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Safety During Construction of Concrete Buildings— A Status Report

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Safety During Construction of Concrete Buildings— A Status Report

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CONTENTS

SI Conversion Units

In view of present accepted practice in this technological area, U. S. customary units of measurements have been used throughout this report. It should be noted that the U. S. is a signatory to the General Conference on Weights and Measures which gave official status to the metric SI system of units in 1960. Readers interested in making use of the coherent system of SI units will find conversion factors in ASTM Standard Metric Practice Guide, ASTM Designation E 380-72 (Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103). Conversion factors for units used in this paper are:

<u>Length</u>

1 in = 0.0254* metre

1 ft = 0.3048* metre

<u>Area</u>

1 in^2 = $6.4516^* \times 10^{-4}$ $metre^2$

1 ft^2 = 9.2903×10^{-2} $metre^2$

<u>Volume</u>

1 ft^3 = 2.832×10^{-2} $metre^3$

<u>Force</u>

1 lb (lbf) = 4.448 newton

1 kip = 4448 newton

<u>Pressure</u>, <u>Stress</u>

1 psi = 6895 pascal (Pa), (N/m^2)

1 psf = 47.88 pascal (Pa), (N/m^2)

<u>Mass</u>

1 lb = 0.4536 kg

<u>Moment</u>

1 lbf-ft = 1.3558 newton-metre

<u>Temperature</u>

°C = 5/9 (Temperature °F - 32)

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*Exact value

GLOSSARY

Falsework -	Falsework is the temporary structure erected to support work in the process of construction. It is composed of shores, formwork and lateral bracing.
Formwork - (or forms)	Formwork is a part of the falsework which directly supports freshly placed concrete and molds the concrete to the desired size and shape.
Lateral - Bracing	Lateral bracing is a part of the falsework which consists of usually diagonal members and resists lateral loads on the falsework.
Reshores -	Reshores are shores placed firmly under a stripped concrete member where the original formwork has been removed.
Shores -	Shores are either vertical or horizontal members which support directly the formwork.

SAFETY DURING CONSTRUCTION OF CONCRETE BUILDINGS - A STATUS REPORT

H. S. Lew

The current state-of-the-art of safety in concrete building construction is reviewed and summarized. The material presented considers only the technical aspects of the construction safety. Safety of the individual in using equipment and in following construction procedures is not included in this study.

The report presents comparative accident frequencies in concrete construction. Based on reported construction failures, the relative vulnerability of various categories of concrete construction is estimated. The report examines causes of construction failures and reviews major regulatory standards at the federal, state, city and industry level affecting safety in concrete construction.

The factors which affect safety in concrete construction are examined relative to the state-of-the-knowledge and, where appropriate, recommendations are made for areas needing improved standards.

Key words: Building; codes; concrete; construction; falsework; formwork; loads; reshoring; safety; shoring; standards.

1. INTRODUCTION

The construction industry, in general, is known to be one of the high risk industries. Since 1960, annual construction death and disabling injuries have been about 2700 and 220,000, respectively (table 1). These figures are higher than those of the national average of all industries. Accident statistics compared in table 2 reveals that the chance of accidental death in construction is four times greater than the overall occupational hazard average and the chance of disabling accidents is twice that of the average. Construction safety according to these statistics is lagging behind the overall safety of other industries.

Data on frequency and severity of accidents in concrete construction is difficult to assess. As a generic class, neither the National Safety Council nor the Department of Labor publishes data for construction accidents which single out concrete building construction. However, assuming that the

Table 1 Construction Safety Statistics*

Year	Estimated Number of Workers	Estimated Deaths	Estimated Disabling Injuries
1960	3,500,000	2,400	213,000
1961	3,400,000	2,300	210,000
1962	3,250,000	2,400	210,000
1963	3,400,000	2,500	210,000
1964	3,550,000	2,600	220,000
1965	3,700,000	2,700	225,000
1966	3,800,000	2,800	240,000
1967	3,800,000	2,700	230,000
1968	3,800,000	2,800	240,000
1969	4,000,000	2,800	240,000
1970	3,900,000	2,800	240,000
1971	3,800,000	2,700	240,000
1972	4,000,000	2,800	260,000
1973	4,100,000	2,900	280,000
Average	$\simeq$ 3,700,000	$\simeq$ 2,700	$\simeq$ 220,000

*Source: National Safety Council

Table 2. Comparison of Safety Statistics for All Industries to that for the Construction Industry*

Year	Accidental Deaths/100,000 Workers			Disabling Injuries/100,000 Workers		
	(1) All Industries	(2) Construction	Ratio (2)/(1)	(3) All Industries	(4) Construction	Ratio (4)/(3)
1973	17	71	4.2	2,930	6,830	2.3
1972	17	70	4.1	2,915	6,500	2.2
1971	18	71	3.9	2,875	6,315	2.2
1969	18	70	3.9	2,785	6,000	2.2
1967	19	71	3.7	2,945	6,050	2.0
1965	20	73	3.6	3,010	6,080	2.0
1963	21	74	3.5	2,940	6,215	2.1
1961	21	68	3.2	2,960	5,920	2.0
1960	22	73	3.3	3,110	6,100	2.0

*Source: Based on data given in National Safety Council "Accident Facts."

frequency of accidents is related to the frequency of construction failures, an estimate can be made from a comprehensive study of structural collapses and failures during construction based on the report by a committee of the Institute of Civil Engineers in England [1][1]. The study revealed that concrete construction constituted about 12 percent of failures in the construction and an additional 10 percent were temporary structures often related to concrete construction. Taking into consideration that some 32 percent of the cases are not identified, it is reasonable to estimate that 25 percent of all construction failures probably involve concrete construction.

These unfavorable statistics clearly indicate that the concrete construction is a hazardous work. A close examination of all aspects of the construction process which contribute to accidents and failures is justified as well as identification of possible solutions to unsafe construction practices. This report examines causes of construction failures and reviews major regulatory standards at the federal, state, city and industry level governing safety practices in concrete building construction. Where appropriate, research recommendations are given in areas needing information in order to improve existing safety standards applicable to concrete construction.

2. CAUSES OF CONSTRUCTION FAILURE

Failure of concrete construction stems from a number of causes. These include failures related to formwork, premature removal of falsework, inadequate amount of reinforcement, low concrete strength attributed to inferior cement or use of insufficient cement, poor curing conditions during hot and cold weather, etc. Individual case histories of concrete construction failures resulting from various causes are compiled in references 4, 5, 6, and 7. All of these case histories however, occured prior to 1967. Feld's books [4,5] are based on failures which occured from 1900 to 1966, McKaig's book [6] from 1895 to 1960, and Short's report [7] includes a number of failures which occurred prior to 1967 in Great Britain.

Because both construction practices and standards have evolved in the last decade and because there have been substantial revisions in concrete design practice as a result of changes in the ACI Building Code Requirements [8] in 1963 and 1971, a summary of concrete building construction failures since 1963 was developed (table 3). This summary includes those 24 cases reported in Engineering News Record (ENR) from 1964 through 1974. Because the articles reported in ENR are dependent on many factors including their news value, the availability of local reporters, and cooperation of local authorities,

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[1]Numbers in brackets refer to the literature references listed in section 6.

TABLE 3 Construction Failures of Concrete Buildings
Engineering News Record: Reported 1964-1974

	DATE	LOCATION	STRUCTURAL TYPE	APPARENT CAUSES	ENR REFERENCE
1.	12-63	Philadelphia, PA	21-story slipform service core for office building	Formwork fire caused by salamender.	1-9-64 p17
2.	1-64	New York City, NY	Flat slab hospital	Formwork fire caused by heater explosion.	1-9-64 p17
3.	4-64	Madrid, Spain	350 car, 3-story parking garage	Inferior cement suspected responsible for low concrete strength of columns.	4-9-64 p29
4.	9-64	Washington, D.C.	6-story flat plate office building	Formwork collapsed during casting. No lateral bracing for shores suspected.	9-17-64 p61
5.	5-65	Jacksonville, FL	4-story school	Formwork collapsed due to overloading of shoring with stacks of metal pans.	5-13-65 p29
6.	5-65	Italian Riviera, Italy	B-story apartment	No information available.	5-20-65 p24
7.	7-65	Concord, NH	5-story office building	Shoring failure.	7-29-65 p15
8.	11-65	Platteville, WI	Waffle slab roof	Tubular steel shoring collapse during casting.	11-18-65 p67
9.	4-66	Ottawa, Canada	12-story flat plate building	Inadequate reshoring and premature removal of forms.	4-7-66 & p72 5-5-66 p11
10.	5-66	Athens, Greece	2-story papermill	Inadequate lateral bracing of 29-foot high shores.	5-19-66 p30
11.	5-67	Ft. Worth, TX	Waffle slab, library roof	Metal shoring failure suspected.	5-18-67 p33
12.	1-68	Chapel Hill, NC	Roof section of student union	Formwork collapsed during casting. Improper formwork placement blamed.	1-11-68 p31
13.	6-68	Arlington, VA	12-story office building	Formwork collapsed during casting. Insufficient lateral bracing blamed.	6-13-68 & p25 6-27-68 p7
14.	3-69	Pittsburgh, PA	Flat slab hospital addition	26-ft high falsework and shoring failure.	3-6-69 p13
15.	B-69	Buenos Aires, Brazil	22-story apartment	Premature removal of formwork caused collapse of balcones.	B-7-69 p37
16.	9-69	Rockville, MD	7-story office building	Heavy rains undermined shores.	9-25-69 p21
17.	2-70	Buenos Aires, Brazil	23-story apartment	Nearly completed building totally collapsed. Understrength material blamed.	2-26-70 p13
1B.	1-71	Boston, MA	16-story flat plate apartment	Progressive collapse of 16 stories. Insufficient concrete strength and inadequate reshoring were causes of failure.	1-20-71 p3 2-4-71 p13 7-15-71 p19 B-19-71 p7 11-11-71 p16 12-23-71 p3 1-27-72 p11
19.	3-71	Arlington, VA	3-story parking garage	Formwork collapsed during casting.	3-11-71 p12
20.	6-72	Vancouver, B.C.'	Parking garage and 3-story apartment	Collapse of shoring blamed.	6-29-72 p10
21.	3-72	Bailey's Crossroad VA	26-story flat plate apartment	Premature removal of shores caused progressive collapse of 24-stories.	3-B-73 & p12 4-19-73 p11 5-3-73 p16 5-31-73 p13 6-14-73 p15 7-19-73 p16 10-4-73 p32 11-22-73 p15
22.	8-73	Frankfort, Germany	42-story office building	Fire destroyed formwork and shores.	8-30-73 p11
23.	2-74	Cleveland, OH	21-story hotel	Fire destroyed formwork causing progressive collapse of a portion building.	2-20-74 & p11 4-18-74 p11
24.	6-74	Miami, FL	8-level parking garage	Failure of adjustable wooden shores caused collapse of 31 x 110 ft, B in post-tension slab.	6-6-74 & p3 6-13-74 p11

they are considered to constitute a biased sample of concrete construction failures. However, they probably typify the most serious types of failures. Thus, they can be regarded as a reasonable sample of the type of failures which should receive immediate attention.

A summary of individual failures classified according to the major causes is presented in table 4. While the proportion of individual causes of failure to the number of total failures does not directly correlate to the proportion of actual failures, it does indicate the major possible causes in concrete construction. The major causes in descending order of frequency are:

54% Formwork Failure - This category includes failures due to deficiences in design, erection and assembly of the formwork and inadequate size and spacing of reshores and lateral bracings.

17% Fire - This category includes partial or total destruction of wooden formwork due to fires originating in heating devices for winter concreting.

8% Premature removal of shores - This category includes failures resulting from premature stripping of forms and shores supporting partially matured concrete, usually for economic purposes.

8% Faulty material - This category includes failures due to under-development of the concrete caused by use of inferior and/or inadequate amounts of cement.

4% Overloading - This category includes failures due to storage of construction material in a concentrated area; thereby over-stressing either the concrete or the formwork.

4% Soil failure - This category includes failures resulting from the instability of soil which supports shores and mudsills.

4% Others - This category includes those cases for which accurate information for cause of failures is not available.

In addition to these categories other causes have been cited. These include errors in design of formwork, inadequate connection detail such as insufficient nailing or failure to tighten the lock devices on shores, equipment impact on vertical shores causing a progressive collapse of the entire falsework and displacement of shores due to vibrations produced by men and equipment on the

Table 4 Classified Summary of Construction Failures*

Cause of Failure	Number of Failures	Percent of Total Failures
Formwork Failure:	13	54%
Formwork collapse (2) Shoring failure (6) Inadequate reshoring (2) Inadequate lateral bracing (3)		
Premature Removal of Shores:	2	8%
Over Loading:	1	4%
Soil Failure:	1	4%
Faulty Material:	2	8%
Fire:	4	18%
Others:	1	4%
TOTAL	24	100%

*Source: Engineering News Record (1964-1974)

formwork. As a group, however, more than 60 percent of failures were related to improper falsework practices including premature removal of forms and shores. Consequently, the most benefit can be derived by improving present requirements for concrete construction in building codes and standards, and manuals of practice in this area.

3. REGULATORY AND INDUSTRIAL STANDARDS

3.1. General

For concrete construction, many sets of requirements and standards exist ranging from those of federal standards to those of local building codes. These include:

(1) Federal Standards - Regulations promulgated under the Occupational Safety and Health Act of 1970 (OSHA) which gives the Secretary of Labor authority to promulgate and enforce occupational safety and health standards. All safety requirements relative to construction are given in Construction Safety and Health Regulations [9] published in the Federal Register of June 24, 1974.

(2) State and local building codes - Regulations enacted by local legislatures or councils.

(3) National standards - Consensus standards promulgated by organizations such as the American National Standards Institute (ANSI).

(4) Recommended practices - Recommended practices and procedures promulgated by trade associations and professional organizations such as the Associated General Contractors of America, Inc. (AGC), the Scaffolding and Shoring Institute (S&SI), and the American Concrete Institute (ACI).

The requirements in these documents are not uniform and vary substantially in certain subject areas. In the remaining part of this chapter, these regulatory and recommended practices are reviewed and the interrelationships of these will be examined.

3.2. Federal Standards

The most widely cited federal standards for concrete construction safety are given in Subpart Q (Concrete, concrete forms and shoring) of OSHA's Construction Safety and Health Regulations [9]. By reference the OSHA Standard, section 1926.700(a) makes a blanket inclusion of all provisions of ANSI A10.9-1970, Safety Requirements for Concrete Construction and Masonry Work [10]. For emphasis, Subpart Q repeats, in some cases verbatim, some of the ANSI A10.9 provisions but a contractor must still refer to the ANSI A10.9 in order to comply with the OSHA regulations.

3.3. State and Local Building Codes

In the United States, most local building codes are patterned after the so-called "model" building codes. They are the BOCA [11], National [12], Southern Standards [13], and Uniform Building Codes [14]. Summaries of provisions in these model codes affecting concrete construction are given in Appendix A. Treatment of this subject in these codes is minimal, referring generally to the provisions in ACI 318 [8], ACI 347, Recommended Practice for Concrete Formwork [15], or ANSI A10.9 [10].

3.4. National Standards

In 1931 the American Standards Association Committee (now ANSI) on Standards for Safety in the Construction Industry issued the American Safety Code for Building Construction. Since then, it has been updated and the part on concrete and masonry construction is currently issued as American National Standard Safety Requirements for Concrete Construction and Masonry Work, A10.9-1970 [10]. This is the most comprehensive standard currently available in the U.S. and it is probably the most single important document, as it has been included in its entirety by reference in OSHA's Construction Safety and Health Regulations [9].

The ANSI A10.9 standard provides a comprehensive listing of many important factors which must be considered in concrete construction. Its quantitative treatment of many of its requirements, on the other hand, is not specific. For example, section 6.3.4 requires that imposition of any construction loads on the partially completed structure be approved by the engineer-architect. However, it fails to provide the criteria which the engineer-architect should consider. Similarly, section 8.1.30 requires that the allowable load on the supporting slab should not be exceeded when reshoring. The standard does not specify whether the allowable load is to be based on the strength of slab at the time of reshoring, fully cured 28-day strength, the factored load, or unfactored design load. ANSI A10.9 is currently being revised by the subcommittee which is responsible for its updating. There are many ambiguities in the current standard and they need to be clarified.

Another national standard which influences concrete construction is ANSI 89.1-1972, better known as ACI-318-71, Building Code Requirements for Reinforced Concrete [8]. Its construction coverage is far more comprehensive than the model building codes. It provides a general set of guidelines for placing and curing the concrete, design of formwork, and removal of forms and shores. Quantitative values are not specified for any of the guidelines.

The most comprehensive standard for concrete construction is ACI 347-68, Recommended Practice for Concrete Formwork [15]. This document is the basic source for many of the ANSI A10.9 provisions and consequently for others that use ANSI A10.9 as a model. It provides clear statements which clarify the role of the contractor and of the engineer-architect who issues project drawings and specifications and who supervises certain aspects of the construction process. The document contains many important detailed technical matters not covered in ANSI A10.9. It also contains recommmended formwork practices for special methods of construction, including preplaced aggregate concrete, slipform construction, prestressed concrete, precast concrete, and underwater concrete. An ACI publication, SP-4, Formwork in Concrete [16] which serves as a commentary to ACI 347, has abundant detailed information relative to formwork practice with design aids, examples, and illustrative figures. In fact, SP4 has been cited as a part of the requirements in the U. S. Army Corps of Engineer's Safety Manual [17].

3.5. Recommended Practices

There are two widely distributed recommended practice documents dealing with safety in the construction industry. One is distributed by the Scaffolding and Shoring Institute (S & SI) [18] and the other is by the Associated General Contractors of America (AGC) [19].

The S & SI document provides guidelines primarily for shoring and reshoring, and generally follows closely those included in ANSI A10.9. However, in some cases a few of the important requirements of ANSI A10.9 are not included in this document. For example, section 2.5 of the document follows ANSI A10.9, section 8.1.5 verbatim in describing vertical loads for shoring and formwork. However, while ANSI A10.9, further requires that design for lateral load be not less than the greater of 100 lb per foot of floor edge or 2 percent of total dead load of the floor, the S & SI recommendation is silent on this important requirement for lateral stability of the shoring system. Similarly, section 5.2 of the document duplicates ANSI A10.9, section 8.4.2 for lateral and diagonal bracing, except that it fails to include the requirement that "bracing be installed as the shores are erected."

The AGC Manual covers concrete construction in Chapter 37. The coverage on shoring seems to follow the recommendations of the Scaffolding and Shoring Institute (S & SI). In general, the safety provisions contained in this document is less than that in the S & SI recommendations. It also omits the lateral load requirement for shoring. However, the AGC manual does strongly recommend tests for job-cured cylinders to determine the adequacy of the concrete strength prior to form removal.

3.6. Comparison of Requirements in Existing Documents

Coverage on concrete construction safety in building codes and standards vary widely from a minimal coverage in local building codes (except for the City of New York code) to a detailed coverage in national standards. Most of the requirements found in these documents are patterned partially or wholly, after those in ANSI A10.9, which, in turn, adopted many of the requirements in ACI 347-68. Unfortunately, in the transition to ANSI A10.9, many of the subtle but important features of ACI 347 are lost, including the definition and role of the engineer-architect who is usually a representative of the owner rather than of the contractor.

Many of such subtle differences in the documents are difficult to compare in detail on a one-to-one basis. In this section, design requirements and dimensional tolerances which are found in five widely referenced documents are compared. The five documents include ACI 347-68, ANSI A10.9, OSHA 1926, Recommended Safety Requirements of S & SI, and the AGC Manual. Salient features of the requirements from each of the documents are listed in table 5.

For design of falsework, the treatment of the vertical load in all five documents are similar in that it includes both dead (DL) and live loads (LL); the dead load consists of weight of the formwork and concrete and the live load consists of such loads as workmen, equipment, runway and impact. However, only ANSI A10.9 includes separate design load requirements for both formwork and shoring. ACI 347 includes the requirements primarily for formwork, while both the S & SI and AGC Manual include only the requirements for shoring. Live load requirements in these documents vary from 50 psf to 20 psf including the weight of formwork. Where 20 psf is specified, the live load allowance would be 10 psf if the weight of formwork is assumed to be 10 psf. This is far less than what is considered as a minimum allowance for the weight of workmen, runways, equipment and impact. There is no apparent basis for these figures.

Although rational base for the numerical values are not apparent, both ACI 347 and ANSI A10.9 provide requirements for lateral loads. These include a general lateral load requirement for the formwork system and a special provision for walls and wall bracings. On the other hand, these specific numerical requirements are omitted in the S & SI and AGC documents. It is reasonable to assume that contractors would be more likely to use these documents than ANSI A10.9 or ACI 347. The large number of construction failures resulting from insufficient lateral bracings could be attributed to the omission of lateral load requirements.

Except for the AGC Manual, the other documents caution the contractor about the imposition of any construction loads on the partially matured structure unless such loading has been considered in the design and approved by the engineer-architect. Storage of construction material over a small area

TABLE 5 Summary of Construction Safety Provisions in Regulatory and Industry Standards

	ACI 347 - 68	ANSI A10.9 & OSHA 1926	SCAFFOLDING & SHORING INSTITUTE	ASSOCIATED GENERAL CONTRACTORS
VERTICAL LOADS	DL + LL FORMS: DL = Weight of formwork and concrete LL = Weight of workmen, runways, impact $\nless$ 50 psf SHORES: None specified	DL + LL FORMS: DL = Weight of formwork and concrete LL = Weight of workmen, equipment, runways, impact SHORES: DL + LL $\nless$ 100 psf LL + Formwork $\nless$ 20 psf When motorized carts are used: Add 25 psf to design load	DL + LL FORMS: None specified SHORES: DL + LL $\nless$ 100 psf LL $\nless$ 20 psf When motorized carts are used: Add 25 psf to design load	DL + LL FORMS: None specified SHORES: DL + LL $\nless$ 100 psf LL + Formwork $\nless$ 20 psf When motorized carts are used: Add 25 psf to design load
LATERAL PRESSURE	In section 1.2.2 formulas are given for columns and walls in terms of rate of placement and temperature of concrete in the forms	None specified	None specified	None specified
LATERAL LOADS	FORMS: Wind, dumping of concrete and equipment Greater of 100 lbs/ft of floor edge or 2% of D.L. of floor WALL FORMS: WL $\nless$ 10 psf Bracings for wall forms: 100 lb/lineal ft of wall applied at the top SHORES: None specified	FORMS: Wind, impact of concrete and equipment Greater of 100 lbs/ft of floor edge or 2% of D.L. of floor WALL FORMS: WL $\nless$ 10 psf Bracings for wall forms: 100 lb/lineal ft of wall applied at the top SHORES: Wind, impact of concrete and equipment Greater of 100 lbs/ft of floor edge or 2% of D.L. of floor	None specified	None specified
CONSTRUCTION LOADS	Not permitted unless approved by Engineer-Architect	Not permitted unless considered in design or approved by Engineer-Architect	Strengthening or give special consideration	Not specified
IMPACT	Part of LL	Part of LL	None specified	None specified
TOLERANCES	FORMS: Suggested tolerances are given to ensure dimensional control over finished structural members SHORES: None suggested	FORMS: None suggested SHORES: 1/8 inch in 3 ft	FORMS: None suggested SHORES: 1/8 inch in 3 ft or not more than 1 inch in 40 ft	FORMS: None suggested SHORES: None suggested
REMOVAL OF FORMS AND SHORES	Based on Engineer-Architect specification, or under ordinary conditions, use recommended minimum period of curing	Based on engineer specification or local building code, or under ordinary conditions, use recommended minimum period of curing	Based on approval of qualified engineer	Based on job cured strength

DL = Dead Load
LL = Live Load
WL = Wind Load

has been a cause of construction failures. Collapse of a small area can often lead to a progressive collapse resulting in the total collapse of a structure.

Extensive listing of formwork tolerances are given in ACI 347 for various structural elements. The primary intent of these tolerances is to maintain finished dimensions of structural members within specified limits. To guard against instability of vertical supporting members, such as shores and reshores, both ANSI A10.9 and the S & SI document recommend a tolerance of 1/8 inch for out-of-plumbness in 3 feet. However, it is doubtful whether this requirement is realistic from a practical standpoint in day-to-day field operation. Neither ACI 347 nor AGC have any such requirement.

One of the most critical operations in concrete construction is correct timing of removal of forms and shores so that no damage to the concrete results. For this reason, all four documents stress that removal of the forms and shores should be based on the strength of job-cured cylinder and/or the approval of the engineer-architect.

It is apparent from the above comparison that a lack of uniformity exists in present documents. In many cases, the basis for numerical values of specific requirements are not apparent. Thus, one cannot make judicious selection of quantitative requirements for design of falsework. In the following chapter, deficiencies in these requirements are reviewed and pertinent recommendations are made for upgrading them.

4. FACTORS AFFECTING CONCRETE CONSTRUCTON SAFETY

4.1. General

This chapter reviews those factors which affect the safety of the structure during construction. The basic factors are; design loads for falsework; strength of the falsework which provides temporary support to the structure, and the construction cycle of forming, stripping and reshoring processes. These broad areas can be subdivided into a number of related components each of which consists of several elements. These relationships are shown in figure 1. For each of the subareas, the state-of-the-knowledge is discussed, and inadequacies of requirements in existing regulatory documents are identified, and, where appropriate, recommendations for research to improve existing knowledge are made.

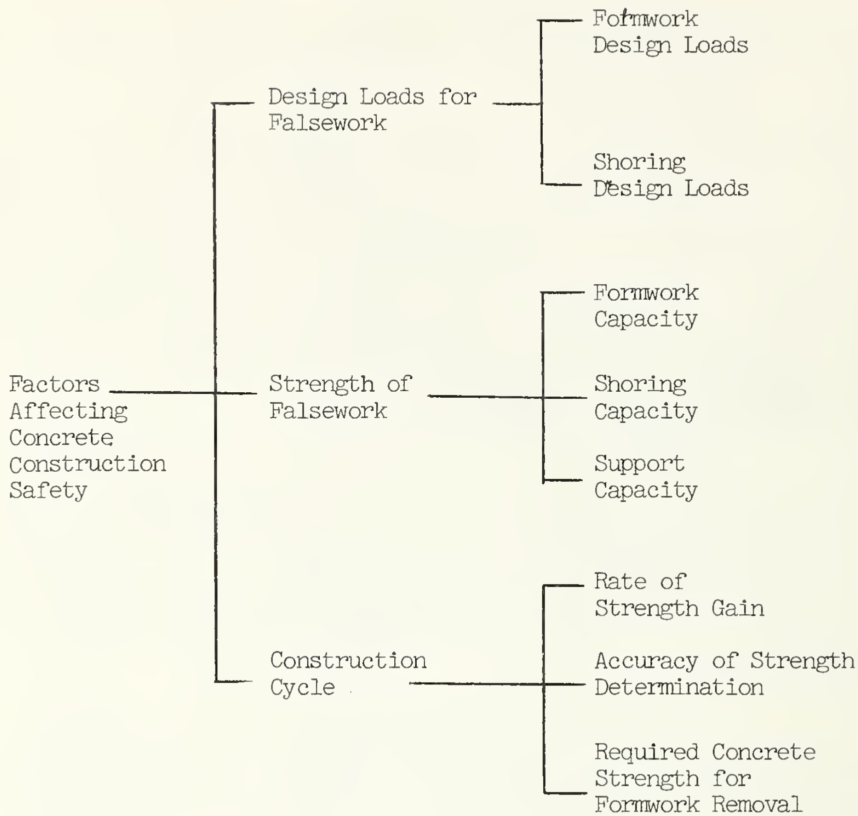

Figure 1. Factors Affecting Concrete Construction Safety

4.2. Design Loads for Falsework

Falsework is composed of formwork, which is in contact with the concrete, shores, and lateral bracing. While gravity loads are supported by formwork and shores, lateral loads are resisted by lateral bracing.

4.2.1. Design Loads for Formwork

The loads which formwork must carry may be divided into six types. These are:

(a) Dead Loads

(b) Live Loads

(c) Lateral Pressure from fresh concrete

(d) Impact

(e) Lateral Loads

(f) Other Loads

(a) Dead Loads - Included under this category are static loads which occur for a considerable period of time during the life of the formwork. It includes the weight of the form itself, the fresh concrete and reinforcement. All regulatory standards mention these two kinds of loading as dead load. It should be noted that both ACI 347 and ANSI A10.9 make reference to concrete as "freshly placed concrete" without explicitly mentioning the weight of reinforcement to be included in the dead load. However, in most cases, use of 150 lb. per cu. ft. for normal weight concrete and 120 lb. per cu. ft. for lightweight concrete can be used to represent the weight of reinforced concrete. Depending on the type of aggregates used, however, the unit weight of concrete can range up to 400 lb. per cu. ft.

(b) Live Loads - Live load consists of the weight of workmen and equipment, runways and other temperary loads that are supported by the formwork during concrete placing and finishing. ACI 347 recommends a minimum value of 50 psf for live load. While this design value appears reasonable because no failures have been attributed directly to excessive live load, the basis for the 50 psf is not apparent. The present trend is to use somewhat less than 50 psf for design of formwork. Although this use is not justified by actual measurements of live loads imposed on the formwork, in recent years the increased use of heavier and larger capacity equipment would seem to suggest that live load be increased rather than decreased. Until accurate assessment of actual live loads is made, 50 psf or greater for design live load would be desirable. Documentation of live load variations in various types of concrete construction using different placement procedures would be invaluable in establishing load factors and design load criteria.

(c) Lateral Pressure - Two important factors influence the lateral pressure exerted on the side of the form by the fresh concrete. They are the rate of placement and the temperature of concrete. As the concrete is being placed, lateral pressure at a given location increases. As it hardens, the concrete changes from a plastic state to a solid state, gradually eliminating the lateral pressure on the form. At low temperatures the concrete takes longer to harden and therefore, concrete is placed in greater depth before the lower portion becomes sufficiently firm to be self-supporting. Because greater hydraulic head can be developed under this condition, greater lateral pressure results.

There are other factors which affect the lateral pressure on the form. These include the type of vibration (internal or external) which is used to consolidate the concrete and which causes the concrete to behave as a fluid along the full depth of vibration, thereby increasing lateral pressure; impact loading caused by free fall of concrete when it is discharged into or on the form; and consistency of concrete. However, the effects of these factors on lateral pressure are relatively small when compared with the other two main factors, and also their effects are considered in usual concrete practice.

ACI Committee 347 has developed workable formulas for maximum lateral pressures (p) on the form, for prescribed conditions of temperature, rate of placement, vibration, weight of concrete, and slump. The formulas listed below are based on limited experimental data but are practical for form designs.

For wall forms with rate of placement not exceeding 7 ft per hour

$$p = 150 + \frac{9000\ R}{T} \qquad \text{(max. 2000 psf or 150 h, whichever is less)}$$

For wall forms with rate of placement greater than 7 ft per hour

$$p = 150 + \frac{43{,}400}{T} + \frac{2800\ R}{T} \qquad \text{(max. 2000 psf or 150 h, whichever is less)}$$

For columns

$$p = 150 + \frac{900\ R}{T} \qquad \text{(max. 300 psf or 150 h, whichever is less)}$$

Where:

p = maximum lateral pressure, psf

R = rate of concrete placement, depth of concrete placed per hour, ft per hour

T = temperature of concrete in the form, °F

h = maximum height of fresh concrete in the form, ft.

The load values obtained by these formulas have been verified for those conditions which represent "good practice." Taylor [20] has suggested a need for more experimental research on placement rates of more than 10 ft per hour and to investigate form pressures due to impact from dumping of concrete in the forms and extreme variations in placing temperature.

(d) Impact - Impact is generally considered as part of the live load and is that produced by dumping of concrete on the form. The magnitude of impact on the form is affected by the quantity of concrete dumped per load and the rate of dumping. Impact can not only produce temporary overloading on the form but it can also cause uplift of supports in adjacent bays. Unless the falsework is securely fastened together, tilting or sometimes loss of shores can occur causing collapse. At present, no data are available on impact measurements to establish quantified provisions. Dynamic measurements on impact load should be made in order to establish a minimum value for design.

(e) Lateral Loads - The most serious deficiency in formwork is in the consideration of lateral loads. Many practical design guides do not include any lateral load provision to warn the designer of the importance of adequate lateral bracing to insure the stability of the falsework.

Lateral loads include wind, cable tensions, inclined supports, impact of placement of concrete, starting and stopping of equipment and earthquake. Most standards and codes recognize these effects except for the earthquake loading. Both ACI 347 and ANSI A10.9 require that forms be designed for lateral loads, in any direction, of not less than 100 lb per ft of floor edge or 2 percent of the total dead load of the floor, whichever is greater.

This lateral force requirement seems to be largely a judgement matter. The British [21] have implemented an increase in their lateral load requirement to 3 percent of the dead load. This increase is based on examination of a recent collapse which was triggered by failure of lateral bracing. An investigation [22] on a California bridge falsework collapse recommended a minimum of 5 percent for the lateral force coefficient. Others recommended as high as 8 percent for the same collapse.

In view of ambiguity in assigning proper values for lateral force, a comprehensive review of lateral force requirements for formwork should be undertaken. The study should consider all factors which can induce lateral forces. Both ACI 347 and ANSI A10.9 use a value of 10 psf for wind on vertical wall forms. This is inadequate at some geographical location in the U. S. and is unrealistic in that the requirement does not vary with factors such as building height, the mean recurrence interval for the wind speed, and the shape of form, etc. It appears that general upgrading of the lateral force requirements is needed.

(f) Other Loads - The design of formwork should also consider any special conditions likely to occur, such as unsymmetrical placement of concrete, uplift, concentrated loads of reinforcement and storage of construction materials, etc. Storage of construction materials has been more often cited as a cause of failure of formwork than others conditions.

In high-rise constructions, excessive construction loads applied to the formwork cause about 17 percent of all building construction accidents. This is due mainly to the vertical spatial distribution problem for construction material in tall buildings. Both OSHA section 1926.700 (e)(1)(i) and ANSI A10.9, section 8.1.1.6 require that when temporary storage of reinforcing rods, material and equipment on top of formwork becomes necessary, those areas be strengthened to meet the intended loads. Although the intent of this requirement is clear, it is probably not realistic in application. Local strengthening of formwork demands careful control of material storage placement at the job site, that often is absent in construction operations. Studies should be made of existing site practices and estimates of actual material storage loads on the falsework.

4.2.2. Design Loads for Shores

Most of the load requirements previously discussed for the formwork also apply to shores. However, ANSI A10.9, Section 8, treats the loads on shores separately, while it is not treated in ACI 347. Five types of loads are considered below.

(a) Dead loads
(b) Live loads
(c) Impact
(d) Lateral loads
(e) Other loads

(a) Dead loads - Dead load for shores include all the dead load considered for the formwork plus the weight of shores and the lateral bracings. ANSI A10.9, section 8.1.5 requires that the minimum total design dead and live loads be not less than 100 psf. This suggests that if ACI 314 recommendation of 50 psf for live load and 10 psf for the falsework are subtracted from this value, only 40 psf is left for dead load or less than a 4-inch concrete slab, assuming the unit weight of 150 lb/ft^3 for normal weight concrete. While the basis for this combined treatment is not apparent, it would be realistic and less confusing to treat the dead and live load seperately.

(b) Live loads - A minimum allowance of 100 psf for a combined dead and live load is suggested in ANSI A10.9, in the S & SI recommendations and in the AGC document. This provision would lead to much less live load than the ACI 347 requirement of 50 psf. For example, for a 6-inch slab only 15 psf is available for live loads after deducting 10 psf for formwork and shores. For an 8-inch slab, no allowance is left for live load. In addition, both ANSI A10.9 and the AGC document require that the minimum allowance for live load and formwork should be not less than 20 psf. The S & SI requires that the live load allowance alone should not be less than 20 psf. Since "heaping" of only 4 inches of extra concrete would produce 50 psf, these smaller values represent an almost insignificant live load. There is no apparent basis for such small values for live load requirement. Similar to the case for formwork, assessment of actual loads on shores should be made in order to arrive at realistic design values.

(c) Impact - Other than impact produced by "dumping" of concrete on the form, direct lateral impact on shores is not common. When it occurs, failure of shores is usually localized. Impact by the "dumping" is usually shared by several shores, and when they are adequately braced, failure of shores can be avoided. Lateral impact produced by starting and stopping of equipment such as motorized buggies, is also resisted by the lateral bracings. As in the case for the formwork, no data on actual impact measurements are available to determine realistic values for design at the present time.

(d) Lateral loads - Shores together with lateral bracings resist the lateral loads transmitted from the formwork above and the wind and other loads directly applied on the shore. Only ANSI A10.9 has a seperate provision for the lateral load for shores, which is the same as that for the formwork. All the comments relative to the later force requirements for the formwork also apply for the shoring. In addition, it is also important to consider forces on individual shores as well as overall forces on the entire shoring system.

(e) Other loads - Special loads that arise in concrete construction are usually transmitted to shores through the formwork. Among the types of loads mentioned in section 4.2.1 (f), the effect of concentrated construction loads on the shore is greater than the others, as inadequately braced shores have a tendency to become unstable under excessive loads. ANSI A10.9, section 8.1.16 cautions the designer about excessive loading.

Since little information on the magnitudes of construction storage loads is available, overall requirements for overload for which shores need to be designed cannot be recommended at this time. A reasonably accurate determination of overloading on shores is necessary to arrive at a realistic load factor for design live load.

4.3. Strength of Falsework

Overall strength of the falsework depends on the strength and stiffness of the formwork, the shoring together with lateral bracings, and the support which provides reaction to the loads transmitted through shores. Factors of safety used in each of these components vary from 1.5 to 4. Some of these factors of safety are based on allowable stresses and others are based on ultimate load tests. Therefore, the current design approach to the total falsework system is not uniform, and thus, safety against collapse of the system cannot be assessed readily and accurately.

Because it is considered a temporary structure, the falsework receives bare minimum engineering attention during its design stage. In many instances, the design and erection are left to the job foreman or superintendent. Because of their limited knowledge of the importance of certain engineering aspects of falsework, such as bracing requirements for lateral loads, the chances of faulty or inadequate design would be high. Even small deviations from proper construction of the falsework would result in a serious reduction in the safety.

In order to ensure the safety of the falsework, ACI 347, section 1.3.2 requires that a design analysis for all formwork, including analysis against buckling of every member, be made in all cases. Little has been written in the engineering literature regarding the analysis of falsework. Because a number of failure studies mentioned numerous examples of buckling of falsework, a set of guidelines for comprehensive analysis involving stability checks for the most common types of falsework needs to be developed.

4.3.1. Capacity of Formwork

Both wooden and metal forms are extensively used for floor slabs, walls and columns. When prefabricated forms are used, ACI 347, section 1.3.1 recommends that manufacturers' recommendations for allowable loads be followed if supported by test reports and successful experience records. On the other hand, when wooden forms fabricated at the site are used, the design is to be based on allowable stresses given in the applicable codes and standards.

Because allowable stresses depend on many factors, including the species grade, size of cross section, moisture content, and duration of loading, one single factor of safety cannot be specified realistically. For stress grade lumbers, the factor of safety in allowable stresses design is about 2.5. Permitting the allowable stress to increase 25 percent for light construction would reduce this factor of safety to 1.87 [16]. In some cases, the factor of safety is not known because of reliance on reference standards or codes to set these allowable stresses.

Where the material has deteriorated from its new condition or has been damaged from previous use, allowable capacity should be reduced to accomodate for the loss of strength. ACI 347, section 1.3.1, merely cautions the designer about this. In Great Britain modification factors which could be used to reduce the allowable stresses have been introduced [21]. Their interim provisions require the basic allowable stresses be multiplied by modification factors.

An in-depth study should be undertaken to evaluate the effects of the reuse of material on overall strength of falsework and develop modification factors as described above. Such factors can then be incorporated into a limit state approach in defining the overall safety of the falsework.

4.3.2. Capacity of Shores

The capacity of shores is affected by three main factors. They are strength variability in the material used for the shoring, the geometric configuration of shores, and construction deviations such as out-of-plumbness, eccentricity with respect to stringers, etc. While strength variation in the material is an important factor, the capacity of shores is significantly affected by the two latter factors. The effect of these parameters are greater on single post shores than on frame-type shores as these are pre-engineered products which frequently have lateral bracings built into the shoring system.

The actual load capacity of shores is usually determined by testing of shores under simulated field conditions. ANSI A10.9 relies heavily on Safety and Shoring Rules developed by the Scaffolding & Shoring Institute and on test results following the S & SI test procedure (Appendix C). The standard test procedure appears reasonable within the tolerance range specified in ANSI A10.9, section 8.1.24. However, a major question arises as to how well average site conditions reflect the condition specified in ANSI A10.9. In an extremely informative British survey [23] of 40 construction sites, actual plumbness and eccentricity were determined for a large number of shores. The ANSI A10.9

allowable construction tolerance of 1/8 inch in 3 feet corresponds to a value considerably less than the smallest deviation measured in the field assessment. Sixty percent of the shores measured were found to be more than 5/16 inch out of plumb in 3 feet; indicating that ANSI A10.9 tolerance would be unrealistic in British practice. Over 10 percent of the shores were as much as 1 inch out of plumb in 3 feet. Twenty percent were found to have end eccentricities greater than 1/2 inch. In view of such a large magnitude of out of plumbness combined with large end eccentricities as found in the British study, the ANSI construction tolerance should be reexamined after similar as-built tolerance surveys are carried out in the United States.

4.3.3. Capacity of Support

The shoring is supported either by soil or floor slabs. The strength gain of the slab will be treated in detail in section 4.4.3. In this section attention is focused on foundation and soil support for the shoring.

One of the recurring causes of falsework failure is inadequate support for the falsework. This inadequacy stems from soil deficiencies, improper falsework foundation load distribution and the effect that environmental factors such as rain and frost have on falsework supports. ANSI A10.9, sections 8.1.12 through 8.1.14 provide general guidelines relative to the input of soil mechanics or foundation engineering into the falsework support design on soils. In general, the language focuses on the strength aspects which are important but does not point out the need for consideration of settlement characteristics of the soil. In this regard, the working bearing pressure should be limited by the maximum allowable settlement.

In many instances, circumstances do not permit or warrent an extensive foundation analysis for falsework. Under these situations a reasonable empirical design method is needed for temporary falsework foundation. An interesting guideline is presented in reference 21, wherein permissible bearing pressures for various type soils and rocks are given in relatively simple terms. Modification factors are presented for the case of incomplete soil information, for special settlement restrictions, for exposure to high water table and for various fill materials. These modification factors are listed in tables 6, 7, and 8. Foundation design approach such as this one would be useful for many medium to small constructions.

TABLE 6 Maximum Allowable Bearing Capacities for Foundation on Fully Compacted Fill (Ref. 21)

Classification of fill	Allowable bearing capacity tonf/ft^2 (kN/m^2)
broken rock	2.0 (200)
well-graded sands and gravels	1.5 (150)
uniform sands and hard shaley clays	1.0 (100)
firm to stiff clays	0.75 (75)

TABLE 7 Modification Factors for Restricted Allowable Settlement (Ref. 21)

Loading period	Cohesive soils	Non-cohesive soils	Rocks
Short-term loading	0.75	0.75	1.0
Long-term loading	0.67	0.75	1.0

TABLE 8 Modification Factors for Flooding or High Ground Water Levels (Ref. 21)

Condition	Cohesive soils	Non-cohesive soils	Rocks
Ground water level at B, or less, below level of foundation (B=width of foundation)	1.0	0.5	1.0
Site liable to flooding	0.67	0.5	1.0

4.4. Construction Cycle

The responsibility of establishing the construction cycle rests with the contractor, because he has the responsibility for completing the construction. However, while the contractor has responsibility for design and erection of formwork, ACI 347 recommends that time of removal of falsework, in part or whole, be specified by the engineer because of the possibilty of damage to the concrete from overloading the incomplete structure. Similarly, ANSI A10.9 recommends that the length of time that forms should remain in place following concrete placement be controlled by the engineer's specification or by local building codes. When field operations are not controlled by the engineer's specification, both ACI 347 and ANSI A10.9 provide tables for determining the time that forms and supports should remain in place under "ordinary" conditions.

In general, the decision as to when the falsework can be removed safely depends on three interrelated factors. These are the rate of strength gain in the concrete, the accuracy of strength determination of in situ concrete and the level of temporary stress and deformation that the structure can withstand.

4.4.1. Rate of Concrete Strength Gain

Among the factors which affect the gain in strength of a concrete, temperature and moisture are the most pronounced. Extensive studies have been made on the development of the compressive strength, primarily measured using the standard 6x12 inch cylinder [24, 25, 26]. The results of these studies indicate that the effects of curing temperature, moisture, and age on compressive strength are generally predictable within reasonable limits. On the other hand, a number of researchers have investigated the relationship between the compressive strength of concrete and maturity [27, 28, 29, 30 and 31]; where maturity is defined as a function of temperature and time. This relationship is based on a concept that samples of the same concrete will have equal compressive strengths if their maturities are the same, regardless of their temperature histories. While this approach appears promising, further study is needed to examine its applicability to cement with higher ranges of heat of hydration and to higher curing temperature.

Although the compressive strength is an important factor in determining the basic strength of a concrete member, the strength of a flexural member at early ages is usually governed by either shear (diagonal tension) or bond strength. Some investigations [31] have assumed that the relationship between these two strength parameters and the compressive strength is the same at any age. To date, little data are available to substantiate this assumption. In view of this, a series of investigations should be made to confirm and to verify the assumption that at early ages, flexural strength, shear and bond strength, as well as the stiffness vary with the same function of the compressive strength as at later ages.

4.4.2. Accuracy of Strength Determination

Determination of the time of form removal is usually based on the results of tests performed either on concrete specimens or on structural members. Both ANSI A10.9, section 6.4.7 and ACI 347, section 2.7.2.1 recommend the use of test results of field-cured cylinders. Although it is common to carry out compression test on cylinders, neither ANSI nor ACI specifies the type of test, e.g., compressive strength test or splitting tensile strength test. Recent investigators [32,33] have shown that the results from cylinder tests, even cured in the similar environmental condition to which the structure is subjected, often do not correlate consistantly with the concrete strength of the structure. This inconsistancy stems from the fact that even when cured at job site, the curing conditions of cylinders are not the same as those of beams, slabs and walls, simply because of the difference in shape and the size of structural sections.

In order to overcome this difference in curing condition, a special curing procedure has been followed by a large construction firm in England. It uses a mobile environmental chamber to cure concrete test specimens. The temperature condition in the chamber is controlled by output of thermocouples which are inserted in the freshly poured concrete. This is to simulate as closely as possible the temperature at which the structural member is cured. While this procedure appears reasonable, no research data are available to substantiate its effectiveness.

There are three types of destructive test methods commonly used to determine the compressive strength of concrete. They are (1) testing of 6x12 inch standard cylinders, (2) testing of cores of various sizes taken from actual structural members and (3) testing of pushout cylinders. The pushout cylinders are prepared at the same time structural members are cast. Concrete is placed in plastic sleeves which are inserted in the respective structural members.

This enables the cylinders to cure in the same manner as the bulk concrete. At the desired time, the cylinder is removed from the structural member and its compressive strength measured. The results of a study [33] show that the coefficient of variation of the compressive strengths of 216 field cured cylinder specimens was 2.4 percent compared with 6.0 percent for an equal number of core specimens and with 3.9 percent for push-out cylinder specimens. The study concluded that "field cured cylinders may provide useful information but do not quantitatively reflect core strength and that push-out cylinders cast in the slab provided a fairly reliable measure, relatively, of core strength."

Since it is cumbersome either to mold and cure large numbers of cylinders or to take cores from the structure and test, it would be desirable to have reasonably accurate nondestructive test methods to determine the strength of concrete for falsework removal. Numerous methods involving the use of impact penetration of steel probes, rebound impact hammer measurements and ultrasonic velocity measuring devices have been suggested. Detailed descriptions of these methods with evaluation of their relative merits are presented in reference 34. In general, individual nondestructive test methods do not measure directly the compressive strength of concrete. They measure some properties of concrete, and the measurements are correlated to the compressive strength empirically.

At the present time, the individual nondestructive test methods do not appear to provide accurate prediction of the in situ strength of concrete. Their applicability to "green" concrete for the purpose of determining the time of form removal has not been thoroughly evaluated. The use of nondestructive test methods for this purpose needs further investigation.

4.4.3. Required Concrete Strength for Formwork Removal

Because the falsework cost can range up to 60 percent of the total cost of concrete construction, for desire of economy, forms and shores are usually removed at an earliest possible time for reuse and, in their place, reshores are placed to transfer the loads to previously cast floors. Reshores are shores placed firmly under a stripped concrete slab or structural members whose original falsework has been removed. To guide this process, ACI 306-66 [35] suggests that shores can be removed and reshores used when the concrete strength is 55 to 65 percent of design strength. ACI 347-68, section 2.7.2.1, recommends that the supports of suspended structural members can be safely removed if the ratio of actual concrete strength to design strength is equal or greater than the ratio of total dead load and construction loads to total design loads, with a minimum concrete strength of 50 percent of the design strength required. For example, in an 8-inch thick flat plate building with 40 psf design live load and 20 psf construction load, this would be $\frac{100+20}{100+40}$ = 0.86 design strength. In buildings with higher live load to dead load ratios, this ratio would decrease. Thus, it seems apparent that the minimum concrete strength for stripping should be considerably greater than 55 percent of design strength as suggested in ACI 306-66.

Transfer of upper level construction loads to more mature lower floors is feasible only if the lower floors have been designed to support the loads. The number of floors which need to be reshored in order to distribute the loads from above depends on the type of structural system, the ratio of design live load to dead load, the magnitude of construction loads, the rate of strength and stiffness gain of concrete and the construction cycle time. Because the number of floors to be mobilized in reshoring is recognized as one of most critical operations in concrete construction, ACI 347-68, section 2.8.3.1 recommends that reshoring operations be planned in advance and be approved by the engineer.

Neilsen [36] was one of the first who studied distribution of loads on shores and on slabs in multistory structures. He made an extensive theoretical analysis of the interaction between the formwork and the slabs supporting the falsework loads. In the analysis he assumed that (1) the slabs behave elastically, (2) shrinkage and creep of the concrete can be neglected for the purpose of analysis, (3) shores are represented by uniform elastic support and (4) the torsional moments and the shearing forces in the formwork are neglected. He expressed the total load carried by the slab which supports the load above and by shores as a percentage of the dead weight of the concrete plus the weight of the falsework on each story. On this basis the maximum calculated load on a floor was 256 percent of the load on each story. His maximum measured load on an individual floor was 200 percent of the load. In his study, Neilsen considered shoring on two or three floors only. The calculations involved are lengthy and can not be readily applied to individual cases.

Grundy and Kabaila [37] developed a simplified analytical method to predict the load on shores and supporting slabs. The significant difference between their approach and that of Neilsen is the assumption that the shores are infinitely stiff in comparison with that of the slabs. With rigid shores, all slabs connected by the shores deflect identically. Consequently, the total load applied to the system, either by casting of new slabs or by removal of shores, is distributed between the slabs in proportion to their relative flexural stiffness. Assuming construction of one floor per week, with shores removed five days after a casting operation, they developed the load distribution sequences for slabs with constant flexural stiffness and for slabs with varying flexural stiffness with age. These are shown in figures 2 and 3, respectively. The load ratios shown are the ratio of the total load being carried by a slab or a set of shores to the dead load of one slab plus the weight of falsework. The load ratios shown on these figures reveal that magnitudes of floor loading between the two cases are very small. This indicates that the error introduced by the assumption of equal slab stiffness is not appreciable on the load distribution analysis. Bresford [38] also concluded from his study that within practical limits, consideration of changes in the stiffness of the slab with age did not change load ratios significantly.

The maximum load ratio obtained by Neilsen was 2.56 and by Grundy and Kabaila was 2.36. This difference is due to the different construction cycles considered in their examples. However, this difference suggests that the effect of ignoring the flexibilty of shores is small. Agarwal and Gardner reported [31], based on their field measurements of loads on shores at two different construction sites, that the simplified Grundy and Kabaila theory predicted maximum construction loads within 15 percent of the measured values. When the differences in stiffness of the concrete slabs were considered, the theory predicted the load within 10 percent.

While the methods of Neilsen and of Grundy and Kabaila give slightly different magnitudes of the load which individual slabs experience during construction, the methods clearly show that the load imposed on slabs, particularly at lower levels, is more than twice the dead load of one slab at ages

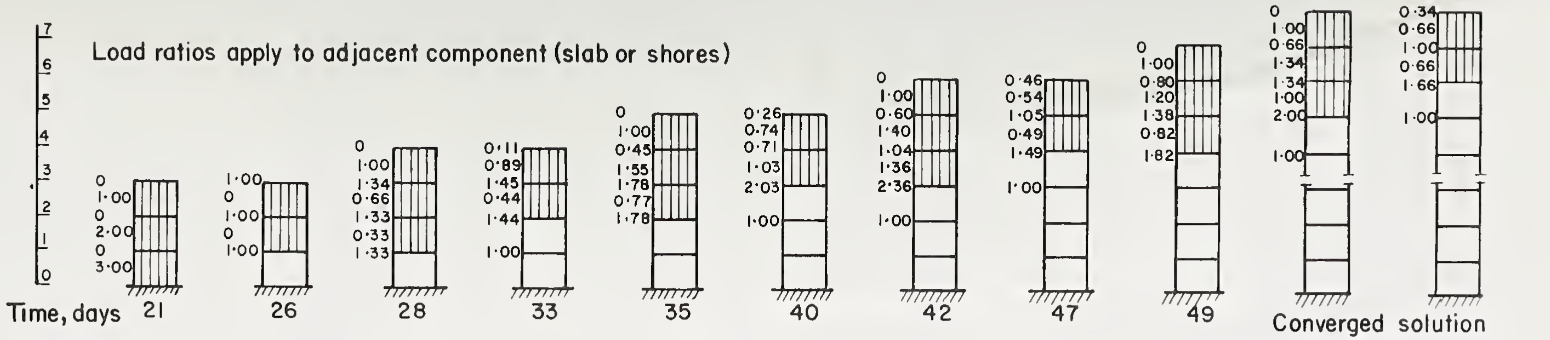

Figure 2. Analysis of Construction Loads Assuming Constant Modulus of Elasticity.

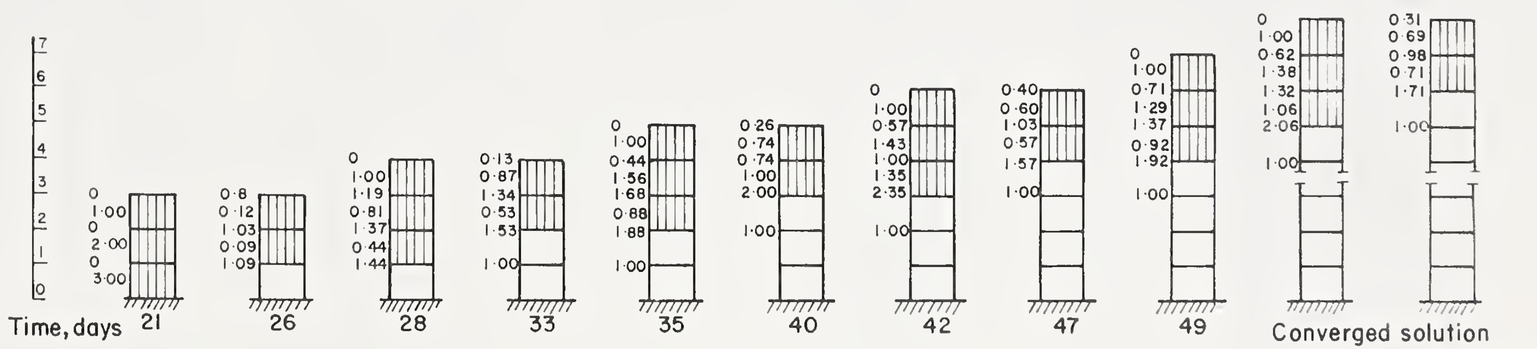

Figure 3. Analysis of Construction Loads Assuming Variable Modulus of Elasticity.

earlier than that at which the design strength of the concrete is attained. Grundy and Kabaila showed that for a 10 inch thick flat plate, the construction loads would exceed service loads by 53 percent and would govern design. For load factor design (currently 1.4D + 1.7L) and using a load factor for construction load of 1.0, live load must exceed 56 percent of dead load in order that the design be governed by (1.4D + 1.7L).

$$U = 1.4D + 1.7L \geq 1.0\ (2.36D)$$

$$1.7L \geq 0.96D$$

$$L \geq 0.56D.$$

The construction load factor of 1.0 would leave no margin for safety and would rely on full strength development of the concrete member. ANSI A10.9, section 8.1.30, certainly implies the load factor of 1.0 in speaking of the allowable load. On this basis, if a load factor of 1.0 is used, without additional construction load, live load must exceed 136 percent of dead load for safe construction.

$$S = 1.0D + 1.0L \geq 1.0\ (2.36D)$$

$$1.0L \geq 1.36D$$

$$L \geq 1.36D$$

This condition is seldom realized in the design of office or apartment buildings.

Since partially matured concrete frames would carry some construction loads, Feld [39] suggests the use of a load factor to increase the load-carrying capacity by 33 percent. Under this consideration, live load must exceed dead load by 77 percent.

$$1.33S = 1.33D + 1.33L \geq 2.36D$$

$$1.33L \geq 1.03D$$

$$L \geq 0.77D.$$

The above analysis clearly show that further study of construction load factors need to be undertaken. The study should consider such factors as live load to dead load ratio, the rate of strength gain of concrete, and construction cycle.

5. CONCLUSIONS

An attempt has been made to identify all factors relating to concrete construction safety, that is, the statistics of deaths and injuries, causes of construction failures, review of existing regulatory and industrial standards as they affect the safety in construction, and review of the-state-of-knowledge. Based on this study the following conclusions are drawn.

(1) Safety in concrete construction is a severe problem in that some 25 percent of all construction failures are related to concrete construction.

(2) Survey of reported failures in concrete buildings under construction indicate that about 62 percent of failures result from inadequate practices in falsework design and erection. Many of the inadequacies, however, can be attributed to numerous conflicts and shortcomings of existing regulatory and industrial standards.

(3) Review of existing documents which deal with safety in concrete construction reveals that there is a lack of consistant design and construction philosophy and uniformity in the regulations. In general, contrary to extensive treatment given to the completed structure, virtually no guidance is given in existing standards and codes as to allowable stresses to be used in relation to the rate of strength development for the concrete and appropriate load factors or safety factors to be used for falsework design. There is no clear distinction made in the regulatory documents as to the scope of applicability of the requirements to different types of structures. For example, all the requirements which may apply to a large multi-story construction would be equally applicable to a single-story dwelling construction.

The role of contractor and engineer-architect is not clearly defined. Although it is stated that design and erection of falsework and safe construction of the permanent structure is the responsibility of the contractor, many critical phases of construction process such as placement of construction loads and removal time of falsework are left for the judgement of an engineer-architect.

(4) Review of existing documents and literature reveals that improvements are needed in all categories which affect safety in construction. The following are specific subject areas needing research.

a) Documentation of actual vertical live loads on falsework.

b) Formulation of a realistic set of lateral load requirements considering geographical location of the structure, occurance of strong wind for short recurrence period, location of falsework with respect to height.

c) Documentation of construction material storage loads.

d) Determination of equivalent hydrostatic loads for rapid rates of placement of concrete under various temperature conditions.

e) Determination of impact loads on falsework.

f) Determination of actual falsework construction tolerances from field surveys.

g) Evaluation of the bracing requirements which reflect actual construction tolerances.

h) Development of a simplified foundation design procedure for falsework in relation to type and size of structure.

i) Documentation of strength and stiffness gain characteristics of concrete with time under various curing conditions.

j) Development of improved nondestructive test procedures for determining in situ strength of concrete.

k) Determination of the proper levels of concrete strength required for falsework removal considering both strength and deformation.

l) Determination of construction load factors for design of falsework and for shoring and reshoring analysis.

6. ACKNOWLEDGMENTS

The contribution of Professor John E. Breen of the University of Texas of Austin to the study of safety in concrete building construction is gratefully acknowledged.

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APPENDIX A

SUMMARY OF PROVISIONS OF MODEL BUILDING CODES
AFFECTING CONCRETE CONSTRUCTION SAFETY

A1. BOCA Basic Building Code - 1975
(Building Officials & Code Administrators International, Inc.)

Section. 841.1

Requires that the construction of reinforced concrete buildings on structures be followed in accordance with the provisions in ACI 347-68, Recommended Practice for Concrete Formwork.

In addition, sections 710.4 and 1303 requires special provisions for construction loads.

A2. Natonal Building Code - 1967 (American Insurance Association)

Section 913.1 and 1201.1

Requires that reinforced concrete construction be followed in accordance with the provision in ACI 318-63 and USAS A10.2 1944, Safety Code for Building Construction. It should be noted that both of these references are outdated. The latest edition of these references are ACI 381-71 and ANSI A10.9-1970, respectively.

Section 913.8

Requires that forms and shoring supporting structural members not be removed until members have sufficient strength to support own weight and "such loads as may come upon them."

Section 1210.6

Requires that the material for temporary construction such as platform, support and tarpulins be made of fire retardent treated material.

A3. Southern Standard Building Code - 1973 and-1974 revision.
(Southern Building Code Congress)

Section 1601

Refers to the provisions in ACI 318-71.

Section 2101.9

Requires that all temporary equipment shall be substantially constructe and erected to ensure the safety of workmen.

A4. Uniform Building Code - 1973
(International Conference of Building Oficials)

Section 2606 (a)

Forms "shall be properly braced or tied together so as to maintain position and shape. Forms and their supports shall be designed so that previously placed structures will not be damaged."

Section 2606 (b)

Prohibits construction loads exceeding design loads on unshored structur Requires job-cured test specimens strength and structural analysis for removal of shores and imposition of construction loads.

APPENDIX B

SUMMARY OF PROVISIONS OF LOCAL BUILDING CODES AFFECTING CONCRETE CONSTRUCTION SAFETY

B1. Atlanta

Sec. 901 requires structures to carry all permanent and construction loads without exceeding allowable stresses. Further requires temporary supports to be governed by such allowable stresses.

Sec. 913.8 - form provisions identical to National Building Code.

B2. Baltimore

Sec. 6006 requires registered engineer to design and supervise construction of all controlled concrete construction.

Sec. 6651 requires forms to be designed for a hydrostatic pressure equivalent to a fluid weighing 150 lb/cu.ft.

Sec. 6652 allows wood and metal form stresses 50 percent higher than for permanent construction.

Sec. 6654 requires forms to be removed in a way to insure complete safety of structure and after structure has sufficient strength to support its weight and any loads imposed.

B3. Boston

Sec. 710.4 limits construction loads and stresses to normal design limits for complete structures.

Sec. 842.0 requires approved inspection personnel for all concrete construction.

Sec. 1303.1 and 1303.2 - same as BOCA Code.

B4. Buffalo

1972 City Code still based on ACI 318-56 except in special cases 318-63 may be approved. Sec. 204 requires concrete work to be supervised by engineer responsible for its design. Also requires complete records of temperature and curing histories of concrete.

B5. Chicago

Sec. 68-1 requires construction stresses to meet same limits as finished structure design stresses.

Sec. 69-3.1 requires inspection of work during construction to be under a registered architect or structural engineer.

Sec. 76-2 requires stresses due to wind, dead, and material storage and erection equipment loads during construction not to exceed allowable stresses in design codes.

B6. Denver

Sec. 2302(b) requires temporary loads during construction be investigated and provided for by the responsible person imposing such loads.

Sec. 5900(b) limits loading of structures, parts of structures, temporary supports, etc., to safe carrying capacity.

B7. District of Columbia

Requires building official inspection of forms and reinforcement before concreting to insure forms are substantial. Specifies formwork to be structurally designed.

B8. Jacksonville, Florida

Sec. 900-901.2 requires temporary supports to be limited to normal design stresses.

Sec. 900-913.5 limits construction loads on unshored portions of structure to design loads. Gives building official power to require job cured test cylinder strengths prior to form removal. Construction loading and shore removal to depend on member strength gain.

Sec. 900-913.7 requires building official inspection of formwork.

B9. Los Angeles

Sec. 91.0311 requires approval of formwork by a structural inspector selected by the engineer.

Sec. 91.2617 requires cylinder tests before removal of form shoring or bracing if forms are to be removed before 7 days for slabs and 15 days for beams and girders.

B10. New Orleans

Sec. 2610 requires forms to be properly braced and tied and not to be removed until concrete has gained sufficient strength to support safely its own weight and superimposed loads. Building Official may require forms to remain in place for a specified time.

B11. New York City

This city code is the most detailed and comprehensive of all local codes examined regarding concrete construction safety.

Sec. 1900.8 specifies interim fire protection facilities, including hoists for fire fighters and standpipes.

Sec. 1900.9 specifies design to be done by registered architect or engineer whenever "design" is required.

Sec. 1904.3 is a comprehensive requirement for formwork.

B12. New York State

Sec. 304-12 requires all structural members and temporary supports to be strong enough to suffer no damage under construction loads.

B13. Ohio

Requires complex work to be under supervision of a registered engineer or architect.

Sec. 1210.02 requires all construction operations to keep building within allowable stresses and to insure stability of the structure.

B14. Philadelphia

Building official may require forming and shoring design and removal sequence analysis.

B15. Pittsburgh

No building or building part or any temporary support shall be loaded in excess of its safe carrying capacity.

B16. Seattle

Identical to Uniform Building Code.

B17. South Florida

Sec. 2301.1(b) requires buildings to be designed to withstand construction loads without exceeding design loads. Forms are to be removed in a way to insure complete safety of structure. Beam bottom forms and shoring for slabs, beams, and girders are not to be removed for 14 days unless approved by building official after test results show sufficient strength gain.

Sec. 3305 requires storage of construction materials in a structure during building operations to be done with due consideration of structural stresses developed which may not exceed design stresses.

B18. Wisconsin

Requires construction of any building of over 500,000 cu ft volume to be under supervision of an architect or engineer. Form removal must insure complete safety of structure and critical forms and supports are not to be removed until members have sufficient strength to carry dead load plus any imposed construction loads.

APPENDIX C

SCAFFOLDING AND SHORING INSTITUTE RECOMMENDED PROCEDURE

for

COMPRESSION TESTING OF SCAFFOLDS AND SHORES

C1. Scope

This procedure is intended to cover the compression testing of equipment used for scaffolding and vertical shoring.

C2. Definition of Terms

The definition of terms below, relating to the compression testing of equipment used for scaffolding and shoring should be considered as applying to the terms used in these methods of compression testing.

ACCESSORIES - Those items other than frames, braces, or post shores used to facilitate the construction of scaffold and shoring.

ADJUSTMENT SCREW - A leveling device or jack composed of a threaded screw and an adjusting handle used for the vertical adjustment of the shoring and formwork.

ALLOWABLE LOAD - The ultimate load divided by factor of safety.

BASE PLATE - A device used to distribute the vertical load.

COUPLER OR CLAMP* - A device for locking together the component parts of a tubular metal scaffold.

COUPLING PIN - An insert device used to connect lifts or tiers vertically.

CROSS BRACING - A system of members which connect frames or panels of scaffolding laterally to make a tower or continuous structure.

DEAD LOAD - The load of forms, stringers, joists, reinforcing rods, and the actual concrete to be placed.

EXTENSION DEVICE - Any device, other than an adjustment screw, used to obtain vertical adjustment of shoring towers.

FACTOR OF SAFETY - The ratio of ultimate load to the allowable load.

FORMWORK - The material used to give the required shape and support of poured concrete, consisting primarily of:

Sheathing - material which is in direct contact with the concrete such as wood, plywood, metal sheet or plastic sheet.

Joists - Members which directly support sheathing.

Stringers or ledgers - members which directly support the joists, usually wood or steel load-bearing members.

*These terms may be used synonymously.

FRAME OR PANEL - The principal prefabricated, welded structural unit in a tower.

HORIZONTAL SHORING - Metal or wood load-carrying beam or fabricated trussed section used to carry a shoring load from one bearing point, column, frame, post, or wall to another.

JOISTS - See Formwork.

LIFTS OR TIERS* - The number of frames erected one above each other in a vertical direction.

LIVE LOAD - The total weight of workmen, equipment, buggies, vibrators, and other loads that will exist and move about due to the method of placement, leveling and screeding of the concrete pour.

LOAD BEARING MEMBER - Any component of a scaffold structure which is directly subjected to load.

LOCKING DEVICE - A device used to secure the cross brace to the frame or panel.

POST SHORE or POLE SHORES* - Individual vertical member used to support loads.

a. Adjustable Timber Single Post Shore - Individual wooden timbers used with a fabricated clamp to obtain adjustment and not normally manufactured as a complete unit.

b. Fabricated Single Post Shores - Type I: single all-metal post, with a fine adjustment screw or device in combination with pin and hole adjustment or clamp.

   Type II: Single or double wooden post members adjustable for a metal clamp or screw and usually manufactured as a complete unit.

c. Timber Single Post Shores - Wood timber used as a structural member for shoring support.

RESHORING - A system used during the construction operation in which the original shores are removed and replaced in a sequence planned to avoid any damage to partially cured concrete.

SAFE LEG LOAD - The load which can safely be directly imposed on the frame leg. (See Allowable Load)

SHOCK LOAD - Impact of material such as the concrete as it is released or dumped during placement.

SHORE HEADS - Flat or formed metal pieces which are placed and centered on vertical members.

SHORING LAYOUTS - A properly designed drawing prepared prior to erection showing arrangement of equipment for proper shoring.

SILL OR MUD SILL* - A footing (usually wood) which distributes the vertical shoring loads to the ground or slab below.

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*These terms may be used synonymously.

SPAN - The horizontal distance between posts, columns, or upright support members.

STRINGERS OR LEDGERS* - see formwork.

TESTING APPARATUS OR FIXTURE - A special purpose device fabricated for the express purpose of testing scaffolding and shoring.

TESTING MACHINE - A compression testing machine of a type usually found in Universities, Colleges, and reputable Testing Laboratories.

TIMBER STRESSES - Stress-grade lumber conforming to recommended tables in "Wood Structural Design Data Book," by National Lumber Manufacturers Association, Washington, D.C.

TOWERS - A composite structure of frames, braces, and accessories.

TUBE AND COUPLER SHORING - An assembly used as a load-carrying structure consisting of tubing or pipe which serves as posts, braces, and ties, a base supporting the posts, and special couplers which serve to connect the uprights and join the various members.

ULTIMATE LOAD - The maximum load which may be placed on a structure before its failure due to buckling of column members or failure of some component.

C3. Calibration of Testing Devices

(a) The device used to determine loads applied shall be calibrated and certified either immediately before or after the testing by a reputable testing laboratory.

(b) Testing machines used for compression testing shall be calibrated in accordance with ASTM Specification E4 of current revision during the preceeding 12 month period.

C4. Test Specimens

(a) Scaffold and shoring components shall be selected at random from inventory and shall exhibit approximately the same variations in measurements as would be expected from random sampling including mill tolerances on thickness of various members.

(b) Measurements of specimens. Thickness measurements, when required, shall be made with a suitable micrometer. All other dimensions shall be made with a commercially obtainable measuring tape and all dimensions reported to the nearest 1/16 inch.

C5. Procedure of Test

(a) The scaffold tower or shore to be tested shall be erected in such a manner as to simulate field conditions and aligned vertically so that it is not out of plumb more than 1/8" in three feet. No greater attempt should be made to adjust the components concentrically than would be expected in actual use.

(b) The load shall be applied directly on the load bearing member or members by use of load transfer beams or cross head of testing machine; or directly by hydraulic jacks in an approved testing apparatus or fixture.

C6. Duration of Test

The scaffolding tower or shore shall be subject to increasing loads until the ultimate load is reached.

C7. Speed of Testing

(a) The allowable limits for rate of loading on scaffolding towers shall be not less than 5,000 lbs. per minute not more than 10,000 lbs. per minute.

(b) The allowable limits for rate of loading on Post Shore shall be not less than 1,000 lbs. per minute nor more than 2,000 lbs. per minute.

(c) The rate of loading in each test shall remain constant.

C8. Types of Tests

(a) Scaffolding leg loading shall consist of frames erected into towers composed of four (4) vertical legs with normal bracing, base plates, and/or adjustment screws. When adjustment screws are used they shall be extended equally on the top and equally on the bottom, but top and bottom extensions need not be the same. All four load bearing legs shall be subjected to simultaneous loading until the ultimate load is reached by the weakest leg. Tests according to this method are "A" series tests.

(b) Scaffolding horizontal member loading. The scaffolding components shall be erected into towers composed of four (4) vertical legs with normal bracing, base plates, or adjustment screws on the bottom. The load shall be applied to the horizontal members of the panels to simulate uniform loading. Loading shall be continued until the ultimate load is reached. Tests performed according to this method are "B" series tests.

(c) Post Shores shall be tested individually at their minimum and maximum heights and at every foot throughout their operating range. The shores may be tested in both a braced condition and an unbraced condition with the individual test data displayed as a graph showing allowable load versus overall height with the manner of bracing, if any, clearly indicated. Loading shall be continued until ultimate load is reached. Test performed according to this method are "C" series tests.

(d) Extension devices - shall be positioned in or upon the legs of the scaffold and tested in the manner outlined in paragraph 8 (a). The extension devices may be tested extended from the top, bottom or both ends of the legs, and also in a braced or unbraced condition. The devices shall be tested at their maximum and minimum height and at every foot through their operating range with the individual test data displayed as a graph showing allowable load versus extended length and the manner of bracing, if any, clearly displayed. Tests performed according to this method are "D" series tests.

(e) Scaffolding leg loading shall consist of frames erected into towers composed of four (4) vertical legs with normal bracing, base plates and/or adjustment screws. When adjustment screws are used, they need not have the same adjustment for any of eight adjustment screws in any 4-legged tower. All four load bearing legs shall be subject to simultaneous and/or variable loading until the ultimate load is reached for the weakest leg. Tests performed according to this method are "E" series tests.

C9. Witness of Test

All tests must be witnessed by a reputable independent testing laboratory or University, who must attest that the test was performed in accordance with applicable provisions of this standard.

C10. Report of Test Results

Test results shall be reported on Form A (see attached) including drawing of test setup with the following:

(a) Ultimate Total Test Load
(b) Ultimate Leg Load
(c) Type of Test
(d) Laboratory
(e) Witness

TEST REPORTING FORM A

SCAFFOLDING and SHORING INSTITUTE

1. Submitted by: Date of Test ____________

____ Test Number ____________

____

2. Type of Test (Machine ________ or Appartus ________)

   a. Series (A), (B), (C), (D), (E)

   b. Number of Tiers 1, 2, 3, 4, 5, 6, 7, ________, (Circle One)

   c. Ultimate Total Test Load ______________________________

   d. Ultimate Leg Load Each __________, __________, __________, __________

   e. Ultimate Shore Load ______________________________

   f. Ultimate Ledger Load ______________________________

   g. Total Extension Beyond Leg; Top __________", Bottom __________"

3. Witness to Test

   a. Company Representative ______________________________

   b. Independent Laboratory ______________________________

   c. Other Witness ______________________________

   d. Other Witness ______________________________

4. Certification:

I certify that the above described test was performed in accordance with the applicable provisions of the Procedure for Compression Testing of Scaffolds and Shores as published by the Scaffolding and Shoring Institute.

____
(Laboratory)

By ______________________________

5. Attach Sketch of Test

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The current state-of-the-art of safety in concrete building construction is reviewed and summarized. The material presented considers only the technical aspects of the construction safety. Safety of the individual in using equipment and in following construction procedures is not included in this study.

The report presents comparative accident frequencies in concrete construction. Based on reported construction failures, the relative vulnerability of various categories of concrete construction is estimated. The report examines causes of construction failures and reviews major regulatory standards at the federal, state, city and industry level affecting safety in concrete construction.

The factors which affect safety in concrete construction are examined relative to the state-of-the-knowledge and, where appropriate, recommendations are made for areas needing improved standards.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Building; codes; concrete; construction; falsework; formwork; loads; reshoring; safety; shoring; standards.

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