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Elements of Structural Engineering in Traditional Architecture

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Abstract—This paper deals with the structural design aspects in traditional building science which are dealt with in various Vāstu texts. The study is based on the living tradition of indigenous Architecture in Kerala region in India. Kerala style of traditional Architecture is more timber intensive when compared to other parts of South India. Through this study, it can be concluded that various rules depicted in the ancient texts for the design of various structural elements such as beams, columns etc. have logical basis. These design rules and specifications have many astonishing similarities in its contents and parallels in its approach when compared to modern structural Engineering.

Key words- Structural Engineering, Traditional Architecture, Vāstuvidyā, Column Design, Beam Design, Allowable stress.

I. INTRODUCTION

Many Engineering theories and practices are profoundly dealt in the Vāstu texts, but are not yet brought to light. The main reason for the marginalization of the Vāstuvidyā is that it is viewed as an occult science. The mystic nature of the many topics dealt in Vāstu texts has given such an impression and the deliberate attempts of Vāstu practitioners to retain such a shade have aggravated the situation. In reality if many topics in Vāstu texts are read in the light of modern knowledge, astonishingly many parallels could be drawn. The rules depicted in Vāstu texts for detailing of various structural elements such as columns, beams, roof elements etc. are amazing to a modern reader. In this paper an attempt is made to analyse the structural engineering aspects dealt in Vāstu texts. For the study, popular Vāstu texts in south India, especially Kerala region are referred to.

The main primary sources used for this study are codes for Rituals in Kerala Temples named *Tantrasamuccaya* (TS) written by Cennās Nārāyaṇan Nampūtiripāṭ (b. 1426 CE), text on residential architecture, the *Manuṣyālayacandrikā* (c.1525 CE) written by Tirumaṅgalatt Nīlakaṇṭhan (b. 1500 CE) , *Śilpiratna* (SR) written by Srikumara, and its Malayalam version, *Bhāṣā Śilpiratna*, produced subsequently by an unknown author. Another text widely referred is *Vāstuvidyā* (VV) written by an unknown author and is probably older than MC and SR. It mainly deals with residential architecture and properties and use of popular building materials used in those periods. These texts though written mostly in Sanskrit were made available to craftsmen and carpenters too. They studied these texts as a part of their family tradition and used to memorize the entire verses. Even today these lineages are kept unbroken by a few families.

II. TRADITIONAL STRUCTURAL ARRANGEMENT

Traditional religious as well as secular buildings in Kerala are mostly timber intensive constructions. Basically they are all supported either on masonry walls (Laterite or stone) or pillar (timber, rock or masonry) supported on firm base. Wall plates or beams are placed over the walls or pillars. The column (pillar) base supported on firm bed formed over well compacted earth packed with boulders or firm rocky ground. The structure mainly consists of columns (pillars) or walls, its base and column capital beams/ wall plates. The roof supported by rafters, ridge piece and reapers which forms a threedimensional framework which carries the roofing element. The traditional roofing materials for important buildings were tiles made from clay. Copper sheets were extensively used for temples.

Regarding the materials of construction, the column base and columns are generally made of wood, solid rock or well-built masonry. The Roofing support is essentially wooden frame work with rafters, ridge piece, battens (reeper) etc. made of hard wood. The roof elements are mostly timber construction and rarely solid rock-cut panels. Regarding building materials SR (Chapter 14, Verse 1) states that, Rock, Brick, Lime, timber, Tiles, Mud blocks and metals are the main building materials. The traditional structures were made using these materials. Vāstu texts explicitly have stated the rules to detail the various components of the building using the above materials. Let us examine the detailing of various structural elements and its analysis and comparison in terms of modern theory.

III. DETAILING OF VARIOUS PARTS OF COLUMNS

A. *The Column Base*

These columns are erected on a strong base made of either hard rock or strong wood according to the material of construction of column. If columns are of stone cut, the base will also be of hard rock. In the case of timber or masonry columns, the base can either be of hard wood or rock. These are called as Oma (Padapīṭha) in Vāstu literature. While fixing the measurements of various structural elements, the top dimension of the column is taken as a unit (module) and is called a Daṇḍa (D_t). According to *Manuṣyālayacandrikā* (Chapter 5, Verse 22), the Padapīṭha (oma) made with hard stone or hard wood , square, octagonal, or sixteen sided or in some places circular should be placed with width equal to the diagonal at the base of the pillar and height (thickness) equal to the half of the width or 1/3,1/4,1/2 less than that". According to SR (Chapter 21), the size of the base (Oma) shall be 2Dt (twice the top dimension of the column) and thickness base (Oma) shall be one-fourth of that. *Bhāṣā Śilpiratna* another popular text, written in Malayalam states that the base (oma) will have the shape of the base of the column and size shall be 2 or 3 Dt or diagonal of the Base width (Db). Thickness shall be ½ or ¼ of its lateral dimension.

Columns are placed on the Base blocks (Oma) by providing a recess in the Base block (oma) and by providing a key (projection) in the column base. This projection shall be square in shape and size equal to 1/3 of the dimension of the column bottom portion. MC (Chapter 5, Verse 23) states that 'All Pillars with square tenons of width equal to one–third of own width should be placed above their own oma (Base-block) with said tenons joined with their own mortises" .The column projection shall have diameter ¾ of bottom size or 4/5of bottom size. (Verse 54: SR).These projections act as shear connectors preventing the column from sliding in any direction.

Analysing from structural point of view, it can be seen that the Base block is intended to keep the column in position and the same time to transfer the vertical load from column to the ground by distributing to more area. The Column is connected to the base block only through a tenon (key). This kind of connection will ensure that column is held in position without transfer of any moment. Thus it becomes equivalent to hinged connection. This is essentially required since there no structural foundation available to carry any moment.

As stated above, the minimum lateral dimension of the block specified is $\sqrt{2}.D_b$ and hence the minimum area that will distribute will be twice the area of the column and hence the stress will be reduced to half. The maximum size specified is $3D_t$ and hence stress below the base block will be approximately 1/7 of the column stress at bottom dimension as D_t varies from $5/6$ to $11/12$ of Db.

If P is the load on the column, stress below base block (oma) (p) will be

$$A = 3.(D_t)^2 = \frac{121}{16}(D_b)^2$$

$$p = P / A = \frac{16P}{121.(D_b)^2}$$

The maximum projection from face of column will be:

$$x = \frac{1}{2}\left(\frac{33}{12}D_b . - D_b\right) = \frac{21}{24}D_b$$

$$\because D_t = \frac{11}{12}.D_b$$

Bending moment =

$$M = \frac{px^2}{2} = \frac{49P}{968}$$

Required thickness =

$$t = \sqrt{\frac{6M}{f_t}} = \sqrt{\frac{147P}{242\,ft}}$$

Also

$$fc = \frac{P}{(D_b)^2}$$

$$W = 3D_t$$

$$t = D_s\sqrt{\frac{147\,f_c}{242\,f_t}} = D_t\sqrt{\frac{0.6\,fc}{ft}} = \frac{W}{4}\sqrt{\frac{f_c}{f_t}}$$

The specified thickness varies from $W/4$ to $W/2$. Thus for materials like timber when $fc/ft \approx 1$, $W/4$ shall be adopted and for stone where $fc/ft \approx 5$. Thus the specification and practice followed are perfectly matching with the stress analysis results using modern theory.

The minimum size of base-block (W) specified is 1.414 Db. In such case, when minimum thickness of W/4 is considered, projection will be 0.212 D_b, which have dispersion angle (α) roughly 45º.

$$\alpha = \tan^{-1}\left(\frac{0.25}{0.22}\right) = 48.65^\circ$$

In the case of Plain concrete pedestals, as per the clause 34.1.3 of IS 456:2000, the angle between the plane passing through the bottom edge of the pedestal and the corresponding junction edge of the column with pedestal and the horizontal plane shall be governed by the expression: $\tan\alpha \le 0.9\sqrt{\frac{100p}{fck}+1}$ where p = calculated maximum bearing pressure at the base of the pedestal in N/mm2, and fck = characteristic strength of concrete at 28 days in N/mm2.

Assuming that column is stressed to its ultimate capacity, we have

$$\tan\alpha \le 0.9\sqrt{\frac{100p}{fck}+1} = 0.9.\sqrt{\frac{2P}{.D_b^{\,2}}.\frac{D_b^{\,2}}{P}+1} = 1.55$$

$$\therefore \alpha = 57.17^\circ$$;

B. *Columns*

The pillars (Columns) of important structures were mainly made of carefully selected solid rock architecturally treated from bottom to top. Timber (wooden) columns and masonry pillars are also not so uncommon.

The shapes generally adopted are Square, Octagon, Hexa-decogon (sixteen sided polygon) and circular. Regular polygons (Square, Hexagon etc.) and circular are the common geometry adopted for columns and in special occasions rectangular and T Shaped columns are seen to have provided. As these pillars were mainly rock cut or timber for architectural beauty, above cited different shapes were mixed in a column producing many aesthetically pleasing combinations. These are also defined and named.

Design of Column: When homogeneous material is used, the determination of required size of a column according the material of construction and quantum of super imposed load is the main design step. Let us examine how the required size was determined in traditional way.

According to MC (Chapter 5, Verse 24), the least lateral dimension shall be 1/4, 1/5, 1/6, 1/7, 1/8, 1/9, 1/10 or 1/11 of its height The effective height of the Pillar or column is defined as the measurement from the bottom of the Oma to top of

Pothika or in other words it is the height including Pothika (Column capital) and Oma (Column Base block). However the height of the Pedestal below the Oma will not be considered (MC Verse 21 Page 205).

According to SR (Chapter 21, Verse 46), the lateral dimension of the column shall be shall be L/6 to L/12 where L is the height of the column as defined above. It is pertinent to note that the ratio L/D is identified as the key factor in the sizing of columns in the traditional texts Moreover in the all the texts they have stated the upper limit of L/D ratio as 11 or 12. Similarly Chapter 250 of *Matsyapurāṇa*, which deals with the design of pillars, says that the dimension of the pillar shall be 7h /80 where h, is the height of the pillar. This works out to l/d = 80/7=11.2. In the *Bṛhatsaṁhita* of Varāhamihira, it is said that minimum lateral dimension of column at top shall be 81/800 of height. (Chapter:51 Verse 27, p. 266). This will be also in the range of 1/10 when lateral dimension of column at bottom is considered.

In traditional buildings, the spacing between the columns never exceeded the column height and the span of the building never exceeded twice the height of the column. Thus all these dimensions were related.

Thus if we consider the total load transferred will be as follows:

$P = wl^2$: where w is the total load per unit area and l spacing between the columns and $2.l$ span of the building.

Thus

Direct Stress

$$\sigma_c = P/A = \frac{wl^2}{D^2} = w\left(\frac{l}{D}\right)^2 = w\lambda^2$$; where D is the lateral dimension of square column.

Assuming that column has approached the limit of Intermediate column:

Euler's Stress,

$$\sigma_e = \frac{P}{A} = \frac{\pi^2 E}{\left(l/r\right)^2} = \frac{k}{\lambda^2}$$ where k is a constant $\lambda = \frac{l}{D}$

Applying Rankine-Gordon equation

$$\frac{1}{\sigma_{\max}} = \frac{i}{\sigma_e} + \frac{1}{\sigma_c} \quad \frac{1}{\sigma \max} = \frac{\lambda^2}{k} + \frac{1}{w\lambda^2} = \frac{w\lambda^4 + k}{kw\lambda^2}$$

$$\sigma \max = \frac{kw\lambda^2}{k + w\lambda^4}$$

Maximum load that can be applied

$$w = \frac{\sigma \max .k}{k\lambda^2 - \lambda^4} = \sigma.\left(\frac{1}{\lambda^2\left(1 - \frac{\lambda^2}{k}\right)}\right)$$ Where k in the square columns is $k = \frac{\pi^2 E}{12}$

Or

$$\frac{\sigma}{w} = \lambda^2\left(1 - \frac{\lambda^2}{k}\right)$$ Where $k = \frac{\pi^2 E}{12}$ & $\lambda = \frac{L}{D}$

As an example if we consider the following for a construction of teak wood column;

Here it may be noted that w is the load per unit area acting on the roof/floor and σ is the allowable stress and hence irrespective of the variation of the height, it will solely depend upon the selected L/D ratio only. Thus any test carried out on scaled model will validate the structure with the same material and same unit load per area.

In modern practice, also in the structural design of any column the criteria are End condition (Whether fixed/partially fixed/pinned etc.), Eccentricity & slenderness and codes have set limits for Eccentricity and slenderness.

In this context, it may be noted that in the modern design practice we are considering minimum eccentricity as per IS 456: 2000;

$$\frac{l}{500} + \frac{D}{30} \leq 20mm$$

Where l effective height of column measured in mm and D lateral dimension under consideration in mm. The maximum height of column specified as 8H or 5760mm. Then using l/D as 12 (Max). the lateral dimension will be 5760/12=480 In such a case the eccentricity as per the above clause will be

$$e = \left(\frac{5760}{500} + \frac{480}{30}\right) = 27.52$$

Applying a factor 0.75 for effective height after considering the deductions for Oma and Pothika; e=20.25 which fairly matches with modern stimulation regarding eccentricity limit. Thus it may be noted that the maximum column height specified in the traditional texts has also relevance when viewed from modern theory.

C. *Pothika* (Column Capital):

Pothika is a structural element provided at the top of column on to which the beam is placed. This Pothika will ensure proper connection between the column and beam and also will evade chance of shear failure at the column beam junction. These Pothikas are also architecturally treated and based on the size bear different names. The Pothika width (W) same as bottom width of the column is Uttama (Superior), same at middle width Madhyama (Medium) and top width Adhama (Inferior) (SR pp. 274).

The length of the Uttama Pothika shall be 5 D_t and thickness shall be same as width W. length shall be Madhyama Pothika will have length equal to $4D_t$ and it will be having thickness W/2. The Adhama type will have length equal to D_t and minimum thickness of W/3. In another approach Width (W) of Pothika shall be size of column at bottom, middle or at top. Length 3Dt, 3.5Dt, 4Dt, 5 Dt Thickness shall be W, W/2, 2/3W, 4/5 W, 3/5W, 3/4 W.

From structural point view also, in order to resist shear force, it is always desirable to provide a column capital. These Pothikas are fixed on the columns by means of shear keys provided at the top of the column as in the case of Oma. Then the wall plates/ beams are fixed to Pothika by means of wooden keys having size one-third of the width of the Pothika.

IV.DETAILING OF BEAMS AND WALL PLATES

The Wall plates/Beams having width same as that of column base (Db) and depth same as that depth is called Khaṇḍottara. Depth equal to ¾ of D_b is called Patrottara and ½ of D_b is called Rūpottara. This Khaṇḍottara is recommended for all major structures. (Ref: SR p. 234) The Depth of Rūpottara can Db/2 or 5/8 of Db, 11/15, 6/9, 7/11 (SR Verses 2 and 3 p. 334). Patrottara will have w/3 as depth (Verse 4, MC p. 218 Verse 31).

Here it may be noted that beam width is kept same as the column width at base and depth is altered depending up on the requirement. For major structures, square beams are recommended. From structural point, it is economical to have more depth than width since moment carrying capacity is proportional to the square of the depth. Then why a square beam is recommended? In order to have proper connection between the column and beam the width of the slightly more than the top width of the column is a practical requirement. More over these beams are of mainly timber construction, hence structurally more depth will not produce more carrying capacity since stress decreases when distance between outer fibre from the Neutral axis increases. In order to compensate this reduction, usually a term called form factor is applied. Form factor

$$K = 0.81.\left(\frac{D^2 + 894}{D^2 + 550}\right)$$ when D is taken in cm & D>30cm.

As stated earlier the beam span will not be more than the column height and hence span /depth ratio of the beams also will same as that of column. Let us analyze this using modern theory.

The maximum deflection, δ in a uniformly loaded beam will be as follows.

$$\delta = \frac{5}{384}\frac{wl^4}{EI} = \frac{5}{384}.\left(\frac{wl^2}{8}\right)\frac{8l^2}{EI} = \frac{40}{384}.\frac{2f.I}{D}.\frac{l^2}{EI} = \left(\frac{80f}{384E}\right)\left(\frac{l^2}{D}\right) = \frac{5}{24}\frac{f}{E}$$

Where f is allowable stress in bending and E is modulus of elasticity.

But allowable deflection in the case timber beams is as given below.

$$\delta = \frac{l}{240}$$

$$\therefore \frac{l}{D} = \frac{E}{50f} . = \frac{0.02E}{f}$$

For timber beams, say Teak wood considering the stresses,

$$f = 14N/mm^2$$

$$E = 9600N/mm^2$$

Thus $9600/700 = 13.71$

The traditional texts have fixed this ratio conservatively as 12 and have set the maximum value as 16 (Ref. SR) i.e. 50 % higher as in most cases the actual stress will be less than the allowable stress. In the above case, actual stress corresponding to the maximum l/d of 16 works out to 600 N/mm2 which is very reasonable and practical.

For the calculation of the length of the rafter both graphical method and analytical method are suggested. For calculating analytically, the length of the common rafter using the property of right triangle._The relationship between the sides and hypotenuse of the right triangle (Pythagoras theorem) is known as Bhuja-Koṭi-Karna Nyāya and is known from Vedic age (*Āpastambhaśulbasūtra* mentions this relationship). The SR says to add the square of the half width to the desired height of the roof and to take square root to get the length of the common rafter. For the slant rafter (Vikṛti), sum the squares of the half the width, desired height and the distance of the rafter from the entre point of the width and then take the square root to get the length of the vikṛtilūpa. (SR Chapter 33 verses 1-5). In modern terms lengths of prakṛtilūpa.(common rafter) and vikṛtilūpa (slant rafter) are respectively

$L_p = \sqrt{\left(\frac{W}{2}\right)^2 + H^2}$; $L_v = \sqrt{\left(\frac{W}{2}\right)^2 + H^2 + D^2}$ where W is span , H is the roof height and D is the Distance if slant rafter from centre of width.

V. CONCLUSIONS

Above discussions reveal that in detailing various structural elements in the traditional architecture, Kerala has scientifically developed taking into consideration, all the required aspects such as strength and utility. Moreover by adopting a modular concept, optimum use of materials and their re-use was ensured. By setting an inter-relation in the sizing of columns, beams, rafters, ridge piece etc. the wood cutting was made easy with maximum utility.

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