig. 6. These curves represent the usual time-dependent creep deflection in wooden structures. The results are summarized in Table 1.

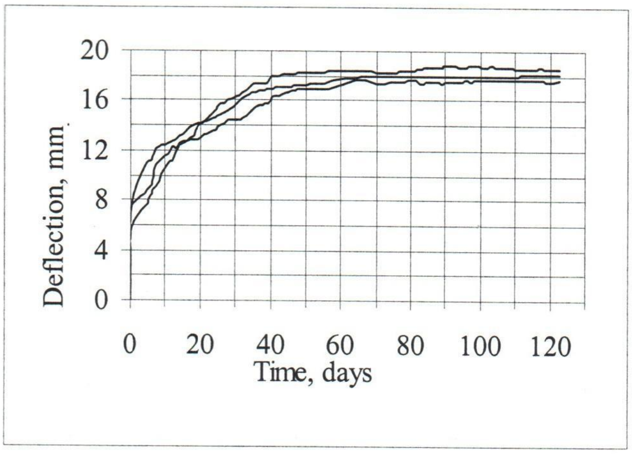

Fig. 6 Load-deflection curves for long term loading test on round timber trusses

The deflection that occurred 5 minutes after application of full design load was considered to be a direct result of the instantaneous elastic deformation of the members and slip at the joints due to the stresses induced in the members and at the joints. The final deflections of the trusses after 4 months (120 days) of sustained loading were considered as being due to creep deflection. It has been mentioned in the literature[12] that creep behaviour of timber structures can be of great importance and should be incorporated in the design considerations.

Table 1 Summary of loading tests - Mean values

Initial deflection after 5min. (mm)	Deflection after 2 months (mm)	Creep deflection (mm)	Ratio of creep deflection to initial deflection
7.3	18.1	10.8	1.48

It has also been mentioned that in timber trusses, the connections used to join the timber members together into a truss make a considerable contribution to the creep deformations. For example, BS5268: Part 3[13] recommends that for trussed rafters, calculated deflections should be multiplied by 1.25 to allow for long term effects due to creep deflection and joint movement. In this study, the factor was found to be equal to 1.48 as shown in Table 1.

4.2 Theoretical Analysis

Using finite elements analysis software, the vertical deflection of the mid-point of the bottom chord at joint 9 in Fig. 4 was found to be equal to 1.73mm. This deflection was due to the contributions of the elastic deformations of the truss members to the total deflection at joint 9. To this deflection must be added the contributions due to slip at the various joints. It is very difficult to account for the contributions of all the slips at all the joints of the truss to the vertical deflection of the mid-point of the truss. Empirical methods have been suggested to carry out this analysis for various types of structures. For example, Clause 16 of BS5268, Part 3[13] suggests that for trussed rafters, slips may be calculated as the summation:

$$\sum F_u sn \qquad (4)$$

Where F_u is the force in each member due to a unit load applied at the node point where deflection is to be calculated, s is the slip of the nail or tooth at maximum permissible load, and n is the number of components of slip per member.

In this analysis, only the contribution of slip at the heel joints and the tensile splice joints were considered. It was considered that the slip at the joints connecting the internal web members and the apex joint would not make any significant contribution to the deflection of the mid-point of the bottom chord. The joint slips at maximum permissible load were obtained from the results of the joint tests conducted by Lusambo[4] who gave a value of 10.03mm. The total deflection of joint 9 is, therefore, equal to the sum of the elastic deflection and the slip deflection, that is, 1.73 + 10.03 = 11.76mm. Using the recommended factor of 1.25 to account for creep deflection, the total deflection was found to be equal to 11.76 x 1.25 = 14.7mm. If a factor of 1.48 is used, as suggested by the results of the tests in this study, then the total deflection is 11.76 x 1.48 = 17.4mm. The latter value is quite close to the long-term deflection found from the experiments, i.e. 18.1mm.

5.0 Discussion

The average initial deflection of the trusses was 0.62 of the theoretical result (i.e. 7.34/11.76). Therefore, the theoretical analysis was found to over-predict the deflections. The reasons for the over-estimations may be due to the fact that the simulation of the semi-rigid joints may not have fully represented the actual joints of the truss. Furthermore, the slip deflection was empirically calculated using slip that would occur at the permissible load for the joint, whereas, the actual slip may in fact be less because the loads at the joints were not actually equal to the permissible loads.

6.0 Conclusion

This study has demonstrated the use of probability-based limits-states criteria in arriving at the design load for the round timber trusses. Further work is required to determine what factors should be used in timber design practice in Zambia.

The closeness of the theoretical and experimental results demonstrates that the finite elements method may be used with confidence to analyze round timber trusses for deflections and member forces just like for other types of structures.

7.0 References

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