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APPLICATION OF EUROCODE 5 RECOMMENDATIONS TO BOLTED JOINTS IN SRI LANKAN TIMBER SPECIES

A preliminary experimental investigation

by

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1.Introduction

The design of bolted joints in timber is based on the behaviour of a single fastener under specific conditions with modification factors used to account for different design conditions. Empirical and analytical models have been developed to predict the fastener capacity and the load-deformation relationship. Until recently, national codes tabulated the capacity of dowel type (nailed/bolted) fasteners based on empirical data obtained by testing typical joints of particular geometry under specific conditions. More recent codes, including Eurocode 5 (EC5) have adopted the analytical model proposed originally by Johansen (1949), validated and modified by subsequent researchers. This model assumes that the resistance of the joint is due to the bending resistance of the dowel type fastener and the bearing resistance of the timber.

This paper describes an experimental study that was carried out to ascertain whether the Eurocode recommendations based on the European yield model could be applied to bolted joints in Sri Lankan timber species. The study (Dias et.al. 1998) consisted of testing different configurations of 3 member bolted joints loaded parallel to the grain in different species of timber and comparing the experimental load with that predicted by the European yield model.

2.0 Eurocode recommendations

2.1 Background

The European Yield Model (EYM) was proposed originally by Johansen (1949) to predict the lateral load capacity of dowel type fasteners. It assumes that the resistance of the joint is due to the bending resistance of the dowel fastener and the bearing resistance of the timber. Different modes of failure are identified where either the compressive strength of the timber beneath the fastener is reached while the fastener remains straight or one or more plastic hinges form in the fastener. The failure load corresponding to each mode is determined using equations of equilibrium and assuming load deformation behaviour. The resistance of the joint is given by the minimum of the failure loads determined. The exact failure mode is governed by the joint geometry and the material properties such as the fastener yield moment and the embedding strengths of the timber or wood based materials.

The original work by Johansen (1949) was on bolted joints. Subsequent researchers have demonstrated the applicability of the EYM to a wider range of fasteners. Moller (1951) applied the theory to nailed joints in single and double shear. He developed design charts that help directly identify the failure mode of the joint. Meyer (1957) extended the theory to include frictional effects. Larsen (1973) argued for the inclusion of the yield model in the Scandinavian codes. Hilson et.al. (1987), Rodd et.al. (1987) and Whale et.al. (1989) conducted extensive research to develop a data base for inclusion in the Eurocode 5. BS 5268 (1996), the latest revision, adopts the yield model for the design of dowel type joints. The applicability of the bolted wood joint yield model was tested on American timbers (McLain & Thangjitham 1983, Soltis, Hubbard & Wilkinson 1986, and Soltis & Wilkinson 1987) and EYM based equations are now the basis for the reliability based codes in the United States (McLain et.al. 1993, Wilkinson 1993).

2.2 Design Resistance Equations

The expressions for the design resistance for double shear dowel connected timber joints as given in Eurocode 5: Part 1-1 are given below with their corresponding failure modes. The failure modes are illustrated in Fig: 1. The design resistance per shear plane of the bolted joint is taken as the minimum value of R_d given by equations (1) to (4) for double shear joints.

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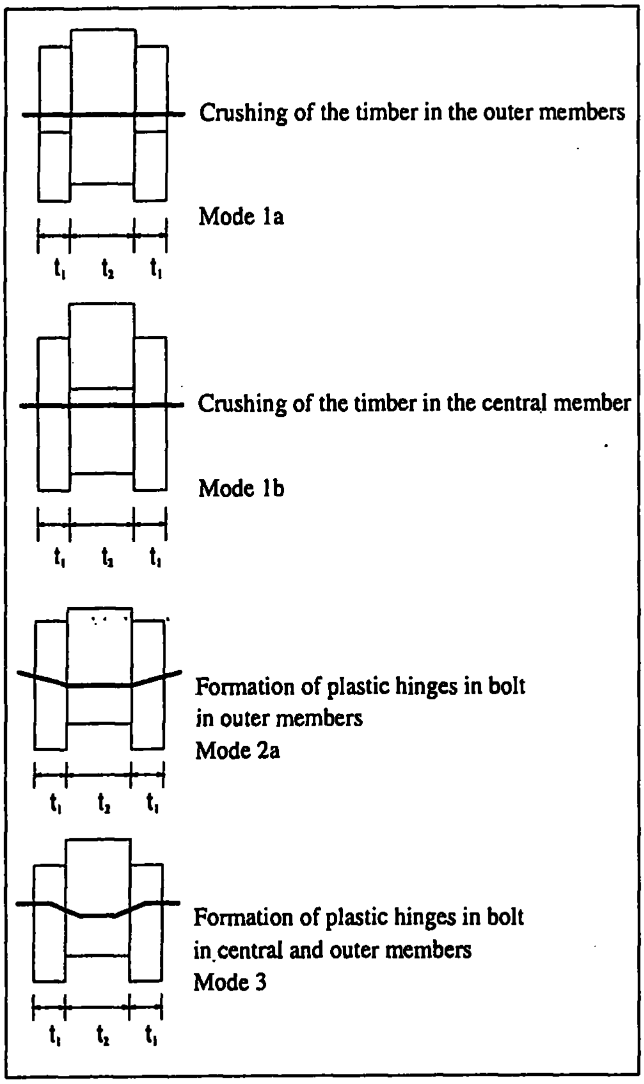

Figure 1: Failure modes of bolted timber joints in double shear

Symmetrical Double shear joints

Mode 1a crushing of the timber in outer member

$$R_d = f_{h,1,d} t_1 d \quad (1)$$

Mode 1b crushing of the timber in central member

$$R_d = 0.5 f_{h,1,d} t_2 d \beta \quad (2)$$

Mode 2a formation of one plastic hinge in the bolt in outer member

$$R_d = 1.1 \frac{f_{h,1,d} t_1 d}{2+\beta} \left[\sqrt{2\beta(1+\beta) \frac{4\beta(2+\beta) M_{y,d}}{f_{h,1,d} d t_1^2}} - \beta \right] \quad (3)$$

Mode 3 formation of plastic hinges in the bolt in central and outer members

$$R_d = 1.1 \sqrt{\frac{2\beta}{1+\beta}} \sqrt{2 M_{y,d} f_{h,1,d} d} \quad (4)$$

In double shear joints t_2 is the central member thickness and t_1 the outer member thickness.

$f_{h,1,k}$ and $f_{h,2,k}$ are the characteristic embedding strengths of outer members 1 and central member 2.

$f_{h,d} = \frac{k_{mod} f_{h,k}}{\gamma_m}$ is the design embedding strength of material with subscripts 1 and 2 referring to members 1 and 2. k_{mod} is the modification factor for service class and duration and γ_m the partial safety factor for timber.

$\beta = \frac{f_{h,2,d}}{f_{h,1,d}}$ is the ratio of embedding strengths of timber

and $\alpha = \frac{t_2}{t_1}$ is the ratio of member thicknesses.

d is the diameter of the bolt. $M_{y,d}$ is the design yield moment of fastener given by $My,d = \frac{M_{y,k}}{\gamma_m}$ where

$M_{y,k}$ is the characteristic yield moment of bolt and γ_m the partial safety factor for bolts.

Since R_d is the design resistance per shear plane, in symmetric double shear joints the lateral load capacity of the joint is $2R_d$.

The Johansen equations have been derived assuming that both the bolt and the timber are ideal rigid plastic materials. This approximation simplifies the analysis and does not make a significant difference to the final result (Hilson, 1995). The factor 1.1 in modes 2 and 3 type failure is to account for the enhanced resistance offered by the friction between the bolt and timber and the constraint produced by the washers or bolt heads when the bolt deforms. This was not accounted for in the theoretical formulation.

2.2.1 Design parameters

The embedding strength of the timber is defined as the average compressive stress at maximum load in a specimen of timber or timber based material under the action of a stiff linear dowel type fastener with the axis of the fastener perpendicular to the surface of the specimen. Since bending of the fastener must be prevented, a special type of joint test is required. In this test the bending deformation of the dowel is minimised by clamping its ends in steel side plates and by limiting the thickness of the specimen to typically twice the dowel diameter. A typical embedment test arrangement is shown in Figure 2.1, with a typical load vs displacement curve in Fig: 2.2. Details on determining the embedding strength of timber are available in EN 383 (1993). Rodd et. al. (1987) describe suitable apparatus for measuring embedding strength.

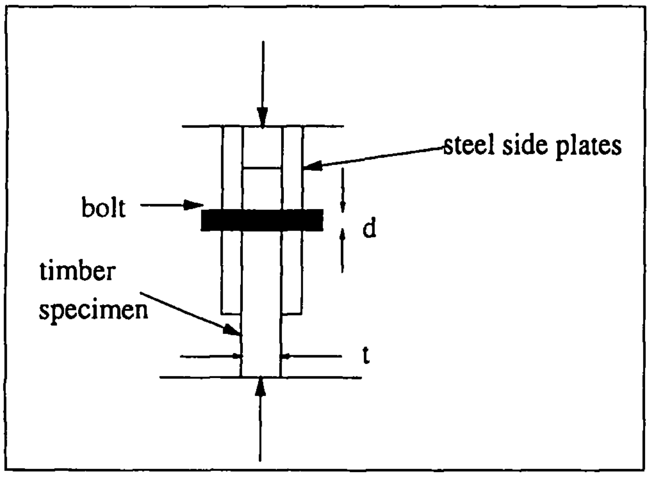

Figure 2.1: Test arrangement to determine embedding strength

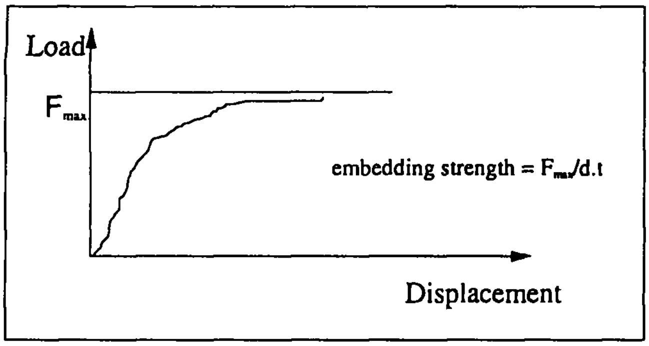

Figure 2.2: Typical load vs displacement curve

The embedding strength depends on the fastener, the manufacture of the joint, the density of timber or the quality of the timber based material.

EC5 recommends the following values for the characteristic embedding strength for bolts up to 30 mm diameter.

for timber stressed parallel to the grain

$$f_{h,0,k} = 0.082(1\text{-}0.01d)\rho_k \text{ N/mm}^2$$

for timber stressed at an angle to the grain;

$$f_{h\theta,k} = \frac{0.082(1\text{-}0.01d)\rho_k}{k_{90}\sin^2\theta + \cos^2\theta} \text{N/mm}^2$$

for hardwoods, $k_{90} = 0.90 + 0.015d$

where ρ_k is the characteristic density in kg/m³ and d is the nail diameter in mm and θ is the direction of load with respect to the grain direction of timber.

The method of determination of the yield moment of dowel type fasteners as given in EN409 is for nails only. It has however, been verified for bolts by Ehlbeck and Werner (1995) who state that in principle it can be used for bolts and dowels.

EC5 recommends the following values for the characteristic yield moment for round steel bolts.

$$M_{y,k} = 0.8f_{u,k} \frac{d^3}{6} \text{ Nmm}$$

Where $f_{u,k}$ is the tensile strength of the fastener in N/mm² and d is the bolt diameter in mm

3.0 Experimental study

3.1 Selection of parameters

The behaviour of bolted timber joints depends on several factors listed in Table 1. This investigation is limited to the study of the more important factors.

3.1.1 Timber species

Palu, a timber of high density and Lunumidella a timber of low density were selected for the study. The timber was obtained from the State Timber Corporation. The bending strength, compression strength and modulus of elasticity were determined for each of these species by testing of small clear specimens according to BS 373(1957). The results are given in Table 2. The density of each piece of timber making up a joint was also determined.

3.1.2 Fastener strength

The effect of fastener strength was not specifically investigated. However, the yield strength and ultimate tensile strength of 10 bolts representing different bolt sizes were determined. Mean yield strength of 397.5 N/mm² and mean ultimate strength of 541.6 N/mm² were obtained for the bolts tested.

3.1.3 Joint details

The study was limited to 3 member symmetrical bolted joints, consisting entirely of timber. The bolts are thus loaded in double shear.

The study covered three sizes of bolts commonly used in Sri Lanka, that of 9.5 mm, 12.7 mm and 15.9 mm diameters. The bolts were obtained from a hardware merchant and washers of the required sizes were turned out at the workshop.

For each species and each bolt diameter, bolted joints of three different geometries were tested. They were such that the outer member thickness to central member thickness was in the ratio 1:1, 1:1.3 or 1:1.4 and 1:2.

Table 1
Factors affecting the behaviour of a bolted timber joint

INTERNAL FACTORS	**Mechanical Properties**	Timber – Compressive strength, Specific Gravity Fastener – bending strength, yield strength
	Joint details	Diameter Length Ratio of length/diameter Number of fasteners Pattern Spacing, end and edge distances Thickness of member Number of shear planes Size of pre-drilled holes
	Physical properties	Coefficient of friction Moisture absorption Natural defects
EXTERNAL FACTORS	**Applied load**	Type – Lateral or withdrawal Direction with respect to grain of timber Duration – short, medium or long
	Service conditions	Moisture content Temperature Humidity

Table 2
Mechanical properties of Palu and Lunumedella

	Palu	**Lunumidella**
Bending strength (N/mm^2)		
Mean	116.0	37.3
Standard Deviation	15.1	8.8
Number of specimens	18	18
Compressive strength (N/mm^2)		
Mean	59.5	15.9
Standard Deviation	5.2	2.4
Number of specimens	40	18
Modulus of elasticity (N/mm^2)		
Mean	10,290	4340
Standard Deviation	1330	1100
Number of specimens	18	18
Density (kg/m^3)		
Mean	1187	360
Standard Deviation	40.3	42.2
Number of specimens	54	54
Moisture content (%)		
Mean	14.9	16.1
Standard Deviation	1.2	0.5
Number of specimens	40	18

The outer member thickness was maintained at 33 mm for the bolted joints of Palu and 38 mm for the bolted joints of Lunumidella. Two replicates of each bolted joint were tested. Thus 18 test specimens of each species were tested. Table 3 gives a summary of the different configurations of joint geometry that were tested.

The recommendations of BS 6948 (1989) were complied with regard to the number of fasteners in each joint, their spacing, end and edge distances. Fig 3.1 and 3.2 give the details.

3.1.4 Physical properties

The effect of coefficient of friction, moisture absorption and natural defects was not studied. However, care was taken in the preparation of the joint to select timber with no defects.

3.1.5 Applied load

The study consisted of testing 3 member bolted timber joints, laterally loaded in compression. The load was applied parallel to the grain of all three members. The rate of loading was such that the time to failure for the joint was typically 10 minutes.

Table 3
Summary of design parameters tested

Species		Palu		Lunumidella	
Bolt diameter (mm)	Number of replicates of joint test specimens	Thicknesses of outer/inner members (mm/mm)	Ratio of thicknesses of outer/inner members	Thicknesses of outer/inner members (mm/mm)	Ratio of thicknesses of outer/inner members
9.5	2	33/33	1:1	38/38	1:1
	2	33/45	1:1.4	38/50	1:1.3
	2	33/75	1:2	38/75	1:2
12.7	2	33/33	1:1	38/38	1:1
	2	33/45	1:1.4	38/50	1:1.3
	2	33/75	1:2	38/75	1:2
15.9	2	33/33	1:1	38/38	1:1
	2	33/45	1:1.4	38/50	1:1.3
	2	33/75	1:2	38/75	1:2

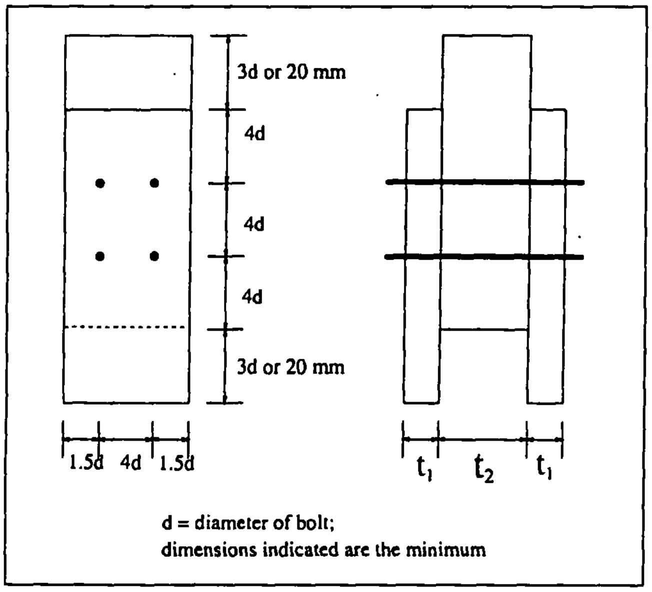

Figure 3.1: Dimensions of test specimen for bolts of diameter 9.5 mm

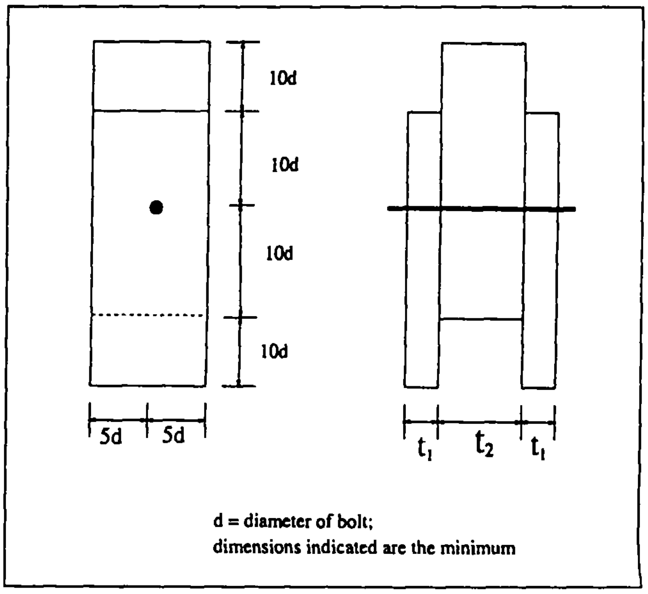

Figure 3.2: Dimensions of test specimen for bolts of diameter 12.7 mm and 15.9 mm

3.1.6 Service conditions

Each bolted joint was assembled at least 24 hours prior to testing. There was no record maintained of moisture content of timber, nor ambient temperature and humidity prevailing at the time of test.

3.2 Experimental procedure

Photograph 1 shows the test apparatus used for the study. The load was applied using the Amsler Universal Testing Machine with a capacity of 200 tonnes. The load was measured using proving rings of 10 tonne or 30 tonne capacity as appropriate. A dial gauge facilitated the measurement of vertical displacement of the joint.

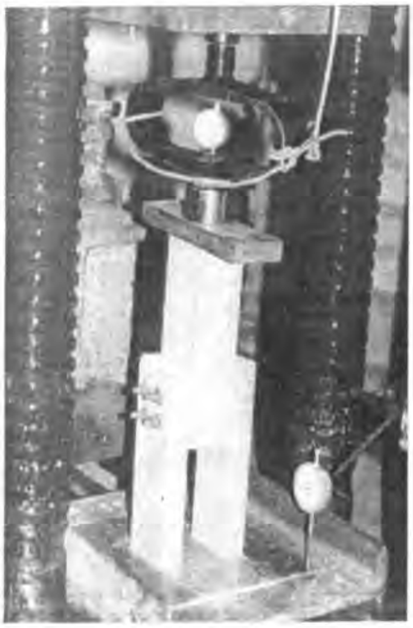

Photo 1: Test Set up

4.0 Results

4.1 Theoretical Results

The lateral resistance per shear plane of the bolted timber joints for each of the species Palu and Lunumidella as given by the Eurocode 5 recommendations is given in Tables 4.1 and 4.2 respectively.

4.1.1 Input data

A spreadsheet was used for the computations.

The values of density used for the study are the mean density of the 3 timber members comprising the bolted timber joint.

All factors of safety were assumed as unity since the actual failure load is required.

Embedding strength was determined using the expressions given in the Eurocode 5 recommendations. The yield strength of the bolt has been assumed as 400 N/mm^2.

4.1.2 Discussion of results

Table 4.1 indicates that the failure mode of the bolted joints of Palu timber consisting of 9.5 mm and 12.7 mm bolts is mode 3 (ie. the formation of plastic hinges in both the central and outer members). Failure in the bolted joints consisting of 15.9 mm bolts occurs with the formation of plastic hinges in the outer members only. The ratio of inner member thickness to outer member thickness has little effect on the values of lateral resistance.

Table 4.2 indicates that the failure mode of the bolted joints of Lunumidella timber consisting of 9.5 mm bolts is mode 2 (ie. the formation of plastic hinges in outer members). Failure in the bolted joints consisting of 12.7 mm and 15.9 mm bolts occurs either with the formation of plastic hinges in the outer members or crushing of the central timber member depending on the ratio of inner member thickness to outer member thickness.

4.2 Experimental results

4.2.1 Load deformation curve

Figs: 4.1 and 4.2 illustrate the load deformation curves for the entire range of bolted joints of Palu and Lunumidella respectively. The load capacity of the 9.5 mm bolted joint, consisting of 4 bolts has been divided by a factor of 4 to determine the capacity corresponding to a single bolt.

The bolted joints of 12.7 and 15.9 mm diameter bolts have a greater stiffness than those of 9 mm bolts. This was more pronounced in the bolted joints of Palu timber.

The largest deflections were associated with bolted joints of outer/inner member thickness ratios of 1:2 while the smallest deflections were associated with outer/inner member thickness ratios of 1:1. This observation is supported by photographic evidence. In the bolted joints where the outer/inner member thickness ratio is 1:2, there is considerable bending of the bolt at failure. In the joints where the outer/inner member thickness ratio is 1:1, there is no visible bending of the bolt and failure is by crushing of the timber.

Table 4.1
Lateral resistance per shear plane for bolted timber joints of Palu as given by Eurocode recommendations

APPLICATION OF EC5 RULES FOR BOLTED JOINTS TO TROPICAL HARDWOODS
SYMMETRICAL DOUBLE SHEAR JOINTS

	DIAMETER OF BOLTS (mm)								
	9.50	12.70	15.90	9.50	12.70	15.90	9.50	12.70	15.90
thickness of outer member(mm)	33	33	33	33	33	33	33	33	33
thickness of central member(mm)	33	33	33	45	45	45	75	75	75
Thickness t1 (mm)	33	33	33	33	33	33	33	33	33
Thickness t2 (mm)	33	33	33	45	45	45	75	75	75
Alpha = ratio of thicknesses t2/t1	1.000	1.000	1.000	1.364	1.364	1.364	2.273	2.273	2.273

DETERMINATION OF YIELD MOMENT OF BOLTS FOR THE DIFFERENT DIAMETERS

Tensile strength (N/mm^2) 400
Material factor of safety 1

Char: bolt yield moment Myk (N.mm)	45727	109247	214383	45727	109247	214383	45727	109247	214383
Design bolt yield moment Myd (N.mn)	45727	109247	214383	45727	109247	214383	45727	109247	214383

DETERMINATION OF EMBEDMENT STRENGTH FOR DIFFERENT SPECIES

k,mod 1
material factor of safety 1

Density of timber (kg/m3)	1203	1167	1220	1248	1204	1151	1057	1166	1196
	1188	1191	1178	1140	1126	1085	1073	1226	1095

Direction of grain w.r.t. load of timber members

outer members	0	0.00
central member	0	0.00

	design embedment strength (with pre-drilling) - f,hd (N/mm2)								
bolt diameter (mm)	9.50	12.70	15.90	9.50	12.70	15.90	9.50	12.70	15.90
outer members	89.27	83.54	84.13	92.61	86.19	79.38	78.44	83.47	82.48
central members	88.16	85.26	81.24	84.60	80.61	74.82	79.63	87.76	75.51
beta = ratio of strengths	0.99	1.02	0.97	0.91	0.94	0.94	1.02	1.05	0.92
mode 1a	27988	35012	44145	29035	36122	41648	24591	34982	43276
mode 1b	13819	17866	21313	18083	23033	26768	28367	41798	45025
mode 2	11707	16314	22526	11921	16456	21480	10510	16391	21962
mode 3	9657	16833	26113	9641	16724	25208	9115	16950	25502
Resistance Rd per shear plane (N)	9657	16314	21313	9641	16456	21480	9115	16391	21962

Mode 1a is the crushing of outer timber members
Mode 1b is the crushing of central timber member
Mode 2 is the formation of plastic hinge in fastener within the outer timber members
Mode 3 is the formation of plastic hinges in fastener within both outer and central timber members

Table 4.1: contd ....

APPLICATION OF EC5 RULES FOR BOLTED JOINTS TO TROPICAL HARDWOODS
SYMMETRICAL DOUBLE SHEAR JOINTS

	DIAMETER OF BOLTS (mm)								
	9.50	12.70	15.90	9.50	12.70	15.90	9.50	12.70	15.90
thickness of outer member(mm)	33	33	33	33	33	33	33	33	33
thickness of central member(mm)	33	33	33	45	45	45	75	75	75
Thickness t1 (mm)	33	33	33	33	33	33	33	33	33
Thickness t2 (mm)	33	33	33	45	45	45	75	75	75
Alpha = ratio of thicknesses t2/t1	1.000	1.000	1.000	1.364	1.364	1.364	2.273	2.273	2.273

DETERMINATION OF YIELD MOMENT OF BOLTS FOR THE DIFFERENT DIAMETERS

Tensile strength (N/mm^2)	400								
Material factor of safety	1								
Char: bolt yield moment Myk (N.mm)	45727	109247	214383	45727	109247	214383	45727	109247	214383
Design bolt yield moment Myd (N.mn)	45727	109247	214383	45727	109247	214383	45727	109247	214383

DETERMINATION OF EMBEDMENT STRENGTH FOR DIFFERENT SPECIES

k,mod	1									
material factor of safety	1									
Density of timber (kg/m3)		1260	1170	1217	1203	1230	1225	1205	1172	1220
		1251	1238	1178	1165	1130	1174	1100	1306	1229

Direction of grain w.r.t. load of timber members		
outer members	0	0.00
central member	0	0.00

	design embedment strength (with pre-drilling) - f,hd (N/mm2)								
bolt diameter (mm)	9.50	12.70	15.90	9.50	12.70	15.90	9.50	12.70	15.90
outer members	93.50	83.76	83.93	89.27	88.05	84.48	89.42	83.90	84.13
central members	92.84	88.62	81.24	86.45	80.89	80.96	81.63	93.49	84.75
beta = ratio of strengths	0.99	1.06	0.97	0.97	0.92	0.96	0.91	1.11	1.01

mode 1a	29314	35102	44036	27988	36902	44326	28034	35162	44145
mode 1b	14552	18571	21313	18480	23115	28964	29081	44525	50535
mode 2	12207	16455	22496	11666	16685	22560	11557	16630	22713
mode 3	9897	17005	26097	9610	16826	26116	9472	17232	26393
Resistance Rd per shear plane (N)	9897	16455	21313	9610	16685	22560	9472	16630	22713

Mode 1a is the crushing of outer timber members
Mode 1b is the crushing of central timber member
Mode 2 is the formation of plastic hinge in fastener within the outer timber members
Mode 3 is the formation of plastic hinges in fastener within both outer and central timber members

Table 4.2
Lateral resistance per shear plane for bolted timber joints of Lunumidella as given by Eurocode recommendations

APPLICATION OF EC5 RULES FOR BOLTED JOINTS TO TROPICAL HARDWOODS

SYMMETRICAL DOUBLE SHEAR JOINTS

	DIAMETER OF BOLTS (mm)								
	9.50	12.70	15.90	9.50	12.70	15.90	9.50	12.70	15.90
thickness of outer member(mm)	38	38	38	38	38	38	38	38	38
thickness of central member(mm)	38	38	38	50	50	50	75	75	75
Thickness t1 (mm)	38	38	38	38	38	38	38	38	38
Thickness t2 (mm)	38	38	38	50	50	50	75	75	75
Alpha = ratio of thicknesses t2/t1	1.000	1.000	1.000	1.316	1.316	1.316	1.974	1.974	1.974

DETERMINATION OF YIELD MOMENT OF BOLTS FOR THE DIFFERENT DIAMETERS

Tensile strength (N/mm^2)	400
Material factor of safety	1

Char: bolt yield moment Myk (N.mm)	45727	109247	214383	45727	109247	214383	45727	109247	214383
Design bolt yield moment Myd (N.mn)	45727	109247	214383	45727	109247	214383	45727	109247	214383

DETERMINATION OF EMBEDMENT STRENGTH LUNUMIDELLA

k,mod	1
material factor of safety	1

Density of timber (kg/m3)	351	488	397	368	336	348	342	348	372
	371	490	342	349	342	237	344	363	382

Direction of grain w.r.t. load of timber members

outer members	0	0.00
central member	0	0.00

	design embedment strength (with pre-drilling) - f,hd (N/mm2)								
bolt diameter (mm)	9.50	12.70	15.90	9.50	12.70	15.90	9.50	12.70	15.90
outer members	26.05	34.93	27.38	27.31	24.05	24.00	25.38	24.91	25.65
central members	27.53	35.08	23.59	25.90	24.48	16.34	25.53	25.99	26.34
beta = ratio of strengths	1.06	1.00	0.86	0.95	1.02	0.68	1.01	1.04	1.03

mode 1a	9403	16859	16542	9859	11608	14500	9162	12022	15500
mode 1b	4970	8464	7125	6151	7773	6497	9094	12376	15707
mode 2	4713	9026	10821	4786	7008	9425	4579	7207	10819
mode 3	5305	10841	14458	5287	9026	12665	5173	9242	14643
Resistance Rd per shear plane (N)	4713	8464	7125	4786	7008	6497	4579	7207	10819

Mode 1a is the crushing of outer timber members
Mode 1b is the crushing of central timber member
Mode 2 is the formation of plastic hinge in fastener within the outer timber members
Mode 3 is the formation of plastic hinges in fastener within both outer and central timber members

Table 4.2: contd ....

APPLICATION OF EC5 RULES FOR BOLTED JOINTS TO TROPICAL HARDWOODS
SYMMETRICAL DOUBLE SHEAR JOINTS

	DIAMETER OF BOLTS (mm)								
	9.50	12.70	15.90	9.50	12.70	15.90	9.50	12.70	15.90
thickness of outer member(mm)	38	38	38	38	38	38	38	38	38
thickness of central member(mm)	38	38	38	50	50	50	75	75	75
Thickness t1 (mm)	38	38	38	38	38	38	38	38	38
Thickness t2 (mm)	38	38	38	50	50	50	75	75	75
Alpha = ratio of thicknesses t2/t1	1.000	1.000	1.000	1.316	1.316	1.316	1.974	1.974	1.974

DETERMINATION OF YIELD MOMENT OF BOLTS FOR THE DIFFERENT DIAMETERS

Tensile strength (N/mm^2)	400								
Material factor of safety	1								
Char: bolt yield moment Myk (N.mm)	45727	109247	214383	45727	109247	214383	45727	109247	214383
Design bolt yield moment Myd (N.mn)	45727	109247	214383	45727	109247	214383	45727	109247	214383

DETERMINATION OF EMBEDMENT STRENGTH LUNUMIDELLA

k,mod	1								
material factor of safety	1								
Density of timber (kg/m3)	367	321	285	353	431	385	309	393	375
	353	286	302	344	350	353	360	369	364

Direction of grain w.r.t. load of timber members

outer members	0	0.00
central member	0	0.00

	design embedment strength (with pre-drilling) - f,hd (N/mm2)								
bolt diameter (mm)	9.50	12.70	15.90	9.50	12.70	15.90	9.50	12.70	15.90
outer members	27.24	22.98	19.65	26.20	30.85	26.55	22.93	28.13	25.86
central members	26.20	20.47	20.83	25.53	25.06	24.34	26.72	26.42	25.10
beta = ratio of strengths	0.96	0.89	1.06	0.97	0.81	0.92	1.17	0.94	0.97
mode 1a	9832	11090	11875	9457	14890	16042	8278	13577	15625
mode 1b	4728	4940	6292	6063	7955	9677	9517	12580	14967
mode 2	4789	6611	9327	4661	7906	10773	4362	7654	10739
mode 3	5299	8527	12916	5214	9636	14475	5094	9565	14497
Resistance Rd per shear plane (N)	4728	4940	6292	4661	7906	9677	4362	7654	10739

Mode 1a is the crushing of outer timber members
Mode 1b is the crushing of central timber member
Mode 2 is the formation of plastic hinge in fastener within the outer timber members
Mode 3 is the formation of plastic hinges in fastener within both outer and central timber members

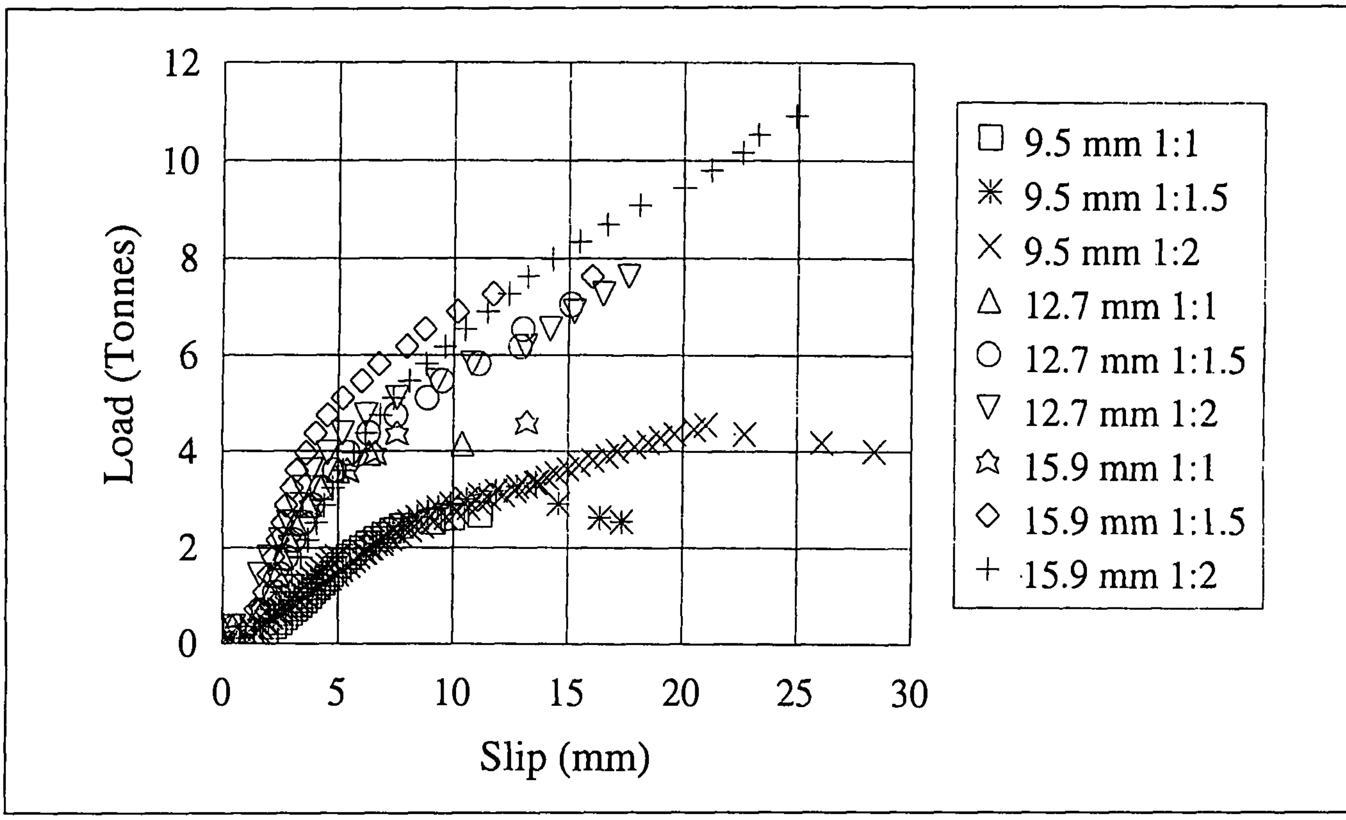

Figure 4.1: Load slip curves for double shear bolted joints of Palu timber

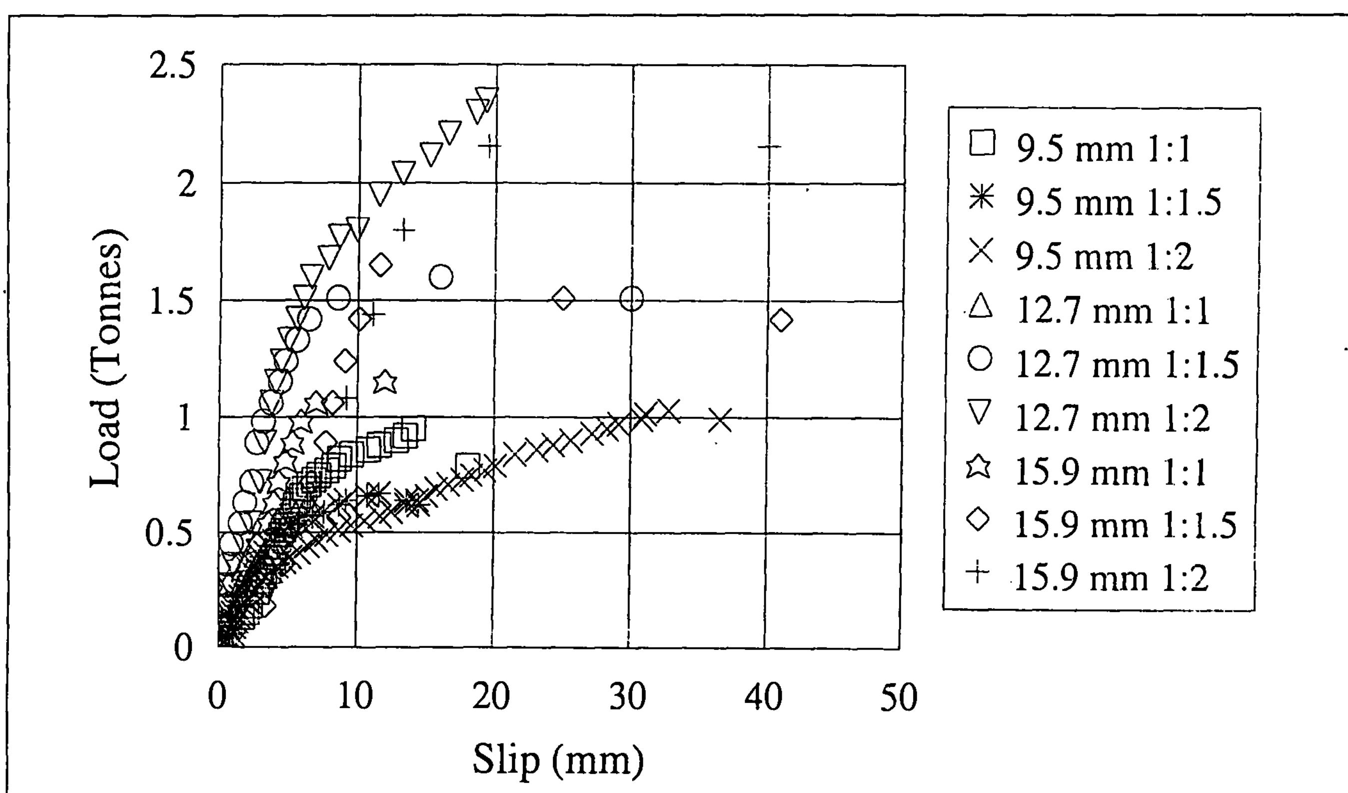

Figure 4.2: Load slip curves for double shear bolted joints of Lunumidella timber

4.2.2 Lateral resistance

The lateral resistance per shear plane has been determined from the load deformation curve. The lateral resistance of the joint is considered as the maximum load on the curve. The values of lateral resistance per shear plane for each of the bolted joints of Palu and Lunumidella are tabulated in Tables 4.3 and 4.4 respectively. For the bolted joints of Palu, the replicate specimens gave very similar results. This was not as evident with the Lunumidella specimens.

Table 4.3
Comparison of predicted and experimental results of bolted joints in Palu timber

Bolt Diameter (mm)	Thicknesses of outer/inner members (mm/mm)	Lateral resistance per shear plane (kN) For bolted timber joints in double shear of Palu timber			
		Set 1		Set 2	
		Expt.	EC5	Expt.	EC5
9.5	33/33	13.18	*9.66*	14.00	*9.90*
	33/45	16.40	*9.64*	16.48	*9.61*
	33/75	22.29	*9.11*	19.88	*9.47*
12.7	33/33	20.36	*16.31*	20.78	*16.45*
	33/45	34.53	*16.39*	30.31	*16.68*
	33/75	37.38	*16.46*	35.86	*16.63*
15.9	33/33	22.51	*21.31*	25.11	*21.31*
	33/45	37.38	*21.48*	38.01	*22.56*
	33/75	53.46	*21.96*	51.70	*22.71*

Table 4.3
Comparison of predicted and experimental results of bolted joints in Lunumidella timber

Bolt Diameter (mm)	Thicknesses of outer/inner members (mm/mm)	Lateral resistance per shear plane (kN) For bolted timber joints in double shear of Lunumidella timber			
		Set 1		Set 2	
		Expt.	EC5	Expt.	EC5
9.5	38/38	3.47	*4.71*	4.66	*4.73*
	38/50	3.06	*4.79*	3.27	*4.66*
	38/75	6.72	*4.58*	5.06	*4.36*
12.7	38/38	5.89	*8.46*	3.08	*4.94*
	38/50	4.36	*7.01*	7.85	*7.91*
	38/75	-	*7.21*	11.53	*7.65*
15.9	38/38	5.20	*7.12*	5.64	*6.29*
	38/50	5.66	*6.50*	8.09	*9.68*
	38/75	10.59	*10.82*	10.59	*10.74*

4.2.3 Failure Patterns

Photographs 2 and 3 show the different failure patterns obtained for the bolted joints tested.

Photograph 2 shows the sectional end elevation of bolted joints of Lunumidella timber consisting of 9.5 mm bolts, with the outer member thickness to central member thickness in ratios of 1:1, 1:1.3 and 1:2.

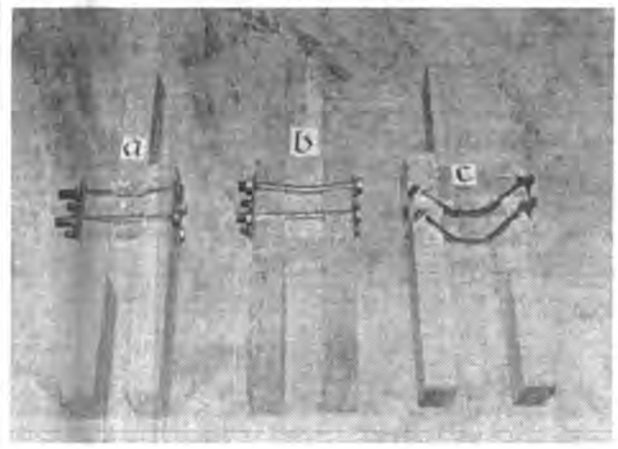

Photo 2: Sectional end elevation of Timber Joints Lunumidella timber and 9.5 mm steel bolts
a - 1:1 b - 1:1.4 c - 1:2

Photograph 3 shows the sectional end elevation of bolted joints of Palu timber consisting of 12.7 mm bolts, with the outer member thickness to central member thickness in ratios of 1:1, 1:1.4 and 1:2.

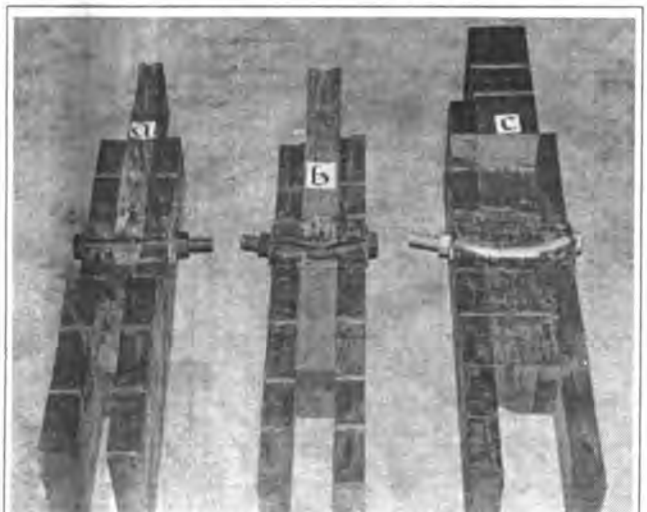

Photo 3: Sectional end elevation of Timber Joints Palu timber and 12.5 mm steel bolts
a - 1:1 b - 1:1.3 c - 1:2

It is seen from these photographs that in the bolted joints consisting of members of equal thickness, failure has occurred by the crushing of timber with hardly any bending of the bolt visible. Whereas, in the bolted joint consisting of a thicker central member, a little bending of the bolt is observed, with more pronounced bending observed in the bolted joint having a ratio of outer member thickness to inner member thickness of 1:2.

4.3 Comparison of results

Eurocode 5 underestimates the lateral resistance in all except one of the bolted joints of Palu that were tested. The best agreement is that for those joints with the ratio of outer member thickness to inner member thickness of 1:1, where the EC5 value is about 71% to 95% of the experimental value. The greatest difference was observed for those joints with the ratio of inner member thickness to inner member thickness of 1:2, where the EC5 value is only about 41% to 48% of the experimental value.

In the majority (14 of the 17 test specimens) of the Lunumidella specimens EC5 overestimates the lateral resistance by a factor of 1.01 to 1.61. The underestimates were in the range 0.66 to 0.88 of the experimental lateral resistance. No specific trends were identified as to the best agreement of EC5 and experimental values.

5.0 Conclusions and recommendations

5.1 Conclusions

This preliminary study based on different configurations of double shear joints of two extreme densities showed that EC5 underestimates the lateral resistance for bolted joints of high density timber, while for bolted joints of low density timber it overestimates the lateral resistance. However, the estimated values are within 40% to 160% of the experimental values. Thus further work is recommended to ascertain whether the Eurocode 5 recommendations could be applied to bolted joints of Sri Lankan timber species, whether any modifications are required and what they are, in order to adopt the EC 5 recommendations for bolted joints of Sri Lankan timber species.

5.2 Recommendations for future work

The embedment strength of Palu and Lunumidella timber were obtained directly from the expression given in the Eurocode 5. No testing was carried out, to verify the applicability of this expression. It is recommended that in future work, the embedment strength too be determined experimentally.

This preliminary test series was limited to timber of two extreme densities; Palu with a very high density and Lunumidella with a very low density. Further work should include timbers of an intermediate density range.

Loading of the bolted timber joints was restricted to the parallel to grain direction of timber. It is recommended that testing of bolted timber joints with the load applied in directions other than the parallel to grain direction should also be carried out.

The outer member thickness of all the bolted timber joints was maintained at 38 mm for those of Lunumidella and 33 mm for those of Palu. It is suggested that the outer member thickness should also be varied in future testing programmes.

6.0 Acknowledgements

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