ANALYSIS OF SHEAR WALLS IN TALL BUILDINGS

By

RAMESH K. AILAWADHI

Bachelor of Civil Engineering

Panjab University

Chandigarh

INDIA

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Report Adviser

Dean of the Graduate College

PREFACE

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NOMENCLATURE

P	Concentrated lateral load
W	Uniformly distributed lateral load
M_o	Moment of one shear wall
I	Moment of inertia of the wall
A	Area of the wall
T	Integral shear force
q	Shear force in laminas
l_1, H	Total height of the wall
b	Width of the lintel
h	Story height
δr, Δr	Relative displacement

CHAPTER I

INTRODUCTION

1.1 General:

In the early post-war period the lateral stability to buildings was provided essentially by an extension of rigid structural frames. The stability of such frames depended largely on the monolithic connection between columns and beams. Since these connections were to be fully rigid, they resulted in a complicated arrangement of reinforcement in the case of reinforced concrete frames and involved friction grip bolted or welded connections in the case of steel frames.

During the past few years, the increasing cost of land has changed the architectural trend towards taller buildings with more open spaces and gardens at the ground level. This trend has also been caused by the increase in population and propserity on the one hand, and limited space in urban areas on the other.

A tall building may be visualised to be a cantilever structure supported at the ground and free at the top. The shear distribution in such a building, subjected to a uniform lateral pressure, bears a linear relation, with a zero value at the top and increasing to a maximum at the ground level. Since an increase in the height of a building causes larger moments at the base, bigger sections of columns will be required to support it. As such, the height of a building, supported on columns, may reach a stage such that any further increase in its height will require column sections big enough so as to touch each other. In such a case it is more feasible to introduce a wall rather than to use such closely spaced columns. Such walls are called shear walls and they serve the purpose of not only strengthening but stiffening tall and slender buildings against lateral wind and seismic loads. This stiffening may be achieved in various other ways, too. In framed structures it may be obtained by bracing members, by the rigidity of the joints, by complete shear truss assemblies acting in conjunction with the frame, or by infilling the frame with shear resistant panels. An obvious simplification of the latter is the shear wall construction.

1.2 Definition of a Shear Wall:

Frischmann and Prabhu[1] have defined a shear wall as a structural system providing stability against wind, earth tremors or blasts, deriving its stiffness from inherent structural form. The system can consist of a plane wall, part of a curved wall, a closed hoop, a rectangular box of a system of concentric or eccentric cores.

1.3 Planning of the Buildings:

The design of a high-rise building must permit maximum flexibility of internal layouts which is normally achieved by planning the structure to accomodate a basic module for windows, air-conditioning and heating units, the lighting installations, etc. It is also desirable to eliminate obstructing internal beams and to keep the open floor space free from columns.

The structural planning basically involves providing sufficient stability against horizontal forces. This is found, in practice, to be best provided by developing the inherent stiffness of the enclosure walls. Such walls should be so located as to carry as much of the weight of the floor system as possible since this has the effect of pre-loading the walls. Ideally, they should be so proportioned that the increase in stresses due to lateral loading is within the allowable increase in the permissible unit stresses so that no additional strengthening is required for lateral loads.

Concrete shear walls provided in tall multi-storied buildings generally run throughout the height of the structure. The walls are designed to cantilever from foundation, and the floor slabs acting as diaphgrams connecting the shear walls distribute the horizontal loads to the vertical stiff shear walls, which in turn transmit them to the foundation where the fixed end is provided. The foundations are designed to distribute these highly concentrated loads over a sufficient area so as to prevent overstressing of the soil. Since the horizontal loading is mainly resisted by shear walls, the floor system needs to be designed to carry vertical loads only.

In tall apartment buildings where size of the service core is relatively small, extra stability can be provided by introducing at critical sections flank walls in concrete to act as shear walls. These can coincide with division walls between dwellings, or in some cases partition walls can be stiffened to act as shear walls. The floor can then be semi or wholly prefabricated to act as diaphgragms.

1.4 Scope of the Report:

This report is a study of methods of analyzing shear walls with openings in tall buildings subjected to lateral loads, like wind load, seismic load, vibrations and blast effects. Various methods currently available and their relative merits are discussed qualitatively. The interaction of shear wall and frames is also discussed briefly.

CHAPTER II

LATERAL LOADS ON TALL BUILDINGS

2.1 Wind Loading:

The wind load forces depend on the mean hourly wind speed, the estimation of an appropriate gust factor, shape and pressure coefficients and the effect of local topography. The wind loads are normally applied on the building as an equivalent uniformly distributed load for its full height.

Natural wind has the potential to cause sway of the whole building, depending on its dynamic properties. For a constant wind pressure, the overturning moment at the bottom of a building varies with the square of the height. The escalation of wind velocity with height further increases this moment as well as the overall horizontal shear force. Tall buildings built in the last decade, with modern techniques, have a much lower frequency and much reduced damping than previous construction and require careful checking as they are liable to gust-induced sway.

2.2 Effects of vibrations:

These have to be considered in relation to the effect of the stresses induced on the fatigue life of the structure, and the effect of vibration on people in the building.

The human body is quite susceptible to vibration and the amplitude that can be tolerated is considerably less than would be permitted purely from stress considerations and static wind loading on the building and this, therefore, should be the criterion for the design. It is generally believed that "acceleration", "change of acceleration" and "frequency of vibration" are the main causes of human discomfort.

The effect of vibrations is studied on models tested under controlled conditions in wind tunnels, reproducing such effects as pressures on cladding, air flow studies, aerodynamic stability and minimum structural damping.

2.3 Effects of Earthquake:

Earthquake forces result from the vibratory motion of the grounds on which the structure is supported. The ground vibrates both vertically and horizontally, but the vertical component has negligible effect on the structure due to its inherent vertical strength.

The allowance of earthquake forces in the design of structures at the present time is empirical, based on the performance of structures in earthquake zones.

In some countries, building regulations require that, in addition to the normal wind forces, the structure be designed to withstand a minimum total lateral seismic force which is assumed to act non-concurrently in the direction of each of the main axes of the building, equivalent to a given percentage of the weight of the building. The percentage generally varies from 1 to 13% depending upon the location of the structure in relation to the earthquake zones.

In addition, walls and partitions are anchored to the rest of the building to resist a force of 20% of their weight and members such as parapets, ornamentation and cladding are usually required to be anchored for 100% of their weight.

2.4 Blast Effects:

The effect of wind on a structure is generally considered by using an equivalent static load but the effect of a blast is definitely a dynamic one. The blast effect can be allowed for by using acknowledged methods of dynamic analysis of structures with load values possibly obtained from experience or model analysis. This complicated analysis is, for further discussion, considered out of scope of this report.

2.5 Openings in Shear Walls:

Shear walls in tall buildings seldom run solid throughout the height of the structure. They normally have openings for doors, windows, corridors and may even be discontinued completely at lower levels of the building, to allow large uninterrupted areas for a concourse. These openings and discontinuities generally carry local stress concentrations. The uppermost and the lowest connecting beams are referred to as end beams and the piers of such walls may be fixed in same or in separate foundations or in rigid basement floors. The analysis of shear walls, especially with openings, will be discussed in the following chapters.

CHAPTER III

METHODS OF ANALYSIS

3.1 General:

This Chapter presents various methods of analyzing shear walls with openings. The Magnus method and the Continuous System methods are considered relatively exact methods of analysis. The Cantilever method is an approximate method. A brief discussion on the Stiffness method and the Finite Element method of analyzing shear walls is also included in the latter part of the Chapter.

3.2 Magnus Method:

Formulas have been developed by Magnus (2) for the internal forces, bending moments, and horizontal deflections for walls on rigid and non-rigid foundations. The following assumptions are made by Magnus in his analysis:

1. Deflections due to shear strain are negligible.
2. All openings are of equal width and occur vertically above one another at every level.
3. The lintels are of uniform stiffness.
4. The story height is constant throughout the height of the building.

5. The cross-sectional area and stiffness of each wall element are constant throughout the height of the building.

6. There is a point of contra-flexure at mid-span of each lintel.

7. The material of which the wall is constructed is homogeneous and isotropic and all stresses are within the elastic range.

In this analysis, the shears in the lintel beams are considered as primary unknowns (Figure 3.1). The equations to solve for these

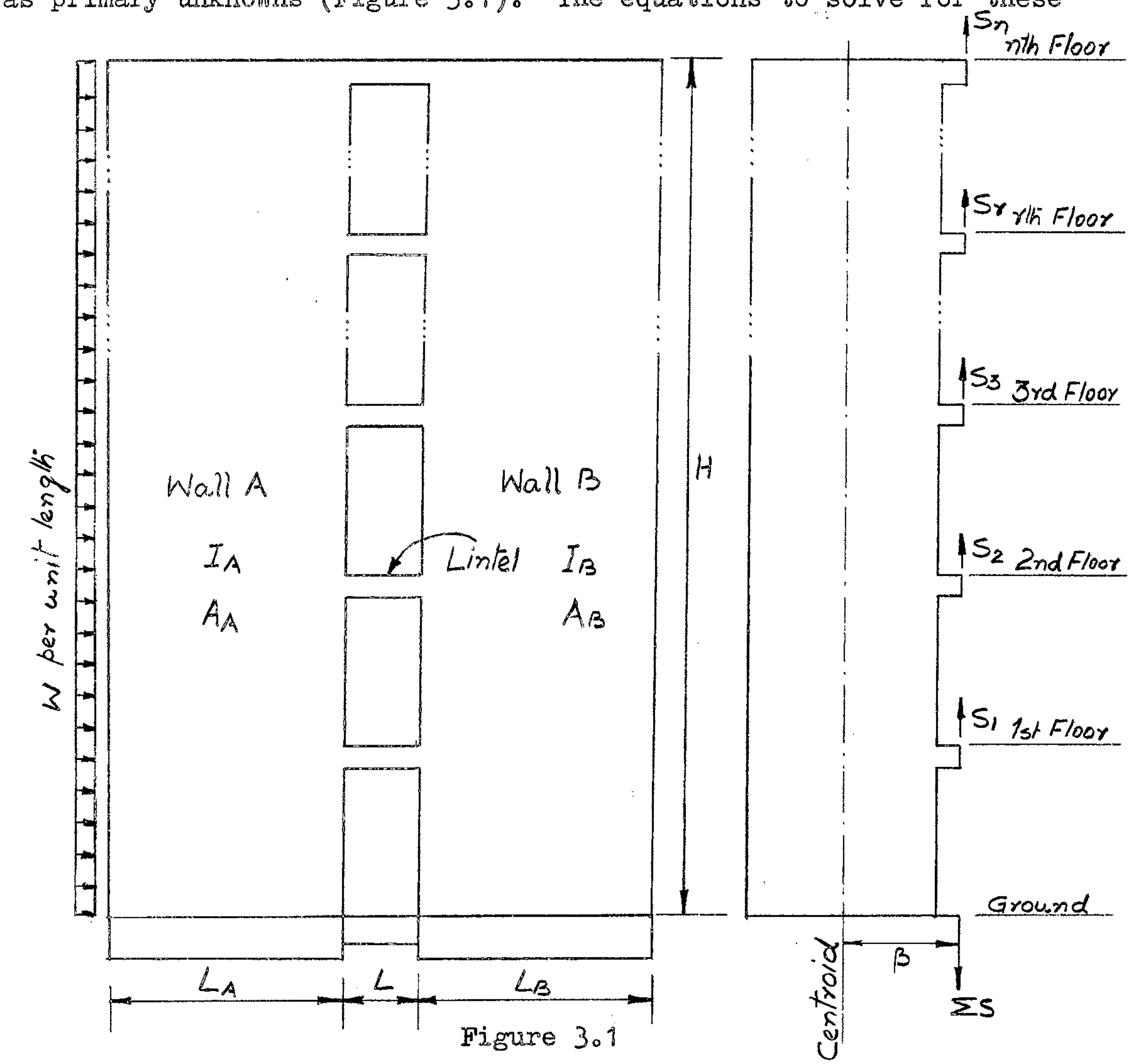


Figure 3.1

Shearing forces on lintels of a pierced shear wall unknowns are set up in the form of the compatibility equations for the relative deformations induced at the mid-spans of the beams in the basic structure obtained by releasing the structure of vertical displacement continuity at the midspan sections of the beams.

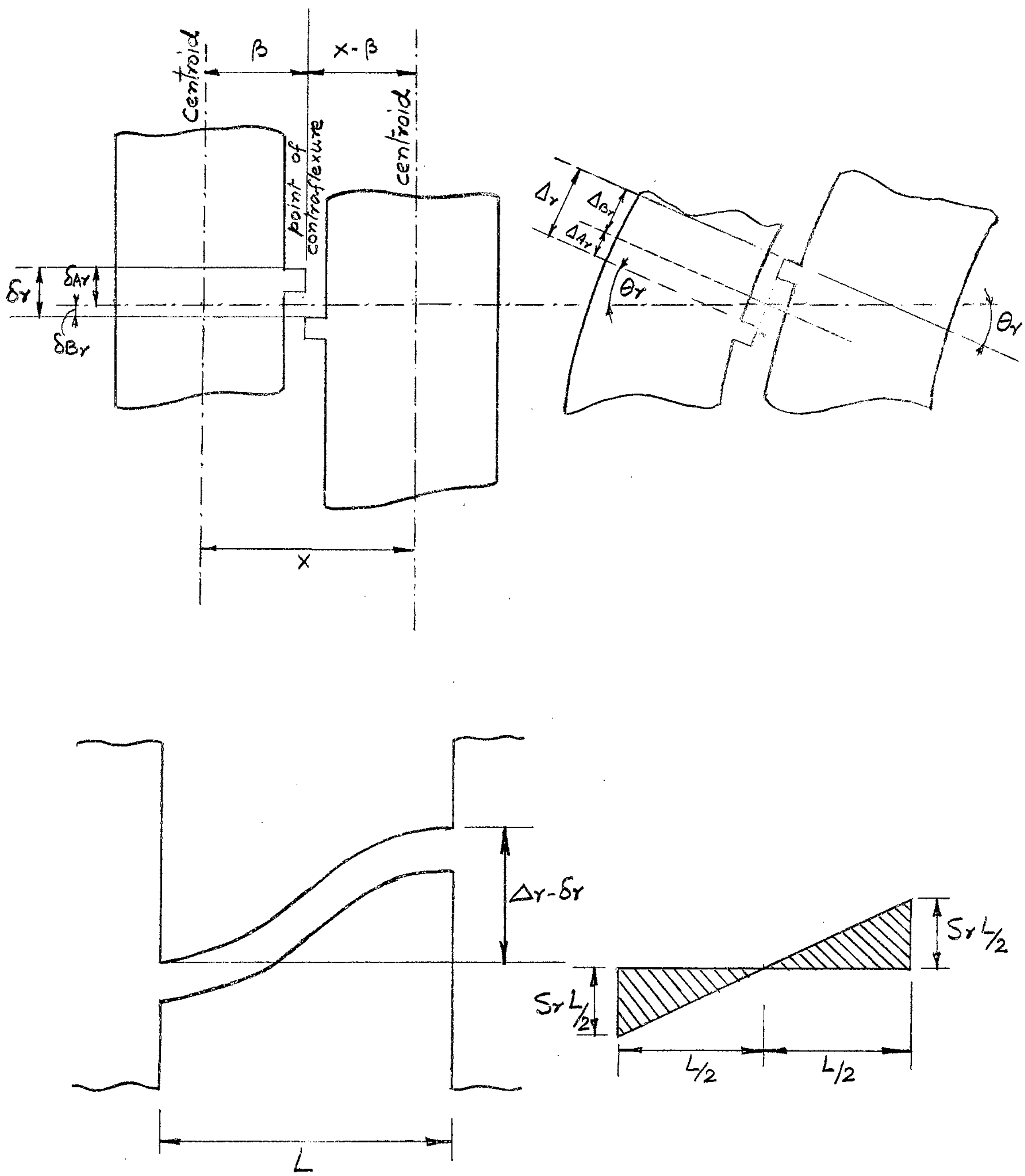


Figure 3.2

Effect of vertical forces and bending

The effect of lateral loads is distributed in the walls A and B (Figure 3.1) in proportion to their flexural rigidities. The relative displacements δ_r and Δ_r due respectively to axial and bending deformations of the walls due to the applied loads and unknown shears are computed (Figure 3.2). These net relative displacements are equated to those produced by bending deformations of the lintel beams to obtain the compatibility equations. The effect of differential settlement of wall footings in a non-rigid foundation can easily be included.

To facilitate the computational work, Magnus has prepared design charts for the shear forces in lintels, bending moments in walls, and horizontal displacements of the wall[2].

3.3 Continuous System Method:

The method consists of replacing a discrete system of lintels by a continuous substitute system for analysis purposes. This continuous substituted system consists of laminas of very small width, continuously distributed throughout the height of the building.

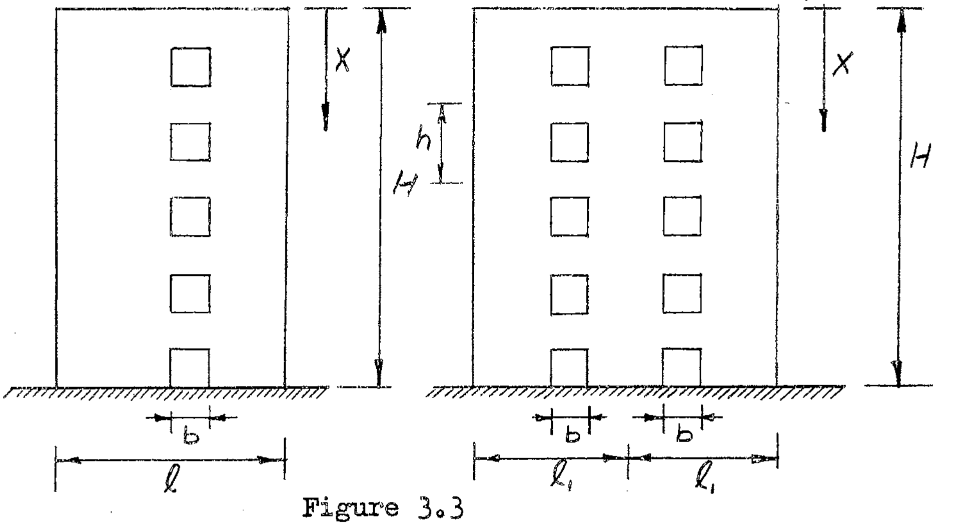


Figure 3.3

Walls containing single and double bands of openings

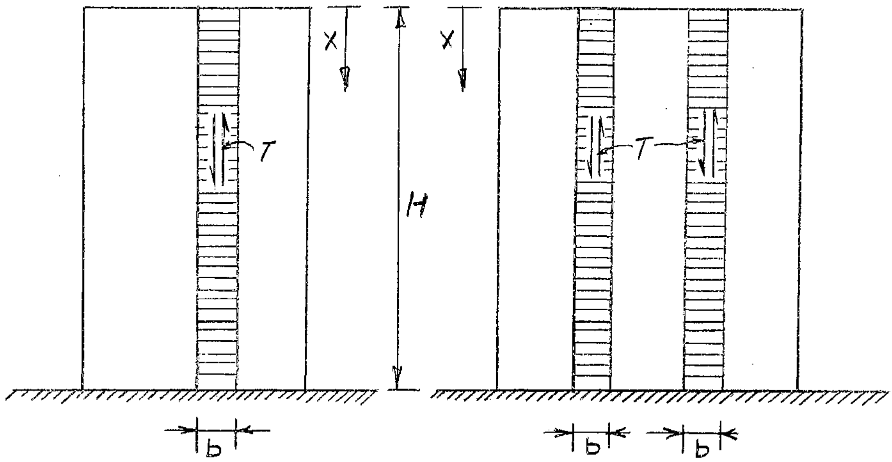


Figure 3.4

Substitute system

Of the methods of analysis proposed using this concept of analysis of shear walls, those of Riko Rosman [3] and Hubert Beck[4] are particularly noteworthy. The basic approach of both of them is the same. Various assumptions made by them are summarized below:

1. Values like story height, width of openings, cross-sectional area of the wall, moment of inertia of the wall, modulus of elasticity, etc. are assumed to be constant throughout the height of the wall.
2. The upper end beam has one-half the cross-section and one-half the moment of inertia of an interior connecting beam.
3. The points of contraflexure are assumed to be at mid-spans of the connecting beams.
4. The connecting beams have rectangular cross-sections and in their longitudinal direction they are considered absolutely rigid.

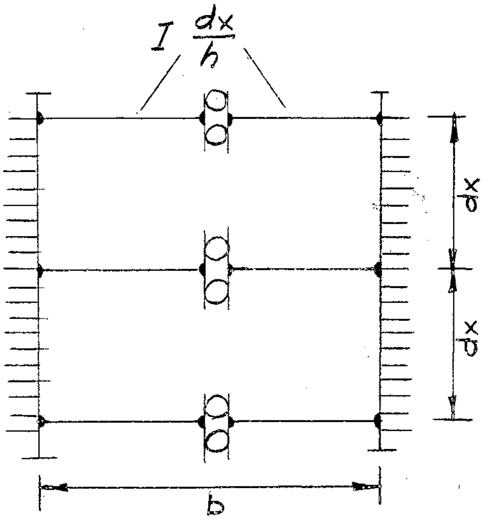


Figure 3.5

Detail of Base System

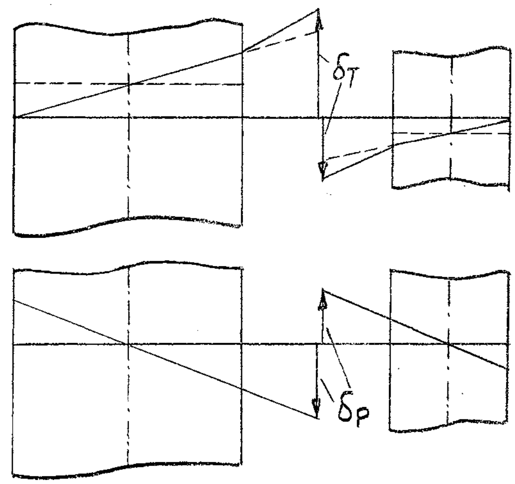


Figure 3.6

Displacement Diagrams

In each case, the problem is formulated by considering the wall to consist of two piers with a band of opening-laminas running throughout the height of the wall. The shear force in the laminas is considered as the redundant and a differential equation is established to solve for it. The lateral load P or W acting on the wall produces a deformation δP in the basic system which is counteracted by the shear force T in the laminas. The governing differential equation is obtained from the compatibility condition

$$\delta P = \delta T$$

at any typical location in the wall.

The major difference in the derivation of the governing differential equation in the two cases lies in the fact that Rosman takes the integral shear force 'T' in continuous connections as a statically redundant function whereas Beck keeps the function of shear force of the laminas 'q' as unknown. Taking into account the deformations due to bending moment, the contribution of normal forces in the piers and shear forces in the connecting beams, the differential equations derived by Rosman and Beck respectively are:

$$\frac{d^2T}{dx^2} - a^2T = -\gamma x \quad \text{——— I}$$

and

$$\frac{d^2q}{dx^2} - \left(\frac{\bar{\bar{a}}}{l_1}\right)^2 q(x) = -\frac{2}{a}\left(\frac{\bar{\bar{a}}}{\gamma l_1}\right)^2 \frac{dM_o}{dx} \quad \text{——— II}$$

These are linear differential equations of the second order with constant coefficients wherein a and $\bar{\bar{a}}$ are functions of elastic and geometric properties of the wall, γ being the function of applied lateral load on the wall.

These equations are solved and the constants of integration are obtained from the boundary conditions of the shears at the top and the bottom of the wall.

The assumptions made in the methods of Rosman and Beck seem to impose some limitations on their use as discussed below:

The thickness of a wall in a building is usually not kept constant throughout its height and also the values of modulus of elasticity may vary since a richer mix of concrete is used in the lower portion of the wall and a relatively poor mix is employed in the upper reaches.

The above equations are derived taking into account either a concentrated load or a uniformly distributed load, and may not be applicable for other types of loading on the wall.

The architectural requirements sometimes demand unsymmetrical openings in the wall, in which case again the analysis proposed may not be applied.

3.4 Cantilever Method:

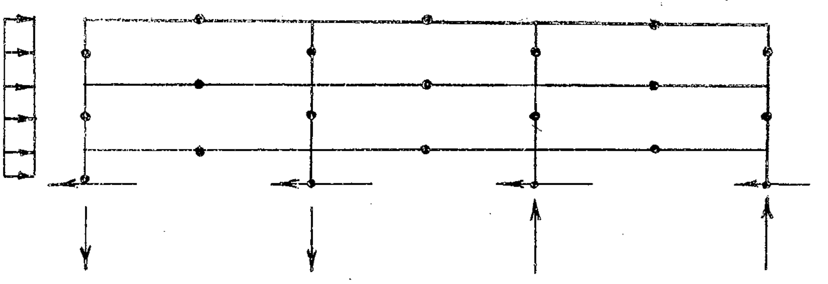


Figure 3.7

Frame-work of Columns and Beams

The approximate method known as the Cantilever method of analysis of building frames may be extended to the analysis of shear walls with openings. This method reduces a statically indeterminate problem to a determinate one by the following assumptions:

1. There is a point of inflection at the centre of each girder.
2. There is a point of inflection at the centre of each column.
3. The intensity of axial stress in each column of a story is proportional to the horizontal distance of that column from the centre of gravity of all the columns of the story under consideration.

In case of shear walls, the piers are considered as columns and the connecting lintels as beams. The procedure follows the following steps in proceeding from the top to the bottom of the frame:

1. The axial forces in columns at mid-height are computed.

2. The moments and shears in beams are computed.

3. The moments and shears in columns are computed.

4. Finally, the axial forces in the beams are computed.

In the case of a shear wall with a single band of openings, it can be shown that the shear in any lintel is given by the relation

$$S_L = \frac{Vh}{2\gamma}$$

where

S_L = Lintel shear

V = Total horizontal shear on the wall at the section.

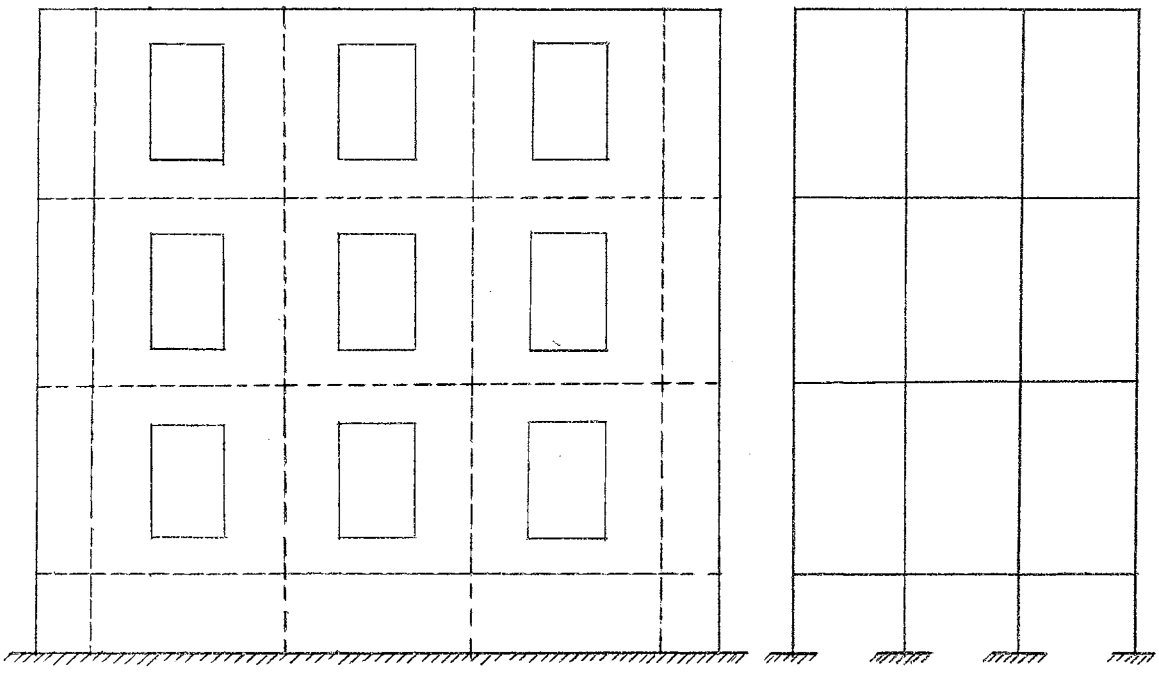
h = Story height

and γ = Distance between the centre of beam and the centre of column.

3.5 Stiffness Method:

The stiffness analysis of rigid-jointed planner frames may be extended to shear walls. The shear wall is treated as an idealised frame in which the members are represented by their center-lines (Figure 3.8). Axial deformations and shear deformations can be included in the analysis. Also, the variation in elastic and/or geometric properties of the structural elements with the height of the wall can be allowed for. Another advantage of the method is that no restrictions be placed on symmetry of openings in the wall.

As usual, a diagonally banded stiffness matrix is obtained. The number of unknowns increases with the increase in the number of stories in the structure and the use of electronic computers becomes necessary.



Original Structure

Idealized Structure

Figure 3.8

3.6 Finite Element Method:

The stress distribution in shear walls, coupled with lintel beams, presents a boundary value problem in Elasticity. It can also be considered as a plane stress boundary value problem in a multiple-connected region. One of the most appropriate techniques to deal with such a problem is the Finite Element method. The method consists of discretizing the structural continuum to be analyzed into small finite elements interconnected at specific nodal points (Figure 3.9). These finite elements possess the same material properties as does the continuum. The assemblage of these finite elements, subjected to boundary forces concentrated at the respective boundary nodal points, results in some displacement at all nodal points of the elements. In

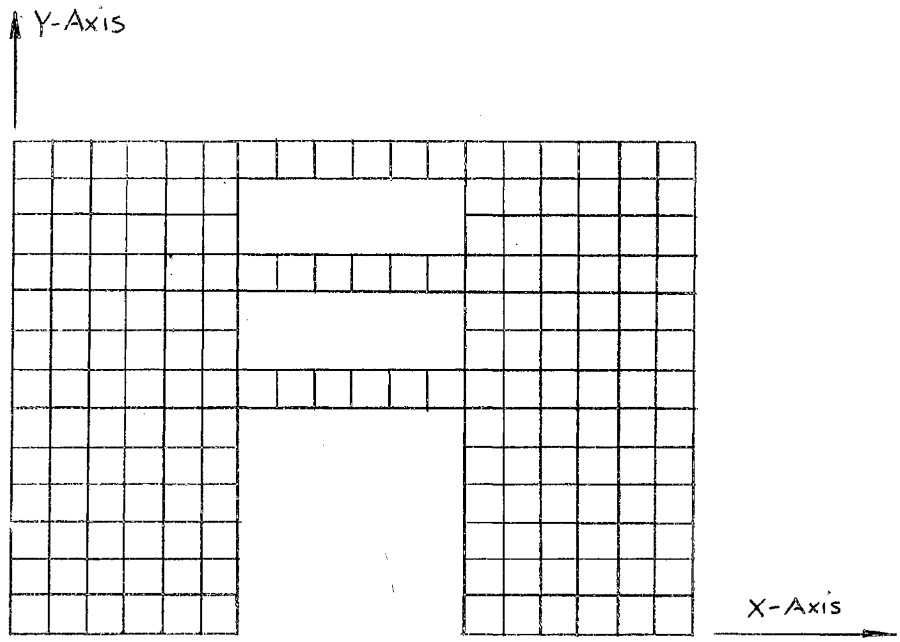


Figure 3.9

Finite-element representation

order to maintain compatibility of displacement on the boundary of each element, an arbitrary displacement function is assumed. A bilinear displacement function is assumed for the rectangular elements, whereas a linear function is assumed for triangular elements. It has been found that the rectangular elements are more accurate and more convenient for application to shear wall problems than the triangular or the constant stress elements. From the assumed displacement function, a stiffness matrix is derived relating the nodal displacements and nodal forces of a finite element. By correctly superimposing the stiffness matrices of all the elements, the nodal displacements and nodal forces of the complete assemblage of elements can be related by a single stiffness matrix equation:

$$[K]\left\{U\right\} = [F]$$

where

$[K]$	=	the stiffness matrix of the assemblage of elements and of the order of 2n, n being the total number of nodal points.
$\left\{U\right\}$	=	the nodal displacement vector.
$[F]$	=	the nodal force vector.

The above equation can be solved to determine the displacement vector for a given set of forces concentrated at nodal points and for specified boundary displacements or forces. From the nodal displacement vector, the stresses and strains in the elements throughout the wall can be evaluated.

The accuracy of this method lies in the fineness of the grid-- i.e. the smaller the size of the element, the more accurate will be the analysis. Since the matrix obtained in this method involves numerous unknowns, the use of a computer becomes necessary to solve for it. The specific advantages of this method over other methods are as follows:

1. The distortion of shear walls, i.e. the lengthening and shortening of the external vertical sides because the walls act as deep beams, is taken into account.
2. The stress concentration at the corner junction of the lintel beams and walls is accounted for.

3. The local distortions of the surfaces of the shear walls caused by the moments and forces exerted by the connecting lintel beams are taken into account.

CHAPTER IV

INTERACTION OF SHEAR WALL AND FRAMES

Many of the modern multi-story buildings contain specially arranged walls which resist the horizontal forces and act in conjunction with the moment resisting frames consisting of columns, connecting beams, and slabs.

In tall buildings comprised of walls and frames, the frames are usually assumed to carry only vertical loads whereas shear walls are designed to take up the lateral forces. In the absence of such walls it would be practically uneconomical to reinforce the structural system to resist the lateral forces.

The combination of a shear wall and a frame constitutes a system which is statically highly indeterminate. Also, two basically different components --a wall and a frame--are tied together to produce one structure. It can, however, be concluded that the distribution of forces between the frames and the shear walls makes it a more economical structure because the interaction provides a reduction of reinforcement in a shear wall. Also, the one-third increase in allowable wind and earthquake forces generally permit the accomodation of additional stresses in the frame with no increase in reinforcement over the major part of all tall structures.

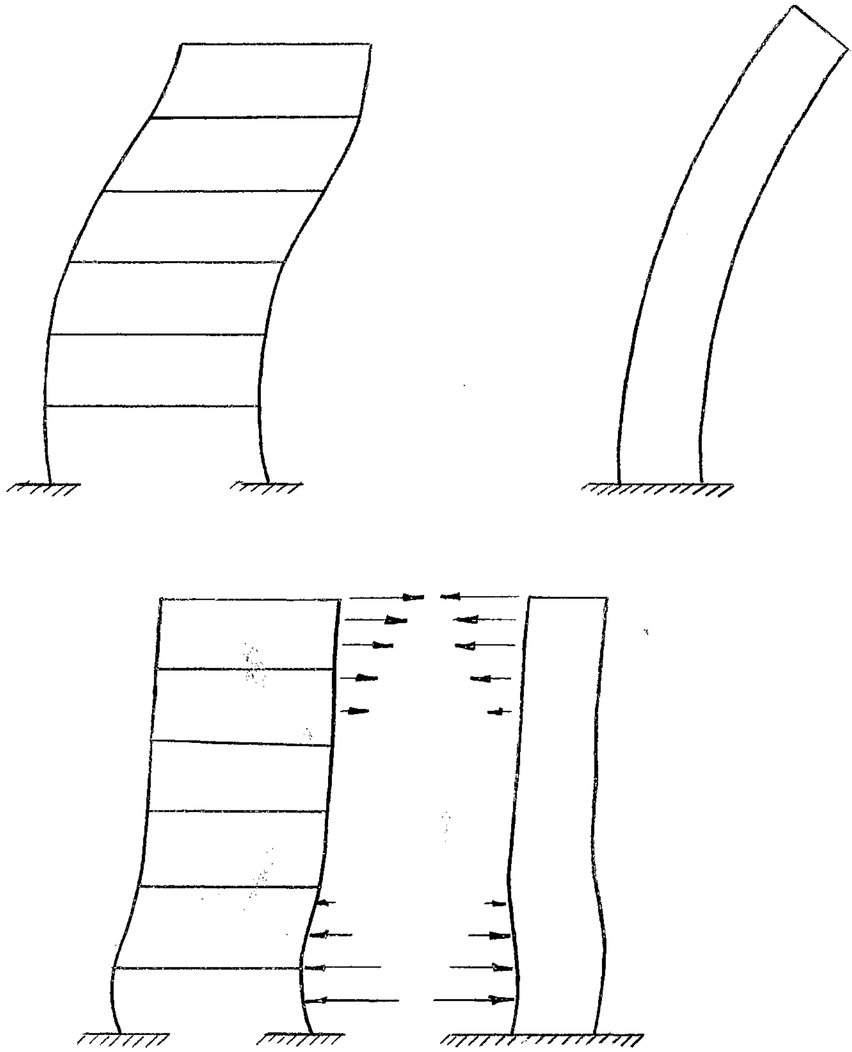


Figure 4.1

A frame, a wall, and a combined structure under lateral loads.

Figure 4.1 shows graphically the behaviour of a frame alone, a wall alone, and a combined structure under the effect of lateral loads.

CHAPTER V

SUMMARY AND CONCLUSIONS

In multi-story buildings, shear walls are provided to offer resistance to lateral movements that may be caused by winds, earthquakes, etc. The shear walls provided as such are not generally solid walls but contain openings, doors, windows and corridors, etc., which may be symmetrical or unsymmetrical. The introduction of openings in such walls makes their structural analysis a highly redundant problem.

The analysis of shear walls with openings has been done by different methods. Magnus, in his method, takes the shear in the lintels as unknown and gives charts for lintel shear, bending moments in walls and horizontal displacement of the wall. Beck and Rosman replace a discrete system of lintels by an equivalent continuous system of laminas and derive the governing differential equation to analyze the shear wall for the shear forces in the lintels. In all these methods the shear in lintels is considered as an unknown and is obtained from the compatibility condition of deformations due to lateral load and vertical shear.

A shear wall with openings can be treated like a frame and an exact analysis can be carried out by the Stiffness method or by the Finite Element method. For both these methods the use of electronic computers is sometimes necessary.

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VITA

Ramesh K. Ailawadhi

Candidate for the degree of

Master of Science

Report: ANALYSIS OF SHEAR WALLS IN TALL BUILDINGS

Major Field: Civil Engineering

Biographical:

Personal Data: Born April 21, 1944 at Renalla, W. Pakistan, the son of Mr. and Mrs. Ram Saran Dass.

Education: Graduated from Panjab Engineering College, Chandigarh, India, with Bachelor of Engineering (Civil) degree in April, 1965. Entered Oklahoma State University in January, 1969, and completed requirements for the degree of Master of Science in May, 1970.