STRUCTURAL JOINTS IN GLULAM

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Joints in large glulam timber frames contribute significantly to the cost of the assembled structural system. Because of the demands of aesthetics and the continuing need to achieve structural efficiency and cost competitiveness, timber jointing methods are steadily evolving. Many jointing options are currently available to the designer. Appropriate choice of joint type will ensure an efficient load transfer element together with ease of manufacture and assembly.

This paper presents a New Zealand perspective on jointing solutions with illustrations from successful projects constructed locally and overseas with varying environmental conditions and code requirements. The advantages and disadvantages, of each system will be discussed.

INTRODUCTION

The success of timber structures depends to a significant degree on the joint details employed. Structural joints can cost from 5% to in excess of 50% of the value of un-jointed glulam members. They can dictate the final member size, consume up to 70% of the design effort, and if not carefully detailed be visually unattractive. It is therefore of prime importance that the correct choice of joint type is made early in the development of a project so as to balance the client's requirements in regard to appearance and cost while at the same time providing a sound technical solution. Dialogue between the designer and the manufacturer at this early stage is crucial to achieving an optimum result.

New Zealand's remote location from the major markets of the world, provides additional challenges to New Zealand manufacturers looking at global markets for their engineered timber products. Transport costs and practical limitations on length can dictate member joint positions at other than optimal structural locations adding a further factor to be considered in the design.

The predominant timbers used in New Zealand for manufacturing glulam members are radiata pine and Douglas fir. The properties of these plantation grown exotic species do not necessarily match the properties of similar species grown in other parts of the world. This has implications when these timbers are used in overseas projects where compliance with local design codes is required. Permissible timber strength properties and fastener loads given in the New Zealand Timber Structures Standard NZS 3603 are often not consistent with published data in other national design standards. A near doubling in the required number of fasteners has been found in some cases. This can have a major effect on the economics and appearance of a given jointing system and an understanding of and familiarity with the specific project compliance documents (codes) is therefore essential.

Earthquake resistance is of major concern in many parts of the world and much emphasis is given to detailing structures for ductility, or the ability of the structure to behave inelastically. Timber, being essentially a brittle material, has little inelastic behaviour and as such all effort to provide ductile behaviour must focus on the parts of the structure able to respond appropriately – namely the steel connecting elements. The zones of inelastic behaviour in the connecting elements are at this stage most appropriately designed to be away from the timber/connector interface and as such are outside the scope of this paper. It is known that nail/dowel type frame connections exhibit hysteretic energy absorbing behaviour due to fastener yielding and crushing of the wood. Ongoing research [1] confirms this, but because of the large variability in wood properties even within a species grade, no definitive design data is available to enable confident capacity and ductility detailing at the timber/connector junction. Recent research with hollow dowel connectors does show some promise [2].

With the increasing awareness of fire hazard and the need to detail structures to achieve acceptable fire resistance attention must be given to the influence of fire on structural connections. Many of the jointing systems used do not have an inherent fire resistance and need protective coverings to reach the desired performance level.

COMMON JOINT TYPES

The joint systems listed in this review are those commonly used in N.Z. today. Some traditional timber connectors (toothed plate connectors, split rings and shear connectors) have not been included as they are used infrequently and design data on these connectors is no longer included in the New Zealand Timber Design Code.

Nailed Joints

Nails are widely used for connecting small section timber framing members, and since the 1970's they have been successfully used in conjunction with pre-drilled steel plates or plywood plates [3,4] for moment connections in large glulam frames (Figs 1,2,3).

Nails used in large numbers for significant structural joints have the advantage of transferring the joint loads through many small fasteners thus minimizing localized stress concentrations. Care should however be taken when placing nails in the outer critically stressed laminations of a glulam member [5].

Moment resisting joints can effectively be made using nails as there is no initial slip with a nailed joint since a nail always fits the hole into which it is driven. Nail fixing is a simple low-tech system, not particularly tolerance critical and thus ideal for site joints. However, attention must be given to maintaining correct frame alignment at the time of assembly as nailed joints once fixed lock-in any incorrect geometry [6].

The analysis of nailed moment joints can be based on rivet group theory although a finite element model by Hunt showed peak nail forces to be about 20% greater than rivet group theory suggests [7]. However since only a small number of nails within the joint are in extreme locations this is not considered critical to joint performance. Joints designed using the rivet group theory have performed well.

The visual appearance of plywood or steel plate nailed joints may be unacceptable in community facilities or buildings with a high public profile but this is not generally a consideration in industrial applications. Steel plates are able to develop the full strength of a glulam member without the need for a haunch or increased frame depth in the joint region. However with large pre-drilled steel plates hand nailing is a slow and onerous task for assemblers, particularly when nail holes become clogged with zinc or other corrosion protection coatings. Where a haunch can be tolerated the use of plywood connecting plates and nails fixed using compressed air guns overcomes these difficulties and greatly reduces joint assembly time. High strength hardwood ply joints, and composite sheets using radiata pine plywood with high yield steel strips, have been successfully used for large span frames [8].

Nailed joints have minimal fire resistance unless adequately protected with sacrificial timber or a non-combustible overlay [9].

Plywood or steel gusset plates are generally nail fixed to one end of the connecting glulam members prior to dispatch from the factory e.g. to the top end of the column in the case of a portal frame. Nailing of the other end of the gusset is then completed on site. The cost of gusset plates and pre-nailing for portal frame structures varies from 20% to 30% of the total frame cost.

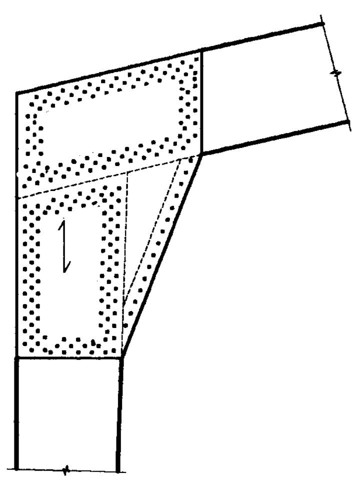

Figure 1 Nailed Plywood Gusset

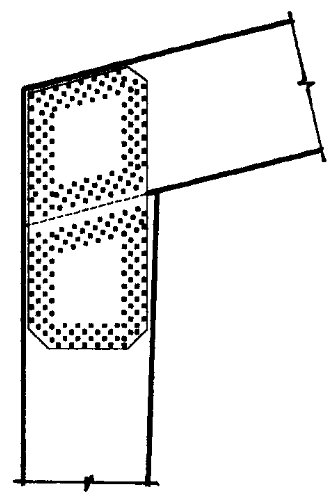

Figure 2 Nailed Steel Gusset

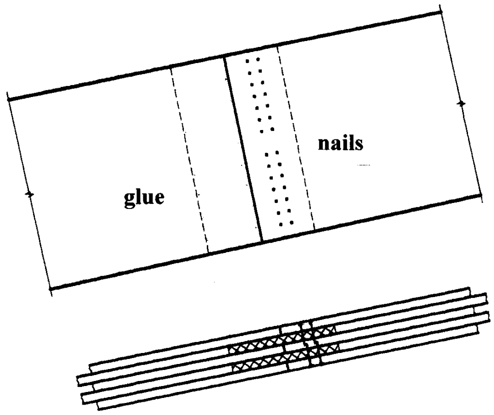

Figure 3 Nailed Timber Splice Joint

Site erection of the portal frames generally proceeds as follows (Fig. 4): The wall columns with the gussets attached are erected and braced into position; the roof beams are laid out on the floor and purlins and other materials fixed in place over two to three bays; this total assembly is lifted to the top of the columns when nailing of the gussets to the roof beams is completed, care being taken to observe the design Engineer's specified pre-cambers. This type of portal construction is competitive with steel frames.

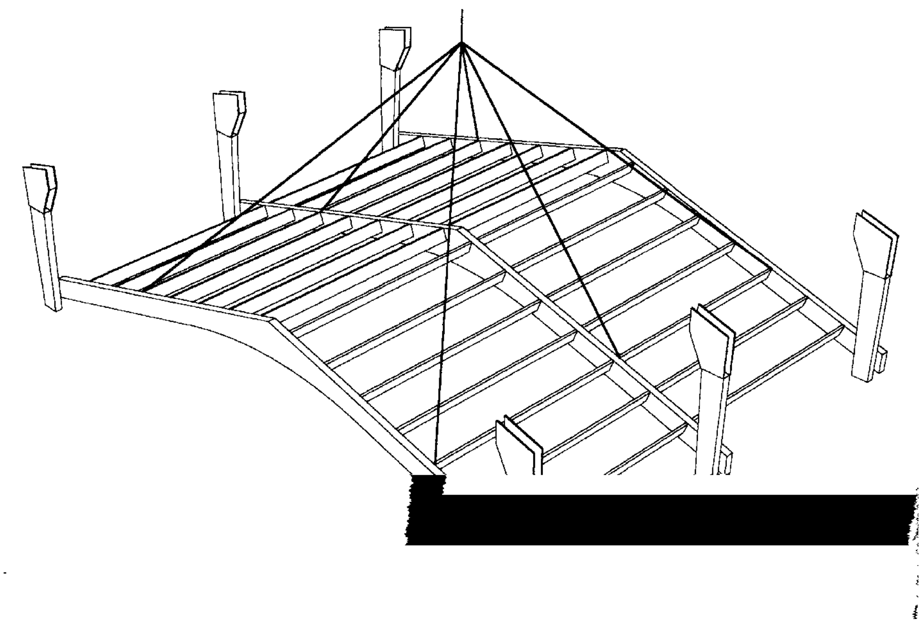

Figure 4 Portal Frame Erection Method

Bolted Joints
Bolts are the most widely accepted method of connecting timber to timber and timber to steel (Figs 5,6). All timber design codes have performance data for bolts although a comparison of the bolt data given in these documents shows significant variations. Bolt spacing, end distances, washer sizes, and basic loads can be different. Experience on a major project using N.Z. radiata pine revealed that nearly twice the number of bolts were required for compliance with BS5268 compared to NZS 3603. Subsequent tests on full-scale joints confirmed the appropriateness of the joint designs using the N.Z. code values and the lesser number of fasteners [10,11].

Bolts can be supplied with corrosion protection or as stainless steel and can therefore achieve good durability in extreme exposure environments.

Compared to other dowel type fasteners bolts have the advantage of being able to carry axial load in addition to shear loads provided suitable sized washers or bearing plates are specified.

Bolted joints are not recommended for structures which are sensitive to joint displacement or rotational movement. Holes into which bolts are fixed are for practical reasons larger than the bolt size resulting in an initial joint slip as load is applied. Also, because of the large end distances and spacing required for bolts significant secondary moments can result from the offset between the applied load and the bolt group centre of resistance. Calculation of permissible moment for a given bolt group is also more difficult than applying a simple rivet group approach since each fastener has a different orientation to the timber grain direction therefore requiring the application of Hankinson's formula for each bolt.

Fire protection of bolted joints can be achieved by providing cover protection. This is not normally acceptable for visual reasons and intumescent paint systems have been employed. Justification for intumescent paint systems is derived principally from fire tests on steel only connections. There is a need for design information on fire resistance of bolted timber to timber and timber to steel connections. It has been the author's practice to provide sufficient fire protection to the exposed part of the connector to limit the temperature of the bolts to 300^0C so as not to seriously degrade the bolt-timber interface [12].

Typical bolted joints designed to transfer shear and axial loads cost approximately 20% of the glulam frame value. Although this is not excessive, when compared with nailed joints bolts do give a higher connection cost per unit of load transfer e.g. 1/M16 bolt loaded at 45^0 to the grain with steel side plates can transfer the same load as 18/3.55 x 45mm nails at a relative completed joint cost of about 1.3 to 1. This relative cost difference increases with increasing bolt diameter.

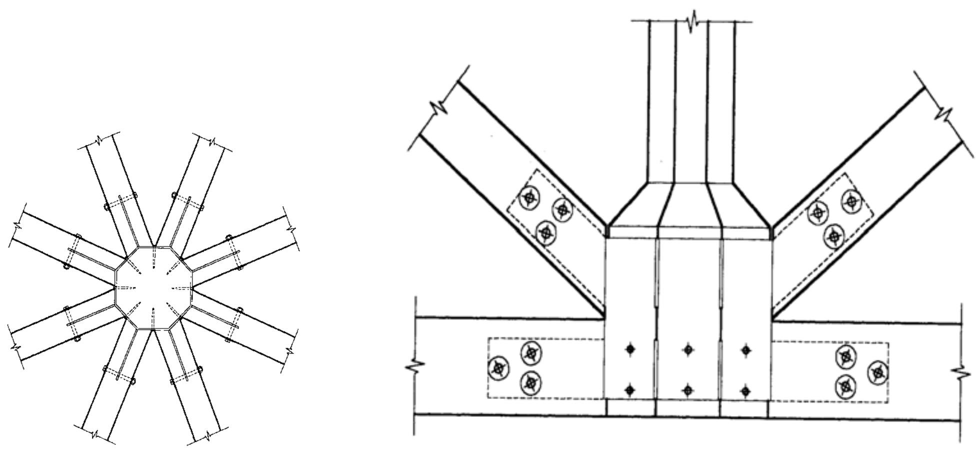

Figure 5 Multi-Member Bolted Joint

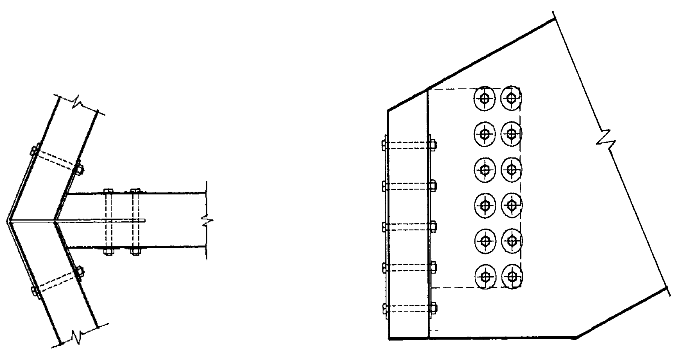

Figure 6 Bolted Rafter to Tie Beam Connection

Glued Cross-Lapped Joints

The joint is formed in a factory by gluing and cross-lapping or interleaving multiple timber members. The procedure can be used for the manufacture of timber trusses but is predominantly used for portal frame knee joints (Fig. 7). This method of developing full moment resisting joints is commonly referred to in N.Z. as the McIntosh joint, McIntosh Timber Laminates Ltd being the company that first introduced the system [13].

Transfer of load through a cross-lapped glued joint is by means of shear at the glue interfaces. A simple method of determining the allowable joint moment load is to apply rivet group theory having defined a maximum safe shear stress at the glue line. A more rigorous method is to apply fracture mechanics theory as developed by Komatsu [14]. For typical portal knee joints with normal roof pitch both methods give similar results.

Cross-lapped glued joints are the most structurally efficient method of developing full strength rigid moment resisting joints, they are visually attractive with clean lines, and with sufficient number of layers of timber can develop good fire resistance.

Factory conditions with high levels of quality control are needed for this system as fabrication tolerances are critical and the gluing operations are sensitive to environmental conditions, such as temperature, moisture, and cleanliness.

The multiple layering aspect of the system does require more timber compared with a single section frame however the additional section width can be of advantage when leg members carry high axial loads or are unrestrained laterally. Frames using this system have been used to advantage for supporting overhead gantry cranes.

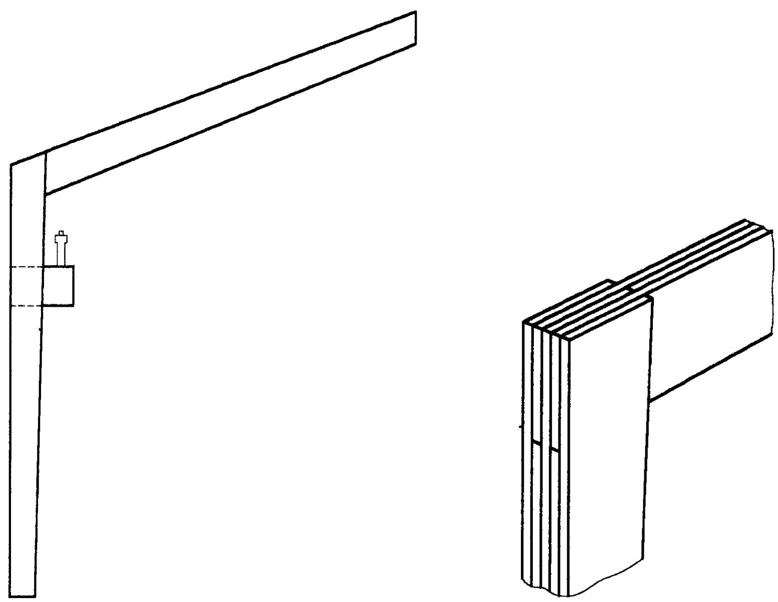

Figure 7 Glued Cross–Lapped Joint

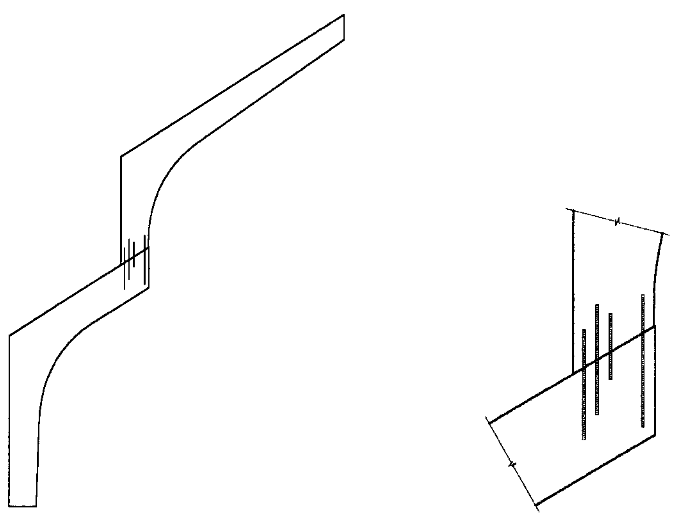

Figure 8 Epoxy Grouted Threaded Rods

The erected cost of portal frames using the McIntosh system are comparable to site fixed steel or plywood gusset frames due to the reduced site assembly time. Transport of the complete rafter/leg members must however be given consideration.

Epoxy Grouted Steel Rods

The use of epoxy grouted steel rods is gaining increasing acceptance in New Zealand due to ongoing research and development and is proving to be a very useful method of joining large timber sections (Figs 8,9). Rigid and completely hidden joints are feasible and some fire resistance is possible given adequate sacrificial timber protection to the embedded rods [15].

The present interest in and use of this joint type is due to original work in Denmark by Riberholt [16] and local research at the University of Canterbury, New Zealand [17,18].

Experience in reviewing failed joints due to inadequately mixed and incorrectly applied epoxy adhesives on site leads to the conclusion that all gluing operations should be done in a factory environment with adequate quality control and skilled personnel. Gluing of epoxy grouted steel rods on site **is not** considered appropriate particularly since the effectiveness of the grouting operation can not be visually checked. Although becoming less common there still persists an attitude in the building industry of the "miracle epoxy" – a super adhesive that solves all construction problems. This is not the case and correct choice, mixing and application of epoxy adhesives is crucial. Best results have been achieved by using a low viscosity epoxy that can flow around the embedded rod ensuring full encapsulation.

A number of different applications of the epoxy rod system have been used in significant timber projects but in all cases the joint has not been required to develop the full strength of the glulam section. The method has been successfully used for portal frame knee joints where the frame size is governed by deflection rather than strength, and for site splicing long members. In each case the final site connection has been made using common construction techniques with purpose made couplings and steel shear pins or cement grout anchor sleeves. The latter is a component of the Alan H Reid (N.Z. & Australia) high strength reinforcing bar product range for concrete. The grout sleeve is screw fixed to one threaded Reid bar and the bar to be spliced then slotted into the grout sleeve which is injected with a special cement grout (Fig. 9). The timber section has to have sufficient dimensions to completely house the grout sleeve which requires a hole diameter of approximately five times the bar diameter.

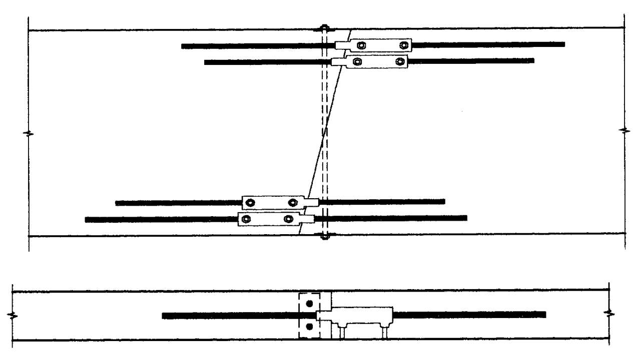

Figure 9 Epoxy Grouted Reid Bar & Coupler

Available research on steel rods epoxy grouted into N.Z. radiata pine [17,18] and specific project strength tests give confidence for the design of joints for moment and axial forces but shear transfer due to dowel action of the rods has not been well reported. Riberholt [19] gives an equation for characteristic lateral load of a joint which is a function of the specific gravity of the timber but no confirming data on N.Z. timber is available. It has therefore been the author's practice where high shear loads are present to provide for joint shear transfer other than by means of the epoxy grouted rods.

Careful thought must be given to any minor axis beam bending forces that may be required to be transferred across the joint since these joints have very little lateral bending strength. Problems can arise in long beams if temporary stiffeners are not provided at the splice joints during lifting and erection.

Stress concentration in the timber where the steel rods terminate has been identified [21] and is receiving research attention at the University of Auckland N.Z. through the Timber Engineering Research

Fellowship. From work to date it is recommended that the ends of the rods be tapered to reduce stress concentration effects.

The cost of epoxy grouted steel rod joints is comparable to other systems.

Drift Pins

Drift pin connections are dowel type joints similar to bolts but without the end moment restraint provided by the washer and bolt head or nut (Fig. 10). The connections have a tidy appearance with the joint region uncluttered by bolt heads, nuts and washers. Though a common connection system in the northern hemisphere the system has not been widely used in New Zealand.

Researchers such as Komatsu [20] have demonstrated the usefulness of this type of joint for moment resisting connections. As could be expected drift pins fitting through tolerance holes in internal steel splice plates give good low initial slip compared with bolted joints. Komatsu also observed that the smaller the diameter of the pin the higher the initial joint stiffness but the lower the joint ultimate load. His work also showed evidence that smaller pin diameters reduce the likelihood of the pins promoting a timber splitting failure.

The limited use in N.Z. is due in part to the lack of code guidance on the characteristic loads of drift pins and also the need for high precision joint details to achieve the desired pin fit. Experience with this type of joint has demonstrated a need for a high level of site supervision to avoid hammer damage to the timber members and surface splitting of the timber at the leading end of the pins as they are driven. Successful joints using multiple timber members have been made assuming characteristic pin loads of about 80% of the code bolt values, this reduction being an estimate of the effect of removing the rotational restraint due to the bolt head and washer. This restraining effect is clearly a function of fastener diameter, timber thickness and material properties. More code development and guidance is necessary before drift pin connections are seen in regular use in New Zealand.

Fire resistance is likely to be better than similar bolted joints because of the smaller surface of dowel exposed to the heat source. This should reduce the build up of temperature in the connector and reduce the possibility of charring at the connector timber bearing surface. No fire research has yet been reported in N.Z. on joints with drift pin connections.

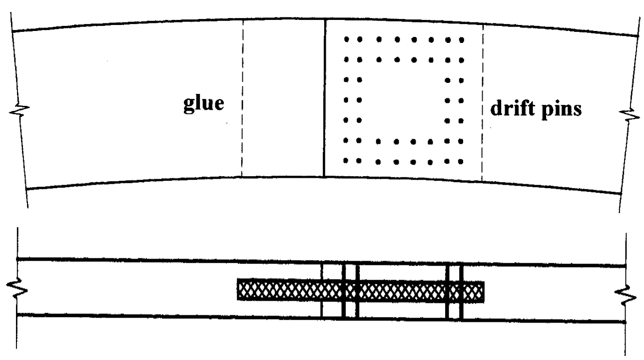

Figure 10 Timber & Drift Pin Connection

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