A RESEARCH PROGRAM ON THE EARTHQUAKE RESISTANCE OF SHEAR WALL BUILDINGS

by

A. C. Heidebrecht(I) and W. K. Tso(II)

ABSTRACT

This paper describes a research program on the earthquake resistance of shear wall buildings being conducted at McMaster University and sponsored by the Canada Emergency Measures Organization. The purpose of this program is to study the behaviour of small scale shear wall buildings experimentally and analytically in order to improve the design criteria for earthquake and blast loading.

The experimental phase of the program involves the construction of a number of small scale shear wall buildings designed and built to simulate typical full scale shear wall structures. These buildings have been constructed using cement mortar in order to simulate the actual stress-strain relationship in concrete. A typical structure is shown in the attached photograph (Plate I) and illustrates a shear wall building with circular wall openings. These buildings have been subjected to static lateral load tests and are being tested dynamically as well. The dynamic tests involve controlled foundation motion programmed to simulate actual earthquake excitations.

The analytical phase of the program involves the development of analytical techniques to describe the load-deformation characteristics of the structures during static and dynamic loading and also the study of cracking and failure criteria. Investigations have shown that Vlasov's thin-walled elastic beam theory gives a very reasonable description of the deformation of the structures, when compared with the measured test values.

(I) Associate Professor, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada.

(II) Assistant Professor, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada.

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INTRODUCTION

In the context of modern day construction, a shear wall is defined as an element within a building which has the specific function of resisting lateral loads such as those which occur because of earthquake or wind excitation of the structure. Elements of this type may be in the form of walls, elevator shafts, stairwells, etc. A shear wall building differs from other buildings in that the entire system of load bearing walls is considered to act together in resisting lateral loads. Such buildings are now quite commonly used for both apartment and office buildings and range in height up to thirty-five stories. Many examples of this type of construction can be found in Hamilton, Toronto and Montreal as well as other North American cities.

The floor plan of a typical shear wall apartment building is shown in Figure 1. A typical feature of such buildings is the two sets of shear walls. The first set consists of a large number of parallel shear walls separating the apartment units in one direction. The second set consists of a pair of walls perpendicular to the first set. The space between the second set of walls is usually the corridor. In addition, some glass curtain walls form the exterior walls of the apartment. The configuration of most such structures is similar, with minor differences due to actual geometry and due to architectural detail.

Shear wall building construction procedures vary somewhat but the largest proportion have concrete walls whose only reinforcement is "temperature" steel, which does not contribute significantly to the flexual strength of the wall. The floor slabs are usually reinforced concrete panels which are either "keyed" into the walls by means of slab projections fitting into wall slots or are cast with the walls and have slab reinforcement bent up and down into the walls.

The basic thickness for the walls in the shear wall building is determined from the static load bearing design. The analysis for resistance to lateral loads varies but is generally rather crude. One method in use is the computation of an overall base shear stress (the total lateral force on the building divided by the total wall cross-sectional area) which is compared with the nominal allowable concrete

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(I) Associate Professor, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada.

(II) Assistant Professor, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada.

shear stress for a check on the adequacy of lateral load resistance. Other methods differ in detail but none takes any consideration of the dynamic nature of the lateral load acting on an essentially "brittle" structure.

In view of the above, a program of investigation and research into the earthquake resistance of shear wall buildings was initiated at McMaster University under the sponsorship of the Canada Emergency Measures Organization. The purpose of this program is to develop more realistic analytical methods which can be used to describe the static and dynamic behaviour of shear wall buildings and apply the results of analysis to the development of more realistic design criteria. At the outset of this program, it was agreed that the analytical studies would be accompanied by extensive experimental work using small scale shear wall buildings. The remainder of this paper describes the details of this program and the results achieved in the work done to date.

GEOMETRICAL CONFIGURATION OF SMALL SCALE STRUCTURES

Figure 2 shows a perspective sketch of the basic structure studied in this program. It is "E" shaped in cross-section, has a wall thickness of 0.5 inches, has a height of 96 inches and is 16" x 40" in plan. This structure was chosen because its basic shape and proportions are representative of typical shear wall buildings. It should be noted that this is not a true structural model since it is not based on a particular full size structure. It was decided not to use a model of an actual structure in order to study the general behaviour of a slightly less complex system and draw conclusions regarding the characteristics of this class of structural systems. This would not be possible if a detailed model were studied.

The program includes four distinct phases of development of the basic structure, namely:

A. the basic structure without floors or wall openings,
B. the basic structure with wall openings but without floors,
C. the basic structure with floors but without wall openings,
D. the basic structure with both floors and wall openings.

The structures constructed in accordance with the geometry as described in A, B, C, D are designated as series A, B, C, and D respectively. Each of the phases of development includes both static and dynamic testing, the details of which will be described later in the paper. The reason for the above phase arrangement is to enable the development of some understanding of the separate effects of wall openings and floors and their interaction in the behaviour of the complete structure as defined in the fourth phase. Photographs of the structures in series B and C are shown in Plates I and II. The structure is proportionally equivalent to an eight storey building so that eight pairs of wall openings and eight floors were used in series B and C respectively. Circular wall openings are used rather than rectangular openings in order to minimize the effects of localized stress concentrations.

CONSTRUCTION OF BUILDINGS

Due to the extremely small wall thickness and in order to simulate the essentially "brittle" nature of actual structures of this type, it was decided to use unreinforced mortar to manufacture the small scale structures. The mortar design includes silica sand, crushed limestone, ordinary Portland cement and water. The proportions were determined from an extensive series of comparative tests based on achieving reasonable workability of the fresh mix and low shrinkage of the final product. The silica sand and crushed limestone are combined to yield a total aggregate grading curve which has the same general characteristics of aggregate use in normal concrete work. The average compressive strength at 28 days is approximately 6800 p.s.i., based on tests of 2 inch cubes; the modulus of elasticity is determined from both the compression tests and from dynamic modulus tests, and varies between 4×10^6 and 5×10^6 p.s.i.

The basic apparatus used in the construction process is the wooden formwork shown in Plate III. The basic structure without base is cast in this formwork and allowed to set in the formwork for three to four days prior to being erected on its base, with formwork intact. The formwork is then stripped from the model and the model attached to its base. The model is attached to the base by fixing small steel angles to the base around the walls of the structure and then filling in the gaps between the angles and the walls with a putty like high strength epoxy. This procedure provides a fixed base connection and also eliminates any tendency for shrinkage cracks to form near the base prior to loading.

STATIC LOADING STAGE

The primary purpose of the static loading stage is to develop mathematical models for lateral stiffness of the different phases of development of the structure so that these can be used in a dynamic analysis. A secondary purpose is to study the failure loads and the accompanying failure cracking patterns.

The static loading stage for all the phases consists of applying an eccentric concentrated load at the top of the structure. It is true that this does not directly simulate the load distribution due to motion of the foundation of the structure, but it does permit the study of the general characteristics of the deformation of the structure when subjected to lateral loads.

The static load is applied through a loading cap attached to the top of the structure. The loading cap has dual purpose in the sense that it distributes the concentrated load into the various components of the structure and that it also maintains the cross-sectional "E" shape at the top of the structure. The load is applied through by means of either a hydraulic jack or a screw-type jack. The screw-type jack is preferred since it controls displacement and therefore permits a better control of the loading cycle, particularly as failure is approached.

Deformation characteristics of the structure during static loading are obtained by making measurements of longitudinal strain and lateral displacement. Longitudinal strains are measured using foil type electric resistance strain gauges; lateral displacements are measured using dial gauges. The detailed pattern of location of gauges varies from test to test but the general intent is to obtain cross-section distributions of strain and displacement at various height levels in order to study the nature of strains in the cross-section and the deformation of the cross-section itself. Gauges are also aligned vertically to obtain longitudinal distributions of strain and displacement. The combination of these results enables one to postulate suitable mathematical models which can be used to describe the deformation characteristics of these structures.

The investigations to date have resulted in static tests being completed on structures in series A, B, and C. The results of some of these tests are discussed later in the paper. Plate II shows a series B structure after completion of the static testing procedure.

DYNAMIC LOADING STAGE

The purpose of the dynamic loading stage is to investigate the dynamic load-deformation characteristics and also the nature of failure, and then to compare the results with predictions based on mathematical models developed from the static tests. The results of these investigations, both static and dynamic, will then be synthesized to arrive at recommendations for design criteria for such structures.

The dynamic loading is obtained by mounting the structure on a dynamic simulation shaking table, whose motion can be programmed according to a predefined time history of displacement or acceleration. This particular system can be excited at frequencies up to 100 c.p.s. and at an acceleration level of 1 g with maximum "live" weight capacity of 3000 pounds.

Measurements of displacement, acceleration and strain are made during the motion by using appropriate transducers whose signals are recorded on magnetic tape. The formation of cracks just prior to failure can be examined using a high speed motion picture camera. The dynamic loading stage of this program is in progress.

EXPERIMENTAL RESULTS

A total of four structures was built for the static testing stage of series A. The forms of these buildings were essentially thin-walled beams with an "E" shape cross-sectional contour. The structures in this series were not manufactured in exactly the same manner as those of later series; experience with this series was used to modify techniques which were then applied to later structures. The results of the static tests on the series A structures are discussed in the following paragraphs.

Figures 3 and 4 show the cross-sectional distribution of the longitudinal strain at heights of 2 inches and 45 inches above the base respectively for Structure A2 at a load of 250 pounds. The position of the load is shown on each diagram; failure occurred at a load of 800 pounds. The experimental values of strain are denoted by circles on each diagram. The theoretical strain distributions shown on the figures were obtained from calculations based on Vlasov's thin-walled beam theory(1), treating the base as fixed and the top of the structure as a free end. The value of the modulus of elasticity used is that of the initial tangent modulus of the stress-strain curve, which was evaluated experimentally as 3×10^6 p.s.i. The theoretical computations were found to be relatively insensitive to the value of Poisson's ratio in the range 0.15 to 0.40; a value of 0.15 was used in the results presented in this paper. An examination of the figures shows good agreement between experimental and theoretical results, both near the base (Z=2") and near mid-height (Z=45").

The load-strain variations at these same heights are shown on Figure 5 for a strain gauge location near the tip of one of the legs of the "E" cross-section. The experimental variation of strain versus load is a straight line whose location is in general agreement with the theoretically evaluated relationship. The experimental and theoretical values are in close agreement at a height of 45" but diverge somewhat near the base. At a height of 2 inches, the theory predicts larger values of strain than are observed experimentally at any given load. It should be noted that the load-strain curves are linear, even at loads near failure. This linear relationship supports the validity of using a linear elastic mathematical model to describe the behaviour of the shear wall structure.

The longitudinal variation of the lateral deflection of a point near the tip of one of the legs of the "E" cross-section is shown in Figure 6. The measured deflections are always larger than the theoretically predicted values but appear to differ by a constant amount at all heights. This observation indicates that the base rotation of the structure during the test is indeed negligible, since such rotation would result in a widening gap between theoretical and experimental values as one proceeds upward from the base. However, in view of the over-estimating of strain and the under-estimating of displacement near the base, it is reasonable to speculate that the actual base condition is not fixed as assumed, but perhaps has some element of slip. Deflection measurements at other positions at various heights indicated that the cross-section underwent translation and rotation at all levels. The cross-sectional "E" shape remains relatively undistorted at all heights except near the base. This rigidity of cross-sectional shape is one of the assumptions of Vlasov's thin-walled beam theory; this is perhaps why the agreement between theory and experiment is better away from the base.

Plate IV shows a photograph of the cracking pattern at failure. The mechanism of failure was initiated at the base of the structure in the corner at which the maximum tensile strain occurs. The highest recorded value of tensile strain prior to failure was 128 micro in per inch which is within the region of tensile cracking strain for cement mortars.

Two structures were built for the static testing stage of series B. Both structures had two rows of circular wall openings, as shown in Plate I. The openings were 5 inches in diameter and spaced vertically at 12 inch centres. The first in the series, structure B1, had the centre of the lowest openings at a height of 18 inches above the base. The second, structure B2, was the same, except for an extra pair of openings centered 6 inches above the base. Therefore structure B1 is similar to a building with no wall openings in the basement whereas structure B2 is comparable to a building with wall openings in the basement. Circular openings were chosen rather than rectangular openings in order to reduce the magnitude of stress-concentrations which would occur at such sharp corners. An investigation by Stiller(2) has shown that the shapes of openings have little effect on the overall stresses if the areas of openings are equal.

The strain distributions for Structures B1 and B2 at a height of 53 inches above the base and at a load of 250 pounds are shown in Figures 7 and 8 respectively. Vlasov's thin-walled beam theory does not take into account wall openings and would therefore not be expected to provide a particularly applicable mathematical model for the structures in series B. The theoretical distributions shown in the figures are not from Vlasov's theory but from a mathematical model which does take account of wall openings.

Several authors have given analytical consideration to the problem of interconnected plane shear walls by replacing the discrete spandrel beams with a continuous system of independently acting laminae having equivalent properties.(3, 4, 5, 6) In particular, Rosman(3) has considered the case for a concentrated load acting on top of the wall. The same mathematical model has been used in this study to give the theoretical distribution shown in Figures 7 and 8.

An examination of the results shows that reasonable agreement exists between theory and experiment for structure B1 but that the agreement is poor for structure B2. Structure B1 failed through the entire cross-section near the base whereas the failure crack entered the lowest pair of wall openings in structure B2. It appears that these additional openings near the base have a profound effect on the strain distribution in the structure, even at loads much below failure. A satisfactory mathematical model for reasonable prediction of the structure in series B has not yet been found.

Two structures were built for the static testing stage of series C, in the form shown in Plate II. The floors were made of the same material as the structure and were cemented in place using a high strength gel type concrete adhesive (trade name Colma Dur, and manufactured by the Sika Chemical Company, New Jersey, U.S.A.). The static tests on these structures have been completed and are in the process of being analysed. It is expected that Vlasov's thin-walled beam will give a satisfactory description of the actual behaviour of these structures since it can be modified to include spaced rigid diaphragms. A preliminary examination of the experimental results show that the cross-sectional deformation is substantially reduced, even at sections near to the base.

DISCUSSION

Further static testing of series C structures is presently in progress. It is anticipated that the first dynamic tests will also be conducted on the series C structures. The reason for this is that the development of a realistic mathematical model to describe the behaviour of this structure appears likely so that the analysis of dynamic test data would be facilitated. It is also true that the structures in series C are more similar to actual buildings than are the structures in series A or B.

CONCLUSIONS

This paper has described a program of research into the use of small scale unreinforced mortar structures to investigate the earthquake resistance of shear wall buildings. The experimental results have shown that a linear elastic mathematical model can be used to decribe the load-deformation characteristics and that Vlasov's thin-walled beam theory in particular can be applied to shear wall structures without floors or wall openings. It has also been shown that this linear elastic behaviour continues very near to failure load. Additional work is required to develop a more realistic model for shear wall structures with wall opening. Existing techniques are valid only for planar structures and do not take into account the rotation of the cross-section. It also appears that Vlasov's thin-walled beam theory can be applied to structures with floors but without wall openings.

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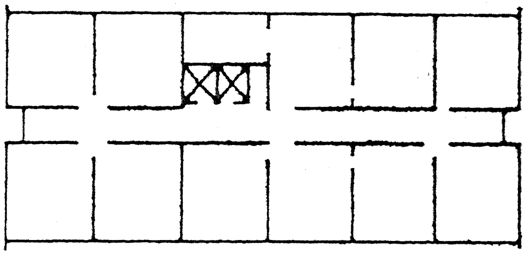


Figure 1. Floor plan of Typical Shear Wall Building.

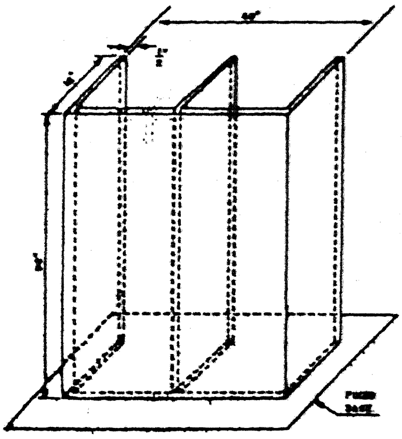


Figure 2. Perspective Sketch of Basic Small Scale Shear Wall Structure.

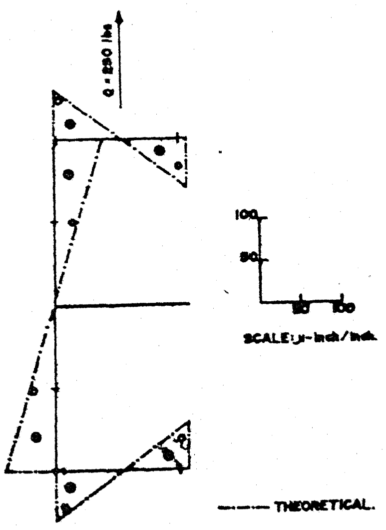


Figure 3. Strain Distribution at Z = 2", Structure A2.

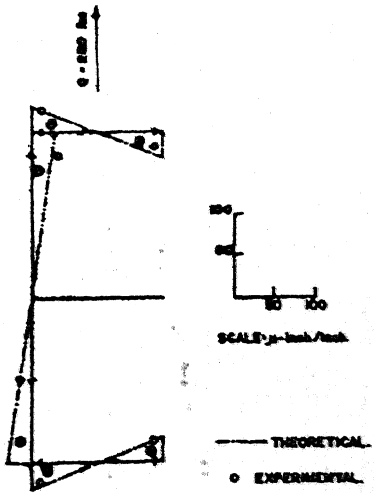
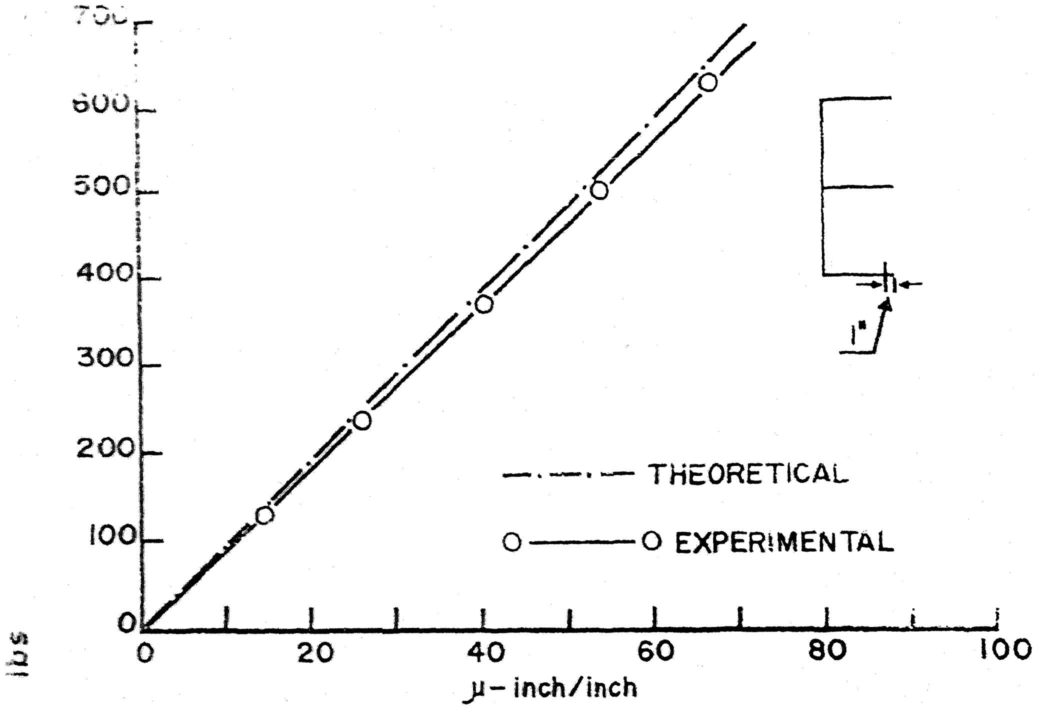
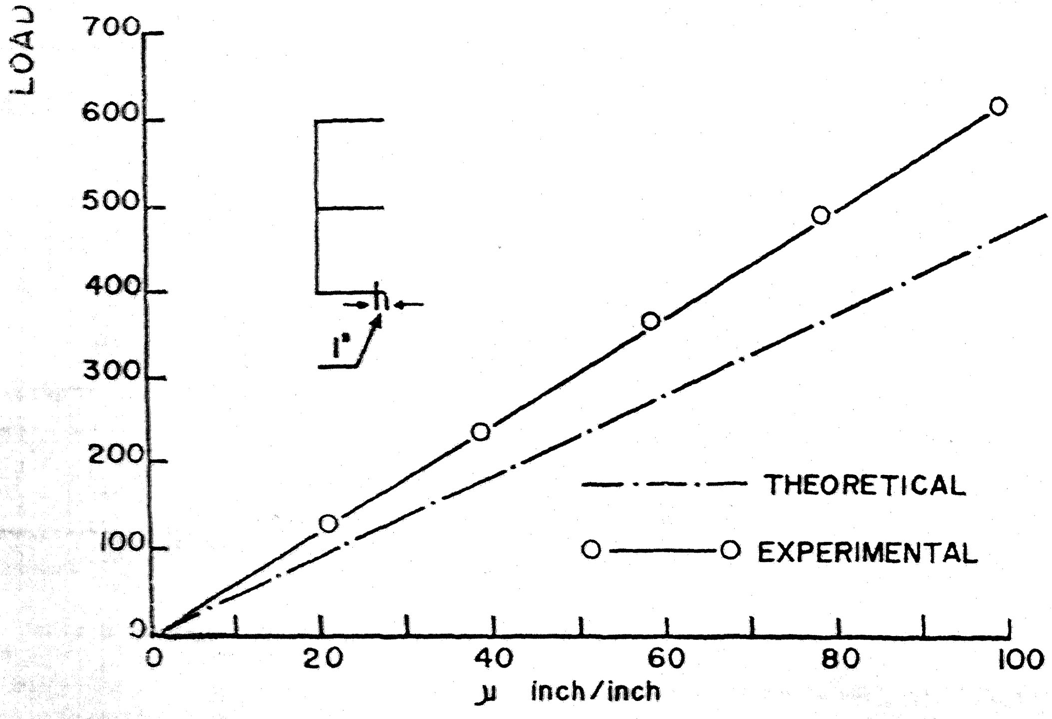


Figure 4. Strain Distribution at Z = 48", Structure A 2.



LOAD-STRAIN CURVES, Z = 45"



LOAD-STRAIN CURVES Z = 2"

Figure 5. Load – Strain Curves, Structure A2

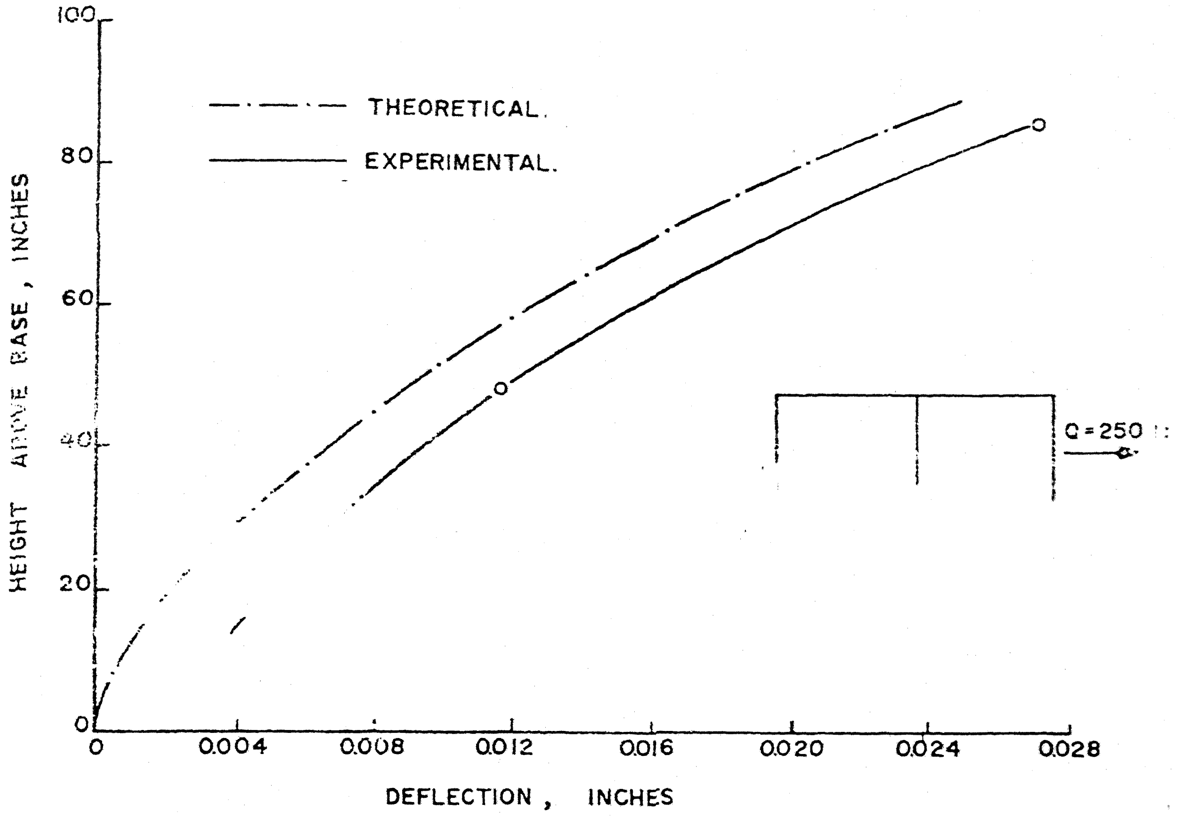


Figure 6. Lateral Displacements, Structure A 2

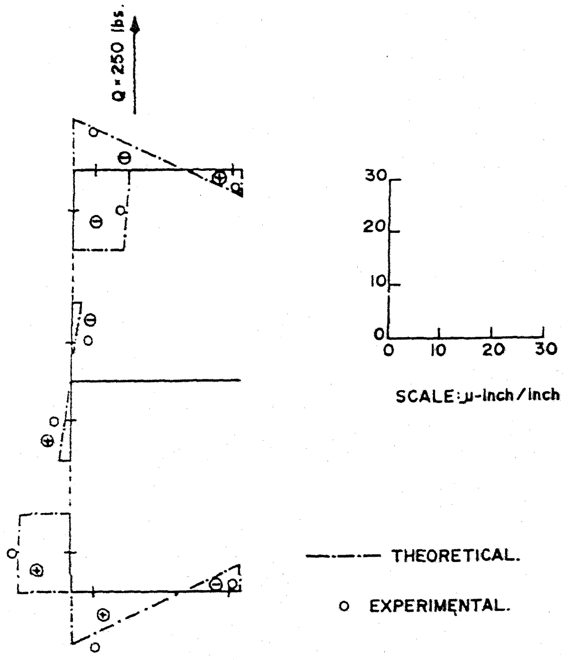


Figure 7. Strain Distribution at Z = 53", Structure B 1.

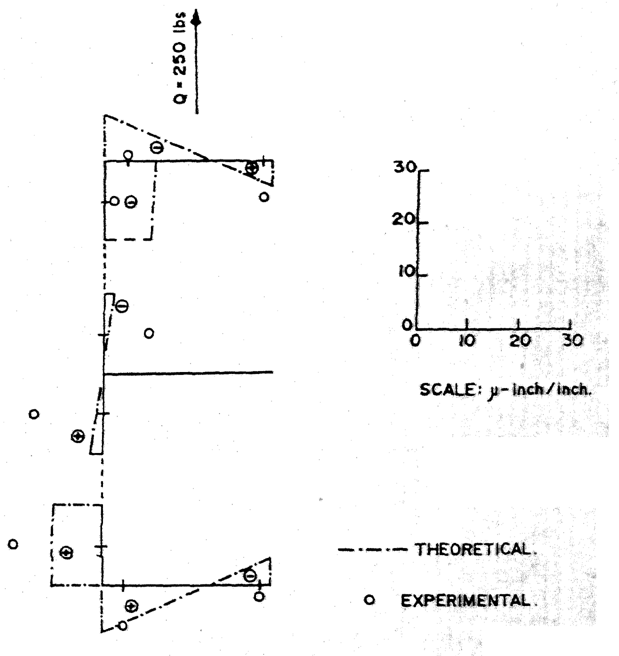


Figure 8. Strain Distribution at Z = 53", Structure B 2

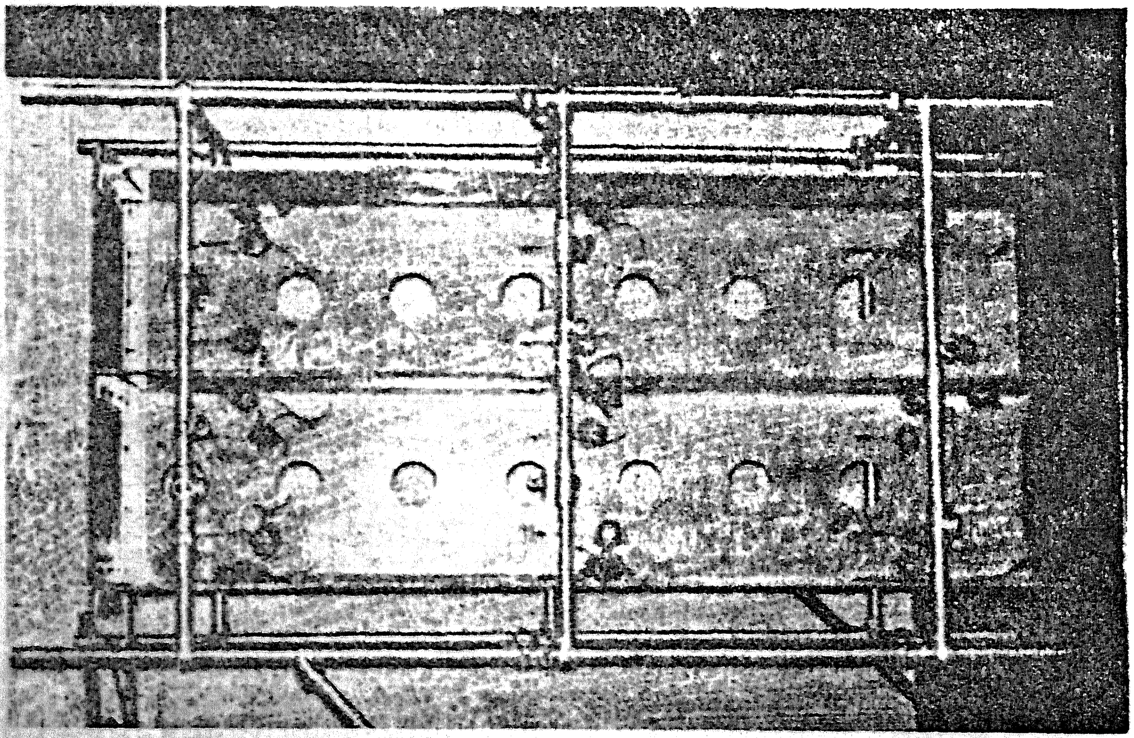


PLATE I BASIC STRUCTURE WITH WALL OPENING

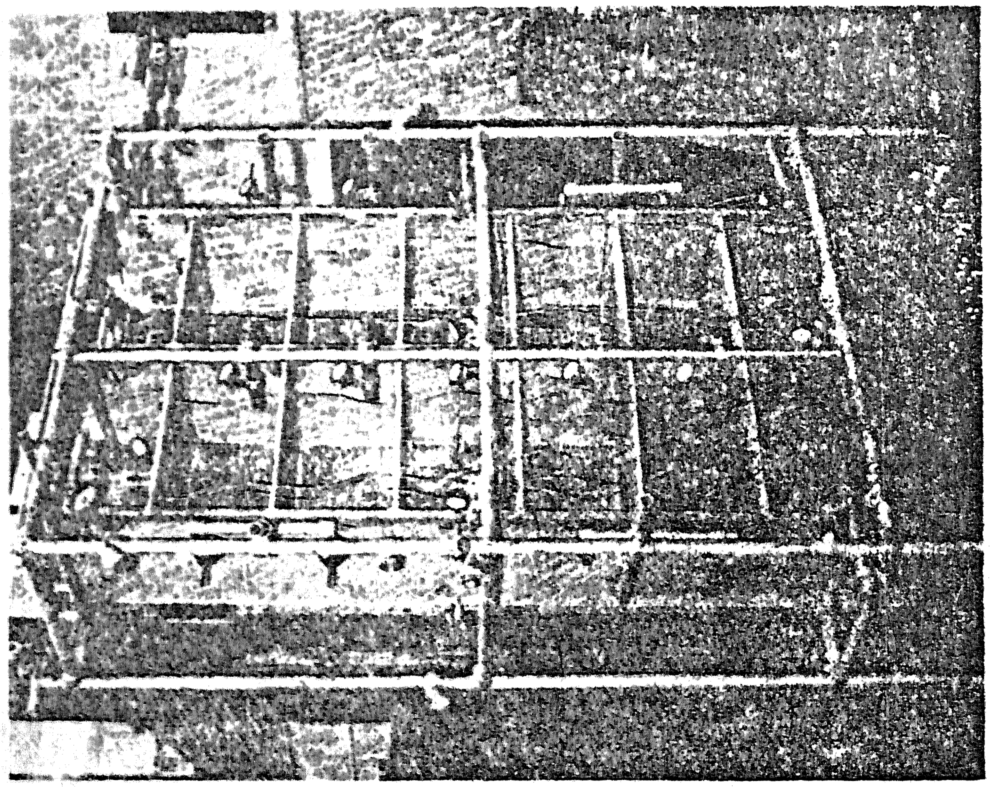


PLATE II BASIC STRUCTURE WITH FLOORS

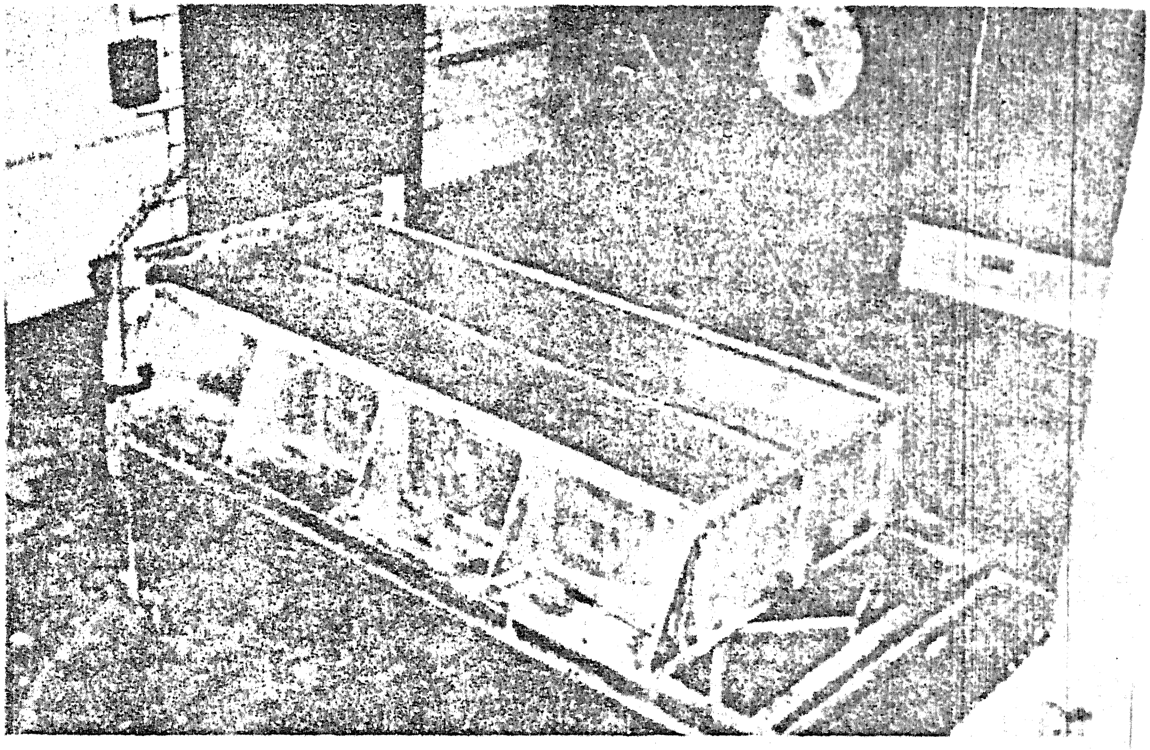


Plate III Formwork Used in Construction of Buildings

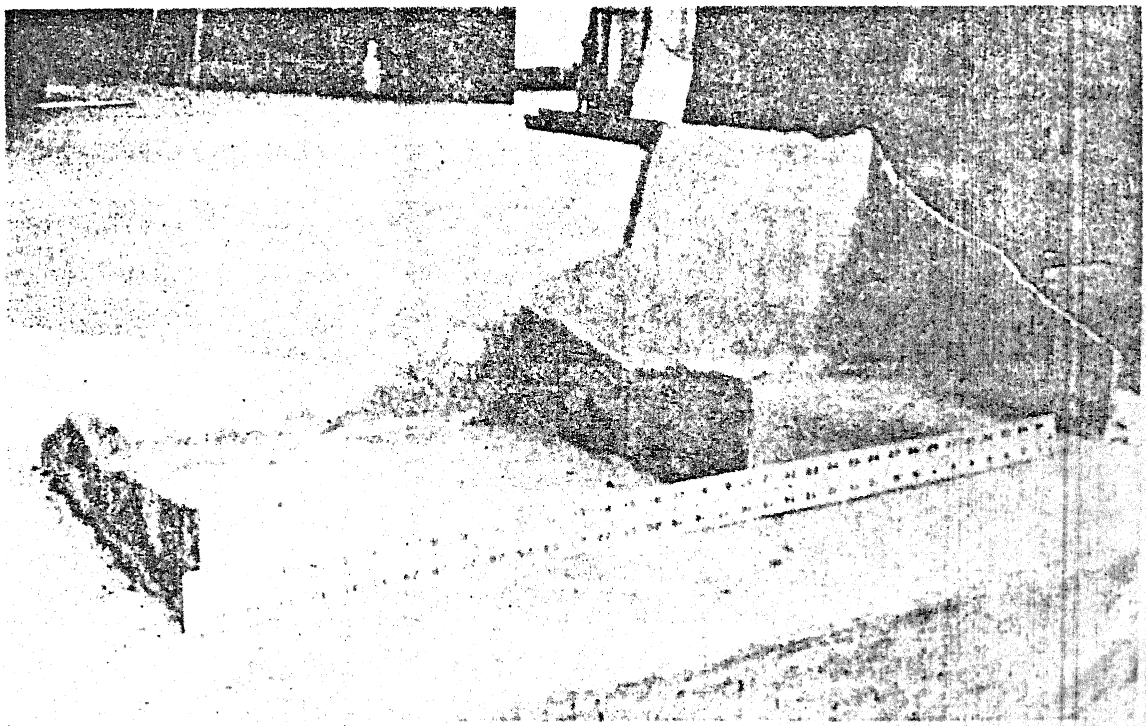


Plate IV Cracking Pattern, Structure A2