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Acacia Mangium Willd as Structural Components and Shear Walls

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Abstract

Acacia Mangium Willd is fast growing wood commonly found in Thailand. It is commonly called Kratin Tepa. It is not popularly used in Thailand as structural components due to the lack of its engineering data for design. The objective of this research is to study physical and mechanical properties of Kratin Tepa. Firstly a series of tests for engineering properties are carried out. Then the statistics of engineering properties with the confidence interval of 99 % and values of failure probability for structural components are calculated. The research scope covers three building types, i.e. residence, office and school. The building height is limited to two stories and floor-to-floor height is 3.00 meters. Finally the appropriate size for each type of structural component is recommended.

Results show that most properties could be represented well by normal distribution. Analysis of structural members spanned 3.00 meters are based on the accepted values of failure probability less than 10^{-4} for deflection of joist and beam, and less than 10^{-6} for short term loading and 10^{-2} for long term loading in case of bucking of column.

Shear walls with height of 3.00 meters and different lengths have been tested. For normal stud construction walls the normal deflection criteria is not satisfied. Walls with diagonal bracing exhibit higher strength and smaller deflection.

Keywords: Mechanical Properties, Shear Wall, Structural Reliability, Softwood

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1. Introduction

In the past for most residence and other small buildings in Thailand wood was used as structural components and finishing materials. But after the reduction of forest area in Thailand at the rate of 2.73 million raise (about 1.24 million acres) per year, the use of wood as main building materials is also reduced due to the high cost of lumber. The forest is reduced from 53% of the total land area in 1961 to 26% of the total land area in 1993 [1].

However, the use of wood as main building materials is still favorable due to its low heat absorption value which is very suitable for tropical climate.

In Thailand there are more than 40 species of trees with high potential to be used as structural components. But due to the lack of systematical study of engineering properties, designer cannot decide to use new tree species as structural members.

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2. Objective

Study physical and mechanical properties of Acacia Mangium Willd in accordance with ASTM Standard [2].

- Analyze statistics of physical and mechanical properties of Acacia Mangium Willd.
- Analyze failure probability of Acacia Mangium Willd structural components.
- Suggest acceptable failure probability value of Acacia Mangium Willd structural components.
- Recommend appropriate size of Acacia Mangium Willd structural components.
- Study behavior of shear wall under lateral loading and recommend further improvement.

3. Scope of Research

The physical and mechanical properties of Acacia Mangium Willd are tested in accordance with ASTM Standard. Statistics of engineering properties are summarized with confidence interval of not less than 99%. The research is limited to two stories building with floor-to-floor height of 3.0 meters. Three building types are considered in this research i.e. residence, office and school. Live loads used in design according to building code are 150 kg/m^2, 250 kg/m^2, and 300 kg/m^2 for residence, office, and school, respectively. The size of wood stated in this research is dressed dimension. Failure probability analyses are based on deflections for beams and joists and compressive stress parallel to grain for columns. The appropriate sizes of components are recommended according to the size available in the lumberyard.

4. Definition

Fast Growing Wood is cultivated tree with diameter of 12 inches within 10 - 15 years.

Wood Structure is a structural system that main structural components are made from wood.

Failure Probability, (p_f) is the probability of an event that structural resistance of the structure (R) will be not greater than load effects (S) for the whole service life as shown in Eq. 1.

$$p_f = \Pr(R \leq S) \tag{1}$$

In reality both R and S could be functions of random variables. Therefore, failure probability may be written more generally as shown in Eq. 2.

$$p_f = \int_{D_f} f_{\underline{X}}(\underline{x})d\underline{x} \tag{2}$$

where $\underline{X}$ is vector of random variables $X_1, X_2, \ldots, X_n$

$f_{\underline{X}}(\underline{x})$ is the joint probability density function of $\underline{X}$

and D_f is the failure domain defined by the limit-state function obtained from structural analysis. For more details about limit-state function, it is referred to [3].

Part A: Properties and Failure Probability of Acacia Mangium Willd as Structural Components

5. Statistical Analysis

Once the physical and mechanical properties with 99% confidence interval are obtained from the tests, the statistics of these properties may be represented in form of mean value, standard deviation and type of distribution. The best-fitted continuous distributions can be obtained by two Goodness-of-Fit Tests, i.e. Chi-Square Test and Kolmogorov-Smirnov Test (K-S Test). For more details about statistical analyses it is referred to [4].

In Chi-Square Test a probability density function is considered from the comparison between observed frequencies in each class interval and the expected frequencies from the assumed analytical model. A particular type of distribution will be accepted if the value of Chi-Square error is less than the corresponding critical value at confidence level of 95%.

In K-S Test a Cumulative Distribution Function (CDF) of an analytical model is considered from the comparison to Cumulative Relative Frequency.

Statistics of engineering properties are calculated. The fitted types of distributions for each engineering properties can be obtained by Goodness-of-Fit Tests. The analytical models include 11 types of distribution used commonly in civil engineering i.e. Normal Distribution, Uniform Distribution, Shifted Exponential Distribution, Shifted Rayleigh Distribution, Gumbel Distribution - Type I - largest, Gumbel Distribution - Type I - smallest, Lognormal Distribution, Gamma Distribution, Fréchet Distribution - Type II - largest, Weibull Distribution - Type III - smallest and Beta Distribution. Each set of data is input in form of text file into CESTTEST software [4], which would calculate and show mean, standard deviation and type of distribution. The software would automatically select fitted distributions as described earlier.

6. Design Criteria

The limit states, i.e. deflection for joist and beam and compressive stress parallel to grain for column are considered in the design. The acceptable values of failure probability for joist and beam are 10^{-4} whereas those for short term loading and long term loading of column are 10^{-6} and 10^{-2} respectively. Using WCCAL-2.0 (Wood Components CALibration) software and design chart presented in [5], the appropriate size of each component is recommended.

7. Test Result and Analysis

7.1 Engineering Properties

The numbers of tested specimens are such that the confidence interval of 99% are guaranteed. Statistics of engineering properties from CESTTEST software are summarized in Table 1.

7.2 Failure Probability

Analyses are made for three building types, namely, residence, office, and school. Nominal live loads and statistics of live loads are summarized in Table 2.

Table 1. Statistics for engineering properties of Acacia Mangium Willd

Testing List	Unit	Mean	Standard Deviation	COV	Number of Samples	Appropriate Distribution[1]
Modulus of Elasticity	kg/cm^2	147,700	23189	0.157	120	**Beta** , Normal
Modulus of Elasticity in Compression Parallel to Grain	kg/cm^2	56,500	10566	0.187	120	**Normal** , Weibull , Beta
Modulus of Elasticity in Tension Parallel to Grain	kg/cm^2	154,200	30069	0.195	120	**Frechet**
Compression Parallel to Grain	kg/cm^2	369.13	49.1	0.133	120	**Gamma** , Lognormal , Normal
Compression Perpendicular to Grain	kg/cm^2	109.07	17.7	0.162	120	**Beta** , Normal , Weibull, Gamma ,Lognormal
Tension Parallel to Grain	kg/cm^2	1029	186.2	0.181	120	**Weibull** , Normal
Tension Perpendicular to Grain	kg/cm^2	25.06	4.7	0.187	120	**Beta** , Normal , Gamma, Weibull ,Lognormal
Toughness	kg/cm^2	396.42	50.7	0.128	120	**Gamma** , Lognormal
Hardness	kg	537	45.1	0.084	120	**Gumbel Largest** , Lognormal, Gamma
Shear Parallel to Grain	kg/cm^2	91.51	19.9	0.217	122	**Normal**
Cleavage	kg/cm	43.84	7.5	0.171	100	**Gamma** , Beta , Normal, Lognormal
Moisture Content	percent	23.46	3.7	0.157	100	**Beta** , Rayleigh , Lognormal
Specific Gravity	-	0.718	0.1	0.077	120	**Beta** , Normal , Gamma, Lognormal
Shrinkage						
Tangential Shrinkage	-	3.14	0.6	0.183	120	**Lognormal** , Gamma , Rayleigh , Gumbel Largest , Beta , Weibull
Radial Shrinkage	-	3.46	0.7	0.205	120	**Beta**

Remark [1] distribution listed in order with respect to goodness of fit

Table 2. Statistics of live load for building types in Thailand

Building Type	***Nominal Value*** (kg/m^2)	**Collected Data** [6]			
		Mean	***Mean/Nominal Value***	**Coef. of Variation**	**Type of Distribution**
Residence	150	182.40	1.216	0.186	Normal
Office	250	350.80	1.403	0.182	Normal
School	300	163.30	0.544	0.133	Normal

Procedure for wood components design using limit state for deflection is shown in Fig.1

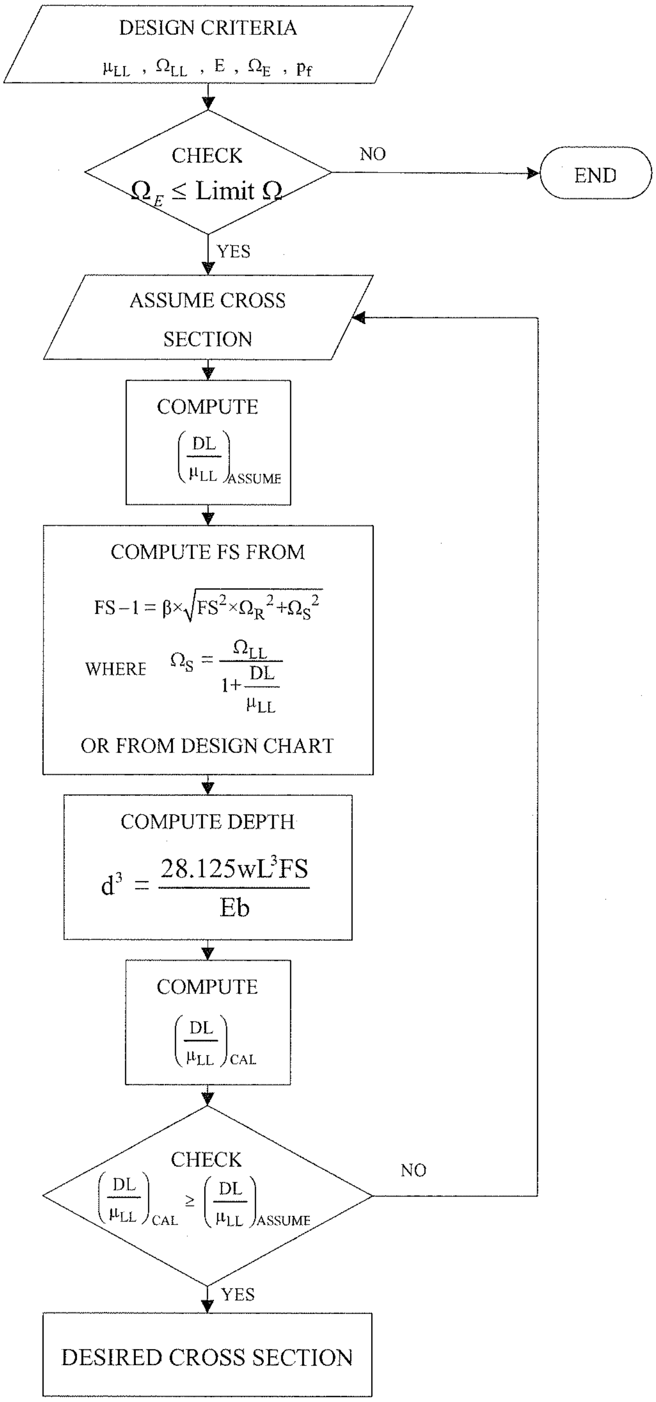


Fig.1 Flow chart for design of wood components using limit state for deflection.

The symbols appeared in the above flow chart are as follows :

Ω = Coefficient of Variation of wood

μ = Mean

β = Safety Index

FS = Central Safety Factor

R = Structure Resistance

S = Load Effects

The results from analyses are shown as follows:

- **Joist**

For each building type, 1½" wide joists are placed at 30 cm apart with span 3 m. The safety factors of joists are shown in Fig. 2 to Fig. 4.

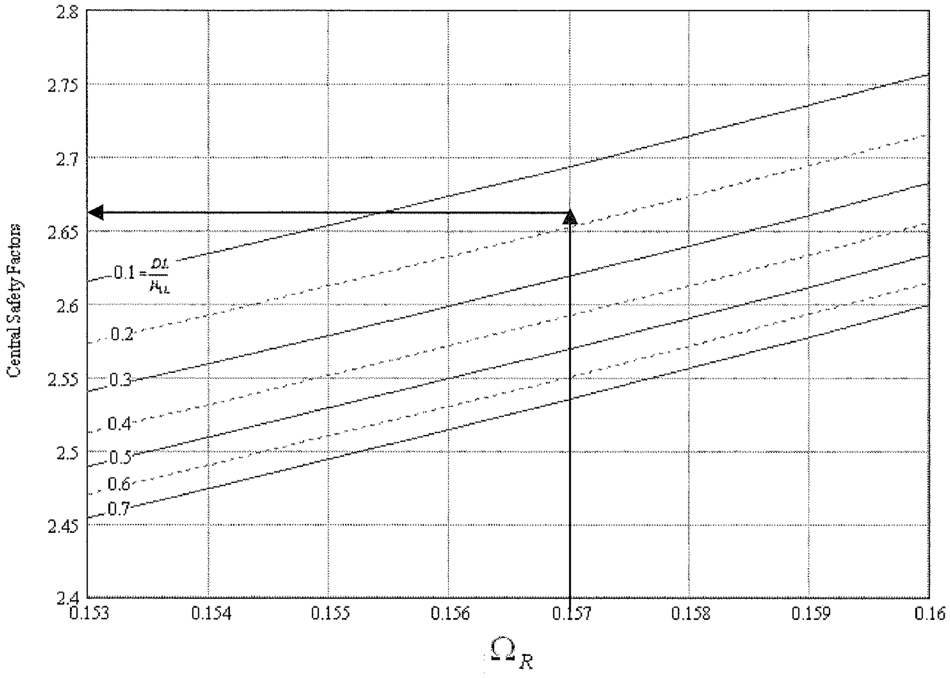


Fig. 2 Safety Factor of 1½" wide joist span 3 m at 30 cm spacing for residence building

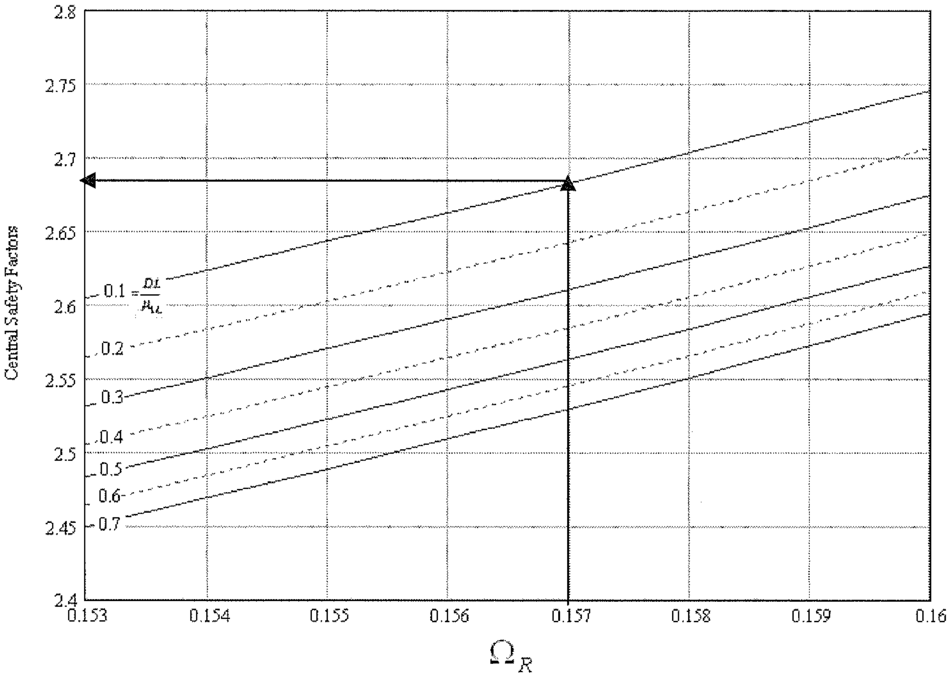


Fig. 3 Safety Factor of 1½" wide joist span 3 m at 30 cm spacing for office building

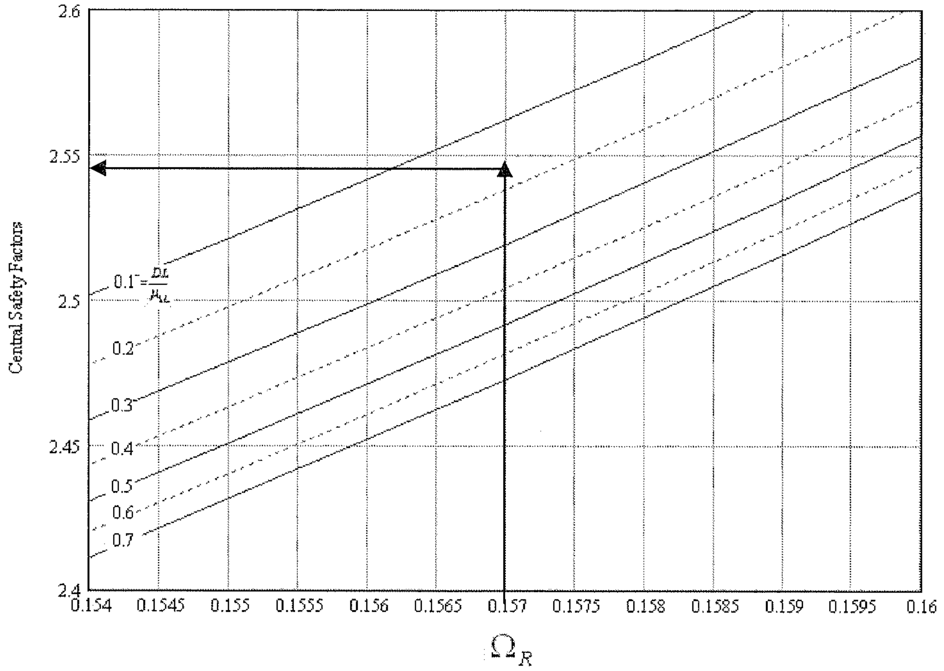


Fig. 4 Safety Factor of 1½" wide joist span 3 m at 30 cm spacing for school building

Using safety factors from the above design charts, the depth of joists can be calculated as follows :

- For residence building, depth of joist = 6.552"
- For office building, depth of joist = 8.002"
- For school building, depth of joist = 6.209"

- **Beam**

Fig. 5 to Fig. 7 show safety factors of double beams with 2" width and 3 m span length for residence, office and school buildings respectively.

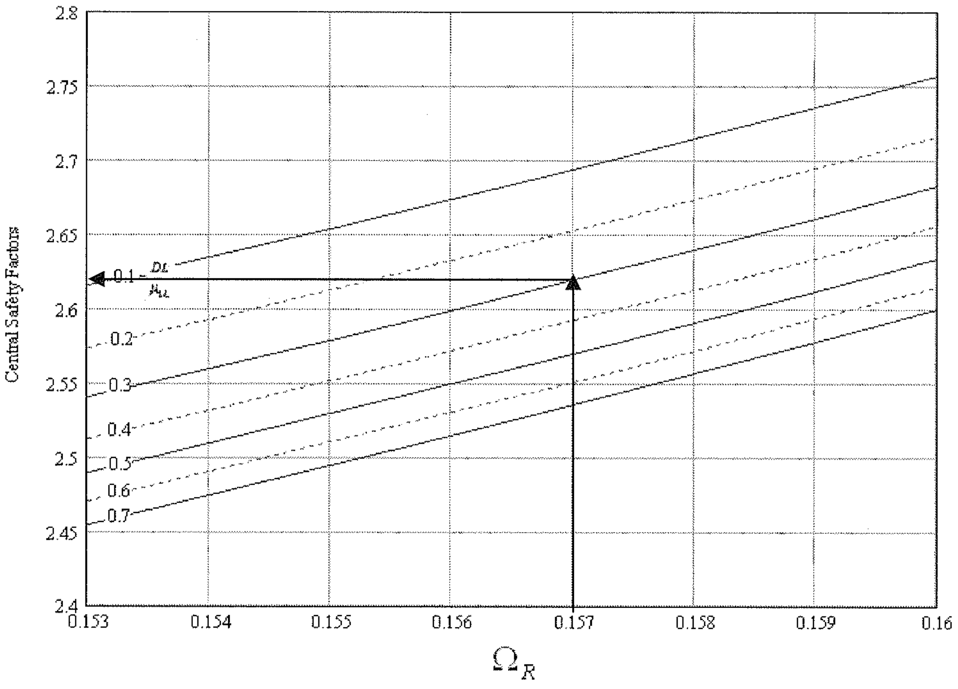


Fig. 5 Safety Factor of 2-2" wide beam span 3 m for residence building

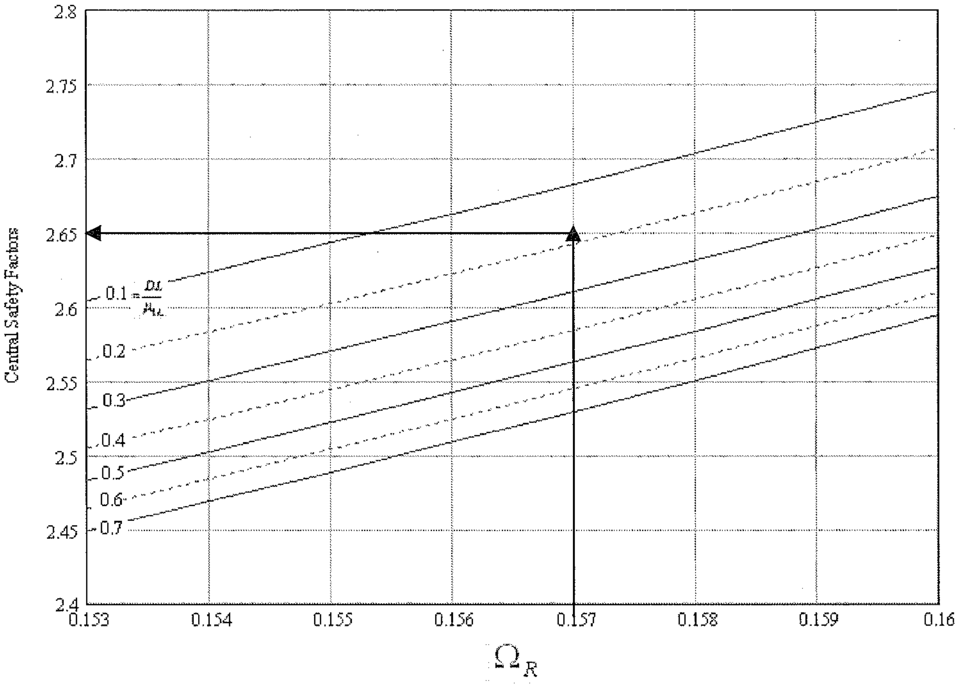


Fig. 6 Safety Factor of 2-2" wide beam span 3 m for office building

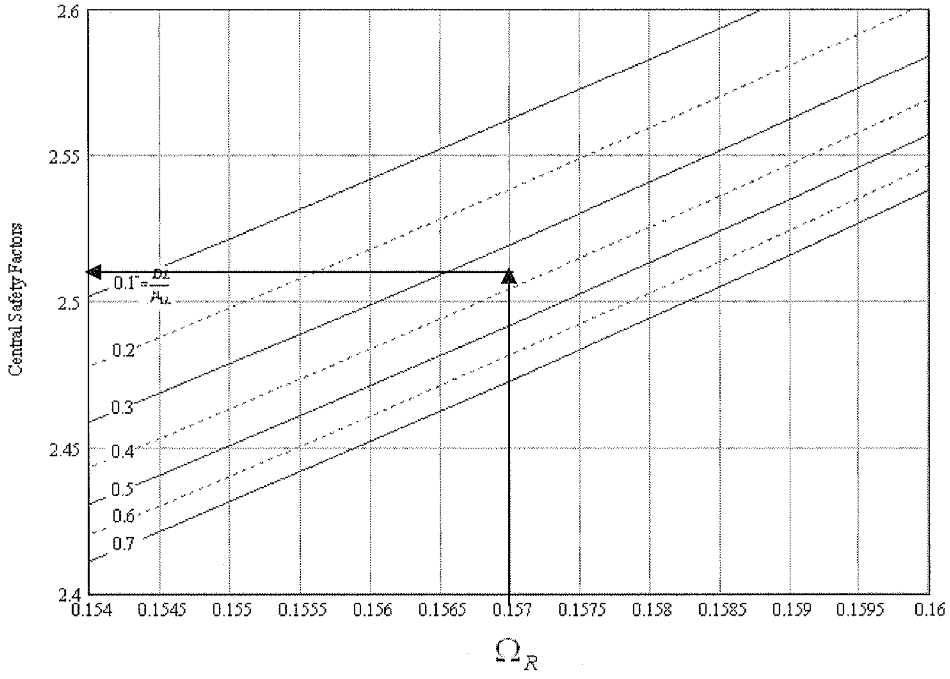


Fig. 7 Safety Factor of 2-2" wide beam span 3 m for school building

Using safety factors from the above design charts, the depth of beams can be calculated as follows :

- For residence building, depth of beam = 10.496"
- For office building, depth of beam = 12.650"
- For school building, depth of beam = 10.062"

Procedure for wood column design using limit state for buckling is shown in Fig.8

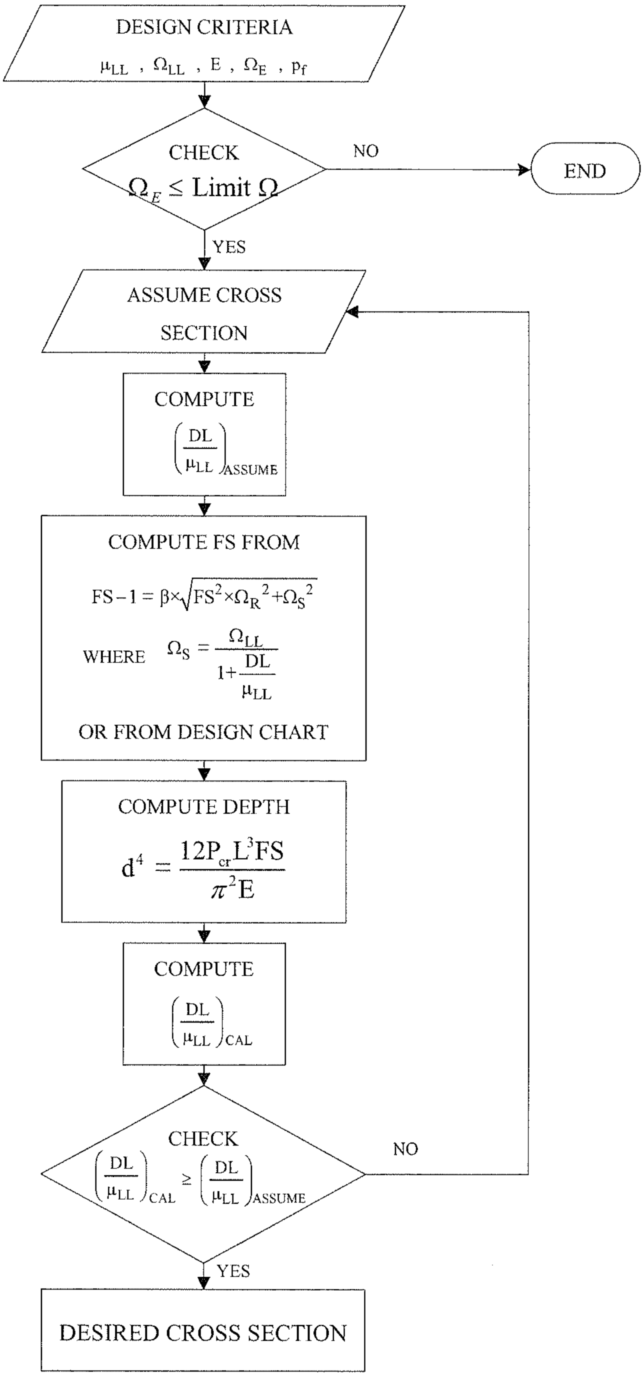


Fig.8 Flow chart for design of wood components using limit state for buckling.

The results from analyses are shown as follows:

- **Column , 2nd floor**

Fig. 9 to Fig. 11 show safety factors of columns with 4" width and 3 m span length for residence, office and school buildings respectively.

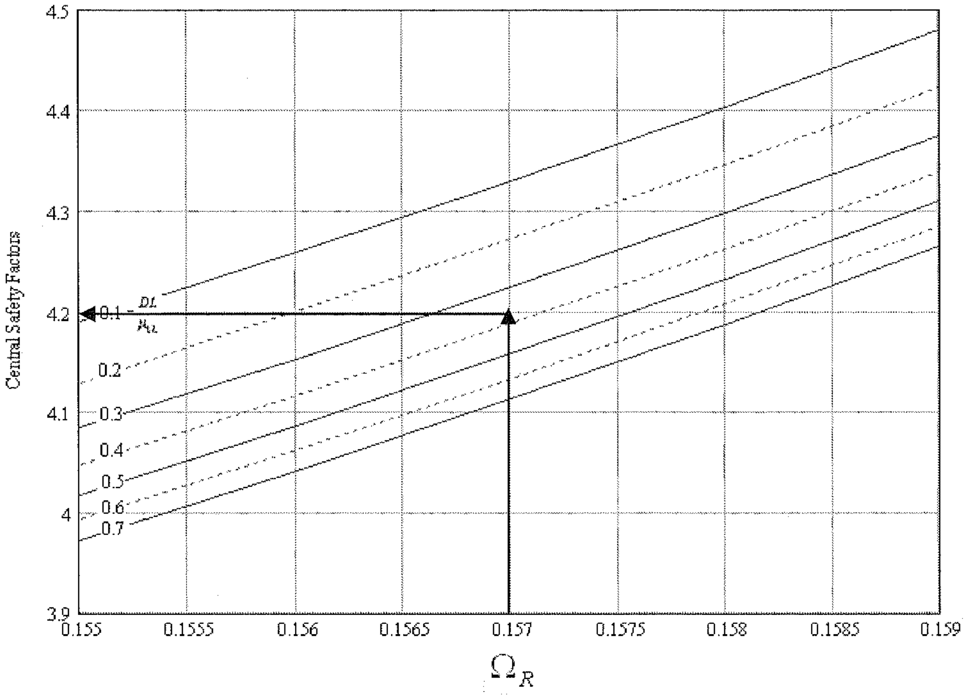


Fig. 9 Safety Factor of column for residence building

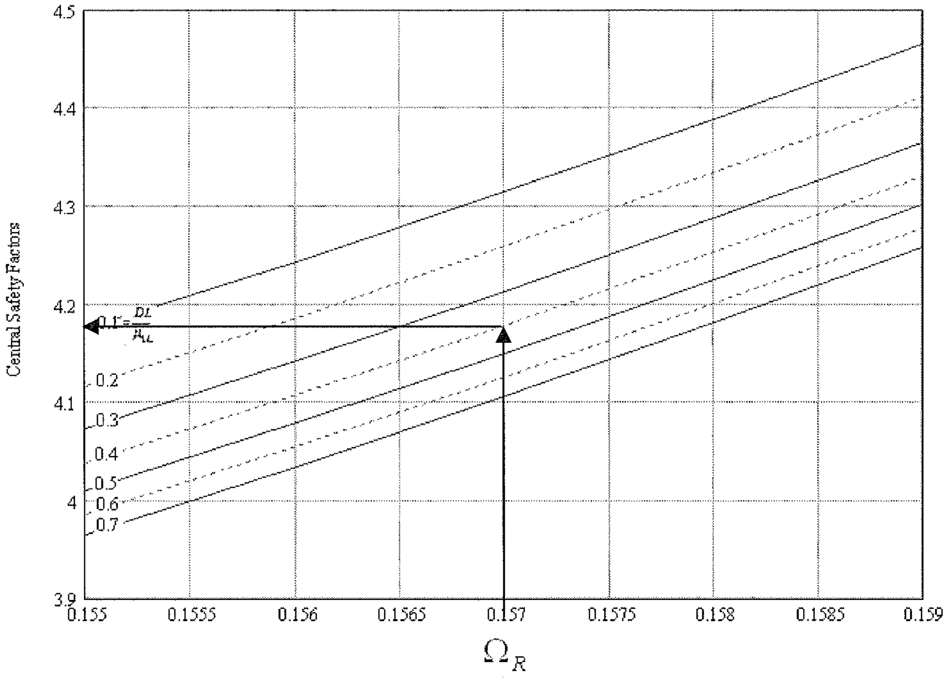


Fig. 10 Safety Factor of column for office building

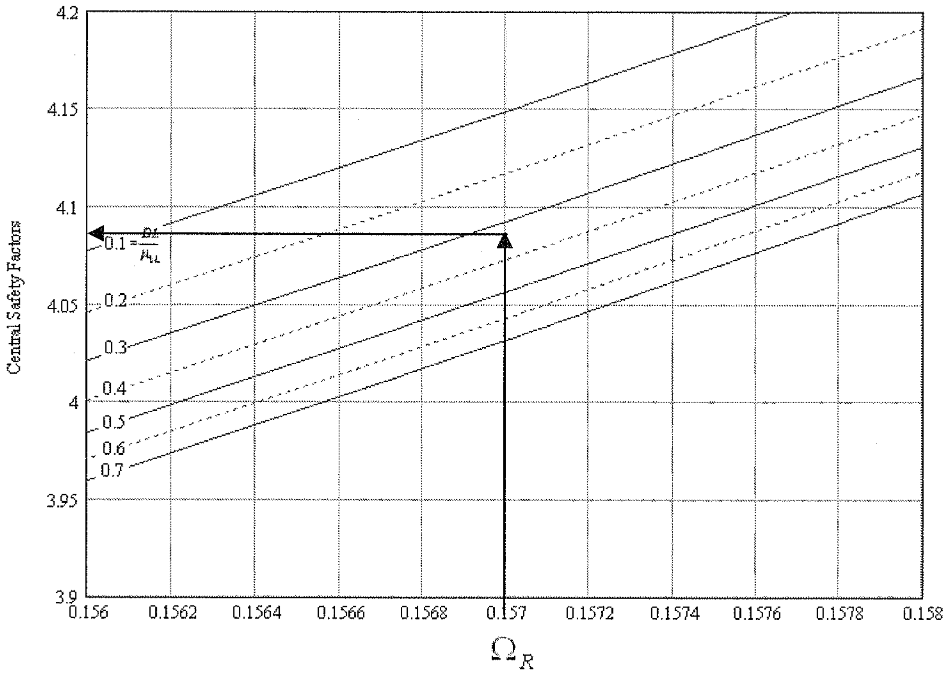


Fig. 11 Safety Factor of column for school building.

Using safety factors from the above design charts, the depth of 2nd floor columns can be calculated as follows :

- For residence building, depth of column = 2.936"
- For office building, depth of column = 2.945"
- For school building, depth of column = 2.915"

- **Column, 1st floor**

Fig. 12 to Fig. 14 show safety factors of columns with 6" width and 3 m span length for residence, office and school buildings respectively.

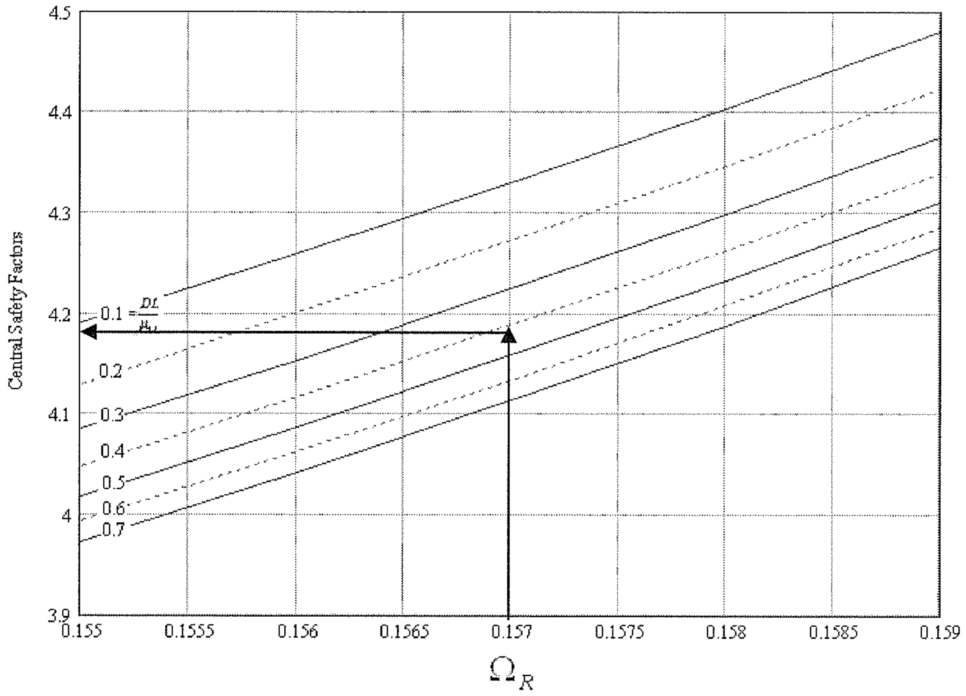


Fig. 12 Safety Factor of column for residence building

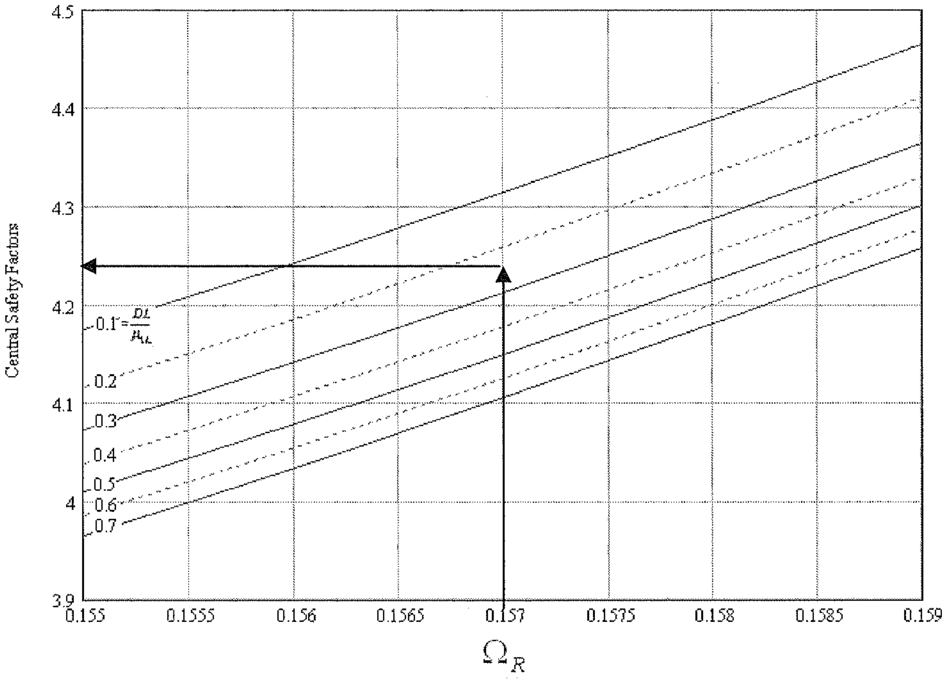


Fig. 13 Safety Factor of column for office building

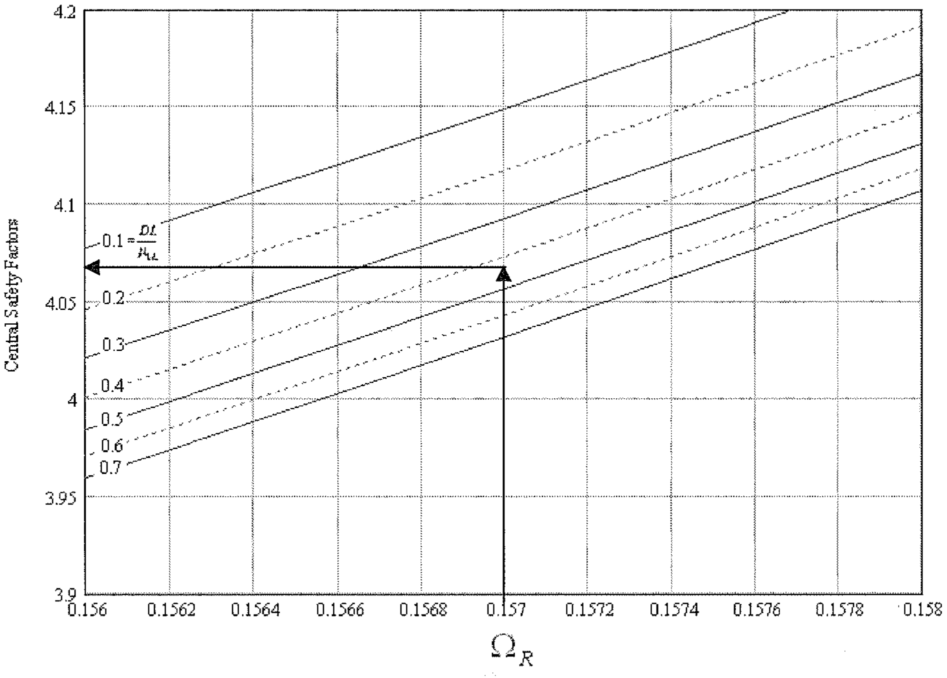


Fig. 14 Safety Factor of column for school building

Using safety factors from the above design charts, the depth of 1st floor columns can be calculated as follows :

- For residence building, depth of column = 4.340"
- For office building, depth of column = 4.845"
- For school building, depth of column = 4.232"

Part B: Shear Wall

8. Built – Up Wood Plank Shear wall

Typical built-up wood plank shear wall 3 m in height is used to resist earthquake or wind forces. The wall consists of 1" x 4" wood planks attached to 1½" x 3" horizontal and vertical studs by nails. The spacing of the studs is 50 cm [7] , [8] , [9]. It was found that wood plank shear walls are quite flexible. They resist low lateral load at serviceability limit state i.e. lateral deflection of 15 mm (½ % of wall height)[10]. Wall with stud spacing at 25 cm can resist higher lateral load [7]. Diagonal stud reinforcement around the perimeter of wall also increases lateral load capacity of wall [8].

9. Structural Model of Wood Plank Shear Wall

In this research, 4 sizes of wall with 2 specimens for each size have been tested. The length of wall are 1.5 , 2.0 , 2.5 , and 3.0 m. The wall consists of 1" x 4" wood planks attached to 1½" x 3" horizontal and vertical studs by nails. The spacing of the studs is 50 cm. All walls are reinforced with 1½" x 3" diagonals. Structural model of walls are shown in Fig.15.

Analyses of walls are performed using STAAD.Pro 2004 software. The wall is fixed at one end and laterally loaded at the free end. The load deflection relation are compared to those obtained from test.

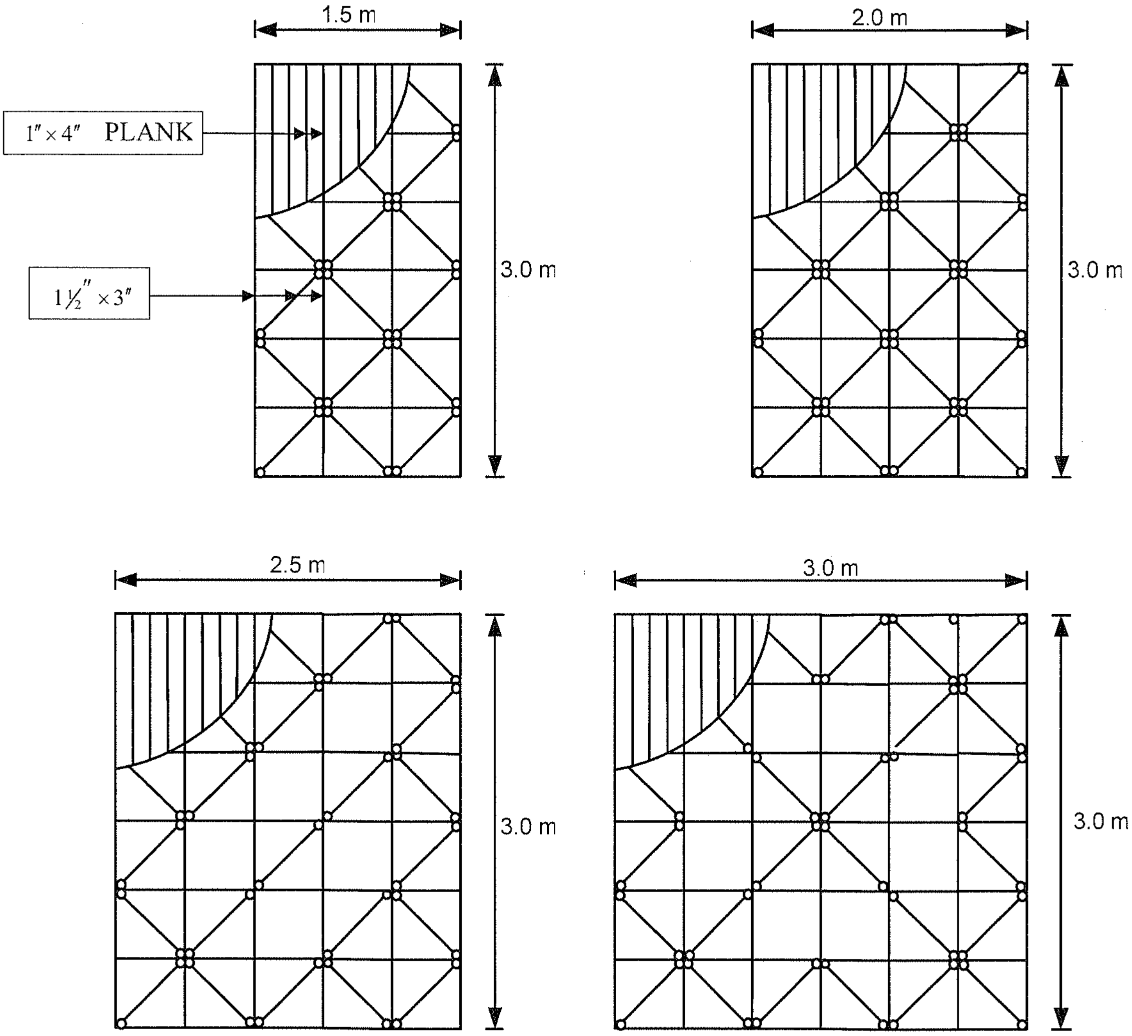
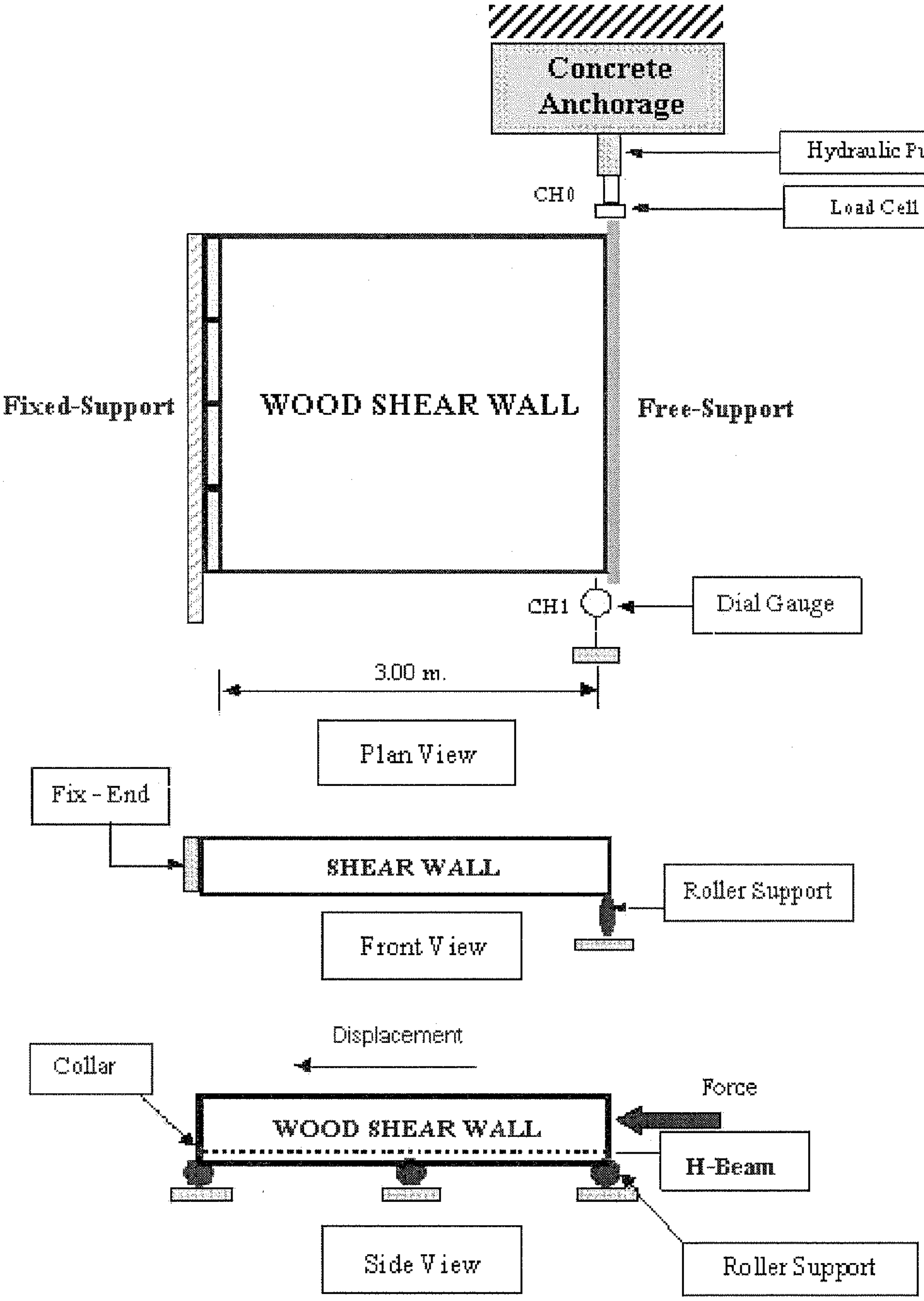


Fig. 15 Structural model of wood plank shear walls

10. Test Equipment

The shear wall test equipment is schematically shown in Fig. 16. The wall is installed in horizontal position. It is fixed at the base while uniform linear distributed load is applied at the top as shown in Fig. 17.



CH0 : Load Channel
CH1 : Deflection Channel

Fig.16 The schematic arrangements of shear wall test equipment

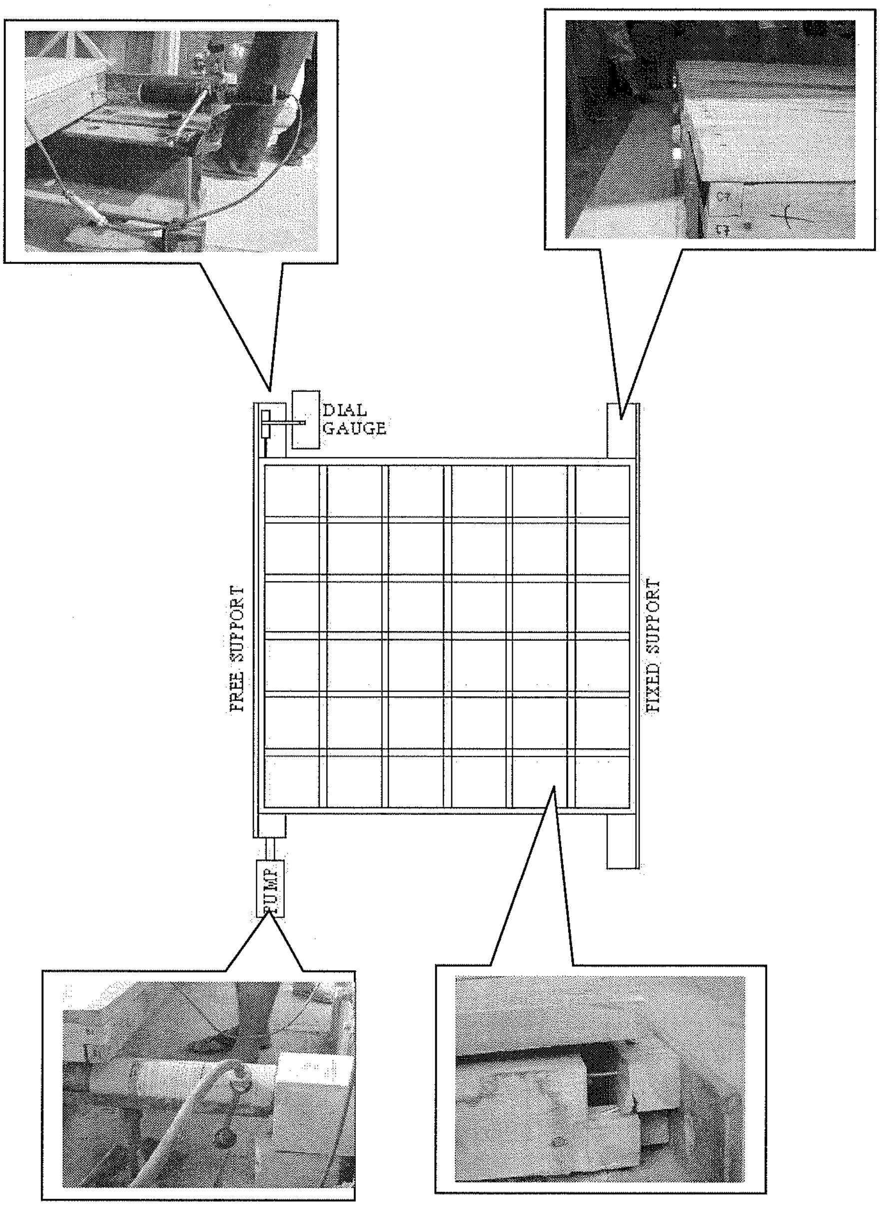


Fig. 17 Installation of shear wall panel with test equipment

11. Test Results

Wall types with length of 1.5 , 2.0 , 2.5 , and 3.0 m have been tested. Each type consists of 2 specimens. Each wall is fixed to the base with ¾" bolts. Test results are shown in Fig.18 to Fig.21. The load-deflection curves have been corrected for friction and non-alignment of load application.

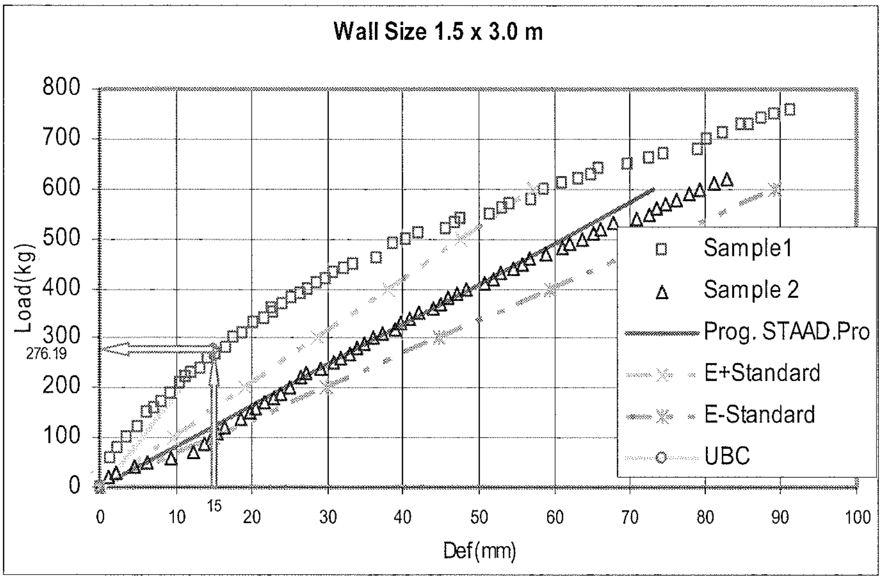


Fig. 18 Comparison of load-deflection relation from test and that from structural analysis

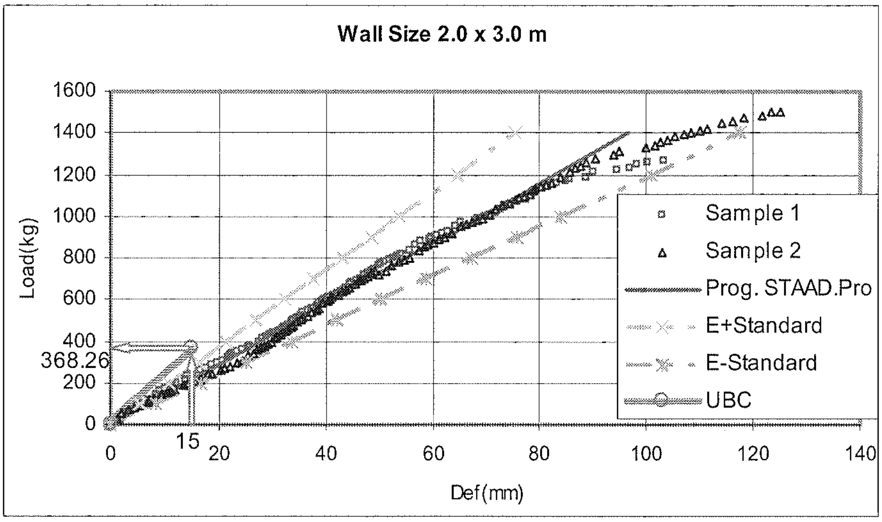


Fig. 19 Comparison of load-deflection relation from test and that from structural analysis

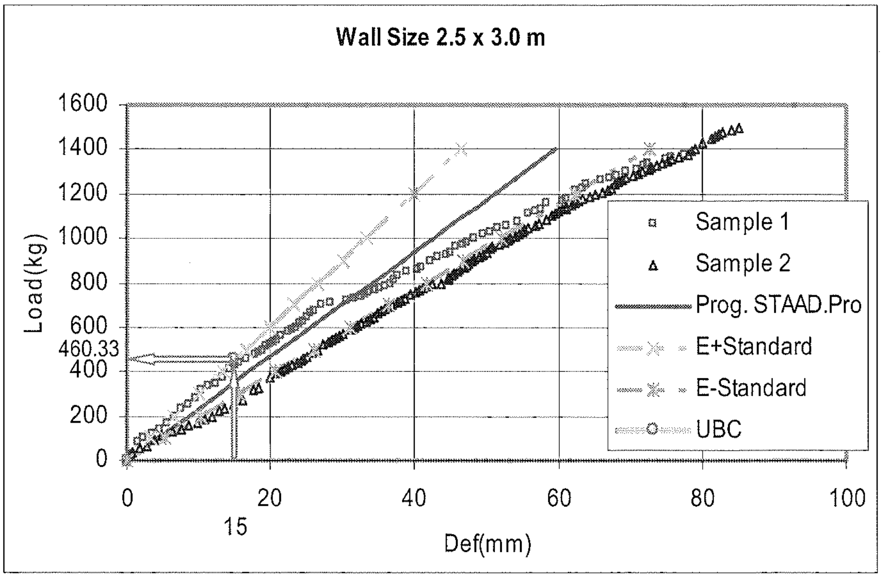


Fig. 20 Comparison of load-deflection relation from test and that from structural analysis

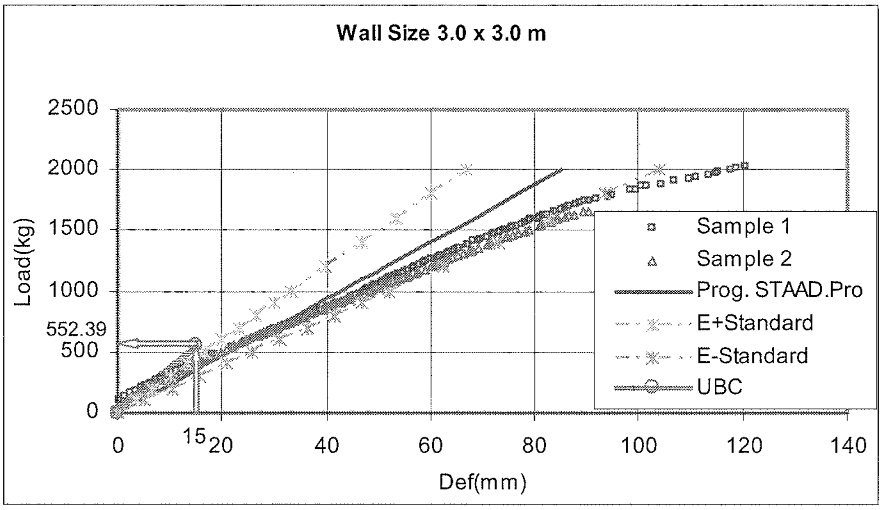


Fig. 21 Comparison of load-deflection relation from test and that from structural analysis

At initial stage the wall behaves linear elastically. Then the load-deflection relation becomes curve when the wall starts to yield. The behavior of wall under loading is closer to monolithic wall. The load application stops when failure occurs due to overturning effect at fixed base.

The load-deflection relation obtained from structural analyses are shown for comparison with test results. It can be seen that structural model may well represent the elastic portion of test result.

Load-deflection relation from bending test of wood specimen exhibits linear elastic behavior, then starts to curve when the specimen yields. The last portion of load-deflection relation has flatter slope. Using 3 values of modulus of elasticity from bending test in structural analysis of 3.0 x 3.0 m wall, the predicted load-deflection curve is shown in Fig. 22.

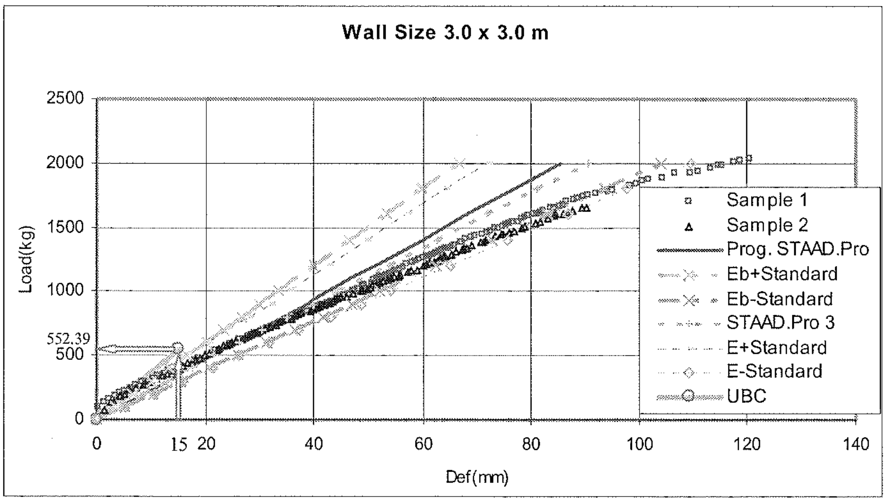


Fig.22 Comparison of load-deflection relation from test and that from structural analysis using 3 values of modulus of elasticity

12. Shear Wall Analysis

12.1 Lateral load resistance

Based on serviceability limit state that lateral deflection of wall shall not exceed 0.5 % of wall height [10] , thus , at deflection of 15 mm , the lateral load from test is summarized in Table 3. The required lateral load for each wall type [10] for the 2-story house in Part A is shown in Table 3. The lateral load from test is lower than that required by code[10].

Table 3. Comparison of lateral load from test and that from design code

Wall Size (m)	From Test (kg)	From Design Code (kg)
1.5 x 3.0	187.1	276.19
2.0 x 3.0	221.46	368.26
2.5 x 3.0	339.87	460.33
3.0 x 3.0	413.84	552.39

12.2 Overturning

From the test, failure of wall occurs due to overturning effect at fixed base. Using the anisotropic properties of wood, that is, modulus of elasticity in tension which is higher than that in compression, the location of neutral axis can be calculated from Fig.23 [11] ,

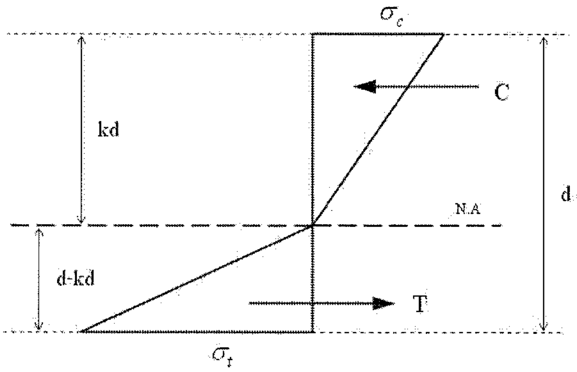


Fig.23 Stress diagram at fixed base of shear wall

and equation 3 :

$$(n-1)k^2 - 2nk + n = 0 \tag{3}$$

where $n = E_t / E_c$

E_t = Modulus of elasticity in tension parallel to grain

E_c = Modulus of elasticity in compression parallel to grain

The withdrawal load of nail is then calculated and shown in Table 4.

Table 4. Withdrawal load of nail at failure

Wall Size (m)	Sample No	Withdrawal Load (kg)
1.5 x 3.0	1	17.17
	2	16.85
2.0 x 3.0	1	16.58
	2	13.08
2.5 x 3.0	1	7.88
	2	10.92
3.0 x 3.0	1	11.7
	2	17.56

Conclusion

Failure probability analysis of joist and beam show that structural components of office building have higher tendency to failure than those of residence and school buildings respectively. The results correspond with ratio of collected value to nominal value of live load, i.e., highest for office and lowest for school buildings.

The size for each component is recommended as follows :

- 1½" x 8" joist can be used in residence and school buildings at spacing of 30 cm. For office building, the recommended size is 1½" x 10" at spacing of 30 cm
- 2-2" x 12" beam is recommended for residence and school buildings. For office building the recommended size is 2-2" x 14"
- 4" x 4" for second floor column is recommended for all types of building.
  6" x 6" for first floor column is recommended for all types of building.
- Wall with diagonal bracing is more rigid and behaves closer to monolithic panel. It exhibits low lateral deflection. Failure of wall occurs due to overturning effect at fixed base.

- The serviceability limit state for deflection of wall is not satisfied. It is anticipated that larger size and closer spacing of vertical and horizontal studs may increase lateral load at serviceability limit state for deflection.

Acknowledgements

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