EUROPEAN YIELD MODEL METHOD FOR BOLTED TIMBER JOINT DESIGN - REVIEW

by

M.T.P. Hettiarachchi , A.D. Nawagamuwa

Abstract

The European Yield Model (EYM) for dowelled timber joint design differs radically from the empirical models, which were previously adopted by Codes of Practice on Structural Timber Design. The EYM has been adopted in the recent editions of these codes of practices and it is also the basis of joint design in Eurocode 5:Part 1-1.

This paper outlines the design procedure of the EYM for bolted timber joints based on a thorough literature review. Previous studies on experimental verifications and comparison of the model with empirical models are also discussed. The advantages and limitations of the model are identified.

1. Introduction

Various forms of round pins are used to connect structural members made from many different materials. These connections are called mechanical connections because they use the mechanism of the pin to transfer loads between members. Common forms of pin-type joints are bolts, nails and dowels. The bolted connection is an important and common connection type used in wood construction. It is quick and easy to install, allows field assembly with no surface preparation and is insensitive to most environmental variables. One only needs to be able to drill properly aligned holes, install the bolt, and provide finger tightening of the nut. Although, the bolted joint is simple in appearance, its behaviour under load is quite complex.

The strength and stiffness of a bolted connection depends on the physical and geometrical properties of the members and fastener and other factors as given in Table 1.

The fundamental requirement for efficient design of structural timberwork, whether it is on working stress approach or a limit state basis, is the knowledge of the load-deformation and strength properties for various types of mechanical joints. It is prohibitive to obtain all the information on mechanical joint required for inclusion in design codes by mass testing of joint specimens. This is because of many possible combinations of geometric, material, loading and environmental variables (Table 1) that must be considered. Although, during the past century, several studies on bolted connections have been conducted, each study has investigated one or more of the properties that affect connection behaviour. So that, there has been considerable research over the last six decades aimed at providing suitable analytical models, which predict the short-term strength and/or stiffness properties under lateral loading.

The European Yield Model (EYM) describes a set of possible yield modes that are based on the bending resistance of the fastener, the embedment strength of the member material, some geometric parameters of the joint and assumed mechanical relationships and thus gives a rational approach to design of dowel-type joints. Also it is adaptable to various material properties.

The aim of this paper is to review the EYM method for bolted joint design. Results obtained by some past investigations are included. The basis for design data of bolted and nailed timber joints in British Standard 5268: Part 2: 1984 and National Design Specification 1986 (NDS-86) and their shortcomings are discussed. Comparison of the EYM with the Trayer's empirical model, which is the basis for bolted joint design in above codes of practices are also included. Methods followed by BS 5268:Part 2:1984 and NDS-86 to provide joint strength of bolted and nailed joints and their shortcomings are discussed. The advantages and limitations of the EYM are also described.

Eng. (Dr.) (Ms.) M T P Hettiarachchi, BSc Eng(Hons), MSc, (London), Dic & PhD (London), AMIE(SL), Senior Lecturer, Department of Civil Engineering, University of Moratuwa.

A D Nawagamuwa, BSc (Hons), Presently working as an Assistant Lecturer at the Department of Civil and Environmental Engineering, University of Ruhuna.

Internal Factors	Mechanical Properties	Joint member	Compressive strength Specific gravity
		Fastener	Bending strength Yield strength
	Joint	Diameter of fastener Thickness of joint members Ratio thickness/diameter Number of fasteners Pattern Spacing, end & edge distances Number of shear planes Size of pre-drilled holes	
	Other than mechanical properties	Coefficient of friction Moisture absorption Natural defects	
External Factors	Applied Load	Type	Lateral or withdrawal
		Direction	Parallel Perpendicular or Other
		Duration	Short Medium or Long
	Service Conditions	Moisture content Temperature Humidity	

Table 1: Factors governing the strength of bolted connection

2. Previous Codes of Practices and Their Basis

In the past the working load design values for bolted joints have been determined from the results of short duration tests on relatively small numbers of replicate joints. One approach made estimates of lower percentile value, eg: lower first percentile value, assuming a normal distribution, and these were then divided by a factor to account for safety and workmanship and to reduce the strength to an equivalent long-duration value. Data available from the above tests are generally insufficient to enable reliable estimates.

2.1 BS 5268:Part 2:1984

BS 5268:Part 2:1984 uses the working stress approach to provide design resistance values for structural timber joints based on empirical data.

The design data for nailed and bolted joints presented in BS 5268:Part 2:1984 have been obtained by substituting basic material properties into appropriate empirical equations. The basic lateral loads for nailed timber-to-timber joints are based on work by Brock in 1950's, and design values are given by dividing empirical ultimate load by an appropriate load factor. Load factors were selected as 3.0 for solid timber and 4.0 for hardboard (Hilson et al. 1990). The basic lateral loads for bolted joints loaded parallel to grain were derived from the original work by Trayer in 1932. Trayer's design loads were based on not exceeding the experimental proportionality limit load (Hilson et al. 1990). Therefore, there is no consistency in the methods used for deriving design loads for nailed and bolted joints in BS 5268:Part 2:1984.

The British Standards have now incorporated the European grading system and terminologies. What was previously known as "stress grading" is now termed "strength grading". The BS 5268:Part 2:1996, the latest edition of British Standards for structural timber design, has included these changes and design values for nailed, bolted or dowel joints have been changed to bring them in line with Eurocode 5, in which the design values are based on EYM.

2.2 NDS-86

The NDS-86 also uses empirical equations fit to varied test data to provide allowable lateral strengths for nail, bolt and wood-screw and lag-screw connections. These equations were developed at different times by different workers resulting in an inconsistent basis for design loads between fastener types. Additionally, allowable connection strengths have been derived from experimental results using disparate methods (McLain et al. 1993).

The NDS-86 design for strength of a single bolted joint is also mainly based on the research conducted by Trayer.

EYM is the basis for conversion of NDS-86 to an equation format in the NDS-91, since it would be able to predict the yield strengths for various connection geometries and material combinations for two and three member joints (Wilkinson 1993). Many of these connections are not addressed by NDS-86.

2.3 Trayer's Work

Trayer tested three member connections loaded in compression with side members one half the thickness of the center member and a range of main member thickness to bolt diameter ratio from 2 to 12 (Patton-Mallory et al. 1997). Bolt diameters ranged from 1/4 inch to 1 inch and were of two yield strengths only (Soltis et al. 1986), whereas larger diameter bolts and different yield strengths are usually used today.

Historically, most changes to design values have arisen from research topics, such as effect of metal side plates and interpretation of results for geometries not considered by Trayer. Extrapolating beyond Trayer's results has been controversial. The uncertainty due to extrapolation has resulted in typically conservative design values, which are aimed at keeping service load well below the estimated joint proportional limit.

3.0 Theory of European Yield Model

3.1 Introduction

Fundamental to an efficient utilization of bolted joints is an understanding of their mechanical behaviour under load. A number of models have been developed to determine the strength, of bolted timber joints, analytically. Examples of models include beam on elastic foundation, force-displacement equations, and finite element and yield theory model. Joints with dowel type fasteners are usually analysed as two-dimensional problems in which a beam representing the fastener, loads a foundation representing the joint members (Fig. 1).

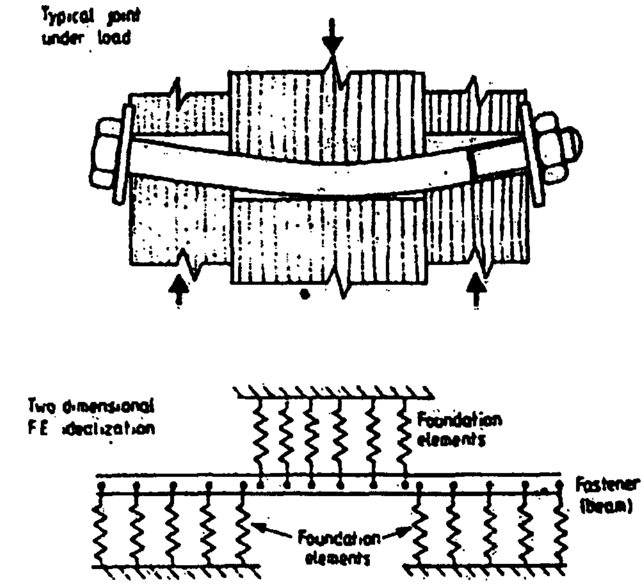

Figure 1: Two dimensional finite element idealization for joints with dowel type fasteners (Source: Smith and Whale 1987)

The load-deformation problem then reduces to the solution of the differential equation,

$$\frac{d^2M}{dx^2} = q \quad (1)$$

where,

- M: Fastener bending moment
- q: Force per unit length of the foundation be neath the fastener at point x

q is known as the embedment force per millimetre thickness.

3.2 European Yield Model

By assuming that both fastener and timber are ideal rigid-plastic materials, Johansen in 1949 derived explicit solutions (equations 2 to 11) to equation 1 capable of predicting the ultimate strength of dowel-type joints. The proposed model is referred to as European Yield Model (EYM). In 1973, Larsen expanded this model to describe the joint strength where wood members have different embedment properties (McLain & Thangjitham 1983). The yield theory provides an analytical method to predict the strength of a two or three member dowel-type joint. It is based on equillibrium equations resulting from free body diagrams of a dowel in a wood member. EYM assumes that the failure of dowel type joint occurs due to either bearing failure of the joint member or bending failure of the fastener. These assumptions provide several modes of failures (Figures 2 & 3) depending on connection member dimensions, member strength and bolt strength. In an actual joint the load carrying capacity will correspond to the lowest value obtained for Rd by substituting into the full set of equations. The equation giving the lowest capacity will also identify the failure mode. This model is often referred to as the "yield theory" or "yield model" because it describes how fastener yielding contributes to bolted-dowel joint strength.

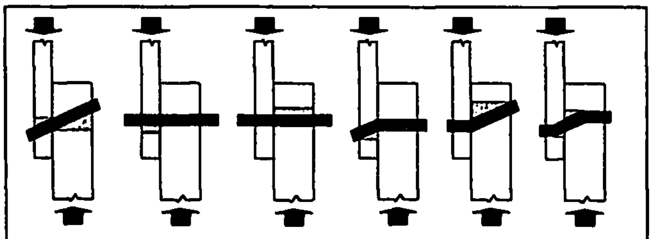

Figure 2: Failure patterns for single shear wood joints

Design resistance equations for single shear joints are:

$$\text{Mode 1: } R_d = \frac{f_{h,1,d} t_1 d}{1+\beta}\left[\sqrt{\beta+2\beta^2(1+\alpha+\alpha^2)+\beta^3\alpha^2} - \beta(1+\alpha)\right] \text{ N} \quad (2)$$

$$\text{Mode 1a: } R_d = f_{h,1,d} t_1 d \text{ N} \quad (3)$$

$$\text{Mode 1b: } R_d = \beta f_{h,1,d} \alpha t_1 d \text{ N} \quad (4)$$

$$\text{Mode 2a: } R_d = 1.1\frac{f_{h,1,d} t_1 d}{(2+\beta)}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(1+\beta)M_{y,d}}{f_{h,1,d} d t_1^2}} - \beta\right] \text{ N} \quad (5)$$

$$\text{Mode 2b: } R_d = 1.1\frac{f_{h,1,d} \alpha t_1 d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\frac{4\beta(1+2\beta)M_{y,d}}{f_{h,1,d} d \alpha^2 t_1^2}} - \beta\right] \text{ N} \quad (6)$$

$$\text{Mode 3: } R_d = 1.1\sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_{y,d} f_{h,1,d} d} \text{ N} \quad (7)$$

Design resistance equations for double shear joints are:

$$\text{Mode 1a: } R_d = f_{h,1,d} t_1 d \text{ N} \quad (8)$$

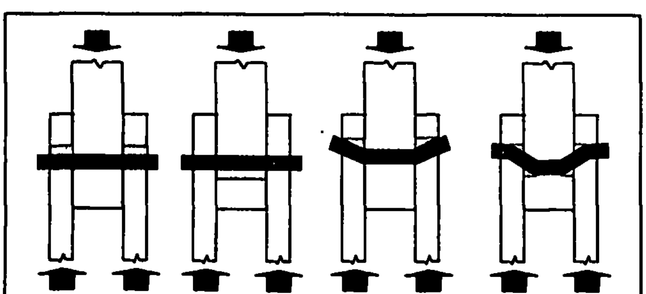

Figure 3: Failure patterns for double shear wood joints

$$\text{Mode 1b: } R_d = 0.5\beta f_{h,1,d} \alpha t_1 d \text{ N} \quad (9)$$

$$\text{Mode 2: } R_d = 1.1\frac{f_{h,1,d} t_1 d}{(2+\beta)}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_{y,d}}{f_{h,1,d} d t_1^2}} - \beta\right] \text{ N} \quad (10)$$

$$\text{Mode 3: } R_d = 1.1\sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_{y,d} f_{h,1,d} d} \text{ N} \quad (11)$$

in which,

α	$= t_2/t_1$
t_1, t_2	= thickness of side and main members respectively in mm
β	$= f_{h,2,d}/f_{h,1,d}$
$f_{h,1,d}, f_{h,2,d}$	= design embedment strength of side and main members respectively in N/mm²
d	= bolt diameter in mm, and
$M_{y,d}$	= design bolt yield moment in Nmm

These equations, which are derived from static analysis, predict failure loads due to either bearing failure of joint members (Mode 1, 1a and 1b) or the simultaneous development of bearing failure of the joint member and formation of plastic hinges in the fastener (Mode 2, 2a, 2b and 3).

3.3 Definition of Yield Load

The yield strength predicted by the EYM can be defined at any point on the load-deformation curve (Figure 4) obtained from a test of dowel-type joint.

In the United States, the yield strength is defined by offsetting the initial slope of the load-deformation curve by a deformation equal to 5% of the bolt diameter and locating the load at which the offset intersects the curve (Figure 4a). This definition has been adopted for both the LRFD specifications and NDS-91 (McLain et al. 1993).

In their publications, Soltis et al. (1986) and Soltis and Wilkinson (1987) have used the method 4a to define the yield load while McLain et al. (1993) and Wilkinson (1993) have used the method 4b.

The design embedment, $f_{h,d}$ strength of the joint member is given by,

$$f_{h,d} = \frac{k_{mod} f_{h,k}}{\gamma_m} \text{ N/mm}^2 \quad (12)$$

in which,

k_{mod} = modification factor for service class and duration
$f_{h,k}$ = characteristic embedment strength in N/mm²
γ_m = partial safety factor for timber

and, the design yield moment, $M_{y,d}$, of dowel fastener is given by,

$$M_{y,d} = \frac{M_{y,k}}{\gamma_m} \text{ Nmm} \quad (13)$$

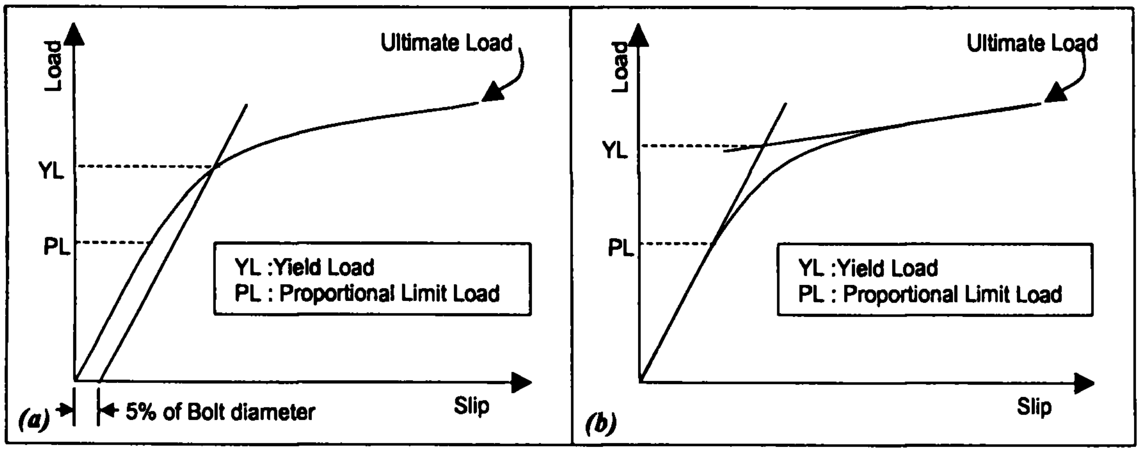

Figure 4: Schematic diagrams of load-slip curve showing different definitions of yield load, proportional limit load and ultimate load

in which,

$M_{y,k}$ = characteristic yield moment of fastener in Nmm
Y_m = partial safety factor for bolts

The EYM recommends the following approximation to the characteristic yield moment, $M_{y,k}$, for round steel bolts.

$$M_{y,k} = 0.8 f_{u,k} \left(\frac{d^3}{6}\right) \text{ Nmm} \qquad (14)$$

in which

$f_{u,k}$ = characteristic yield strength of bolt in N/mm²

Since R_d is the design resistance per shear plane, in symmetrical double shear joints the lateral load capacity is equal to $2R_d$.

3.4 Embedment Strength

Embedment strength is an important system property and is essential to calculate the design resistance capacity of the bolted or dowel-type joint. It is defined as the ultimate bearing strength and is calculated by dividing the ultimate load by the projected area of the dowel in the member. This can be found from an embedment test, which may be regarded as a symmetrical three-piece joint test, using steel side members and a wood or wood-based sheet material central member in which a bearing failure is enforced under lateral load. Further guidance on the determination of embedment strength is given in EN 383: "Determination of embedding strength and foundation values for dowel type fasteners".

EYM provides the following formulae to calculate the characteristic embedment strength, $f_{h,k}$, for bolts up to 30mm diameter,

timber loaded parallel to the grain,

$$f_{h,o,k} = 0.082\,(1-0.01d)\rho_k \quad \text{N/mm}^2 \qquad (15)$$

timber loaded at an angle to the grain,

$$f_{h,\alpha,k} = \frac{0.082(1-0.01d)\rho_k}{k_{90}Sin^2\alpha + Cos^2\alpha} \quad \text{N/mm}^2 \qquad (16)$$

in which

P_k = characteristic density of member material in kg/m³

α = direction of load with respect to the grain direction of timber (degrees) and,

for hardwoods: $K_{90} = 0.90 + 0.015d$ (17)

for softwoods: $K_{90} = 1.35 + 0.015d$ (18)

It may be seen from Johansen's equations that the input required in order to predict the ultimate load capacity of a joint comprises some geometric parameters, the plastic moment capacity of the fastener and the embedment strength of the timber.

The EYM for bolted connections is well developed and is fully documented by Soltis and Wilkinson (1987), McLain and Thanjitham (1983), Patton-Mallory (1989) and others. Numerous researchers have published verification of EYM for several connection types [Soltis et al. (1986, 1987), McLain and Thangjitham (1983), Whale and Smith (1986)].

4. Advantages of the EYM

The EYM provides not only a simple but a rational design procedure for bolted timber joints based on the joint geometry, member properties and fastener properties.

EYM equations are easily incorporated into computer programs; alternatively, tables of design values may be readily generated. Also, they can be rewritten in different forms to suit different purposes.

EYM would allow designers to calculate the appropriate load for any joint arrangement and would identify the mode of failure to be expected. It would also enable engineers to assess the sensitivity of joint strength to variation in the design parameters. A further advantage of this approach would be that joints made from new sheet materials could easily be introduced in to the code. All that would be required would be knowledge of the appropriate embedment strength equation for the sheet material.

5. Previous Experimental Investigations on Eym

5.1 Presentation of Joint Strength Results

Many researchers have provided their results of bolted timber joints in the form of normalized strength. Normalization is done by dividing the joint strength by a known strength property and bearing area under the fastener. It is usually presented in the way of plotting versus the t2/d, thus in the dimensionless form.

There are two different methods, which the researchers have usually used to normalize the joint strength results. Soltis and Wilkinson (1987) have compressive strength as know strength property while McLain and Thangjitham (1983) have used the embedment strength. Trayer also used compressive strength to normalization his results. The normalized strength, Rn, can be calculated as,

$$R_n = \frac{Rd}{Pt_2 d} \qquad (19)$$

Soltis et al. (1986) tested three member single bolted joints loaded in directions both parallel and perpendicular to grain. The comparison between yield theory and experimental for parallel to grain load indicate good agreement between theory and experimental (Figure 5a). The theory overestimates proportional limit and underestimates ultimate strength. The yield theory slightly overestimates the experimental proportions limit loads of perpendicular to grain tests (Figure 5b).

The thickness of each side member was one-half that of the central member. Also, the central and side members were cut from adjacent locations in wood specimen and are assumed to have equal embedment strength. Both

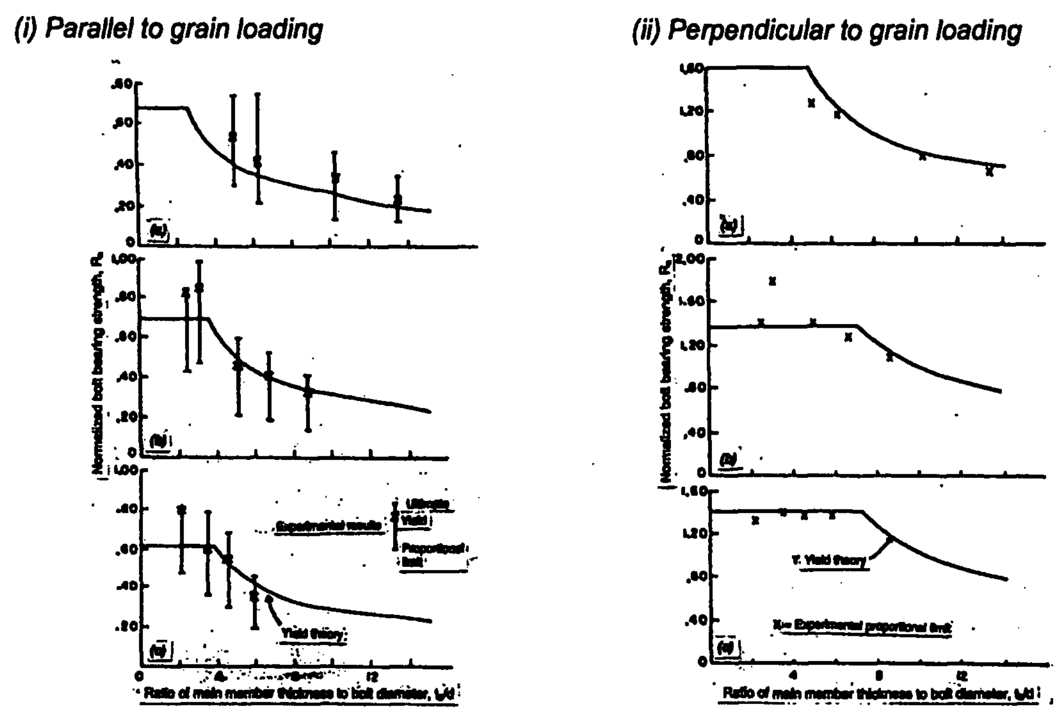

Figure 5: Comparison of results of Soltis et al. with EYM for three member joints (a). 1/2 inch; (b). 1 inch; and (c). 1 1/2 inch bolts - (Source: Soltis and Wilkinson, 1987)

above limitations are unable to perform in general practices. They used low carbon steel bolts having the diameters of 1/2, 1 and 1-1/2 inches whereas the larger diameter bolts and bolts of different strength are used today.

6. Comparison of EYM With Trayer's Model

(a) Hardwood with steel and wood side members

(b) Softwood with steel and wood side members

(c) Softwood with steel side members

(d) Hardwood with steel side members

Soltis and Wilkinson (1987) compared Trayer's results and the yield theory. Comparison of Trayer's proportional limit load and the yield load predicted by the EYM for three member joints with steel and wood side members loaded parallel to grain are shown in Figure 6a for hardwood and Figure 6b for softwood. Comparison between EYM and three member bolted joints made form softwood and hardwood with steel side plates are shown in Figures 6c and 6d respectively. This result could be expected because of the proportional limit load usually fall below the yield load (Figure 4). Comparisons between results of number of researchers with EYM are presented in full details in Soltis and Wilkinson (1987). Much of the research has been done with parallel to grain loading. The yield theory agrees more closely with the results of parallel to grain loading than of perpendicular to grain loading, for which fewer data exists.

Hilson and Whale (1990) have used Johansen's theory to appraise the values for nails and bolts presented in BS5268:1984. The results of this analysis show that, for nailed timber to timber joints, the BS5268:1984 values are on average about 23% higher than the theoretical predictions. This is due to the fact that in the original tests, nail heads were driven home, thus enabling an axial force to develop which, after deformation, provides an additional resistance component. In nailed sheet material to timber joints a similar effect applies, but to a

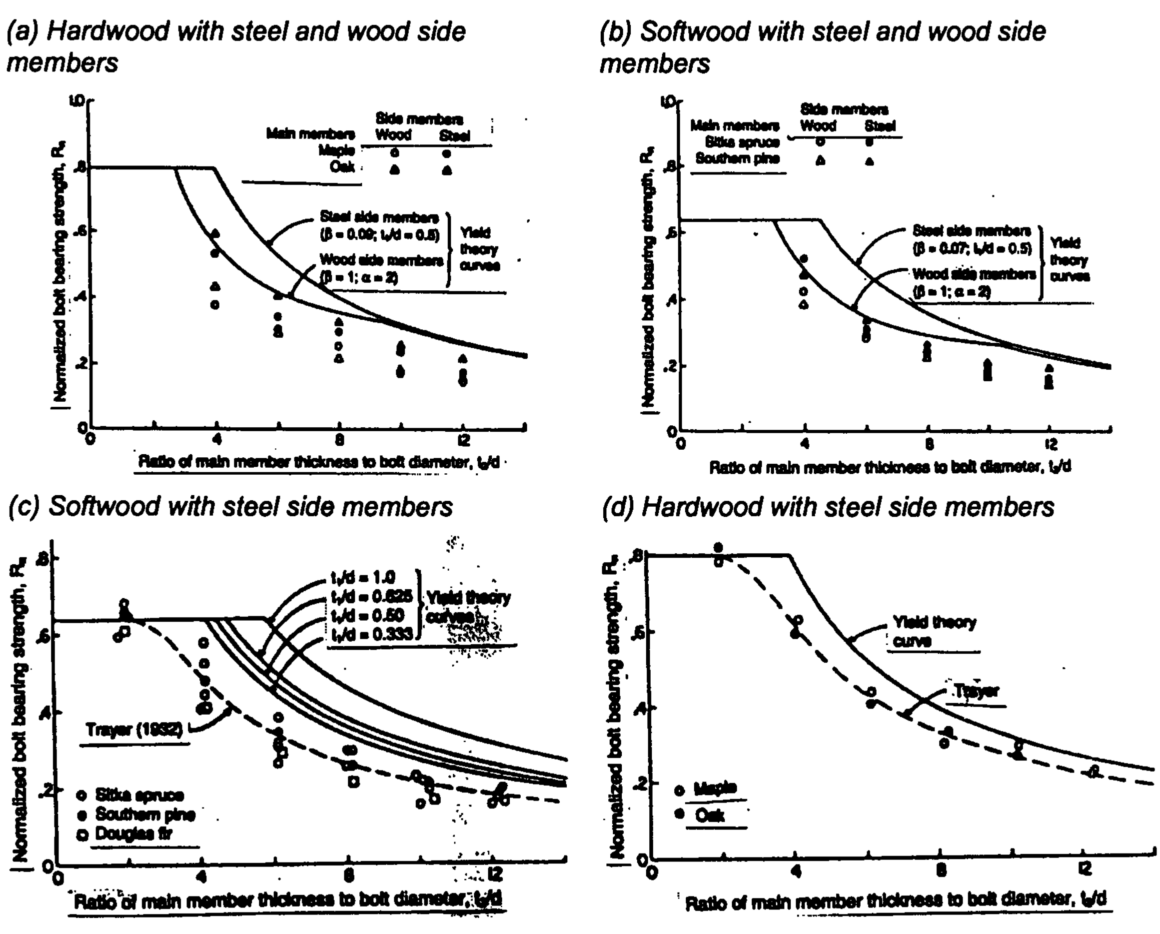

Figure 6: Results for Trayer's proportional limit and Yield load (EYM) for three member joints parallel to grain loading. -(Source: Soltis and Wilkinson, 1987)

lesser degree and the BS 5268:1984 values are found to be about 12% higher than theoretical. In bolted joints a comparison is more difficult, so the theory was used to calculate the load factor implicit in the BS 5268:1984 data. This was found to vary from 1.41 to 4.38.

7. Limitations and Shortcomings of Eym

There are several assumptions made in the derivation of yield theory equations, which are not met in general practice.

* The degree of the fixity of the bolt ends due to heads, nuts and washers. This fixity will serve to reduce the likelihood of the occurrence of some failure modes. Additionally, the end fixity will result in a tensile force in the bolt and cause the normal force between joint members to increase. Consequently, there will be an increase in the influence of friction between the joint members, which is not accounted for by the model.

* Additionally, as the bolts bend there will be a component of the tensile force in the direction of loading.

Therefore, the predicted values are most likely to be conservative compared to actual test results and the degree of conservatism will depend on the governing failure mode. This frictional influence could be predicted if the coefficient of the friction and tensile force in the bolt were known. However because of the relaxation and hygroscopic characteristics of wood, the influence of friction would widely vary in practice. Thus, for design purposes, it should be ignored.

Examination of failure modes indicates that bolt end fixity will be likely to preclude model failure in single shear joints due to end fixity provided by bolt head, nut and washers, oversize holes and especially the lack of symmetry. The only exception to this would be with thin members with large bolt diameters, which are to be unlikely in practice. Therefore, mode 1a is disregarded as a practical failure mode. However they may occur if there is a significant difference between the resistance capacity of the two members. Modes 2a and 2b in single shear joints will be possible only if one member is much thinner or weaker than another. Therefore, the end fixity will tend to force the single shear joints towards mode 3. In double shear joints, mode 1a is unlikely unless the side members are very thin or very weak or if the bolt is quite large. Any flexure in the bolt will retard the formation of mode 1a failure.

The applicability of the yield model for developing design values is subject to several limitations;

* Deformation, which is an important characteristic in limit state design, in a joint may be as important as a limiting load. The model does not incorporate this factor

* The yield load predictions assume that the joints do not fail due to the axial load on the net section and the end/edge distances are sufficient to prevent failure due to shear or splitting.

* The model assumes that the joint is well manufactured and that the fit of the bolt in the hole is nearly perfect. This second assumption is unrealistic in practice.

* Friction is ignored in the model since it is unpredictable and will change with the time and the environment experienced by the joint.

* The loads predicted by the model cannot be used directly in a working stress design without some rational compensation for safety.

8. Eurocode 5 Procedure for Bolted Joint Design Based On EYM

The EC 5 uses Johansen's theory as the basis for the calculation of the ultimate strength of joints made from nails, staples, screws, bolts and dowels, but uses simplified forms of the equations. For bolted joint design, EC 5 requires fewer bolts than designs to BS 5268:1984 because of the high load factors implicit in most of the BS 5268:1984 values (Hilson and Whale 1990).

As the fastener deforms under applied load, axial force could be developed for failure modes 2 and 3. These are caused by friction between the fastener and the timber and also by the constraints produced by the head of fastener and the washers assemblies in bolts. The force in the inclined part of the fastener will have a component parallel to the applied load and will therefore, enhance the resistance. EC5 takes this effect in to account by enhancing the resistance for modes 2 and 3 failures by 10%.

9. Conclusions

Based on embedment strength of joint members, yield moment of the fastener and some geometric parameters the EYM proposed a more logical approach to bolted timber joint design and it is adaptable to various material properties. It expresses the general trend of existing data. As expected, experimental results at the proportional limit usually fall below the yield theory curves, because the proportional limit load is smaller than the yield load (Figure 4). Trayer's empirical curve also fits the yield theory reasonably well.

The yield theory provides insight in to the joint parameters. For example, diameter of bolt (d) and the main member thickness (t_2) are the determining properties for joint yield strength. The effect of changing of member materials (wood, wood-based sheet materials, hardboard etc.) and bolt yield strength on the joint strength can be predicted well.

In developing the existing codes of practice, it is better that, rather than using tabulated data, basic material property equations and full set of Johansen's equation be presented instead.

Because of discrepancies between the assumptions in the model and actual practice discussed above, some modifications are required to suit the local conditions of relevant countries.

Many researchers have tested only the side member thickness is one-half of that of the side member. Moreover, most of results are available for parallel to grain loading. Therefore, it is required to verify the model for a wider range of member thickness and different loading directions.

10. References

BRITISH STANDARD INSTITUTION (1993). Determination of embedding strength and foundation values for dowel-type fasteners BSEN 383. BSI, London. pp. 3-8.

EHLBECK, J., WERNER, H. (1995). Bolted and doweled-joints - I. Lecture C6 in Timber Engineering STEP 1. Centrum Hout, The Netherlands.

HILSON, B.O., WHALE, L.R.J., SMITH, I. (1990). Characteristic properties of nailed and bolted joints under short-term lateral load. Part 5: Appraisal of current design data in BS 5268:Part 2:1984 'Structural use of timber'. Journal of the Institute of wood science. Vol.11, No. 6. Institute of wood science. pp-208-212.

HILSON, B.O., WHALE, L.R.J. (1990). Developments in the design of timber joints. The Structural Engineer. Vol. 68. No.8. pp. 148-150

HILSON, B.O. (1995). Joints with dowel type fasteners - Theory. Lecture C3 in Timber Engineering STEP 1. Centrum Hout, The Netherlands.

McLAIN, THOMAS E., SOLTIS, LAWRENCE A., PLOOCK Jr., DAVID G., WILKINSON, THOMAS L. (1993). LRFD for engineered wood structures - connection behavioural equations. Journal of Structural Engineering, Vol. 119, No. 10. ASCE. pp. 3024-3038.

McLAIN, THOMAS E., THANGJITHAM, SURROT (1983). Bolted wood-joint yield model. Journal of Structural Engineering, Vol. 109, No. 8. ASCE. pp. 1820-1835.

PATTON-MALLORY, MARCIA, PELLICANE, PATRICK J., SMITH, FREDERICK W. (1997). Modeling bolted connections in wood: review. Journal of Structural Engineering, Vol. 123, No. 8. ASCE. pp. 1054-1062.

SMITH, I., WHALE, L.R.J. (1987). Characteristic properties of nailed and bolted joints under short-term lateral load. Part 1: Research philosophy and test programme. Journal of the Institute of wood science. Vol.11, No. 2. Institute of Wood Science. pp-53-59.

SOLTIS, LAWRENCE A., WILKINSON, THOMAS LEE (1987). Bolted connection design. General technical report. FPL-GTR-54, US department of agriculture.

SOLTIS, LAWRENCE A., HUBBARD, FINN K., WILKINSON, THOMAS L. (1986). Bearing strength of bolted timber joints. Journal of Structural Engineering, Vol. 112, No. 9. ASCE. pp. 2141-2154.

WILKINSON, T.L. (1993). Bolted connection design values based on European yield model. Journal of Structural Engineering, Vol. 119, No. 7. ASCE. pp. 2169-2186.