STRUCTURE AND ITS ENCLOSURE

A Preliminary Investigation into Medium Rise (6 storey) Residential Units Using Pinus Radiata Timber Poles as the Main Structural Members

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Abstract
Pinus radiata, also known as Monterey pine, has only a very small natural habitat of 7000 acres, which is on the west coast of the USA and Mexico. However, in New Zealand, this species grows exceeding well. Over 1.3 million hectares of land have been planted in pinus radiata and it is the basis of a multibillion-dollar-a–year export industry.

The rate at which the planted pinus radiata is maturing and requiring felling will increase continuously over the next 20 years. New technologies and forms of use need to be explored to add value to this resource.

This paper presents a prototype 6 storey residential building that is designed with the beams and columns consisting of pinus radiata poles. It addresses the following issues in relation to pole use – environmental effects; strength and non-destructive testing; variability and dimensional stability; economics; fire and sound resistance; prefabrication; transporting and site erection.

The conclusions of this initial research is that pole type buildings would have no disadvantages when compared to those constructed in the usual material of reinforced concrete but should create major advantages for the environment.

Pinus radiata stems are a renewable resource, require little energy during manufacture and absorb carbon from the atmosphere, thus reducing green house gases. A pole building structure will store more carbon within its timber than is released into the atmosphere during manufacture. This suggests these buildings may provide a carbon credit to the developer.

Introduction
"Pinus radiata (Monterey pine), once an obscure botanical oddity clinging to existence on the California coast, has become New Zealand's great timber tree, covering 1.3 million hectares of land and forming the basis of a billion-dollar-a–year export industry. In it's last centuries of its few million years of existence, Pinus radiata has managed to sneak a living in 3 patches along the Californian coast and on two islands off Mexico. Total area of natural habitat: about 7000 hectares, the largest area consisting of a small forest on the Monterey Peninsula" (Chris Hegan/Geoff Mason – *NZ Geographic*, Oct/Nov 1993)

Radiata is used extensively in NZ for residential construction. Over 80% of new housing uses radiata framing.

This paper discusses the question – are radiata poles suitable as the column and beam members in medium storey residential construction? The main reason for asking this question is due to the increasing numbers of NZ radiata stems becoming mature and requiring felling over the next 20 years. [1] It is important to consider new ways of utilising and adding value to this resource.

Over the last 35 years pinus radiata poles have been used extensively as columns, foundation piles and as the vertical cantilever members of retaining walls. They exist under a continual and often a reasonably high state of compressive or bending stress. Due to a minimum of in service problems during the last 35 years, radiata poles have gained the reputation as a competent structural product.

Before reinforced concrete gained prominence in the 1930's NZ had a tradition of using timber for the construction of railway and road bridges. They supported rail truck loadings of up to 80 tonne.

At present, the structural members for medium rise buildings are typically either reinforced concrete or steel. The development of timber systems for multi-storey building are under way in many parts of the world. However, we are not aware of researchers considering timber poles as the main structural elements.

We are proposing, in this paper, that pinus radiata columns and beams form a simple post-beam system to support the gravity loads. Residential units have regular party walls which are available to act as shear walls and resist the horizontal loads. Moment resisting joints that are difficult to construct using timber are not necessary.

This preliminary investigation considers the following issues:

a. Dimensional Stability – does the use of poles reduce the problems associated with timber multi-storey buildings?
b. Environment – is this form of construction more beneficial than conventional concrete buildings?
c. Strength – do commonly available radiata poles have the required strength?
d. Variability of Timber Poles – material properties; section shape; and member straightness.
e. Non-destructive Strength Testing – is this available?
f. Economics – how do the costs of pole structure elements compare to those of a medium rise R.C building?
g. Fire Resistance – is a fire resistance of 1-hour possible?
h. Sound Proofing – can an acceptable level be achieved?
i. Prefabrication – are the pole building elements suitable for prefabrication?
j. Transport and Exporting – can the building elements be sent by sea container?
k. Site Erection – are the required building construction techniques and suitably skilled personnel available?

Prototype Pole Building – 'P.P.B.'

A 6 storey 'prototype pole building' has been designed using pinus radiata poles for the columns and floor support beams. The shear walls are constructed of plywood over timber framing *(figures 1 to 5)*. The proposed plan provides suitable spaces for residential units and minimises interruptions to floor areas by columns. The poles are also arranged for optimising the ground floor as car shelter. Four cars can park under each unit in plan.

The pole member sizes for the P.P.B. were calculated and used for estimating building costs, CO_2 emissions and energy required for production etc.

Reinforced Concrete Floors of P.P.B. Research by Nicholls and others is currently being undertaken in NZ on the subject of timber floors in multi-storey construction. This research is attempting to arrange local building products to create floors which have adequate soundproofing and fire resistant qualities.[2]

Because these studies are not yet complete, a R.C. floor has been chosen for the P.P.B. The floor concrete is 70mm thick on .75 mm thick high yield steel tray decking. The steel tray is typical with a profile to assist shear between the steel and concrete.

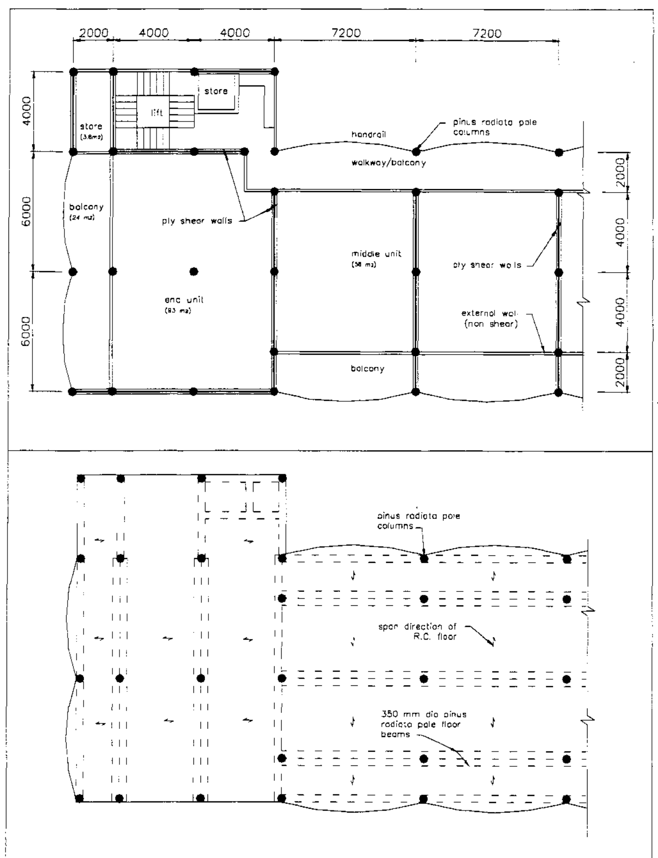

Fig. 1. Prototype Pole Building - above, plan of units; below, plan of main structure.

Apartments with socially independent families or groups of people need a good level of sound insulation. Concrete floor systems have been used for so long their acoustic performance is what people are used to and has become the benchmark. New timber floor systems, to date, have not produced an equivalent resistance to footfall noise and are less likely to have market acceptance. [3]

An advantage of the concrete floor when compared to a lighter timber floor is that the tension forces in the columns, due to wind loading, are considerably reduced. Virtually all loads transferred in the joints between pole column members are axial compression and thus simple to achieve.

DISCUSSION OF THE ISSUES

Dimensional Stability. This subject is often associated with multi-storey timber buildings. Dimensional instability occurs due to timber shrinking and expanding with drying and varying moisture content. These effects result in variations in building dimensions and affect claddings etc. When wood moisture content alters, considerably more dimensional changes occur across the grain than along the grain. The P.P.B. has 20m high columns that consist of 3 no. 7m approx long poles end on end. Because the timber grain is parallel over the entire height of the column, changes in building height are reduced to a minimum.

Experience at the BRE house 2000 project has shown that the moisture content of the timber framing stabilised around 12.5% and then remained relatively constant in the residential environment. [4] The maximum variation in moisture content observed during building use was 1%. If the poles members for a multi-story building are kiln dried before manufacturing to match the expected in-use moisture content, then only small dimensional variations would be expected.

Environment. Currently in NZ pinus radiata, when used under dry conditions, is not treated chemically and remains disease and borer free. However, for use in countries where termites exist, this topic may require further investigation.

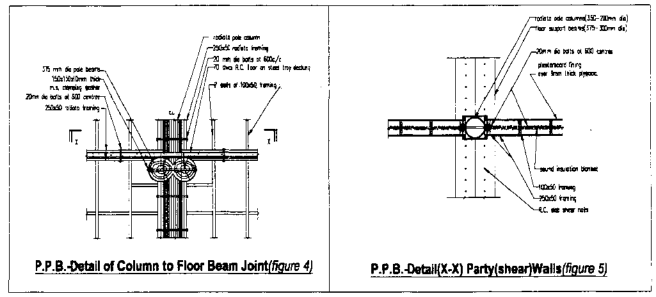

Fig. 1. Prototype Pole Building - left, detail of column to floor beam joint; right, detail (X-X) party (shear) walls.

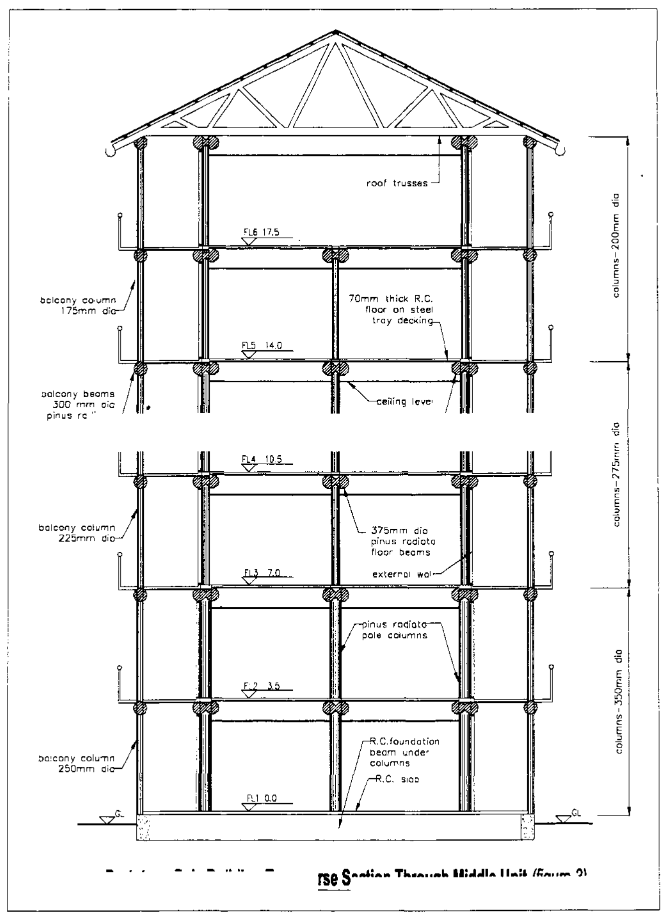

Fig. 2. Prototype Pole Building - transverse section through middle unit.

The typical form of construction for medium rise residential units is R.C. with reinforced concrete block masonry party walls and pre-stressed concrete floor units spanning between these walls.

With respect to helping the environment there are two measurable criteria we can apply - carbon dioxide released into the atmosphere and energy required during production.

Table 1 compares the energy for manufacture for the P.P.B. and a typical similar R.C. building. The table also compares the weight of carbon released into the atmosphere as CO_2. The values for energy and carbon released for the various building products are from a paper by Buchanan and Honey [5] The negative value of carbon released for the P.P.B. of – 2.0 Kg/sq.m. means that the carbon released into the atmosphere during manufacture is less than the quantity permanently stored in the timber structure. The estimated amount of carbon released into the atmosphere by the R.C. building is 55.0 Kg/sq.m.

The energy required for manufacture of the P.P.B. is 43% that used by the R.C. alternative.

It is conclusive that buildings with pole structural elements will assist the environment significantly better than R.C. buildings.

Strength. The loads considered on the P.P.B. are from the NZ loadings code NZS 4203[6]. The building dead load is 2.9kn per square metre of floor area. The floor live loads are 1.5Kpa and 2Kpa for domestic floors and balconies respectively. The roof snow load has a maximum value of 2Kpa which covers all areas of NZ up to an altitude of 600m.

ENERGY USED AND CARBON DIOXIDE EMMISIONS IN MANUFACTURE FOR STRUCTURES OF PROTOTYPE POLE BUILDINGS AND R.C. ALTERNATIVE (per sq.m. of floor area)						
PROTOTYPE POLE BUILDING - Radiata Pole Columns & Beams + Framed Shear Walls (ply sheathed) + R.C. Floors						
Structural Element	Material	Volume/sq.m. *(cu.m/sq.m.)*	ENERGY USED		CARBON EMITTED	
			Energy/Volume *(Gj/cu.m.)*	Energy Used *(Gj/cu.m.)*	Net C./Volume *(Kg/cu.m.)*	Carbon Emission *(Kg/cu.m.)*
Columns	Timber pole	0.0100	0.8	0.008	-245	-2.54
Beams	Timber pole	0.0580	0.8	0.046	-245	-14.21
Floor Slab	Steel	0.0010	448	0.448	8117	8.12
	Concrete	0.0700	7.3	0.511	182	12.74
Shear Walls	Framing	0.0191	1.0	0.019	-235	-4.49
	9mm ply	0.0073	1.2	0.009	-220	-1.60
			Total Energy = 1.0 Gj/sq.m.		Total C. Emitted = -2.0 Kg/sq.m.	
REINFORCED CONCRETE MEDIUM RISE RESIDENTIAL BUILDING - Reinforced Masonry Walls + R.C. Floors						
Structural Element	Material	Volume/sq.m. *(cu.m/sq.m.)*	ENERGY USED		CARBON EMITTED	
			Energy/Volume *(Gj/cu.m.)*	Energy Used *(Gj/cu.m.)*	Net C./Volume *(Kg/cu.m.)*	Carbon Emission *(Kg/cu.m.)*
Shear Walls	Blocks+Conc.	0.0897	7.3	0.65	182	16.33
	Reinforcing Concrete	0.0003	448	0.13	8117	2.44
Floor Slab	Reinforcing	0.1500	7.3	1.10	182	27.30
		0.0011	448	0.49	8117	8.93
			Total Energy = 2.4 Gj/sq.m.		Total C. Emitted = 55.0 Kg/sq.m.	

Table 1

CALCULATIONS SUMMARY FOR PROTOTYPE POLE BUILDING *(middle units have critical loads and spans)*									
PINUS RADIATA POLE COLUMNS *The column design strengths are for poles with a minimum outer density of 350 kg/cu.m.*									
Location in middle units	Supports Floor Only			Supports Floor & Deck			Supports Deck Only		
Floor levels	1&2	3&4	5&6	1&2	3&4	5&6	1&2	3&4	5&6
Pole diameter (mm)	350	275	200	350	275	200	250	225	175
Max. ultimate axial compression, N*c (Kn)	967	628	289	909	528	223	457	295	132
Column design strength, N*c (Kn)	1004	717	293	1004	717	293	486	379	180
PINUS RADIATA POLE BEAMS - Combined Section with R.C Floor - 7.2 Span *The beam design strengths are for poles with a minimum outer density of 450 kg/cu.m.*									
Location in middle units	Supports Floor Only			Supports Floor & Deck			Supports Deck Only		
Floor levels	2			2			1		
Pole diameter (mm)	375			325			300		
Max. ultimate axial compression, N*c (Kn)	15.1			19			14.9		
Column design strength, N*c (Kn	144			114			48		
	153			117			61		

Table 2

The wind loads assumed on the P.P.B. is for all locations in NZ that are relatively flat but exposed and without obstructions to wind. The resulting basic wind speed is 48m/s.

The earthquake load applied was for a plan with 3no. middle units between the end units. The horizontal loads were deduced assuming the ply shear walls having limited ductility, a medium earthquake zone (zone factor = 0.6), and 'intermediate' type soils. The resulting lateral force coefficient, C is 0.14.

For major earthquake zones, as identified in areas of Calfornia and New Zealand, where the 'zone factor' becomes 1.2 only the columns supporting floor and deck loads are affected. The poles for levels 1 & 2 increase from 350mm to 400 mm dia; those supporting levels 3 & 4 change from 275mm to 300mm dia; and the poles of levels 5 & 6 remain at 200mm dia.

Calculations for pinus radiata pole member section sizes were carried out. An abbreviated form of these calculations accompanies this article (Table 2). The calculations are for the members for the 'middle units' because they are slightly more loaded than those of the 'end units'.

As expected, the required pole column diameters reduced with height. The maximum diameter for the pole columns is 350mm and the minimum is 175mm.

The floor beams supporting floor only are typically a pair of 375mm diameter radiata poles that form a combined section with the R.C. floor. The beams supporting floor plus balcony are similar except that 2 no. 325mm dia. stems are required. The beams carrying balcony only can be 1 no.300mm dia. The shear connection between the pole beams and the concrete is provided by 5mm dia*125long nails. The nails are driven 75mm into the poles and remain 50mm into the concrete slab. The ends of the floor beams shaped to fit around the pole columns and are supported on 2 no. 250*50 radiata studs which are usually part of a shear wall. The floor load in the 2 no. 250*50 studs is transferred into the pole columns via M20 bolts at 600 centres.

Radiata poles of the above diameters and at the required lengths are readily available.

The shear walls are illustrated in figures 7 & 9. They consist of 2 no. 100*50 framed walls with a 50mm gap between them. Each outer wall face is lined with a layer of 9mm thick plywood that provides shear resistance. The maximum shear force in the walls is 28Kn/m (increasing to 45Kn/m for major earthquake zone loading). This can be supported by the proposed 2 layers of 9mm thick plywood which together have a strength capacity of 90.2Kn/m. The shear walls' top and bottom plates are 250*50 that are bolted to the R.C. floors for the transference of horizontal shear forces from the wall above to the wall below. The ply shear walls could be replaced with diagonal steel bracing if required.

Variability of Timber Poles. Timber poles do not have material properties that are as uniform as steel and batched concrete. This lack of uniformity in poles is due to various physical features - checks, end splits, individual knots, knot groups, nodal swelling, spiral grain, sweeps, short crooks. The NZ standard NZS 3605 [7] gives allowable criteria for these features, so that pole strengths are assured. The improving methods of assessing timber pole strength properties are discussed in the next section.

The diameter specified for a peeled pole, being for the small end or for the top of the tree, means the section is always bigger than nominated.

The varying diameter and pole roundness are an issue when another building product is required to butt up to the pole. Where a pole member is required to bare or butt up to another member, it will need to be cut with a blade to have a flat and regular surface. A very small amount of timber will need to be cut off to form this surface. For example, to create a 75 wide surface on a 300mm dia. pole requires a 4.8mm deep loss to the surface of the pole.

Sound 'straight' pole stems are commonly available and in relatively long lengths. Lengths of 14m or more are common. In this regard, pole stems have an important advantage over sawn timber that has typical maximum lengths around 6m.

Each column of the P.P.B. consists of 3 poles of 7m length. This arrangement allows for reductions in pole diameter with building height and stem lengths that are practical for transporting.

Non-destructive Testing. Testing by Walford showed that failure stresses for NZ grown softwoods are dependent on the dry density of the timber existing at the outer 20% of the pole radius. [8] Thus, when the density of this outside layer is established, the timber strength can be calculated.

During the last decade considerable development has occurred for the measurement of stem density using Acousto-ultrasonic (AUS) based methods. [9] . These methods of testing relate propagation velocity of the longitudinal ultrasound wave with wood density and modulus of elasticity. There are two types – stress wave propagation and natural frequency vibration. The accuracy range is 4%. This type of non-destructive testing is also useful for detecting pole defects.

The 4-point strength test is a recognized method of testing pole bending strength in NZ and Australia. This quality assurance test is frequently used for timber power transmission poles before they are exported. In this test, the pole is supported at each end and the deflection is monitored while two jacks place load along the length of the stem.[10]

Economics. Table 3 compares costs of main structure for the P.P.B. and a similar R.C. building. It concludes that the pole/timber structure is 82% the cost of the R.C. structure.

Timber poles are a relatively cheap form of timber at NZ$240 (US$100) per cubic metre. The cost of sawn lumber is NZ$800(US$340) and glulam is NZ$2000(US$840) per cu.m. When estimating the manufacture and erection costs of the pole structural elements in table 3 we have been conservative at NZ$380(US$160). This cost covers strength testing, assessing straightness, trimming flat faces, and drilling boltholes etc. The cost of pole element fabrication would decrease with production output because investment in automated procedures would be justified.

A timber pole type building is significantly lighter than the R.C. alternative and, as a consequence, would have reductions in foundation costs. The table 3 analysis does not include this difference in foundation costs.

Fire. Good fireproofing would be very important to avoid a conflagration with possible loss of life and a resulting drop of public confidence in timber multi-storey building.

In the P.P.B. each residential unit is an independent fire cell bounded above and below by a R.C. slab. The pole columns are lined with plasterboard. The pole floor support beams are protected by a fire rated suspended ceiling below and a R.C. slab above. Plasterboard lined party walls running floor to ceiling exist between the units. Fire protection could be increased further, if local codes require, by the use of sprinklers.

The relevant NZ code considers the charring rate of radiata pine as 0.65mm per minute [11]. Thus, the amount of surface charring expected in a 1hour fire is 39mm. This leads to a reduction of the diameter of a round section by 78mm. Theoretically, in a 1-hour fire a 350mm dia. beam becomes 272mm dia. and a 300mm dia. column changes to 222 mm dia.

Should anything go wrong with the plasterboard linings, the pole members would appear to have reasonable strength after a 1-hour fire.

Sound Insulation. We have explained above that concrete floor slabs were chosen to ensure a good level of protection from vertical noise transference. Sound insulation blanket would also be located on the ceilings below the R.C. floors.

The resistance to footfall noise increases as the natural frequency of the floor system increases. Typical timber floors have natural frequencies well below that of concrete floors. Timber floors have

MAIN STRUCTURE COSTS IN $NZ AND $US (per sq.m. of floor area) FOR STRUCTURES OF PROTOTYPE POLE BUILDING AND REINFORCED CONCRETE ALTERNATIVE						
PROTOTYPE POLE BUILDING - Radiata Pole Columns & Beams + Framed Shear Walls (ply sheathed) + R.C. Floors						
Structural Element	Material	Volume/sq.m. *(cu.m./sq.m.)*	COST $NZ		COST $US	
			Material cost *($NZ/cu.m.)*	Floor area cost *($NZ/cu.m.)*	Material cost *($US/cu.m.)*	Floor area cost *($US/cu.m.)*
Columns	Radiata pole	0.0100	620	6.20	260	2.60
Beams	Radiata pole	0.0580	620	35.96	260	15.08
Floor	R.C. on Steel Decking	0.0710	1130	80.23	475	33.70
Shear walls	Framing	0.0191	1440	27.50	605	11.55
	Plywood	0.0073	3000	21.90	1260	9.20
			Total = $NZ 171.97		Total = $US 72.13	
REINFORCED CONCRETE MEDIUM RISE RESIDENTIAL BUILDING - Reinforced Masonry Walls + R.C. Floors						
Structural Element	Material	Volume/sq.m. *(cu.m./sq.m.)*	COST $NZ		COST $US	
			Material cost *($NZ/cu.m.)*	Floor area cost *($NZ/cu.m.)*	Material cost *($US/cu.m.)*	Floor area cost *($US/cu.m.)*
Shear walls	Reinforced Masonry	0.0897	1100	98.67	462	41.44
Floor	Prestressed Floor	0.1000	1100	110.00	462	46.20
			Total = $NZ 208.67		Total = $US 87.64	

Table 3

been constructed with concrete toppings to increase mass and improve acoustic performance. The toppings have gone someway to emulating the properties of concrete floors but their relatively high cost has proven to be a problem.[3]

Hopefully, economically viable timber floor systems will eventually be developed with suitable acoustic properties and they will replace concrete floor systems.

At the party walls, sound insulation is provided by sound absorbing fibreglass blanket between the 2 lots of timber framing. *(figure 9).* This arrangement, in association with plasterboard linings of sufficient thickness, has been found to supply adequate insulation against horizontal sound transference.

Prefabrication. Maximising prefabrication would be important for leading to efficiencies and reductions in costs of manufacture.

A brief method for pole member fabrication might be as follows:

1. pole assessed by laser beams to ensure straightness, lack of bowing, required diameter etc
2. pole assessed, non destructively, to ensure required strength and lack of defects
3. pole cut to length
4. centre of stem at both ends electronically identified and pole clamped with end centres at defined locations
5. flat surfaces cut (where a pole member butts another member)
6. bolt holes drilled
7. members tagged with identification.

Robot technology would be suitable for manufacturing these members and turn labour intensive processes into supervised automated ones.

Transport and Exporting. All the P.P.B. items, except the floor pole beams at 7.2m, are less than 5.9m long and will fit into a flat rig container. The floor beams would need to go in a 40-foot container. Round poles would expect to have approximately 25% air voids after packing.

The non-pole building items of timber framing and steel tray decking lose minimal volume when in a stack. In most cases we would expect the concrete to be supplied locally.

It appears that the building components could be transported reasonably efficiently.

Erection. The on-site jointing of the pole columns and floor support beams involve simple bolted and nailed connections. The R.C. floor construction is common and straightforward. The simple erection methods mean that there are possibilities for marketing this product in various countries and employing local construction workers.

The floor beam poles, at 350Kg,, are the heaviest structural member. This weight is typical for medium rise building elements but would require cranage.

Conclusions

We can conclude from the above discussion that pinus radiata poles as the main structural members in medium rise residential construction have no significant disadvantages when compared to the R.C. alternative. The two systems have a similar cost. However, buildings using timber structural elements proved to be significantly better for the environment.

This conclusion suggests that further research into using radiata poles as the main structural elements of medium rise residential units is justified. A possibility for that the next step in this research would be to test apparently suitable radiata poles for compression strength. This would ensure avoiding the worst possible form of building collapse – column failure.

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