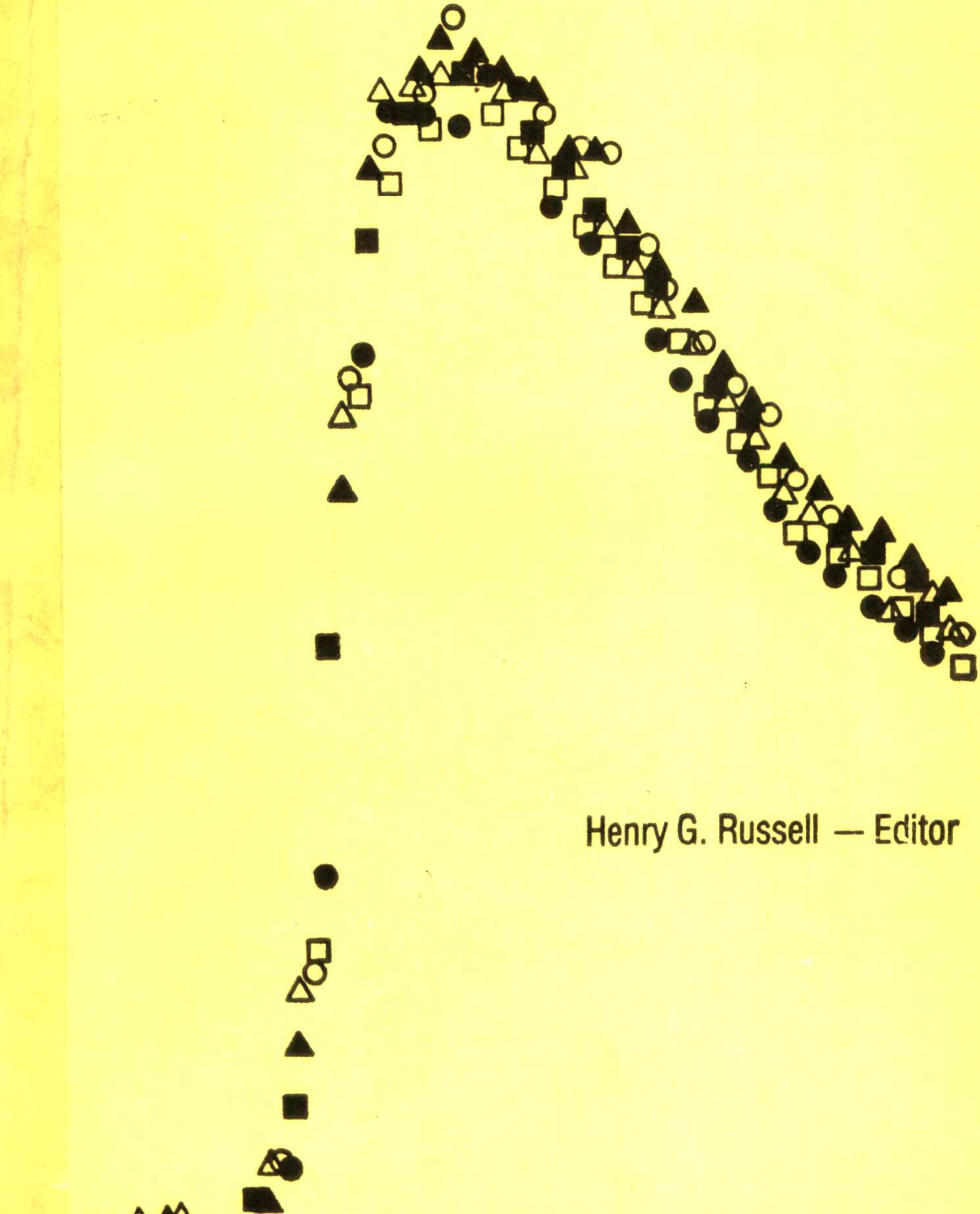
High-Strength Concrete



Henry G. Russell — Editor

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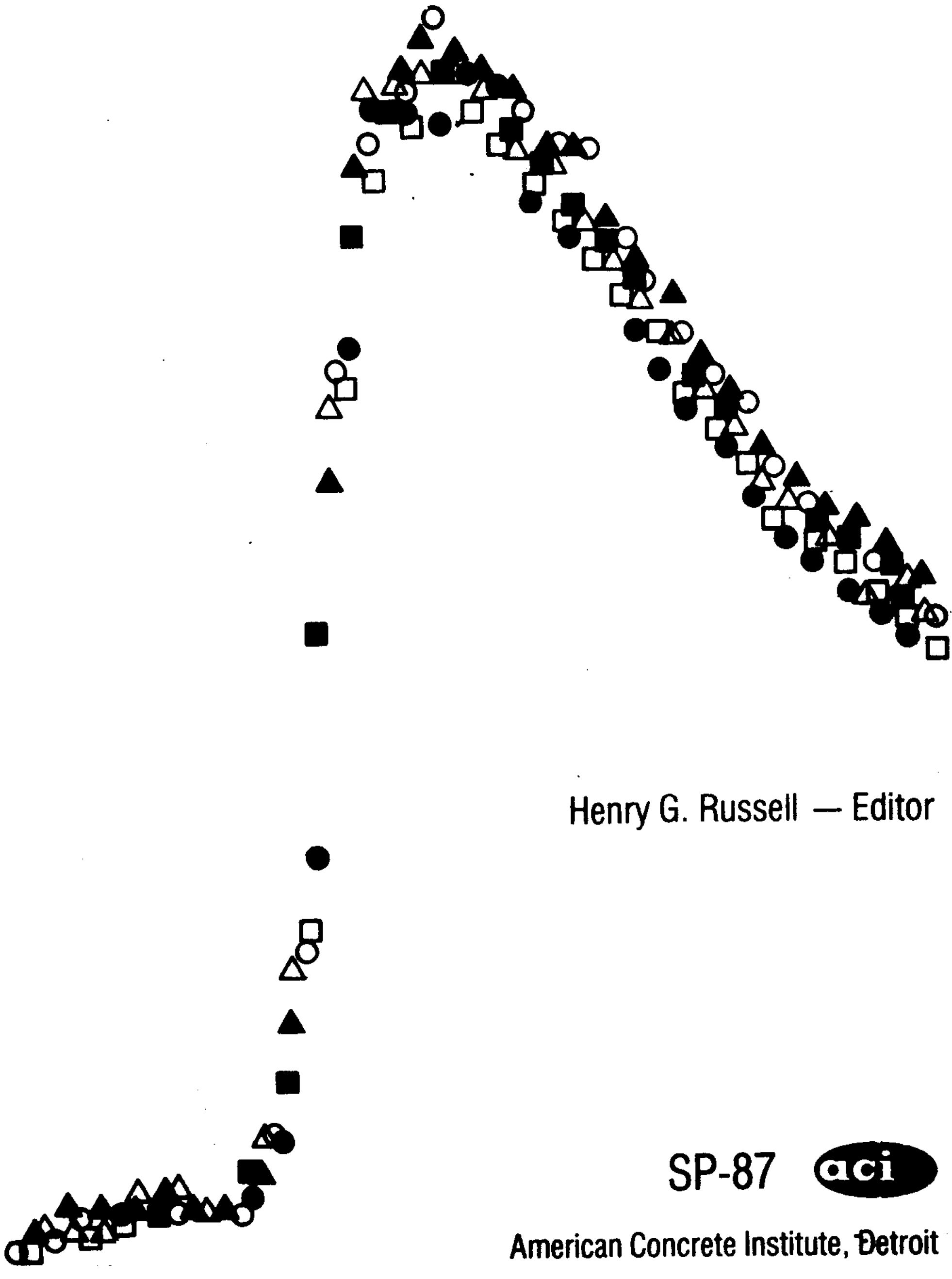

Henry G. Russell — Editor

SP-87

American Concrete Institute, Detroit

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PREFACE

High-strength concretes are used frequently in applications requiring slender members to carry large loads or span long distances. The purpose of this publication is to highlight applications of high-strength concretes, innovative approaches to their use, design implications, and research results. This volume is divided into two parts. Part 1 deals with applications of and innovations with high-strength concrete. Part 2 contains papers that describe design implications and research.

RECENT ACI ACTIVITIES

In 1979, ACI Committee 363--High-Strength Concrete was organized with the mission of studying and reporting information on high-strength concrete. As a first step toward accomplishing its mission, the "State-of-the-Art Report on High-Strength Concrete" was published in the July/August 1984 ACI JOURNAL, with discussion appearing in the January/February 1985 JOURNAL. The committee also sponsored a session on high-strength concrete at the 1982 Annual Convention and co-sponsored with Committee E703 a seminar on high-strength concrete at the 1983 Annual Convention. In 1984, a session entitled "High-Strength Concrete: Applications and Design Considerations," was held at the Fall Convention; and in 1985, two sessions on "Research and Experience with High-Strength Concrete" were sponsored at the Fall Convention.

Papers presented at the 1984 and 1985 Fall Conventions form the basis of this special publication. Fifteen papers were presented at the technical sessions, of which 14 are published in this symposium volume. Contributions were received from four different countries.

APPLICATIONS AND INNOVATIONS

Early applications of high-strength concrete emphasized its use to reduce column dimensions. More recently, high-strength concrete has been used to meet special project objectives such as large composite columns and stiffer structures. In turn, the use of high-strength concrete has prompted the application of more stringent quality control requirements.

In the paper 75-Story Texas Commerce Plaza, Houston--the Use of High-Strength Concrete, high-strength concrete as a composite material with structural steel is discussed. The author suggests that a composite section with high-strength concrete permitted an accelerated construction schedule, smaller column sizes, a more economical structural frame, and a greater stiffness in the structure as a whole.

Producers of prestressed, precast concrete products have traditionally used relatively high-strength concretes to reduce prestressing losses, obtain early release from formwork, and reduce member sizes. But, more recently, high-strength concretes are being used as a means of increasing the capacity of long-span members, controlling deflection, and in other more sophisticated applications. Some of these are discussed in Impact of High-Strength Concrete on Design and Service Behavior of Prestressed Precast Members.

The standard ACI procedures for establishing mix proportions may not be appropriate for high-strength concretes produced with higher than normal cement contents and high performance water-reducing admixtures. In geographic areas where high-strength concretes have not been used previously for large structures, it is important to evaluate available materials carefully and to identify expected levels of performance. In High-Strength Concrete in Seattle, the series of tests used to evaluate alternate mix materials, determine heat of hydration, and obtain mechanical properties of the concrete are described.

Development and research on high-strength concrete in France are described in the paper entitled High-Strength Concrete: How to Use it Every Day. In Canada, the use of silica fume and other special materials to produce a 13,000 psi concrete in the field are reviewed in Development and Experimental Use of a 90 MPa Field Concrete. Mechanical properties of the concrete are reported. The market for high-strength concrete has evolved gradually as a result of cooperative effort between the designers, contractors, concrete suppliers, and testing laboratories. In Statistical Controls for High-Strength Concrete, some methods of evaluating the laboratory test results of the compressive strength of high-strength concrete are discussed.

DESIGN IMPLICATIONS AND RESEARCH

For design strengths above 6,000 psi, the designer must be aware that many of the existing standards and codes are based on lower strength concretes. Engineering judgement may be necessary for utilization of higher strength concretes. Information needed by the design and construction professional will come from ongoing research. Part 2 of this symposium volume describes some of the completed and ongoing research. The applicability of existing design criteria for higher strength concretes is evaluated.

Current equations relating modulus of elasticity, tensile strength, and other mechanical properties of concrete to compressive strength are largely derived on the basis of data gathered from low- and moderate-strength concretes. The potential significance of the mechanical properties for design are critically examined in Design Implications of Current Research on High-Strength Concrete. Particular attention is given to areas where present ACI code provisions may not apply. In High-Strength Concrete--Material Properties and Structural Behavior, the properties and uses of high-strength concrete at early and late ages are discussed in detail.

Structural properties of high-strength concrete members are examined in the papers Structural Bending Properties of Higher Strength Concrete, Shear Tests of High- and Low-Strength Concrete Beams with Stirrups, and Reinforced Corbels of High-Strength Concrete. In all three papers, comparisons are made between laboratory test results and existing design procedures.

To ensure adequate ductility in columns, confinement of the concrete is necessary. In Lateral Reinforcement for High-Strength Concrete Columns, equations for predicting the performance of confined high-strength concrete elements are presented.

One alternate way of enhancing ductility is through the effective use of fibers. The principles and results for this approach are discussed in Properties of High-Strength Fiber Reinforced Concrete. The biaxial strength envelope and failure mechanism for high-strength concretes are discussed in detail in Behavior of High-Strength Concrete under Uniaxial and Biaxial Compression.

Committee 363 wishes to thank all authors who have contributed to this volume and to the staff of ACI who helped organize the symposiums and prepare this publication. Thanks are also due to the members of Committee 363 and all reviewers of papers. Without their cooperation, publication of this symposium volume would not have been possible.

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Chairman, ACI Committee 363

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75-Story Texas Commerce Plaza, Houston — the Use of High-Strength Concrete

By Joseph P. Colaco

Synopsis: The article describes the use of high-strength concrete in the 75-story composite frame for the Texas Commerce Plaza in Houston. The advantages of the high-strength concrete were to reduce column sizes and to increase stiffness. All the concrete in this tower (approximately 100,000 cyd.) was successfully pumped, the highest placement being almost a 1,000' above the street level.

Keywords: columns (supports); concrete construction; high-rise buildings; high-strength concretes; pumped concrete; stiffness.

2 Colaco

Joseph P. Colaco received his PhD in Civil Engineering at the University of Illinois in 1965 and joined Skidmore, Owings & Merrill, Chicago office that same year. In 1969, Mr. Colaco joined Ellisor Engineers, Inc., Houston, Texas; in 1975, he and two partners opened their firm of consulting structural engineers, CBM Engineers (previously named Colaco Engineers, Inc.) in Houston, Texas.

I. INTRODUCTION

The Texas Commerce Plaza Tower in United Energy Plaza is a 75-story office building in downtown Houston. The design was started in 1978 and the structure was completed in 1981. The structure is the tallest composite building in the world and the tallest building west of the Mississippi at the present time.

A photograph of the building is shown in Figure 1. Figure 2 shows the general architectural layout of a typical floor plan and the essential elements of the structural system. The exterior structure of the building has columns placed at 10' (3m.) on centers on four sides but on the fifth side, there is an 85' (26m.) clear span. The exterior columns are composite using a steel erection column and cast-in-place concrete. There is also a cast-in-place concrete 5' (1.5m.) deep spandrel beam at each level (see Figure 3). The interior columns and floor framing use structural steel. The foundation of the tower is a 9'-9" (3m.) thick concrete mat, 63' (19.2m.) below grade. A more detailed description of the building is given in an article by Pickard (1). The exterior composite system, called a "ruptured-tube," is the main element that is used to carry the wind loads on the structure. Since the closely spaced tube is ruptured at the 85' (26m.) clear span front face, the healing of the rupture was required. Several alternates were considered viz. providing diagonals across the front face to complete the "tube" or providing stiff truss elements at discrete floors to tie the ends of the front face together. These alternates were discarded for aesthetic reasons. Hence, the only option was to use the building core. A concrete shear wall is placed next to the front row of elevators and the connection between the interior shear wall and the exterior tube is by very stiff steel link beams in the plane of the floor. There is a secondary stiffness element consisting of a steel girder that spans 85' (26m.) and ties the two triangular concrete front piers of the building. There is a dramatic difference in behavior of the structure. If the rupture were not "healed", the vertical movement from one end of the front face to the other would be approximately 6" at the top of the building.

At the time of the design of Texas Commerce Tower, the state-of-the-art in tall building design in Houston was exemplified by the 50-story concrete One Shell Plaza building and the 55-story InterFirst Tower which is a composite "tube" building. At the start of the Texas Commerce Tower, discussions were held with the Owner on the materials and technology to be used for construction of the building. Due to the poor foundation conditions in Houston, an all-concrete building was ruled out because of its additional weight. The weight would require extremely deep and expensive foundations and would increase the construction time. It was felt, therefore, that the only reasonable choices were the composite building design or an all-steel structure. The architectural features of the building dictated a granite facade which tends to favor the composite building design. Further, experience with the 55-story InterFirst Tower indicated that a composite building could be built fast and economically and minimize foundation premiums. Therefore, it was decided that the building would utilize a composite "tube" system.

At the time of the design of Texas Commerce Tower, the maximum concrete strength utilized in building construction in Houston was 6,000 psi (42MPa) lightweight concrete for One Shell Plaza but most of the building utilized normal weight concrete with 5,000 psi (35MPa) as a maximum strength. This is due to the problems of obtaining higher strengths with river gravel that is a common aggregate in Houston. A 75-story structure utilizing low-strength concrete would result in extremely large columns. The Owners indicated that they would have a maximum exterior column size of 4'x4' at the third floor from a leasing standpoint. Hence, research was conducted on using high-strength concrete to reduce column size. If 5,000 psi were used, the exterior column sizes needed would be 4'x6' which was unacceptable. Discussions with Southwestern Laboratories in Houston indicated that high-strength concrete was being used in limited applications in highway work in Texas. Investigation indicated that if the aggregate were changed from river gravel to a limestone aggregate (which had to be imported into Houston), higher strengths could be achieved. A trial mix was conducted using 7,500 psi (52MPa) as a target design strength. A batch of this concrete was placed on a 24-story tall concrete building in the heat of the summer months to try to simulate a worst case condition. The results were very gratifying. Further discussions with Turner Construction (the Contractor on Texas Commerce Tower) suggested the use of high-strength concrete as a way to minimize costs and column sizes. This analysis confirmed published literature that economical construction is obtained by using high concrete strengths and the lowest reinforcement percentages. Turner retained The Concrete Associates of Dallas as consultants to review mix designs to come up with recommendations for the high-strength concrete. After extensive evaluation and testing, it was concluded that 7,500 psi (52MPa) concrete could be produced in Houston in sufficient quantities and with sufficient quality control to proceed with the design of the project.

II. HIGH-STRENGTH CONCRETE

The outcome of the design was that 7,500 (52MPa) normal weight concrete was utilized in exterior columns, spandrel beams and shear wall from the mat foundation upto the 7th floor, and 6,000 psi (42MPa) was utilized for these elements from the 8th to the 30th floors. The mat foundation itself utilized 6,000 psi (42MPa) concrete. An extensive discussion of the mix designs, quality control and results of the entire program are described by Cook(2). Due consideration was taken of the Contractor's requirement that the concrete be pumped and also, of hot weather conditions in Houston. Texas Commerce Tower is unique in that all the concrete on the project was pumped with the highest concrete placement being about 1,000' (304m.) above street level. The concrete pump used was a Schwing BPA HDD-15 5000 trailer-mounted, 300 horsepower, 6" material cylinders, capable of 2,800 psi on concrete. The actual pressure ranged from 1,700 - 2,400 psi. No problems were encountered with the pumping operation. The mix designs indicated that 630 lb./cyd. (374 kg/m^3) cement with 157 lb./cyd. (93 kg/m^3) fly ash Type C was adequate for the 7,500 psi (52MPa) high-strength concrete in the project. The slump was 4.5 inches (10cm) and the water/cement ratio was 0.33. An ASTM C494 Type A water-reducing admixture was used with a dosage rate of 3 oz./100 lb. of cementitious material. The 7,500 psi (52MPa) concrete was placed during the period from November, 1979 to May, 1980 and the average 28-day concrete strengths were 8,146 psi (56MPa) while the 56-day strengths were 9,005 psi (62MPa). A similar set of numbers was achieved for the 6,000 psi (42MPa) nominal strength concrete. The 28-day averages were 7,257 psi (50MPa) while the 56-day average was 8,340 psi (58MPa). A degree of conservatism was exercised in the Specifications for this project as this was the first time that high-strength concrete was being used in Houston. In later work, 56-day strengths as opposed to 28-day strengths were considered to be the norm.

III. ADVANTAGES OF HIGH-STRENGTH CONCRETE

There are several advantages of high-strength concrete and they can be summarized as follows:

A. Additional Stiffness: One of the considerations in tall buildings is the restriction of inter-story drift under lateral loads. This is required in order to keep architectural elements from having any distress. Almost all tall building designs are controlled by stiffness requirements and hence, the use of high-strength concrete with its high modulus of elasticity results in a lower inter-story drift for the same member sizes. On this project, nominal 7,500 (52MPa) concrete had a modulus of elasticity of approximately 5.7x10^6 psi (39,330MPa) which is substantially higher than that which is obtainable with 5,000 psi (35MPa) concrete. The net result of this high E value is that the maximum deflection of the building under hurricane wind loads will not exceed 16" (41cm.) at the top of the building for wind in any direction.

B. <u>Damping</u>: Extensive discussions were held with the University of Western Ontario that conducted the wind tunnel analysis for the project. A detailed description of the structural elements of the design is discussed by Banavalkar (3). Since the basic wind resisting elements are concrete members, the damping ratio was 2% whereas for an all-steel building, a 1% damping factor is generally used. This resulted in a much lower peak acceleration in the wind tunnel test. The building accelerations at the top floor of the building were in the range of 18 milli-gs for a 10-year recurrence interval which is below the generally accepted criteria for the threshold of discomfort due to building motion.

C. <u>Axial Shortening</u>: The differential movements of vertical elements in tall buildings are a critical item in the constructability of level floors. In a composite frame, the problem is exacerbated by the fact that the interior columns of structural steel have only elastic axial shortening while the exterior composite columns are subjected not only to axial shortening due to stress but to shrinkage and creep. The use of high-strength concrete which has a higher modulus of elasticity reduces the axial shortening of the concrete columns. The use of limestone aggregate and the use of fly ash (which lowers cement content) reduce the shrinkage of the concrete columns. Axial shortening compensation tables were developed for the entire structure and interior steel column lengths were adjusted at 10-story increments to try to attain level floors. A detailed description of this is given in the paper by Banavalkar (3). In the worst case, at the roof level the columns at the end of the 85' clear span were placed 2.5 inches (6.3cm.) higher than the columns in the middle of the long faces.

D. <u>Construction Techniques:</u> One of the key ingredients of tall building economics is the ability to build the building as rapidly as possible. The General Contractor suggested two techniques both of which accelerated the construction schedule. These techniques were pumping of the concrete in the exterior frame and the use of a custom-made three-story steel formwork assembly that was self-climbing. Each side of the form assembly not only included the column and spandrel forms but also had lifting column system which enabled the formwork to climb. The column forms and spandrel forms were all hinged. One of the advantages of high-strength concrete in this configuration is that the columns and spandrel beams could be stripped early-on due to the low stress level and the relatively high concrete strengths. The average concrete strengths were 3,827 psi (26MPa) at 1-day and 5,218 psi (36MPa) at 3-days for the 7,500 psi (52MPa) concrete. The construction proceeded at the rate of two floors per week which at least equals that for structural steel construction.

IV. CONCLUSION

The use of high-strength concrete on Texas Commerce Tower has proved to be extremely successful in meeting the Owner's objectives, namely: reducing the column sizes (to increase the leasability of the floors); the development of rapid construction techniques; and, the satisfactory performance of the building from a stiffness and motion perception standpoint.

V. ACKNOWLEDGEMENTS:

A project of the magnitude of Texas Commerce Tower involves the hard work of all the team members (Owners, Architect, General Contractor, Concrete Consultant, Concrete Suppliers, etc.). The writer wishes to acknowledge all of them and the CBM Engineers' design team headed by Dr. P. V. Banavalkar and Mr. Tony Abyad.

VI. REFERENCES

1. Pickard, Scott S., "Ruptured Composite Tube Design for Houston's Texas Commerce Tower," Concrete International, July, 1981

2. Cook, James E., "Research and Application of High-Strength Concrete Using Class C Fly Ash," Concrete International, July, 1982.

3. Banavalkar, P. V., "Texas Commerce Tower, Houston (Texas USA)," Proceedings of International Conference on Tall Buildings, Singapore, October 22-26, 1984.

Fig. 1--Texas Commerce Tower in United Energy Plaza, Houston

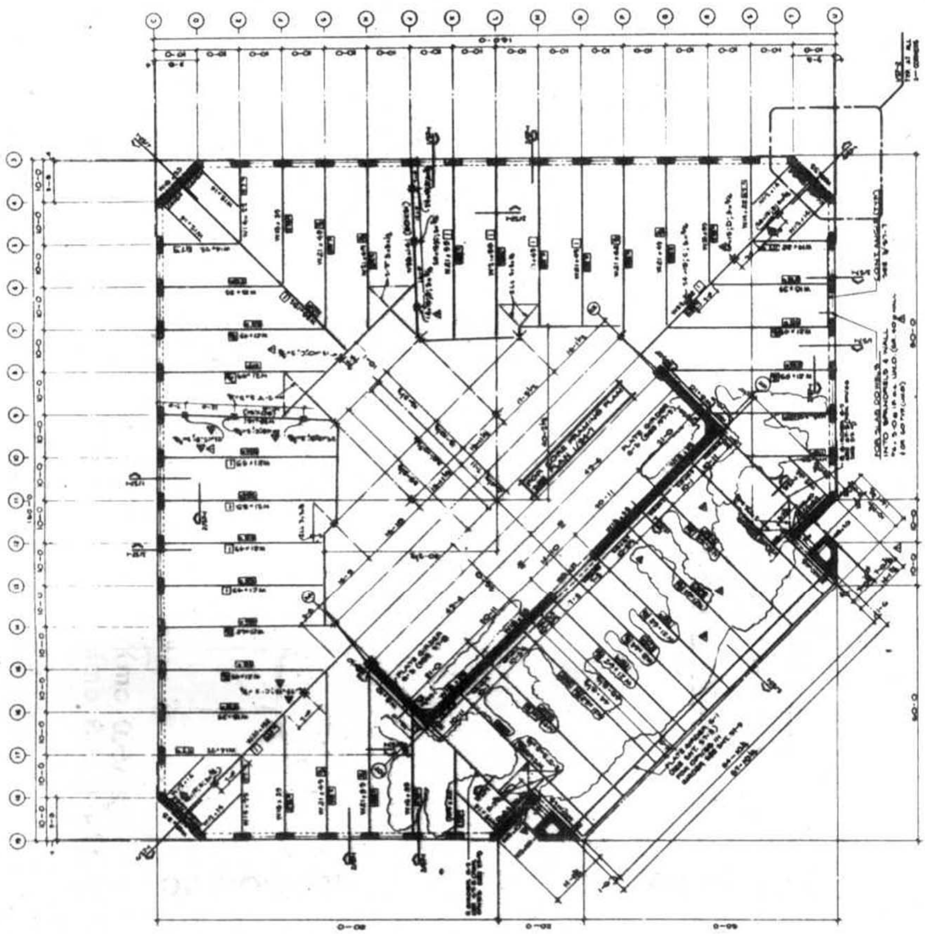

Fig. 2--Typical floor plan

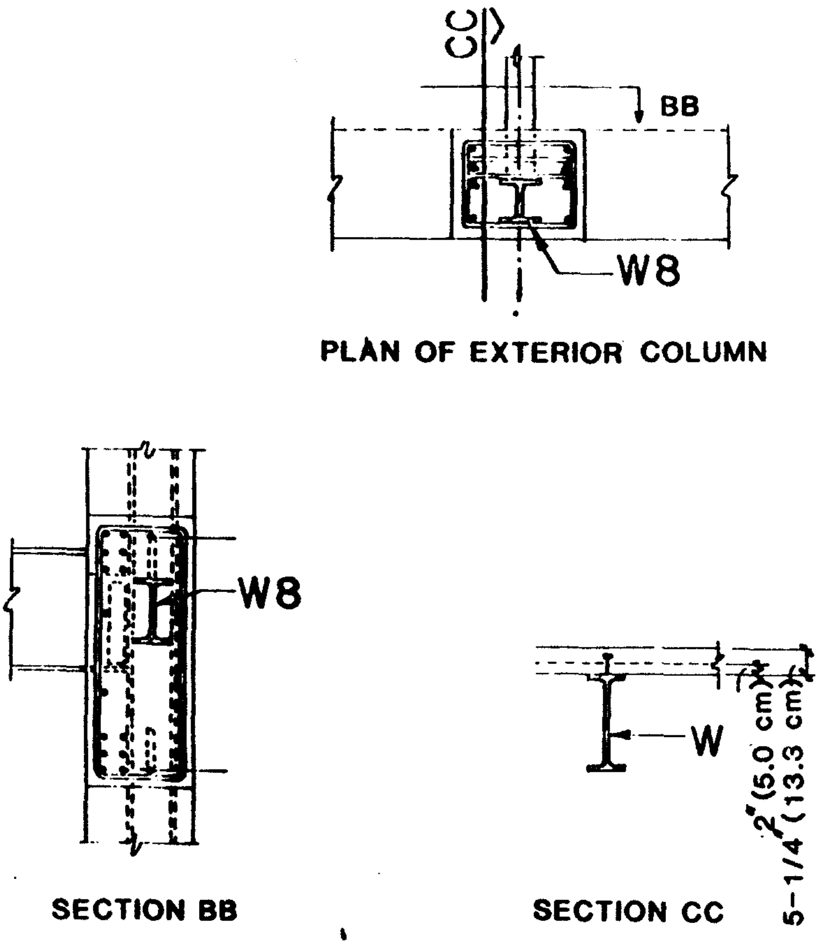

Fig. 3--Column, spandrel, and floor beam details