SUITABILITY OF RAT-TRAP CONSTRUCTION FOR SEISMIC AREA

A DISSERTATION

submitted in partial fulfilment of the requirements for the award of the degree

of

MASTER OF ENGINEERING

in

EARTHQUAKE ENGINEERING

(With Specialization in Structural Dynamics)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled **"SUITABILITY OF RAT-TRAP CONSTRUCTION FOR SEISMIC AREA"**, in partial fulfilment of the requirements for the award of the degree of **MASTER OF ENGINEERING** in **EARTHQUAKE ENGINEERING** with specialization in **Structural Dynamics**, submitted in the Department of Earthquake Engineering, University of Roorkee, Roorkee is an authentic record of my own work during a period of about 5 months from November 1998 to March 1999 under the supervision of **Dr. B.C. Mathur**, Professor, Department of Earthquake Engineering, University of Roorkee, Roorkee and **Sri R.N. Dubey**, Lecturer, Department of Earthquake Engineering, University of Roorkee, Roorkee, India.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree or diploma.

Place : Roorkee

Dated : March २२ , 1999

Asim Kumar Srivastva

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

Housing like food and cloth is a basic need of a human. India is the second most populous nation of the world. With such a large population, housing is an acute problem. Low and middle - income groups find it very difficult to build their own houses.

Brick masonry is cheaper as compared to R.C.C. construction for low rise buildings and is made more economical by using Rat-Trap bond construction developed by famous architect of Kerala, Mr. Lauri Baker. However, more than 50% area of our country, India, is seismically active. In the past severe earthquakes all over the world, masonry buildings have generally been damaged the most. Therefore, to check its safety in seismic areas, a one room building of size 3.5m×3.5m×3m with doors and windows (one brick thick wall) in seismic zone IV made by Rat-Trap bond is analysed by Pier method. The results have been compared with that of the conventional English bond construction of same shape and size. It is found that the stresses developed in Rat-Trap bond masonry are within permissible limit. Tensile stress developed which is critical in earthquake prone area is less in Rat-Trap bond construction as compared to that developed in English bond construction. Details of junctions are also proposed for such constructions for placing of vertical reinforcement.

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CHAPTER - 1

INTRODUCTION

Masonry constructions in brick and stone are the most common forms and even mud also is used in masonry and as mortar in such constructions. Mud walls in building construction with or without fibre reinforcement continue to dominate the rural housing of the poors. Large numbers of mud walls are built more by convention or by local practice. Brick masonry is extensively used in walls, retaining walls, pillars, piers, arches, and wells. Stone masonry was the most popular for monuments and state buildings before the advent of reinforced concrete. Of course, the brick masonry constructions continue to dominate the scene either as local bearing walls or as filler walls in multi-storey buildings.

Brick masonry is preferred over other type of masonry due to the following reason [8]:

- Bricks are of uniform size and shape, and hence they can be laid in any definite pattern.
- Brick units are moderate in weight and small in size. Hence they can be easily handled manually.
- Bricks don't need any dressing.
- The art of brick laying can be understood very easily and even unskilled masons can lay brick masonry.
- Bricks are easily available locally. Due to this, they don't require transportation from long distances.
- Ornamental work can be easily done with bricks.

- Light partition walls and filler walls can be easily constructed in brick masonry.

Like food and cloth a house is the basic need of a human being. India is the second most populous nation of the world. With such a large population housing is an acute problem. Low and middle- income group finds it very difficult to build their own houses. Thus there is urgent need to reduce the cost of construction by adopting the newly developed techniques. Brick masonry is cheaper, as compared to R.C.C. construction for low rise buildings and can also be made more energy efficient and economical. This economy can be achieved by different ways like using hollow bricks, changing the pattern of bricks in construction of walls known as 'BOND' coupled with built-in cavities etc. However the walls constructed by these different techniques should be able to withstand and transfer the loads acting on the roofs of the foundation. Also, functionally, the walls should provide necessary thermal comfort, fire safety and adequate ventilation. One such type of bond (other than the conventional bonds known) is 'Rat-trap' bond. This bond in brick masonry is of late gaining popularity as a technique for masonry construction for low cost housing and is promoted by various organisations all over the country. The bond, developed by famous architect of Kerala Mr. Lauri Baker, results in 25% saving of bricks and mortar. [1]

In the past severe earthquakes all over the world, the masonry buildings have generally been damaged the most because of their heavy weight, low shearing resistance, lack of proper bonding between longitudinal and cross walls and poor workmanship. So more studies and experiments on masonry structures in seismic zones are required. The aim of the present study is to examine the suitability of the 'Rat-trap' bond construction in seismic zones. Comparison of stresses developed in the 'Rat-trap' bond and the conventional 'English' bond has been done by Pier method to assess the seismic safety status of the two forms of bonds.

CHAPTER 2

REVIEW OF LITERATURE

2.1 BONDS IN BRICK MASONRY

Bond is the inter-placement of bricks, formed when they lay or project beyond those immediately above or below them. It is the method of arranging the bricks in courses so that individual bricks are tied together and the vertical joints of all the successive courses don't lie in the same vertical line. Bond of various types by their elevation or face appearance. On account of their uniform size and shape, the bricks can be arranged in a variety of patterns giving rise to different type of bonds.

If the bricks are not arranged properly, continuous, vertical joints will result. An unbonded wall with its continuous vertical joints has much less strength and stability. Bonds help in distributing the loads over a large area. Since bricks are small units, having uniform dimensions, the process of bonding is easily performed.

The commonly adopted bonds in brick -work are Stretcher Bond, Header Bond, English Bond, Flemish Bond, Facing Bond, English Cross Bond, Brick on Edge Bond, Dutch Bond, Raking Bond, Zigzag Bond, Garden Wall Bond.

Housing which is one of the basic needs of a human being, has gone beyond the reach of common man in our country. Housing problem is quite complex - a problem of income of common man on one side and a problem of allocation of sufficient funds by the government on the other side. The study on the income patterns of our people will show that it is very difficult to bring down the cost of land, building materials and construction cost in line with income of our people. Therefore, for reducing the cost, development of new techniques has become a necessity. Towards this effort, Rat-Trap bond has come as a distinct possibility in which material saving is about 25% and is of late gaining popularity as an alternative technique for masonry construction for low cost housing.

2.2 RAT-TRAP BOND

The famous architect Mr. Lauri Baker has developed this Rat-Trap bond. Rat-Trap bond masonry, also referred to as Rowlock or Rolock walls, may be defined as a wall comprising of two leaves, each leaf being built of burnt clay bricks placed on edge (bull stretchers), separated by a cavity and tied together with bull header bricks to insure the integrity of the two leaves (4).

This system uses brick-on edge with a cavity behind every facer brick. This bond is not possible with modular bricks. It is possible only by using traditional bricks, which is practical. The dimensions of traditional bricks vary from place to place. Their length varies from 20cm to 25cm, width varies from 10cm to 13cm and thickness varies from 5cm to 7.5cm. The commonly adopted nominal size of traditional brick is 23cm×11.4cm×7.6cm (9"×4.5"×3") approximately. The cavity left in the Rat-Trap bond depends upon the size of the brick and is 7.8cm by using brick of size 23cm×11.4cm×7.6cm. The bricks are laid with cavity left between two leaves of bricks on edge with a header after every stretcher. All frogs of the bricks are kept towards cavity.

Half or cut bricks should be avoided as far as possible by adjusting the thickness of the mortar joint. If half cut bricks are unavoidable they should be placed near the end of the walls [4].

In the conventional brick masonry, one face of wall is neither in plumb nor in line due to uneven size of bricks. Therefore pointing can't be provided for exposed brick- work. In the Rat-Trap bond, both faces can be made in plumb and line by adjusting the cavity. Thus pointing can be provided on both sides, if so desired, to improve aesthetics and avoid plastering. A plan of alternate course of Rat-Trap bond is shown in Figs. 1 & 2.

2.3 DESIRABLE PLACEMENT OF OPENING [4]

IS:4326-1993 has suggested the following points for opening in masonry structures:

(a) Top of opening in the building should be at the same level, so that a continuous lintel band could be provided over them.

(b) The total width of opening should not be more than half of the length of the wall between the adjacent cross walls.

(c) The opening should preferably be located away from the corner by a clear distance equal to at least 1/8th of the opening.

(d) Horizontal distance between two openings should not be less than 1/4th of the height of the opening.

(e) The vertical distance between two openings one above the other should not be less than 0.6m.

(f) The use of arches to span over the openings is a source of weakness and hence should be avoided, unless steel ties provided.

2.4 ADVANTAGES OF RAT-TRAP BOND MASONRY

(a) Cost

It is obvious that every three brick laid saves one brick in this bond. Also, for every 230mm height of brickwork there is a saving of one layer of mortar. Thus the reduction in brick masonry walls is about 25% without having any adverse effect on the life of the building.

(b) Speed in Construction

Rat-Trap bond is faster to construct with only five courses in 2 feet height of wall as against eight courses in conventional bonds, resulting in 25% to 30% saving in time resulting in lower site over- head costs.

(c) Sound Insulation

A high degree of sound insulation is provided for due to built-in cavity in the masonry walls resulting in a better atmosphere in-side the building.

(d) Thermal Insulation

Good thermal properties of cavity brick walls have long been recognised for energy efficient buildings and more recently have become critical in the attempts to conserve energy.

(e) Aesthetics

Architects and clients are very much concerned and also interested in it. In Rat-Trap bond, the external facades can be exposed brick work making the buildings aesthetically different and satisfying from the architectural view point. To prevent exposed brick- work against moisture penetration, transparent silicon or epoxy paint could be applied.

(f) Safety and strength against seismic forces

This form of construction is expected to perform well during earthquakes. However, no studies in this regard have been reported. For this reason the present work has been taken up to assess the seismic safety status of this construction employing Pier method of analysis.

ANALYSIS BY PIER METHOD

To examine the suitability of Rat-Trap construction in seismic areas, a single room building (with Rat-Trap bond) situated in seismic zone IV is studied and is analysed by Pier Method (The method is given in detail in Appendix B). A building of same shape and size in English bond construction is also analysed to compare the results of the two types of bond construction. For Rat-Trap construction, it is assumed that the cavities are continuous through out for simplicity of calculations. In real practice, these cavities are not continuous. This discontinuity provides extra strength to the structure. Thus our assumption is on conservative side with regard to strength of building .

Reinforced masonry building walls, should not be built of total height greater than 15m subjected to a maximum of four storeys when measured from the mean ground level to roof slab or main tie level [7]. For this reason, the analysis has been made for buildings up to four storey only.

CALCULATION OF DESIGN HORIZONTAL SEISMIC FORCE

The seismic force is considered for the building as per IS:1893-1984 for zone IV with appropriate values of soil foundation factor (β), importance factor (I) and performance factor (K). For seismic zone IV, with $I=1, \beta=1$; K=1.6 and $\alpha_0 = 0.05$, the design base shear is obtained as

$$V_B = KC\alpha_h W = 1.6 \times C \times 1 \times 1 \times 0.05 \times W = 0.08CW \quad ......(i)$$

where, α_h = design seismic coefficient $= \beta I \alpha_0$

W is the total weight of the building and

C is the flexibility coefficient depending on time period of the building.

ANALYSIS OF A SINGLE STOREY BUILDING

The plan of the building chosen is shown in Figs. 3 & 4 for Rat-Trap and conventional English bond respectively. The elevation is shown in Fig. 5 which is the same for both type of bond constructions. The room is one brick thick wall using traditional brick of size 23cm×11.4cm×7.6cm with crushing strength 7.5 N/mm² ~~70Kg/cm²~~ in cement sand mortar 1:6. Since openings in the wall make it weaker, the analysis has been done for the seismic force acting in the longitudinal direction of wall which contains openings.

Dimensions

Plan: 3.96m×3.96m

Height: 3.1m (including 10cm thick R.C.C. roof)

Door: 0.8m×2.0m

Window: 0.9m×1.2m

(A) Total Dead Load

Rat-Trap Bond Construction

Total dead load = dead load due to roof + dead load of walls/2

$$=39204+\frac{7.206\times 18835.2}{2}=107067.23\text{ N}$$

English Bond Construction

Total dead load = dead load due to roof+dead load of walls/2

$$=39204+\frac{9.062\times 18835.2}{2}=124546.3\text{ N}$$

(see Appendix- C for calculation of loads)

(B) Comparison of Time-Period

Time Period $T = 2\pi\sqrt{\frac{m}{K}}$,

where m = mass and

K = stiffness

$m_{Rat\text{-}trap}$ = 107067.23 Kg = m_1 (say)

$m_{English}$ = 124546.30 Kg = m_2 (say)

$K_{Rat\text{-}trap}$ = 2×(2.58+1.9798+1.915)×E = 12.9496 E = K_1 (say)

$K_{English}$ = 2×(3.14+2.29+2.41)×E = 15.68 E = K_2 (say)

Here it is assumed that the shear stiffness of the wall is the sum of rigidities of piers and the rigidity of other portions has been ignored. [1]

(see Appendix- D for the values of shear stiffness of individual pier)

$$\therefore \frac{T_{English}}{T_{Rat-trap}} = \sqrt{\frac{m_2 K_1}{m_1 K_2}} = 0.980$$

$\therefore T_{Rat\text{-}trap} = 1.02\ T_{English}$

Now $T_{English} = \frac{0.09 \times 3.1}{\sqrt{3.96}}$ sec.= 0.14 sec

(Empirical formula for approx. time period of building is $T = \frac{0.09H}{\sqrt{d}}$)[5]

$\therefore$ Corresponding value of C = 1.0

$T_{Rat\text{-}trap}$ = 1.02×0.14 = 0.1428sec.

Corresponding value of C = 1.0

(C) Calculation of Lateral force

Rat -trap bond Construction

Total dead load W = 107067.23 N

As already worked out in equation (i), Base Shear V_B = 0.08CW

=0.08×1×107067.23

= 8565.38 N

As the building is single storey, lateral force at roof = 8565.38 N

Since building is symmetrical about the axis parallel to the force, the lateral force taken by each wall = 8565.38/2

= 4282.69 N

English Bond Construction

Total dead load W = 124546.3 N

As already worked out in equation (i), Base Shear V_B = 0.08CW

= 0.08×1×124546.3

= 9963.7 N

As the building is single storey, lateral force at roof = 9963.7 N

Since building is symmetrical about the axis parallel to the force, the lateral force taken by each wall = 9963.7/2

= 4981.85 N

The calculation of all the stresses has been shown in Table 1 for Rat-Trap construction and in Table 2 for English bond construction.

ANALYSIS FOR FOUR STOREY BUILDING

For the four storey building, it is assumed that all the storeys are same in shape and size. The first storey of this building is similar to the single storey case. As first and the fourth storeys are the critical storeys, the analysis has been` done for the two storeys.

(A) Dead load & Live load

Tat-Trap Bond Construction

Dead load of first storey + live load = 184731.45 N $=W_1$

Dead load of second storey + live load = 184731.45 N $=W_2$

Dead load of third storey + live load = 184731.45 N $=W_3$

Dead load of fourth storey =107067.23 N $=W_4$

∴ Total load W = $W_1+W_2+W_3+W_4$
=661261.58 N

English Bond Construction

Dead load of first storey + live load	=219689.6 N	$=W_1$
Dead load of second storey + live load	=219689.6 N	$=W_2$
Dead load of third storey + live load	= 219689.6 N	$=W_3$
Dead load of fourth storey	= 124546.3 N	$=W_4$

∴ Total load W = $W_1+W_2+W_3+W_4$
= 783615.1 N

(see Appendix- C for calculation of loads)

(B) Calculation of lateral force

It is assumed that the ratio between the time periods of both the buildings are same as that of the single storey case.

$$T_{English} = \frac{0.09 \times 12.4}{\sqrt{3.96}} = 0.56 \sec.$$

Corresponding value of C = 0.75

$$T_{Rat\text{-}trap} = 1.02 \times 0.56 = 0.57 \sec.$$

Corresponding value of C = 0.745

Rat-Trap construction

Total load W = 661261.58 N

∴ Base shear V_B = $KC\alpha_h W$
= 1.6×0.745×0.05×661261.58 N
= 39411.2 N

Lateral force at first storey	= 1656.3 N
Lateral force at second storey	= 6743.3 N
Lateral force at third storey	= 15252.5 N
Lateral force at fourth storey (roof)	= 15758.1 N

(For the distribution of base shear to different storeys, see Appendix -E)

English Bond Construction

Total load W = 783615.1 N

∴ Base shear V_B = $KC\alpha_h W$

= 1.6×0.75×0.05×783615.1 N

= 47017 N

Lateral force at first storey = 1995.7 N

Lateral force at second storey = 8114.3 N

Lateral force at third storey = 18356.34 N

Lateral force at fourth storey (roof) = 18550.66 N

(For the distribution of base shear to different storeys, see Appendix- E)

All the stresses and their combinations have been tabulated in Table 3 for the fourth storey for Rat-Trap construction and in Table 5 for English bond construction.

All the stresses and their combinations has been tabulated in Table 4 for the first storey for Rat-Trap construction and in Table 6 for English bond construction.

(For calculation of different stresses, see Appendix- G)

Table: 1 Combination of Stresses of Single Storey Rat-Trap Bond Construction Building

Pier	Relative Rigidity	Height 'h' (cm.)	Shear force in one wall below roof (N)	Shear Force shared by Pier 'P' (N)	Area of X-section (cm^2)	Area of X-section effective in Shear (cm^2)	Max. Shear Stress 'V' (N/cm^2)	Moment M=Ph/2 (N-cm)
P_{1R}	0.40	120.0	4282.69	1713.0	2167.570	1190.01	2.160	102780.0
P_{2R}	0.31	120.0		1327.6	1265.000	1265.00	1.570	79656.0
P_{3R}	0.29	200.0		1242.09	2807.154	1728.21	1.078	124209.0

Table 1 A.

Pier	Stress due to Dead load & Live load (N/cm^2)	Earthquake Force in XY- direction		Earthquake Force in YX- direction		Max. Compressive Stress (N/cm^2)	Max. Tensile Stress (N/cm^2)
		Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)	Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)		
P_{1R}	–4.3 –4.3	+3.460 –6.360	+1.5300 +1.0710	–3.460 +6.360	–1.5300 –1.0710	9.589	0.989
P_{2R}	–4.3 –4.3	+4.310 –4.310	+0.2450 –0.0588	–4.310 +4.310	–0.2450 +0.0588	8.855	0.255
P_{3R}	–4.3 –4.3	+3.500 –1.864	–0.7200 –1.4400	–3.500 +1.864	+0.7200 +1.4400	7.604	No tension

(–) ve = Compressive Stress ; (+) ve = Tensile Stress

For each pier, two values are given - first value is for the left edge and second value is for the right edge of that pier.

Table : 2 Combination of Stresses of Single Storey English Bond Construction Building

Pier	Relative Rigidity	Height 'h' (cm.)	Shear force in one wall below roof (N)	Shear Force shared by Pier 'P' (N)	Area of X-section (cm^2)	Area of X-section effective in Shear (cm^2)	Max. Shear Stress 'V' (N/cm^2)	Moment M=Ph/2 (N-cm)
P_{1s}	0.40	120.0	4981.85	1992.74	2716.30	1428.3	2.093	119564.4
P_{2s}	0.29	120.0		1444.70	1623.80	1623.8	1.330	86682.0
P_{3s}	0.31	200.0		1544.41	3587.31	2145.9	1.079	154441.0

Table 2 A

Pier	Stress due to Dead load & Live load (N/cm^2)	Earthquake Force in XY - direction		Earthquake Force in YX- direction		Max. Compressive Stress (N/cm^2)	Max. Tensile Stress (N/cm^2)
		Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)	Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)		
P_{1S}	–3.93 –3.93	+3.36 –6.22	+1.430 +1.001	–3.36 +6.22	–1.430 –1.001	9.149	1.289
P_{2S}	–3.93 –3.93	+4.54 –4.54	+0.216 –0.056	–4.54 +4.54	–0.216 +0.056	8.686	0.826
P_{3S}	–3.93 –3.93	+3.50 –1.87	–0.675 –1.350	–3.50 +1.87	+0.675 +1.350	7.150	No tension

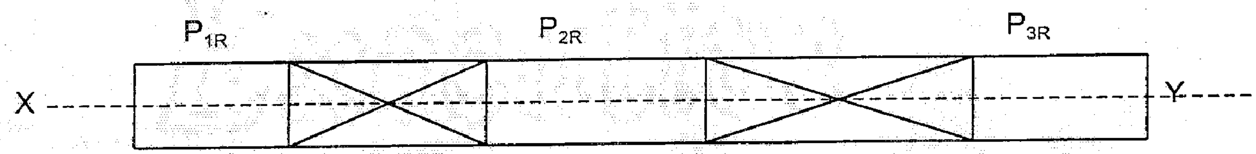
(+) ve = Compressive Stress ; (-) ve = Tensile Stress
For any pier, two values are given - first value is for the left edge and second value is for the right edge of that pier.

Table : 3 Combination of Stresses of Fourth Storey of Four Storey Rat-Trap Bond Construction Building

Pier of fourth storey	Relative Rigidity	Height 'h' (cm.)	Shear force in one wall of fourth storey (N)	Shear Force shared by Pier 'P' (N)	Area of X-section (cm^2)	Area of X-section effective in Shear (cm^2)	Max. Shear Stress 'V' (N/cm^2)	Moment M=Ph/2 (N-cm)
P_{1R}	0.40	120.0	7879.05	3151.620	2167.570	1190.01	3.970	189097.2
P_{2R}	0.31	120.0		2442.50	1265.000	1265.00	2.896	146550.0
P_{3R}	0.29	200.0		2284.93	2807.154	1728.21	1.980	228493.0

Table 3 A

Pier	Stress due to Dead load & Live load (N/cm^2)	Earthquake Force in XY - direction		Earthquake Force in YX- direction		Max. Compressive Stress (N/cm^2)	Max. Tensile Stress (N/cm^2)
		Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)	Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)		
P_{1R}	–4.3 –4.3	+06.37 –11.71	+2.860 +2.002	–06.37 +11.71	–2.860 –2.002	14.008	5.408
P_{2R}	–4.3 –4.3	+07.92 –07.92	+0.450 –0.108	–07.92 +07.92	–0.450 +0.108	12.670	4.070
P_{3R}	–4.3 –4.3	+06.43 –03.43	–1.335 –2.660	–06.43 +03.43	+1.335 +2.660	10.390	1.790



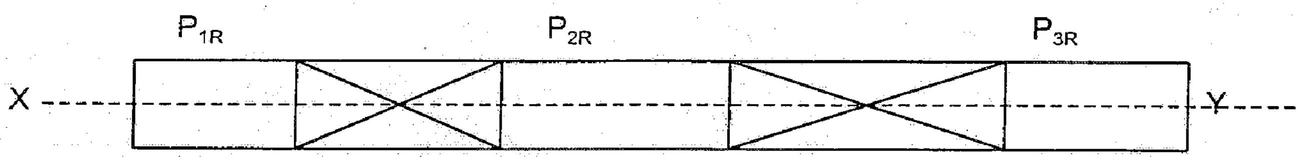
(–) ve = Compressive Stress ; (+) ve = Tensile Stress
For any pier, two values are given - first value is for the left edge and second value is for the right edge of that pier.

Table : 4 Combination of Stresses of First Storey of Four Storey Rat-Trap Bond Construction

Pier of first storey	Relative Rigidity	Height 'h' (cm.)	Shear force in one wall of first storey (N)	Shear Force shared by Pier 'P' (N)	Area of X-section (cm^2)	Area of X-section effective in Shear (cm^2)	Max. Shear Stress 'V' (N/cm^2)	Moment M=Ph/2 (N-cm)
P_{1R}	0.40	120.0	19705.6	7882.24	2167.570	1190.01	9.935	472934.4
P_{2R}	0.31	120.0		6108.74	1265.000	1265.00	7.240	366524.4
P_{3R}	0.29	200.0		5714.62	2807.154	1728.21	4.960	571462.0

Table 4 A

Pier	Stress due to Dead load & Live load (N/cm^2)	Earthquake Force in XY - direction		Earthquake Force in YX- direction		Max. Compressive Stress (N/cm^2)	Max. Tensile Stress (N/cm^2)
		Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)	Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)		
P_{1R}	–27.5 –27.5	+14.93 –29.30	+25.770 +18.040	–14.93 +29.30	–25.770 –18.040	68.20	13.20
P_{2R}	–27.5 –27.5	+19.81 –19.81	+04.100 –00.984	–19.81 +19.81	–04.100 +00.984	51.41	No Tension
P_{3R}	–27.5 –27.5	+16.10 –08.57	–12.100 –24.100	–16.10 +08.57	+12.100 +24.100	60.17	05.17



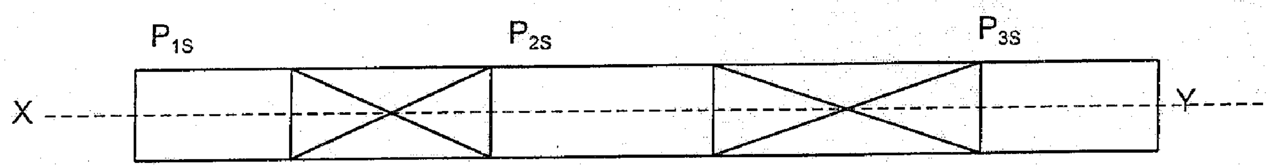
(–) ve = Compressive Stress ; (+) ve = Tensile Stress
For any pier, two values are given - first value is for left edge and second value is for right edge of that pier.

Table: 5 Combination of Stresses of Fourth Storey of Four Storey English Bond Construction

Pier Of Fourth Storey	Relative Rigidity	Height 'h' (cm.)	Shear force in one wall of fourth storey (N)	Shear Force shared by Pier 'P' (N)	Area of X-section (cm^2)	Area of X-section effective in Shear (cm^2)	Max. Shear Stress 'V' (N/cm^2)	Moment M=Ph/2 (N-cm)
P_{1s}	0.40	120.0	9275.33	3710.13	2716.30	1428.3	3.896	222607.8
P_{2s}	0.29	120.0		2690.0	1623.80	1623.8	2.500	161400.0
P_{3s}	0.31	200.0		2875.2	3587.31	2145.9	2.010	287520.0

Table 5 A.

Pier	Stress due to Dead load & Live load (N/cm^2)	Earthquake Force in XY - direction		Earthquake Force in YX- direction		Max. Compressive Stress (N/cm^2)	Max. Tensile Stress (N/cm^2)
		Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)	Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)		
P_{1S}	–3.93 –3.93	+06.26 q11.58	+2.633 +1.843	–06.26 +11.58	–2.633 –1.843	13.667	5.807
P_{2S}	–3.93 –3.93	+08.45 –08.45	+0.397 –0.103	–08.45 +08.45	–0.397 +0.103	12.777	4.917
P_{3S}	–3.93 –3.93	+06.51 –03.50	–1.240 –2.480	–06.51 +03.50	+1.240 +2.480	9.910	2.050



(–) ve = Compressive Stress ; (+) ve = Tensile Stress

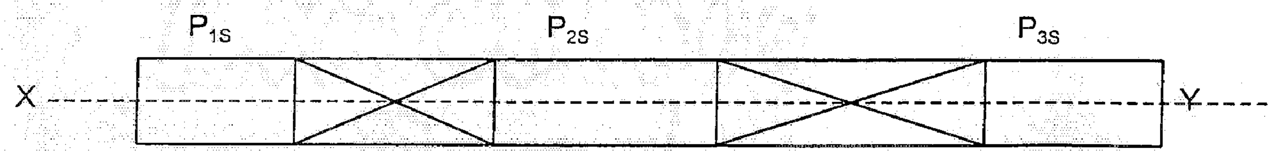
For any pier, two values are given - first value is for the left edge and second value is for the right edge of that pier.

Table: 6 Combination of Stresses of First storey of Four Storey English Bond Construction

Pier Of First storey	Relative Rigidity	Height 'h' (cm.)	Shear force in one wall of first storey (N)	Shear Force shared by Pier 'P' (N)	Area of X-section (cm^2)	Area of X-section effective in Shear (cm^2)	Max. Shear Stress 'V' (N/cm^2)	Moment M=Ph/2 (N-cm)
P_{1s}	0.40	120.0	23508.5	9403.0	2716.30	1428.3	9.870	564180.0
P_{2s}	0.29	120.0		6817.9	1623.80	1623.8	6.300	409074.0
P_{3s}	0.31	200.0		7287.6	3587.31	2145.9	5.094	728760.0

Table 6 A

Pier	Stress due to Dead load & Live load (N/cm^2)	Earthquake Force in XY - direction		Earthquake Force in YX- direction		Max. Compressive Stress (N/cm^2)	Max. Tensile Stress (N/cm^2)
		Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)	Max. Bending Stress (N/cm^2)	Overturning Stress (N/cm^2)		
P_{1S}	–25.7 –25.7	+14.86 –29.36	+24.600 +17.220	–14.86 +29.36	–24.600 –17.220	65.16	13.76
P_{2S}	–25.7 –25.7	+21.41 –21.41	+03.720 –00.970	–21.41 +21.41	–03.720 +00.970	50.83	No Tension
P_{3S}	–25.7 –25.7	+16.50 –08.83	–11.585 –23.170	–16.50 +08.83	+11.585 +23.170	57.7	6.30



(–) ve = Compressive Stress ; (+) ve = Tensile Stress

For any pier, two values are given - first value is for left edge and second value is for right edge of that pier.

Comparison of Results for English & Rat-Trap Bond Construction

On the basis of studies reported on one and four storeyed buildings, the following observations are made :

- For single storey building, all stresses for both the bonds of construction are under permissible limit.
- Shear stress, which is critical for brick masonry, in the pier of Rat-trap bond construction is more than that of the English bond construction but within the permissible limit.
- Compressive stress is also more in Rat-trap bond construction but this is also in the permissible limit.
- Bricks have very little tensile strength. In Rat-trap bond construction tensile stress developed is less as compared to that produced in English bond construction.

Suitability of Pier Method

To check the suitability of Pier method, study has been made of two models of a one brick thick wall (size 3.96m×3m) has been made in finite element based COSMOS/M package. One model is wall of Rat-Trap bond and the other is of English bond construction. Same amount of horizontal force is applied at the top of the walls in its plane. Top end of walls is kept free to move in the direction of applied lateral force. Other movements of both the ends for both walls are kept restrained. Displacements of the two walls are plotted which are shown in Fig. 10 for Rat-Trap bond and in Fig. 11 for English bond.

COSMOS/M Result

$$\frac{\text{Shear stiffness of English bond}}{\text{Shear stiffness of Rat - Trap bond}} = \frac{\text{Max. displacement of Rat - Trap bond}}{\text{Max. displacement of English bond}}$$

(as the lateral force applied is same for both models)

$$= \frac{0.000680}{0.000520} = 1.3077$$

Pier method Results (single storey building)

Shear stiffness of English bond construction

$$= 2 \times (0.0314 + 0.02298 + 0.0241)E = 0.1566E$$

Shear stiffness of Rat-Trap bond construction

$$= 2 \times (0.0258 + 0.019798 + 0.01915)E = 0.122496E$$

where E is the modulus of elasticity of brick masonry.

(see Appendix - D for the calculation of shear stiffness of individual piers)

$$\therefore \frac{\text{Shear stiffness of English bond}}{\text{Shear stiffness of Rat - Trap bond}} = \frac{0.1566E}{0.122496E} = 1.2784$$

Thus, we see that the ratio of shear stiffness obtained by Pier method is close to that obtained by COSMOS/M. This gives strength to use of Pier method of analysis when lateral forces are encountered.

DETAILING OF REINFORCEMENT

In seismic areas, masonry buildings require steel reinforcement at certain locations to take care of tension resulting from seismic loads. IS:4326-1993 gives details of such provisions with regard to conventional brick bonds. Vertical reinforcement, in the form of mild steel bars, is provided in brick columns, brick walls and brick retaining walls. In such a circumstance, special bricks, with one or two holes extending up to the face, are used. Vertical mild steel bars are then placed in the holes. These bars are anchored by steel plates or wire tie at some suitable interval. This requires skilled labour and extra money for providing special bricks.

Vertical reinforcement can also be given by leaving holes at the corners of the walls and these pockets are filled with vertical steel bar with mortar/concrete.

Figure 6 shows the arrangement for vertical steel in one brick thick wall as suggested by IS:4326-1993. This also requires skilled labour and cut bricks (thus wastage of bricks). Also, this hole is not exactly at the centre of the corner.

In Rat-Trap bond construction, some parts of holes are continuous. Using this, a bond similar to Rat-Trap bond, is worked out and suggested for one brick thick wall in which a continuous pocket (of size 7.6cm×7.8cm) is available at the corner which is exactly at the centre of the corner of the wall. It requires neither skilled labour nor extra money for special bricks. There is no wastage of brick also. The plan of this type of bond is shown in Fig. 7 & 8.

Thus, the ease of placing vertical reinforcement is an extra advantage of Rat-Trap bond construction over the conventional English bond.

CONCLUSION

For the construction of low cost houses in seismic zones having better thermal conditions, within the available resources of our country, the 'Rat-trap bond' is a good solution.

Shear is critical in brick masonry buildings and more so in seismic areas due to lateral force of earthquake. Although shear stress produced in Rat-trap bond of construction is more as compared to that in English bond, but remains under the permissible limit. The tensile stresses produced in flexure are less in Rat-trap bond construction. Thus the Rat-trap bond construction system can lead to better, low cost and energy-efficient buildings in India which has more than 50% area in active seismic zones.

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MATERIAL PROPERTIES AND ALLOWABLE STRESSES

Material Properties

- Size of the traditional brick = 23cm × 11.4cm ×7.6cm
- Unit Weight of R.C.C. = 25000 N/m^3
- Unit Weight of brick masonry[5] = 1920kg/m^3 = ~~1883502~~ 18835.2 N/m^3
- Modulus of Elasticity of brick masonry[2] = 5130 MP$_a$
- Poission's ratio of brick masonry[2] = 0.145

Permissible Stresses[5]

- Permissible shear stress in mortar not weaker than 1:6 mix (M_1 type)

$$f_s = 0.1 + \frac{f_d}{6}$$

where f_d is the compressive stress due to dead loads in N/mm^2

In any case, this value should not be greater than 0.5 N/mm^2.

SINGLE STOREY BUILDING

(a) Rat-Trap Bond Construction

$$f_d = 4.3 \text{ N/cm}^2$$

$$= 0.043 \text{ N/mm}^2$$

$$\therefore f_s = 0.1 + \frac{0.043}{6} = 0.1072 \text{ N/mm}^2$$

$$= 10.72 \text{ N/cm}^2$$

Under design seismicity, increase in permissible stress[5] = 33.3%

∴ Allowable shear stress = 10.72×1.333 =14.3 N/cm^2

(b) English Bond Construction

$$f_d = 3.93 \text{ N/cm}^2$$
$$= 0.0393 \text{ N/mm}^2$$
$$\therefore f_s = 0.1 + \frac{0.0393}{6} = 0.10655 \text{ N/mm}^2$$
$$= 10.655 \text{ N/cm}^2$$

Under design seismicity, increase in permissible stress(5) = 33.3%

∴ Allowable shear stress = 10.655×1.333 =14.203 N/cm²

FOUR STOREY BUILDING

FOR FOURTH STOREY

(a) Rat-Trap Bond Construction

$$f_d = 4.3 \text{ N/cm}^2$$
$$= 0.043 \text{ N/mm}^2$$
$$\therefore f_s = 0.1 + \frac{0.043}{6} = 0.1072 \text{ N/mm}^2$$
$$= 10.72 \text{ N/cm}^2$$

Under design seismicity, increase in permissible stress(5) = 33.3%

∴ Allowable shear stress = 10.72×1.333 =14.3 N/cm²

(b) English Bond Construction

$$f_d = 3.93 \text{ N/cm}^2$$
$$= 0.0393 \text{ N/mm}^2$$
$$\therefore f_s = 0.1 + \frac{0.0393}{6} = 0.10655 \text{ N/mm}^2$$
$$= 10.655 \text{ N/cm}^2$$

Under design seismicity, increase in permissible stress(5) = 33.3%

∴ Allowable shear stress = 10.655×1.333 =14.203 N/cm²

FOR FIRST STOREY

(a) Rat-Trap Bond Construction

f_d = 27.5 N/cm^2

= 0.275 N/mm^2

$$\therefore f_s = 0.1 + \frac{0.275}{6} = 0.1458 \text{ N/mm}^2$$

= 14.58 N/cm^2

Under design seismicity, increase in permissible stress[5] = 33.3%

∴ Allowable shear stress = 14.58×1.333 =19.435 N/cm^2

(b) English Bond Construction

f_d = 25.7 N/cm^2

= 0.257 N/mm^2

$$\therefore f_s = 0.1 + \frac{0.257}{6} = 0.1428 \text{ N/mm}^2$$

= 14.28 N/cm^2

Under design seismicity, increase in permissible stress[5] = 33.3%

∴ Allowable shear stress = 14.28×1.333 =19.035 N/cm^2

- Permissible tensile stress in mortar not weaker than 1:6 mix (M_1 type)

  = 0.14 N/mm^2 = 14 N/cm^2

  Under design seismicity, increase in permissible stress[5] = 33.3%

  ∴ Allowable tensile stress = 14×1.333 = 18.662 N/cm^2

- Permissible compressive stress

It is assumed that brick of crushing strength 7.5 N/mm^2 in mortar 1:6 mix (M_1 type) has been used.

∴ Basic stress = 0.74 N/mm^2

Ratio of height to thickness of brick of size 23cm×11.4cm×7.6cm

= 7.6/11.4

= 0.67 < 0.75

∴ Modification factor for shape of masonry unit = 1

Slenderness ratio may be taken as short in view of L section.

Increase in allowable stress due to earthquake consideration = 33.3%

Area of that pier of Rat-Trap construction effective in shear which is critical

$= 2167.57 cm^2 > 3000 cm^2$

∴ Area reduction factor will not be applied.

Area of that pier of English bond construction effective in shear which is critical

$= 2716.3 cm^2 > 3000 cm^2$

∴ Area reduction factor will not be applied.

∴ Allowable compressive stress for Rat-Trap construction

$= 0.74 \times 1 \times 1.333$

$= 0.986\ N/mm^2$

$= 98.6\ N/cm^2$

Allowable compressive stress for English bond construction

$= 0.74 \times 1 \times 1.333$

$= 0.986\ N/mm^2$

$= 98.6\ N/cm^2$

PIER METHOD

In any structure, if openings are there then piers are formed between the openings. All the forces coming on the structure are assumed to be taken by these piers.

Assumption [1]

(i) The rotational deformations of the portions above and below the openings are much smaller than those of the piers between the openings and are neglected.

(ii) Shears are assumed to be shared among the piers such that there tops deflect by the same amount.

(iii) Piers are assumed to be restrained against rotation at the ends but as free to deflect and shear deformations are also considered.

(iv) In calculating overturning stresses, it is assumed that stresses in the piers are proportional to the distance from the neutral axis.

Method

Step 1

First of all, relative rigidities of all the piers are found and the total shear is distributed to them in proportion to their rigidities. If the shear produced in any pier be 'F' then maximum bending moments at their top and bottom sections will be $\frac{Fh}{2}$ where h is the height of the pier.

Step 2

The maximum shear stress in the pier is calculated by $\frac{1.5F}{A_{eff}}$ where A_{eff} is the area of the pier effective in shear. Factor 1.5 is taken to allow for the variation in the shear on a homogeneous section [3]

Step 3

For moment M= $\frac{Fh}{2}$, maximum bending stress f_b is calculated as $\frac{M}{S}$ where S is the sectional modulus.

Step 4

For calculating overturning stress f_0, assumption (iv) is used. If A_1, A_2, A_3...... are the areas of the piers and X_1, X_2, X_3..... are the distances of the points considered from neutral axis then proportionality constant K

$$= \frac{M_0}{A_1X_1^2 + A_2X_2^2 + A_3X_3^2 + ...}$$

where M_0 is the overturning moment about the critical section.

Knowing the proportionality constant, the stresses due to overturning may be found as KX_1, KX_2, KX_3 etc.

Step 5

Then stress due to dead load and live load f_a is calculated.

Step 6

Combining all the stresses, the maximum and minimum stresses on the section of each pier is determined by

$f = f_b + f_0 + f_a$

which may be positive or negative depending upon the relative magnitudes and signs of the component stresses.

CALCULATION OF TOTAL DEAD LOAD & LIVE LOAD

Single Storey Building

Rat-trap Bond Construction

Dead load of roof = $3.96 \times 3.96 \times 0.1 \times 25000$

$= 39204$ N

Volume of Walls = $(3.96^2 - 3.5^2) \times 3 - 0.23 \times 0.8 \times 2 - 2 \times 0.23 \times 0.9 \times 1.2$
$- 32 \times 0.23 \times 0.078 \times 3 - 6 \times 0.23 \times 0.078 \times 1 - 4 \times 0.23 \times$
$0.078 \times 1.8 - 2 \times 0.176 \times 0.078 \times 1.8$

$= 7.206 m^3$

$\therefore$ Total dead load = dead load due to roof + dead load of walls/2

$$=39204 + \frac{7.206 \times 18835.2}{2} = 107067.23 \text{ N}$$

English Bond Construction

Dead load of roof = $3.96 \times 3.96 \times 0.1 \times 25000$N

$= 39204$ N

Volume of walls = $(3.96^2 - 3.5^2) \times 3 - 2 \times 0.23 \times 0.8 \times 2 - 2 \times 0.23 \times 0.9 \times 1.2$

$= 9.062 m^3$

$\therefore$ Total dead load = dead load due to roof+dead load of walls/2

$$= 39204 + \frac{9.062 \times 18835.2}{2} = 124546.3 \text{ N}$$

Four Storey Building

Live load on floors = 2500 N/m^2

For seismic calculation, 25% of live load will be taken(6).

$\therefore$ Live load on 1_{st}, 2_{nd}, and 3_{rd} floor for calculation of seismic force

$$= \frac{2500 \times 3.96 \times 3.96}{4} \text{N} = 9801 \text{N}$$

For seismic force calculation live load on roof should be neglected[6]

As all the storeys are assumed to be of same shape and size, the volume of all the walls will be same for every storey.

Tat-trap Bond Construction

Dead load of first storey + live load

= Dead load of first floor + Dead load of walls of first storey/2+Dead load of walls of second storey/2+Live load on first floor

$=39204+7.206\times18835.2+9801 = 184731.45$ N $=W_1$

Dead load of second storey + live load

= Dead load of second floor + Dead load of walls of second storey/2+Dead load of walls of third storey/2+Live load on second floor

= 184731.45 N $=W_2$

Dead load of third storey + live load

= Dead load of third floor + Dead load of walls of third storey/2+Dead load of walls of fourth storey/2+Live load on third floor

= 184731.45 N $=W_3$

Dead load of fourth storey

= Dead load of roof + Dead load of walls of fourth storey/2

=107067.23 N $=W_4$

$\therefore$ Total load W $= W_1+W_2+W_3+W_4$

=661261.58 N

English Bond Construction

Dead load of first storey + live load

= Dead load of first floor + Dead load of walls of first storey/2+Dead load of walls of second storey/2+Live load on first floor

$=39204+9.062\times1883502+9801 =219689.6$ N $=W_1$

Dead load of second storey + live load

= Dead load of second floor + Dead load of walls of second storey/2+Dead load of walls of third storey/2+Live load on second floor

$=219689.6$ N $\quad =W_2$

Dead load of third storey + live load

= Dead load of third floor + Dead load of walls of third storey/2+Dead load of walls of fourth storey/2+Live load on third floor

$= 219689.6$ N $\quad =W_3$

Dead load of fourth storey

= Dead load of roof + Dead load of walls of fourth storey/2

$= 124546.3$ N $\quad =W_4$

$\therefore$ Total load W $\quad = W_1+W_2+W_3+W_4$

$= 783615.1$ N

SECTIONAL PROPERTIES OF PIERS

Notations used

h = height of the pier

d = length of the pier

A = area of X-section of the pier

A_{eff} = area of X-section of the pier effective in shear

Y_L = distance of left edge from neutral axis

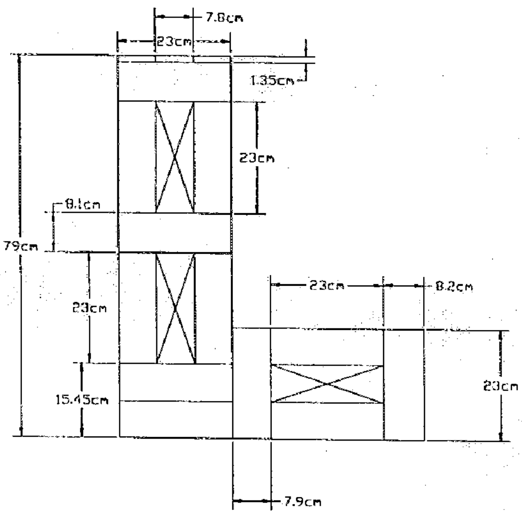
Y_R = distance of right edge from neutral axis

S_1 = section modulus at left edge

S_2 = section modulus at right edge

t = thickness

Pier P_{1R}



h = 120cm = 1.2m

d = 62.1cm = 0.621m

t = 23cm = 0.23m

Max. flange width $= \frac{h}{12} + 3t = \frac{120}{12} + 3 \times 23 = 79\text{cm}$

A $= (79\times23+23\times39.1)-3\times23\times7.8-1.35\times7.8$

$= 2167.57\ \text{cm}^2$

$= 0.216757\text{m}^2$

$A_{eff} = 2167.57-3\times23\times7.8-1.35\times7.8$

$= 1190.01\text{cm}^2$

$= 0.119001\text{m}^2$

Neutral Axis from left edge

$$= \frac{79\times23\times\frac{23}{2}+39.1\times23\times\left(23+\frac{39.1}{2}\right)-2\times23\times7.8\times\frac{23}{2}-23\times7.8\times\left(30.9+\frac{23}{2}\right)}{2167.57}\text{cm}$$

$=21.88\text{cm}$

$=0.2188\text{m}$

Y_L $= 21.88\text{cm} = 0.2188\text{m}$

Y_R $= 40.22\text{cm} = 0.4022$

Moment of Inertia about neutral axis

$$= \frac{79\times23^3}{12} + 23\times79\times\left(21.88-\frac{23}{2}\right)^2 - 2\left[\frac{23\times7.8^3}{12} + 23\times7.8\times\left(21.88-\frac{23}{2}\right)^2\right] -$$

$$\left[\frac{1.35\times7.8^3}{12} + 1.35\times7.8\times\left(21.8-\frac{23}{2}\right)^2\right] + \frac{23\times39.1^3}{12} + 23\times39.1\times\left(62.1-21.88-\frac{39.1}{2}\right)^2$$

$$-\left[\frac{7.8\times23^3}{12} + 7.8\times23\times\left(62.1-21.88-8.2-\frac{23}{2}\right)^2\right]$$

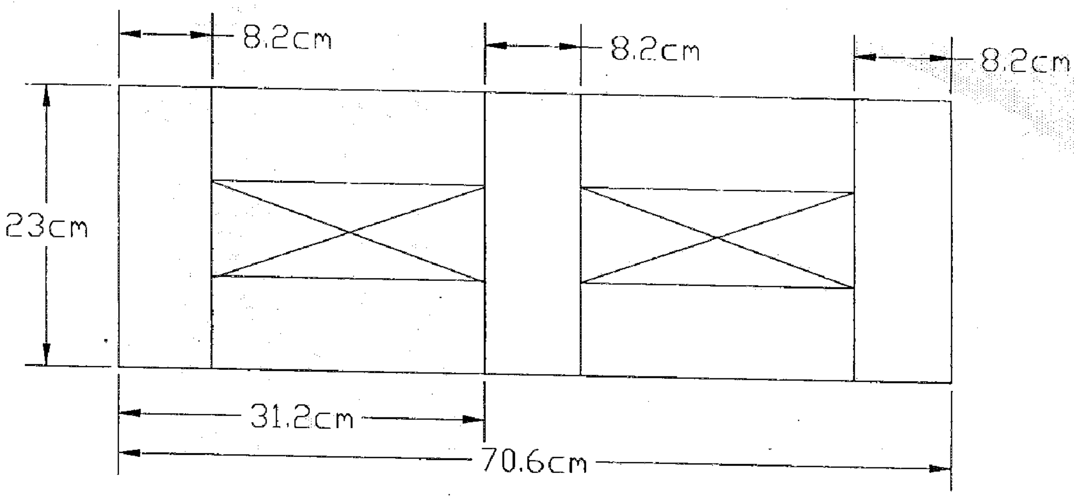
$= 649553.1745\text{cm}^4$

$= 649553.1745\times10^{-8}\,\text{m}^4$

$$S_1 = \frac{649553.1745}{21.88} = 29687.07\text{cm}^3$$

$$S_2 = \frac{649553.1745}{40.22} = 16150.0\text{cm}^3$$

Pier P_{2R}



h = 120cm = 1.2m

d = 70.6cm =0.706m

t = 23cm = 0.23m

$A = A_{eff} = 23 \times 70.6 - 2 \times 23 \times 7.8$

$= 1265 cm^2 = 0.1265 m^2$

$Y_L = Y_R = 35.3cm = 0.353m$

Moment of Inertia about neutral axis

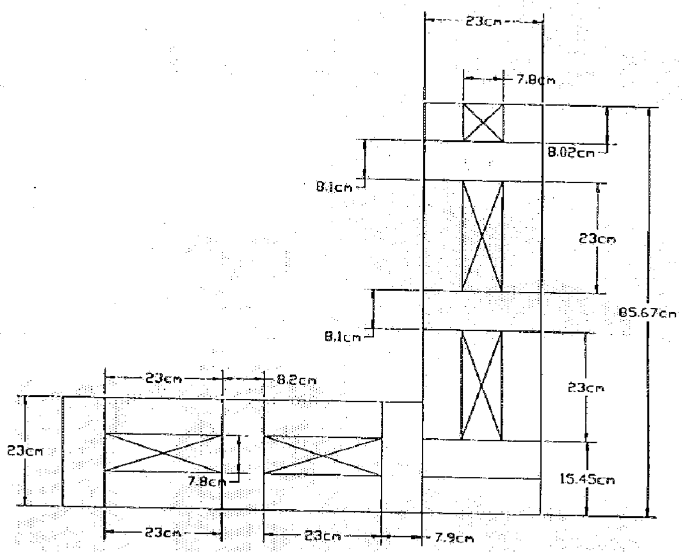
$$= \frac{23 \times 70.6^3}{12} - 2 \times \left[\frac{7.8 \times 23^3}{12} + 7.8 \times 23 \times \left(\frac{70.6}{2} - 8.2 - \frac{23}{2} \right) \right]$$

$$= 653052.6 cm^4$$

$$= 653052.6 \times 10^{-8} m^4$$

$$S_1 = S_2 = \frac{653052.6}{35.3} = 18500.07 cm^3$$

Pier P_{3R}



h = 200cm = 2.0m

d = 93.3cm = 0.933m

t = 23cm = 0.23m

Max. flange width $= \frac{h}{12} + 3t = \frac{200}{12} + 3 \times 23 = 85.67\text{cm}$

A = 23×85.67+70.3×23–4×23×7.8–7.8×8.02

= 2807.154cm² = 0.2807154m²

A_{eff} = 93.3×23–2×23×7.8 = 1728.21cm²

= 0.172821m²

Neutral Axis from left edge

$$= \frac{85.67 \times 23 \times \frac{23}{2} + 70.3 \times 23 \times \left(23 + \frac{70.3}{2}\right) - [2 \times 23 \times 7.8 + 7.8 \times 8.02] \times \frac{23}{2} - 23 \times 7.8 \times \left(30.9 + \frac{23}{2}\right) - 23 \times 7.8 \times \left(93.3 - 8.2 - \frac{23}{2}\right)}{2807.154}$$

= 32.43cm

= 0.3243m

Y_L = 60.87m = 0.6087m

Y_R = 32.43cm =0.3243m

Moment of Inertia about neutral axis

$$= 23 \times \frac{70.3^3}{12} + 23 \times 70.3 \times 25.72^2 - \left[\frac{7.8 \times 23^3}{12} + 7.8 \times 23 \times 41.17^2\right] - \left[\frac{7.8 \times 23^3}{12} + 7.8 \times 23 \times 9.97^2\right]$$

$$+ \frac{85.67 \times 23^3}{12} + 85.67 \times 23 \times 20.93^2 - 2 \times \left[\frac{23 \times 7.8^3}{12} + 23 \times 7.8 \times 20.93^2\right] -$$

$$\left[8.02 \times \frac{7.8^3}{12} + 8.02 \times 7.8 \times 20.93^2\right]$$

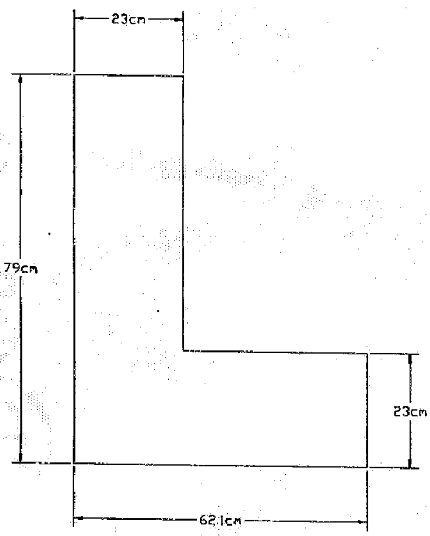
$$= 2161099.654 \text{cm}^4$$

$$= 2161099.654 \times 10^{-8} \text{m}^4$$

$$S_1 = \frac{2161099.654}{60.87} = 35503.53 \text{cm}^3$$

$$S_1 = \frac{2161099.654}{32.43} = 66638.9 \text{cm}^3$$

Pier P_{1S}



h = 120cm = 1.2m

$d = 62.1cm = 0.621m$

$t = 23cm = 0.23m$

Max. flange width $= \frac{h}{12} + 3t = \frac{120}{12} + 3 \times 23 = 79cm$

$A = 23 \times 79 + 23 \times 39.1$

$= 2716.3cm^2 = 0.27163m^2$

$A_{eff} = 23 \times 62.1 = 1428.3cm^2$

$= 0.14283m^2$

Neutral axis from left edge

$$= \frac{23 \times 79 \times \frac{23}{2} + 23 \times 39.1 \times \left(23 + \frac{39.1}{2}\right)}{2716.3}$$

$= 21.78cm$

$Y_L = 21.78cm = 0.2178m$

$Y_R = 40.32cm = 0.4032m$

Moment of Inertia about neutral axis

$$= \frac{79 \times 23^3}{12} + 79 \times 23 \times 10.28^2 + \frac{23 \times 39.1^3}{12} + 23 \times 39.1 \times 20.77^2$$

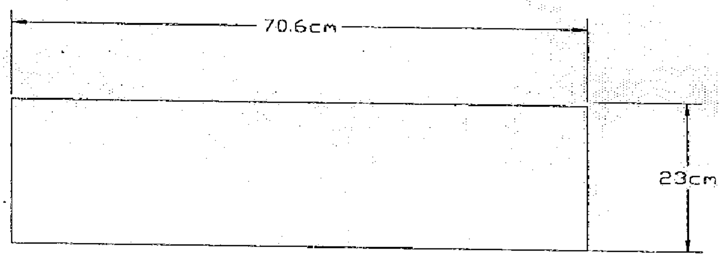
$= 774640.27cm^4$

$= 774640.27 \times 10^{-8} m^4$

$$S_1 = \frac{774640.27}{21.78} = 35566.6cm^3$$

$$S_2 = \frac{774640.27}{40.32} = 19212.31cm^3$$

Pier P_{2S}



$h = 120cm = 1.2m$

$d = 70.6cm = 7.06m$

$t = 23cm = 0.23m$

$A = A_{eff} = 23 \times 70.6 = 1623.8cm^2$

$= 0.16238m^2$

Neutral axis from left edge = 35.3cm = 0.353m

$Y_L = Y_R = 35.3cm$

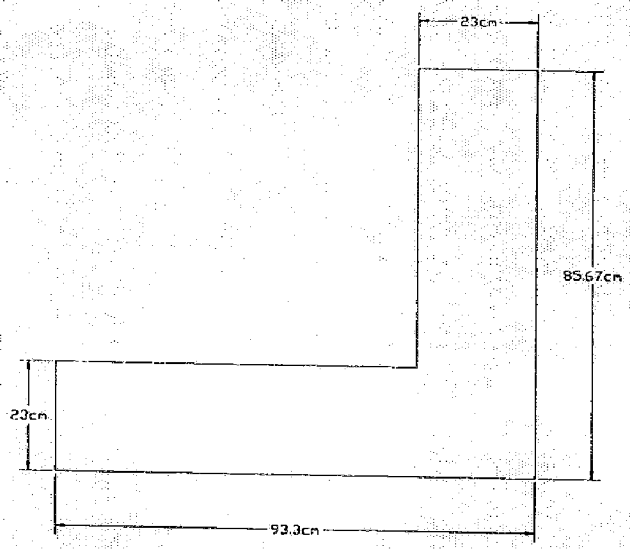
Moment of Inertia about neutral axis

$$= \frac{23 \times 70.6^3}{12} = 674467cm^4$$

$$= 674467 \times 10^{-8} m^4$$

$$S_1 = S_2 = \frac{674467}{35.3} = 19106.7cm^3$$

Pier P_{3S}



h =200cm = 2.0m

d = 93.3cm = 0.933m

t = 23cm = 0.23m

Max. flange width $= \frac{h}{12} + 3t = \frac{200}{12} + 3 \times 23 = 85.67\text{cm}$

A = 23×70.3+23×85.67 = 3587.31cm^2

= 0.358731m^2

A_{eff} = 23×93.3 = 2145.9cm^2

= 0.21459m^2

Neutral axis from left edge

$$= \frac{23 \times 70.3 \times \frac{70.3}{2} + 23 \times 85.67 \times \left(70.3 + \frac{23}{2}\right)}{3587.31}$$

$= 60.77\text{cm}$

y_L = 60.77cm = 0.6077cm

y_R = 32.53cm = 0.3253m

Moment of inertia about neutral axis

$$= \frac{23 \times 70.3^3}{12} + 23 \times 70.3 \times 25.62^2 + \frac{85.67 \times 23^3}{12} + 23 \times 85.67 \times 21.03^2$$

$$= 2685510.9 \text{cm}^4$$

$$= 2685510.9 \times 10^{-8} \text{m}^4$$

$$S_1 = \frac{2685510.9}{60.77} = 44191 \text{cm}^3$$

$$S_2 = \frac{2685510.9}{32.53} = 82555 \text{cm}^3$$

Calculation of Relative Rigidities of Piers

(a) Rat-Trap bond construction

Shear Rigidity of Pier P_{1R}

$$= \frac{E}{1.2\left[\dfrac{1.2^2}{12 \times 649553.1745 \times 10^{-8}} + \dfrac{3}{0.119001}\right]} = 0.0258E$$

Shear Rigidity of Pier P_{2R}

$$= \frac{E}{1.2\left[\dfrac{1.2^2}{12 \times 653052.6 \times 10^{-8}} + \dfrac{3}{0.1265}\right]} = 0.019798E$$

Shear Rigidity of Pier P_{3R}

$$= \frac{E}{2.0\left(\dfrac{2.0^2}{12 \times 2161099.654 \times 10^{-8}} + \dfrac{3}{0.172821}\right)} = 0.01915E$$

∴ Relative rigidity of Pier P_{1R}

$$= \frac{0.0258E}{0.0258E + 0.019798E + 0.01915E} = 0.4$$

Relative rigidity of Pier P_{2R}

$$= \frac{0.019798E}{0.0258E + 0.019798E + 0.01915E} = 0.31$$

Relative rigidity of Pier P_{3R}

$$= \frac{0.01915E}{0.0258E + 0.019798E + 0.01915E} = 0.29$$

(b) English bond Construction

Shear Rigidity of Pier P_{1S}

$$= \frac{E}{1.2\left[\frac{1.2^2}{12 \times 774640.27 \times 10^{-8}} + \frac{3}{0.14283}\right]} = 0.0314E$$

Shear Rigidity of Pier P_{2S}

$$= \frac{E}{1.2\left[\frac{1.2^2}{12 \times 674467 \times 10^{-8}} + \frac{3}{0.16238}\right]} = 0.02298E$$

Shear Rigidity of Pier P_{3S}

$$= \frac{E}{2.0\left[\frac{2.0^2}{12 \times 2685510.9 \times 10^{-8}} + \frac{3}{0.21459}\right]} = 0.0241E$$

$\therefore$ Relative rigidity of Pier P_{1S}

$$= \frac{0.0314E}{0.0314E + 0.02298E + 0.0241E} = 0.4$$

Relative rigidity of Pier P_{2S}

$$= \frac{0.02298E}{0.0314E + 0.02298E + 0.0241E} = 0.29$$

Relative rigidity of Pier P_{3S}

$$= \frac{0.0241E}{0.0314E + 0.02298E + 0.0241E} = 0.31$$

DISTRIBUTION OF BASE SHEAR

Rat-trap construction

Total load W = 661261.58 N

Base shear V_B = 39411.2 N

Calculation of storey shears

	W_i	h_i	$W_i h_i^2$	Lateral force $= V_B \frac{W_i h_i^2}{\sum W_i h_i^2}$	Lateral force taken by one wall	Storey Shear
Fourth storey	107067.23	12.35	16330161.6	15758.1	7879.05	15758.1
Third storey	184731.45	9.25	15806084.7	15252.5	7626.25	31010.6
Second storey	184731.45	6.15	6987005.27	6743.3	3371.15	37753.9
First storey	184731.45	3.05	1718464.32	1656.3	828.15	39411.2
			$\sum W_i h_i^2 = 40841715.89$			

English Bond Construction

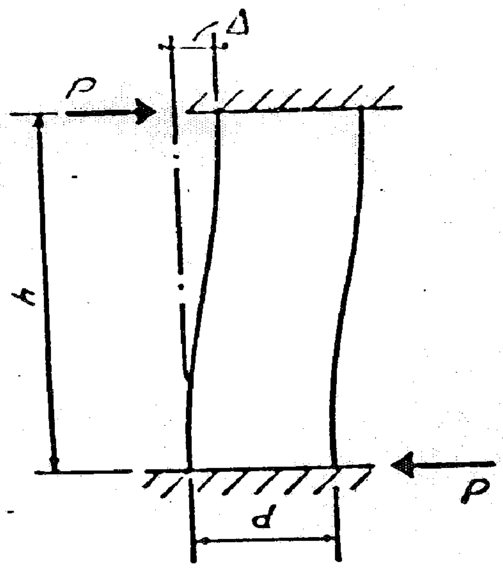
Total load W = 783615.1 N

Base shear V_B = 47017 N

Calculation of storey shears

	W_i	h_i	$W_i h_i^2$	Lateral force $= V_B \frac{W_i h_i^2}{\sum W_i h_i^2}$	Lateral force taken by one wall	Storey Shear
Fourth storey	124546.3	12.35	18996113.04	18550.66	9275.33	18550.66
Third storey	219689.6	9.25	18797191.4	18356.34	9178.17	36907
Second storey	219689.6	6.15	8309209.9	8114.30	4057.15	45021.3
First storey	219689.6	3.05	2043662.5	1995.70	997.85	47017
			$\sum W_i h_i^2$ = 48146176.84			

EXPRESSION FOR SHEAR STIFFNESS (RIGIDITY) OF PIER



Consider a pier of height h and width d fixed at both ends. Let I be the moment of inertia of the pier about the neutral axis of the pier, E be the modulus of elasticity of the material of the pier and G be the modulus of rigidity of the pier.

Let, due to a horizontal force P, total deflection Δ occurs. All piers in any one wall having a top connecting element must deflect an equal amount; therefore, the piers will each tend to resist the total applied force in proportion to their rigidities.

Now $\Delta = \Delta_m + \Delta_s$ where

$$\Delta_m = \frac{Ph^3}{12EI} = \text{deflection due to moment}$$

$$\Delta_s = \frac{1.2Ph}{GA_{eff}} = \frac{1.2Ph}{0.4EA_{eff}} = \text{deflection due to shear}$$

(For brick masonry G=0.4E is assumed[3])

A_{eff} is the area of X-section of the pier effective in shear.

$$\therefore \Delta = \Delta_m + \Delta_s$$

$$= \frac{Ph^3}{12EI} + \frac{3Ph}{EA_{eff}}$$

$$= \frac{Ph}{E}\left(\frac{h^2}{12I} + \frac{3}{A_{eff}}\right)$$

$$\therefore \text{Shear rigidity} = \frac{P}{\Delta} = \frac{E}{h\left(\frac{h^2}{12I} + \frac{3}{A_{eff}}\right)}$$

CALCULATION OF STRESSES

Calculation of Stresses due to Dead load & Live load

SINGLE STOREY BUILDING

Rat-Trap bond construction

Total W = 107067.23 N

Total area of piers in one wall = 2167.57+1265+2807.154

= 6239.724 cm^2

$$\therefore \text{Stress } f_{aR} = \frac{107067.23}{4 \times 6239.724} = 4.3 \text{ N/cm}^2$$

English bond construction

Total W = 124546.3 N

Total area of piers in one wall = 2716.3+1623.8+3587.31

= 7927.41 cm^2

$$\therefore \text{Stress } f_{as} = \frac{124546.3}{4 \times 7927.41} = 3.93 \text{ N/cm}^2$$

FOUR STOREY BUILDING

FOURTH STOREY

(i) Rat-trap Bond Construction

Same as calculated in single storey case

$$f_{aR} = \frac{107067.23}{4 \times 6239.724} = 4.3\text{N / cm}^2$$

(ii) English Bond construction

$$f_{aS} = \frac{124546.3}{4 \times 7927.41} = 3.93\text{N / cm}^2$$

FIRST STOREY

(i) Rat-trap Bond construction

Total W = 661261.58 N

$$\therefore f_{aR} = \frac{661261.58}{4 \times 6239.724} = 27.5 N/cm^2$$

(ii) English Bond construction

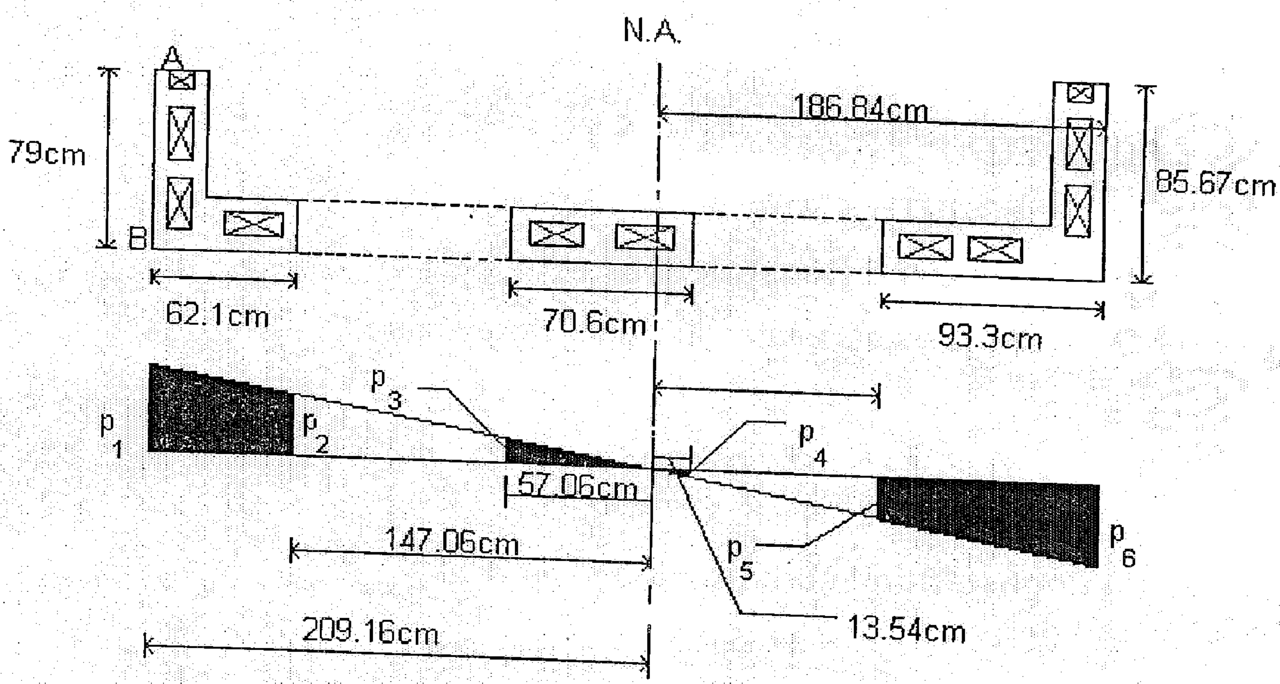
Total W = 783615.1 N

$$\therefore f_{as} = \frac{783615.1}{4 \times 7927.41} = 25.7 N/cm^2$$

Calculation of stress due to overturning

Rat-Trap bond construction

X-section of the wall being considered and distribution of overturning stress is



Neutral axis from AB

$$=\frac{2807.154\times 32.43+1265\times 208.6+2167.57\times 374.12}{2807.154+1265+2167.57}=186.84\text{cm}$$

$$p_2=\frac{147.06}{209.16}p_1=0.7p_1; \qquad p_3=\frac{57.06}{209.16}p_1=0.273p_1;$$

$$p_4=\frac{13.54}{209.16}p_1=0.065p_1; \qquad p_5=\frac{93.54}{209.16}p_1=0.447p_1;$$

$$p_6=\frac{186.84}{209.16}p_1=0.89p_1$$

$$\therefore p_2=0.7p_1; p_4=0.24p_3; p_5=0.502p_6$$

If F_1, F_2 and F_3 are the forces produced in piers P_{1R}, P_{2R} and P_{3R} respectively due to the overturning moment then,

Point of application of F_1 from AB

$$=\frac{62.1}{3}\left[\frac{2\times 0.7p_1+p_1}{0.7p_1+p_1}\right]=29.22\text{cm}$$

Point of application of F_2 from AB

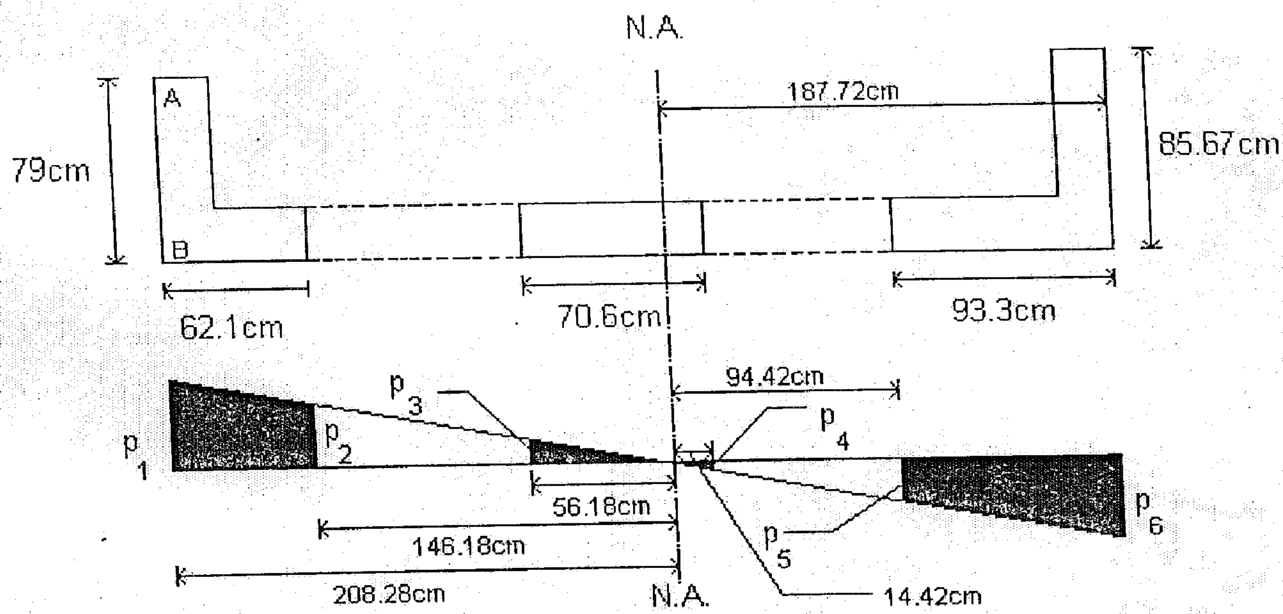
$$=62.1+90+\frac{57.06-13.54}{3}\left[\frac{2\times 0.065p_1+0.273p_1}{0.065p_1+0.273p_1}\right]=169.4\text{cm}$$

Point of application of F_3 from AB

$$=302.7+\frac{93.3}{3}\left[\frac{2\times 0.89p_1+0.447p_1}{0.89p_1+0.447p_1}\right]=354.5\text{cm}$$

English Bond Construction

X-section of the wall being considered and distribution of overturning stress is



Neutral axis from AB

$$= \frac{2716.3 \times 21.78 + 1623.8 \times 187.4 + 3587.31 \times 363.47}{2716.3 + 1623.8 + 3587.31} = 208.28\text{cm}$$

$$p_2 = \frac{146.18}{208.28} p_1 = 0.7 p_1; \qquad p_3 = \frac{56.16}{208.28} p_1 = 0.27 p_1;$$

$$p_4 = \frac{14.42}{208.28} p_1 = 0.07 p_1; \qquad p_5 = \frac{94.42}{208.28} p_1 = 0.45 p_1;$$

$$p_6 = \frac{187.72}{208.28} p_1 = 0.9 p_1$$

$$\therefore p_2 = 0.7 p_1; p_4 = 0.26 p_3; p_5 = 0.5 p_6$$

If F_1, F_2 and F_3 are the forces produced in piers P_{1S}, P_{2S} and P_{3S} respectively due to the overturning moment then,

Point of application of F_1 from AB

$$= \frac{62.1}{3}\left[\frac{2 \times 0.7 p_1 + p_1}{0.7 p_1 + p_1}\right] = 29.22\text{cm}$$

Point of application of F_2 from AB

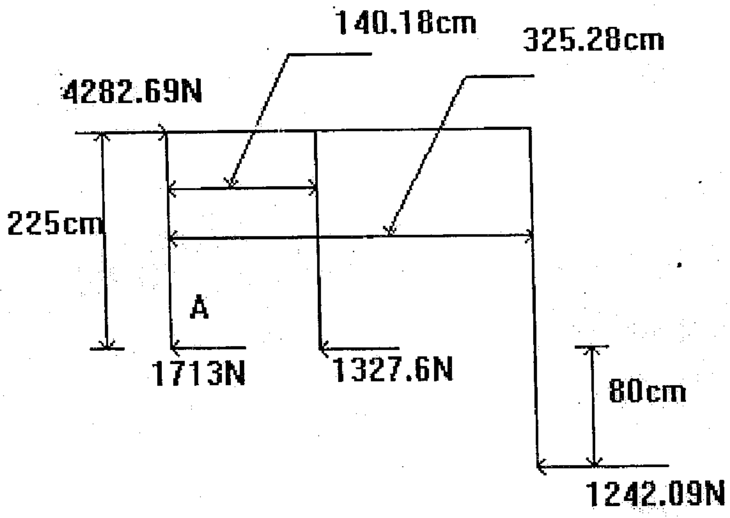
$$= 62.1 + 90 + \frac{56.18 - 14.42}{3}\left[\frac{2 \times 0.07 p_1 + 0.27 p_1}{0.07 p_1 + 0.27 p_1}\right] = 168.88\text{cm}$$

Point of application of F_3 from AB

$$= 302.7 + \frac{93.3}{3}\left[\frac{2 \times 0.9 p_1 + 0.45 p_1}{0.9 p_1 + 0.45 p_1}\right] = 354.5\text{cm}$$

SINGLE STOREY BUILDING

(i) Rat-trap Bond construction



Overturning moment M_0 about A

$$=4282.69\times225+1242.09\times80 = 1062972045 \text{ N-cm}$$

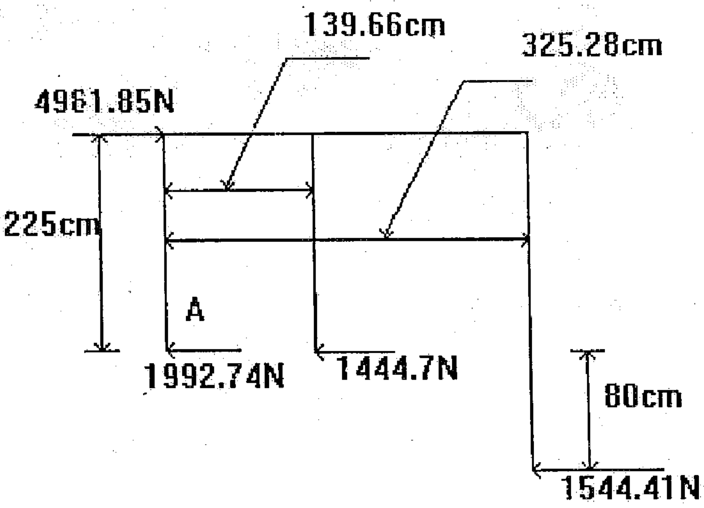
$$\therefore \text{Proportionality constant} = \frac{M_0}{\sum A_i X_i^2} = \frac{1062972.45}{1535533112} = 0.007$$

∴ Average overturning stress in pier P_{1R} = 0.007×187.28 = 1.3 N/cm^2

Average overturning stress in pier P_{2R} = 0.007×21.76 = 0.152 N/cm^2

Average overturning stress in pier P_{3R} = 0.007×154.41 = 1.081 N/cm^2

(ii) English Bond construction



Overturning moment M_0 about A

$$= 4981.85 \times 225 + 1544.41 \times 80 = 1244334.05 \text{ N-cm}$$

$$\therefore \text{Proportionality constant} = \frac{M_0}{\sum A_i X_i^2} = \frac{1244334.05}{191583505.7} = 0.0065$$

∴ Average overturning stress in pier P_{1S} = 0.0065×186.28 = 1.212 N/cm²

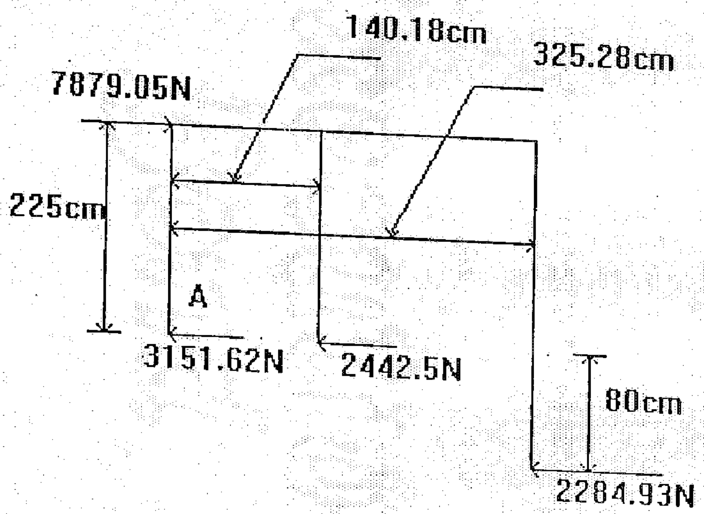
Average overturning stress in pier P_{2S} = 0.0065×20.88 = 0.136 N/cm²

Average overturning stress in pier P_{3S} = 0.0065×155.19 = 1.01 N/cm²

FOUR STOREY BUILDING

FOR FOURTH STOREY

(i) Rat-trap Bond construction



Overturning moment M_0 about A

$$= 7879.05 \times 225 + 2284.93 \times 80 = 1955580.65 \text{ N-cm}$$

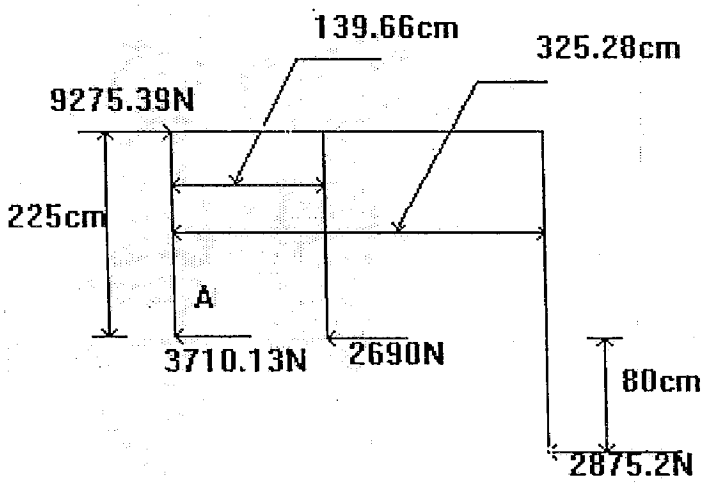
$$\therefore \text{Proportionality constant} = \frac{M_0}{\sum A_i X_i^2} = \frac{1955580.65}{153553311.2} = 0.013$$

∴ Average overturning stress in pier P_{1R} = 0.013×187.28 = 2.43 N/cm²

Average overturning stress in pier P_{2R} = 0.013×21.76 = 0.28 N/cm²

Average overturning stress in pier P_{3R} = 0.013×154.41 = 2.0 N/cm²

(ii) English Bond construction



Overturning moment M_0 about A

$$= 9275.33 \times 225 + 2875.2 \times 80 = 231696.25 \text{ N-cm}$$

$$\therefore \text{Proportionality constant} = \frac{M_0}{\sum A_i X_i^2} = \frac{2316965.25}{191583505.7} = 0.012$$

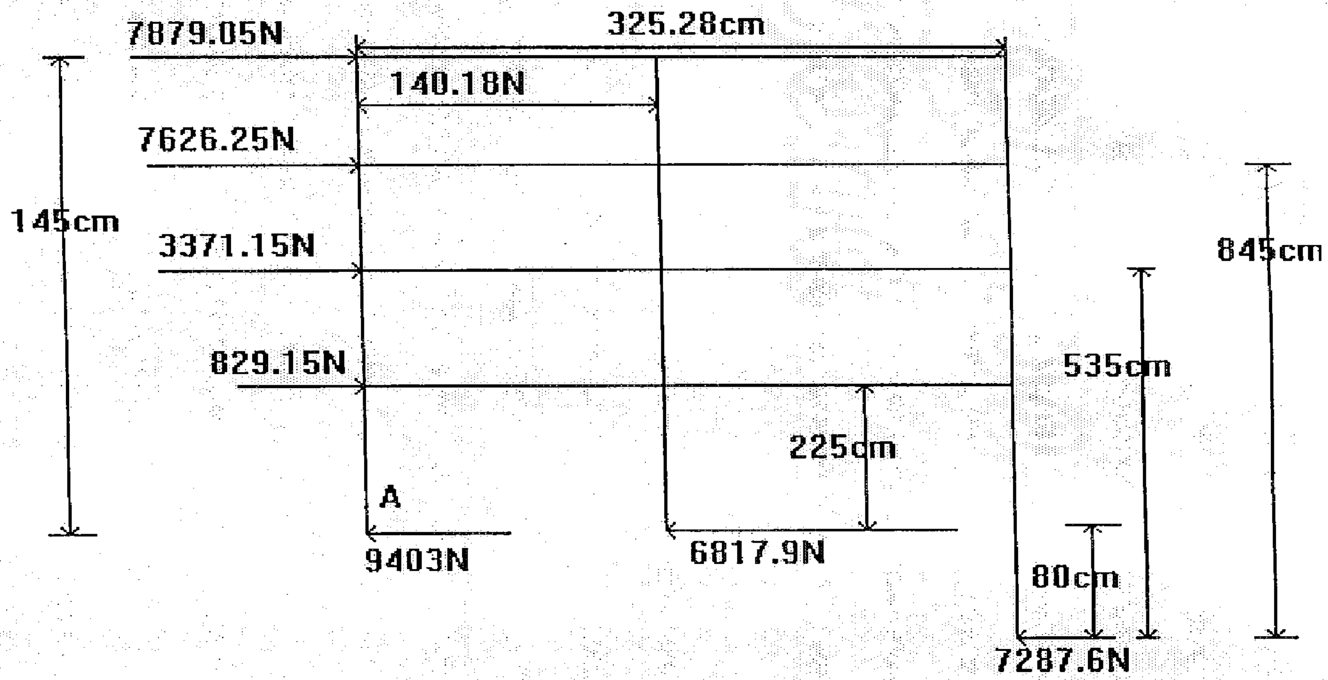
$\therefore$ Average overturning stress in pier P_{1S} = 0.012×186.28 = 2.238 N/cm^2

Average overturning stress in pier P_{2S} = 0.012×20.88 = 0.25 N/cm^2

Average overturning stress in pier P_{3S} = 0.012×155.19 = 1.86 N/cm^2

FOR FIRST STOREY

(i) Rat-trap Bond construction



Overturning moment M_0 about A

$=829.15\times225+3371.15\times535+7626.25\times845+7879.05\times1155+5714.62\times80$

$= 17991777.6$ N-cm

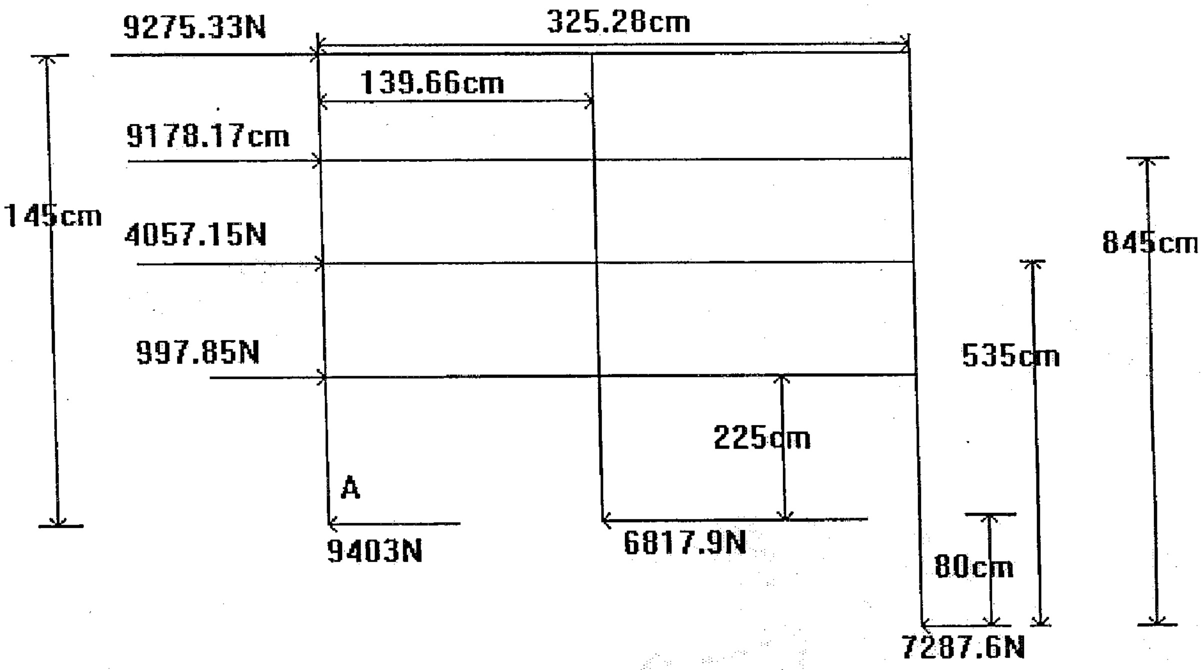
$$\therefore \text{Proportionality constant} = \frac{M_0}{\sum A_i X_i^2} = \frac{17991777.6}{153553311.2} = 0.117$$

$\therefore$ Average overturning stress in pier P_{1R} $= 0.117\times187.28$ $= 21.91$ N/cm^2

Average overturning stress in pier P_{2R} $= 0.117\times21.76$ $= 2.55$ N/cm^2

Average overturning stress in pier P_{3R} $= 0.117\times154.41$ $= 18.1$ N/cm^2

(ii) English Bond construction



Overturning moment M_0 about A

$= 997.85 \times 225 + 4057.15 \times 535 + 9178.17 \times 845 + 9275.33 \times 1155 + 7287.6 \times 80$

$= 21446659.3$ N-cm

$\therefore$ Proportionality constant $= \dfrac{M_0}{\sum A_i X_i^2} = \dfrac{21446659.3}{191583505.7} = 0.112$

$\therefore$ Average overturning stress in pier P_{1S} $= 0.112 \times 186.28$ $= 20.9$ N/cm^2

Average overturning stress in pier P_{2S} $= 0.112 \times 20.88$ $= 17.38$ N/cm^2

Average overturning stress in pier P_{3S} $= 0.112 \times 155.19$ $= 23.17$ N/cm^2

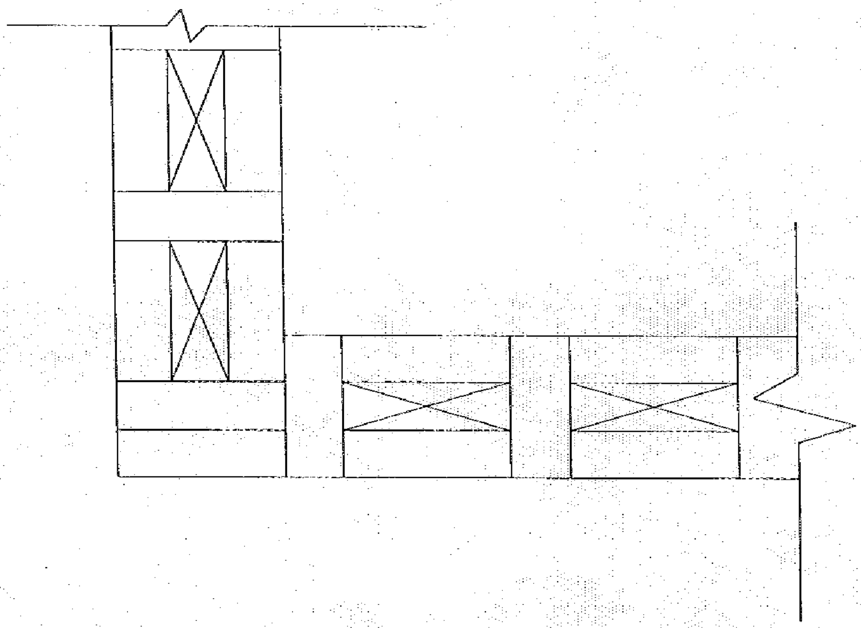


Fig. 1 - Plan of Courses 1,3,5,.... in Rat-Trap Bond

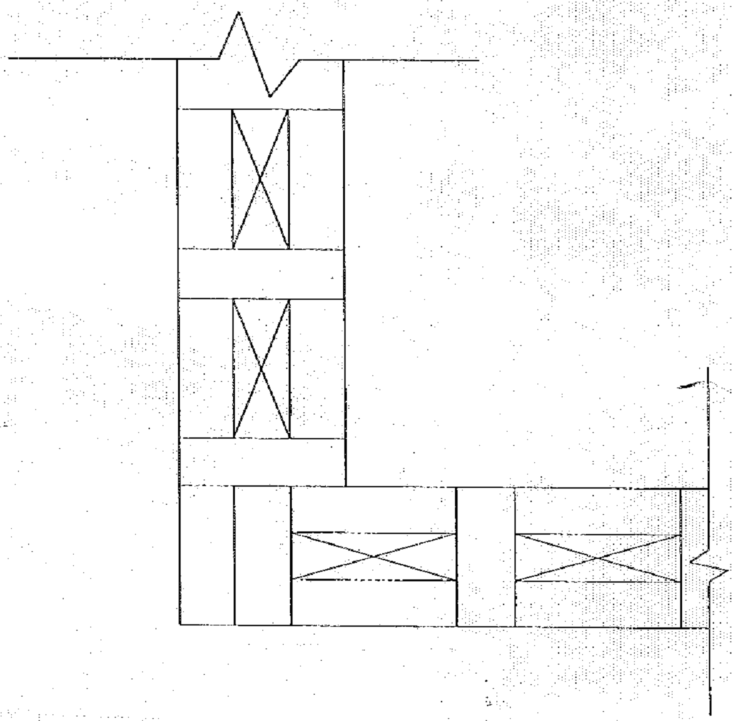


Fig. 2 - Plan of Courses 2,4,6,.... in ~~English~~ Rat-trap Bond

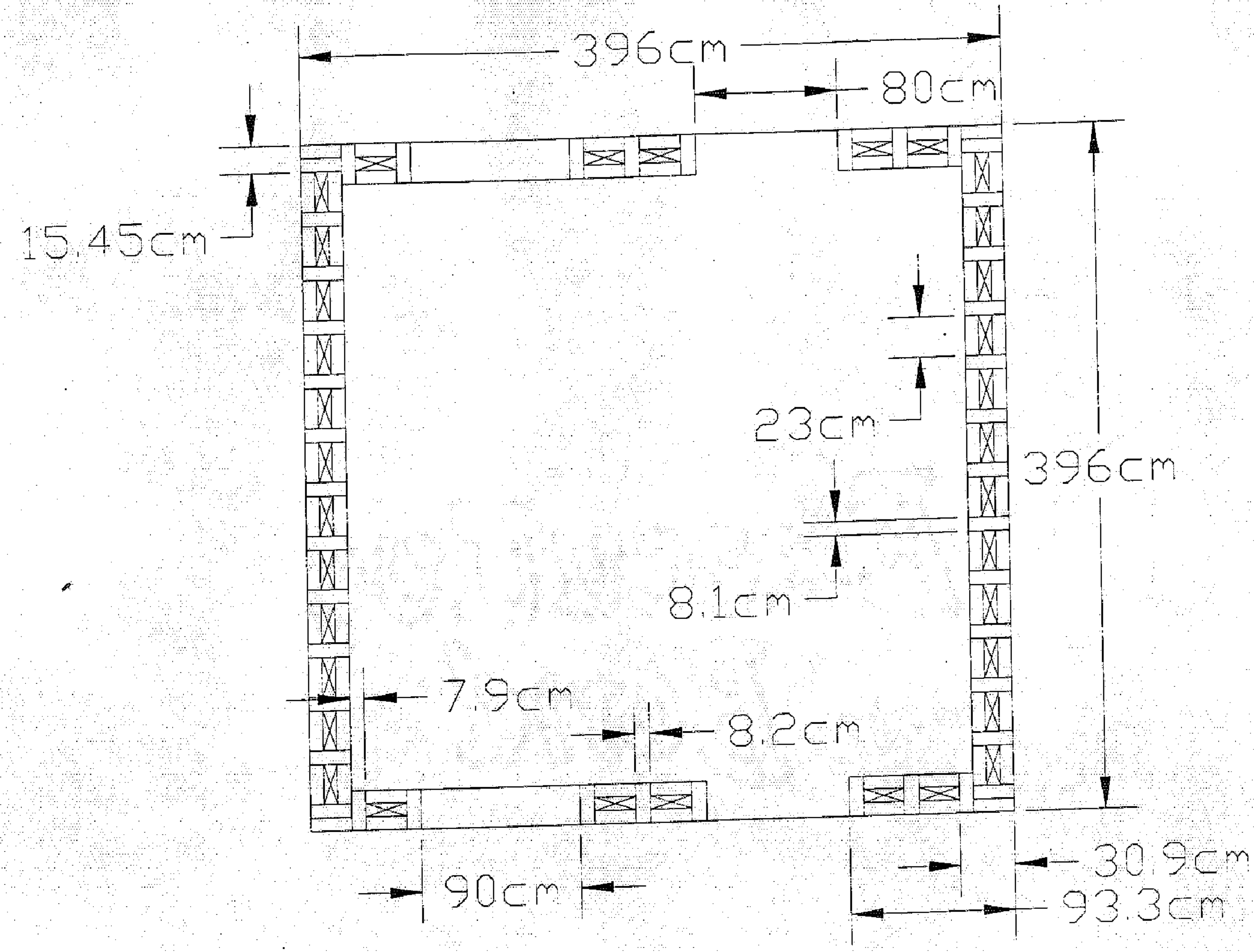


Fig. 3 - Plan of Rat-Trap Bond Construction

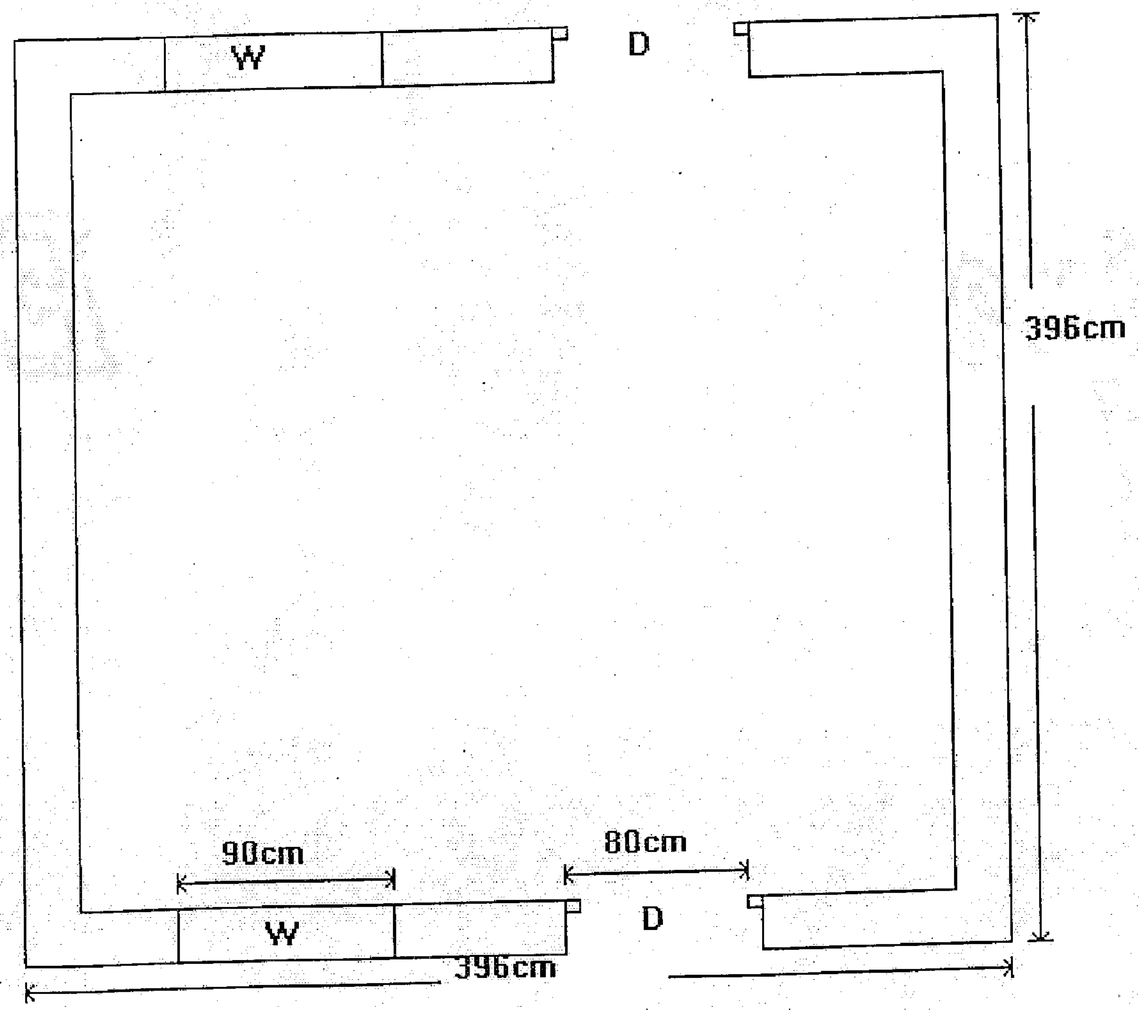


Fig. 4 - Plan of "English" Bond Construction

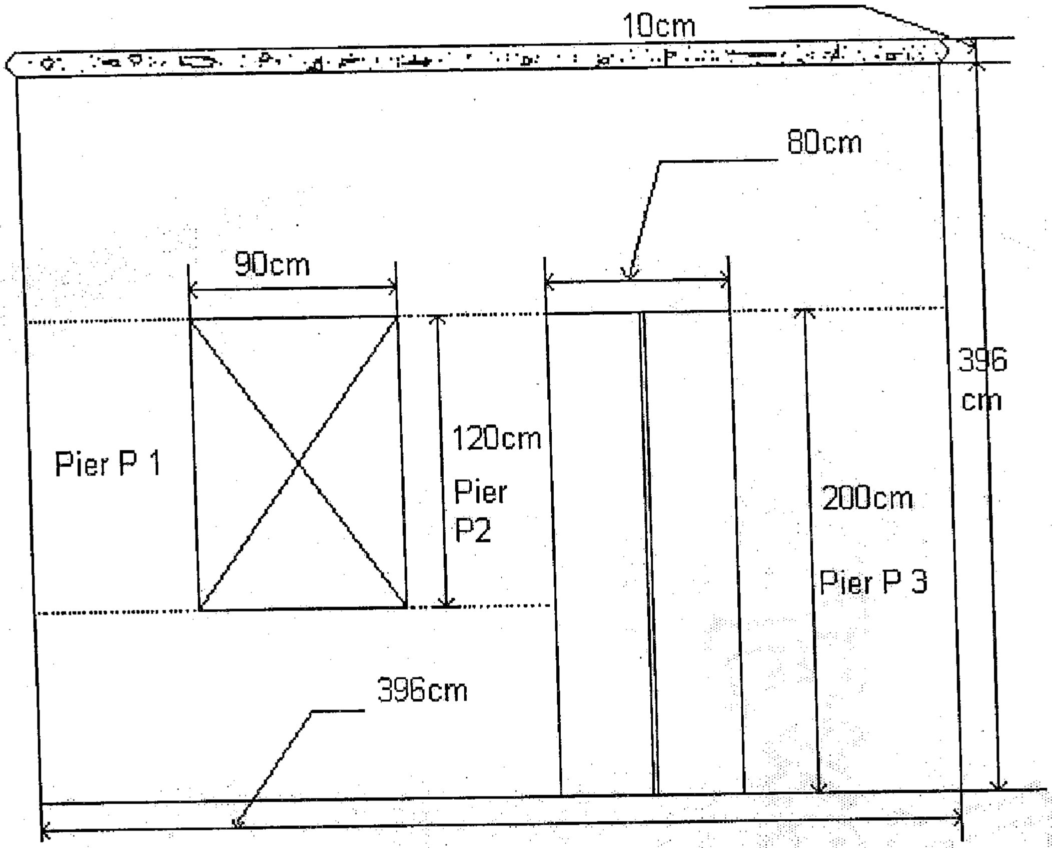


Fig. 5 - Elevation of Single Storey Building for Both Rat-Trap & English Bond

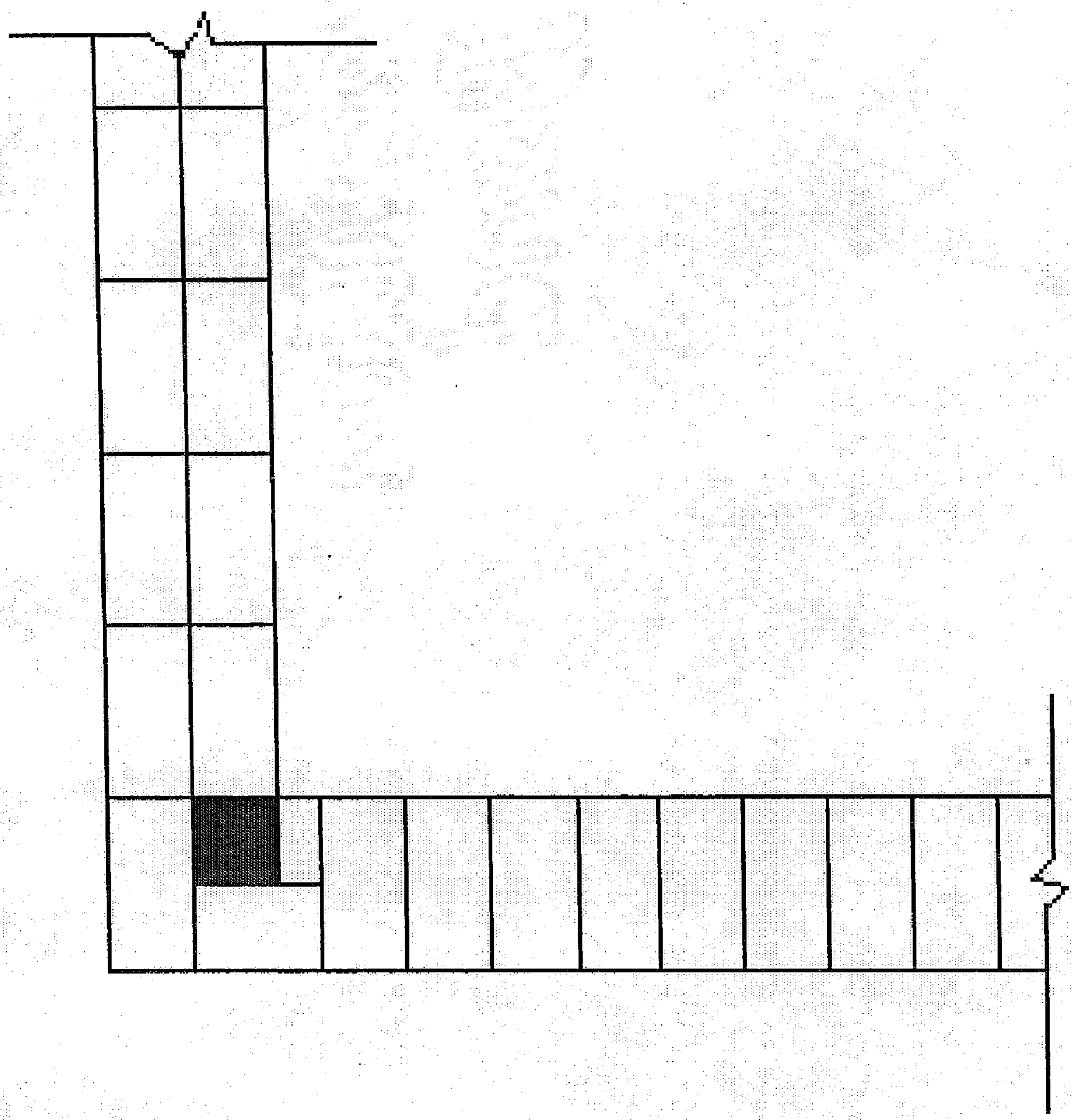


Fig. 6 - Arrangement for Vertical Steel in English Bond as in IS:4326-1993

(Black Space is the Pocket available for Vertical Reinforcement)

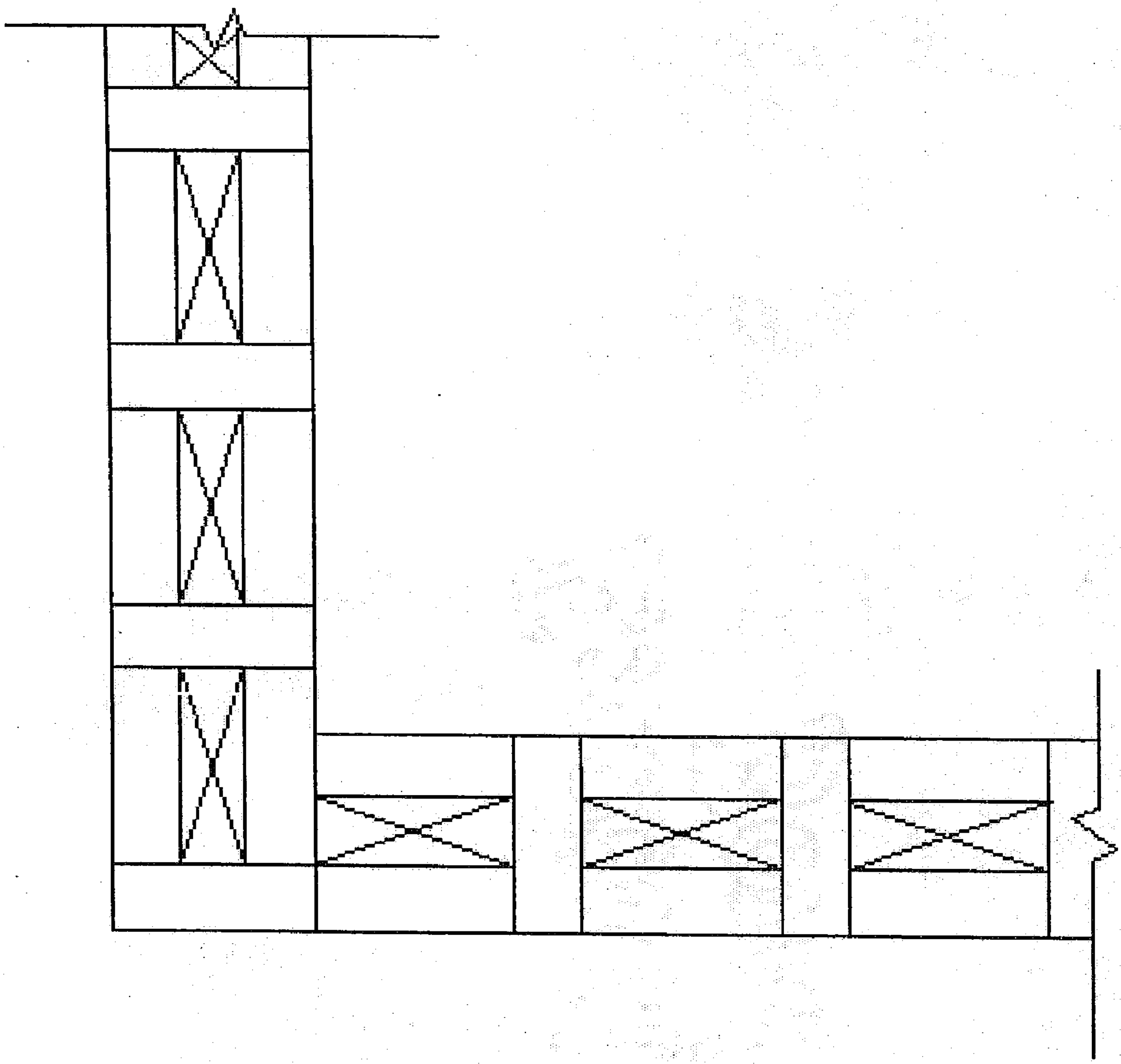


Fig. 7 - Plan of Courses 1,3,5,.... of Proposed Bond

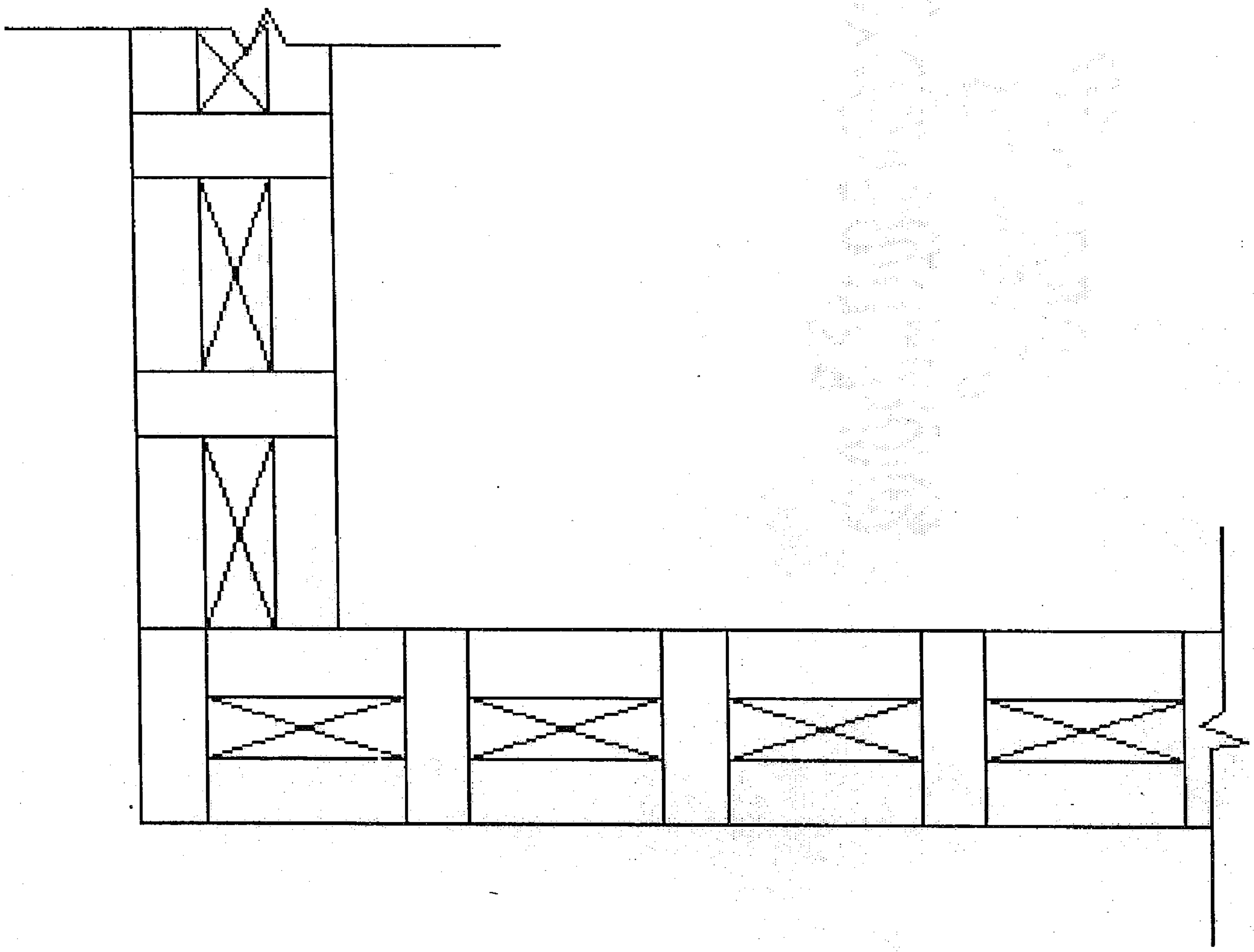


Fig. 8 - Plan of Courses 2,4,6,.... of Proposed Bond

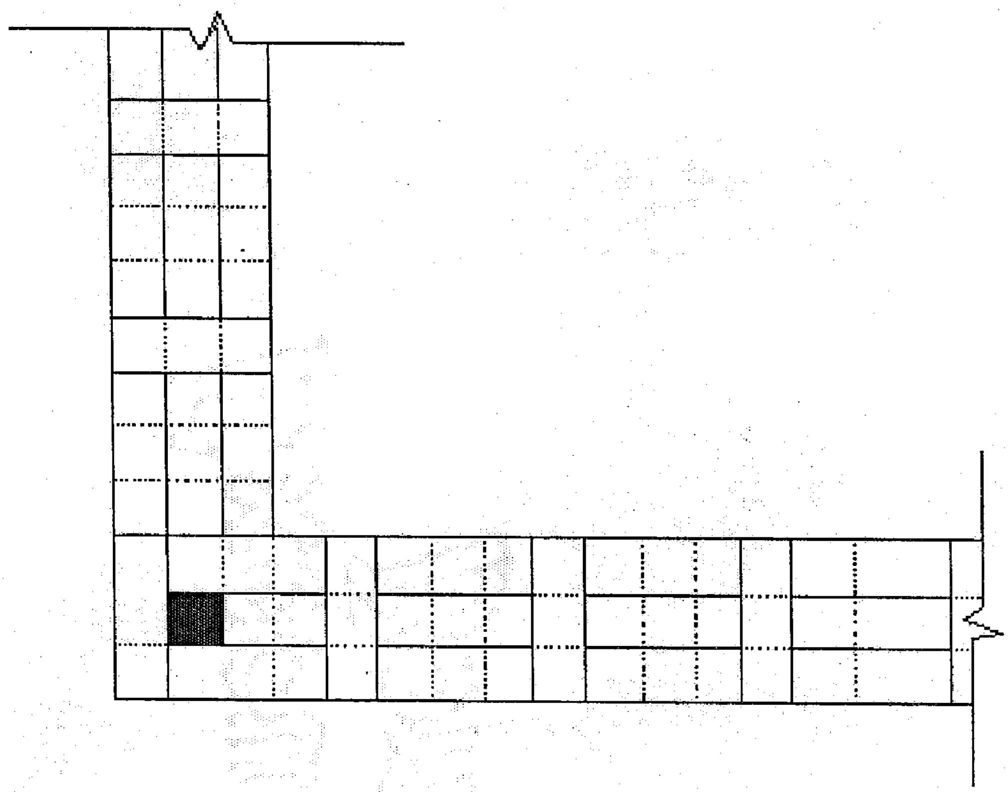


Fig. 9 - Plan of Superposition of Even Course Over Odd Course of Proposed Bond (Black space is the pocket available for vertical reinforcement)

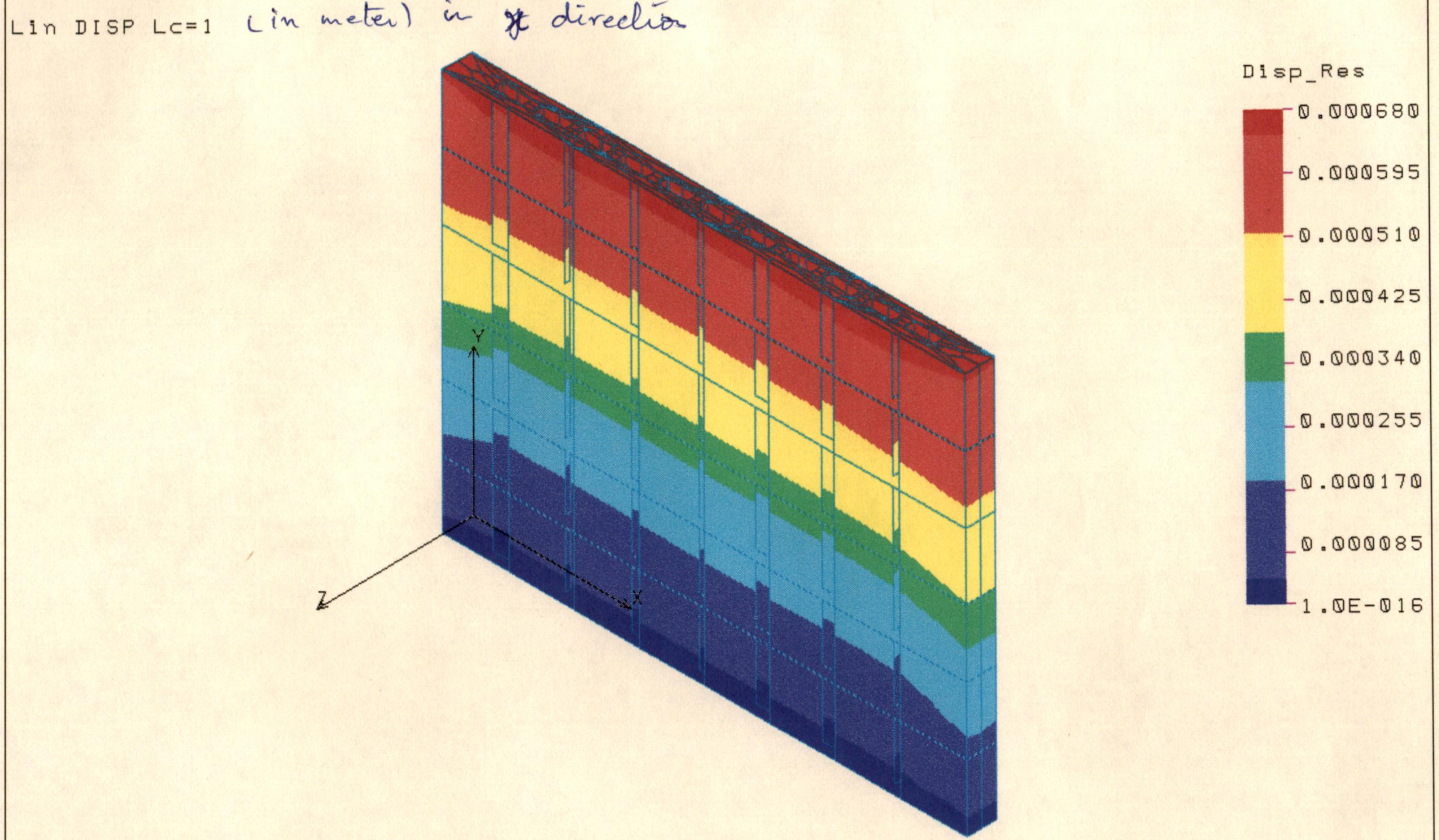


FIG. 10 DISPLACEMENT CONTOUR OF ONE WALL OF RAT-TRAP BOND BY COSMOS/M

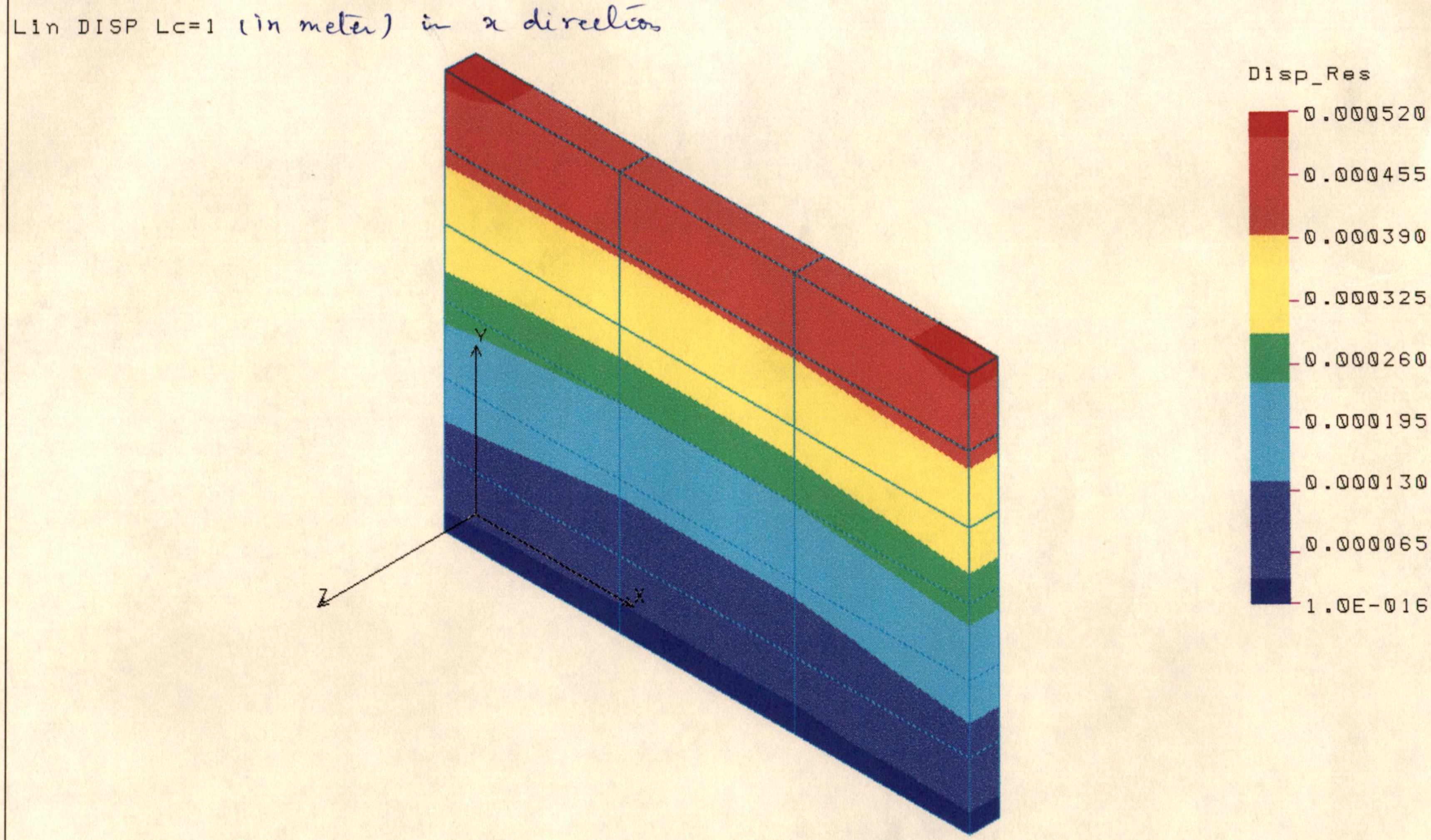


FIG. 11 DISPLACEMENT CONTOUR OF ONE WALL OF ENGLISH BOND BY COSMOS/M