Behaviour of Round Notched Timber Sections

JUSTIN DEWEY, *College of Science* and RABIN TULADHAR, *Engineering, JCU, Townsville, Australia*

ABSTRACT

Timber is widely used in the construction of bridges in Australia. An interesting feature is that girders used in these structures are often round in profile. Notching of the girders end is required for seating purposes and to create levelness in the top of the structure. This reduces the strength of the girder due to concentrations of high shear and cross-grain tensile stress at the re-entrant corner.

It is known that rectangular timber members with a tapered notch slopes will sustain significantly larger failure loads. This also appears to be the case in round notched members. Experiments undertaken at James Cook University have shown round timber members, sniped to a depth of 25% of total depth and with a taper of 1:4 will, on average, achieve a load 26% higher than a member with a stepped slope (1:0). Initial failure is still due to tension perpendicular to the grain before shear failure ensues with slippage of the fibres parallel to the grain. A tapered slope of 1:4 also significantly reduces the time between notch failure and shear failure occurring by a factor of three.

INTRODUCTION

Timber bridges have been built in Australia since before federation. Often the girders used in these structures are round in profile. These round members are notched at both ends for seating purposes and to create evenness in the top of the structure. A factor leading to large snipe depths is that often the replacement member is larger in diameter than the one being substituted. Sniping reduces the capacity of the girder due to the concentration of high shear and cross-grain tensile stresses at the re-entrant corner. This can cause cracks to propagate along the grain leading to catastrophic brittle failure of the girders.

The behaviour of round timber members is not very well understood in either flexure or shear as it is not often used for structural purposes in this profile. As such, there has been very little research undertaken in terms of the derivation of design values. A review of the literature shows that most methods used are little different to the design equations used for rectangular members. This ignores the fact that the grain profile in natural round members is completely different. Research related to sniping of circular members is also extremely limited. Department of Transport and Main Roads (TMR) has found that the majority of investigation undertaken on notching of timber beams has been on rectangular shaped softwoods used in regions other than Australia [1].

Failure Mechanisms of Notched Timber Bridges Girders

The principal actions that a timber girder must resist are bending and shear [2]. Bending is greatest at the middle of the span due to the weight of the structure and live loads. Tensile forces form in the longitudinal direction in the extreme bottom fibres while compressive forces occur in the fibres above the neutral axis. Shear failure is more likely to occur in spans with short effective lengths and girders that have been sniped. For notches applied on the tension side of timber, the concentration of shear and tensile stresses perpendicular to the grain can lead to a catastrophic brittle failure which tends to rip girders into a top and bottom section parallel to a fault along the grain (Figure *1*) [3, 4]. Girders should not be sniped to a greater depth than 15 % of residual depth (i.e. after top seating is formed) and an absolute maximum loss of 30 %. At these notch depths bolted strengthening should be applied [5]. This equates to an approximate area percentage of 10 % and 25 % respectively.

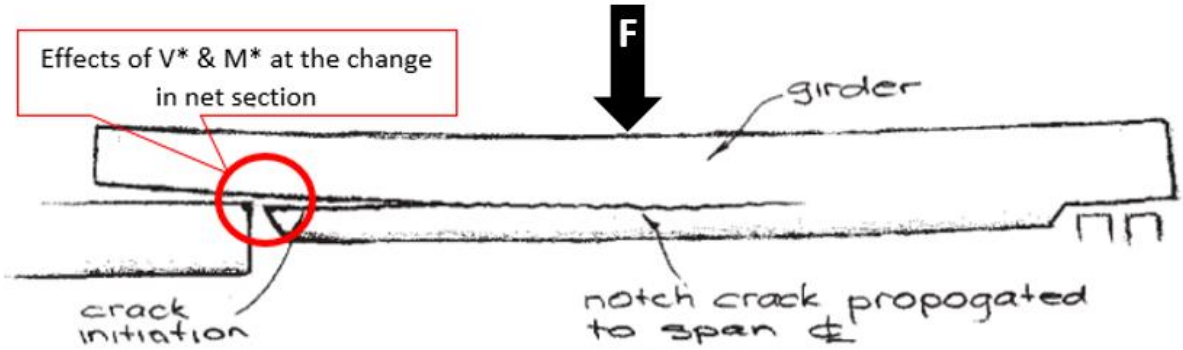


Figure 1 Effect of shear failure in a timber girder [2].

There are three distinct modes of failure in notched sections (*Figure 2*). Mode 1 applies when tension occurs perpendicular to the grain at the notch due to a load applied perpendicularly. Mode 2 relates to sliding of the grain due to forces parallel to the grain and the less common Mode 3 is due to torsion or rolling shear. Mode 3 is not applicable to round sections due to their inherent stability. In AS1720 mode 1 and mode 2 are represented as characteristic tensile strength perpendicular to the grain (f_t'), and characteristic strength in shear parallel to the grain (f_{sj}') respectively. Mode 1 initially occurs at the centre of the width of the notch before propagating laterally outward towards the surface. Mode 2 occurs in a sudden brittle manner in the form of the fibres sliding laterally past each other. This is often fatal as the shear crack will propagate to the centre of the span at which point the overall cross section is reduced in an area likely to experience large bending moments.

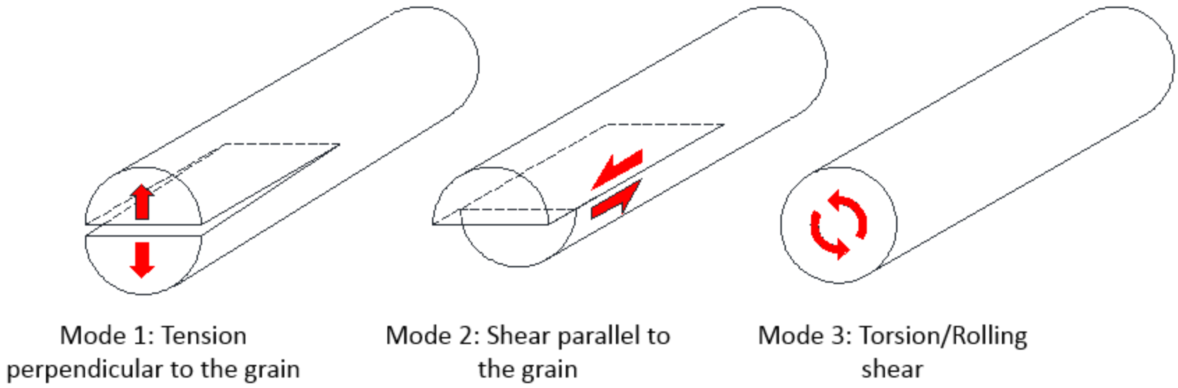


Figure 2 failure modes of round timber due to the effects of flexural shear

A common rule of thumb states that a tapered notch of 1:4 will increase a notched sections capacity by approximately three times [6]. Some other methods to reduce these stress consentrations are to predill the notch corner creating a curve which reduces the effects of stress. Another option is to taper the cut away from the horizontal at a less severe angle. A gradual tapering of the notch negates the effects of increased stress [7, 8]. Eurocode 5 [9] states that notches with slopes greater than 1:10 have very little effect on strength and thus the stress concentrations at the notch can be ignored. Keeping the distance between the face of the support and the internal notch corner small will also help to reduce any effects caused by bending [10].

It has been noted by researchers that cracking at the internal corner cannot be stopped. This occurs when the end grain is exposed to the environment. Due to the capillary action encountered at the cut face, an uneven distribution of drying may occur leading to additional stresses at this point due to cycles of shrinkage and swelling. Shrinkage in timber can cause tensile failure across the grain. In round members, due to the radial grain profile this can occur in any direction (*Figure 3*).

Figure 3 Radial drying cracks

Round Notched Timber Design Methods

Although sniping occurs on all round timber bridge girders there appears to be very little information regarding the design of these notched sections. A review of the literature shows that actual round design equations are based on rectangular sections with the assumption that the behaviour of the different cross section and grain profile is similar. Also lacking are experimental studies dealing with this unique profile. *Figure 4* shows the different notations used in design standards found in the literature.

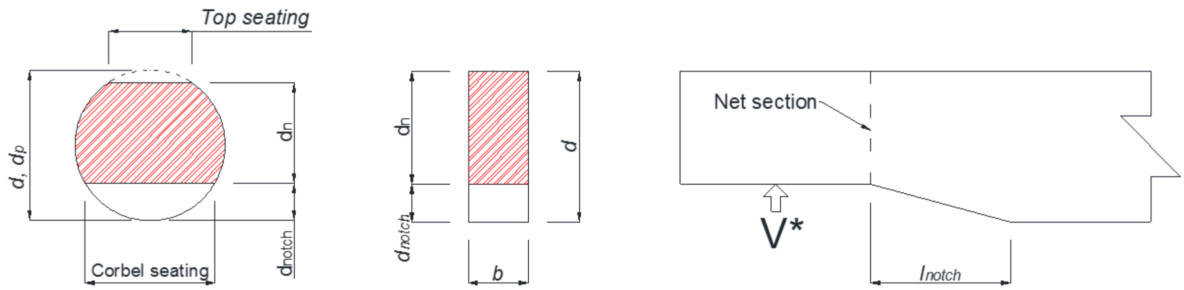


Figure 4 Notch geometry provided in different standards [8]

AS 1720.1—2010

AS1720.1 2010 concentrates purely on rectangular sections, making no allowance for round sections with regard to notching. The design procedure (*Equation 1*) is based on linear elastic fracture mechanics (LEFM) taking into account both the shear effects and bending moment encountered at the change of net section (*Figure 4*). AS1720.1—2010 states that if the notch is raking it can sustain significantly larger loads due to the reduction in stress at the notch. This is accounted for with the coefficient g_{40} for sawn notches on a beams edge.

$$\frac{6\,M^*}{bd_n^2} + \frac{6\,V^*}{bd_n} \leq \emptyset\, g_{40}\, k_1\, k_4\, k_6\, k_{12}\, f'_{sj} \qquad \textit{Equation 1}$$

Equation 1 takes into account the effects of both bending stress and shear stress at the notch to determine a load at which at which shear failure occurs parallel to the grain [8]. With regard the left hand side of Equation 1, longitudinal Bending stress and shear stress perpindicular to the grain are both determined at the net section with the shear stress being multiplied by a factor of four (*Equation 2*). Tension stresses perpindicular to the grain are not considered in this approach. On the right hand side of Equation 1 , g_{40} is a coefficient used to account for notching, k_1 is a duration of load factor, k_4 a moisture content factor, k_6 a temperature effect factor and k_{12} a stability factor not often used in round sections due to their inherent stability. f'_{sj} refers to shear stress due to a force parallel to the grain. If the notch is in close proximity to the support any bending effects can be neglected. AS1720.1 2010 states that either shear or moment effects can be ignored if the action is in the negative direction. This is not an unusual occurrence in well maintained bridges as the decking creates a fixed condition over the girder and corbel at the support. This perhaps should be ignored as over time the connection often becomes loose due to shrinkage of the timber away from connections [5]. This factor of four applied to the shear stress massively reduces design loads. No other standards have this sort of requirement.

$$f_b + 4 \cdot f_s \leq \emptyset\, g_{40}\, k_1\, k_4\, k_6\, k_{12}\, f'_{sj} \qquad \textit{Equation 2}$$

In Equation 1, a reduction factor, g_{40} (*Table 1*) is incorporated that accounts for the depth and profile of the sawn notch on the beams edge. AS1720.1 2010 makes no distinction whether this refers to percentage depth of notch or percentage area of notch, although it is the same in rectangular members. Different equations are used to determine g_{40} for a rectangular section depending on the depth of the notch relative to the total depth of the member. Also taken into account is the slope of the notch. AS1720.1 2010 treats 10 % loss of depth as a worst case scenario with values for g_{40} constant after this.

Table 1 Coefficient g_{40} for sawn notch on beam edge (All dimensions in millimetres)

Notch angle slope	$d_{notch} \geq 0.1d$	$d_{notch} < 0.1d$
$l_{notch}/d_{notch} = 0$	$9.0/d^{0.45}$	$3.2/d_{notch}^{0.45}$
$l_{notch}/d_{notch} = 2$	$9.0/d^{0.33}$	$4.2/d_{notch}^{0.33}$
$l_{notch}/d_{notch} = 4$	$9.0/d^{0.24}$	$5.2/d_{notch}^{0.24}$

Design Approaches For Notched Round Sections

A thorough review of the literature shows there have been three methods published to determine capacity of notched round sections. These equations simply substitute section properties of round timber in the design equations derived for rectangular sections. The National Design Specification for Wood Construction: With Commentary and Supplement, Design Values for Wood Construction [11] published in 2005 provides *Equation 3* to design for actual shear stress parallel (f_v) to the grain in round sections. For un-notched round beams it refers to [12] which states that shear stress at the neutral axis is within 5% of actual stresses when using (VQ/It) or $(4V/3A)$. The NDS thus recommends using the more conservative ⅔ rather than ¾ to determine design values for tension notched sections.

$$V = \frac{2}{3}\, A \cdot f_v \qquad \textit{Equation 3}$$

Another method to determine capacity of a round section notched on the tension face is *Equation 4* published in Division 23 Building Regulations [13] and cited by Wilkinson [5]. This method uses a depth ratio to determine a reduction factor to account for the concentration of stresses at the notch. It can be seen that at small notch depths there is very little loss of strength and at a notch ratio of 75% the strength is reduced by only 25 % from *Equation 3*.

$$V = \frac{2}{3} \cdot A_n \cdot f_v \left(\frac{d_n}{d}\right) \qquad \textit{Equation 4}$$

An updated National Design Specifications [14] published in 2015 by the American Wood Council nominate design procedures for notched round sections subjected to bending (*Equation 5*). The same method is also used in the timber designers manual (TDM) [10] although their notation is different. Shown below is the method published in the NDS where V_r' is the equivalent of V_r (reference shear force) when it is multiplied by various reduction factors and F_v' is the adjusted shear reference strength. The notch depth is again accounted for using a depth ratio, not an area ratio. In *Equation 5*, the depth ratio, always less than 1, is squared meaning that the strength reduction can be considerable, particularly for large notch depths. For a depth ratio of 75% there is a reduction in capacity of 44%.

$$\mathrm{V}_\mathrm{r}' = \frac{2}{3} F_v' A_n \left(\frac{d_n}{d}\right)^2 \qquad \textit{Equation 5}$$

The above methods vary little from rectangular sections as they use the net cross sectional area remaining above the notch (A_n) as opposed to the shear plane area (A_s). These methods also do not take into account the effects of tension perpendicular to the grain or stress concentrations at the notch corner. No account is given to tapering notches with design values being the same whether stepped or tapered. Both the NDS [14] and TDM [10] state that a gradual taper increases strength at the notch but do not provide recommendations on taper angle or increases in capacity.

Deflection is not usually an issue with both The Timber Designers Manual [10] and the AITC [15] stating that the effects on deflection due to a notch will barely be noticed as it is a function of stiffness (EI) over the full girders span. Thus, keeping the distance to the notch from the support small, any effects of deflection are minimized. The NDS [14] state that notch depths up to 1/6 of total depth and notch lengths less than 1/3 of beam depth do not affect the stiffness of the girder. ICC 400 2007 [16] – Standard on the design and construction of log structure’s states notches are not permitted in the middle third of beams subjected to bending or to exceed 25 % of the actual log depth. Notches between the supports and middle third of the beam are not to exceed 1/6 of depth and not extending into the middle third. For bending members with circular cross-section and notched on the tension face in accordance with the limits of this section, the allowable design shear shall be calculated in accordance with Equation 5.

Figure 5 below shows the vast difference between design methods when using a constant shear strength (5.4 MPa) and constant diameter (100 mm) of a notched round section at 25 % notch depth to design for a stepped notch. AS1720.1 2010 is extremely conservative due the fact that capacity is further reduced by a factor of 4. The next most conservative, the timber designer's manual, provides values nearly double for stepped notches.

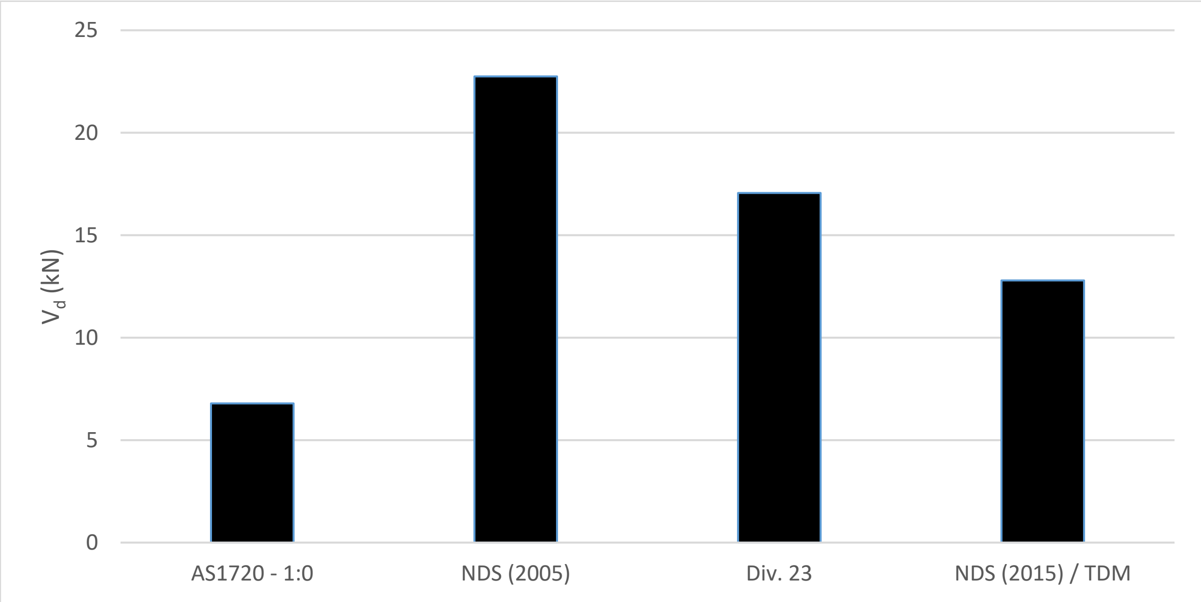


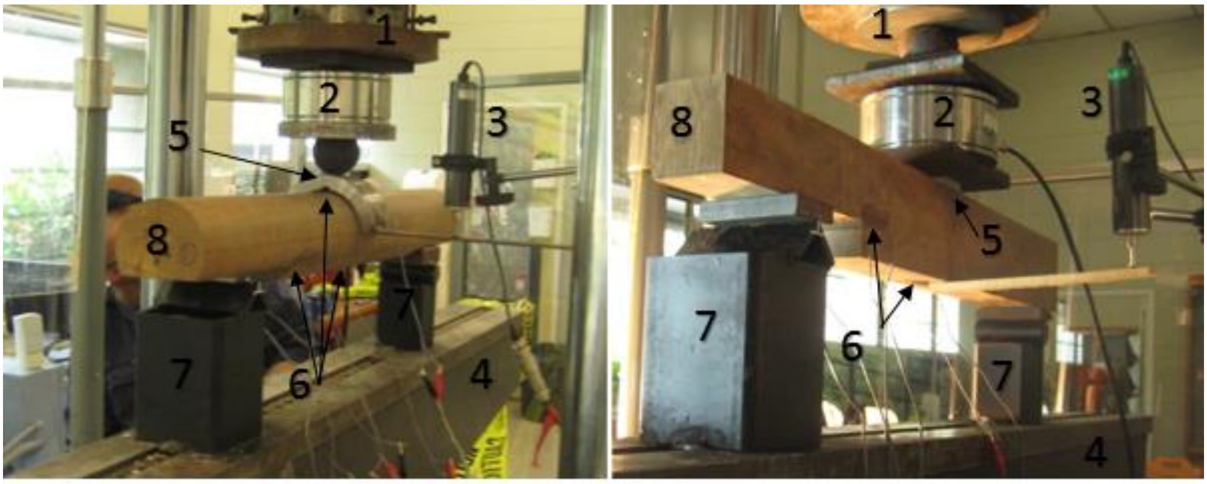
Figure 5 Shear value design method using round values (notch at 25 %)

EXPERIMENTAL TESTING

Setup

Notching of twelve rectangular and sixteen round timber members in notch depth to length ratios of 1:0, 1:2, and 1:4 were created to determine if angle has any effect on increasing the capacity of notched round timber members. These angles have been nominated in design publications for use with rectangular sections. The notch depth was kept at a constant 30 % depth in rectangular members and 25 % of the diameter in round members (*Table 1*). This equates to an area percentage of 30 % and 19.5 % respectively. Testing was conducted on a MTS machine located at James Cook University using a load rate of 10 kN a minute.

For all experiments, the set up consisted of a centrally loaded, simply supported, three point test (*Figure 6*). The supports were 600mm apart, from centre to centre, and the member was placed so it sat over the support at 100mm in from either end (100mm from notch corner). This arrangement consisted of the notched end supported by a pin support and un-notched end supported by a roller. A 5mm x 40mm x 60mm steel plate was placed over the knife edge and roller to distribute the load. Two 5mm x 40mm x 24mm steel plates were placed under the load point. These were placed towards the outside of the beam so as to allow strain gauges placed centrally to function. A 50 mm LVDT was placed directly below the load point on the flat surface created by a 3mm ply strip glued to the specimen. The same set-up was used for the round specimens except a flat face was created on the opposite end to the notch to allow a flat bearing surface. A 25mm thick by 40mm wide steel section with an internal diameter of 100 mm was milled to act as a load plate. This curving surface fit snugly over the round profile of the timber. This steel section had a 3mm x 40mm x 300mm long, straight piece of metal welded to one side to support the LVDT.



1. MTS
2. Load cell
3. LVDT
4. Reaction frame
5. Loading plate
6. Strain gauges
7. Supports
8. Specimen

Figure 6 Experimental test setup

Strain gauges were placed in the same locations for all specimens tested. A 2mm (FLA2–11–3L) strain gauge was placed vertically, five millimetres from the notch corner allowing strain perpendicular to the grain to be recorded. A 30mm (PFL–30–11–3L) strain gauge was placed horizontally, directly above the vertical strain gauge to measure longitudinal strain at mid span. This arrangement was mirrored on both sides of the specimen allowing an average strain to be determined. 30mm strain gauges (PFL–30–11–3L) were placed centrally on the tension and compression surfaces to measure longitudinal strain at the site of the load. All strain gauges were attached using CN adhesive with no surface preparation to the smooth timber prior to testing. This was deemed adequate as strain has been shown to be unreliable in timber, although it does allow identification of initial mode 1 notch opening.

Materials

All timbers used were of the same species, Corymbia maculata, a commonly used girder species. Rectangular specimens were rough sawn before having the notch cut using a bandsaw. Rounded specimens were of a lower quality box heart and were first sawn square before being made round using a timber lathe. Notches for the round sections were created using a milling machine (*Table 2*. Attempts were made to cut sections without defects but this proved difficult with regards the round sections as defects that were not initially visible became apparent upon machining.

Table 2 Notch profile section properties[5]

	Measurement	*Units*	*Rectangular*	*Round*
Section Properties	Total depth	mm	100	
	Width	mm	60	
	Diameter	mm		100

	Notch depth	%	30	25
	Notch area	%	30	20
	Total area	mm^2	6000	7854
	Area removed	mm^2	1800	1535
	Neutral axis from support	mm	35.00	33.57
Shear Plane Area (It/Q)	First moment of area (Q)	mm^3	147000	212090
	Second moment of area from support (I)	mm^4	6860000	9589605
	Thickness at centroid (T)	mm	60	98.52
	Shear plane area (A_s)	mm^2	2800	4455
Elastic Section Modulus	Second moment of area	mm^4	1715000	2470534
	Elastic section modulus	mm^3	49000	73602

Results

Nearly all failures in the stepped notched specimens initiated due to mode 1 tension perpendicular to the grain at the re-entrant corner. Mode 2 shear failure would happen in a sudden brittle manner with the crack propagating from the initial mode 1 failure site parallel to the grain to below the load point (*Figure 7*). Failure in the tapered notches would generally happen in a sudden brittle manner with mode 1 and mode 2 occurring simultaneously. Another difference was that when mode 1 failure occurred in the stepped notches it would initiate from the re-entrant corner whereas with the tapered notches failure would occur on the sloped face further away from the sharp corner. Often, failure in the tapered notches followed weaknesses in the radial direction creating a failure in the form of a truncated pie slice with the truncation occurring at the re-entrant corner.

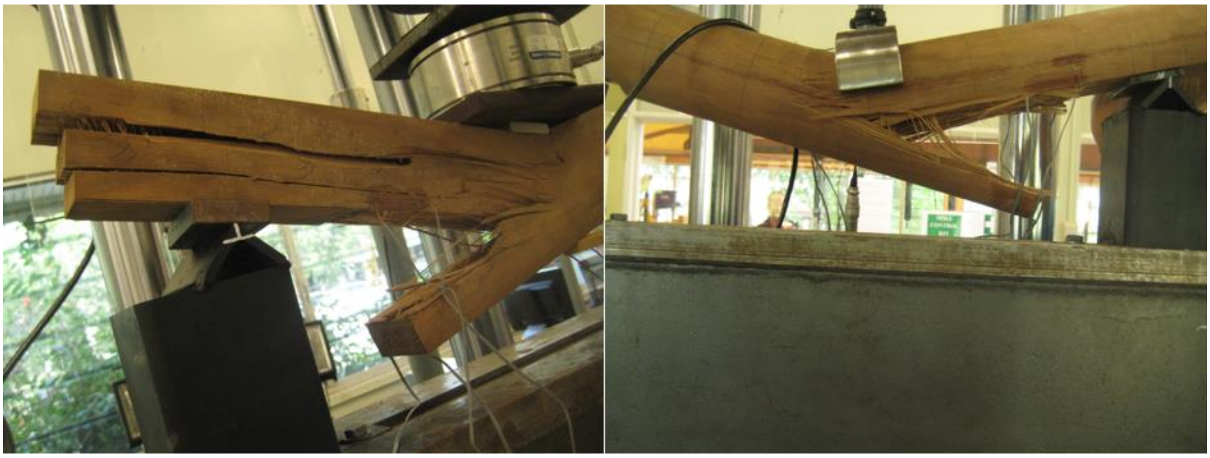
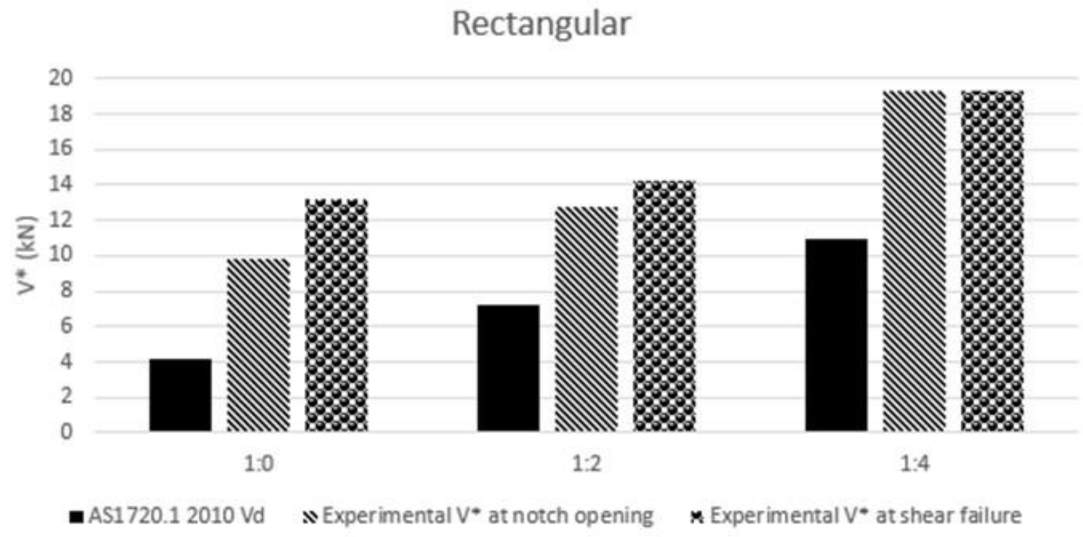


Figure 7 typical experimental failure

It is hard to compare rectangular to round failure values directly as the quality of timber and section profiles are different. Both the rectangular and round notched girders, however, exhibited similar behaviour. A taper significantly delays notch opening and decreases the reduction in capacity caused by notching. *Figure 8* shows a comparison of design loads found using AS1720.1 2010 and experimental values for initial mode 1 notch opening and mode 2 shear failure. Only g_{40}, the shear plane area of the net section and an assumed shear strength parallel to the grain (5.4MPa) were used. These design values would be further reduced by a factor of phi. It can be seen that all experimental values exceeded AS1720.1 2010 design capacities. The stepped notch had an average factor of safety between average experimental capacity and design capacity of a factor of 3.3. The 1:2 and 1:4 taper showed factors of 2.5 and 1.9 respectively. Thus a much higher factor of safety is encountered in the stepped notches. The notch profile yielding the lowest member capacities for both rectangular and round sections was found to be a stepped notch. Tapered notches of 1:4 on rectangular sections were found to achieve higher mode 2 failure capacities by an average 29% while in round sections it was average of 26 %. This slope also delayed crack opening and ultimately shear failure. Notch crack growth was found to be more brittle and sudden in the rectangular specimens than the round which showed a more gradual crack growth. This was assumed to be due to the differing fibre arrangement between the rectangular and round specimens. Also observed was that the 1:4 taper although much stronger gave no indication of failure with both mode 1 and mode 2 happening within a very short time period.



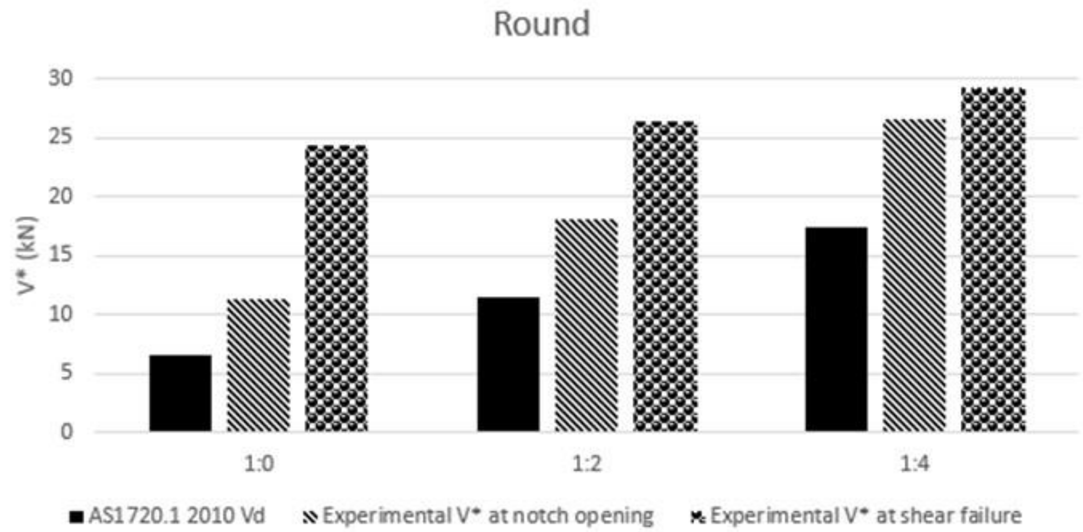


Figure 8 Average failure loads for rectangular and round specimens

Figure 9 shows the increase in capacity prior to mode 2 shear failure occurring in the experimental sections. The 1:4 tapered notch averaged an increase in capacity of 26% while the 1:2 taper increased shear capacity by 13%. These are significant increases for very little effort at time of installation although every effort should be made to avoid overcutting at the notch in any direction as this was found to be a failure initiator.

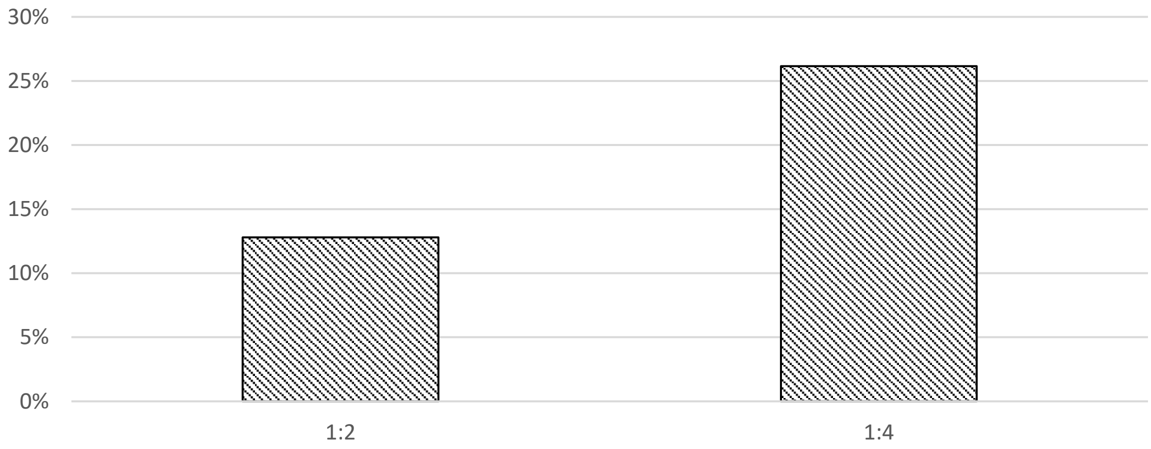


Figure 9 Average increase in shear capacity (mode 2) from an stepped notch

Figure 10 shows a comparison of various design standards against experimental values for stepped notched round sections. Values for International standards (NDS, Division 23, and TDM) are found using the net section at the notch, depth ratios and an assumed characteristic shear strength perpendicular to the grain of 5.4 MPa. The final column shows a comparison.

AS1720.1 2010 is by far the most conservative. It was one of only two methods, the other being NFDS (2015) / TDM, which consistently gave design values lower than actual experimental mode 2 failure loads for stepped notches. NDS 2005 is far too generous even when using the more conservative 2/3. The Division 23 method would likely fall into the same category even after further reduction values for timber were accounted for.

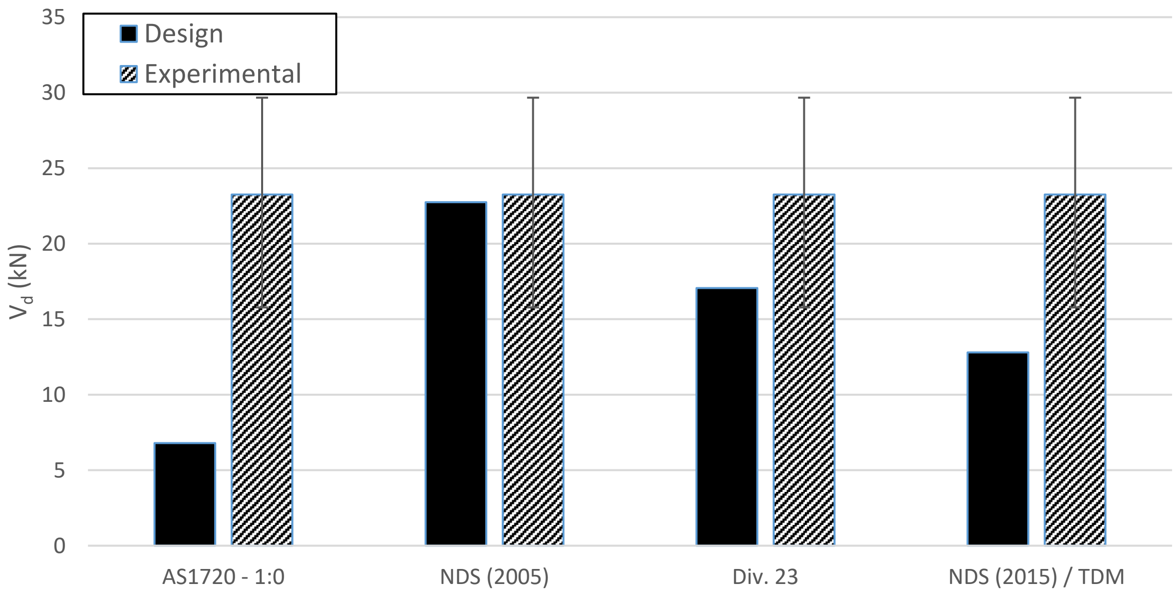


Figure 10 design values vs experimental results

Conclusions

The best performing round notched timber specimens when subjected to three point bending were those with a taper of 1:4. On average these showed an increase in capacity prior to mode 2 failure of 26 % when compared with stepped notches. Failure types for stepped and tapered notches also differed with the former showing obvious signs of mode 1 crack opening at the notch prior to mode 2 brittle shear failure.

The most conservative design method was determined to be AS1720.1 2010 ultimate design for shear and bending using the remaining net section above the notch to determine shear plane area. This method would further reduce strength once all reduction values for ultimate limit state and timber are considered. Although the most conservative, the factor of four applied to the shear stress massively restricts design ensuring sections required are much too big. This leads to greater expense due to the increase in growth time to get a large enough sections of hardwood

From this study it is recommended that if opening at the re-entrant corner is observed in a notch with a tapered slope, intervention should be immediately applied in the form of bolted strengthening as the section may be near its full capacity.

References

1. Queensland Department of Transport Main Roads, *Bridge Inspection Manual Appendix H*. 2004.
2. Queensland Department of Transport Main Roads, *Bridge Inspection Manual*, B.A.M.-S. Division, Editor. 2004: QLD.
3. Steffen Franke, Bettina Franke, and Annette M Harte, *Failure modes and reinforcement techniques for timber beams–State of the art.* Construction and Building Materials, 2015. **97**: p. 2-13.
4. Robert Jockwer, *Structural behaviour of glued laminated timber beams with unreinforced and reinforced notches.* 2015.
5. Kym Wilkinson, *Capacity Evaluation and Retrofitting of Timber Bridge Girders*, in *Civil Engineering*. 2008, Queensland University of Technology: QLD.
6. Queensland Department of Transport Main Roads, *Timber Bridge Manual* in *Part 1 - Background.* 2005.
7. Queensland Department of Transport Main Roads, *Timber Bridge Manual* in *Part 2 - Component Maintenance*. 2005.
8. Australian Standard, *AS 1720.1—2010 Timber structures Part 1: Design methods*. 2010.
9. European Committee for Standardization (CEN), *EN.1995.1.1.2004. Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings.* 2004.
10. E Carl Ozelton and Jack A Baird, *Timber designers' manual*. 2008: John Wiley & Sons.
11. American Forest, Paper Association, and American Wood Council, *ASD/LRFD, NDS, National Design Specification for Wood Construction: With Commentary and Supplement, Design Values for Wood Construction*. 2005: American Forest & Paper Association.
12. E.P. Popov, S. Nagarajan, and Z.A. Lu, *Mechanics of Materials*. 1976: Prentice-Hall.
13. Building Regulations, *Divsion 23 Building Regulations ChIX, Art 1*. 1996.
14. American Wood Council, *National Design Specification® (NDS®) for Wood Construction* 2015.
15. Construction American Institute of Timber, *Timber Construction Manual (6)*. 2012, Somerset, US: Wiley.
16. International Code Council, *ICC-400-2007 Standard on the Design and Construction of Log Structures*. 2007: United States.

Acknowledgements

The authors would like to acknowledge support from Mr Scott Anderson of Rockfield Technologies for help in preparing the timber test specimens.

Bio

Justin Dewey

Mr Dewey completed a trade in carpentry and joinery before beginning a career in timber truss and wall frame detailing. When the GFC hit, Mr Dewey decided to study civil engineering at JCU. He completed a Bachelor of Engineering with first class honors and is currently studying for a Ph.D. in structural engineering at JCU supported by JCU APA scholarship.

Dr Rabin Tuladhar

Dr Tuladhar is a senior lecturer at James Cook University, Townsville Australia. His research interest includes concrete engineering, structural health monitoring, and strengthening of aged infrastructure.