Behaviour of nailed timber box beams

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Abstract—**Experimental investigations on nailed built up timber box beams of different cross sectional profiles in which the flanges and webs are both entirely of timber are carried out with the objective of understanding the behaviour of the different nailed built up beam configurations and identify their potential as an alternative to the use of solid timber beams. In particular the effect of web thickness, overall depth and shape of flange on the load carrying capacity and flexural rigidity of timber box beams are investigated.**

Timber beams consisting of webs of 25 mm thickness and overall depth of 225 mm are the most cost effective. The profile of the flange does not have a significant effect on either the load carrying capacity or flexural rigidity. It is observed that flexural rigidity and load capacity are better correlated with the second moment of area and section modulus of only the webs of the box beam rather than that of the entire box beam.

Keywords—nailed timberbox beams; flexural rigidity, moment capacity

I. INTRODUCTION

A. Background

Timber is unique among construction materials in that it is a renewable resource. It has an added advantage that the manufacture of timber from the tree consumes less energy and causes less pollution when compared to other construction materials. However, today, timber is increasingly becoming a scarce resource due to indiscriminate felling of trees. An endless supply of timber and timber based materials can be ensured with the adoption of prudent forestry management techniques and using timber with care so that its full potential is realised.

The size of a tree determines the maximum dimensions of the timber section that are produced. Large cross sections of timber are difficult to obtain and are very costly. Adopting the familiar structural principle of the I beam (a pair of flanges separated by a web) as the most efficient cross sectional profile for bending action, timber and plywood have been combined to build up beams that span distances that solid timber beams alone cannot. Built up timber box beams are a means of value addition to small dimension timber and board materials which otherwise have limited application thereby ensuring the conservation of the timber resource.

It is reported that built-up beams with plywood webs and solid timber flanges were widely used since the mid 20^{th} century [1]. It has been later reported that the solid timber flanges are being replaced by laminated veneer lumber (LVL) and that the plywood webs are being replaced by oriented strand board (OSB) [2] These built up beams are assumed to utilise the material more effectively as the bending stresses are resisted by the flanges and the shear stress is resisted by web. Using this principle a range of cross sectional profiles could be built up. The flanges are connected to the webs either by nailing or gluing. More recently a study on the influence of cross section on the strength of timber beams confirmed that the boxed I beam displayed better structural performance in terms of flexural rigidity and bending and shear capacity relative to the other beam profiles tested [3].

An extensive review of literature on the state of the art of built up beams has been made in 1974 [4]. The performance of ply-web beams in service has been examined and key areas in the design and manufacture which were of concern were identified in [5].

The deformation due to shear and nail distortions make the analysis of nailed built up sections difficult. The effect of nail slip in nailed plywood web box beams was analysed by Booth [1] who provided a solution for a box beam that is simply supported and carries a uniformly distributed load. The behaviour of the beam is represented by a second order differential equation, solutions which are presented in the form of charts. An alternative method is presented in [6] where they develop an approximate and conservative method of modelling the deformation in nailed thin webbed timber box beams, which could be combined with commercially available software.

B. Rationale

The strength and stiffness capacity of built up beams depend not only on the material properties of the plywood and timber used but also on the beam configuration and method of connection. Most research work carried out on the behaviour of built up beams relates to glued cross-sections rather than nailed cross sections. It was in this context that a series of experimental investigations on nailed built up timber/plywood box beams of different cross sectional profiles that were carried out by final year undergraduates under the supervision of the writer with view to understand the behaviour of different nailed built up beam configurations and identify their potential as an alternative to the use of solid timber beams (Hettiarachchi, 7).

The studies showed the definite potential of combining small dimension timber which otherwise is of limited use, with plywood webs of suitable thickness in the form of built up ply box beams. The experiments identified that the built-up beams have a similar flexural rigidity to that of solid timber beams and while they exhibit a lower ductility, they are suitable where limiting deflection is the governing criterion in the design of the timber beam. It was also observed that while the timber flanges are expected to carry the bending stresses and the plywood web the shear stress, the failure modes indicated that the plywood web failed in bending in the tension zone, contrary to what was anticipated. A possible reason was that the available plywood was not of the quality used in structural applications. Since structural plywood is not readily available in Sri Lanka, the potential for using such built up timber ply-web beams is limited and would incur greater cost.

This paper discusses a series of pioneering experimental investigations on nailed built up timber box beams of different cross sectional profiles in which the flanges and webs are both entirely of timber with a view to understand the behaviour of the different nailed built up beam configurations and identify their potential as an alternative to the use of solid timber beams. No literature was available on such all timber box beam construction.

C. *Aim and Objective*

The aim of this research study on the behaviour of built up timber box beams is to promote the use of such built up beams for structural applications in Sri Lanka by providing adequate design guidance with respect to the configuration, in particular the choice of web thickness, overall depth, shape of flange. The specific objectives are

- to identify if any, the most appropriate and effective configuration in relation to the structural behaviour of the beam, through a series of tests on nailed timber box beams of different configurations; i.e. the dimensions of the component members.
- recommend simplified methods to determine the load carrying capacity and flexural rigidity of built up nailed timber box beams

II EXPERIMENTAL INVESTIGATIONS

A. *Effect of Beam Configuration*

Six nailed timber box beams of different cross sectional profiles in which the two flanges and two webs were both entirely of Ginisapu timber were built up and tested in bending. All beams were 1800 mm long and tested under two point loads at approximately 1/3rd the span as shown in Fig: 1.

Fig: 1 – Two point loading system for box beams

The salient dimensions of the different box beam configurations are given in Table 1.

Table 1 – Salient Dimensions of the timber box beams

Beam	Overall Depth H (mm)	Flange width b (mm)	Flange width a (mm)	Total web thickness t (mm)
1	151.2	47.3	43.3	46.8
2	226.0	46.1	47.1	24.7
3	226.0	46.5	47.5	46.6
4	223.3	45.7	46.3	37.2
5	303.0	45.5	46.3	49.6
6	228.9	102.5	24.7	48.3

The load deflection curves are shown in Fig: 2.

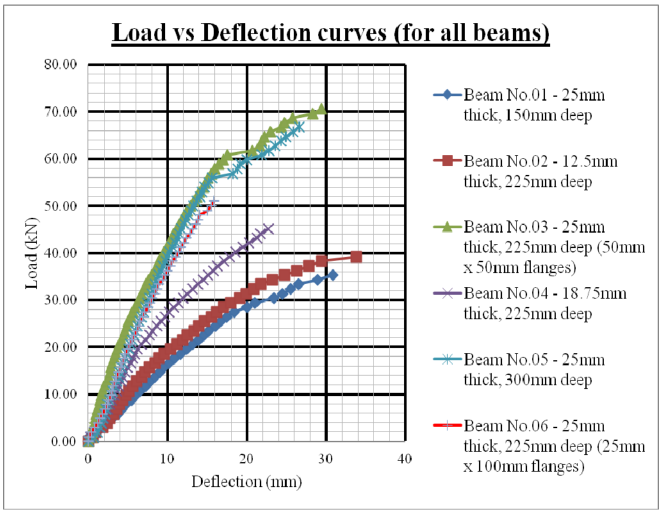

Fig: 2 - Load deflection curves

A summary of experimental loads for the different beams tested is provided in Table 2.

Table 2 – Summary of experimental loads for the different beams

Beam	1	2	3	4	5	6
Maximum Load (kN)	36	40	72	45	67	78
Load at 0.003 span (kN)	10	12	29	19	23	23
Ratio of Maximum to Load at 0.003 span	3.6	3.33	2.48	2.37	2.91	3.39

It is noted from Table 2 that the maximum load exceeds the load that causes mid span deflection of 0.003 of the span, by a factor or 2.4 to 3.6 thus providing sufficient warning of failure.

The effect of web thickness was studied by testing three timber box beams each of 225 mm nominal overall depth and 12.5, 18.75 and 25 mm thick timber planks. It is observed from Fig: 2, that as the web thickness increases, the ultimate load carrying capacity increases from 40 kN to 70 kN. The load at mid span deflection of 6 mm (0.003 of the span) increases from 12 kN to 29 kN indicating an increase in the flexural rigidity of the box beams with thicker webs.

The effect of overall depth was studied by testing three timber box beams each of 150 mm, 225 mm and 300 mm nominal overall depth and 25 mm thick planks. An almost two-fold increase is observed in load carrying capacity for the two deeper beams compared to that of the 150 mm deep beam. However it is also noted that the difference in load carrying capacity and flexural rigidity between the 225 mm deep beam and the 300 mm deep beam is marginal with the 225 mm deep beam displaying a slightly higher capacity and rigidity. This is attributed to the lateral buckling that occurs in the deeper beam. Bearing failure beneath the supports was observed as well in the 300 mm deep beam.

Two timber box beams each of 225 mm nominal overall depth and 25 mm thick webs were built-up using solid timber flanges of the same cross sectional area but of different cross-sectional dimensions. Both beams exhibited a similar flexural rigidity with the wide flanged beam being marginally less.

B. Failure Modes

A timber beam could fail in five different modes; those of bending, shear, bearing, deflection and lateral buckling. Figs: 2a to 2g show the timber box beams after failure.

Fig: 2a clearly illustrates the shear failure that occurred in the box beam that was made of 12.5 mm webs. Failure occurred at the neutral axis where it is subject to the maximum shear stress. Twisting of this beam is also observed.

Fig: 2a – Beam 2 - 12.5 mm web and 225 mm depth

The box beam comprising 25 mm thick webs failed in tension in a web initiated at a knot (Fig: 2b).

Fig: 2b – Beam 3 - 25 mm web and 225 mm depth

Fig: 2c shows the diagonal split that occurred in the box beam with 18.75 mm thick webs. The split is located in the zone between the support and the load point, which is subject to both shear and bending.

Fig: 2c – Beam 4 – 18.75 mm web and 225 mm depth

In the 150 mm deep beam, failure was due to tension failure of the 25 mm thick web as shown in Fig: 2d.

Fig: 2d – Beam 1 - 150 mm deep beam

The failure mode of the deepest beam of 300 mm depth is shown in Fig: 2e. It twisted in the lateral direction and ultimate failure was due to tension failure in the webs and tension flange. Bearing failure was also observed at the support.

Fig: 2e Beam 5 – 300 mm deep beam

In the 225 mm deep beams made up of wide flanges, the beam in which the webs were nailed to the flange, tension failure of the web took place (Fig: 2f).

Fig: 2f – Beam 6 - 25 x 100 mm flange (web nailed to flange)

The second moments of area for the different beams are given in Table 3.

Table 3 – Second moments of area of timber box beams

Beam	I_{xx} (mm^4)	I_{yy} (mm^4)	I_{xx} webs (mm^4)
1	26,043,276	9,929,109	13,480,934
2	59,309,129	5,607,793	23,855,897
3	82,287,352	14,846,510	44,826,000
4	68,417,236	9,562,047	34,516,588
5	185,142,994	20,065,579	114,981,592
6	101,314,318	49,305,189	48,372,830

The effect of beam slenderness on the failure mode is summarised in Table 4.

Table 4 – Effect of Beam slenderness on failure modes

Beam	Ratio of span/depth	I_{xx} / I_{yy}	Failure Mode
1	11.90	2.6	Tension failure of web
2	7.96	10.6	Twisting of beam with shear failure at mid height of web
3	7.96	5.5	Tension failure of web
4	8.06	7.2	Diagonal splitting of web
5	5.94	9.2	Twisting of beam, Tension failure of webs and bottom flange
6	7.86	2.1	Tension failure of web, splitting at nails

It is seen that the span to depth ratio has no effect as different modes of failure have occurred at the same span to depth ratio. Whereas, the effect of the ratio of second moments of areas about the major and minor axis on the failure mode of the built up beam is clearly evident. Twisting of the beam occurred in those beams with an I_{xx} to I_{yy} ratio of around 10.

Table 5 - Summary of failure modes for plybox beams extracted from Hettiarachchi [7]

Overall depth (mm)	Web thickness (mm)	Ratio of span to depth	Ratio of I_{xx} to I_{yy}	Failure mode
150	9	12	5.46	Bending
300		6	20.71	Twisting
150	18	12	3.19	Bending
300		6	11.59	Bending
150	12	12	4.47	Bending
225		8	9.86	Twisting

This is similar to that obtained from earlier research related to plybox beams constructed with timber and plywood available in Sri Lanka [7].

C. Variation of Flexural rigidity with section properties

Fig: 3 shows the correlation of flexural rigidity with the section modulus of the built up beams. The 300 mm deep beam is excluded as the deflection will includes a component due to shear deflection.

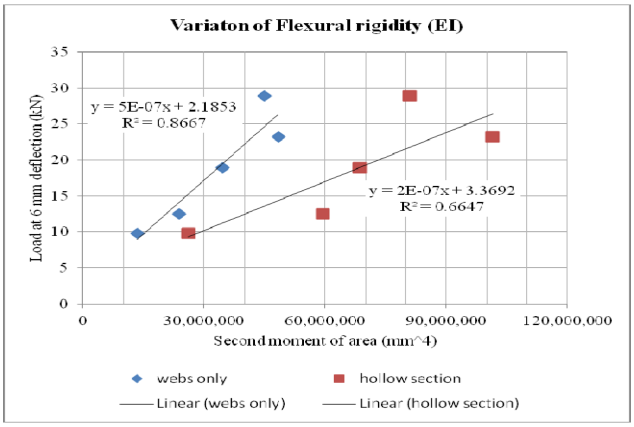

Fig: 3 Variation of Flexural Rigidity of built up beams

A better correlation (R^2 = 0.8667) is obtained with the second moment of area considering only the webs of the box beam than with that of the entire box beam considered as a hollow section (R^2 = 0.6647).

D. Variation of maximum load capacity with section modulus

The variation of maximum load with section modulus considering the beam section as a box section comprising webs and flanges acting together as an integral member and that considering the contribution by the webs only are plotted in Fig: 4.

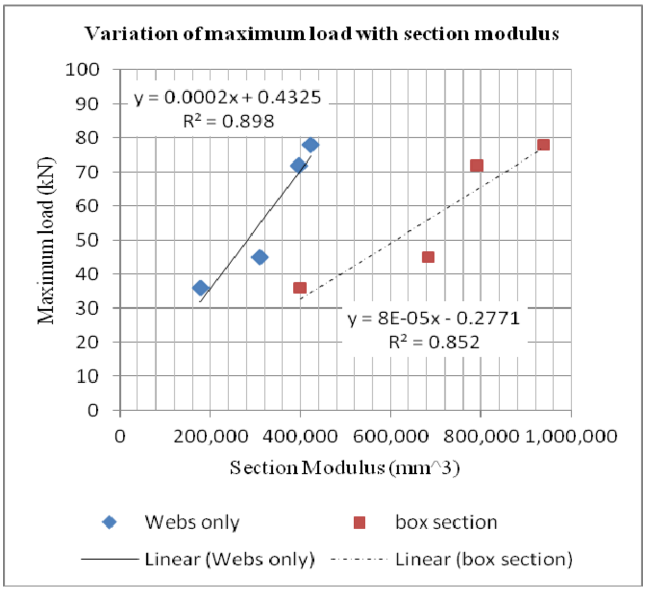

Fig: 4 Variation of load capacity of built up beams with section modulus

Again it is observed that the correlation when considering section modulus of only the webs is higher (R^2 = 0.898) than that considering section modulus of the entire box section (R^2 = 0.852). Beams that twisted are not considered as the mode of failure is that of lateral buckling and not bending failure of the webs.

Tests on timber beams made of Amba (*Mangifera indica*) and Ginisapu (*Michelia champaca*) are discussed in [8]. The Modulus of elasticity and bending strength for each of the timber species were determined from tests on solid timber of cross sectional dimensions 50 mm x 150 mm and are given in table 6.

Table 6 Section Properties

Species	Modulus of Elasticity (N/mm^2)	Bending strength (N/mm^2)
Amba	6635	34.75
Ginisapu	7702	40.55

Two replicates each were tested for each of the species. The built up beam consisted of timber flanges of 50mm x 50mm cross sectional dimensions and timber webs of 25mm thickness x 225mm overall depth. The beam dimensions corresponded to the optimum configuration as found in [9].

A single row of nails at mid height of the flange was used to connect the webs to the top and bottom flanges of the beams. The nails used were of 3mm diameter and 38 mm length. They were spaced at 60 mm intervals along the length of the beam.

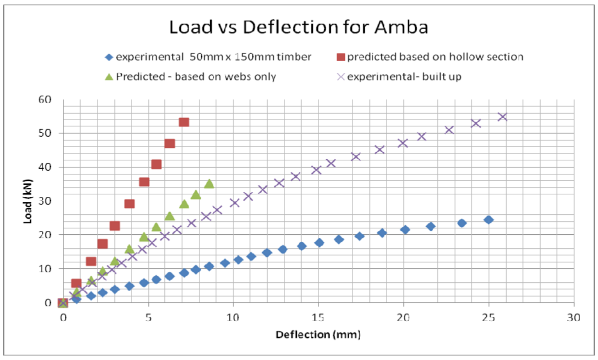

Fig: 5a - Load deflection curve for Amba timber

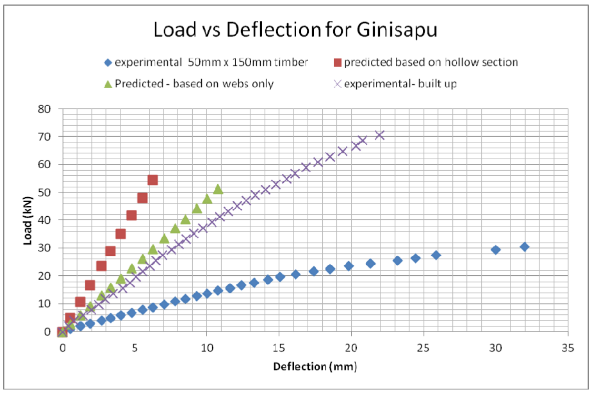

Fig: 5b - Load deflection curve for Ginisapu timber

Vertical deflection of the beam is predicted using the modulus of elasticity determined from Table 4 and second moments of area corresponding to only that of the webs and that of the entire built up section. The values are plotted in Figs 5a and 5b for Amba and Ginisapu timber respectively. It is very clearly seen from Figs: 5a and 5b that the predicted values of deflection corresponding to the entire built up section are significantly less than the experimental deflections at the corresponding load. However, it is observed that the deflection predicted based on a second moment of area corresponding to only that of the webs of the built up section closely matches that of the experimentally obtained deflection of the built up beam, particularly at the initial stages. Similar behavior is observed in both timber species. The deviation is marginally higher in Amba than in Ginisapu. Values are compared at a deflection of 0.003 of the span (4.89mm), which is the maximum allowable deflection in design of timber beams. The experimental load at 4.94 mm in Amba is 82.4% of the predicted value while in Ginisapu the experimental value is 81.2% of the predicted value at a deflection of 5.08 mm.

Table 7 gives the maximum load carrying capacity of the built up beams based on the section modulus of the built up section and that corresponding to that of the webs only.

Table 7 Load Capacity of built up beams

Species	Load capacity (kN)			
	Calculated based on section modulus of		Experimental	
	Built up section	Webs only	Specimen 1	Specimen 2
Amba	109.9	53.96	56.98	54.94
Ginisapu	128.11	62.89	70.63	62.78

It is seen that the values based on the webs only closely match those of the experimental values, indicating that the load is carried by the webs of the built up section and that the flanges are not effective in sharing the load carrying capacity.

III CONCLUSIONS

These studies have shown the potential of combining small dimension timber with timber webs of suitable thickness in the form of built up box beams.

It has been possible to identify optimum dimensions for flanges and webs of such all timber box beams from these experiments. Timber beams consisting of webs of 25 mm thickness and overall depth of 225 mm have been shown to be the most cost effective.

The profile of the flange does not appear to have a significant effect on either the load carrying capacity or flexural rigidity.

It is observed that flexural rigidity and load capacity are better correlated with the second moment of area and section modulus of only the webs of the nailed box beam rather than that of the entire nailed box beam.

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