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Low-Level Dynamic Characteristics of Four Tall Flat-Plate Buildings in New York City

by

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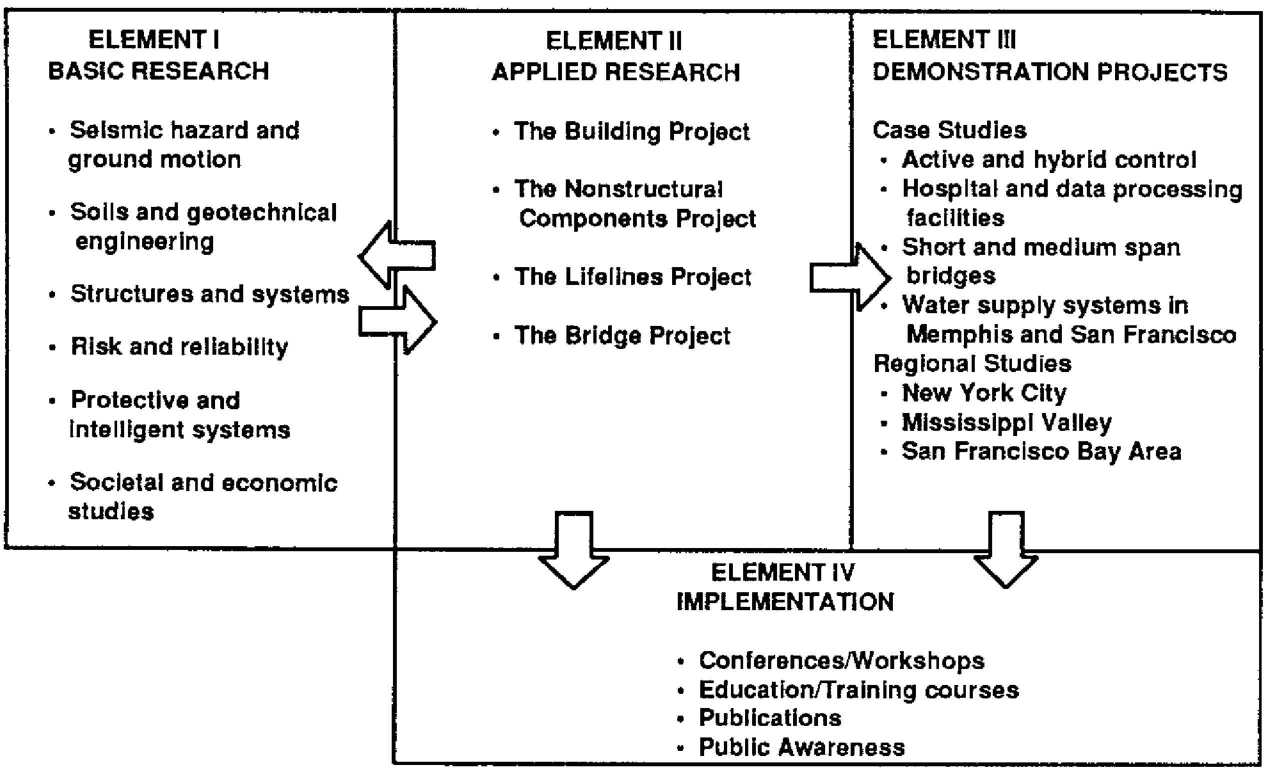
PREFACE

The National Center for Earthquake Engineering Research (NCEER) was established to expand and disseminate knowledge about earthquakes, improve earthquake-resistant design, and implement seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures in the eastern and central United States and lifelines throughout the country that are found in zones of low, moderate, and high seismicity.

NCEER's research and implementation plan in years six through ten (1991-1996) comprises four interlocked elements, as shown in the figure below. Element I, Basic Research, is carried out to support projects in the Applied Research area. Element II, Applied Research, is the major focus of work for years six through ten. Element III, Demonstration Projects, have been planned to support Applied Research projects, and will be either case studies or regional studies. Element IV, Implementation, will result from activity in the four Applied Research projects, and from Demonstration Projects.



Research in the **Building Project** focuses on the evaluation and retrofit of buildings in regions of moderate seismicity. Emphasis is on lightly reinforced concrete buildings, steel semi-rigid frames, and masonry walls or infills. The research involves small- and medium-scale shake table tests and full-scale component tests at several institutions. In a parallel effort, analytical models and computer programs are being developed to aid in the prediction of the response of these buildings to various types of ground motion.

Two of the short-term products of the **Building Project** will be a monograph on the evaluation of lightly reinforced concrete buildings and a state-of-the-art report on unreinforced masonry.

The **structures and systems program** constitutes one of the important areas of research in the **Building Project**. Current tasks include the following:

1. Continued testing of lightly reinforced concrete external joints.
2. Continued development of analytical tools, such as system identification, idealization, and computer programs.
3. Perform parametric studies of building response.
4. Retrofit of lightly reinforced concrete frames, flat plates and unreinforced masonry.
5. Enhancement of the IDARC (inelastic damage analysis of reinforced concrete) computer program.
6. Research infilled frames, including the development of an experimental program, development of analytical models and response simulation.
7. Investigate the torsional response of symmetrical buildings.

*The evaluation of existing buildings for seismic effects has been one of the main goals of the **Building Project**. The primary emphasis has been on concrete structures that were designed only for gravity loads. One problem in the evaluation and design of structures for dynamic loads is the accurate analytical representation of the stiffness and damping properties. This report presents the results of field tests on four flat-plate structures, which are a very common type of structural system in the East. Such tests on real buildings include the effects of the interaction of walls with the other elements. The low-level ambient wind vibration tests help the calibration of analytical methods, especially in the determination of the effective width of floor slabs.*

ABSTRACT

Many reinforced concrete structures utilize flat plates to provide lateral resistance when architectural constraints prevent wide-spread use of shear-walls. Understanding the resistance of flat-plate frames to large lateral loads is important for serviceability as well as seismic vulnerability assessment of hundreds of buildings on the East Coast. In February of 1991, the authors collected ambient vibration measurements to study the behavior of four flat plate, reinforced concrete structures in Manhattan ranging from 27 to 52 stories. All but one structure rests on a rock supported foundation. This report presents the development of ambient vibration analysis software based on the fast Fourier transform. Long ambient vibration records allow accurate power spectrum estimation. A robust peak picking method, also tailored for ambient vibration data, facilitates the interpretation of auto-power and phase spectra. Damping estimates based on spectral peak band-widths are very sensitive to bias and leakage errors in the spectrum estimate However, root-mean-square statistics of acceleration as well as of velocity and displacement can reasonably be estimated from the auto-power spectrum of response acceleration. Measured fundamental periods are shorter than those calculated from the 1982 UBC formula, but are longer than those calculated from the 1988 UBC Code or the proposed NYC Seismic Code. The results presented herein provide a base-line set of periods, deflections, and damping ratios to be compared to results expected to be obtained during strong winds. Periods estimated from ambient, mostly wind-induced vibration measurements are used to calibrate finite element models of the structures, and are compared to values calculated from code design rules. A future goal of this on-going research is to relate effective flat plate width to lateral load level at service load levles, i.e., between ambient conditions and strong winds. Estimating dynamic parameters under various loading conditions coupled with ultimate load tests on model structures is intended to reveal the load-dependent stiffness of these structures.

ACKNOWLEDGEMENTS

The structural engineering firm of Rosenwasser/Grossman, P.C., initiated this study, designed the buildings, and arranged access to them. The researchers thank the owners of the four buildings tested, The DeMatteis Organization, Grand Palais Associates, and Rose Associates, for their cooperation in this study. Financial support for this project was provided by Rosenwasser/Grossman, P.C., and The National Center for Earthquake Engineering Research under grant No's. NCEER 91-1011 and 91-1031.

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SECTION 1
INTRODUCTION

Since the late 1960's, building codes for tall structures in New York City have increasingly emphasized structural resistance to wind and other lateral loads. Forthcoming New York City Building Code revisions will include seismic provisions and will increase the lateral design loads for many tall structures. Many high-rise structures in New York City are residential, especially in the upper stories. Architectural constraints in high-rise apartment buildings preclude the prevalent usage of shear walls to resist lateral forces. Consequently, in order to enhance their lateral resistance, several hundred buildings have incorporated, and rely upon, flat plates. In the structures studied herein, the flat-plate system is designed to resist a considerable portion of the lateral loads, the remainder of which is carried by shear walls interacting with the frame. In existing design codes for seismically active regions of the country, the base shear resistance of the structure is prescribed as a function of the structure's first natural period. Codes provide simplified formulas for estimating a building's fundamental period at its ultimate capacity. However, the actual dynamic properties of the structure at service load levels and at limit state levels may differ considerably from values estimated using codified formulas. Periods computed in the design process, which correspond to a 100-year wind producing roof deflection of H/400, are longer than the measured ambient periods, which correspond to deflections as small as H/ 2,000,000. In addressing wind response, serviceability considerations, and occupant comfort, extensive dynamic measurements of some of the tallest structures in New York City, such as the World Trade Center (aspect ratio = 6), and several other slender concrete structures (aspect ratio ≥10), have been undertaken in the past [Grossman 1990]. However, many moderately sized buildings, between 30 and 60 stories, have, as of yet, been overlooked by such dynamic analyses. The current trend toward more slender structures and reduced foot-print areas could result in greater sway in, albeit, shorter structures, and present an engineering challenge not found in squatter, although taller buildings. The combined conditions of the reduction in shear wall areas, more slender structures, consideration of occupant comfort, and more demanding codes with respect to lateral loads call for a method to assess the strength of flat plates in resisting lateral loads at ultimate conditions, as well as the behavior of flat-plate structures at service load levels. This report presents work in progress to meet these challenges. The ambient vibration measurements of this study are being compared to partially completed detailed computer modeling by the designers of the four "as built" reinforced concrete flat-plate framed structures. The design methodology used in the comparison [Grossman, 1987] was fine tuned in a parallel study [Grossman, in progress] using ultimate laboratory load tests of flat-plate sub-structures [Moehle, 1990].

Of key interest is the contribution of several structural and non-structural elements to the structure's lateral resistance, and the degradation of the lateral resistance at greater deflections. The dependency of parameters such as the effective flat-plate width, the effective shear wall stiffness, and the effective coupling-beam moment of inertia, on the deflection of the structure is uncertain, and needs to be determined reliably.

For purposes of comparing lateral sway among different buildings, roof deflections can be expressed as a fraction of the total height of the structure, H. For example, typical roof deflections under ambient conditions are less than H/800, the 100-year wind deflections are on the order of H/400, and seismic deflections should not exceed H/200.

The scale of these structures virtually precludes forced response experiments and traditional modal analysis. Nonetheless, ambient vibrations are very informative and have certain advantages, namely:

1. The length of time for data recording can be arbitrarily large, allowing for long-duration spectral averages and, hence, improved spectral resolution.

2. Structures vibrating in ambient conditions (at small amplitudes) behave more linearly than structures responding to earthquakes. Structural parameters, estimated from response records alone, are time-invariant if the excitation is stationary and the structure exhibits linear elastic behavior over the course of a single measurement record.
3. The variance of the response acceleration is nearly independent of the section of the data record being analyzed. Adjusting the recorder gains to the known signal level before recording begins, maximizes the signal-to-noise ratio of the recording, without the risk of clipping the data.
4. Comparing the motion of the structure subjected to forces during strong winds to pre-determined thresholds of human comfort or perception is useful in assessing serviceability.

The immediate objectives of this study are to:

1. Develop parameter estimation software for the analysis of ambient vibration measurements from large scale structural systems. The software package computes auto-power spectra and phase spectra between a "measurement" or "response" sensor and a "reference" sensor. It also picks spectral peaks, a feature which facilitates the estimation of the following dynamic parameters: natural frequency, amplitude, phase, damping ratio, and root-mean-square displacement, velocity, and acceleration. The programs require discrete building-response (output) time-records only.
2. Verify the results from the programs developed in step 1 with a parallel but independently developed routine. Verify the root-mean-square computations with small-scale tests on laboratory models.
3. Compare experimentally estimated periods with periods computed (in a parallel study) by finite-element modeling of the "as-built" structure.
4. Establish a set of base-line parameters for comparison with future tests during different

wind conditions.

The <u>long-range objectives</u> of this study are to:

1. Assess the actual contribution of flat-plates, shear walls, and coupling beams to the overall lateral stiffness in four similar, reinforced concrete structures.
2. Compare the buildings' compliance with current and proposed New York City design codes for wind and seismic forces respectively.
3. Compare the natural periods of structures under construction to their periods after some wind storms. Model the measured buildings in their "as built" condition using state of the art software not available to the design team at the time the structures were designed. Investigate the influence of partitions and cladding on the building's response to lateral loads.
4. Investigate the influence of foundations and soil conditions on the measured building response at different periods.

In conducting the measurements and analysis, the researchers enlisted equipment and expertise from the Lamont-Doherty Geological Observatory of Columbia University (L-DGO), and from the Department of Civil Engineering and Operations Research of Princeton University. The buildings measured were designed by the firm of Rosenwasser/Grossman, P.C. L-DGO has a wide interest in the measurement and analysis of earthquake-induced ground motions. It provided the geophones, accelerometers, recording instruments, and some of the pre-processing and analysis hardware used in this study. Professor Shi Yuan's experience in ambient vibration analysis expedited the development of a systematic and robust software package. The spectral analysis routines were written at Princeton University's Department of Civil Engineering and Operations Research, and verified by methods independently developed at L-DGO.

Following this introduction, Section 2 contains a description of the four buildings chosen for the study. Section 3 reviews the standard code procedures of estimating a building's period. Sections 4 and 5 present the measurement and experimental data analysis methods respectively. Section 6 compares the finite-element results to the experimental results. Section 7 discusses the research underway to evaluate the resistance of flat plates to lateral loads, and Section 8 contains the conclusions.

SECTION 2
DESCRIPTION OF THE BUILDINGS

The four reinforced-concrete frame structures each represent a common type of east-coast construction; the design philosophy for all the buildings requires using flat plates to improve resistance to lateral forces. Buildings A and B were under construction during the measurements. Building A is a new building and was clad up to two-thirds its height at the time of the measurements; it was not occupied. It had interior partitions up to the 45^{th} floor. The partitions' mass was positioned (stored) in the upper stories, although the partitions were not yet installed. Building B was a new, bare, unclad, and unoccupied concrete frame at the time of the measurements. Buildings C and D were completed and occupied during the measurements; they both had brick cladding. Building D was constructed during the mid 1970's, was topped-out but remained partially un-clad for several years during the 1970's recession. It was finished several years later and is now fully occupied. Figures 2-1 to 2-4 describe the typical structural floor plans, the elevation views of the four buildings, and other pertinent information. Table 2-I summarizes some of the building features.

TABLE 2-I Overview of the Four Buildings

	A	B	C	D
Number of Stories	52	40	27	48
Effective building height	486 ft.	423 ft.	248 ft.	460 ft.
Inter-story height	9'-0.5"	9'-8"	8'-8"	8'-10"
Foot Print (NSxEW)	112' x 92'	80.5' x 90'	80' x 121'	176' x 145'
Aspect Ratio (NS, EW)	4.3 5.3	5.3 4.7	3.1 2.1	2.6 3.2
Foundation	piles	rock	rock	rock
Number of Load-Bearing Columns	31	27	42	54
Thickness of the floor slab	8.5 in.	8.5 in.	8 in.	8 in.

Building A is the only building of the four utilizing a pile foundation. Twenty-five feet of fill overlays 90 to 130 feet of poorly graded, saturated sands with little silt, having standard penetration test blow counts (N values) ranging between medium compact ($10 < N < 30$) at the top 50 feet of the sand strata to compact ($N > 30$) at the deeper strata (> 75') where the piles were fetched. These strata occupy a portion of the southern end of Manhattan. They have a long history of settlement of existing buildings when, at adjacent lots, displacement piles are driven (by impact hammers) to support new structures. Augured piles were therefore recommended for Building A when in close proximity to adjacent existing structures, in order to reduce settlement that would have been caused by the vibration from impact hammers. However, the augured piles were difficult to control during the construction period because of loss of ground into the augured shaft.

The water table is approximately 10 feet below the fill (35' to 40' below street level) and liquefaction of the top strata, while a remote possibility, needed not to be considered for this structure in accordance with the existing or newly proposed NYC Code. Piles are long (90 feet minimum for the augured piles and about 110 feet for the driven pipe piles). Even if some liquefaction were to occur, it is unlikely that it would cause the loss of building support. S3 = 1.5 would have been the appropriate site category and coefficient for this structure had it been designed according to the now newly proposed NYC Seismic Code. The building's design preceded the proposed NYC Seismic Code.

Buildings B and D are supported by spread footings, bearing on rock of class 3-65 and 2-65 [20-40 ton/sq.ft. capacity] and the proposed NYC Seismic Code assigns a site coefficient of So = 0.67 for such sites. Building C is supported on spread footings and short piles to rock [class 3-65, 20 ton/sq.ft.] and its site coefficient will require further study (but is likely to be S1 = 1.0) .

All four buildings are considered by the proposed NYC Seismic Code to be Dual Systems having concrete shear walls with concrete Ordinary Moment Resisting Frame [OMRF (Rw = 5)].

Concrete ordinary moment resisting frames (OMRF's) are, in these cases, flat plates without spandrel beams. This system became popular in eastern U.S. cities after the Second World War, initially with spandrel beams, but since the 1970's often without them. The flat plate is therefore an important lateral load-resisting structural member.

Shear-wall frame interaction is present in all four structures. In building A, for example, about 50% of the total lateral overturning moment is resisted by shear deformation of the columns and slabs and the remainder by flexural action of the coupled structural walls. Recent laboratory testing [Hwang and Moehle 1990, 1991a, 1991b] and a sensitivity review [Grossman 1991] allow determination of the flat-plate effectiveness at different lateral load levels. Other studies [Grossman 1987, Moehle and Wallace 1990] provide recommendations to estimate the structural wall stiffness acting under varied gravity and lateral loads. A follow-up study will attempt to verify these earlier studies by comparing the measured dynamic properties of the structures with the computed dynamic properties obtained using the methodologies proposed in Section 7 to estimate stiffnesses.

The flat plates were designed to support a considerable portion of the lateral loads in addition to gravity loads. The column-slab joints were designed to transfer large moments and continuity of bottom mat reinforcing was required to account for reversal of moments. In these structures the integrity requirements of the 1989 ACI Code were generally observed, even though they were constructed before such requirements became mandatory.

FIGURE 2-1 BUILDING A - Typical Floor Plan and Elevation

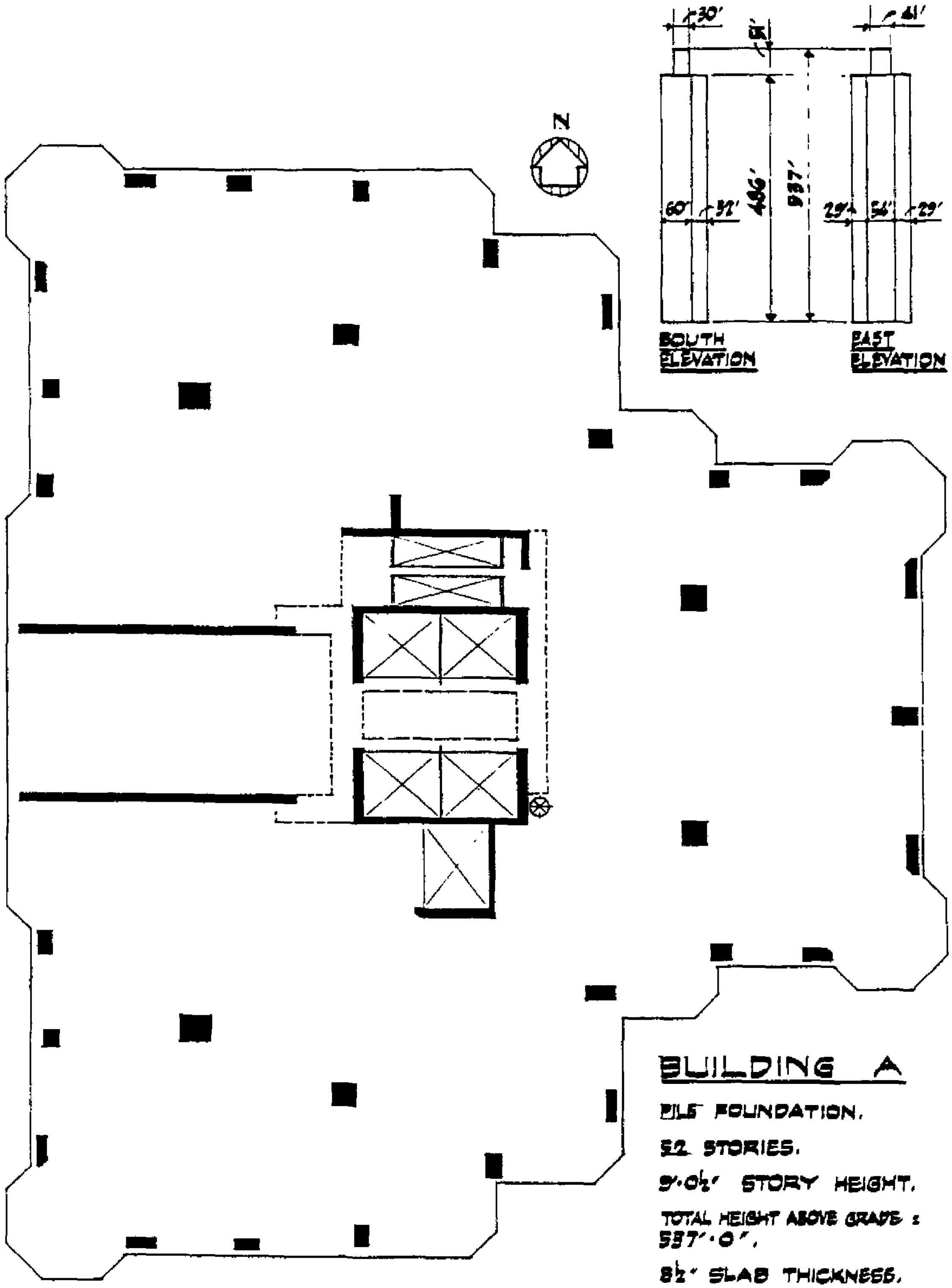

FIGURE 2-2 BUILDING B - Typical Floor Plan and Elevation

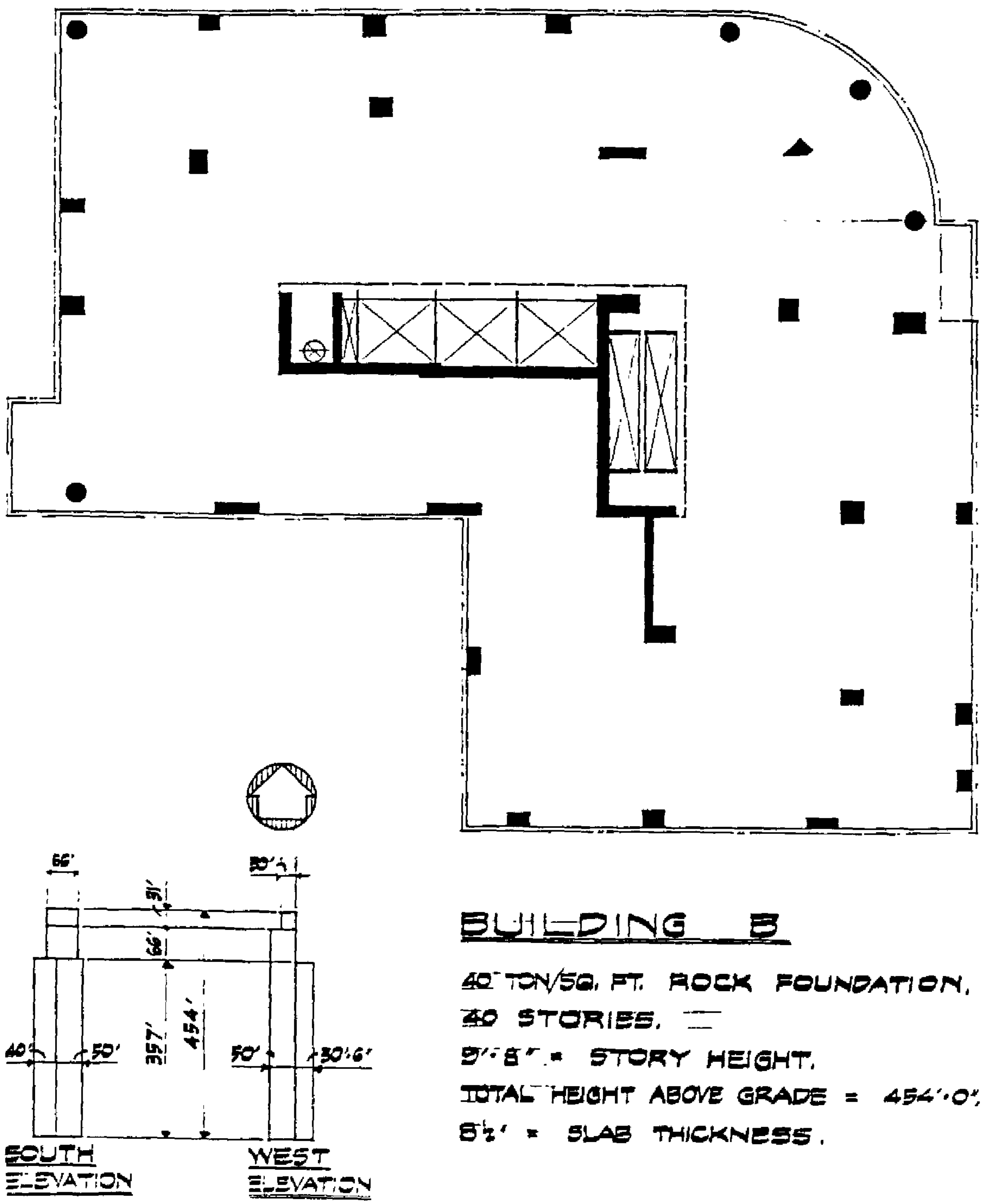

FIGURE 2-3 BUILDING C - Typical Floor Plan and Elevation

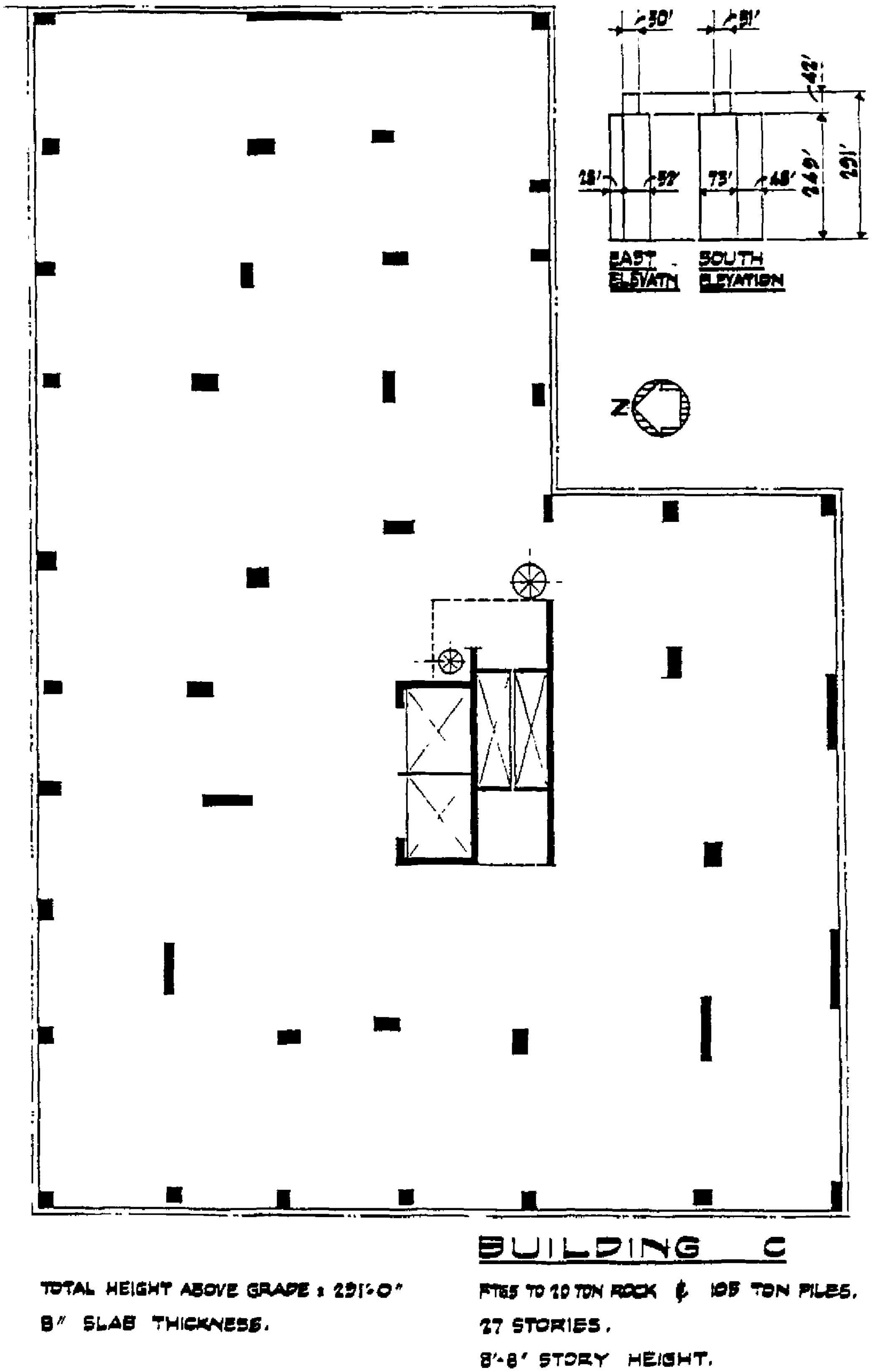

FIGURE 2-4 BUILDING D - Typical Floor Plan and Elevation