Timber Frame Moment Joints with Glued-In Steel Rods
- A Designer's Perspective

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Abstract:

Significant evidence based on experimental research exists to give designers confidence in the use of theoretical equations to evaluate the pull-out strength of threaded steel rods glued into timber. However the mechanism of load transfer through a timber frame moment joint utilizing glued-in steel rods requires more than understanding simply the tension performance of a glued-in rod.

This paper presents a method of evaluating joint strength for moment and axial forces based on traditional mechanics theory adapted for use with timber. It takes into consideration the effects of time dependant deformation in timber at bearing interfaces and considers also the effects of stress concentrations imposed by the steel rods on the timber. The approach provides a methodology for joint design that has been successfully used in many projects.

1.0 Introduction:

Structural joint design in its simplest form involves unidirectional force transfers. A variety of traditional fastening methods employing dowel type, toothed plate or glued connections are appropriate. Epoxy grouted glass fibre rods or threaded/deformed steel bars are also available to the designer and are readily analysed using equations for pull out strength developed from laboratory based research programmes [1,2,3,4,5,9,10].

The challenge for design engineers comes in adapting the results of such research to practical use in joints which involve the transfer of forces from the primary members through the joint system. Consideration must be given to various combinations of the typical applied load components of moment, shear and axial force together with effects of time dependant deformation (creep). In addition the designer must be aware of the potential for strength reducing stress concentrations in the timber members at critical load transfer points.

This paper looks at the application of the reinforced concrete analysis approach known as the transformed area method for the design of epoxy grouted steel rods in elastically designed frame moment joints. Compression reinforcing has not been considered in this discussion although it may be used in design if appropriate.

2.0 Joint Analysis - Traditional Mechanics Theory:

The assumptions used are that plane sections remain plane and that the traditional elastic transformed area concept is applicable. Research on frame corners [6] lends support to the assumption of a linear stress distribution for the timber compression zone.
From frame analysis joint loads are known and section size is most likely defined although this may require change to ensure joint strength requirements are met.

Timber failure occurs predominantly in a brittle fashion so thought needs to be given to providing where possible connection components that have predictable yield patterns that limit the build up of potential brittle failure loads. If necessary steel hubs with significant post yield deformation (ductility) can be designed for seismic resistance but such systems are not included in this discussion.

With reference to reinforced concrete beam technology a balanced design is when the allowable compressive and the allowable tensile stresses are reached in the section at the design load. Applying this theory to timber it is generally desirable to design a timber/steel rod joint as an "under-reinforced" section to ensure that steel

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yields prior to the development of compression failure in the timber. Should limited timber compression failure occur it is however unlikely to lead to sudden brittle collapse.

In the application of this method it is assumed that the choice of adhesive for securing the threaded or deformed steel rods into the timber will provide a strong bond with the timber and have a stiffness greater than that of the timber so that adhesive deformation can be ignored. Epoxy resin adhesives have demonstrated good performance in service and are considered appropriate as they exhibit stable properties under short and long term loads in varying humidity and at normal operating temperatures of below 50°C [7,8].

Figure 1 shows a timber member cross-section of depth '*D*' and width '*b*' with tension only rod reinforcing a distance '*e*' from the bottom edge. The section has an applied moment 'M' resisted by timber compression 'C' and steel rod tension 'T'.

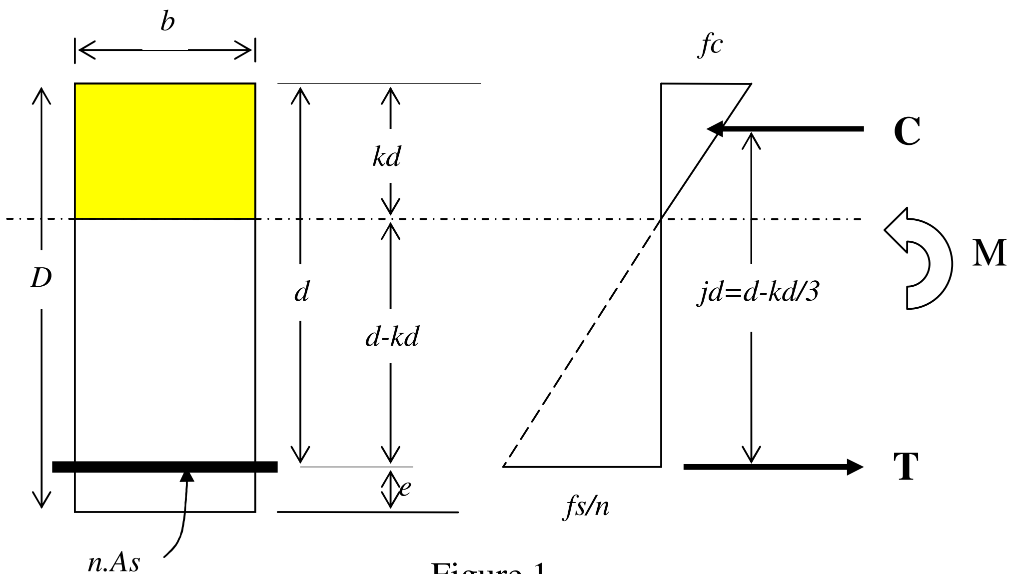

Figure 1

fc = timber compression stress   *fs* = steel tensile stress
modular ratio n = E*steel*/E*timber*
e = rod edge distance

C = *0.5 fc b kd*   T = *As fs*

The neutral axis lies at the centroid of the transformed area. Taking moment of areas about the neutral axis gives a quadratic equation that is solved for *kd.*
$b\,(kd)^2/2 = n.As\,(d-kd)$

Having determined *kd*, *jd* is known and the section moment capacity can be determined.
T = C = M/*jd*

The following simple numerical example illustrates the approach.

Example:

Applied Short Duration Ultimate Moment M*= 51.0 kNm

D = 630 mm   *b* = 115 mm   *e* = 65 mm   *d* = 565 mm

Timber properties: Characteristic tensile stress ft = 10 MPa
“ compr. “ // fc = 24 MPa
“ bending “ fb = 22 MPa
Modulus of Elasticity E*timber* = 10 GPa
Capacity reduction factor $\Phi = 0.8$

Rod properties: 16mm diameter Grade 8.8
Ultimate tensile stress fut = 800MPa
Capacity reduction factor $\Phi = 0.8$
Modulus of Elasticity E*steel* = 200 GPa

Modular ratio n = E*steel*/ E*timber* = 20
$As\ (mm^2) = 156$ $n.As = 3120$
$kd = 150.1$ $jd = 515.0$

C = T = 99.0 kN fc = 14.4 MPa ($\leq \Phi\, fc = 19.2\ MPa$)
fs = 637 MPa ($\leq \Phi\, fut = 640\ MPa$)

In frame knee joint design the timber compression bearing surface is often loaded perpendicular to the grain (Figure 2) and therefore an estimate of E*timber* perpendicular to the grain (E*perp*) is required to obtain an appropriate transformed section property.

There is a degree of uncertainty about E*perp* but if is expected to be about 1/15 to 1/20 of E*parallel*.

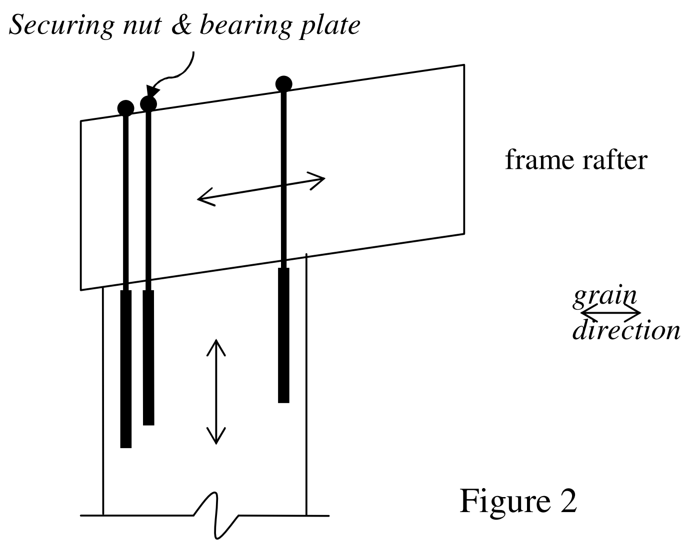

Figure 2

3.0 Creep Deformation:

An issue confronting designers is the effect that time dependant deformation (creep) in the timber will have on the distribution of forces within the joint.

Creep in timber is typically allowed for by factoring up the expected permanent load displacements. This is in effect applying a reduction factor to the elastic modulus for long term loads. Applying this principal to joint design means an effective reduction in E*timber* for long duration load which in turn reduces the lever arm jd and causes an adjustment to the calculated rod force.

In practise the reduction in E*timber* for long term effects is only critical when permanent loads are a significant proportion of the total applied load.

In the above example if a permanent load duration factor of 0.6 is applied to material characteristic stresses and E*timber* is reduced to 5.0 GPa to allow for creep effects, the maximum permanent load moment available is 31.5 kNm. The magnitude of this moment is governed by the timber compression stress ($0.6*\Phi f_c = 11.5$ MPa). The corresponding rod tensile load is approximately 2/3 of the rod capacity.

4.0 Stress Concentrations:

In structural detailing it is recognised that sharp changes in section property and/or forced changes in stress flow paths cause stress concentrations that can lead to premature failure.

Experimental bending tests on jointed timber members [2,3,11] have demonstrated timber rupture initiating at the embedded end of the steel rod in the outer zone in the region of maximum timber bending stress. Assuming that full load transfer from an embedded rod into the timber is completed at the embedded end of the rod it is reasonable to assume that maximum stress in the timber cross-section is achieved at that point. Typically N.Z. plantation grown timber the characteristic strength in tension is in the order of 50% of the characteristic bending stress and therefore timber failure in this transition region at stress levels below the characteristic bending stress is highly probable. It is therefore the author's practice to identify a contributing cross-section of timber into which the rod force is transferred and to and limit the tensile stress in that section to the allowable timber tensile stress. For a single tension rod the area of timber in tension is taken as *b.2e*. For multiple layers of rods the timber tension block for each internal rod is taken as *b.s* where *s* is the rod spacing. For the case of more than one tension rod the tension block for the extreme rod would be checked for an area of *b.(e+s/2)*.

In the numerical example above the tension stress in the timber block is given by

$$f_t = T/(b.2e) = 99.0 \times 10^3/(115*130) = 6.6 \text{ MPa } (<\Phi f_t = 8.0 \text{ MPa})$$

With multiple tension rods the tension stresses in the timber can be controlled by choice of different rod diameters and rod tensile strength. Staggering rod embedment lengths in joints with multiple rods is considered prudent to avoid accumulation of stress concentrations.

Limiting the stress in the timber to the timber characteristic tensile strength defines that the full bending strength capacity of a timber member cannot be developed using glued-in threaded steel rods. Designs using N.Z. plantation grown timber are generally governed by stiffness considerations rather than strength therefore this does not often present a problem.

5.0 Summary:

Application of the above elastic transformed section approach for the design of glued-in threaded steel rods in moment joints has been successfully used by the author in projects for over 15 years. The approach illustrated is a very simple moment only example but in practice the method is expanded to include member axial tension and compression forces.

The likely effects of timber creep deformation at bearing interfaces has been considered in the joint analysis and also limitations applied to timber stresses to counter the effects of stress concentrations imposed by the steel rods at termination points.

The time dependant response of loaded timber bearing surfaces, particularly those surfaces loaded perpendicular to grain are matters that warrant further investigation.

6.0 Update:

.01 Following presentation of this paper at the World Conference on Timber Engineering 2006, Portland USA, an experimental research programme on the long-term performance of epoxy-glued glulam connections has been commissioned at Canterbury University School of Engineering under the supervision of Dr. Massimo

Fragiacomo and Mr. Mark Batchelar. Material and financial support for the project is being provided by McIntosh Timber Laminates Ltd and Building Research. The purpose of the test programme is to better understand the force transfer mechanism within moment joints and to quantify the effects of long term loads on joint performance.

.02 A paper presented at the WCTE 2006 entitled "*Behavior of glulam in compression perpendicular to grain in different grades and load configurations*" [12] supports the expectation of E*perp* between 1/15 to 1/20 of E*parallel* for the perpendicular to grain compression bearing surface within a joint.

7.0 References:

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