Time-dependent performance of reinforced concrete columns: Field investigation of a 70-storey building

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Time-Dependent Performance of Reinforced Concrete Columns – Field Investigation of a 70-Story Building

Performance de colonnes en béton armé en fonction du temps – Essais sur nature d'un bâtiment de 70 étages

Zeitabhängiges Verhalten von Stahlbetonsäulen – Felduntersuchung eines 70-stöckigen Gebäudes

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INTRODUCTION

Reinforced concrete buildings in the United States are being constructed to heights greater than 600 ft. (183 m). Within a story, columns shorten only a fraction of an inch. When these shortenings are added over the full height of the structure, the cumulative deformation may be several inches. Both elastic and time-dependent axial deformations of columns may therefore be important design considerations.

To determine the actual behavior of columns in tall buildings, a 70-story structure was instrumented. After columns were cast, installations were made for measuring vertical strains. These field measurements are supplemented by laboratory tests on non-reinforced specimens made with concrete taken from batches used in the building. This report describes the structure, instrumentation, laboratory tests, and initial field measurements.

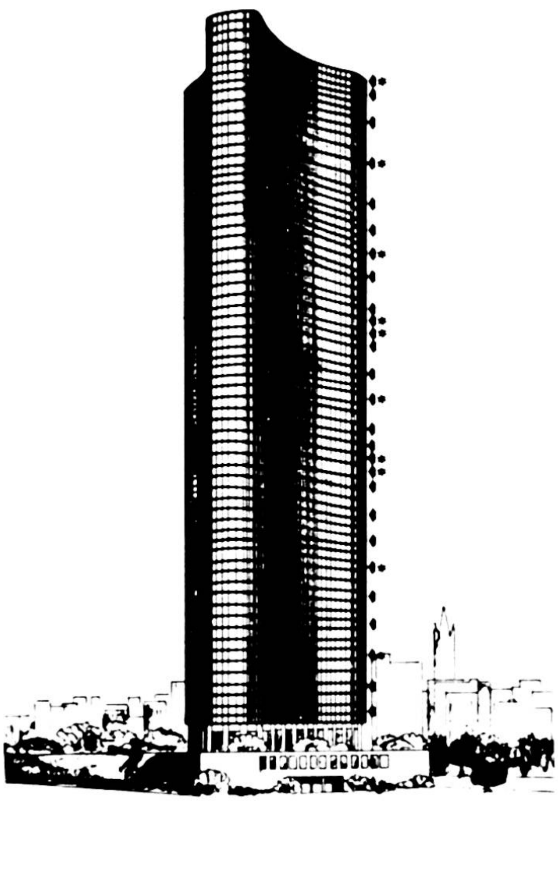

Fig. 1 - Elevation of building

DESCRIPTION OF STRUCTURE

A sketch of the structure is shown in Fig. 1. Total height above grade is 645 ft. (197 m). In plan, the building has three wings shaped as shown in Fig. 2. Each wing is 65 ft. (20 m) wide and extends 117 ft. (36 m) from the center of the building.

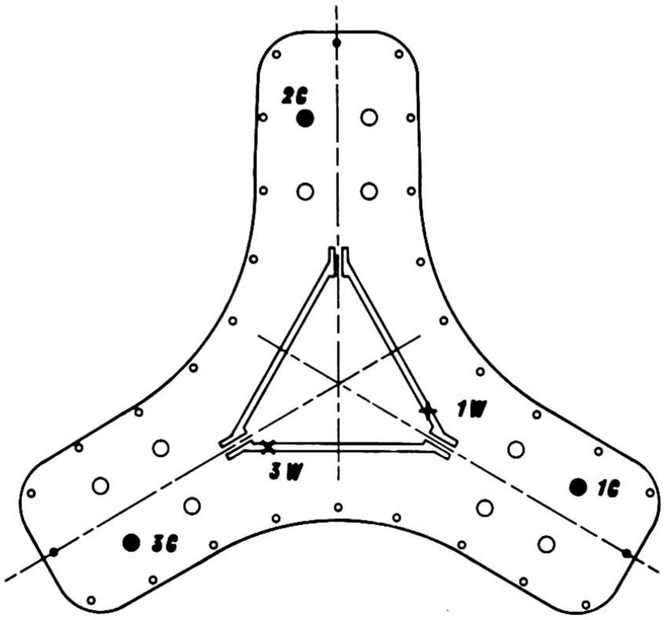

Fig. 2 - Floor Plan

The floors are flat plates 8 in. (20 cm) thick made of lightweight aggregate reinforced with high strength deformed bars. Diameter, design strength of concrete at 28 days, and design yield stess of reinforcement for the interior columns are given in Table 1. Normal weight concrete is used in the columns.

Construction of the first story of the building was started in June, 1966. The 70th story was completed in December, 1967. Weather permitting, the building was cast at the rate of one floor every three working days.

TABLE 1 -- PROPERTIES OF INTERIOR COLUMNS

Story No.	Column Diameter		Concrete Design Strength		Yield Stress of Reinforcement	
	in.	cm	psi	kg/cm^2	ksi	kg/mm^2
1	40	102	7500	528	75	53
11	40	102	7500	528	75	53
12	40	102	7500	528	60	42
16	40	102	7500	528	60	42
17	40	102	6000	422	60	42
29	40	102	6000	422	60	42
30	36	91	6000	422	60	42
34	36	91	6000	422	60	42
35	36	91	5000	352	60	42
43	36	91	5000	352	60	42
44	30	76	5000	352	60	42
58	30	76	5000	352	60	42
59	30	76	3500	246	60	42
68	30	76	3500	246	60	42

FIELD MEASUREMENTS

A Whittemore mechanical strain gage[1] with a gage length of 20 in. (51 cm), is used to measure vertical shortening of the columns and core walls. With an initial gage length of 20 in., the 0.0001 in. (0.0025 mm) dial gage indicates five millionths strain per dial division. Gage installations were made after the columns were cast and forms were removed. Reference discs and a portion of the Whittemore gage are shown in Fig. 3. In taking readings, the Whittemore dial gage is first set to a fixed reading over a gage length determined by a standard bar made of Invar steel. Air temperature and surface temperature of the concrete are recorded using a thermocouple connected to a potentiometer.

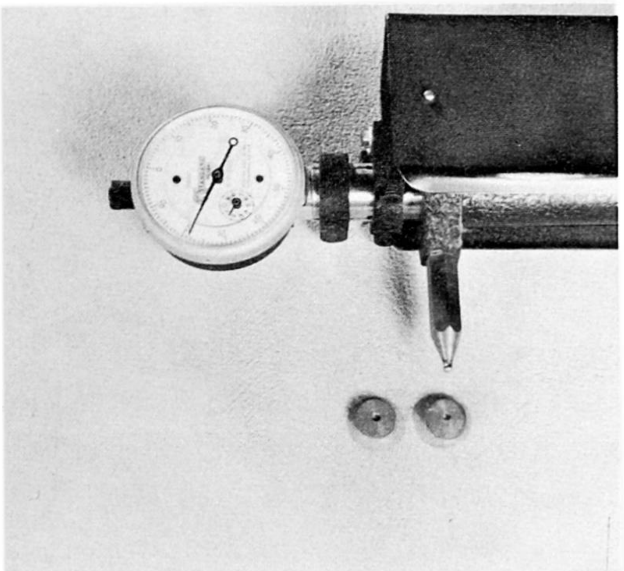

FIG. 3 - Whittemore Strain Gage

Three columns and two locations on the core wall of selected stories are instrumented. These installations are identified as 1C, 1W, 2C, 3C and 3W on Fig. 2. About every third story, Column 1C and core wall location 1W are instrumented with one gage line. Specified stories where these single gage lines are installed are indicated by arrows in Fig. 1. Asterisks in Fig. 1 indicate stories in which all three columns, each with three gage lines, and both core wall locations are instrumented. Stories above and below floors where column sizes change are monitored at installations 1C, 2C, and 3C, each with three gage lines. These gage lines are spaced at about 90 degree intervals around half the column perimeter. The more completely instrumented stories are spaced about every ten floors.

Relative humidity in Column 1C is measured with a Monfore humidity probe[2] at floors 10, 19, 43, 58 and 61. Hollow tubes are cast into these columns to permit measuring humdity at the center of the column, midway between the center and surface of the column, and about 2 in. (5cm) from the surface of the column. Temperature within the humidity wells can also be measured. Surface temperature and interior column temperature agree within ±3F (± 1.7 C).

LABORATORY TESTS

Samples of each of the four concrete mixes used in casting columns and core walls of the building were obtained and brought to the laboratory for tests. For each mix, sixteen 6 x 12-in. (15 x 30 cm) cylinders were cast at the building site. The cylinders were transported to the laboratory the day following casting. At the laboratory, the cylinders were stripped from the molds and stored at 100 percent relative humidity and 73 F (23 C) until ready for test.

Compressive strength and modulus of elasticity are measured 28, 90, and 180 days, and also one and two years after casting. At 28, 90, and 180 days, one cylinder is placed under sustained constant load to measure time-dependent shortening. The applied load produces a cylinder stress equal to 25 percent of the nominal concrete design strength. With each sustained load test, a companion cylinder having no applied load is used to measure drying shrinkage. The cylinders used in this time-dependent study are stored at 50 percent relative humidity and 73 F (23 C) once the test is started.

The coefficient of thermal expansion was measured for each of the four concrete mixes. To do this, one cylinder from each mix was taken from moist storage and sealed in copper foil. Length of these moist concrete specimens was measured at temperatures of 40, 73, and 100 F (4, 23, and 38 C).

PRESENTATION OF DATA

Because of the limited length of this paper permitted by IABSE, only data related to columns in the 1st and 30th stories will be presented and discussed. Concrete used in casting these columns are designated as A and B, respectively. Measured compressive strength and modulus of elasticity versus age for these concretes are shown in Table 2.

TABLE 2 -- MEASURED PROPERTIES OF CONCRETE

Age of Concrete	Compressive Strength, *				Modulus of Elasticity, *			
	Mix A		Mix B		Mix A		Mix B	
	psi	kg/cm²	psi	kg/cm²	10^6 psi	10^6 kg/cm²	10^6 psi	10^6 kg/cm²
28-day Design	7500	528	6000	422	5.00	0.35	4.46	0.31
28 days	7940	558	7810	549	4.80	0.34	5.01	0.35
90 days	9250	650	9530	670	5.78	0.41	4.84	0.34
180 days	9910	697	9790	688	5.84	0.41	6.16	0.43
1 year	10300	724	10210	718	6.59	0.46	6.29	0.44

* Average of two cylinders

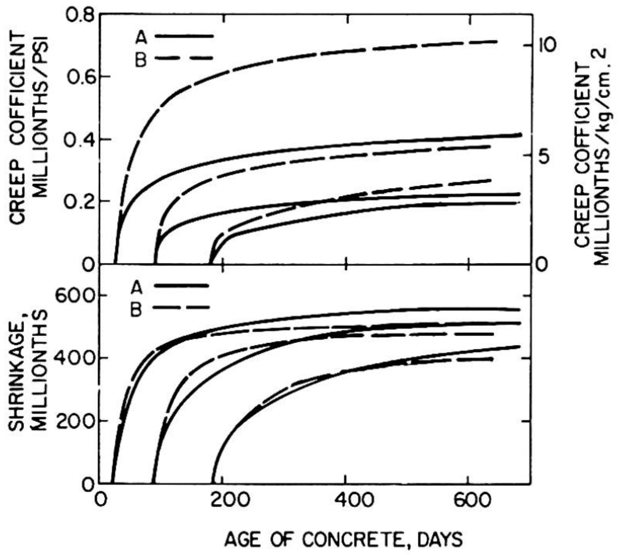

Fig. 4 - Creep and Shrinkage of Concrete

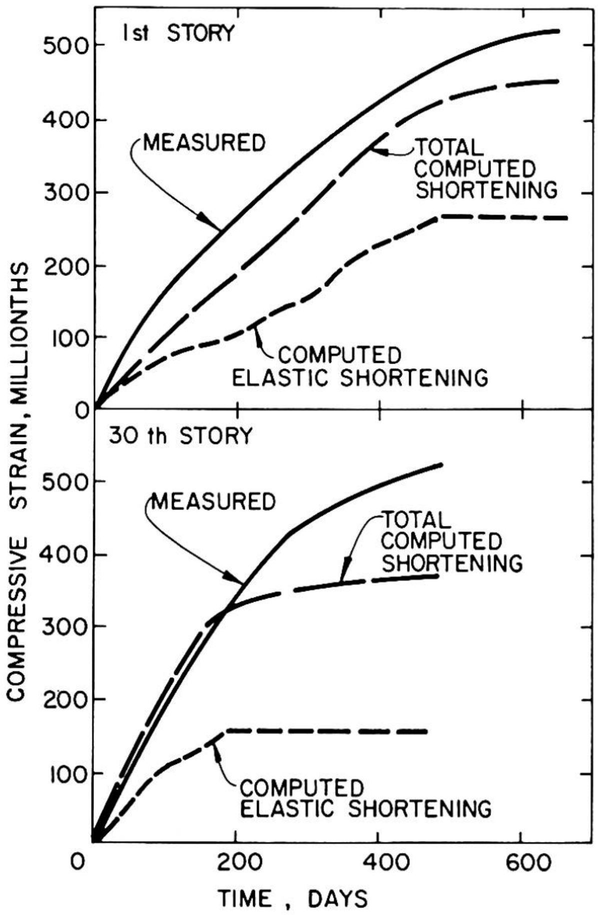

Fig. 5 - Deformation of Columns

Creep and drying shrinkage characteristics of the two field-obtained concrete mixes are shown in Fig. 4. These data are from laboratory tests of the 6x12-in. (15x30 cm) plain concrete cylinders. Cylinders were removed from moist curing and placed under test at 28, 90, and 180 days after casting.

The temperature coefficient measured in the laboratory tests was about 5 millionths per degree Fahrenheit (9 milliionths per degree Centigrade). This value applies over the temperature range of 40F to 100F (4C to 38C).

Measured deformations of the reinforced columns in the 1st and 30th stories are shown in Fig. 5. The curves are the average strains for the 3 columns in each story. Strain readings are adjusted to a column temperature of 73F (23C) using the measured temperature coefficient. Temperature of the columns varied between 40F and 80F (4C and 27C) during this field investigation.

Elastic shortening was computed using the steel percentage and the measured modulus of elasticity of concrete since this value changed with time. This shortening is due to the weight of the structure alone; i. e., columns and weight of a tributary floor area used in design. Increments of load applied to a column were about 37 kips (17 t) per story. Actual time of construction was used in computing column loads. Column reinforcement was 5.5 percent in the 1st story and 3.8 percent in the 30th story.

At the end of construction, computed elastic shortening was about 260 and 160 millionths for the 1st and 30th story columns, respectively. Total measured strain was about 510 millionths in the 1st story columns at 600 days and 500 millionths in the 30th story columns at 400 days.

Relative humidity in the interior of the columns was greater than 90 percent when the column was 18 months old. Most readings at the two interior locations showed a relative humidity greater than 95 percent. Relative humidity of concrete near the surface of the column was difficult to measure accurately due to influence from the atmosphere.

TENTATIVE ANALYSIS

Time-dependent column shortening is affected by volume/surface ratio and the amount of reinforcement. By taking these two factors into account, deformation of columns in a building may be predicted from laboratory tests on small plain concrete cylinders.[3]

Hanson and Mattock[4] have shown that the amount and rate of creep and drying shrinkage of concrete decreases as the volume/surface ratio increases. Tests were made on plain concrete specimens that had volume/surface ratios from 1 to 6 in. (2.5 to 15 cm). Data from these tests were extrapolated to the volume/surface ratios of 10 and 9 in. (25.4 and 22.8 cm) for the 1st and 30th story columns. Thus, size-effects between time-dependent shortening of the laboratory test cylinders and that of the columns were determined.

Pfeifer[5] conducted tests on specimens with equal volume/surface ratio but with reinforcement varying from 0 to 8.4 percent. The tests demonstrated that time-dependent deformation decreases with increasing amounts of reinforcement. Using data from Pfeifer's tests, creep and drying shrinkage of plain concrete cylinders were related to creep and drying shrinkage of specimens with 3.8 and 5.5 percent reinforcement by interpolation. These reinforcement percentages correspond to the amounts in the 30th and 1st story columns.

Using the laboratory test data shown in Fig. 4, creep and drying shrinkage strains for concretes A and B were determined for the same time interval and stress conditions as the field measurements. These strains were modified by factors to account for volume/surface ratio and amount of reinforcement for the 1st and 30th story columns.

By this method, total computed shortenings agree satisfactorily with measured shortenings to the end of construction. Only dead load of the structure was used in computing total shortening. The differences shown in Fig. 5 between measured and computed total shortening after the end of construction may be due to live load effects.

In this tentative analysis it is assumed that effects of volume/surface ratio and amount of reinforcement may be treated separately. It is also assumed that the factors determined for these two effects can be applied to any concrete mix. The extensive test data obtained during this long-time study should permit evaluation and improvement of this analysis.

CONCLUDING REMARKS

The data described and presented in this report are examples of the initial results of a long-term study. It is intended that these measurements of the behavior of the building will be continued for ten years after construction began. Such information should lead to methods of closely predicting the performance of actual structures.

ACKNOWLEDGMENTS

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SUMMARY

A 70-story reinforced concrete building has been instrumented to obtain measurements of time-dependent deformation of columns and core walls. Standard laboratory tests are being conducted on cylinders of concrete taken from batches used in casting the structure. Measurements of column shortening at two levels in the building and of characteristics of the concretes used are presented. It is intended that measurements will continue for a total of ten years after construction began. These tests should provide a correlation between laboratory test data and the performance of prototype buildings.

RÉSUMÉ

Un bâtiment en béton précontraint de 70 étages a été équipé d'instruments pour obtenir des mesures des déformations en fonction du temps sur les colonnes et les murs du noyau. Des tests de laboratoire standards sont faits sur des cylindres de béton pris des mêmes mélanges. Les mesures des raccourcissements des colonnes à deux niveaux du bâtiment et des caractéristiques des bétons utilisés sont présentés. On a l'intention de continuer les mesures pendant 10 ans depuis le début de la construction. Ces tests devraient permettre une comparaison entre les données déterminées au laboratoire et la performance de bâtiments-type.

ZUSAMMENFASSUNG

Ein siebzigstöckiges Stahlbetongebäude wurde mit Instrumenten dergestalt ausgerüstet, dass Messungen über zeitabhängige Verformungen von Säulen und Kernwänden angestellt werden konnten. Standardversuche wurden an Betonzylindern aus im Bauwerk gebrauchten Teilen durchgeführt. Es werden die Messungen der Säulenkürzung auf zwei Höhen des Gebäudes und die Betoncharakteristiken angegeben. Es ist beabsichtigt, die Messungen über zehn Jahre nach Baubeginn durchzuführen. Diese Prüfungen sollten eine Beziehung zwischen Laborversuchen und der Verformung am Versuchsgebäude ergeben.