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# Strength of timber connections under potential failure modes: An improved design procedure

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## HIGHLIGHTS

- An improved design procedure is proposed for different failure modes of connections.
- The wood effective thickness is taken into account at each potential failure zone.
- Wood embedment and fastener moment capacities are considered at different limit states.
- Verification is performed using timber rivet joints loaded in different directions.
- Proposed design approach can be extended to other fasteners such as nails and screws.

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## ABSTRACT

The wood engineering community has dedicated a significant amount of effort over the last decades to establish a reliable predictive model to determine the capacity of timber connections under different failure modes, particularly, for wood failure mechanisms. A design procedure is proposed to identify the wood and fastener capacities under possible brittle, mixed and ductile failure modes of timber connections. For the wood capacity, the effective wood thickness is taken into account at each potential failure zone. The fastener failing resistance under yielding and ultimate limit states are determined using the relevant wood embedment strength and the fastener moment capacity. The design procedure presented is verified using tests conducted on rivet joints under longitudinal and transverse loadings on New Zealand Radiata Pine laminated veneer lumber (LVL) and glulam. This design procedure gives the practitioners the ability to predict accurately the connection ultimate capacity and its failure mode.


## 1. Objectives and scope

Structures are detailed from a combination of hinged and moment resisting joints. Connections are often the most critical components of any type of structure. Evaluation of timber buildings damaged after extreme wind and earthquake events have shown that weak connections are one of the major causes of problem [1]. Different brittle, mixed and ductile failure modes of timber connections have long been observed by wood researchers. The wood engineering community has dedicated a significant amount of effort over the last decades to establish a reliable predictive model for the load-carrying capacity of timber connection under different failure modes, particularly, for wood failure mechanisms. Test results from various sources [2–12] demonstrate that for multi-fastener connections loaded either longitudinally, transversely or at an angle to the grain, failure of wood can be the dominant mode. The design procedures for timber connections in most design codes are based mainly on the European Yield Model (EYM) originally proposed in 1949 by Johansen. While the EYM theory provides accurate predictions for connections that fail in ductile fashion, it does not take into account the failure of the connections due to the brittle rupture of wood [5,7].

In addition, in the majority of current codes, the definition of fastener resistance is based on the yielding point. The yielding capacity is defined by using the material property estimated at the 5% offset inserted in the EYM equations. While this can be an acceptable limit state when the design follows exactly an allowable stress approach (ASD), it might not be appropriate today when designers are following the Load and Resistance Factor Design

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**Nomenclature**

$A_{th}$, $A_{sb}$, $A_{sl}$ areas of head, bottom and lateral planes subjected to stress ($mm^2$)
$b$ timber thickness (mm)
$C_{ab}$, $C_{al}$ average to maximum stress ratio on the bottom and lateral shear planes
$C_{fp}$ fracture parameter ($N/mm^{1.5}$)
$C_t$ coefficient depending on the ratio of unloaded edge distance to connection length
$d$ rivet cross section dimension bearing on the wood (mm)
$d_z$, $d_e$, $d_a$ bottom, edge and end distances (mm)
$E$, $G$ modulus of elasticity and rigidity (MPa)
$f_{ax}$ fastener withdrawal resistance per millimetre of penetration (N/mm)
$f_{h,y}$ wood embedment strength at yield point (MPa)
$f_{h,u}$ wood embedment strength at ultimate point (MPa)
$f_t$, $f_v$ wood strengths in tension parallel to grain and shear (MPa)
$f_{tp}$ wood strength in tension perpendicular to grain (MPa)
$h$ member depth (mm)
$h_e$ effective member depth (mm)
$K_h$, $K_b$, $K_l$ stiffness of head, bottom and side lateral resisting planes (N/mm)
$L_p$ rivet penetration depth (mm)
$M_{r,y}$ yield moment capacity of rivet (N mm)
$M_{r,u}$ ultimate moment capacity of rivet (N mm)
$n_p$ number of plates
$n_R$, $n_C$ number of rivet rows and columns
$p_{wh}$, $p_{wb}$, $p_{wl}$ maximum applied load causing failure on head, bottom and lateral planes (N)
$P_{c,ult}$ connection ultimate resistance (N)
$P_h$, $P_b$, $P_l$ distributed loads on head, bottom and side lateral resisting planes (N)
$P_{r,yld}$, $P_{r,ult}$ yield and ultimate capacities of fastener (N)
$P_{s,tef}$, $P_{s,b}$ wood resistance in partial and full width splitting (N)
$P_{w,a}$, $P_{w,b}$, $P_{w,c}$ load-carrying capacities of wood corresponding to failure mode a, b, and c (N)
$P_{w,tefe}$, $P_{w,tefy}$ load-carrying capacities of wood corresponding to $t_{ef,e}$ and $t_{ef,y}$ (N)
$R_h$, $R_b$, $R_l$ relative stiffness ratio for head, bottom and side lateral resisting planes
$t_{ef,e}$, $t_{ef,y}$ wood effective thickness for brittle and mixed failure modes (mm)
$w_{net}$ net section of joint width (mm)
$\beta$, $\gamma$ effective crack length coefficient for partial and full width splitting (mm)
$\eta$ factor depending on end distances and joint width

(LRFD) method [13]. Using the LRFD philosophy, a designer can evaluate the reliability of a structure with regard to its ultimate behaviour under extreme loads (e.g., earthquake and wind) with significant displacements where knowledge about the connection capacity beyond the yielding load is crucial. In recognition of this fact, developing an accurate design procedure to be able to determine the wood and fastener capacities in different possible connection failure modes under ultimate design loads is necessary.

To verify the design procedure presented, timber rivets as dowel-type fasteners were used on the conducted joint failure tests. The rivet joints were loaded longitudinally and transversely on New Zealand Radiata Pine laminated veneer lumber (LVL) and glulam. Rivets are tight-fit fasteners since the head is wedged into the steel plate hole. Therefore, they can provide high load-transfer capacity and high stiffness steel-timber connections [13]. Rivets are part of the Canadian CSA-O86 [14] and American NDS [15] wood standards. However, there is no closed form solution for the strength prediction of this type of connection under wood failure mechanisms. Also, these standards restrict the use of rivets to specific configurations and for glulam and sawn timber of some limited species [7].

## 2. Proposed design procedure

### 2.1. Potential failure modes

The design of timber joints using dowel-type fasteners such as rivets, nails and screws is governed by either the brittle, mixed or ductile failure mode of the joint. The occurrence zone of these potential failure modes is illustrated on a typical load–deflection curve of a timber joint (Fig. 1). The block tear-out failure in parallel-to-grain loading and splitting in perpendicular-to-grain loading are the possible failure modes of the wood.

In the brittle zone, the fasteners deflection is in the elastic range, therefore, the effective wood thickness for the joint corresponds to the elastic deformation of the fasteners, $t_{ef,e}$ [16], as shown in Fig. 2a. In this failure zone, the wood capacity of the connection, $P_{w,tefe}$, is less than the fastener yielding resistance, $P_{r,yld}$. It should be noted that the $P_{r,yld}$ is not an ultimate failure but constitutes a boundary. As the yield point is reached, the effective wood thickness reduces if the yield mode is not Mode I. This reduction in effective wood thickness, $t_{ef,y}$, leads to the generation of a new connection failure mode (Fig. 2b). If the wood capacity of the new connection, $P_{w,tefy}$, cannot resist the fastener yielding load ($P_{w,tefy} < P_{r,yld}$), a sudden wood failure with slight deflection on the fasteners which is called mixed failure mode occurs. Even if $P_{w,tefy} > P_{r,yld}$, the mixed failure mode can happen as the deflection of the connection progresses if $P_{w,tefy}$ is lower than the connection ultimate ductile strength, $P_{r,ult}$. If the wood strength based on $t_{ef,y}$ is greater than $P_{r,ult}$, the ductile failure governs and there is no wood rupture.

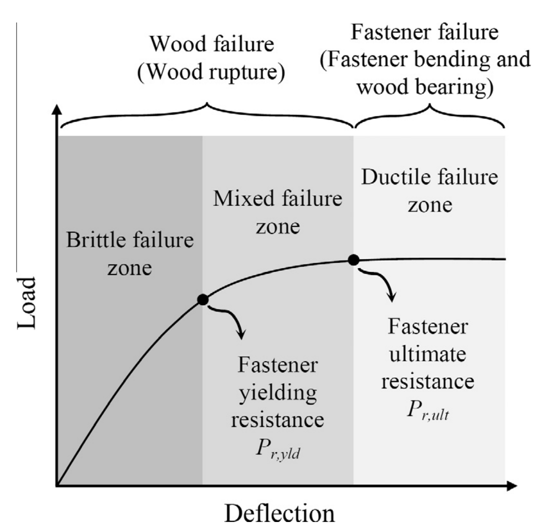


**Fig. 1.** Occurrence zone of potential failure modes of timber rivet joints.