THE EFFECT OF WASHERS ON BOLTED JOINTS IN TIMBER

by

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Abstract

Washers specified for bolted joints in timber structures are larger and thicker than those specified for bolted joints in steel structures. This important distinction is not clearly evident in local usage of bolted joints in timber structures. Non-adherence to accepted norms of timber engineering as regards washers is encouraged by: (a) Difficulty of purchasing larger washers from the market without placing a special order; (b) Lack of attention to washer sizes in design drawings except the indication of bolt diameters, and (c) Belief of some designers that harder local timber can transfer loads with small washers compared to weaker softwoods used in countries where design codes are drafted. However, there are others who doubt whether use of small washers will substantially reduce the load carrying capacity while adversely affecting the overall performance of a joint. A study on use of washers was considered opportune to investigate whether it is prudent to deviate from accepted norms of timber engineering and use small instead of large washers.

The study consists of testing 108 bolted joints in timber as well as conducting numerous tests on moisture content and relative density of timber, and tensile strength of steel bolts. It covered three types of washer usage (joint without washers, washers specified for steel structures, and washers specified for timber structures) and three ranges of relative density of timber (GINISAPU for low density, KOS for medium density, and HORA for high density).

The investigation demonstrated that larger washers specified for timber structures should be used even for local timber due to higher strength development as well as superior overall performance by minimised initial slip, greater elastic range and ductility to provide adequate warning before failure.

1.0 Introduction

In Sri Lanka timber is used for structural applications such as roofwork, ceiling structures, temporary floors, floors subjected to chemical attack or light loads, formwork, falsework, pedestrian bridges for temporary access or aesthetic considerations, bridge decks of Bailey bridges or short span steel bridges, temporary towers, look out huts at security installations, supports for cofferdams or excavations, and shoring or underpinning of structures in distress.

Jointing of different parts is often a necessity in timber structures and a bolted joint is a well accepted joint type which performs in shear, tension or both. Bolted joints are preferred for: (a) transfer of higher loads at a joint; (b) transfer of loads in permanent structures to make way for easier repair work; (c) situations where joints should be repeatedly engaged and disengaged as in formwork or Bailey bridge decks; (d) jointing harder species of timber; (e) situations where tensile loads should be transferred; and (f) situations where thicker members frame into a joint.

In local usage of bolted joints, a major deviation from the well established norms of timber engineering is the use of smaller washers meant for steel structures instead of larger washers recommended for bolted joints in timber. Sizes of washers for bolted joints in timber structures are specified in CP 112[1] and BS 5268[2] to be thicker and larger than those used in steel structures due to lower bearing stresses that can be resisted by timber. The continuation of the present practice is encouraged by the fact that many designers do not specify washer sizes clearly except indicating bolt diameters and also by the fact that larger washer sizes are not abundantly available in the market.

Arguments in favour of smaller washer sizes are: (a) As CP 112[1] and BS 5268[2] washer sizes were developed primarily base d on research on softwoods, and since local hardwoods are much stronger, reduction of washer sizes may be justified; (b) The largest bolt size used in Sri Lanka is 16mm while that used elsewhere may be up to 36mm. However, thicknesses are not very different so that local joints may resist bearing stresses even with smaller washers; and (c) If it is granted that smaller washers are adequate, then their utilization will enable attainment of significant cost savings. Arguments against are: (i) Use of smaller washer sizes will

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amount to the development of only a fraction of the load carrying capacity inherent in the bolted joint; (ii) Extra cost on use of larger washers can be offset by reduction of bolt diameter or reduction of the number of bolts at the joint; and (iii) Better load distribution imposed by larger washers can improve elastic response of the joint by minimising joint slip and extending elastic range. Validity of these arguments can only be assessed by research.

A similar problem arose when extending theoretical concepts of steel structures to light gauge steel structures, which are of very thin steel sections. When users began fabricating light gauge steel structures with bolted joints sans washers, thus violating accepted norms, a research study[3] resolved the issue. The present problem is not very different, and a research study on viability of use of small washers was considered opportune.

2.0 Objectives

The main objectives of this investigation were as follows: (a) To assess the performance of three types of bolted joints: bolts without washers, bolts with small washers meant for steel structures, and bolts with large washers specified for timber structures; (b) To study how performance of the above three types of bolted joints varies with species of timber of high, medium and low density varieties; (c) To study the overall behaviour of above joint types as regards slip, load-deformation curve, extent of deformation, ultimate load, elastic range, plastic range, and mode of failure; and (d) To make recommendations on the best configuration for use of washers in bolted joints of local timber structures.

3.0 Formulation of the Investigation

3.1 General

Timber is a material greatly influenced by many variables and testing conditions, and a bolted joint in timber is no exception. For a test programme to be meaningful, the influential variables and critical test conditions that affect the performance of a bolted joint in timber should be identified and controlled so that all test results could be converted to a standard condition. Standard procedures[4,5,6,7] are now available for testing timber joints, but significant differences in test procedures, different edge and end distances specified in different national codes, need to alter moisture content and relative humidity values to suit local conditions, and need to alter some test conditions to generate data for solving the problem under consideration, mean that those standard test procedures cannot be adopted without appropriate modifications.

In order to identify and control the influential variables and critical test conditions, as well as to ascertain recent trends in development of design recommendations, a literature survey[1-22] was conducted. Based on its results, particularly paying attention to previous studies on behaviour of timber joints, important variables and test conditions were controlled as described in succeeding sections.

3.2 Control of Variables

(a) Type of species: In determination of the type of species, it was considered necessary to cover the entire range of local timber. However, due to the difficulty of testing all the species, three species belonging to the three density (kg/m^3) ranges namely, high ($d > 800$), medium ($800 > d > 640$) and low ($640 > d$) were to be selected based on availability, cost, structural strength and popularity. The following species were initially considered :

High density -Hora, Naa, Palu, Alubo, Mee, Siyambala, Burutha, Dun, Hedawaka, Kirikon, Kon, Milla and Halmilla;

Medium density -Thekka, Dawata, Gammalu, Helamba, Hik, Kohomba, Kolon, Kos, Kumbuk, Liyan, Neralu, Pelen, Muruta, Tawwenna and Suriya;

Low density -Ginisapu, Mahagony, Na-imbul, Netawu, Sabukku, Telambu and Uruhonda.

The species eventually selected were Hora (high density) Kos (medium density) and Ginisapu (low density). Their botanical names are respectively Dipterocarpus zeylanicus, Artocarpus heterophyllus and Michaelia champaca.

(b) Diameter of bolt : The common sizes of bolt diameter used[8,9,20] in Sri Lanka for timber structures are 10,12 and 16mm with 12mm and 16mm being the most and least preferred respectively. In contrast, BS 5268[2] recommends a large variety of sizes consisting of 8,10,12,16,20,24,30 and 36mm.

At bolt yield, bearing stresses under the washer (or nut with no washer) do not depend on diameter because washer (or nut) diameter is a known multiple of the bolt diameter. However, previous research[8,9] has indicated that bearing failure under washer takes place when "thickness of middle member/bolt diameter ratio" is high. To make this ratio large, diameter of bolt was kept fixed at 10mm in this study and hexagonal headed black bolts complying with BS 4190[21] were used.

(c) Thickness of members : The common sizes of thickness of thinner member used[8,9,20] in Sri Lanka re 25,32,38 and 50mm, with 50mm used less often. In contrast, BS 5268[2] recommends a large variety of sizes consisting of 16, 19, 22, 25,32, 36, 38, 44, 47, 50, 63, 75, 100 and 150mm.

To place washers in a critical condition: (a) thickness of thinner member should be as small as possible; (b) "thickness of middle member/bolt diameter ratio" should be as large as possible; and (c) ratio in (b) above should exceed 5.5 so that post-yield behaviour of the bolt will influence joint performance[8,9]. To satisfy above conditions, thickness of thinner member was kept at 38mm so that ratio in (b) above was 7.6.

As recommended by standard procedures for testing of bolted joints[4,5,6], thickness of the middle member was kept at 76mm so that it is twice that of each thinner member (38mm). The middle member thickness specified in BS 6948[4] was not complied as this will place washers in a less critical condition.

(d) Direction of the application of load to the grain direction : In accordance with standard test procedures[4,5,6] tests were carried out on joints with load parallel to grain direction as well as those with load perpendicular to grain. Load in any other direction was expected to be obtained from Hankinson's formula[2].

(e) End and edge distances : Those were controlled to comply with BS 5268[2] so that joint strength is not influenced by their variations.

(f) Number of bolts : Standard methods prefer single-bolt joints, although ASTM D 1761[5] has permitted multi-bolt joints, and BS 6948[4] has recommended four-bolt joints for bolt diameters less that 12mm. single-bolt joints were adopted because of their wide popularity among research workers, simplicity, saving in materials, ease of fabrication, lower failure loads, higher deformations which make measurement easy, lesser likelihood of experimental errors, and lesser likelihood of distortion or internal stressing due to uneven moisture movement.

(g) Washers : Usage of washers was considered an important variable and following three cases were considered : (i) Washers specified in BS 5268[2] and BS 4320[22] for timber structures which are larger; (ii) Washers available in the market which are smaller and meant to comply with requirements of washers to steel structures; and (iii) Bolts with nuts only sans washers.

Washers for a 10mm diameter bolt in a timber structure[2,22] should possess a minimum thickness of 2.5mm and a minimum outside diameter (or side of a square) of 30mm. Square washers complying with above were turned out at the workshop for this study.

Washers for a 10mm diameter bolt in a steel structure[22] should possess either a minimum thickness of 2mm and a minimum outside diameter of 21mm for ordinary black washers, or a minimum thickness of 1.6mm and a minimum outside diameter of 18.75mm for small light gauge black washers. Locally available washers were 1.3mm thick and 34mm in diameter and, hence, did not comply with either of above. As it was necessary to obtain strength of bolted joints with currently used washers, these were also utilised in the study.

When washers were incorporated into a bolted joint, washers were placed under head and nut in accordance with BS 5268[2].

(h) Selection of material: Bolts, nuts and washers as well as timber were selected at random from stocks available with a reputed hardware merchant and a reputed sawmiller respectively. Washers to BS 5268[2] were turned out at the workshop from the same sheet of steel. These steps ensured good uniformity among bolts as well as timber, so that effect of washers can be freed from other unintentional variations in material quality. Further, portions of timber found to possess any defect were not used in the fabrication of specimens.

(i) Moisture content : In order to remove moisture content as a variable from the study, timber was soaked in water so that moisture content exceeded the corresponding value at fibre saturation point. It was possible to soak the timber after assembly or before assembly and the latter method was selected: (i) to minimise increase of frictional resistance at contact surfaces like timber/washer, timber/timber or timber/bolt shaft due to swelling of timber by moisture uptake; (ii) to prevent uneven changes in moisture content due to some non-exposed surfaces caused by forced contact; (iii) to save material, since if moisture content is tested by removing a small piece from the joint, entire joint has to be discarded, whereas in the other option only that timber piece need be rejected; (iv) to eliminate the chances of the surfaces in contact maintaining higher levels of frictional resistance due to lesser absorption of moisture at the hidden contact faces; (v) to reduce the time of soaking as assembled joints will take a longer time to absorb moisture due to greater thickness at certain locations; and (vi) to eliminate the need for a bigger tank to soak assembled joints as opposed to timber pieces.

(j) Fabrication details : Timber pieces were sawn to the required dimensions and any with defects rejected. Holes were carefully bored, at the required locations, perpendicular to the surface and filed smooth. During drilling it was ensured that each hole was as close as possible to the nominal diameter of the bolt using the next larger drill bit size so that ny hole was never more than 2mm in excess of the bolt size[2]. The drilled timber pieces were soaked in water and moisture content tested at regular intervals to ascertain whether they have absorbed moisture in excess of the fibre saturation point. Moisture uptake was monitored for 15 days and the results are shown in Table 1. The joints were assembled by driving bolts into position with no more pressure than tapping with a wooden mallet. When washers were used, they were inserted under the head as well as the nut of the bolt, and nuts were tightened to finger-tightness but too small to cause crushing of timber under a washer. A minimum of one complete thread was allowed to protrude clear of the nut[2].

(k) Rate of loading and duration of test: Many previous researchers[8,9,13] have used a strain rate of 2.5mm/minute or less. Hence the test specimens were loaded in compression at the rate of 2.5mm/minute ± 30% and this rate of loading complied with ASTM D 1761[5] giving a testing time of about 15 to 20 minutes. Additional information that can be obtained by BS 6948[4] loading procedure was not considered worthwhile for this study.

3.3 Control of Testing Conditions

(a) Type of test: Both two-member and three-member joints are permitted in ASTM D 1761[5] while ISO 6891[6] and BS 6948[4] specify three-member joints. Further, most previous researchers[8,9,11,13] have used the latter. Hence, the three-member joint, in double shear with middle as well as two side members in timber, was adopted as it affords an easier testing condition free of eccentric load application and lesser chance for distortion during deformation, although it entails a higher cost due to greater consumption of timber and longer bolts.

(b) Mode of testing : Both compressive and tensile loadings are recommended in standard methods[4,5,6], while most previous researchers[8,9,11,13] have adopted the former. Mode of testing by compression was adopted because: (i) it can be easily achieved in the laboratory; (ii) stress distribution in the joint is independent of compressive or tensile loading; (iii) timber consumption is less as specimen lengths are smaller; (iv) higher loads can be applied through a testing machine in the compression mode; and (v) better testing machines are required to apply high tensile loads for stronger joints.

(c) Dimensions of test specimen: Dimensions, for economy, should be as small as possible and such that full load can be developed at the joint before premature failures like buckling of members or splitting due to insufficient end or edge distances. Dimensions adopted (see Figure 1) comply with end distances (loaded or unloaded end), edge distances and maximum length to prevent buckling specified in BS 5268[2] and standard test methods[4,5,6].

(d) Number of replications: A large number of replicates per joint configuration gives better accuracy and refined statistical treatment, but increases the cost. Minimum number recommended by BS 6948[4] and ASTM D 1761[5] are 15 and 5 respectively while previous researchers have used 2[15], 3[17], 5[1,2,8,11,13], 6[9] and 10[14]. In this study 6 replicates were used.

3.4 Test Programme

It consisted of the following (i) tests on bolted joints loaded parallel to grain and perpendicular to grain for three densities of timber (high-HORA, medium-KOS, low-GINISAPU) and three usages of washer (no washer, washer for steel, washer for timber); (ii) moisture absorption pattern of soaked timber of the three species; (iii) tensile tests on bolts; and (iv) relative density and moisture content tests on each timber joint.

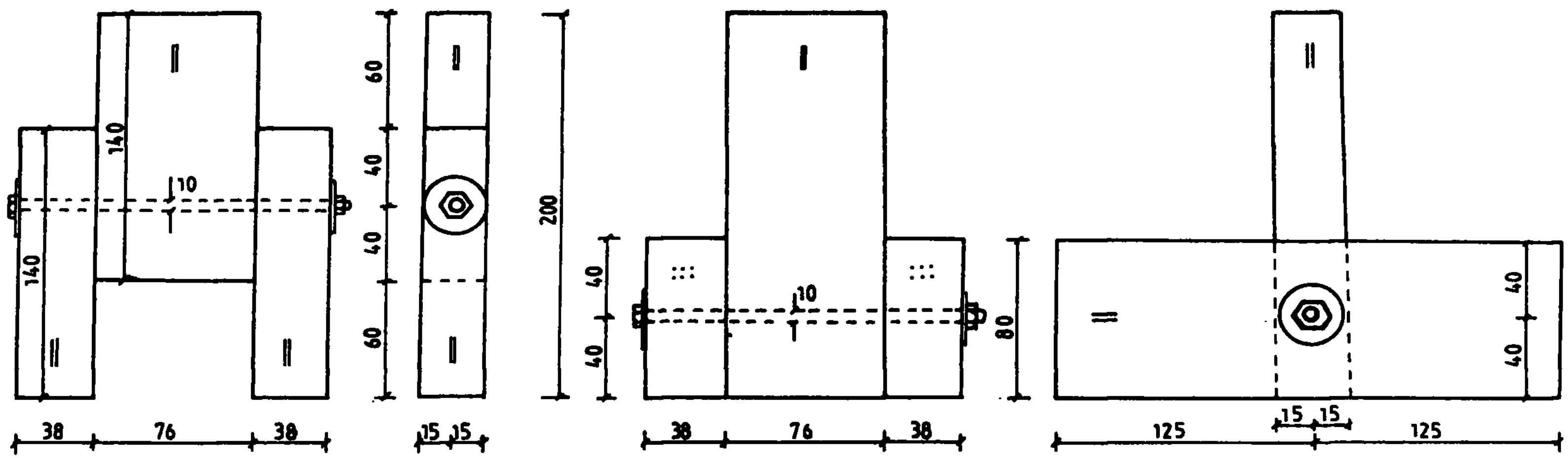
Each bolted joint was loaded recording the load-deformation response of the joint until the maximum load was obtained or excessive deformation took place. On failure of test specimens, portions were cut from uncrushed timber of the failed members and used to determine moisture content and relative density. Tensile tests were conducted on bolts selected at random to ensure that bolts used complied with BS 4190[21]. Moisture content and relative density tests complied with SLS 836[7].

4.0 Results and Analysis

4.1 General

Measurement of variation of moisture content with immersion time (see Table 1) revealed that: (a) smaller members absorb moisture faster; (b) Rate of absorbance is approximately inversely proportional to density; and (c) All the species tested, irrespective of member size, exceed fibre saturation point after 4 days of immersion in water.

Tensile tests on bolts established that they comply with Grade 4.8 Black Bolts of BS 4190[21] which should have a minimum yield strength (0.2% horizontal offset and line parallel to elastic response) of 220 N/mm^2 and a minimum tensile strength of 400 N/mm^2. Coefficients of variation of yield strength and tensile strength were 10.86% and 10.28% respectively indicating the uniformity of the material properties of bolts. Yield strength and tensile strength were 470.2 and 514.8 N/mm^2 respectively.



PARALLEL TO GRAIN

PERPENDICULAR TO GRAIN

FIGURE NOT TO SCALE

::: GRAIN DIRECTION PERPENDICULAR TO THE PAPER
= GRAIN DIRECTION PARALLEL TO THE PAPER
ALL DIMENSIONS ARE IN MILLIMETRES. BOLTS ARE M10

Figure 1 - Test Specimens

Table 1 - Variation of Moisture Content (%) with Immersion Time

Immersion time (days)	Species of timber					
	Ginisapu		Kos		Hora	
	Large*	Small**	Large	Small	Large	Small
1	21.88	23.56	23.68	27.13	27.72	20.83
2	30.00	44.60	28.00	34.50	30.50	29.50
3	40.10	54.60	32.50	42.00	34.00	38.00
4	56.49	63.63	37.03	47.65	37.26	43.97
5	61.44	67.06	39.11	50.79	39.70	46.31
6	64.04	69.97	41.42	53.39	42.40	48.22
7	67.33	72.39	43.31	56.06	43.98	49.88
8	69.47	74.38	44.66	57.75	44.66	51.19
9	70.09	76.60	45.80	59.30	44.70	52.60
10	72.10	78.10	46.80	60.90	45.50	53.00
11	73.67	79.27	47.96	62.13	46.32	53.74
12	74.82	79.82	48.46	63.00	46.35	54.33
13	75.63	80.04	48.76	63.74	46.36	54.62
14	75.80	80.05	49.00	63.80	47.70	55.00
15	76.00	80.06	49.20	64.10	47.80	55.40
Total Variation in 14 days	54.12	56.50	25.52	36.97	20.08	34.57

* Large - 250x80x38 mm piece from load perpendicular to grain specimen (See Figure 1)

** Small - 140x76x30 mm piece from load parallel to grain specimen (See Figure 1)

Table 2 - Coefficients of Variation of Ultimate Loads, % Increase Relative to no Washer Joints, and Failure Modes

PARALLEL TO GRAIN LOADING						
Type and species of timber	Washer usage					
	No washer		Steel washer		Timber washer	
	Mean ultimate load (kN)	Coefficient of variation (%)	Mean ultimate load (kN)	Coefficient of variation (%)	Mean ultimate load (kN)	Coefficient of variation (%)
Low density (Ginisapu)	18.82 (0%)* ((1))**	12.34	24.00 (+27.5%) ((3))	14.8	34.50 (+83.3%) ((3))	20.6
Medium density (Kos)	20.47 (0%)* ((1))	15.70	28.97 (+41.5%) ((1))	16.30	33.39 (+63.1%) ((1))	9.4
High density (Hora)	16.83 (0%)* ((1))**	10.40	19.64 (+16.7%) ((1))	11.80	25.92 (+54.0%) ((1))	12.2

PERPENDICULAR TO GRAIN LOADING						
Type and species of timber	Washer Usage					
	No washer		Steel washer		Timber washer	
	Mean ultimate load (kN)	Coefficient of variation (%)	Mean ultimate load (kN)	Coefficient of variation (%)	Mean ultimate load (kN)	Coefficient of variation (%)
Low density (Ginisapu)	22.51 (0%) ((1))	16.5	30.30 (+34.6%) ((1))	9.0	33.12 (+47.1%) ((1))	9.8
Medium density (Kos)	2.35 (0%) ((1))	26.6	40.81 (+49.2%) ((3))	17.8	35.19 (+28.7%) ((3))	18.7
High density (Hora)	20.90 (0%) ((2))	8.7	24.00 (+14.8%) ((2))	18.1	28.53 (+36.5%) ((2))	7.0

* % increase of ultimate load with respect to joint of the same species but with no washers.

** Failure pattern where 1 = side (outer) members splitting;
2 = middle member splitting and
3 = all members splitting. Bolt bending occurred in all failure modes.

4.2 Overall Behaviour of Bolted Joints

Coefficients of variation of ultimate load values are shown in Table 2. They are low showing uniformity except for the value of 26.6%, which was found to be due to one abnormally low result. Inspection of that failed specimen revealed portions of sapwood infested with borer holes which may have contributed to reduction in strength.

Ultimate load values expressed as percentage increases with respect to joints of the same species but with no washers are shown in Table 2. Results indicate that use of washers improve load carrying capacity and timber washer attains the highest increase except in one instance where steel washers behaved better. This case was attributed to one abnormally high test result in that group which was later found to be due to a slightly larger bolt diameter, which still could go through the drilled hole. In general, timber washers were most efficient in increasing the strength of joints loaded parallel to grain.

When loaded parallel to grain, maximum slip observed near failure point varied between 2.18 times to 11.81 times of that allowed at working load (2.6mm) giving ample warning before failure. When loaded perpendicular to grain, maximum slip observed near failure point varied between 4.57 times to 15.1 times that allowed at working load (2.6mm), demonstrating that joint it most deformable when loaded perpendicular to grain.

Typical load-slip curves for joints loaded parallel to grain and joints loaded perpendicular to grain are shown in Figures 2 and 3 respectively. They clearly show the beneficial effect of washers in (a) extending the limit of proportionality; (b) improving load carrying capacity (c) providing large deformations before failure to give adequate warning before collapse; and (d) minimising initial slip. Timber washers performed best giving the most favourable load-slip response.

Details of the failure patterns observed are shown in Table 2. The predominant failure mode was splitting of side members with bolt bending for both types of loading. However, full strength of joint is considered to be mobilised when all members failed by splitting and this occurred only with washers either steel or timber.

4.3 Basic shear loads

Observed ultimate loads of bolted joints loaded parallel to grain and perpendicular to grain are shown in Tables 3 and 4 respectively. All the moisture contents were above 30% and ultimate loads require no correction for moisture content. Mean relative densities of GINISAPU, KOS and HORA were found to be 0.4928, 0.5294 and 0.6001 with coefficients of variation 5.78%, 5.93% and 5.75% respectively, indicating that materials of each timber species were of uniform quality. Ultimate loads adjusted to the mean relative density of each species by direct proportionality are also shown in Tables 3 and 4.

In accordance with current practice[13,14,19] of developing design recommendations statistically, the relationship used was:

$$\text{Working load of wet timber} = \frac{M-KS}{F}$$

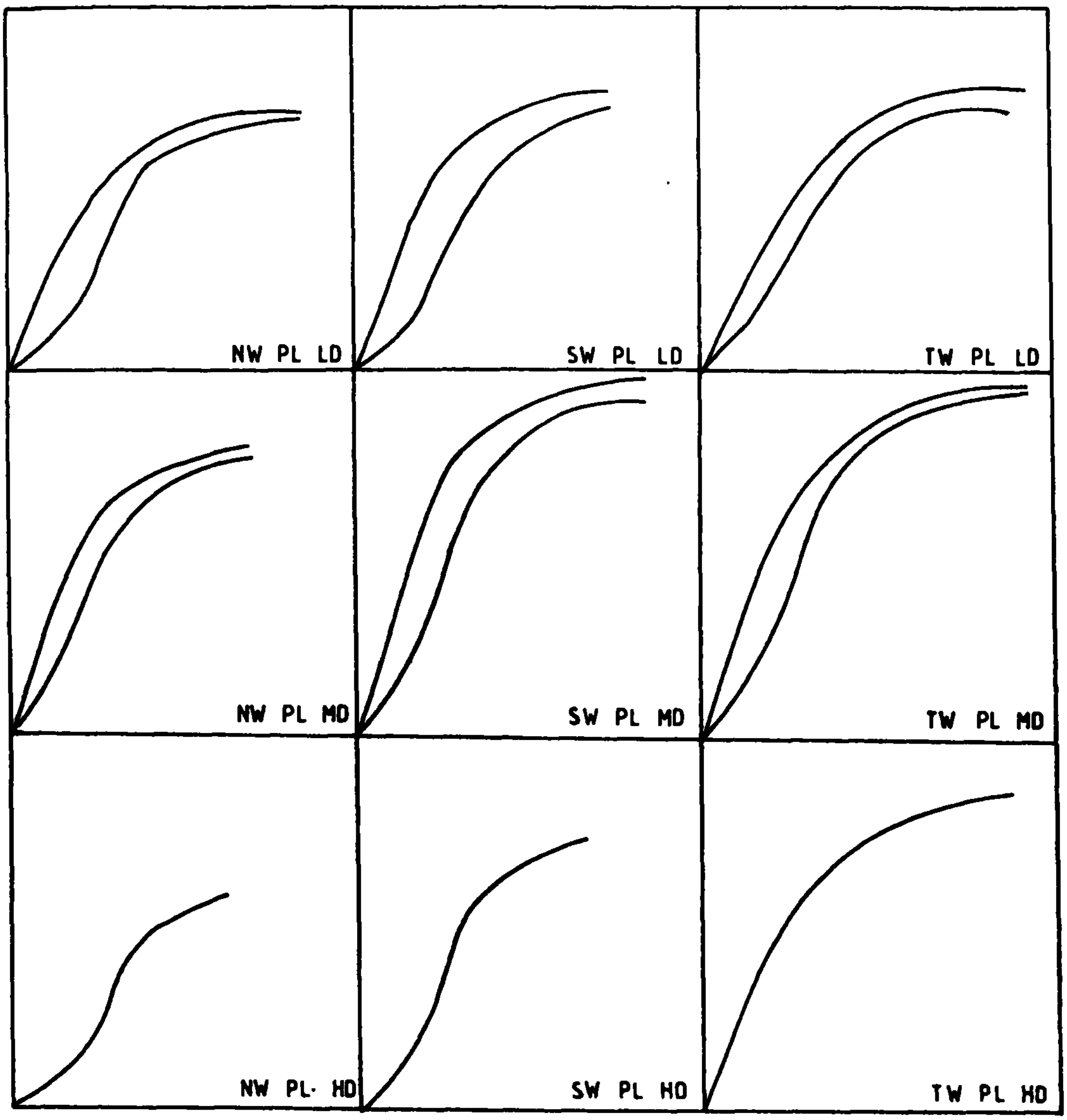
Where M = Mean adjusted ultimate load of wet timber; S = Standard deviation of replicates; K = 1.64 for 5% exclusion specified in BS 5268[2]; and F = 2.5 for bolted joints[14].

Since above working loads were obtained with no regard to elastic behaviour, those working loads were lowered where necessary to ensure that : (i) Allowable joint slip at working load does not exceed 2.66 mm[12]; (ii) Recommended working load is below the limit of proportionality of the load-ship curves; and (iii) Reduced working load is not greater than half the ultimate load of any individual test[12]. These adjustments had to be done in about 50% of the cases.

As the above adjusted values are for three-member joints in double shear (see Figure 1), those were converted to wet basic shear loads in a two-member joint in single shear by dividing by2. In some instances load perpendicular to grain was greater than that parallel to grain and, like in BS 5268[2], in such instances load perpendicular to grain was made equal to the other.

To obtain basic shear loads for the dry conditions the conversion factor recommended in BS 5268[2] was used and corresponding basic shear loads in wet condition were divided by 0.7. The recommended basic shear loads are shown in Table 5. The percentage increases relative to joints with no washers are also shown in that table, which clearly show the benefit of washer usage with timber washer performing as the best.

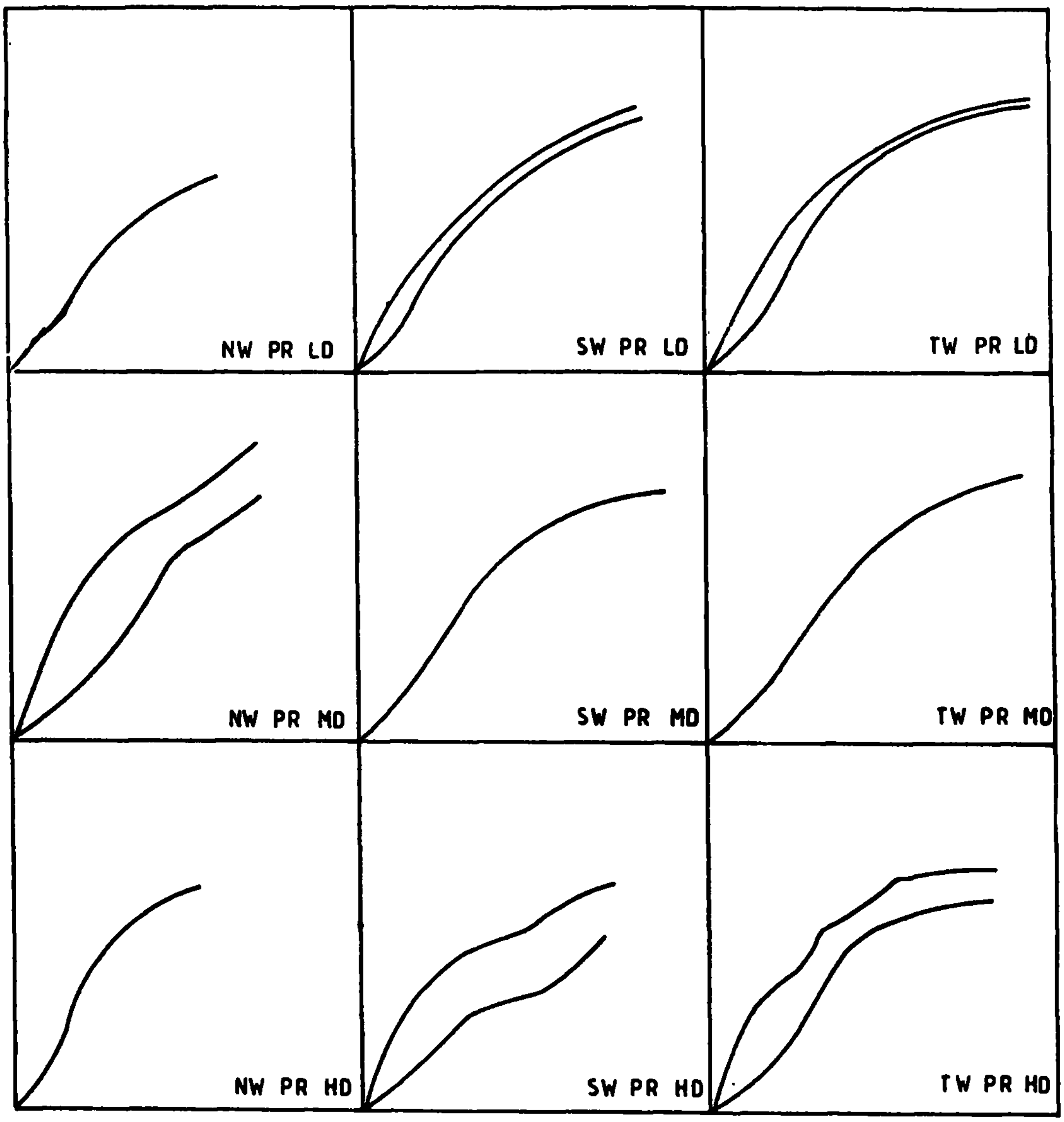
Table 6 compares basis shear loads for one bolt in a two-member joint in dry condition from this study with previous work. Although a strict comparison is not possible due to different exclusion limits used (see Table 6), comparison of trends is possible and joint strengths of local timber are greater than those given in BS 5268[2] or CP 112[1].



KEY:

NW - NO WASHER
SW - STEEL WASHER
TW - TIMBER WASHER
PL - PARALLEL TO GRAIN LOADING
LD - LOW DENSITY TIMBER
MD - MEDIUM DENSITY TIMBER
HD - HIGH DENSITY TIMBER

Figure 2 - Typical Load - Slip Curves for Joints Loaded Parallel to Grain



KEY :

NW - NO WASHER
SW - STEEL WASHER
TW - TIMBER WASHER

PR - PERPENDICULAR TO GRAIN LOADING

LD - LOW DENSITY TIMBER
MD - MEDIUM DENSITY TIMBER
HD - HIGH DENSITY TIMBER

Figure 3 - Typical Load - Slip Curves for Joints Loaded Perpendicular to Grain

Table 3 - Ultimate Loads and Other Physical Properties of Joints Loaded Parallel to Grain

Type and species of timber	WASHER USAGE											
	No washer				Steel washer				Timber washer			
	Ultimate load (Tonnes)	Relative density	Moisture content (%)	Adjusted ultimate load (Tonnes)	Ultimate load (Tonnes)	Relative density	Moisture content load (Tonnes)	Adjusted ultimate load (Tonnes)	Ultimate load (Tonnes)	Relative density	Moisutre content (%)	Adjusted ultimate load (Tonnes)
GINISAPU (Low desnsity)	2.26	0.476	86.0	2.34	2.69	0.565	68.4	2.35	2.88	0.461	86.1	3.08
	1.82	0.520	77.0	1.73	2.88	0.534	65.3	2.66	3.43	0.441	83.0	3.83
	2.08	0.519	86.1	1.98	3.22	0.515	84.1	3.08	4.78	0.496	85.1	4.75
	2.02	0.505	64.4	1.97	2.00	0.447	89.3	2.21	3.30	0.509	75.2	3.20
	1.98	0.554	74.1	1.76	1.92	0.446	81.4	2.12	2.75	0.508	89.0	2.67
	1.70	0.485	70.0	1.73	2.22	0.484	83.5	2.26	3.52	0.486	91.4	3.57
KOS (Medium density)	1.92	0.541	63.1	1.88	3.14	0.542	81.1	3.06	3.74	0.571	76.1	3.46
	1.73	0.557	76.1	1.64	2.62	0.517	77.0	2.68	3.78	0.540	81.2	3.70
	2.34	0.503	89.1	2.46	2.60	0.577	85.4	2.38	2.80	0.515	75.2	2.88
	2.02	0.527	81.0	2.03	2.77	0.523	62.3	2.80	3.14	0.524	81.4	3.17
	2.00	0.519	79.4	2.04	3.68	0.512	68.1	3.80	3.46	0.520	75.0	3.52
	2.24	0.479	68.0	2.47	2.78	0.491	62.3	3.00	3.86	0.554	76.0	3.69
HORA (High density)	1.70	0.573	51.4	1.78	1.88	0.623	54.1	1.81	3.04	0.625	52.1	2.92
	1.76	0.617	63.2	1.71	2.10	0.636	58.0	1.98	2.52	0.571	64.2	2.65
	1.64	0.586	55.0	1.68	2.14	0.638	53.2	2.01	2.50	0.621	61.0	2.42
	1.50	0.605	51.0	1.49	1.74	0.613	57.9	1.70	2.81	0.621	53.2	2.71
	1.74	0.647	57.2	1.61	1.92	0.535	77.1	2.15	2.08	0.582	53.1	2.14
	2.00	0.595	62.3	2.02	2.26	0.574	64.0	2.36	2.64	0.526	54.0	3.01

Table 4 - Ultimate Loads and Other Physical Properties of Joints Loaded Perpendicular to Grain

Type and species of timber	WASHER USAGE											
	No washer				Steel washer				Timber washer			
	Ultimate load (Tonnes)	Relative density	Moisture content (%)	Adjusted ultimate load (Tonnes)	Ultimate load (Tonnes)	Relative density	Moisture content load (Tonnes)	Adjusted ultimate load (Tonnes)	Ultimate load (Tonnes)	Relative density	Moisutre content (%)	Adjusted ultimate load (Tonnes)
GINISAPU (Low density)	2.42	0.476	90.4	2.51	2.73	0.504	90.3	2.67	3.76	0.514	65.1	3.61
	2.30	0.505	85.5	2.25	2.99	0.504	71.2	2.92	3.20	0.485	73.1	3.25
	2.36	0.472	88.6	2.47	3.14	0.447	86.3	3.46	3.20	0.503	79.2	3.14
	1.60	0.495	90.4	1.59	3.01	0.492	77.2	3.02	3.68	0.468	73.2	3.88
	2.66	0.491	92.1	2.67	2.98	0.453	86.1	3.24	3.45	0.499	68.1	3.41
	2.14	0.463	78.1	2.28	3.30	0.506	77.1	3.22	3.08	0.511	87.2	2.97
KOS (Medium density)	1.54	0.527	54.1	1.55	4.08	0.513	67.9	4.21	3.01	0.516	91.2	3.09
	3.02	0.552	70.2	2.89	4.22	0.435	65.4	5.13	3.36	0.532	81.3	3.34
	3.55	0.520	73.0	3.61	4.12	0.548	66.3	3.98	3.96	0.575	54.5	3.64
	2.55	0.582	54.5	2.32	4.44	0.545	59.1	4.31	2.86	0.536	85.6	2.82
	3.42	0.572	52.1	3.16	3.98	0.472	81.2	4.46	3.70	0.498	70.1	3.93
	3.06	0.506	75.1	3.20	3.08	0.567	63.1	2.87	4.90	0.552	49.0	4.70
HORA (High density)	2.40	0.633	57.8	2.27	2.61	0.620	64.2	2.53	2.72	0.607	72.1	2.69
	2.07	0.636	68.0	1.95	2.58	0.556	56.3	2.78	2.96	0.553	70.0	3.21
	2.13	0.646	67.1	1.98	1.66	0.581	64.6	1.71	2.80	0.584	73.1	2.88
	2.06	0.599	53.6	2.06	2.45	0.638	65.1	2.30	2.86	0.571	54.2	3.01
	2.22	0.637	59.8	2.09	2.58	0.654	58.9	2.37	2.68	0.601	51.0	2.68
	2.12	0.524	63.1	2.43	3.02	0.607	45.9	2.99	2.83	0.570	75.4	2.98

Table 5 - Basic Shear Loads for one Bolt in a Two-Member Joint and Percentage Increases Relative to Joints with no Washers

Timber species	Nominal bolt diameter (mm)	Thickness of thinner member (mm)	Washer usage	Basic shear load for one bolt (kN)			
				Parallel to grain		Perpendicular to grain	
				Wet condition	Dry condition	Wet condition	Dry condition
GINISAPU	10	38	No washer	3.00 (0)*	4.29 (0%)	1.96 (0%)	2.80 (0%)
			Steel washer	3.31 (+10.33%)*	4.73 (+10.26%)	2.89 (+47.45%)	4.13 (+47.50%)
			Timber washer	3.94 (+31.33%)	5.63 (+31.24%)	3.33 (+69.90%)	4.76 (+70.00%)
KOS	10	38	No washer	2.08 (0%)	2.97 (0%)	2.08 (0%)	2.97 (0%)
			Steel washer	4.24 (+103.85%)	6.06 (+104.04%)	4.16 (+100.00%)	5.94 (100.00%)
			Timber washer	5.64 (+111.15%)	8.06 (+171.38%)	4.85 (+133.17%)	6.93 (133.33%)
HORA	10	38	No washer	2.78 (0%)	3.97 (0%)	2.78 (0%)	3.97 (0%)
			Steel washer	3.16 (+13.67%)	4.51 (+13.60%)	3.16 (+13.67%)	4.51 (+13.60%)
			Timber washer	4.14 (+48.92%)	5.91 (+48.87%)	4.14 (+48.92%)	5.91 (+48.87%)

* Percentage increase relative to joint with no washers

Table 6 - Comparison of Shear Loads for One Bolt in a Two-Member Joint in Dry Condition

Timber identification	Bolt diameter (mm)	Thickness of thinner member (mm)	Basic shear load for one bolt (kN)					
			Parallel to grain			Perpendicular to grain		
			No washer	Steel washer	Timber washer	No washer	Steel washer	Timber washer
Ginisapu	10	38	4.29	4.73	5.63	2.80	4.13	4.76
Kos	10	38	2.97	6.06	8.06	2.97	5.94	6.93
Hora	10	38	3.97	4.51	5.91	3.97	4.51	5.91
Halmilla*	10	38	–	–	6.02	–	–	6.26
Hora*	10	38	–	5.88	–	–	2.70	–
SC 5+	10	38	–	–	1.61	–	–	1.44
SC6+,SC7+	10	38	–	–	2.09	–	–	2.09
SC8+,SC9+	10	38	–	–	2.09	–	–	2.09
J 1++	10	38	–	–	2.02	–	–	2.19
J 2++	10	38	–	–	1.41	–	–	1.50
J 3++	10	38	–	–	1.36	–	–	1.22
J4++	10	38	–	–	1.03	–	–	0.93

* 1% exclusion [8]
** 1% exclusion[9]
\+ 5% exclusion of BS 5268 hardwoods [2]
++ 1% exclusion of CP112[1]

Table 7 - Ultimate Load Values Parallel to Grain Arranged for a Two-Factor Analysis of Variance

Type and species of Timber (factor B)	Washer Usage (factor A)		
	Ultimate load with no washer (kN)	Ultimate load with steel washer (kN)	Ultimate load with timber washer (kN)
Low density (Ginisapu)	22.96 16.97 19.42 19.33 17.27 16.97	23.05 26.09 30.21 21.68 20.80 22.17	30.21 37.57 46.60 31.39 26.19 35.02
Medium density (Kos)	18.44 16.09 24.13 19.01 20.01 24.23	30.02 26.29 23.35 27.47 37.28 29.43	33.94 36.30 28.25 31.10 34.53 36.20
High density (Hora)	17.46 16.78 16.48 14.62 15.79 19.82	17.76 19.42 19.72 16.68 21.09 23.15	28.65 26.00 23.74 26.59 20.00 29.53

Table 8 - Summary of Analysis of Variance on Ultimate Loads Prallel to Grain

Source of variation	Sum of squares	Degree of freedom	Mean square
Total	2638.390	53	
Cells	1990.760	8	
Factor A (washer usage)	1427.627	2	712.814
Factor B (Density of timber)	447.823	2	223.912
A x B interaction	115.310	4	28.828
Within Cells (error)	647.630	45	14.392

Hypothesis on :	F = Factor mean squae / Error mean square	F statistic	Outcome
(a) Washer usage	$F = \frac{712.814}{14.392} = 49.53$	$F_{0.05(1)2,45} = 3.20$ $F_{0.0005(1)2,45} = 9.04$	Reject Ho at 0.05% level of significance
(b) Density of timber	$F = \frac{223.912}{14.392} = 15.56$	$F_{0.05(1)2,45} = 3.20$ $F_{0.0005(1)2,45} = 9.04$	Reject Ho at 0.05% level of significance
(c) Interaction of washer usage and density of timber	$F = \frac{28.828}{14.392} = 2.00$	$F_{0.05(1)4,45} = 2.58$	Do not reject Ho at 5% level of significance

Table 9 - Ultimate Load Values Perpendicular to Grain Arranged for a Two-Factor Analysis of Variance

Type and Species of timber (factor B)	Washer usage (factor A)		
	Ultimate load with no washer (kN)	Ultimate load with steel washer (kN)	Ultimate load with timber washer (kN)
Low density (Ginisapu)	24.62 22.07 24.23 15.60 26.19 22.37	26.19 28.65 33.94 29.63 31.78 31.59	35.41 31.88 30.80 38.06 33.45 29.14
Medium density (Kos)	15.21 28.35 35.41 22.76 31.00 31.39	41.30 50.33 39.04 42.28 43.75 28.15	30.31 32.77 35.71 27.66 38.55 46.11
High density (Hora)	22.27 19.13 19.42 20.21 20.50 23.84	24.82 27.27 16.78 22.56 23.25 29.33	26.39 31.49 28.25 29.53 26.29 29.23

4.4 Two-factor analysis of variance

Ultimate loads of joints loaded parallel to grain arranged for a two-factor analysis of variance[23] are shown in Table 7 where factor A is washer usage kept at three levels of no washer, steel washer and timber washer while factor B is density of timber kept at three levels of low density (GINISAPU), medium density (KOS) and high density (HORA).

Three hypothesis to be tested, where H_0 denotes the null hypothesis while H_A denotes the alternative hypothesis, are set up as follows:

(a) Hypothesis on washer usage where H_0: washer usage has no effect on ultimate load of bolted joints ($\mu_1 = \mu_2 = \mu_3$); and H_A: Washer usage has an effect on ultimate load of bolted joints ($\mu_1 = \mu_2 = \mu_3$).

(b) Hypothesis on density of timber where H_0 : Density of timber has no effect on ultimate load of bolted joints ($\mu_4 = \mu_5 = \mu_6$); and H_A : Density of timber has an effect on ultimate load of bolted joints $\mu_4 = \mu_5 = \mu_6$).

(c) Hypothesis on interaction of washer usage and density of timber where H_0 : washer usage and density of timber have no interaction on ultimate load of bolted joints; and H_A : Washer usage and density of timber have an interaction on ultimate load of bolted joints.

Table 8 gives a summary of the analysis of variance carried out on ultimate loads parallel to grain. The results of this analysis can be summarised as follows : (a) Washer usage (No washer, steel washer or timber washer) significantly changes ultimate load of a bolted joint; (b) Density of timber (low, medium, and high density) also significantly affects ultimate load; and (c) There is no interaction between washer usage and density of timber.

Ultimate loads of joints loaded perpendicular to grain arranged for a two-factor analysis of variance are shown in Table 9. Hypothesis to be tested were similar to those for joints loaded parallel to grain. Table 10 gives a summary of the analysis of variance carried out on loads perpendicular to grain and the results were a repetition of those loaded parallel to grain.

5.0 Conclusions

The following conclusions are drawn from this study: (a) All the species tested, irrespective of member sizes considered, exceed fibre saturation point after 4 days of immersion in water; (b) Bolts used complied with Grade 4.8 Block bolts of BS 4190[21] and very low coefficients of variation of yield strength and tensile strength demonstrate uniformity of material properties; (c) Mean relative densities of GINISAPU, KOS and HORA were found to be 0.4928, 0.5294 and 0.6001 with coefficients of variation 5.78%, 5.93% and 5.75% respectively, indicating that material of each timber species were of uniform quality; (d) Joint strengths of local timber species are greater than those given in BS 5268[2] or CP 112[1]; (e) Washers specified for bolted joints of timber structures give better overall performance and highest joint strengths; (f) washers with a nominal diameter (or side of a square) and thickness of at least 3.0 times and 0.25 times the bolt diameter, respectively, should be fitted under the head of each bolt and under each nut to develop better structural performance from a bolted joint; and (g) Washer type as well as density of timber affect ultimate load of bolted joints at 0.05% level of significance irrespective of loading direction.

6.0 References

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Table 10 - Summary of Analysis of Variance on Ultimate Loads Perpendicular to Grain

Source of variation	Sum of squares	Degree of freedom	Mean square
Total	3026 266	53	
Cells	1990 405	8	
Factor A (washer usage)	850 447	2	425.223
Factor B (Density of timber)	903 232	2	451.616
A x B interaction	236 726	4	59 182
Within Cells (error)	1035.861	45	23.019

Hypothesis on :	F = Factor mean squac / Error mean square	F statistic	Outcome
(a) Washer usage	$F = \frac{425.223}{23.019} = 18.48$	$F_{0.05(1)2,45} = 3.20$ $F_{0.0005(1)2,45} = 9.04$	Reject Ho at 0.05% level of significance
(b) Density of timber	$F = \frac{451.616}{23.019} = 19.62$	$F_{0.05(1)2,45} = 3.20$ $F_{0.0005(1)2,45} = 9.04$	Reject Ho at 0.05% level of significance
(c) Interaction of washer usage and density of timber	$F = \frac{59.182}{23.019} = 2.57$	$F_{0.05(1)4,45} = 2.58$	Do not reject Ho at 5% level of significance