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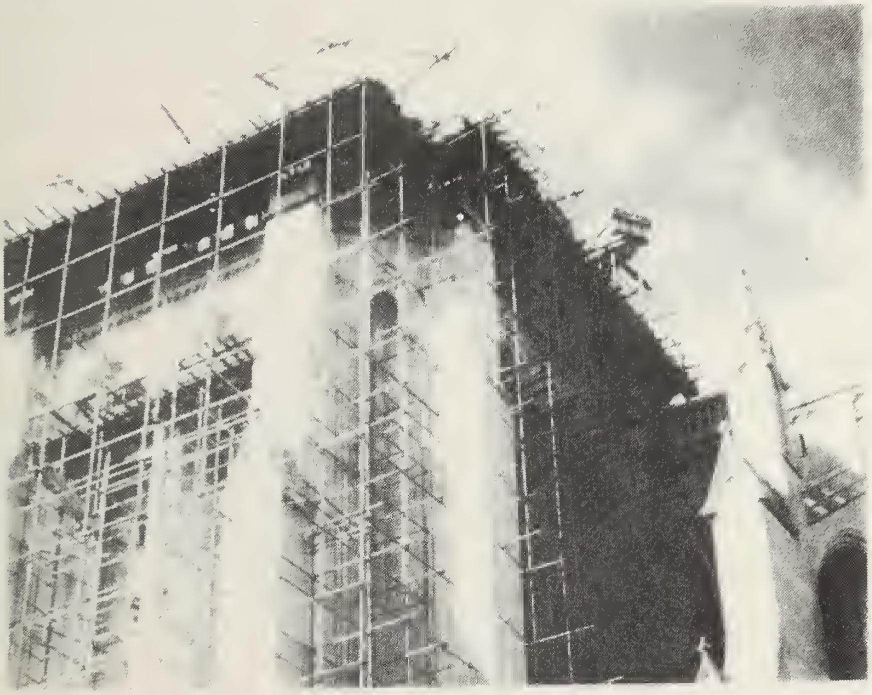

Review of Technical Information on Scaffolds

Structures and Materials Division
Center for Building Technology
National Engineering Laboratory
U.S. Department of Commerce
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Washington, DC 20234

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Prepared for

**National Institute for occupational Safety and Health
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REVIEW OF TECHNICAL INFORMATION ON SCAFFOLDS

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

ABSTRACT

This report presents a review of the available literature on scaffolds and is the third of several inter-related studies of a scaffolding research program at the National Bureau of Standards (NBS). This study was sponsored by the National Institute for Occupational Safety and Health (NIOSH) to improve scaffolding system performance and reduce the number of work related injuries and losses.

Based on a computerized search of the published literature, technical information that could serve to upgrade existing codes and standards for scaffolds or offer direction to future analytical research is presented. This information concerns the design, erection, operation or maintenance of scaffolding systems. Appendix A presents the 21 types of scaffolds under study. In addition, U.S. scaffold patent claims and the manufacturers' literature are reviewed and discussed. Appendix B presents selected finite element structural analyses of scaffolds.

Keywords: codes and standards; construction safety; design; finite element; loads; scaffolds; stability; stiffness; strength; structural safety; work surfaces.

ACKNOWLEDGEMENTS

This report was sponsored by the National Institute for Occupational Safety and Health (NIOSH), Department of Health and Human Services, Washington, D.C. The Construction Safety Group of the NBS is grateful to Mr. Peterson and the Steel Scaffolding and Shoring Institute for providing the experimental test data that are presented herein. The authors wish to express their gratitude to those persons of the NBS staff, in particular Mr. Lou E. Cattaneo, of Structural Engineering, and Ms. E. Cerutti of the NBS Library, for their assistance in searching and gathering the literature. In addition, the authors appreciate the review services of Dr. Kyle Woodward of Earthquake Hazards and Mr. Leo Skoda of Building Materials.

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1. INTRODUCTION

This report presents a review of the available technical literature on the subject of scaffolds used in construction work and other applications. The study of technical literature on scaffolds is part of an ongoing scaffolding research program at the National Bureau of Standards (NBS).

The major objectives of the NBS scaffolding research program are to 1) develop the necessary technical basis for the improvement of current scaffolding provisions in existing codes and standards and to 2) develop a comprehensive set of scaffolding standards. This research is in response to an expressed need to update present scaffolding regulations of the Occupational Safety and Health Administration (OSHA). The need is based on the high rate of worker casualties resulting from scaffolding accidents. In addition, there is a lack of research and analytical data necessary to formulate reliable criteria for the design, erection, operation and maintenance of scaffolding systems.

This report consists of seven chapters and two appendices. Chapter 2 presents background information on the long-range NBS scaffolding research program. A summary of the completed studies is presented along with a description of the remaining studies. Chapter 3 discusses the review of the scaffolding literature. The literature is evaluated for technical content according to certain scaffolding system categories and the findings are presented. Chapter 4 discusses a review of the scaffolding manufacturers' literature to establish the intended use of the various scaffolding products. Chapter 5 discusses a review of United States scaffolding patent claims and Chapter 6 summarizes the findings of this report. Chapter 7 lists the references cited throughout this report and Appendix A presents the 21 major types of scaffolds under study. Appendix B presents finite element structural analyses of selected scaffolding systems.

2. LONG-RANGE SCAFFOLDING RESEARCH PROGRAM

2.1 INTRODUCTION

The National Bureau of Standards developed a comprehensive research program to develop and improve the provisions of codes and standards for scaffolding. This program will identify the problem aspects of scaffolding which frequently lead to worker injury or death, develop an approach by which these problem aspects can be studied through the appropriate analytical methodologies, and finally, reduce the findings of these studies to a usable form.

A long-range research program was conceived and consists of the following six major phases.

1. Review and analysis of scaffolding accident records. The causes of scaffolding accidents resulting in worker casualties were analyzed based on data from existing accident records. This phase has been completed and is presented in a separate report [1].

2. Review of existing scaffolding codes and standards. Provisions used in the design, erection, operation and maintenance of scaffolding systems were reviewed according to certain preestablished criteria. This phase has been completed and is presented in a separate report [2].

3. Perform a technical review of scaffolding-related literature. Existing technical information was identified to minimize the chance of research duplication. The literature review is presented in this report.

4. Perform an in-field study of scaffolding systems currently in use to provide 1) formal documentation and 2) first-hand research data on current field practices. This study has been partially completed and a report of the findings is expected in the near future.

5. Develop a full-scale experimental and analytical research plan to establish the minimum technical basis by which a set of scaffolding standards can be formulated. Details of this plan and its formulation are expected in the near future.

6. Develop performance guidelines and standards for scaffolds to provide the mechanisms by which the developed technical bases can be applied. The development of these guidelines will be based upon the results of the implemented analytical research plan.

2.2 RECENT RESEARCH DEVELOPMENT

The initial efforts of the scaffolding research program were concerned with identifying the causes of scaffolding-related worker casualties. Therefore, the first task performed was a study report, "Analysis of Scaffolding Accident Records and Related Employee Casualties" [1], which presented an analysis of existing scaffolding accident records involving employee casualties. Where possible, the causes were identified as a system failure, environmental factor or as a human factor. Twenty-one major types of scaffolds were identified for the accident analysis and are presented in Appendix A. The accident study provided an insight into major safety-related aspects of scaffolding practices and identified some preliminary measures that could be instituted to mitigate the frequency and consequences of scaffolding-related accidents.

The accident study revealed some interesting trends that provide insight into the nature of critical safety problems. According to the study, 75 percent of the accidents were attributed to system failures. At the component level, failure of anchorages and connections were the most common, followed by foundation, support element, work platform and safety device failures. The study also indicated that the remaining 25 percent of accidents were attributable to environmental and human factors. Based on the recommendations of the accident study [1], a critical review and evaluation of all applicable scaffolding code and standard provisions was carried out.

Applicable codes and standards were gathered and reviewed and the findings presented in a another report; a "Review of Current Codes and Standards for Scaffolds" [2]. This report presented a critical and comprehensive review of the provisions in the existing codes and standards used for the design, erection, operation and maintenance of the twenty-one scaffolding systems identified in the accident study [1]. The provisions were reviewed according to a the following criteria: 1) comprehensiveness, 2) consistency, 3) clarity, 4) adequacy and 5) enforceability. The findings of this report served to identify principle areas of needed scaffolding research.

The review of codes and standards [2, 3, 4] brought into focus deficiencies in current scaffolding provisions. A prevalent trend was the inclusion of the clauses that require compliance with certain expected performance attributes without specifying the necessary criteria by which the level of performance could be established. Most notable was the absence of definitive criteria for the design or evaluation of the adequacy of anchors, connections and foundations. Major deficiencies were noted with regard to the lack of definitive guidelines for the evaluation of strength and stiffness degradation with repetitive use, or provision of appropriate criteria for the repair, maintenance and replacement of damaged components.

The field study is partially complete. The purpose of this task is to gather pertinent field data on various aspects of scaffolding applications in construction work for use in the research phase of the program. The types of information sought include magnitude and distribution of loads, practical tolerances, structural configurations of various systems, type and material composition of components, mode of operations, frequency of use according to type, degradation, and environmental conditions. Field data were collected from construction sites at three major geographic locations (population centers) in the U.S. These data are presently being analyzed and will be the subject of a future report. However, some of the data are used in the structural analysis portions of Appendix B. The remainder of this report presents the findings of the literature review and recommendations as to the direction of future scaffolding research.

3. REVIEW OF THE SCAFFOLDING LITERATURE

3.1 INTRODUCTION

The prevalent lack of technical bases for the existing scaffolding codes and standards [3, 4] is primarily attributable to:

1. A scarcity of technical knowledge, and

2. A lack of transfer of technical knowledge, if existing, to the codes and standards.

A comprehensive review of the scaffolding-related technical literature was performed to identify the severity of the above two attributes.

This literature review is directly related to the analysis of accidents and the review of codes and standards [1,2] previously conducted. The format and approach developed in the earlier studies is followed herein for purposes of comparison and to guide future analytical efforts.

A computerized search of published literature on the subject of scaffolds was performed. This effort used key words related to scaffolding topics with the following search sources:

- COMPENDIX, Comprehensive Engineering Index, Inc.
- NTIS, National Technical Information Service
- MRIS, Maritime Research Information Services
- DDC, Defense Documentation Center
- United States Patent Claims.

The search identified over 500 publications concerning platforms, falsework and scaffolding and hundreds of U.S. scaffolding patent claims. Those publications with applicability to the NBS scaffolding research program were gathered and reviewed for their technical content. Many of the publications not gathered concerned off-shore oil well platforms and other unrelated subjects. Literature was found for only a few of the 21 major types of scaffolds (see appendix A). The tube and coupler and the tubular frame scaffolds (see type 2 and 3, appendix A), were the most common systems discussed in the literature. However, reviewed information included scaffolding categories such as platforms, safety devices, support elements, etc. as is explained below.

3.2 Discussion

The approach used in this study was to search the literature for technical information that would be useful in the design, erection, operation and maintenance of various scaffolding systems. Both theoretical formulations and experimental developments were of interest; however, the validity of any past technical efforts was to be clearly established. Therefore, subjects dealing with theoretical model formulations were of little use unless experimental studies corroborating the theory existed. However, any literature on analytical modeling, existing without experimental corroboration could serve as an aid in formulating analytical models for subsequent NBS research and were thus recognized to be of potential value. In addition, technical research that addressed 'performance' or 'product' testing of specific scaffold types were considered in the review because such information may be applied to a variety of scaffold systems and applications.

As was mentioned, key topics searched and reviewed for technical content concerned the design, erection, operation and maintenance of construction scaffolding. Specifically, design strength values for scaffold components in the form of charts, tables, and graphs which incorporate safety factors, allowable stresses, load data, and sectional properties were searched. Also searched were design, erection and manufacturing tolerance values in conjunction with data concerning the effects of imperfections. Other topics of interest included load survey data, connection and anchorage capacities, and foundation design procedures.

For purposes of comparison, the scaffolding code provision categories identified in the previous two studies [1,2] are maintained and the literature is evaluated for technical content according to each category. These categories are:

1. work platform
2. supporting system
3. strength
4. connections and anchorages
5. foundation
6. stability
7. physical protection
8. accessway
9. environmental safety criteria
10. special provisions.

In addition, the following definitions, also introduced previously, are used:

Accessway	- system which provides access to and from scaffolds
Anchor	- component used for securing scaffold to foundation
Anchorage	- same as anchor, assembly of anchors
Component	- unit used in the assembly of scaffolding systems
Connection	- component providing the means of attaching together various scaffolding components
Element	- component or structural unit other than a connection or anchor
Foundation	- everything providing support to the scaffold system
Platform	- component(s) comprising the work surface of the scaffold
Safety devices	- physical devices installed for the protection of employees, such as guardrails, nets, belts, lanyards and lifelines, screens, etc.
Structural system	- assembly of components serving a structural or load-carrying function.
Subsystem	- a system subassembly consisting of more than one element and one or more connections and/or anchors.
Support element	- element of scaffold subsystem which supports the platform and transmits applied loads to the foundation.
System	- assembly of components serving a specific function.

The following sections discuss the information found in the literature on each of the above scaffold categories.

3.2.1 Platforms

The scaffolding platform consists of that component(s) comprising the work surface and in most situations it can be treated as a separate structural element in the scaffolding system. The platform can be structurally analyzed (e.g. as a simply or continuously supported beam) independent from the other scaffold elements and individual structural safety requirements can be ascertained. The remaining scaffold system elements which provide support to the platform can then be analyzed according to the loading conditions imposed on the support system by the platform.

According to the accident study [1] approximately 7 percent of all scaffolding accidents reviewed were caused by structural failure of the platform which usually consisted of wood planking. The review study of the scaffolding codes and standards [2] revealed that there is an apparent lack of technical basis for the allowable design loads.

The literature search provided limited information on the design of platforms for use as work surfaces in scaffold systems. However, technical documentation on wood construction and design does exist. Principal source documents are the National Design Specification for Wood Construction (NDSWC) [5] and the accompanying NDSWC Supplement [6] and the Timber Construction Manual [7].

A recent study by Eisenacher [8] pointed out inconsistencies within each part and between parts of the OSHA Safety Regulations (Parts 1910, 1915, 1916, 1917 and 1926) on allowable design procedures for wood platforms used in scaffolds. Eisenacher first computed the bending stress in wood planking, based on the allowable OSHA maximum loadings for given spans and timber sizes. A near minimum failure strength was selected using the OSHA-specified minimum allowable strength values of 1500 psi and 1100 psi (a contradiction within the provisions). The computed factor of safety was defined as the minimum allowable strength (OSHA value) divided by the computed stress and multiplied by an explicit safety factor of 1.3 specified by the American Society of Testing Materials (ASTM) Specifications D2555 [9] and D245 [10]. The computed factor of safety for each possible OSHA allowable platform configuration was found to fall in the range of 0.2356 to 5.0167. Most of the computed safety factors were less than the safety factor of 4 required by the OSHA regulations [3, 4].

The report on the review of the scaffolding provisions [2] presented the approach used for the design of timber based on the NDSWC [5], the adopted ASTM D2555 [9] and D245 [10] procedures. After application of appropriate modification factors, upper and lower bound factors of safety were computed for a typical plank configuration and loading. The safety factor was found to range from 2.7 to 6.9. Once again, these values differ significantly from the OSHA-specified safety factor of 4.0. The NDSWC [5] states within its preface that these design procedures have been successful and are therefore widely accepted and followed. The above two works demonstrate that although a rational technical basis does exist for wood design, it has not been incorporated in the existing scaffolding codes and standards.

No information could be found on design of platforms for specific application to scaffolds. Construction scaffolds are generally subjected to harsh conditions and require special design consideration to account for the effects of degradation of materials, load fluctuations and other factors unique to the construction environment. Such factors are not presently part of any recommended design procedures of scaffolding platforms. Also, present scaffolding provisions do not address the design of proprietary prefabricated platform units which are being used with many scaffolding systems.

3.2.2 Support System and Strength

The 'support system' refers to the assembly which provides direct support for the work platform and that transmits all loads to the foundation. The support system consists of various structural elements, connection and anchorage components, etc. Because of the general nature of the subcategory 'strength', it has been combined and addressed in this section with 'support system'. Any literature referring to the structural strength capabilities, directly or indirectly, of the assembled scaffold system is presented in this section.

An experimental approach by which a support system can be analyzed for strength characteristics is to assemble a specific scaffolding system and load it to an observed failure state. This approach has been used extensively in the past. In 1961, 1963 and 1966, the Steel Scaffolding and Shoring Institute (SSSI) performed numerous full-scale laboratory tests on a variety of welded tubular frame-type scaffolds [11,12,13]. The frames used in the testing program were chosen based on their popularity and frequency of use in the United States. The configurations selected were primarily referred to as 'masons-type' frames. The three types of welded tubular frames used in the SSSI studies are shown in Figures 3.1 through 3.3.

Basically, three types of assemblies were tested under selected loading configurations. The 1961 test series consisted of six tests on frame type A and six tests on frame type B (see Figures 3.1 and 3.2). The frames were assembled into single tower configurations 1.5m (5 ft) square and 1, 2, 3, 5, 7 and 9 frames high for each of the two frame types. Identical concentric loads were applied to each column leg at a rate of 8.9 kN (2 kip) per minute with screw-type leveling adjustments set at 305 mm (1 ft) both at the top and bottom. Ultimate capacity was reached when one of the frames in the assembly buckled out of plane (or in the plane of the cross bracing). The results of the 1961 test series are summarized in table 3.1. Figure 3.4 shows a graphical representation of the test results.

The 1963 tests used the same frame types A and B in three series of distributed leg loading tests. The first series consisted of 10 tests on frame type B assemblies with base extensions set at 305 mm at the top and bottom, 1.5 m square in plan, heights of 1, 2 and 3 tiers and subjected to unequal leg loads. The procedure consisted of loading either two or three of the four column legs to 50 and 75 percent of the ultimate frame capacity determined

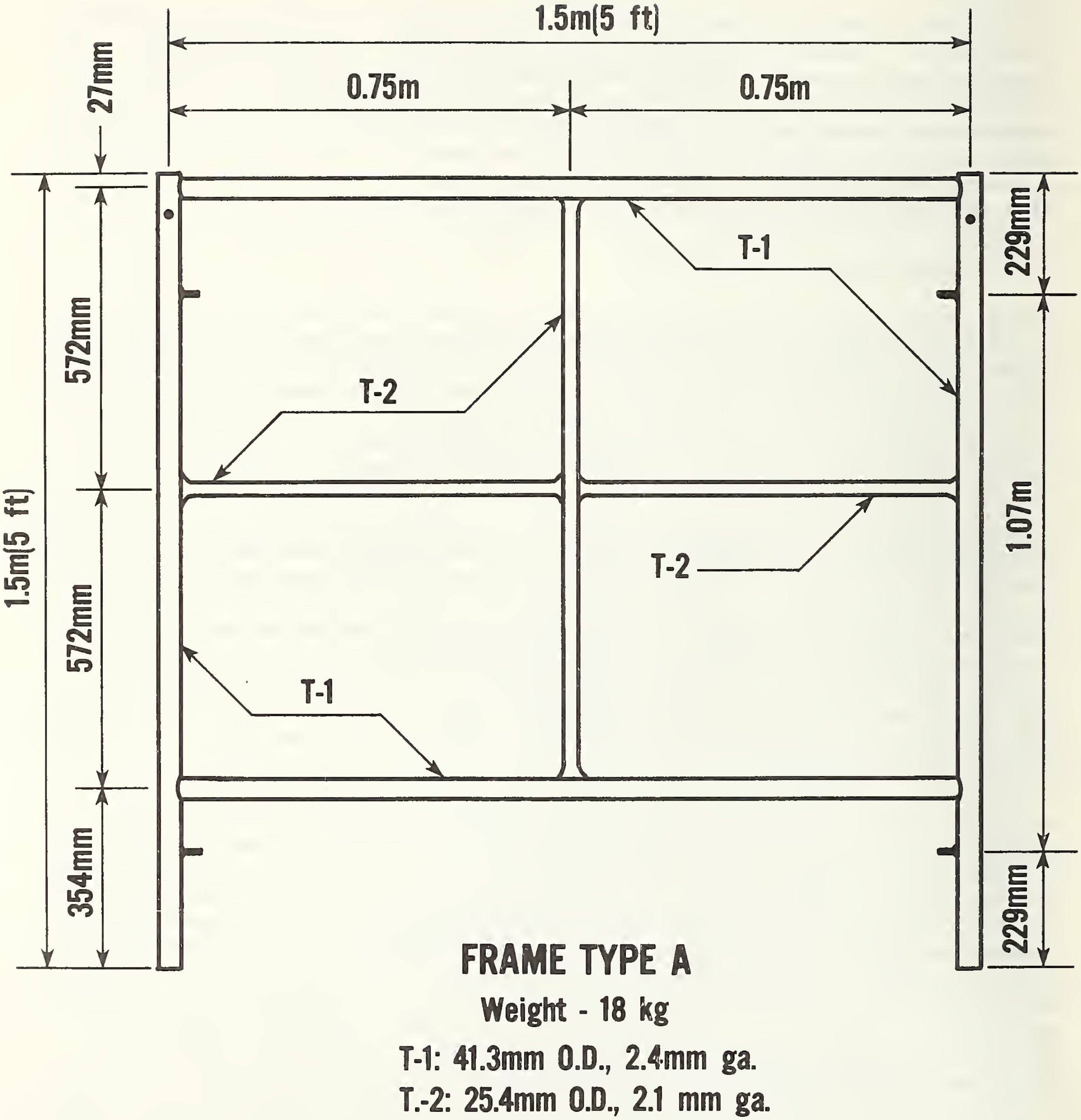

Figure 3.1 Welded fabricated tubular 1.5m by 1.5m frame-type A used in the SSSI studies.

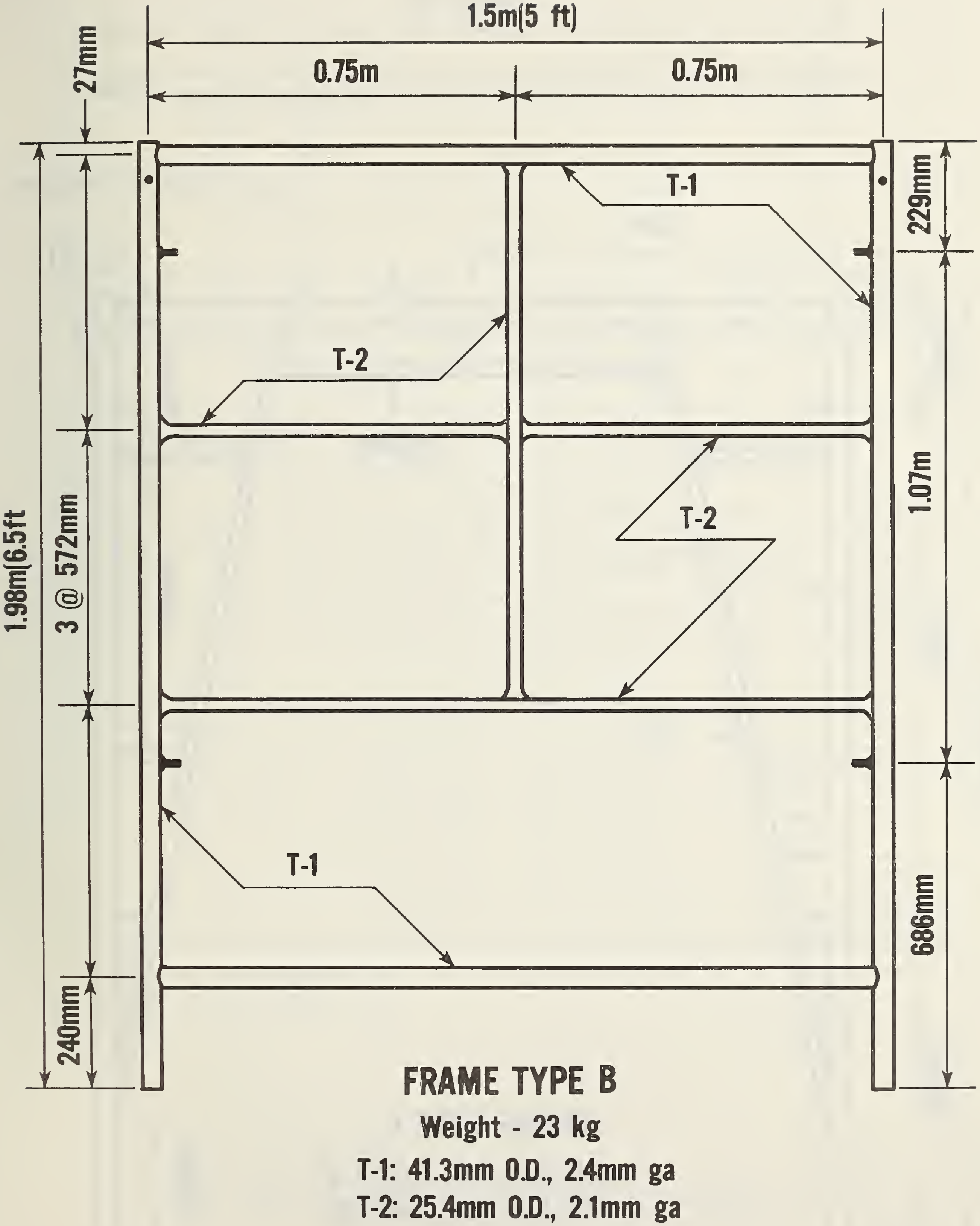

Figure 3.2 Welded fabricated tubular 1.98m by 1.5m frame-type B used in the SSSI studies.

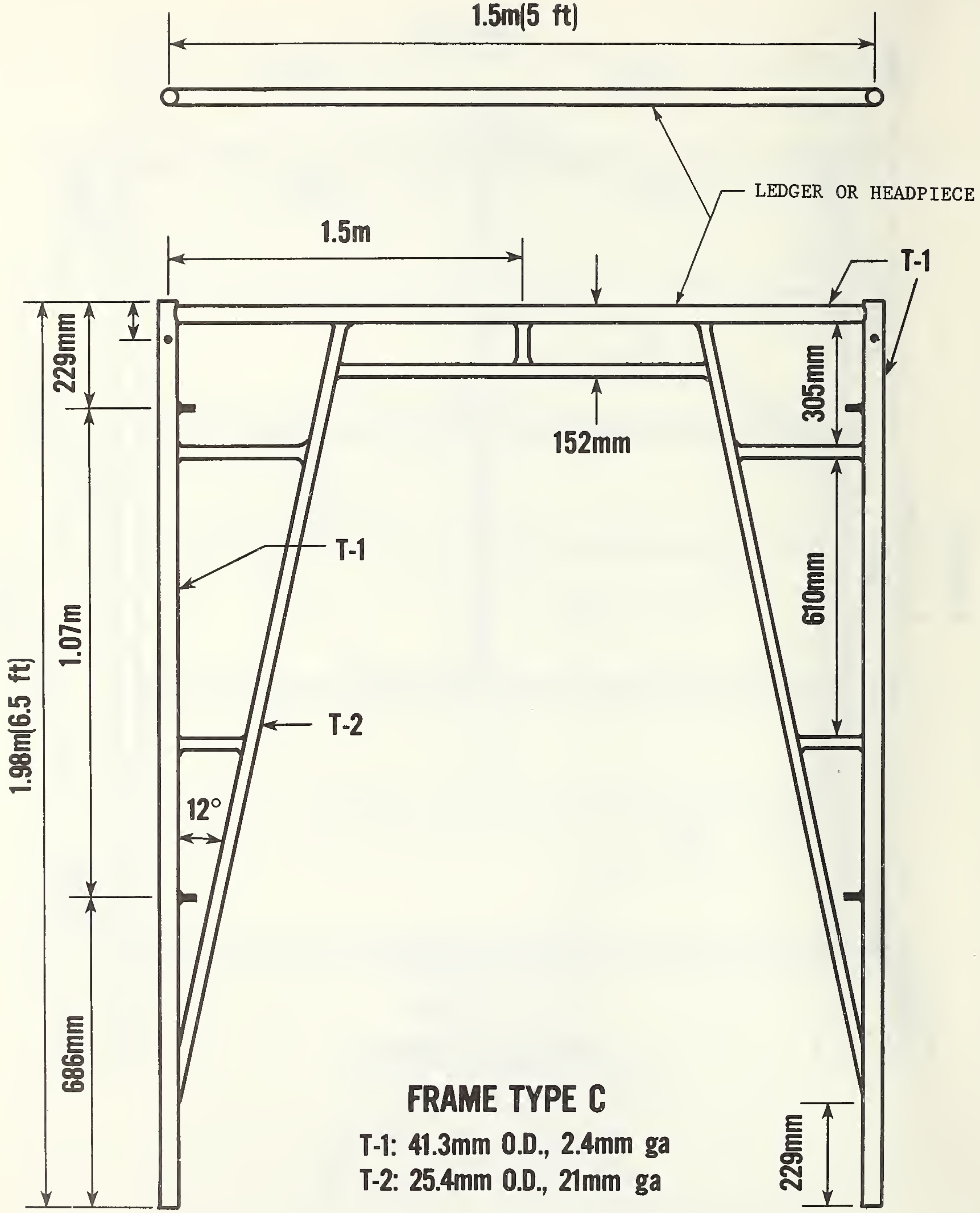

Figure 3.3 Welded fabricated tubular 1.98m by 1.5m frame-type C used in the SSSI studies.

Panel Type*	No. Lifts	Height m (ft)	Total Load kN (kip)	Loading Time min-s	Failure Location lift
B	1	2.6 (8.5)	187.8 (42.2)	6-22	1
B		.6 (15.0)	145.5 (32.7)	4-55	1
B	3	65.5 (21.5)	128.6 (28.9)	3-47	2
B	5	10.5 (34.5)	128.6 (28.9)	3-56	1 & 2
B	7	14.5 (47.5)	128.6 (28.9)	3-50	2 & 3
B	9	18.4 (60.5)	124.2 (27.9)	3-50	3 & 4
A	1	2.1 (7.0)	265.2 (59.6)	8-11	1
A	2	3.7 (12.0)	194.5 (43.7)	6-01	2
A	3	5.2 (17.0)	183.3 (41.2)	6-25	1
A	5	8.2 (27.0)	185.6 (41.7)	6-35	2 & 3
A	7	11.3 (37.0)	179.8 (40.4)	6-32	4 & 5
A	9	14.3 (47.0)	179.8 (40.4)	7-61	1 & 2

* Type A: See Figure 3.1
Type B: see Figure 3.2

Table 3.1 Results for 1961 SSSI simultaneous concentric column-leg load tests

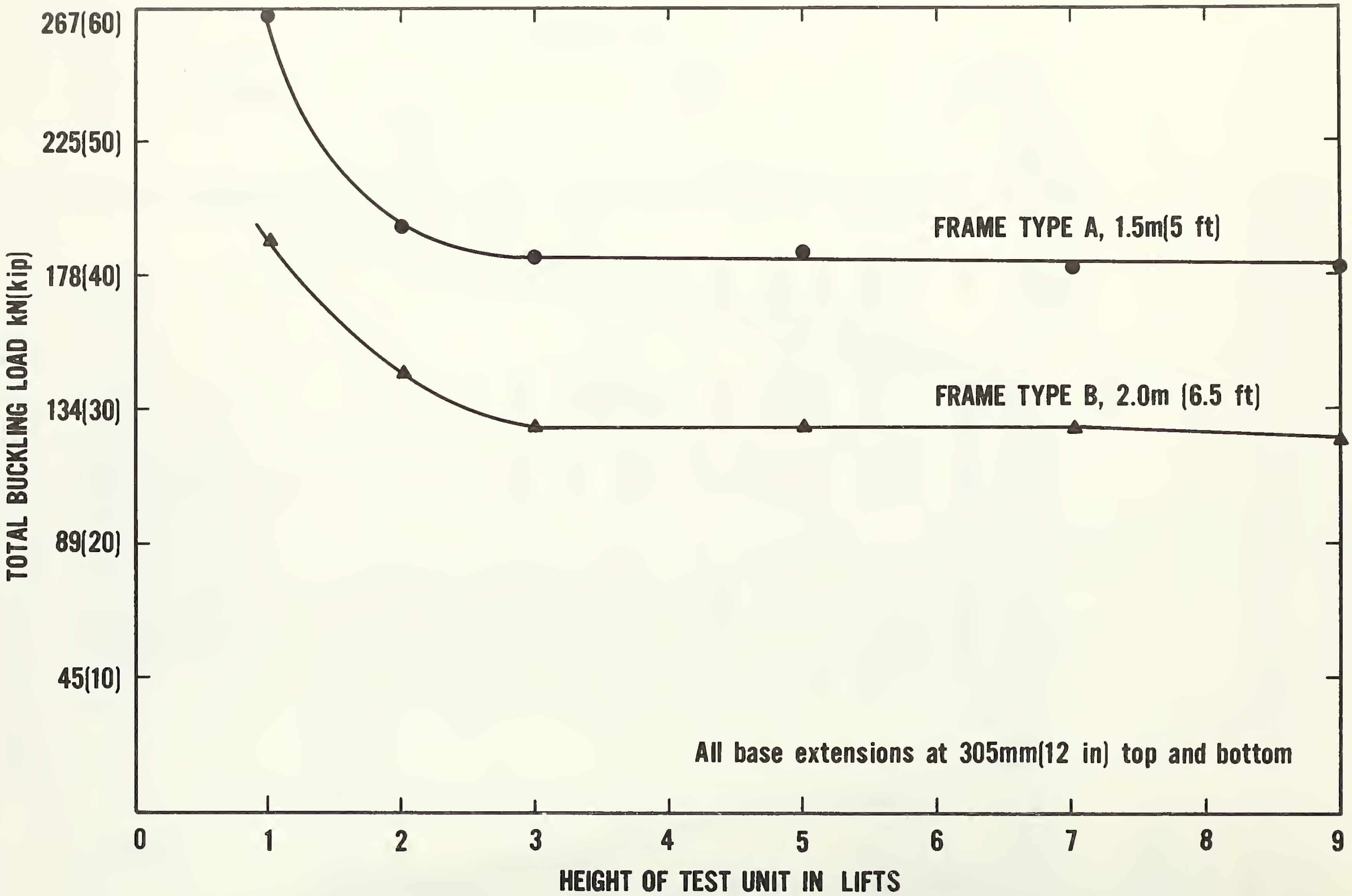

Figure 3.4 Graphic representation of the 1961 SSSI tests. Data presented in Table 3.1.

in the 1961 test series. The remaining leg or legs were continually loaded (ie. without release) until out-of-plane buckling occurred. Figure 3.5 and 3.6 present plots for some of the test results.

The second series of 1963 tests consisted of load tests using variable leveling screw extensions on frame type B assemblies all one tier in height and all column legs were loaded identically to failure at a rate of 8.9 kN per column per minute. The results of the second test series are presented in table 3.2 Figure 3.7 presents a plot of ultimate total tower load for the various jack extensions. For this test series, the average critical load capacity, P_{cr}, for the column leg was greater when the extension was at the bottom of the frame only. The reasoning for this is not fully understood at this time and future analytical and experimental studies should address this phenomenon.

The third and final series of 1963 tests consisted of 1.5 m square towers with three tiers of frame type B and one tier of frame type A (mixed mode). All jack extensions were set at 305 mm and each tower was subjected to identical column leg loading to a failure state as was performed in the second test series. Figure 3.8 shows the results of the mixed mode tests, where the abscissa identifies the tier where frame type A was located. The curve fit to the data shows ultimate column leg capacity was reduced as the frame type A was placed higher in the assembly. Since field studies show that mixing of frame types is common practice, especially when a specific platform elevation is desired, this phenomenon of capacity reduction due to mixed modes warrants further investigation and should be addressed in future scaffolding standards.

The 1966 SSSI scaffold tests consisted of three series using the open ended walkthrough frame type C as designed by SSSI to represent those frames produced by the institute members. This frame type is shown in Figure 3.3. The 1966 test series revealed very interesting information regarding total system behavior under varying load patterns. Since this information will be important to future modeling techniques, it is summarized below.

The first series of tests were performed to determine what effect preloading or pretesting of the frame had on the ultimate scaffold load capacities. The following tests were performed under identical concentric column loadings as in the earlier tests. No scaffold jack extensions were used.

I. <u>Test Description</u>

Test Description	Test Numbers
Three (3) Tests - 1 frame high to destruction	I-500 thru I-502
Three (3) Tests - 3 frames high to destruction	I-503 thru I-505
Two (2) Tests - 1 frame high to 100% design* load, then destruction	I-506 & I-507
Two (2) Tests - 1 frame high to 150% design load, then destruction	I-508 & I-509
Two (2) Tests - 1 frame high to 200% design load, then destruction	I-510 & I-511

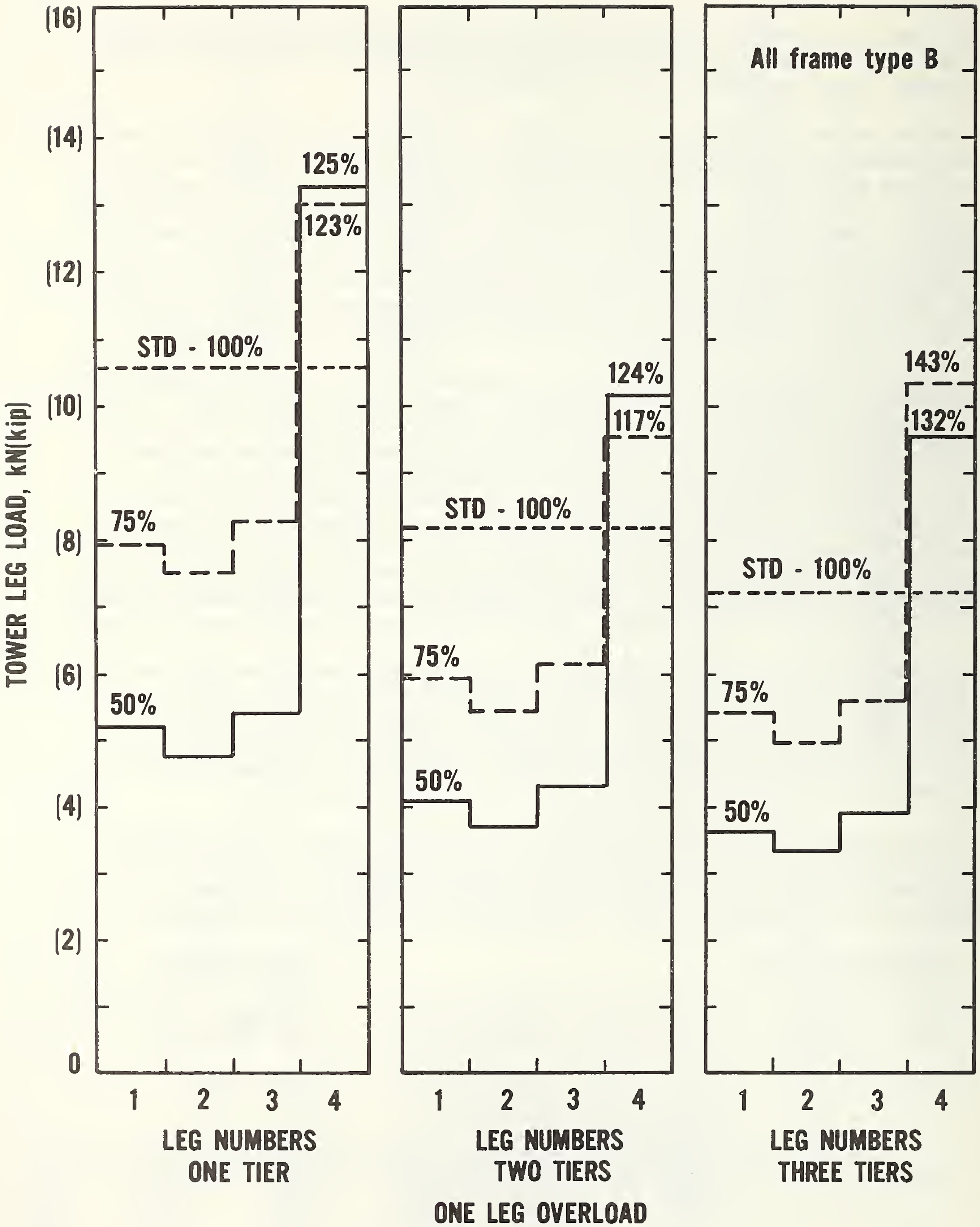

Figure 3.5. Unequal leg loading with one leg overloaded. Results of tests 1 and 2 (SSS1 1963 series).

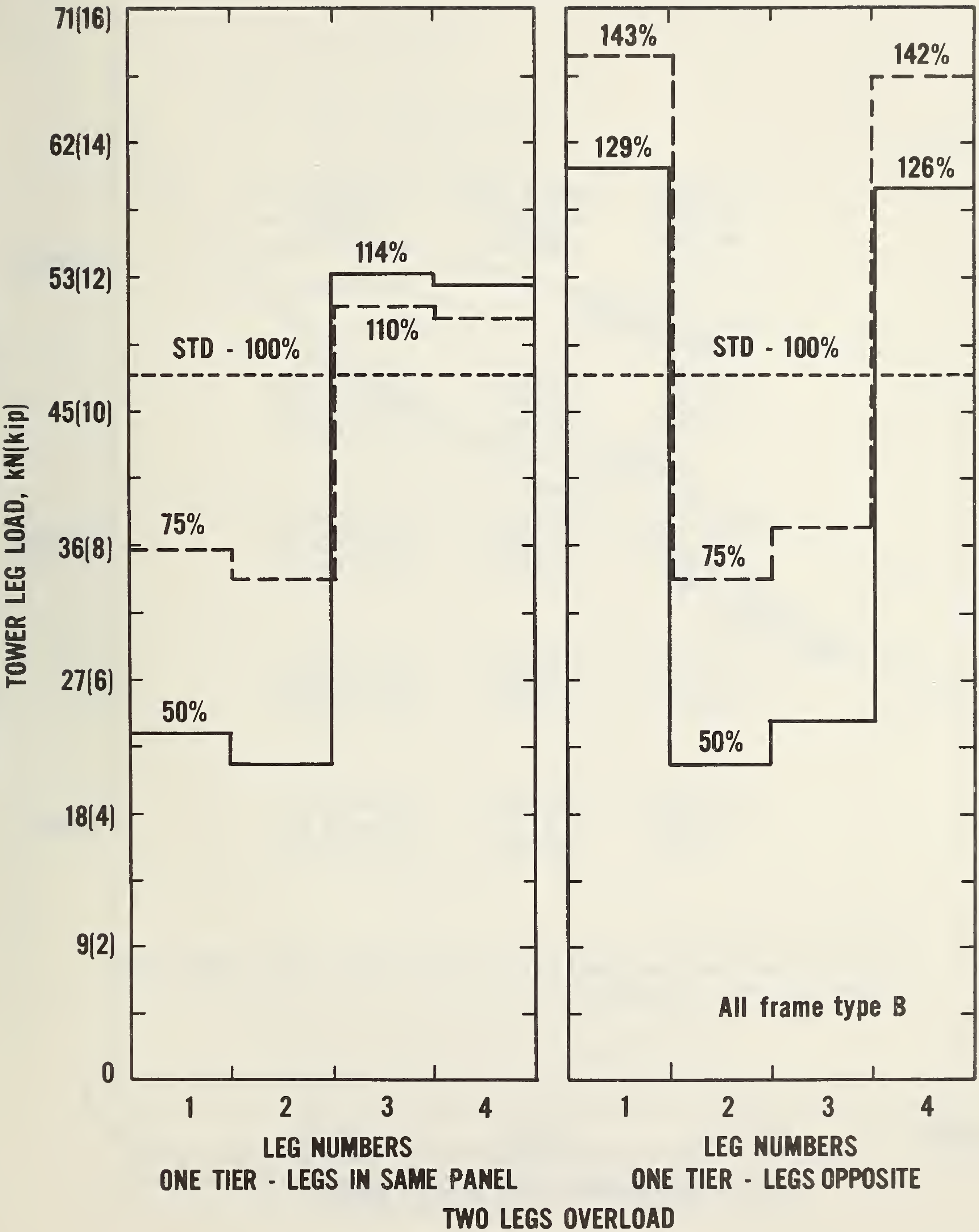

Figure 3.6. Unequal leg loading with two legs overloaded. Results of tests 3-6 (SSSI 1963 series).

Top Jack Extended mm (in)	Bottom Jack Extended mm (in)	Average Leg Buckling Load kN (kip)
0	0	80.7 (18.1)
152 (6)	152 (6)	60.1 (13.5)
152 (6)	0 (0)	58.7 (13.2)
0 (0)	152 (6)	64.5 (14.5)
305 (12)	305 (12)	48.5 (10.9)*
305 (12)	0 (0)	50.7 (11.4)
0 (0)	305 (12)	68.5 (15.4)
457 (18)	457 (18)	42.3 (9.5)
457 (18)	0 (0)	46.7 (10.5)
0 (0)	457 (18)	61.9 (13.9)
610 (24)	610 (24)	31.6 (7.1)
610 (24)	0 0	39.6 (8.9)
0 (0)	610 (24)	57.4 (12.9)

* Average buckling load found to be 46.9 kN (10.6 kip) in 1961 SSSI tests for this configuration.

Table 3.2 Average critical leg buckling loads for frame type B under different base extension configurations (1963).

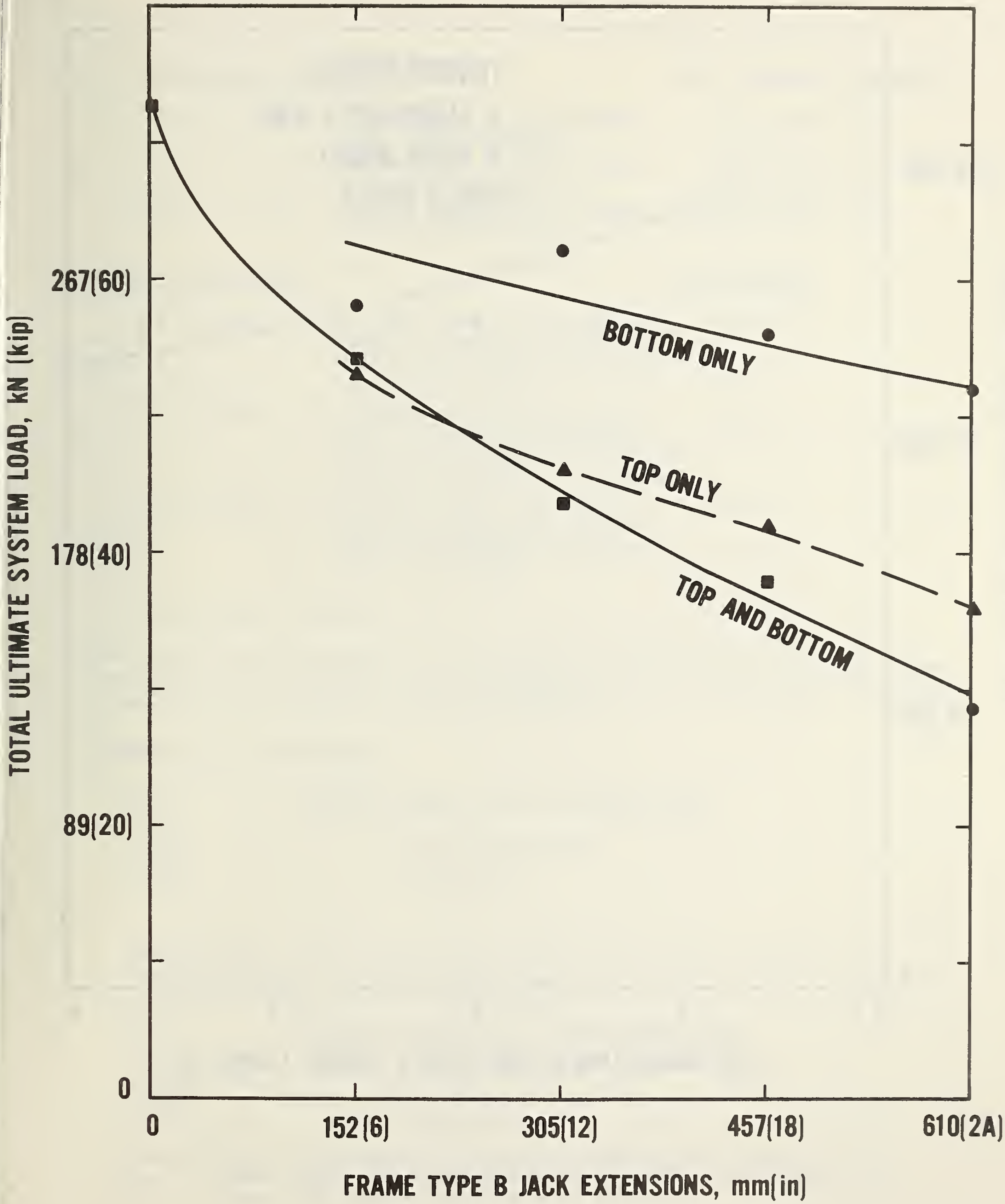

Figure 3.7. Total ultimate tower load plot for variation of base extensions for the 1963 tests (Table 3.2).

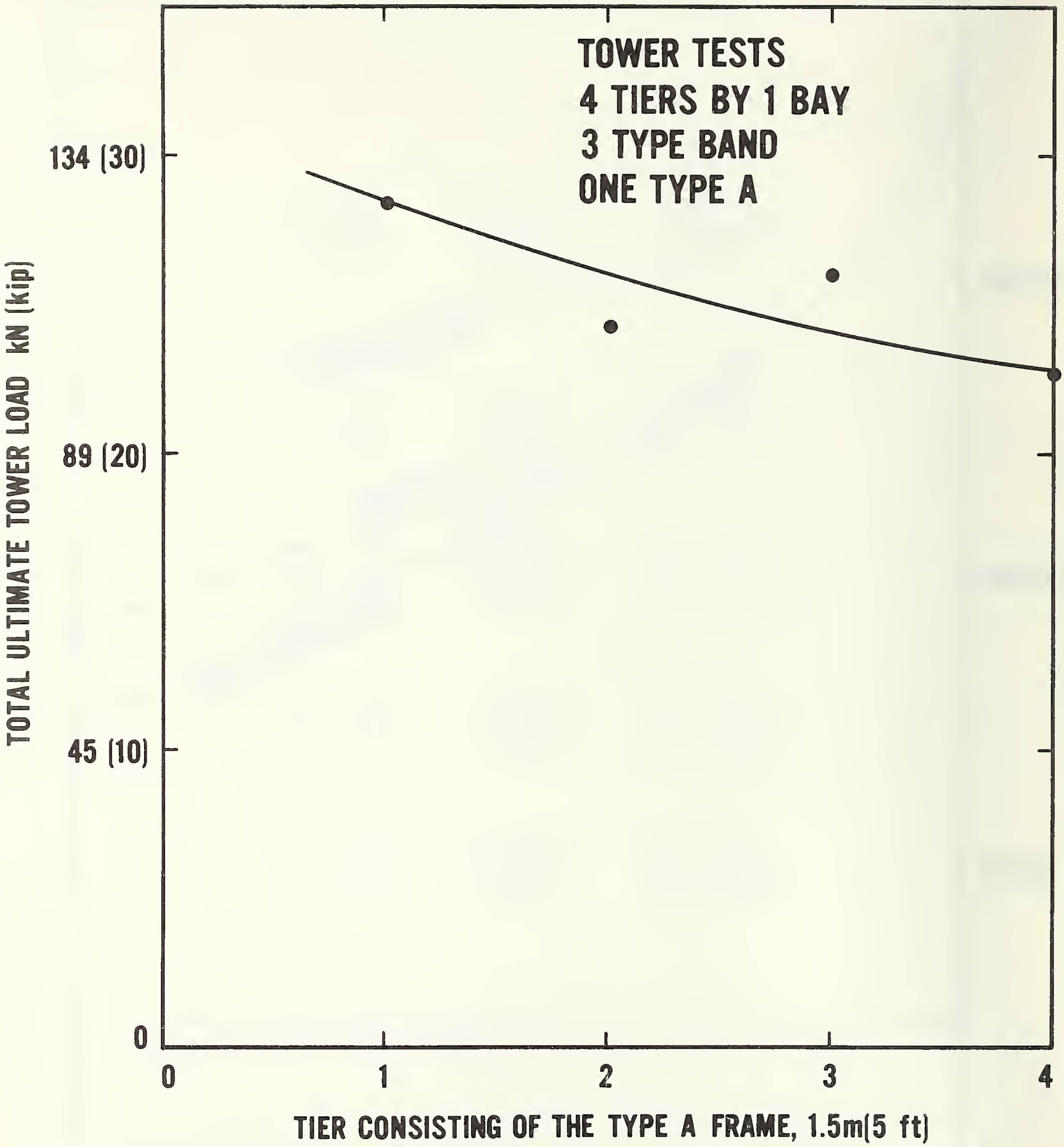

Figure 3.8. Mixed frame modes, four tiers high, total ultimate capacity plot for the 1963 tests.

I. Test Descriptions (continued) — Test Numbers (continued)

Test Description	Test Numbers
Three (3) Tests - 1 frame high to 100% design load, then released	I-512 thru I-514
Three (3) Tests - 1 frame high to 150% design load, then released	I-515 thru I-517
Three (3) Tests - 1 frame high to 200% design load, then released	I-518 thru I-520

Test Description	Test Numbers
One (1) Test - 3 frames high to destruction (after pretesting to 100% of design; equipment from Tests I-512 thru I-514)	I-521
One (1) Test - 3 frames high to destruction (after pretesting to 150% of design; equipment from Tests I-515 thru I-517)	I-522
One (1) Test - 3 frames high to destruction (after pretesting to 200% of design; equipment from Tests I-510 thru I-520)	I-523

Total number of tests = 24

* The design load was defined as the average leg failure load for tests I-500 through I-502 divided by a factor of safety of 2.5. The following represents a summary of the results of this test series.

Summary of I. Test Results

Test	Ultimate Tower Test - one frame high
I-500	221 kN (49.6 kip)
I-501	314 (70.5)
I-502	309 (69.5)

Average tower test - 281 kN load total or 70 kN (15.8 kip) per leg.
Design leg load - 28 kN (6 kip) average

Test	Ultimate Tower Test - three frames high
I-503	151 kN (34.0 kip)
I-504	157 (35.2)
I-505	160 (36.0)

Average tower test three frames high - 156 kN or 39 kN (8.8 kip) per leg.

Test		Ultimate Tower Test
I-506	1 frame high 100% design load, then destruction	223 kN (50.40 kip)*
I-507	1 frame high 100% design load, then destruction	321 (72.2)
I-508	1 frame high 150% design load, then destruction	242 (54.4)
I-509	1 frame high 150% design load, then destruction	273 (61.4)
I-510	1 frame high 200% design load, then destruction	292 (65.5)
I-511	1 frame high 200% design load, then destruction	258 (58.0)

On all of these tests, the pretested load was held for 5 minutes.
Average tower test - 268 kN (60.3 kip)

Test		Ultimate Tower Test
I-521	3 frames high to destruction after pretesting equipment to 100% of design	153 kN (34.4)
I-522	3 frames high to destruction after pretesting equipment to 150% of design	158 (35.5)
I-523	3 frames high to destruction after pretesting equipment to 200% of design	167 (37.5)

Average tower test - 159 kN (35.8 kip)

It was concluded that pretesting or preloading the scaffold frames up to the value of 200 percent of the defined design load had no identifiable effects on the ultimate capacity of the scaffold system for the frame type tested.

The second series of frame type C tests determined the effects on the ultimate leg capacities due to ledger or headpiece loading for various assemblies (see figure 3.3). To avoid any major variations resulting from localized stiffness characteristics of specific scaffold frame types, four equally spaced loads were applied to the ledger for all tests. The tests and the results consisted of the following. Failure was reached when out of plane buckling occurred.

II. Test Description	Test Number
Ledger Loading - 3 frame high tower to destruction	I-524
Ledger Loading - 2 frame high tower to destruction	I-525
Ledger Loading - 1 frame high tower to destruction	I-526

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* Test support beam failed; possible premature failure of frames.

Summary of II. Test Results

Test	Ultimate Tower Test	
I-524	3 frame high	159 kN (35.8 kip)
I-525	2 frame high	173 kN (38.8)
I-526	1 frame high	160 kN (36.0)

Average ultimate test load = 164 kN (36.9 kip)

The SSSI report concluded that alterations of the lift height configurations did not increase or decrease the ledger-load carrying capacity built or designed into a frame. As the results show, the average failure capacity of 164 kN (36.9 kip) is extremely close for the one, two and three height test configurations. However, the report failed to observe an extremely important consideration. The single tier high I-500 through I-502 tests resulted in an average ultimate capacity of 70.3 kN (15.8 kip) per leg. The ledger load in Test I-526 for the same frame resulted in a 40.0 kn (9 kip) per leg ultimate capacity. Using the 2.5 safety factor cited above or the present OSHA-specified safety factor of 4, the allowable leg loads resulted in a 44 percent capacity reduction due to the ledger loading. That is, 16/4 = 4.0 versus 9/4 = 2.25.

Considering that most frame type scaffolds functioning as the platform support system are subjected to distributed ledger loadings, this apparent capacity reduction must be considered in future investigations. It is also observed that this capacity reduction diminishes as the tier height is increased. This behavior is most probably due to the larger number of structural redundancies and greater redistribution of overloads in multipletiered systems. However, tests I-524 through I-526 represent a very limited sampling and the trend of decreasing capacity reduction with increasing tier height should be viewed with caution. Further experimental and supporting analytical research concerning this important topic of ledger loading is clearly needed.

The third and final series of the SSSI 1966 tests concentrated on the effects of continuous bracing in consecutive bays on the ultimate capacity of the system. Again, column legs were identically loaded in a concentric manner as described previously with no base extensions. All bays were braced to the full height of each assembly. The following describes the test series and the results.

III. Test Description	Test No.
One test-3 frames high-two bays wide to destruction	I-527
One test-3 frames high-three bays wide to destruction	I-528
One test-3 frames high-four bays wide to destruction	I-529
One test-1 frame high-two bays wide to destruction	I-530
One test-1 frame high-three bays wide to destruction	I-531
One test-1 frame high-four bays wide to destruction	I-532

Summary of III. Test Results

Test		Ultimate Tower Test	Average Failure Leg Load
I-527	2 bays wide-3 high	203 kN (45.6 kip)	34 kN (7.6 kip)
I-528	3 bays wide-3 high	211 (47.4)*	35 (7.9)
I-529	4 bays wide-3 high	401 (90.0)	40 (9.0)

* One frame accidentally not loaded

Test		Ultimate Tower Test	Average Failure Leg Load
I-530	2 bays wide-1 high	264 kN (59.4 kip)	44 kN (9.9 kip)
I-531	3 bays wide-1 high	437 (93.1)	55 (12.3)
I-532	4 bays wide-1 high	519 (116.6)	52 (11.7)

Tests (I-530 through I-532) Average Failure Leg Load 50 kN (11.3 kip)

For one frame high towers with 2, 3 and 4 bays, the average leg failure load was 49.8 kN (11.3 kip) versus the I-500 through I-502 one frame and one bay series, 70.3 kN (15.8 kip) leg capacity; a 30 percent capacity reduction. However, when the tier height was increased to three, the capacity reduction became insignificant.

A recent paper by Lightfoot et al. [14] describes the design of a test rig capable of testing free standing (no side restraints) scaffolding towers up to 9 m (29.6 ft) high and 1.8 m (5.9 ft) square for vertical loads up to 890 kN (200 kip). Full scale tower tests were performed and the results compared with model predictions of Harung et al. [15] who used manual analytical calculations, as well as a finite displacements program. The towers were the 'tube and coupler' type (see type 2 appendix A) which are not predominant in the United States and the geometric details were not given. Harung also performed experimental tests to determine the characteristic behavior of uniquely braced small scale scaffold models.

Both the analytical and experimental studies of Harung and Lightfoot showed that failure to sustain vertical loading was largely due to overall elastic instability. In addition, the assumption of full fixity at couplings was verified as reasonable for the scaled models. Verification of this assumption for full scale scaffolds is pending. These works demonstrated the possibility of using finite displacements programs as a scaffold design method.

In a recent study by Mansell et al. [16], 'tube and coupler' and 'tubular frame' scaffold towers were proof loaded. Two loading schemes were employed using loading cables to study horizontal restraining effects of conventional test apparatus used by others [14, 15]. Mansell concluded that the strength and safety of a scaffolding system can be misrepresented by using loading cables and that standard test procedures should specify proper simulation of gravity loads as performed by Lightfoot et al. [14].

In another study, Lightfoot et al. [17] investigated the collapse strength of 'tube and coupler' scaffolds of given geometric configurations using eigenvalue and finite displacements programs. The thrust of this paper was to develop the means by which complex scaffolding systems could be easily modeled for analysis. This work has limited utility since current software can be efficiently applied for scaffolding analysis and offers more refined and diverse capabilities than a linear finite displacements program (see appendix B).

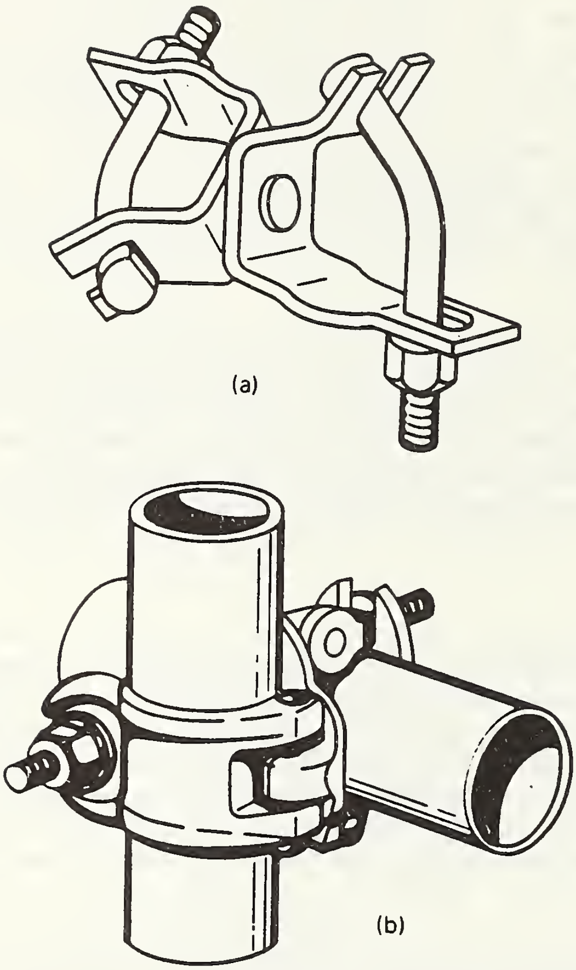
Literature was not found on the categories of 'support systems' and 'strength' for types of scaffolds other than the steel tubular type (see appendix A) or components thereof. In a final effort to comprehensively review the literature for information concerning support elements and strength, documents concerning falsework were reviewed. Falsework systems typically represent heavy duty scaffold systems assembled for the purpose of providing temporary support to a structure under construction. The loads imposed are usually much larger in magnitude than those for conventional work-platform scaffold systems. However, the literature was reviewed because of the marked similarities in the assemblies.

Three documents were identified that dealt with the design of scaffolds for falsework applications [18, 19, 20]. These documents were presented in a manual format and were developed from basic engineering design approaches. Designer aids are presented without detailed formulations for carrying out solutions but highlight the concepts which a designer may need to address. These documents are referenced where appropriate in the later portions of this paper.

3.2.3 Connections

A connection is a component used for the attachment of scaffolding elements. Any physical device used for the purpose of interconnecting scaffold support elements or braces, or for securing work platforms, accessways and safety devices to scaffold systems, fall within the scope of this definition. The accident study [1] indicated that connection failures were the leading cause of failures involving worker casualties, (17 percent of all cases reviewed). Therefore, the technical literature was reviewed on the topic of scaffold connections.

Connections are typically swivel or right-angle rigid couplers, sleeve inserts, pins and welded elements for metal scaffold systems and usually nails and bolts for wood systems (see Figures 3.9 and 3.10). The 'tube and coupler' scaffold (type 2 appendix A) uses a manufactured bolting coupler to connect straight rigid tube elements. According to the accident study [1], this scaffold type involved no connection failures. However, the metal fabricated tubular frame (type 3, appendix A) involved 6 (out of 10 cases) connection failures leading to injury and 8 (out of 17 cases) leading to death. Consequently, the literature was reviewed for technical content concerning connections for scaffolding systems in an effort to enhance any future analytical studies.



Scaffold fittings: (a) swivel coupler, (b) right angle or double coupler.

Figure 3.9 Coupler connections for 'tube and coupler' type scaffold systems.

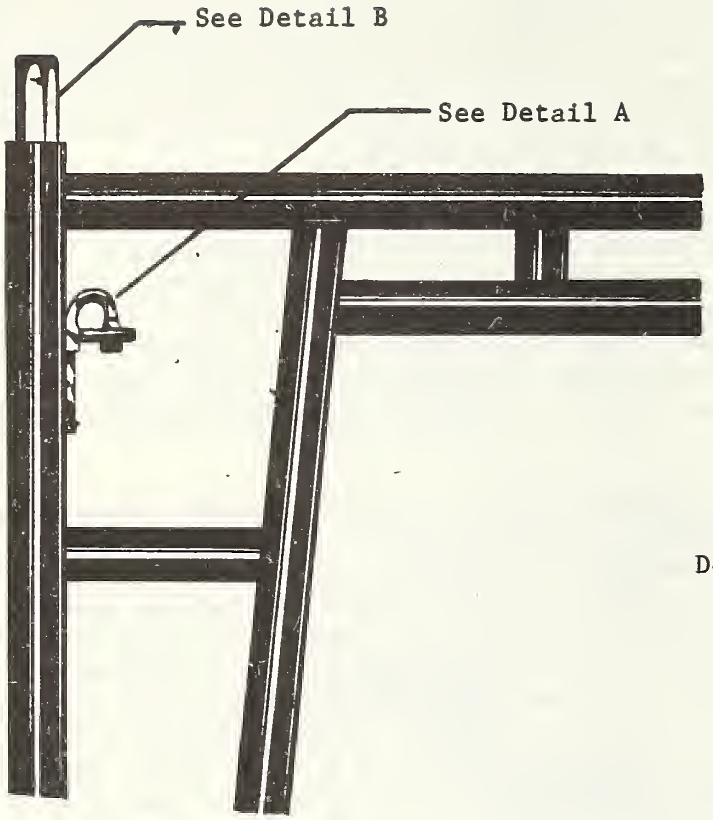
Very little technical information was found concerning metal connections and their structural characteristics applicable to scaffolding systems. A paper titled "The Elastic Analysis of Frameworks with Elastic Connections" by Lightfoot et. al. [21] addressed corrective modeling procedures for planar and grid type frameworks allowing for more realistic elastic joint behavior. These frameworks consisted of members with joints elastically constrained against axial and shear forces as well as twisting moments.

Lightfoot developed modified stiffness matrices, based on conventional approaches, for both frameworks and superimposed them generating a hybrid space frame model. Various joint fixity factors used previously by Monforton et al. [22] based on model behavior were applied by means of a special purpose analysis program. For a tube and coupler portal frame modeled in the study, it was shown that as the overall in-plane moment-supporting capability (or rotational fixity) of the coupler is reduced, the planar member approached a simply-supported condition.

Lightfoot recommended that realistic fixity values for coupler connections be determined prior to future analysis. Lightfoot et al. [23] developed a test rig for scaffold couplers and tested most of the scaffold couplers used in the United Kingdom to determine their stiffness characteristics for initial elastic behavior. Figures 3.11 and 3.12 show the results of some of the coupler tests performed with the test rig. It is seen that a variation of tightening torques had a definite effect on the coupler performance. Lightfoot et al. [24] further developed the idealization of scaffold couplers by theoretically treating them as rigid offsets consisting of elastic connections at both ends. This investigation was based on the asumption of linear elastic behavior and offered no apparent directly usable information.

Field studies have revealed that wood connections are commonly used compositely with other steel scaffolding systems. Review of the scaffolding codes and standards [2] showed that most of the provisions were deficient concerning the topic of wood connections. It was found that CAL/OSHA [25] was slightly more specific in providing minimum nail sizes and some bolt capacity data. However, there was a lack of detailed information concerning wood connection geometry, fastener configuration or quantity, material type, etc.

Many common connections used in scaffolding systems consist of wood with nail fasteners. The 'common' or 'wire type' nail is the most frequently used. Only a few of the scaffolding documents such as CAL/OSHA [25] and the Wisconsin Building Code [26] specify various scaffolding nail requirements which are in disagreement. Future analytical connection and anchorage studies could address the validity of the code specifications. Based on loading conditions and practices determined by field studies, the adequacy of nailed connections can be determined. For instance, CAL/OSHA allows a minimum of two 16-penny nails for 51 mm (2 in) lumber used for bracing purposes. Hurd presents allowable loads for common nails and spikes in "Formwork for Concrete" [27]. This two nail connection when used with a Southern pine 2 by 4 would have an ultimate lateral load capacity of 3.6 kN (756 lb) or allowable of 0.96 kN (108 x 2 = 216 lb) when incorporating a factor of safety of 3.5 as stated by Hurd.



Welded tubular frame unit.

Detail A: Cross-brace pin connection

Detail B: Pin-sleeve connection

Caster-wheel connections used for mobility at scaffold base.

Figure 3.10 Typical 'tubular frame' and 'mobile tower' type scaffold connections.

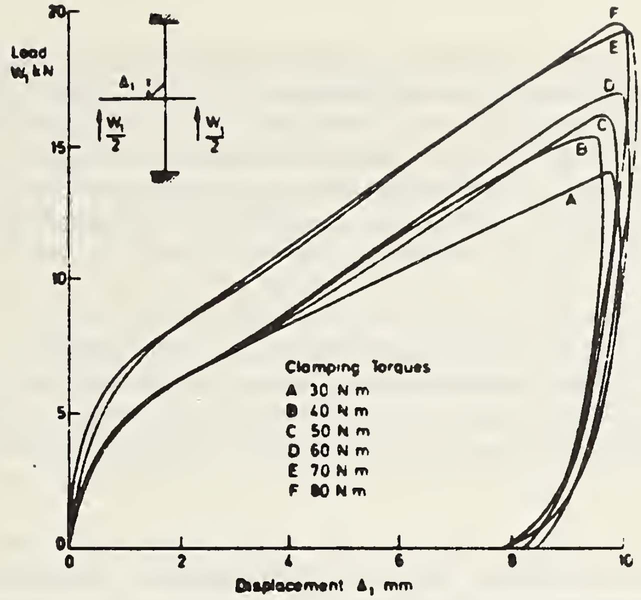


Figure 3.11 Results of shear tests on a Mills swivel coupler for different tightening torques.

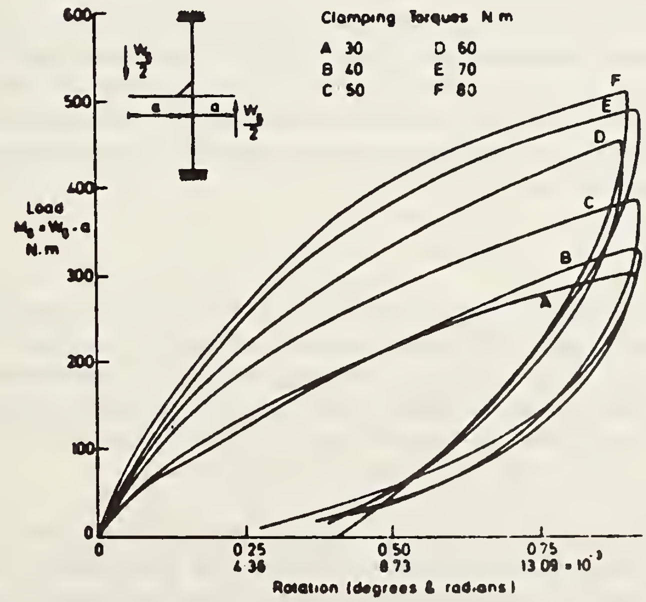


Figure 3.12 Results of twisting tests on a Mills rigid coupler for different tightening torques.

A considerable amount of detailed experimental research has been performed and documented concerning wood fastening devices by E. George Stern at the Virginia Polytechnic Institute, Wood Research and Wood Construction Laboratory [28-35]. Most of Stern's work has been performed for the industrial wood pallet industry. The literature could be divided into three distinct groupings: 1) test and performance criteria for nails and staples, 2) performance testing of nails and staples and 3) performance testing of assembled pallets. Test criteria using the Morgan Impact Bend-Angle Nail Tester (MIBANT) was developed and presented [28, 29]. The overall performance of assembled wooden pallets depended on the performance of the nails and fasteners. The MIBANT tests enabled quality control criteria to be developed for fastener manufacturing and assessment purposes. Once such criteria were established, fastener characteristics were identified through pallet performance testing.

Numerous papers by Stern address the performance testing of various nails and staples used with numerous wood classifications [30, 31]. Such topics as lateral load transmission, withdrawal resistance, toughness, aging effects, holding power, effects due to coated nails and overall performance and effectiveness were discussed. Other papers described assembled wooden pallet performance testing for numerous material, fastener type and geometric configurations [32, 33]. Overall performance was evaluated for pallets subjected to drop and load testing. Even the topic of fastening frozen lumber was addressed [34]; a topic of possible interest for users of woodtype scaffolds in cold climates.

Based on the above and other exhaustive studies, "Tentative Nailing Standards for Warehouse and Exchange Pallets" [35] were developed. It is feasible that a similar process could be followed in developing criteria for scaffolding fasteners. Existing technical information on wood fasteners should be used to avoid duplication of effort and to enhance current code provisions for scaffolding fasteners.

3.2.4 Anchorage

Anchors refer to those components which secure the scaffold system to the foundation. The scope of this definition addresses only those devices which physically connect the scaffold to the support foundation at the support points. The importance of this distinction is emphasized because numerous mechanisms are employed in securing scaffold systems and they must be systematically addressed for proper analysis.

The accident study [1] revealed that 17 percent of the scaffolding accidents leading to injury and 15 percent leading to death were attributed to anchorage failures. For scaffolding accidents leading to injury only, 6 out of 10 anchorage failures occurred with the 'bracket-type' scaffold (see type 16 appendix A) out of a sample of 22 scaffold types. However, for accidents leading to death, the leading type was the 'two-point suspension' (see type 10 appendix A) accounting for 8 out of 13 anchorage failures, followed by the 'bracket type' (3 out of 13).

The integrity of both scaffold types mentioned above depend primarily on adequacy of the anchorages. This is because a single anchor provides total support to part or whole work platforms. The two point suspension scaffolds usually service high elevations and accomodate more than one worker. Failure of a single anchor will therefore cause a collapse of the entire work platform. In multi-point suspension systems, however, failure of one anchor could actually go unnoticed.

Technical literature on anchorage devices in general is quite complex and in abundance. Numerous anchorage devices are available such as concrete inserts and expansion types as well as power driven steel and wood fastening devices. Technical literature providing specific scaffolding anchorage information was not found. Therefore, pertinent information which might serve to aid future studies was extracted from the more general anchorage literature and is presented below.

Recent research concerning anchorage mechanisms typically used with mechanical equipment applications in nuclear power plants was performed by the Tennessee Valley Authority (TVA) [36]. The tests were performed to determine the limiting load capacities and anchorage requirements for concrete inserts, anchor bolts, welded studs and expansion anchors subject to direct tension, direct shear and combined tension and shear. The purpose of the TVA anchorage research program was to provide further insight regarding anchorage design and performance beyond the existing conventional design approaches in an effort to meet those design requirements unique to nuclear power plant considerations. The overall goal was to match anchorage requirements with existing and available anchorage systems thus reducing to a minimum the number of anchorages requiring special final design consideration.

The TVA research program was divided into three parts. The first was concerned with the determination of anchorage embedment requirements for various systems through tensile pullout tests. The second part examined the shear strength for the tensile type anchors and the third involved combined tension and shear tests on various anchor systems. Although some of the testing was concerned with particular proprietary products, these products could apply to scaffolding systems as well. In the first part, initial pullout tests were performed for open-section concrete channel inserts, embedded 19 mm (.75 in) A307 bolts and 16 mm (.625 in) stud groups in standard concrete. Additional tests performed included edge effects and a comparison of epoxy and grouted bolt performance.

A formulation was developed for the necessary embedment length to assure that steel (anchor) failure would occur before concrete (foundation) failure. It was found, based on a limiting stress of $4\sqrt{f'_c}$ from ACI-318 (11.10.3) [37] and the ASTM A307 minimum tensile strength requirements (Table 2) [38], that an embedment length of eight diameters in 144 kN/m^2 (3 ksi) concrete would assure steel failure of a A307 bolt. When edge distance became less than 6 diameters, an increase in embedment of one diameter, per each diameter less than 6 (for edge distances $\geq$ 3 diameters) was required. The following formulation was presented, based on a half cone pullout failure mode, to permit the steel anchor to develop its full capacity.

$$(L + m) \geq 0.58 \sqrt{P_u / \sqrt{f'_c}} \qquad 3.1$$

where:

L = embedment length, inches
m = edge distance, $L/3 < m < L$, inches
P_u = ultimate pullout force, pounds
f'_c = concrete compressive strength, psi.

For concrete compressive strength of 144 kN (3 ksi) and the specified ASTM A307 proof load, the following simplified formulation was presented for A307 bolts.

$$(L + m) \geq 14d \qquad 3.2$$

where:

L = embedded length $\geq 8d$
m = edge distance $\geq 3d$
d = bolt diameter, inches

Tests clearly indicated that a minimum side cover was required to fully restrain the developed lateral pressure resulting from full bearing load transfer at the head of the bolt for 19-mm (.75-in) A307 bolts at 51 mm (2 in) edge distance and 25-mm (1-in) A490 bolts at 114 mm (4.5 in) edge distance. For deep embedments, it was determined that this lateral pressure was approximately one-fourth of the bolts tensile capacity. The formulation presented recommends that the design yield strength of the steel bolt should not exceed:

$$f_y \leq 67 \sqrt{f'_c} \, (m/d)^2 \qquad 3.3$$

where:

f_y = steel yield strength, psi
m = distance from edge to bolt center line, inches
d = bolt diameter, inches

Other interesting concepts presented in the TVA study included epoxy and grouted 19-mm A307 bolts and expansion anchors. Cored receiving holes developed poor bond due to the smooth interface. It was found that by roughening the polished walls, load capacities equal to those for embedded bolts were developed. The general mode of failure for tensile loading of expansion anchors tested by TVA was anchor slip. Preloading of such anchors was not recommended because of the slip characteristics.

The TVA anchorage studies were performed using massive concrete-block test specimens with no reinforcing steel. A study concerned with design loads for concrete inserts was performed by Reichard et al. [39] and used 114-mm (4.5-in) flat slab reinforced concrete specimens. Because these test specimens are more representative of those encountered in scaffold systems (i.e. reinforced concrete walls, ceilings, floors, etc.) the paper was reviewed for technical information which might be of use in later scaffolding developments.

The study was performed for independently mounted malleable iron concrete inserts capable of accepting 19-mm (.75-in) threaded rods. These inserts are fastened to the inside face of the formwork prior to concrete placement and the investigation was limited to cast-in-place embedment lengths equivalent to the anchor length of 79 to 95 mm (3.125 to 3.75 in). Reinforcing steel consisted of No. 5 bars at 152 mm (6 in) on centers in slabs of various span lengths. Some findings are presented below.

It was concluded that for concrete strengths within a range of 144 to 240 kN/m^2 (3 to 5 ksi) and densities of 1840 to 2400 kg/m^3 (115 to 150 pcf), the average static pullout strengths for anchors placed centrally in 1.2 m (4 ft) square specimens could be approximated by:

$$P_u = 2.0 + 0.0012\, W \sqrt{f'_c} \qquad 3.4$$

where:

P_u = specimen pullout strength, (kip)
W = concrete unit weight, (pcf)
f'_c = concrete compressive strength, (psi)

This formulation is of use for scaffold anchorages placed adequate distances from the edges of the reinforced concrete slabs, walls, etc. However, tests performed on slabs continuous over two 3.05 m (10 ft) spans indicated the pullout strengths computed by equation 3.6 could be 10 percent too high because of flexural cracking. A capacity reduction factor of 0.9 was recommended to accomodate for flexural cracking. The TVA studies [36] also recommended that minimum reinforcing be used in certain pullout tests since the high strength A490 bolts developed flexural cracking in the massive unreinforced specimens being used and this influenced the anchorage ultimate capacity. Flexural steel considerations should therefore be incorporated in building designs to account for scaffolding anchorage loads in addition to the conventional building loads. Examples of scaffolding systems where such anchorages can be used are shown in appendix A (see types 8, 9, 10, 11, 16).

Another interesting and useful concept presented by Reichard [39] concerned the effects of reinforcement cover. Test results displayed a linear capacity reduction of pullout strength on the 1.2 m (4 ft) square specimens with 144 kN/m^2 (3 ksi) normal weight concrete to be 6.23 kN (1.4 kip) per inch of additional cover beyond 19 mm (.75 in) of initial minimum cover to a maximum of 76 mm (3 in) of cover. This behavior was attributed to the interaction of the reinforcing steel with the pullout failure cone. With increasing cover, the steel intersects less of the cone and thus less of the insert load is transferred through dowel action. Once again, such behavior should be recognized for scaffolding anchors used with foundations, where considerable concrete cover can be encountered, such as end-fill panel walls, deep ceilings, etc.

Other capacity reduction factors were developed for both fatigue and sustained loading conditions. Mechanized suspension scaffolds (see types 9, 10 and 11 appendix A) frequently induce fatigue loads due to the repetitive winding and ratcheting devices. Reduction factors were recommended for sustained loads (0.85) and for fatigue loads (0.70 and 0.65 for semi-lightweight and normal weight concrete respectively). In addition, experimental scatter factors of 0.82 and 0.75 for normal and semi-lightweight concrete respectively were recommended. All of the above reduction factors were then applied to equation 3.6 as follows:

$$P = B\ (2.0 + 0.0012W\ \sqrt{f'_c}) \qquad 3.5$$

where:

B = appropriate capacity reduction factor.

This formulation was presented for the 19-mm (.75-in) anchors tested for the stated foundations. It was recommended that the fatigue and sustained factors would not be cumulative because of the remote possibility of both conditions occurring simultaneously.

The topics discussed thus far have dealt with only anchorages in concrete. Other anchorage systems commonly used consist of wood with nails, bolts and welded steel or power driven steel fasteners. Numerous proprietary anchorage and fastening devices are available with the manufacturer's recommended applications and design capacities. Discussing such devices individually is beyond the scope of this review and as was recommended in the TVA [54] study, the manufacturer's claims should be checked against sound engineering design principles.

3.2.5 Foundations

Foundation designates that part of the total system which provides support to the scaffold. In this context, the foundation may consist of the ground (footing and flooring) upon which the scaffold bears as well as any other supporting structure such as a partially completed wall of a building to which the scaffold may be attached. Connections between the scaffold and the foundation have been treated as anchorages. In reviewing the multiple scaffolding types presented in appendix A, various "types" of foundation supports are feasible. With the 'fabricated tubular frame' type, the foundation might consist of the earth or concrete floor slabs as well as the wall which provides lateral support. For many of the 'suspension' types, the foundation consists of floor slabs, roof parapets, structural steel elements etc. Thus it becomes evident that scaffolding foundations are not restricted to soils.

The accident study [1] indicated that 14 percent of the scaffolding accidents attributed to foundation failures lead to worker injury and 5 percent to worker death. The review of scaffolding codes and standards [2] revealed major deficiencies and ambiguities among the various provisions regarding the topic of foundation. In addition, failure of the foundation component of a scaffolding system can lead to major collapse resulting in catastrophic consequences. A recent investigative study of the Willow Island cooling tower collapse in West Virginia [40] indicated that the most probable cause of the collapse was due to the imposition of construction loads on the concrete shell structure before adequate strength to support those loads was developed. The resulting catastrophe of this "foundation" failure was the death of 51 men who where working on a scaffold system supported by the shell.

Many scaffolding foundations are constructed at grade level and appear to receive little design consideration. Thornley [41] rates temporary structures such as scaffolding and falsework with least importance allowing permissible foundation settlements that "vary too widely to tabulate." However, as was cited in the review of scaffolding codes and standards [2], many of the provisions contain generalized statements that foundations must be "sound", "rigid" and "capable of supporting the maximum intended load without settlement or displacement". Much of the foundation literature offers information concerning permanent structures which might be readily applicable to scaffolding and is therefore included herein.

Gaylord [42] presents tabulated information concerning the consistency of cohesive (clay) soils as obtained from standard penetration tests. Gaylord concluded the standard penetration test provides the best information that can be economically obtained and used in most routine in-situ situations. Modification of the standard penetration test for surface conditions intended to support scaffolding systems appears feasible and deserves further consideration.

The previously cited publication produced by the Joint Committee of the Concrete Society and Institution of Structural Engineers [18] offers comprehensive information on the design of temporary structures. Concise information on various design topics is discussed and critical aspects are highlighted. Sections 4.10.1 - 4.10.2 of the manual mention the possibility of differential settlement between the permanent structure and the falsework. Section 5.9 addresses the topic of soils and presents some tabulated information on bearing capacities and modification factors. This publication serves to comprehensively address many of the topics of critical importance to safe design of temporary falsework systems. Much of the detailed technical information used in the engineering analysis is omitted. Instead, key areas deserving the design engineer's attention are highlighted in conjunction with substantial reference information in concise graphical and tabular form. It is recommended that this manual be referred to during future development of scaffolding foundation guidelines.

The California Division of Structures produced a manual on falsework design that provides administrative guidelines for the Division's field engineers in charge of bridge construction on State highway projects [19]. The manual provides an approach to bridge falsework design, materials, construction, inspection and contract administration. Similar to the Joint Committee's publication [18], detailed engineering formulations are not specified and are left to the 'responsible party'. The manual does present a comprehensive outline for foundation design and it is recommended that this manual be referred to during future research.

Grant [20] provides a systematic outline for falsework design, from the selection of the proper scaffold system for the job application to the design of its foundation; all based on a similar approach used in the above two documents. Grant does not provide specific design details or procedures, but instead offers a check-list approach to the design process. One of these check-list items is to determine the bearing capacity of soils. Grant provides general soil capacity information and discusses a mechanism to appropriately transfer the loads to a sloped foundation.

3.2.6 Safety Devices

Safety devices protect employees from falls, air-borne objects and other environmental hazards. Some scaffolding safety devices consist of guardrails, safety nets and screens while other devices which are worn by the individual workers include hard hats, eye protection glasses, etc. Positive fall protection devices include a personnel safety belt or harness fastened to an independently supported lifeline. The accident study [1] revealed that 3 percent (2 cases) of the accidents leading to injury and 21 percent (18 cases) leading to death were primarily related to safety devices. It was also noted that nearly three times as many secondary causes (48 versus 18 cases) as primary causes leading to death were related to safety device failure. Review of the individual accident records revealed that a significant portion of the cases involved noncompliance with existing OSHA regulations. The review of scaffolding codes and standards [2] revealed major inconsistencies in the existing safety device provisions and the regulations were unclear. Since safety device-accident relationships have been indicated, the literature is reviewed for technical information of use to future scaffolding research. Since fall protection devices and guardrails are the most common safety devices used, fall protection devices are discussed first followed by guardrails.

Steinberg [43] presents a comprehensive literature study on personnel fall-safety equipment. Steinberg's paper served as a comprehensive descriptive manual for fall-safety equipment and did not offer technical information which could forseeably be used in scaffolding safety device research. Steinberg presents the literature on the physical and anthropometric basis of fall-arrest. In addition, the paper offers substantial and definitive terminology regarding the various fall system components and classifications. Also, consumer-product-type testing information for many of these components is presented. Unfortunately, the enhancement of safe scaffolding practices involves research studies beyond any type-specific product analysis and a study of the product use in the field is needed.

Fattal et al. [44] conducted a study of guardrails used for the protection of employees from occupational hazards. The report compiled anthropometric data and its interrelationship with guardrail geometries for use in experimental work which was documented in another study [45]. The experimental study included resistance testing of guardrail components under static and dynamic loads using human subjects and an anthropomorphic dummy. Nonstructural tests were also carried out to determine the geometric requirements for guardrail safety. Based on these investigations, a model performance standard and a design guide for guardrail systems was prepared.

In order to determine an appropriate guardrail design load, an experimental impact loading of a laboratory model guardrail system was performed. An ultimate unfactored peak load of 2.2 kN (498 lb) was determined (95th percentile anthropometric data incorporated) and reduced to 1.3 kN (300 lb) by incorporating the safety factor used in the design of steel flexural elements [46]. Figure 3.13 shows a graph of the test data. These test data were used to develop a relationship (Figure 3.14) between the dynamic force-to-weight ratio of the test subject and the stiffness of the guardrail system relative to the mock-up system used in the tests.

Fattal presented design approaches for guardrail systems. However, the topics of connection capacity and performance were not addressed. It is recommended that the field study guardrail information be used to select representative guardrail systems and these systems be subjected to further laboratory testing without duplicating those tests already performed by Fattal.

3.2.7 Stability

The term instability, in the simple dictionary sense, pertains to a state in which the slightest change causes still further change. Rolling, overturning, buckling of a leg in compression or excessive drift are some of the typical conditions of scaffolding instability. Present regulations require that scaffolds be braced and laterally supported at specified intervals [2]. However, no design provisions are given to determine size of bracing elements or anchorages used as lateral supports. The accident study [1] reported that numerous casualties resulted from worker loss-of-balance which was attributed to stability problems.

The falsework design manual by the Joint Committee [18] emphasizes the need to incorporate stability requirements in falsework design. Under design detailing, the topic of lateral loads is addressed. These include wind and dynamic effects of moving loads as well as loads produced by secondary effects such as thrust shores (outriggers in the case of scaffolds), guys and tension shores. It was noted that thrust shores will tend to reduce vertical downward forces while guys will increase them. Also, differential settlement would lead to load redistribution to the various system components and must be accounted for in the design process. Each situation described could lead to local or overall instability conditions and result in unsafe conditions.

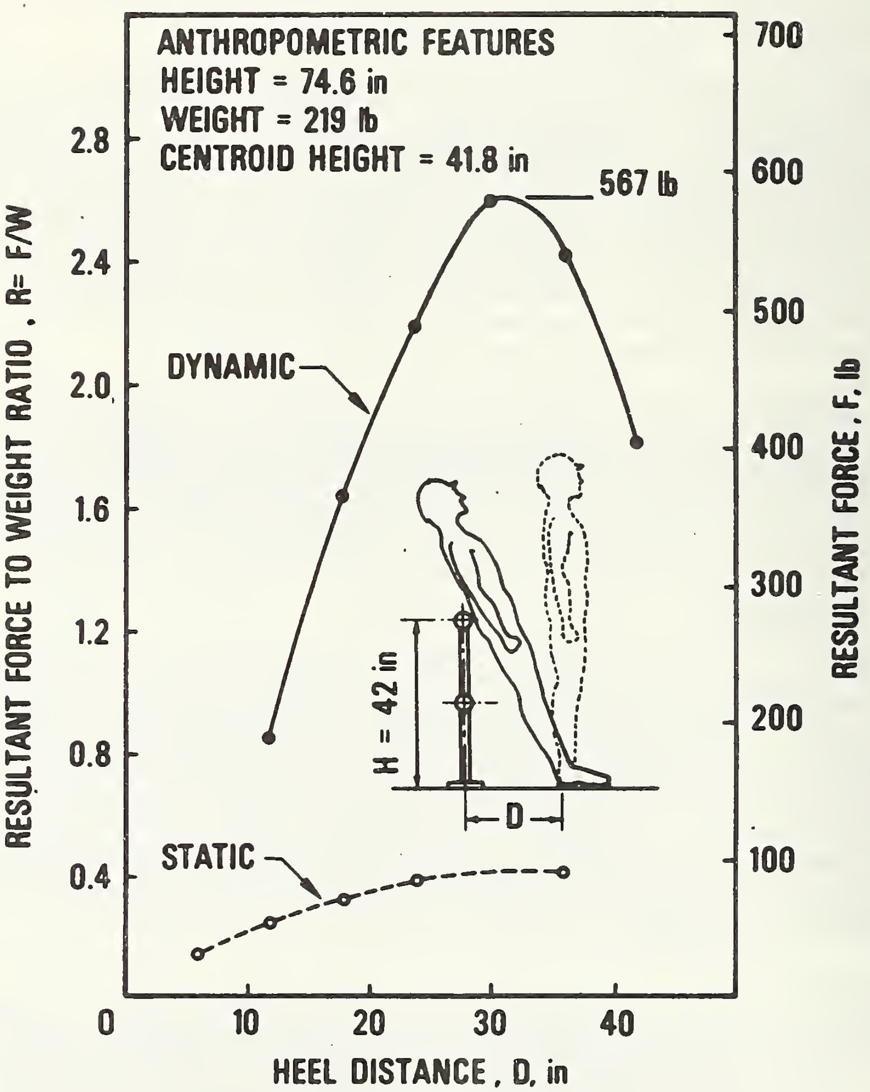


Figure 3.13. Dynamic and static force on the top rail exerted by the 95th percentile dummy vs. heel distance from centerline of rail.

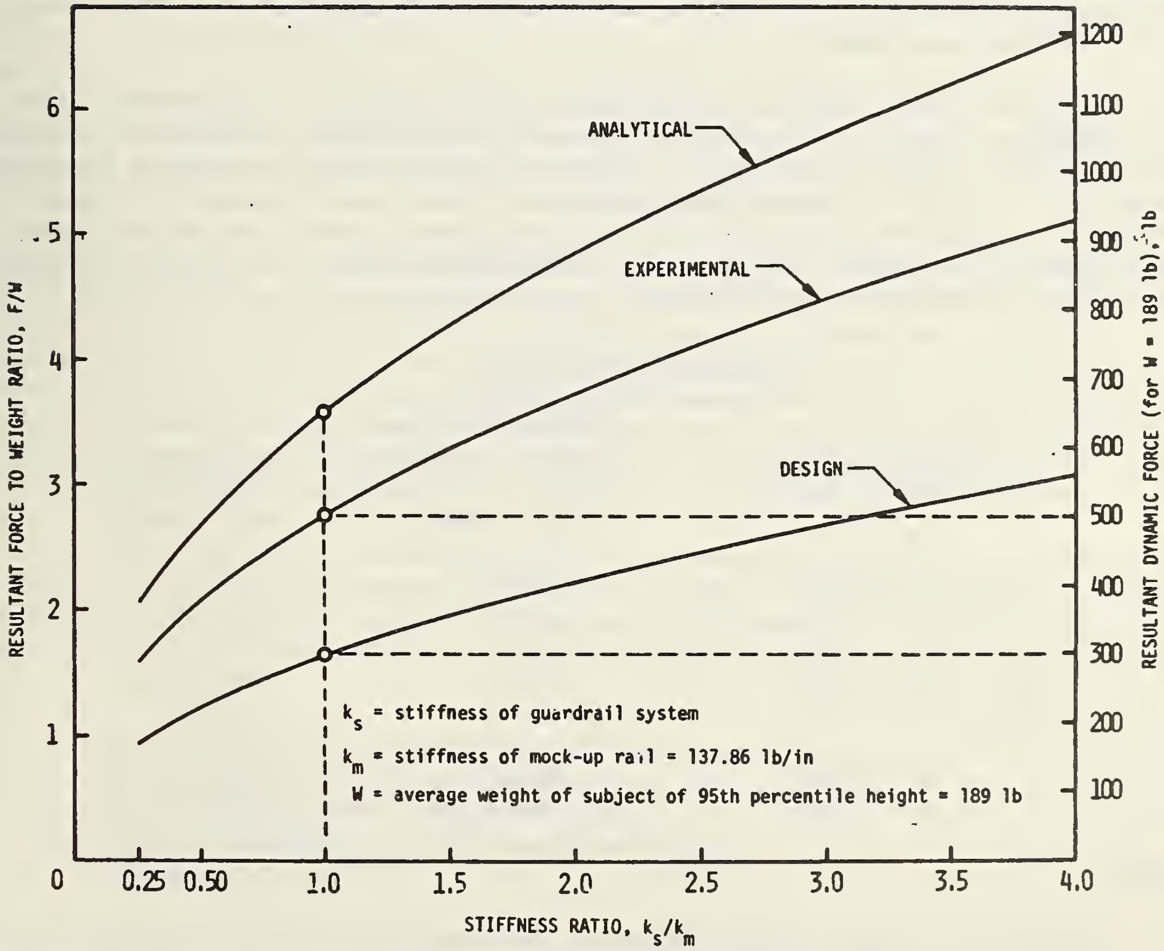


Figure 3.14 Relationship between dynamic force-to-weight ratio of subject and stiffness of guardrail system relative to the mock-up rail.

In an attempt to ensure both lateral and longitudinal stability, the California Falsework manual [19] specifies that all falsework must be capable of resisting an 'assumed' horizontal load in any direction. This 'assumed' load is to be the sum of the actual horizontal loads due to equipment, construction sequence etc., including an allowance for wind, but not less than two percent of the total supported dead load. The falsework bracing system is to provide adequate strength to resist any developed overturning or collapse moment. The overturning and collapse moment values are to be determined similarly by the resultant overturning force acting at its appropriate distance above the ground; however, the term collapse moment refers to that moment resulting in localized instability (collapse) as opposed to overturning. It is the engineer's responsibility to recognize and account for all factors contributing to the overturning moment.

The California manual addressed the design for wind quite extensively. For high capacity shores, the manual refers to the Uniform Building Code, section 2308(g) [47]. However, for other systems of lower capacities (more representative of scaffolds), the minimum horizontal force due to wind effects is specified as the sum-of-the-products of wind impact areas and the following applicable wind pressure values. The wind impact area is the gross projected area of the falsework and the unrestrained structure.

<u>Wind Pressure Values</u>

Height of Impact Area Above Ground (H) m (ft)	For Members Over Traffic Openings and Bents Adjacent kN/m^2 (psf)	At Other Locations kN/m^2 (psf)
$0 < H < 9.14$	96 Q	72 Q
$0 < H < (30)$	(2) Q	(1.5) Q
$9.14 < H < 15.24$	120 Q	96 Q
$(30) < H < (50)$	(2.5) Q	(2) Q
$H > 15.24$	144 Q	120 Q
$H > (50)$	(3) Q	(2.5) Q

where:

$Q = 1 + 0.2\ W\ , \quad < 10$
W = width of the falsework system (ft) measured normal to the projected area of the falsework.

The effects of shielding on the wind impact area are addressed. If adjoining bents are rigidly connected, in the engineers judgement, then the wind load may be distributed to the adjacent bent. The manual offered very concise design examples for calculating the overturning moment due to the specified minimum force (two percent dead load), transverse wind loads and a stability check due to cable bracing between towers. It is recommended that this manual be referred to during the development of future scaffolding performance guidelines.

A comprehensive study of wind loading on falsework was performed by Nix et al. [48]. They used full size installations of modular tubular frame falsework in the NASA-Ames Research Center wind tunnel subjected to 44 m/s (100 mph) winds. Tests considered various tower spacings, wind velocities, oblique incidence angles and variation in the number of tower units in the wind stream. Conclusive findings reported include a design method based on an empirical wind velocity model and the experimental test data. Some of the Nix information is highlighted below.

Figure 3.15a* shows the modular frame unit, assembled to heights of 7 m (23 ft). The towers were independently situated with no intermediate cross-bracings. Figure 3.15b through 3.15d summarize the test tower layout configurations, the concept of wind incident angle and the force and moment resultants determined under the various wind loadings. Nix presented normalized plots of the test data which yielded an 'effective area' for a given wind velocity. This 'effective area' is in units of length squared and is the equivalent 'solid' area the wind impacts with a force equal to the dynamic pressure. If the 'effective area' is divided by an applicable model area, a drag, side or lift coefficient is obtained.

This novel concept was introduced because a drag coefficient for a falsework tower would prove to be meaningless. That is, there is no single dimension which will characterize a falsework tower. Therefore, to avoid interpretation difficulties the drag data were presented in terms of an 'effective area' which is also referred to as normalized drag. Figure 3.16 is a plot representing the normalized drag concept for one and four tower configurations at zero degrees skew and Figure 3.17 is a similar plot for a wind incidence of 90 degrees.

The primary goal of the research effort was to develop sufficient experimental information to permit rational design of wind-resistant bracing for falsework structures. Various factors suspected of influencing the structural integrity of a falsework system subjected to wind loadings were investigated. These included:

1. downwind spacing of falsework units
2. angle of incidence of the wind
3. effects of adjacent falsework units
4. number of falsework units downwind, and
5. wind velocity.

Each of these factors was discussed and presented in the paper. A summary of their individual significance was reported as follows.

1. Not significant.
2. Highly significant - peak at 10° for falsework bent in-plane forces, 80° for out-of-plane forces.

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* See figures at the end of chapter.

3. Highly significant - wind load reduced due to upstream generated turbulance.
4. Significant - conservative value obtained from twelve-tower tests for typical falsework installations.
5. Significant - decrease in effective area with velocity.

Both Figures 3.16 and 3.17 present some interesting concepts and served as a comparison with the method of the Uniform Building Code (UBC) [65] where the normalized drag was computed by the UBC method (Section 2308). Both figures demonstrate the adequacy and inadequacy based on the given conditions. The effects of shielding in the four-tower arrangement becomes apparent in Figure 3.16 when the normalized drag at 161 km/h (100 mph) is compared with the single and four tower arrangements. The latter develops only 70 percent of the former. Figure 3.17 shows that at a 90 degree skew angle, both the one and four tower arrangements develop higher values of 'normalized drag' and behave in a similar fashion due to the independence of the four towers (i.e., towers are not interconnected).

Nix also presented a design method based on the research efforts and findings. This design method is compared with the methods described in the previously discussed California Falsework [19] manual using the Wind Impact Area (WIA) method.

For the computation of a falsework-bent wind overturning movements, Nix recommended the following equation:

$$M = A \times N \times P \times \alpha \qquad 3.8a$$

M = total falsework bent overturning moment
A = equivalent drag area
N = number of towers per bent
P = design pressure
α = height factor.

The equivalent drag area, A, is computed by selecting the appropriate effective area per foot for the design wind velocity in Figure 3.18. This value is then modified by an appropriate tower factor yielding the equivalent drag area. Based on these studies, the following tower factors were recommended.

Tower Factor	Conditions
0.80	bents with > 4 towers for out-of-plane forces
0.90	d.o. for in-plane-forces
1.00	bents < 4 towers for both directions

The height factor, α, and the design pressure, P, were approximated through common velocity gradient and dynamic wind presure formulations. These are,

$$\alpha = h^2/2 + h^3/730, \text{ and}$$
$$P = 0.0256\ (V)^2 \qquad 3.8b$$

where:

h = falsework height, feet
V = wind velocity, ft/s

For a given example considering a six tower falsework bent, 4.9 m (16 ft) in height subjected to 34 m/s (75 mph) wind, the in-plane overturning moment, M, was calculated by Nix (equations 3.8a) and found to be 258 m-kN (190 ft-kip). Using the WIA method [19], M was found to be 488 m-kN (360 ft-kip) for 1.2 kN/m^2 (25 psf). The major variation was attributed to the fact that the WIA does not account for the number of towers as a variable. The Nix equation 3.8a yields larger design loads than the WIA method for configurations of 12 or more towers.

It is recommended that future scaffolding analytical modeling developments use the comprehensive information presented by Nix where applicable. It is also recommended that in conjunction with the Nix information, other technical wind literature sources, such as that presented by Simiu et al. [49], be used to obtain appropriate information (e.g. building geometry effects, wind velocity profile, etc.) for studying the effects of wind on scaffold structures. Building geometries and relative locations will have a substantial effect on the forces developed by the scaffold and are not addressed in the current falsework design literature.

3.2.8 Accessways

Accessway refers to the means of access to and egress from the scaffold work platform. As was cited in the review of scaffold codes and standards [2], except for suspension-type scaffolds, most codes and standards call for ladder or other type of access devices to the work surface. The review study found the scaffolding provisions to be lacking in specific information regarding scaffold accessways. However, the study also stated that codes and standards do exist for ladders, stairs, etc. which are devices commonly used as scaffold accessways. No other specific literature regarding specific scaffolding accessway information was found.

The accident study [1] reported that for accessways, no cases of primary causes of accidents led to injury and only one case led to death. Only a small number of accidents were attributed to secondary causes related to accessways. The application of an accessway device to a scaffolding system appears more important than the integrity of the device itself. Therefore, technical research (e.g. structural analysis, etc.) regarding scaffold accessways does not appear warranted at this time. However, accessway information obtained in the field study should be referred to in future research activities. In particular, the type of accessway provided for given scaffolding systems should be identified along with the methods of use. As was discussed in the accident study [1], accessways were classified under the category of system failure since safe access must be provided through the scaffolding system as a whole. Failure to provide an appropriate access device can lead to unsafe practices and injury.

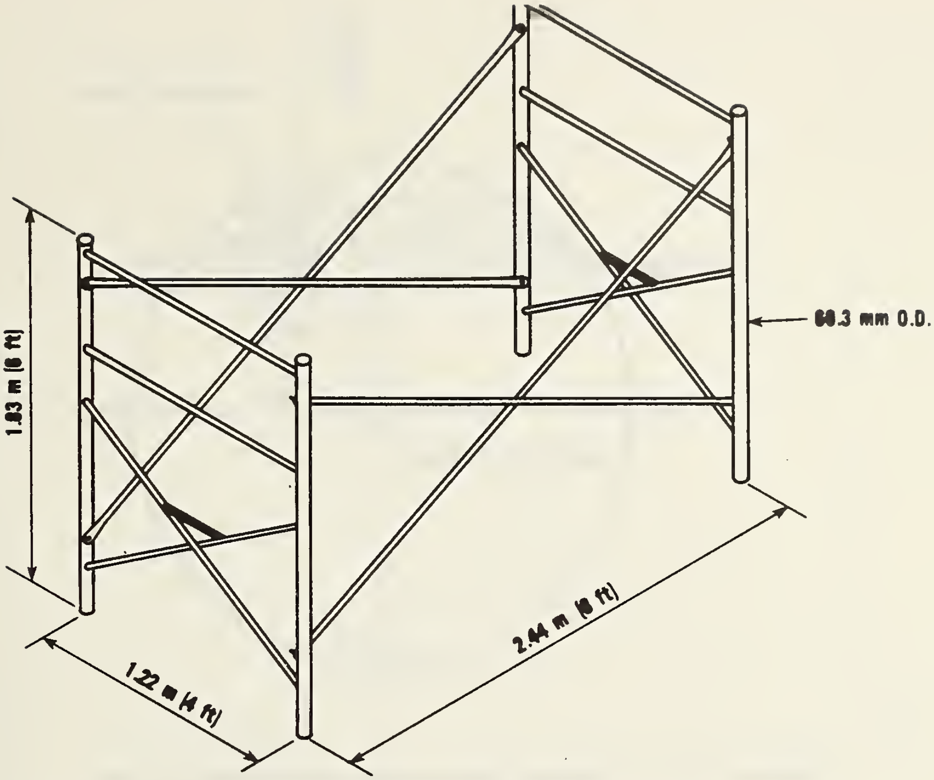

Figure 3.15a. Modular falsework unit studied in the wind tunnel by Nix et al.

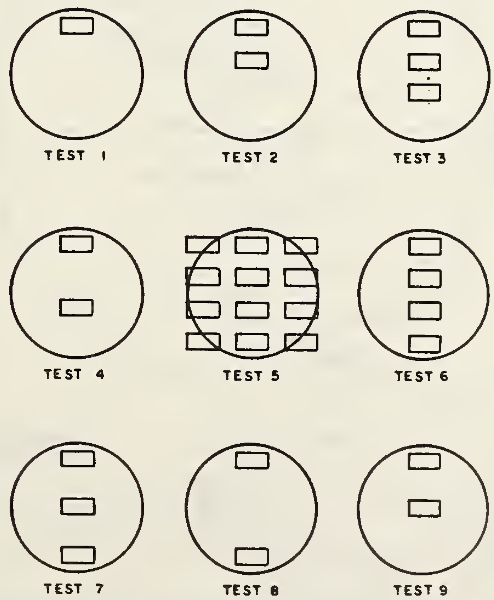

Figure 3.15b. Plan view of wind load study tower test configurations.

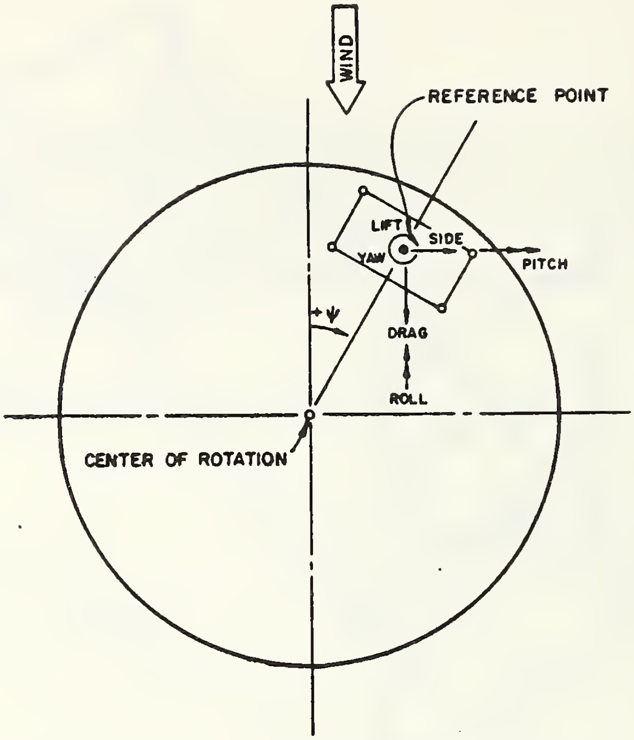

Figure 3.15c. Wind load study reference point forces and moments.

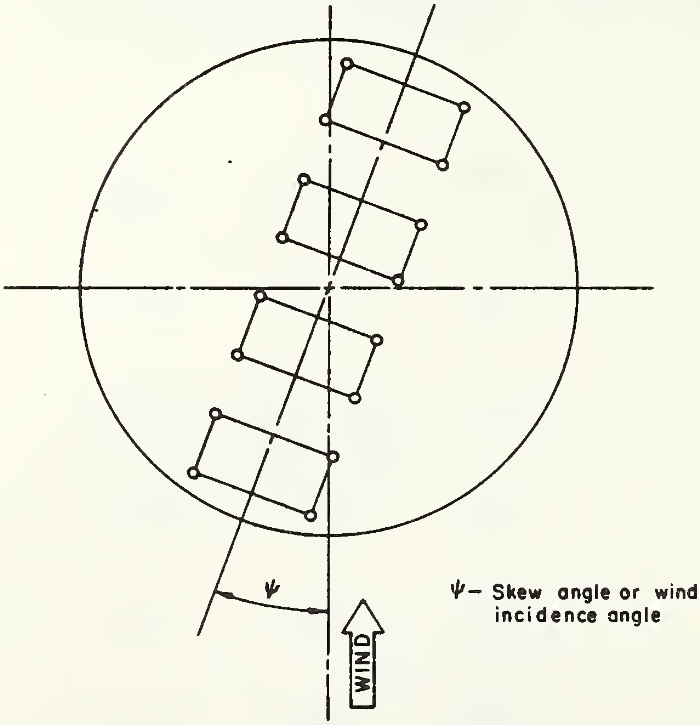

Figure 3.15d. Wind load study tower orientation for a given wind incidence angle.

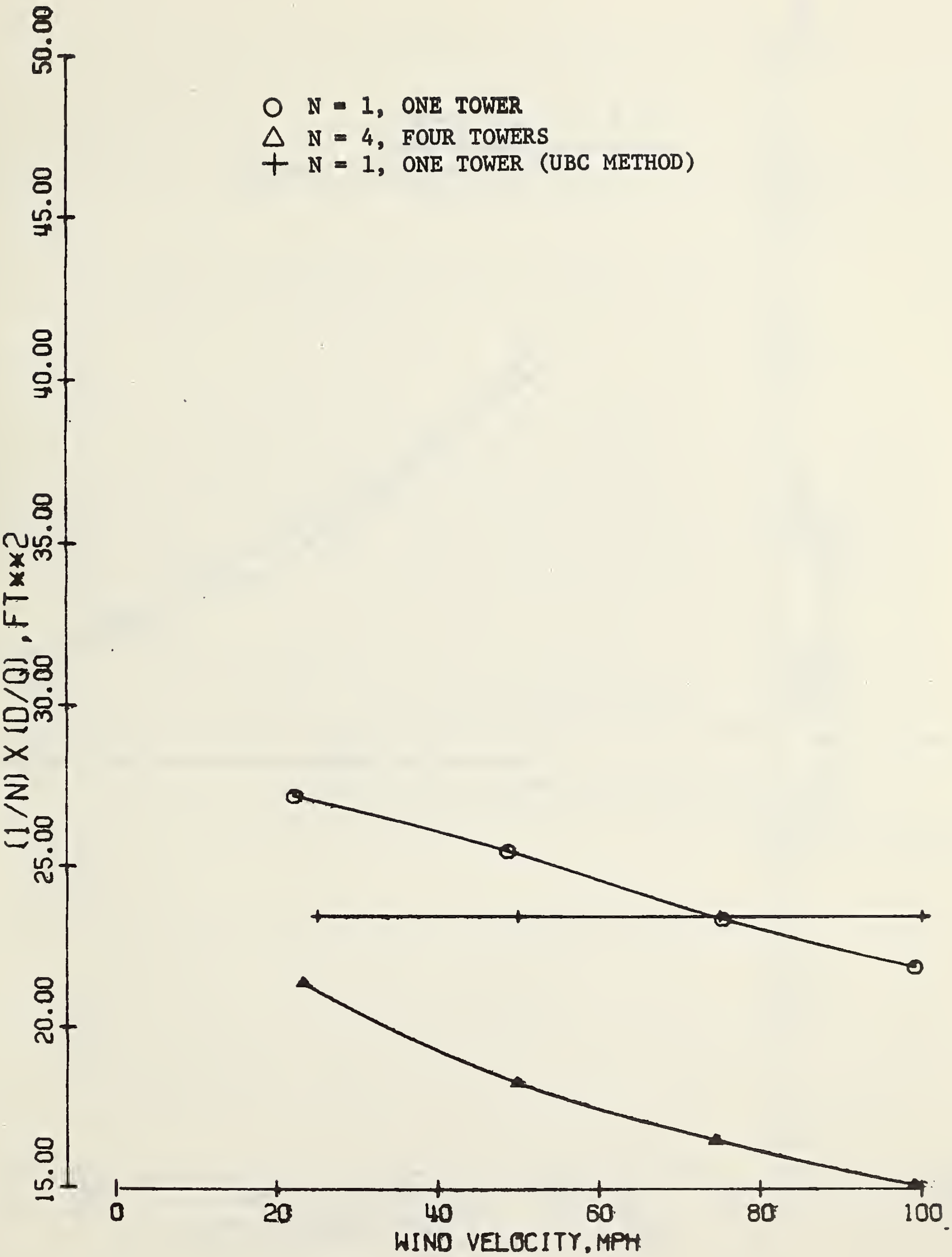

Figure 3.16 Variation of normalized drag with velocity for zero degrees skew (Nix et al.).

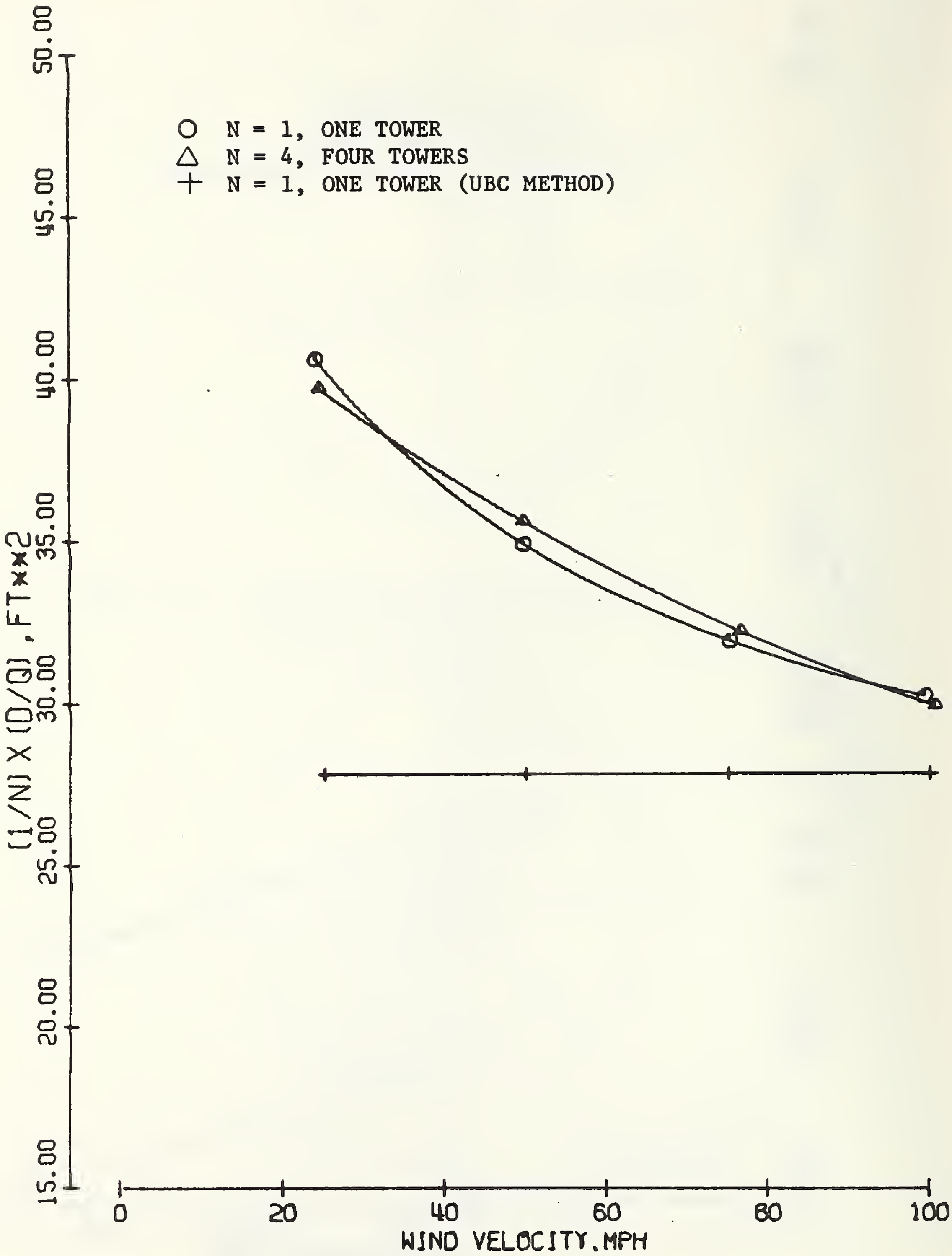

Figure 3.17. Variation of normalized drag with velocity for 90 degrees skew (Nix et al.).

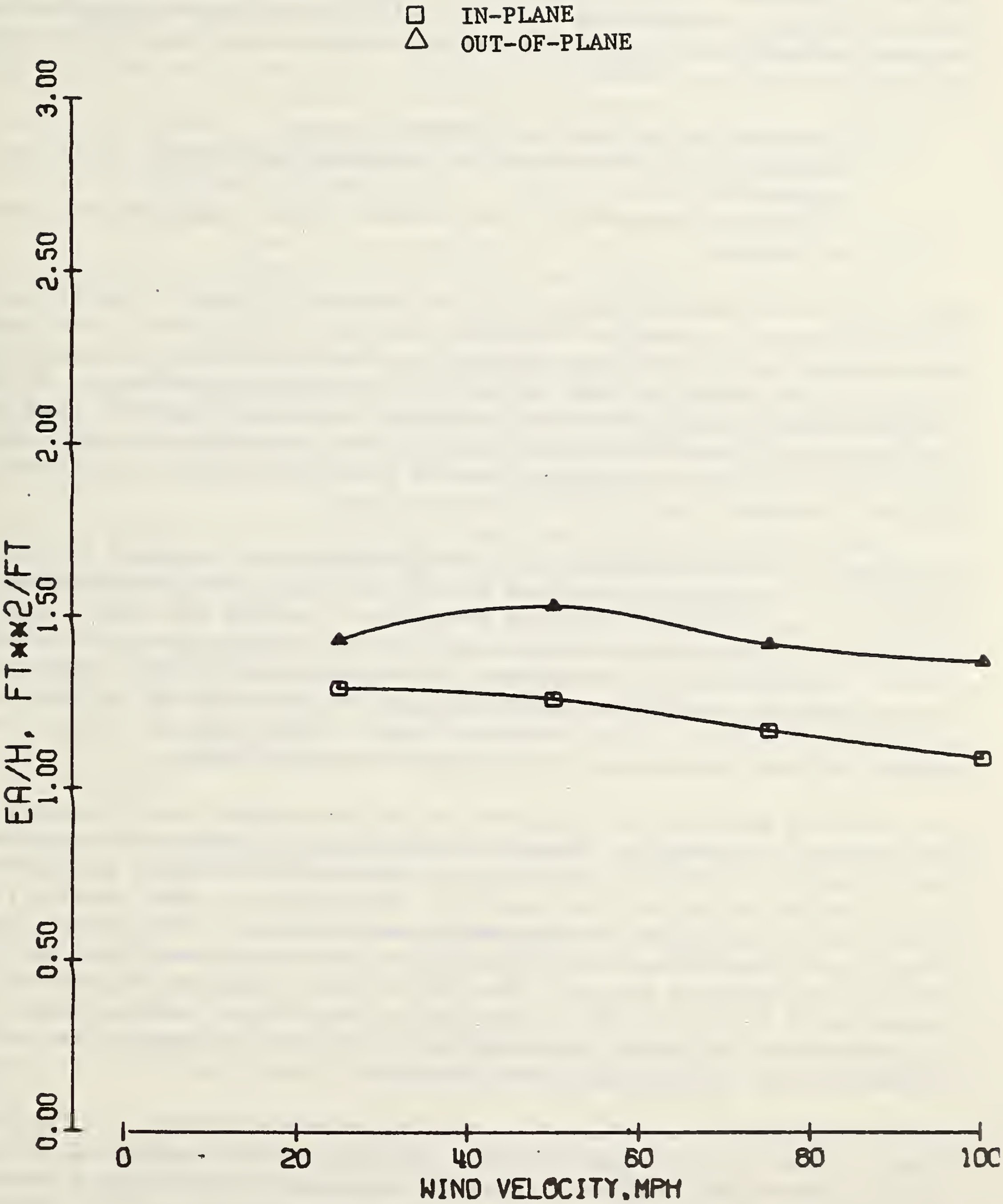

Figure 3.18. Variation of design effective area,EA, per foot of tower height,H, with velocity (Nix et al.).

4. SCAFFOLDING MANUFACTURERS' LITERATURE

In the review of existing scaffolding codes and standards [2], the manufacturers' literature was not presented. In an effort to establish a better understanding of scaffolding products, this literature was gathered and reviewed herein. The objectives of this review are to better understand the manufacturer's:

1. intended use of a given scaffold product,
2. degree of recognition of the existing scaffolding codes and standards,
3. method of determining the product ultimate capacity and factor of safety.

Much of the literature gathered was proprietary in nature and did not offer straightforward information regarding the above objectives. For instance, determining the intended application of a manufacturer's 'tubular frame' type scaffold with regard to load ratings was not easily discerned. The term "standard scaffolding" was used by most of the manufacturers. Few of the scaffold brochures offered load capacity and intended-use type information. Additional literature providing part of this information was obtained through separate requests from certain manufacturers.

With regard to the existing scaffolding regulations reviewed in the previous study [2], the classification of a scaffold duty-rating was indirectly represented by the allowable platform permissible loading and span length. The literature of the major manufacturers of the 'tubular frame' type scaffold (type 3 appendix A) were reviewed. The literature does not convey clearly the definitions or system classifications as described by the current codes and standards [3, 4]. The 'tubular frame' system type was chosen based on its common familiarity and use in construction applications.

One scaffold manufacturer referred to the frame-type as a "standard 5 foot wide center girt panel". Product data available within the brochure specified the allowable column leg load and allowable uniform ledger load with a stated 4 to 1 factor of safety incorporated. Recalling the SSSI studies [11, 12,13], it was pointed out that the assembled configuration (tier height, number of bays, jack extensions, etc.) was relevant to the ultimate load carrying capacity of the scaffold system. The SSSI studies displayed a possible capacity reduction of as high as 44 percent for a ledger-type loading under certain circumstances. It is not known whether or not the allowable load values presented have incorporated such effects.

Another manufacturer referred to the frame-type scaffold as a "standard end frame". The basic brochure did not display intended application, classification or load capacities. Other literature was obtained that showed the test results for frames stacked 3 high. The ultimate load per leg was 50.42 kN (11.33 kip) and the allowable load per leg was 13.62 kN (3.06 kip) resulting in a factor of safety of 3.7 which, when rounded up, yields the OSHA-specified 4.0. Tests were performed with the leveling screws set at 305 mm (12 in) bottom only. According to the SSSI studies [12], this represents the least conservative mode and a 30 percent capacity reduction is possible. The ledger loading capacity presented by the manufacturer reflected an appropriate capacity reduction.

Another manufacturer used the terminology "standard frames". Information concerning intended application, classification and loading capacities was not presented in the basic brochure. A separate document was obtained which presented the load capacities with a statement indicating a 4 to 1 safety factor and based on towers 3 tiers or higher with bottom base extension at 305 mm (12 in). A ledger load capacity reduction existed for that frame similar to those reductions reviewed above. However, other frames are presented with considerably lower ledger capacity reductions and some with a reduction value of zero. Also, it is claimed that the open-ended frame types have a higher ledger load capacity than column load capacity which was in direct conflict with the SSSI study [12] and warrants further investigation.

Another manufacturer used the terminology "end frames" and no distinct classification or loading capacity were presented in the basic brochure. Independent test information was obtained on a tower 4 frames high and with unknown leveling screw extensions. This information presented a safety factor of 4.01 with no data concerning ledger loadings.

Another manufacturer used the terminology "sectional steel scaffolds" and failed to further identify intended application and classification. Loading capacity information was not presented in the scaffolding brochure.

Another manufacturer used the terminology "sectional steel scaffolds" and failed to further identify intended applications and classification. Loading capacity information was not presented in the scaffolding brochure.

Other information of interest that was found to be common among the brochures included the following:

- o Accessways are supplied as separate components and their intended use is directly implied.

- o Horizontal in-plane cross braces are supplied as separate components and are suggested or recommended to be used with rolling scaffold towers.

- o Frames are to be pinned at the connections, and casters bolted to the frames (some brochures more specific than others).

- o All cross-bracing is to be used for each lift with no patterns or skipping in assembled systems. No climbing is to be done on the cross-bracing.

- o Some brochures approve mixed-mode applications (see Figure 3.10).

- o Guardrails are to be provided on all four (4) sides.

- o Assembled towers with a 4 to 1 aspect ratio are to be "secured". Some brochures state that "tie-in" devices or "heavy wire" are to be used at 7.6 m (25 ft) vertical and 9.1 m (30 ft) horizontal dimensions.

- o Side brackets are to be used as work surfaces only, and not to carry loads. Most brochures state that the user should account for overturning effects when using brackets on 'mobile towers' where others do not intend such use and state so.

- o Most of the brochures present a set of recommended safety rules as reprinted from the Scaffolding and Shoring Institute.

It appears that the scaffolding manufacturers have attempted to develop good scaffold products. However, there needs to be a concerted effort toward standardization of information necessary to assure that the products are used as their developers intended and to assure safe scaffolding practices. It is recommended that in any future development of scaffolding guidelines and standards, all efforts incorporate the manufacturers' needs in presenting the products and the users' needs of understanding the proper application of the product. In addition, the findings of the field survey should be reviewed and compared with the information in this section to determine the degree of such communication.

5. UNITED STATES SCAFFOLD PATENTS

Over two hundred United States scaffolding patent claims were identified by means of the computerized literature search. For the purpose of completeness, the listings of these claims were reviewed and those with apparent utility were gathered and reviewed. It is out of the scope of this paper to present any of these claims in their entirety. However, it is recognized that such patent claims have been developed, or demonstrate the potential to be developed, into viable scaffolding components or whole systems. Therefore, in an effort to facilitate future developments of scaffolding safety guidelines and standards, certain discussions are presented below.

Many of the patent claims gathered and reviewed dealt with novel structural scaffolding connections. Most of these connections applied to 'tube and coupler' type scaffolds (see type 2, appendix A). Many of the connection devices consist of components integral to the overall performance once assembled. Loss of components such as locking pins, wedges, bolts, etc., during field practice is very common resulting in incomplete assemblies and lower margins of safety. Also, many of the patents introduce prefabricated components that could be prone to fatigue failure over prolonged use (e.g. sharp angles, open sections, etc.). The introduction of voids (pin-holes, slots, etc.), as is the case with many of the novel devices, can reduce the structural capacity of the system components. It is recommended that any future scaffolding safety guidelines or standards account for such new product developments by means of appropriate provisions.

Other patent claims dealt with special devices to be used in conjunction with scaffolding systems to facilitate the work being performed. One such device was a light fixture hoist assembly shown mounted on the edge of the platform on a 'mobile ladder stand' type scaffold (type 4, appendix A). Such a device will inadvertently affect the geometric stability and might not be initially accounted for in the development of the safety standards. Another device anchors the scaffold plank to the support element. From the patent claim figures, such devices appear to introduce environmental hazards that could trip a worker. Such hazards were discussed in the accident study [1] and were cited as the cause of a number of accidents.

Certain patent claims introduce novel scaffolding 'bracket type' and 'suspension type' systems (type 9, 10 and 16, appendix A) in which the overall structural integrity and system stability are questioned. Two of the suspended-type claims imply that an endless number of work platforms can be introduced for high-rise building facade work.

It is recognized that a patent claim does not cover the details necessary to satisfy the research aspects of this study. However, it is recommended that prior to any market application of novel scaffolding inventions, these inventions comply with the existing scaffolding codes and standards. In addition, it is recommended that the future scaffolding safety guidelines and standards recognize that novel inventions are necessary to advance scaffolding state-of-the-art and to include them in the scope of any newly established provisions.

6. SUMMARY

The review of the literature presented in this report is the third of four tasks of the NBS Scaffolding Research program. The review identifies the problem aspects of construction scaffolding and consolidates scaffolding research information on which future research efforts can build. It identifies the scaffolding-related research previously performed and, based on the research findings, presents the major scaffolding related safety problems and areas of warranted future research.

Adhering to a format developed in two previous scaffolding studies [1,2] the literature was searched and reviewed for technical content which may enhance future studies while minimizing the chance of duplication of efforts. Information on the design, erection, operation and maintenance of construction scaffolding systems was searched. Most of the information presented can be applied to these topics. However, little information was found that directly addressed the erection, operation or maintenance of scaffolding systems.

For the 21 types of scaffolds under study, only the 'tube and clamp' and 'tubular frame' types (see appendix A) were found to be specifically addressed in the literature. Certain technical information was found and was presented on the topics of: work platforms; support system and strength; connections; anchorages; foundations; stability; safety devices; and accessways. It was shown that the existing codes and standards for scaffolds failed to recognize much of this information.

Many work platforms consist of wood planking. It was shown that standard wood design procedures are not recognized by the existing codes and standards and should be incorporated. In particular, the OSHA [3, 4] specified overall safety factor of 4.0 can not be obtained when using certain OSHA specified wood plank sizes and span lengths in conjunction with approved WDSWC [5] wood design procedures.

Under the category of support system and strength, the findings were presented on tests performed on 'tubular frame' scaffolding towers. The structural effects were presented on interchanging different scaffolding frames (i.e., mixed mode), continuous bracing of scaffolding towers, concentrically loading columns versus uniformly loading top ledgers, and use of top and bottom jack extensions. Many of these topics call for further research prior to the development of comprehensive scaffolding standards.

Under the category of connections, additional research is called for on coupler devices used integral with various scaffolding systems. Deficiencies in the existing code provisions on nailed wooden connections are pointed out. Investigative studies are called for with special attention to gathering field practice information.

Design equations were presented for certain concrete anchorage systems. These equations account for steel anchor placement in reinforced concrete and are designed to assure the anchor develops full capacity before concrete failure. Edge distances and amount of concrete cover are taken into account. A good deal of past research has been performed on nailed connections and this information is referenced.

No specific design, maintenance, etc. information was found for scaffolding foundatons. However, various references were cited which provide general outlines to be used by scaffolding system designers.

Field practice information on worker fall protection is needed. Information does exist on the science of fall-arrest and the performance capabilities of the safety devices themselves. However, it is pointed out that the practices in which the worker employs the fall-arrest device are not fully documented. Also, detailed information is presented on guardrail design. This information needs to be extended by incorporating field practice information on guardrail systems.

Considerable state-of-the-art information is presented on wind overturning effects on scaffolding towers. A design procedure is presented and compared with the Uniform Building Code Wind Impact Area method [47, 48]. This procedure should be included in future developments of scaffolding standards.

No specific information was found on the topic of scaffolding accessways. Information obtained from field study practices on accessways is currently being reviewed. The findings of the field study are expected to be presented in a separate report in the near future.

The scaffolding manufacturers' literature was reviewed and discussed in order that field practice information could be compared. It was found that the manufacturers' literature generally fails to communicate the current scaffolding code and standard requirements. The need to standardize scaffold load rating procedures was identified. Currently, the manufacturers test their scaffolding products under various assembled configurations and load applications. Standard test procedures should include field conditions such as foundation settlement, anchorage devices, unsymmetrical platform loads, etc. Finally, the manufacturers' brochures need to effectively communicate to the scaffold user the appropriate limits of the scaffold system for all intended field applications.

For completeness, United States scaffolding patent claims were searched and reviewed. It was revealed that many patent claims are incognizant of the current scaffolding code and standard provisions and may not enhance safe scaffolding practice if adopted without close review.

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APPENDIX A

21 Major Types of Scaffolds Under Study

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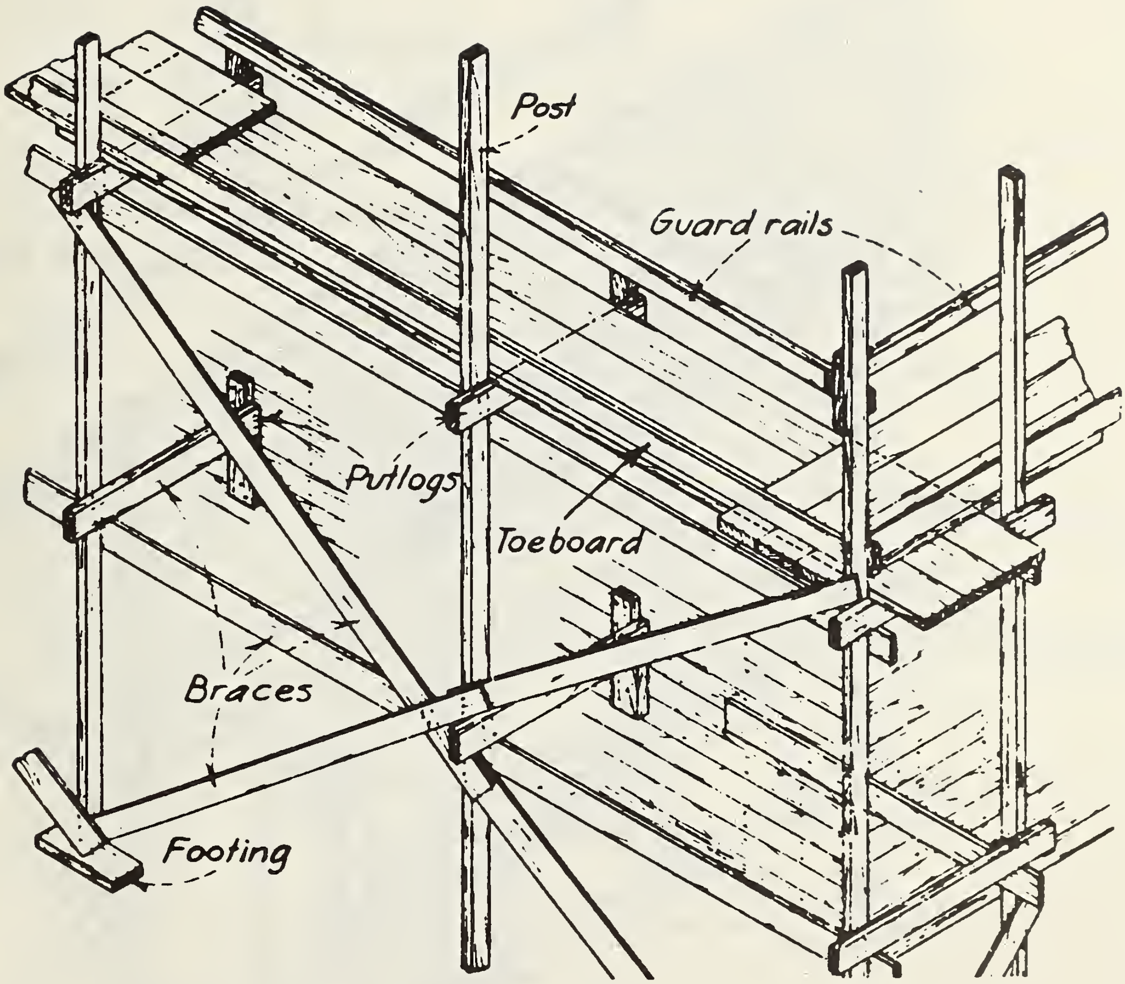
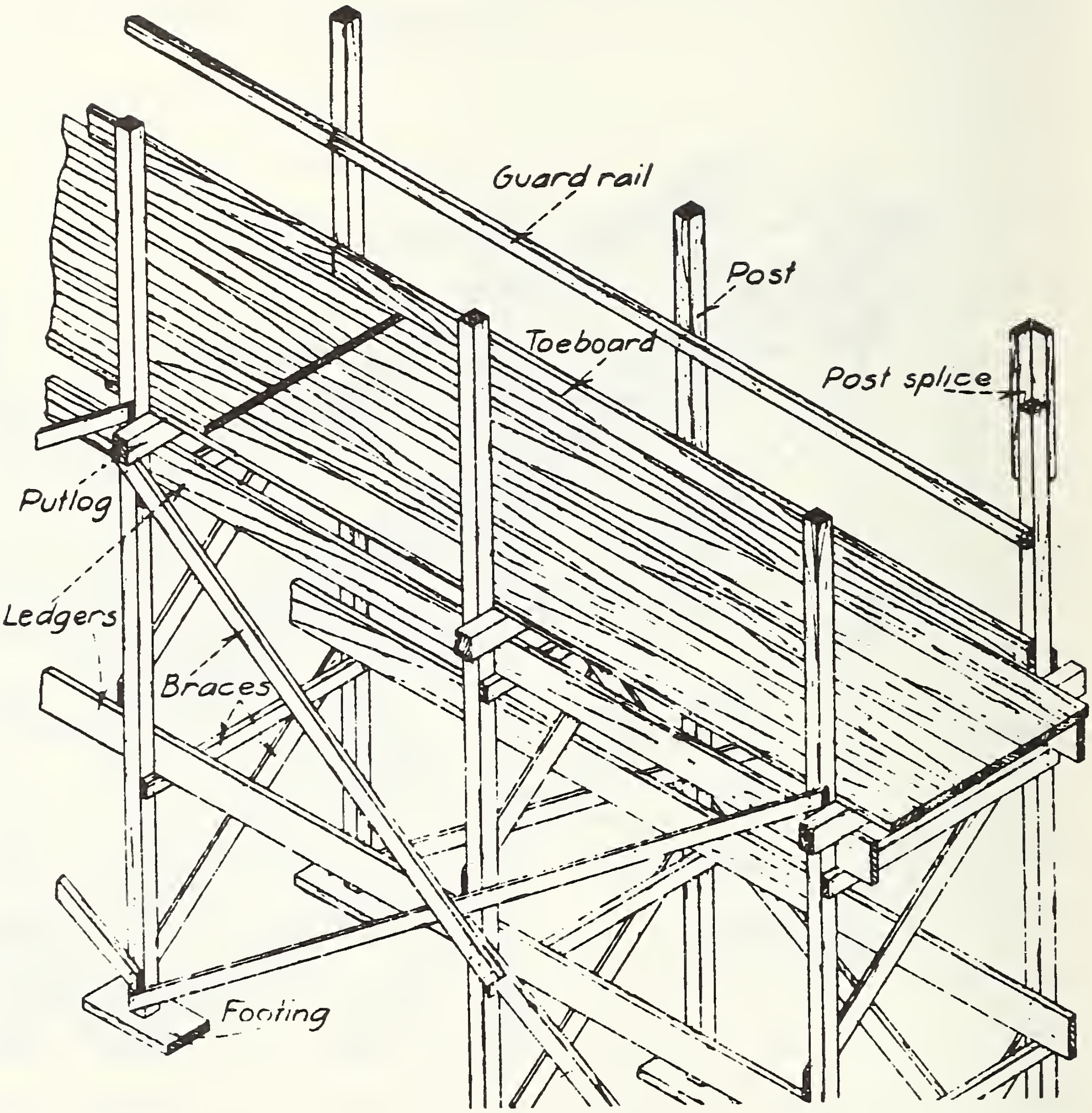


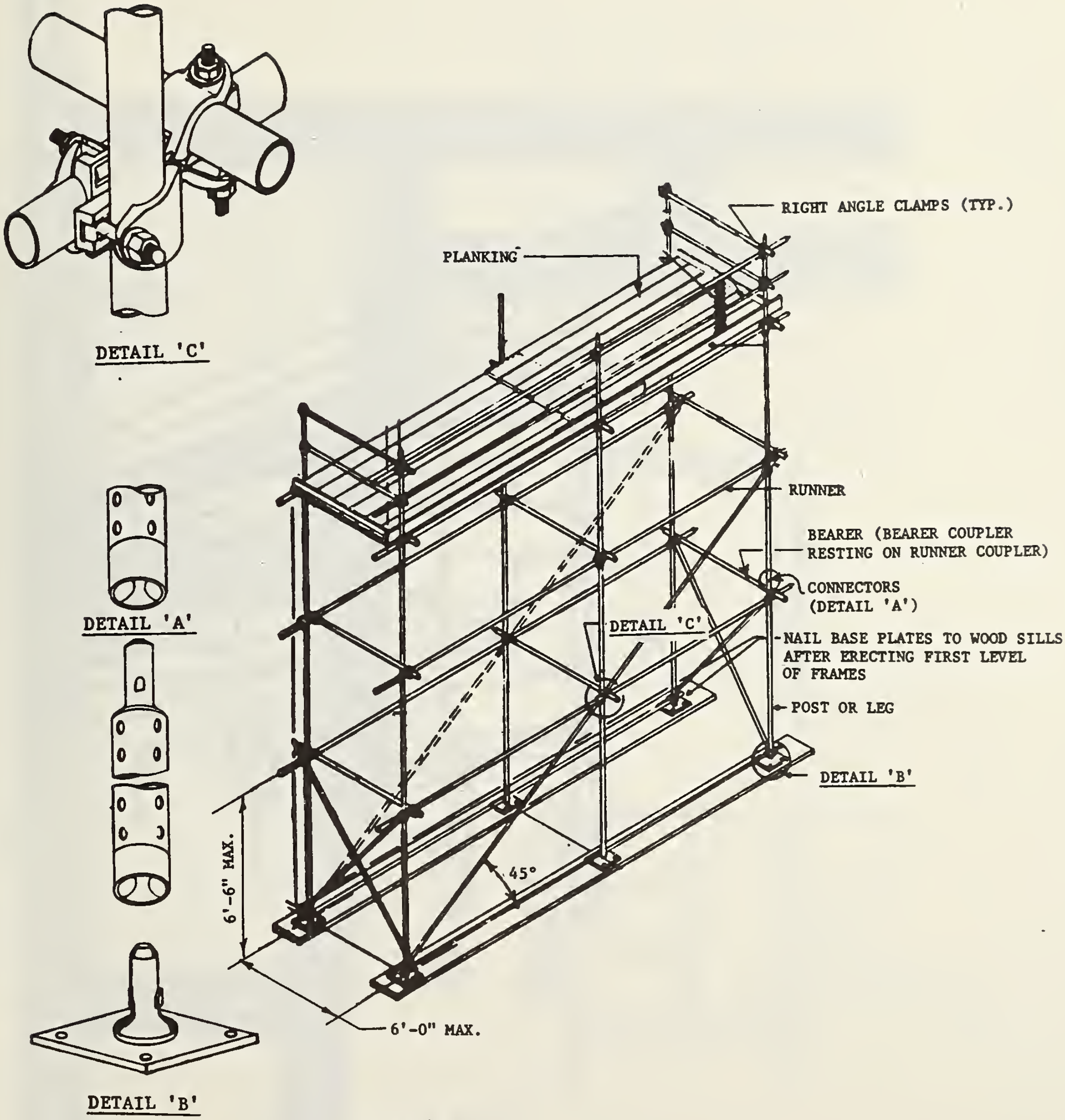
Type 1a

Figure A.1. Wood pole scaffold - (a) single post.



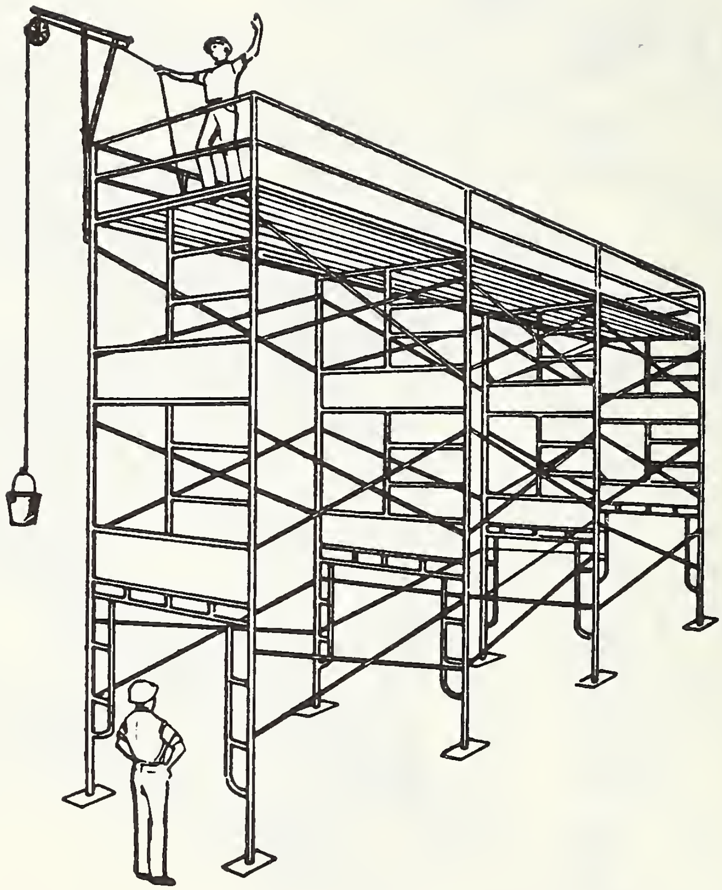
Type 1b

Figure A.2. Wood pole scaffold - (b) double post



Type 2

Figure A.3. Tube and coupler scaffold.



Type 3

Figure A.4. Fabricated tubular frame scaffold.

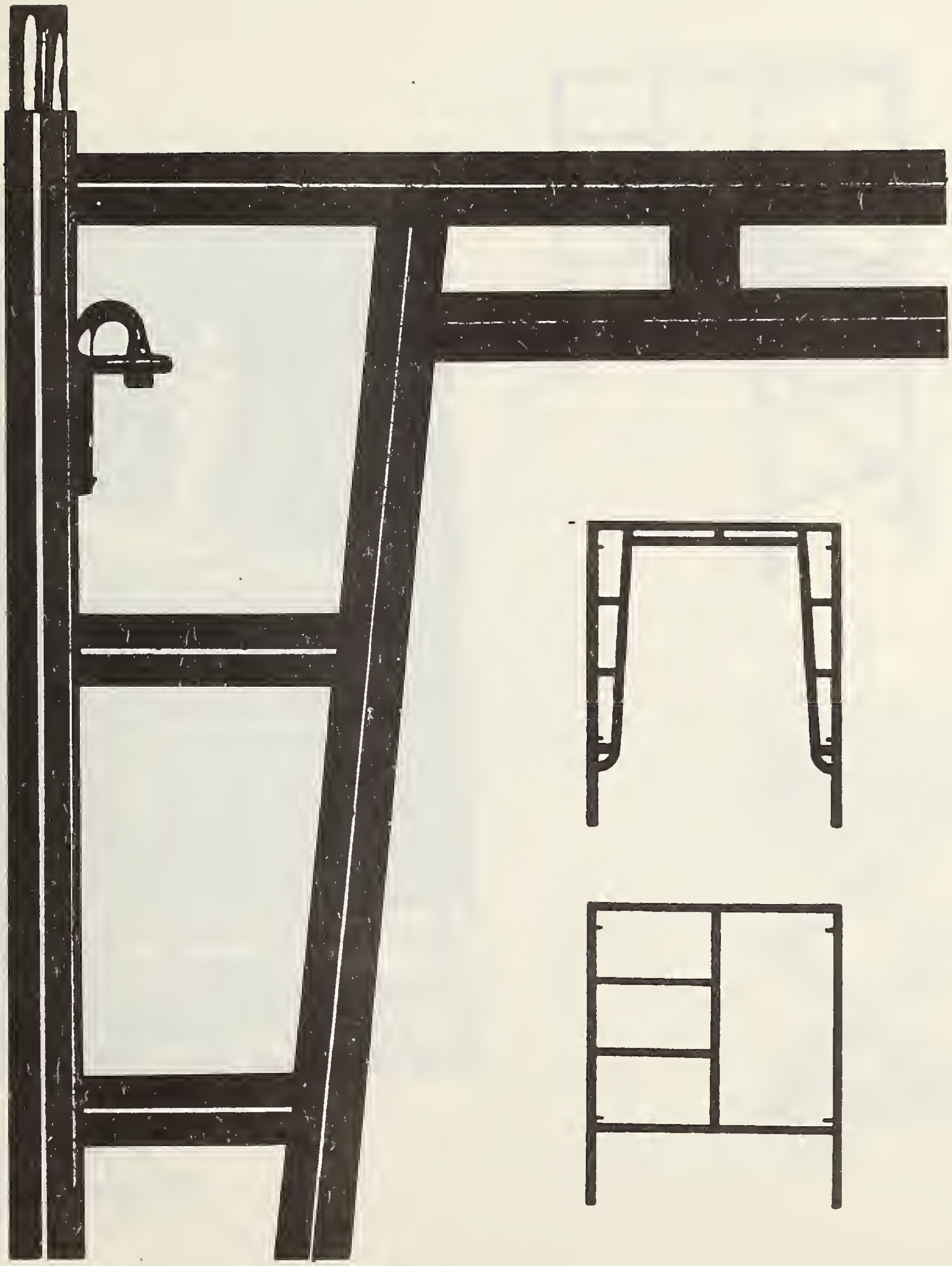
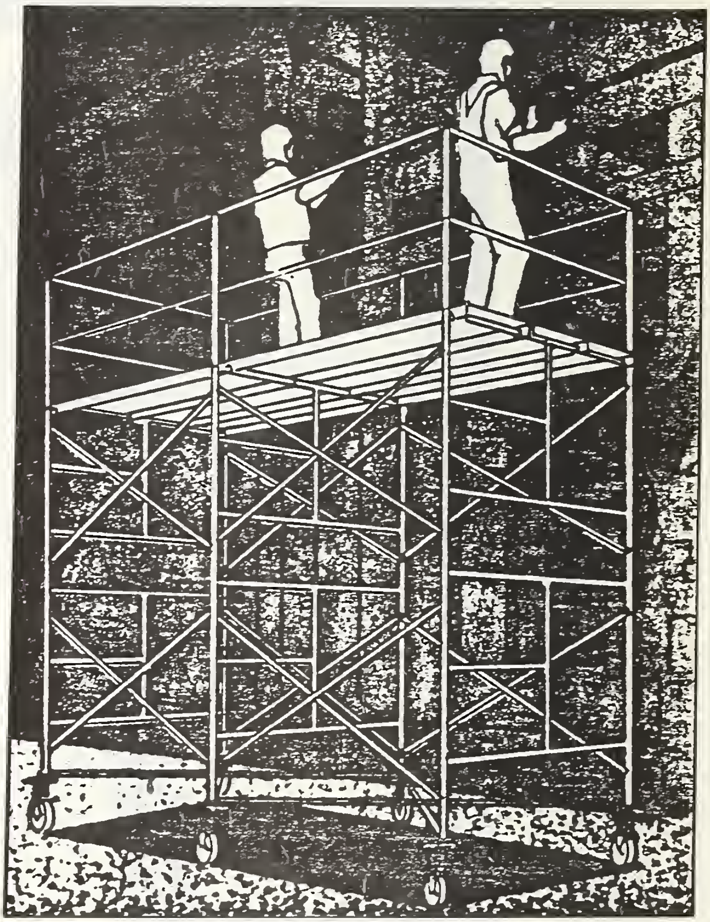


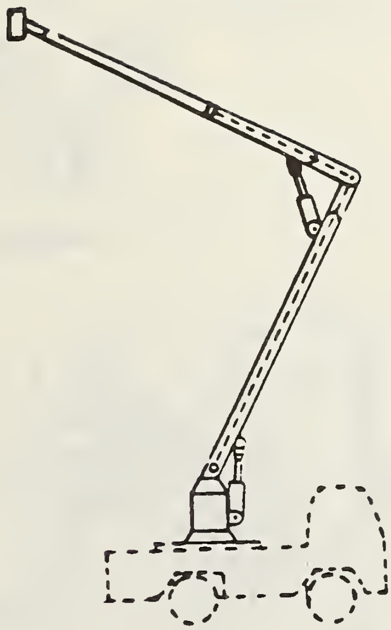
Figure A.5. Tubular frame subsystems.

(a) Type 4

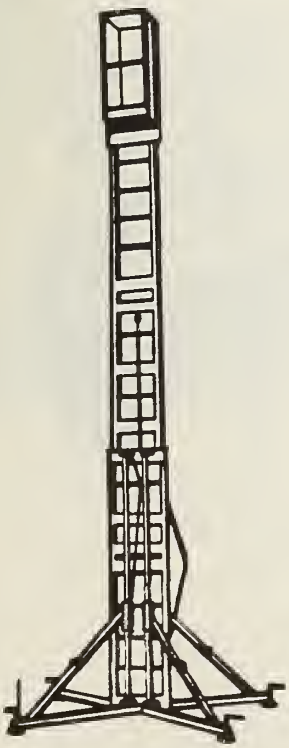


(b) Type 4

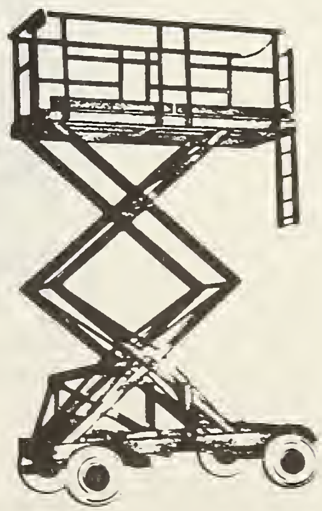
Figure A.6. Manually propelled mobile (a) ladder stand and (b) scaffold (tower).



(a) Type 5

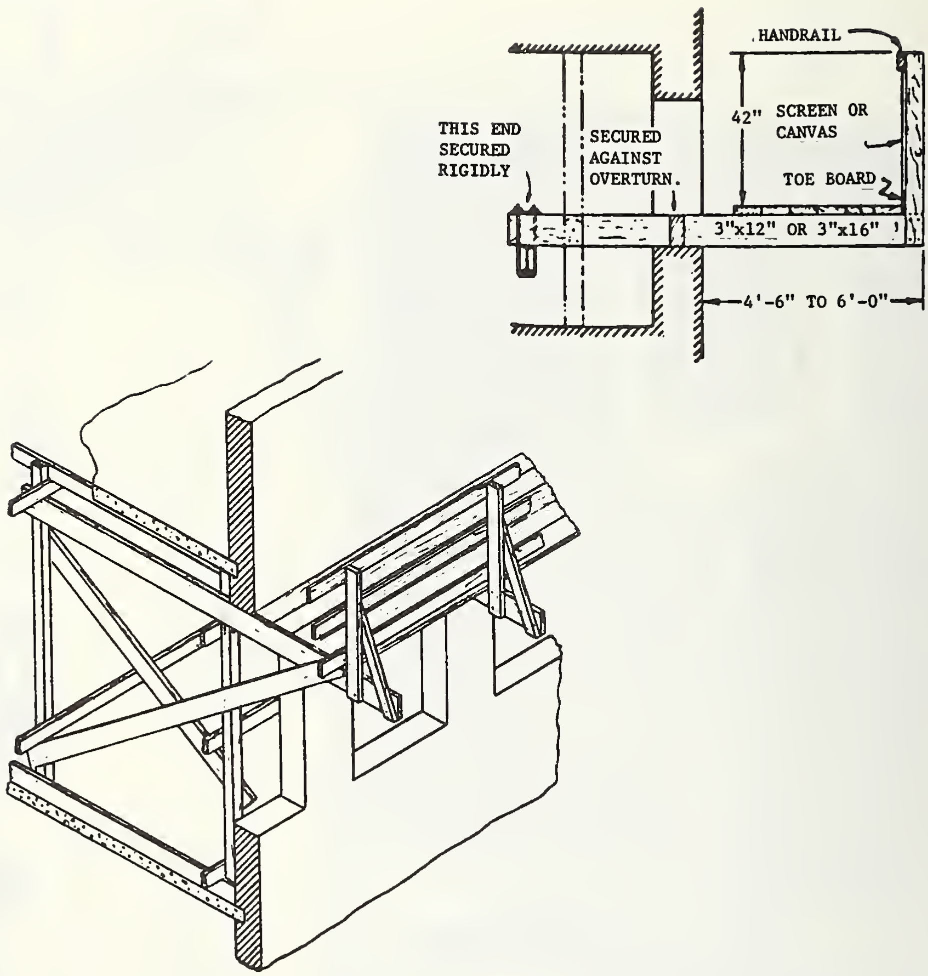


(b) Type 6



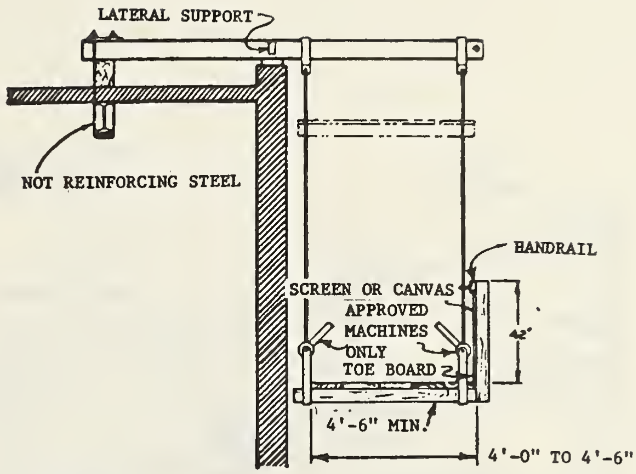
(c) Type 7

Figure A.7. (a) Vehicle-mounted elevating and rotating, (b) telescoping, and (c) self-propelled elevating work platforms.

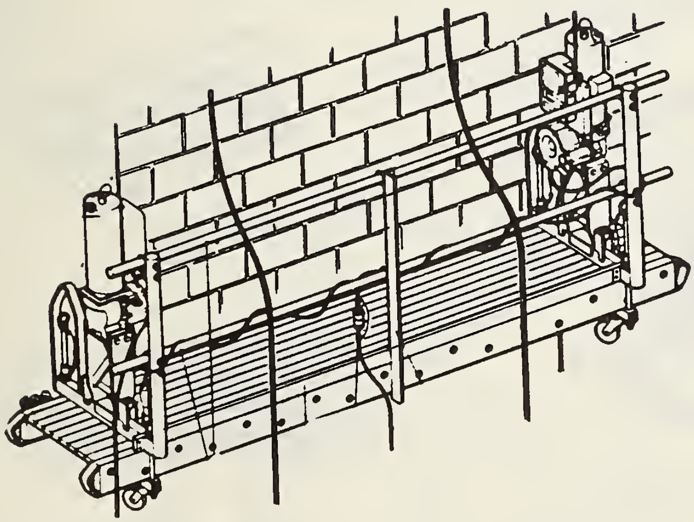


Type 8

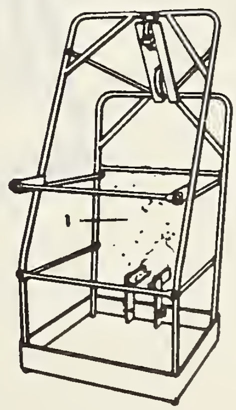
Figure A.8. Outrigger scaffold



(a) Type 9

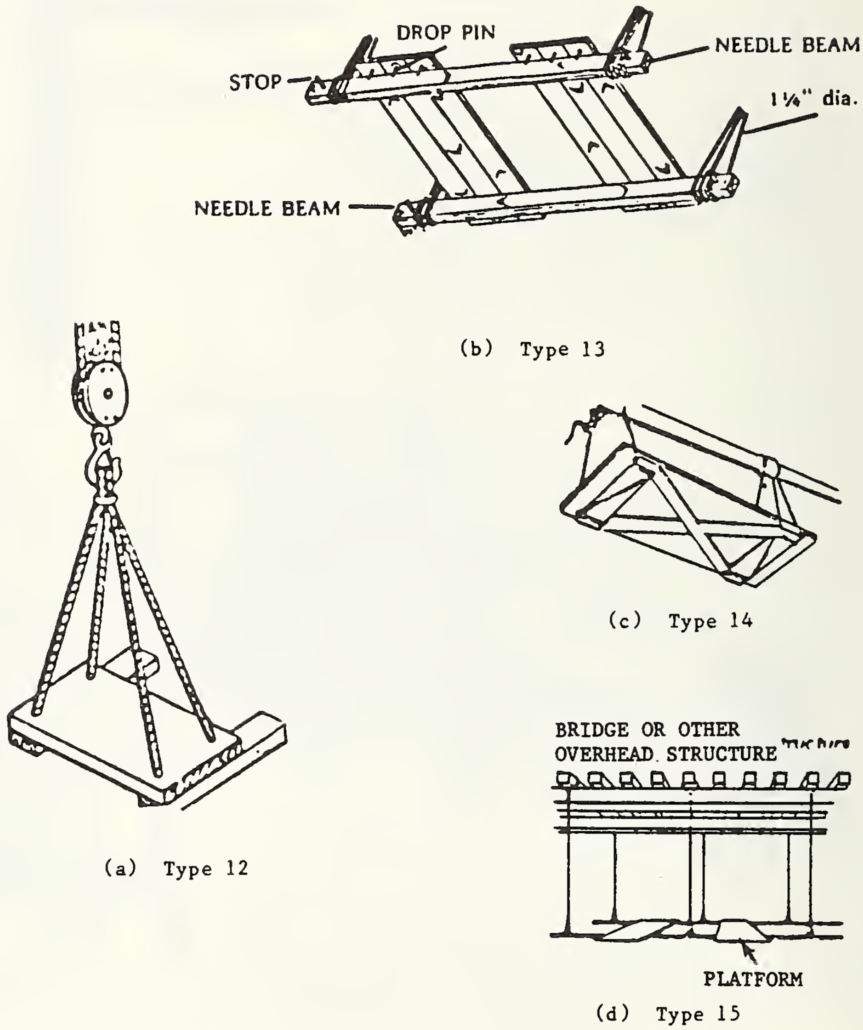


(b) Type 10



(c) Type 11

Figure A.9. (a) Adjustable multiple-point (masons' or stone-setters'), (b) two-point (swinging), and (c) single-point suspension scaffolds.



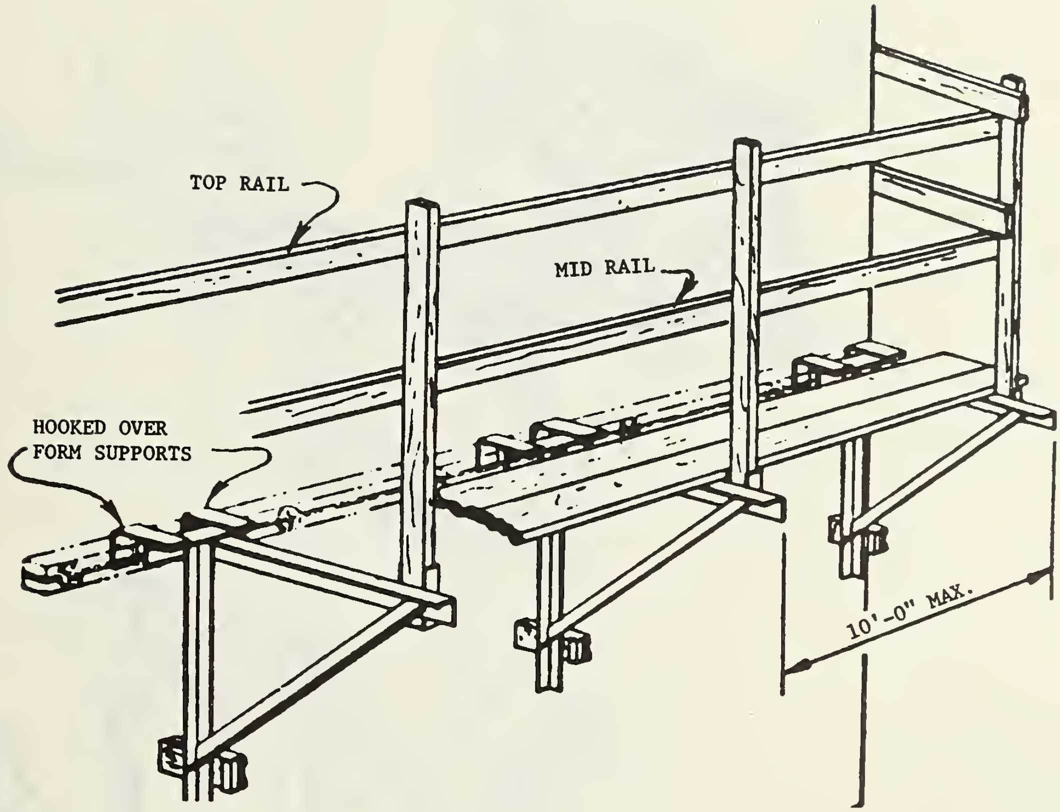
(b) Type 13

(a) Type 12

(c) Type 14

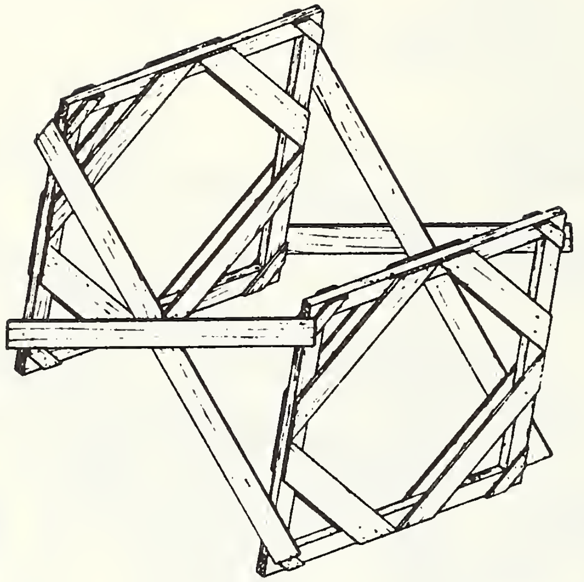
(d) Type 15

Figure A.10. (a) Boatswain's chair, and (b) needle beams, (c) float or ship, and (d) catenary scaffolds.

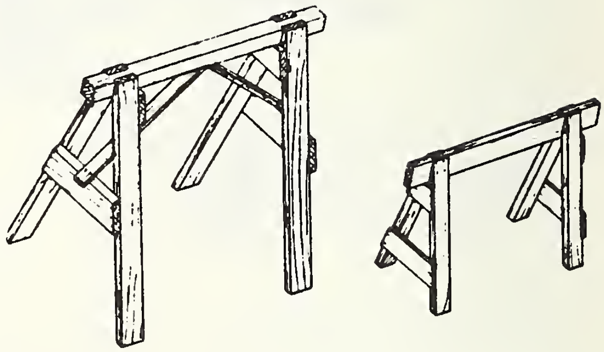


Type 16

Figure A.11. Bracket (carpenters' bracket) scaffold.

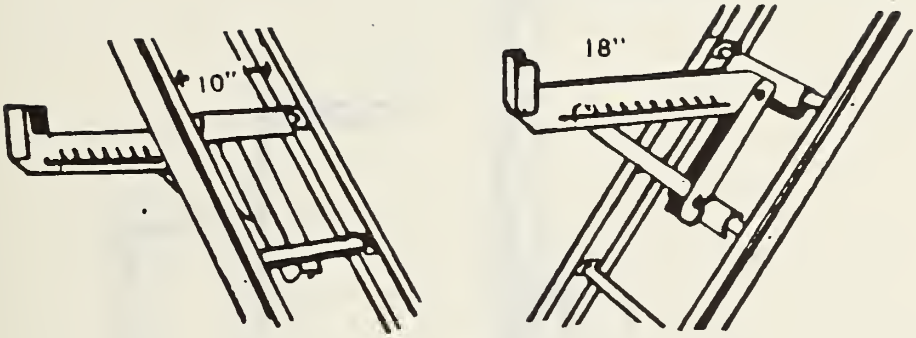


(a) Type 17

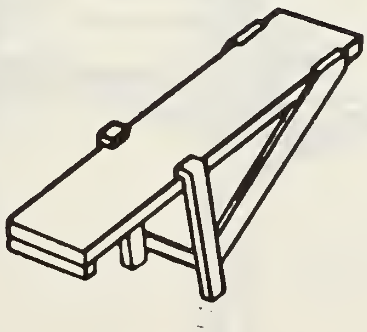


(b) Type 18

Figure A.12. (a) Square (bricklayers' square) and (b) horse scaffolds.

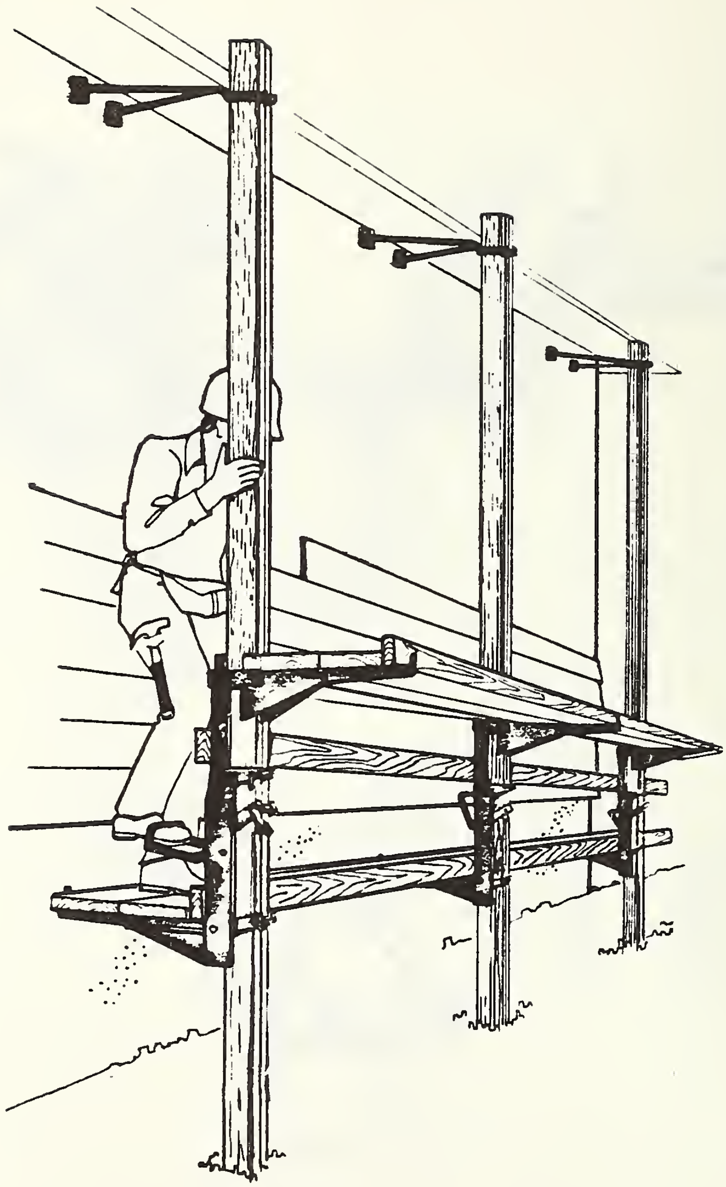


(a) Type 19



(b) Type 20

Figure A.13. (a) Ladder jack and (b) window jack scaffolds.



Type 21

Figure A.14. Pump jack scaffold.

APPENDIX B

STRUCTURAL ANALYSIS OF CONSTRUCTION SCAFFOLDING

TABLE OF CONTENTS

B.1 INTRODUCTION

This appendix presents a demonstration analysis of the 'tubular frame' type scaffolds using a finite element program. Individual components of the 'tubular frame' scaffold as well as an entire system are modeled. A description of the computer software, the analytical models, the analysis and the findings of the study are presented.

The purpose of this appendix is to demonstrate an approach by which in-depth analysis of scaffolding systems can be performed. It is intended that the approach demonstrated below for a selected number of topics be used in future in-depth analytical efforts.

B.2 COMPUTER SOFTWARE

The 'tubular frame' scaffold was modeled using a general purpose structural analysis system, POLO-FINITE [1,2]. POLO (Problem Oriented Language Organizer) [3] is a system designed to aid in the solution of civil engineering problems by providing software tools to support the development of engineering application software. Some of the features of POLO are problem oriented translation, dynamic memory allocation, data management and subsystem integration. FINITE is a general purpose computer program for the analysis of linear and nonlinear structures subjected to static loads. FINITE serves as a sophisticated analytical tool with multilevel substructuring and static condensation modeling features. When used appropriately, these features lead to considerable saving of manpower and computer time. During execution, FINITE operates under the POLO supervisor which makes use of the unique data base and memory management features mentioned above.

Many general purpose structural analysis computer programs are in existence. POLO-FINITE was selected for the following reasons:

- The POLO II supervisor facilitated data input and other execution requirements which often inhibit the efficient use of conventional programs.

- FINITE contains a diverse finite element library and the internal organization is such that new finite elements and nonlinear material models can easily be installed; a possible need concerning future scaffolding analyses.

- FINITE enabled the idealization of the scaffolding structure in the form of mathematical models through recursive formulations of previously defined elements and structural models. Also, cost savings were possible through the substructuring and static condensation features.

B.3 ANALYTICAL MODELS

B.3.1 Selected Scaffolding Models

From among the 21 types of scaffolds shown in appendix A, the 'manufactured tubular frame' is modeled. This system is structurally more complex than other types and is used in diverse applications (i.e. heavy masonry loading, multistory facade work, etc.). Chapter 3 presented the results of numerous full scale experimental tests performed on the 'tubular frame' system and many questions were raised concerning the structural performance of these systems under realistic field conditions. Therefore, two common 'tubular frame' subsystems are modeled to demonstrate a general approach by which some of the topics presented earlier can be investigated further.

The modeled frames are the open-ended and step-type shown in Figures B.1 and B.2. Each consists of similar integrally welded high-strength structural steel tubing and differ only in assembled geometry. FINITE was used to analyze these frames by using previously defined planeframe (later using spaceframe) elements. These are assembled as depicted in Figure B.7 to form a higher level structure, SCAFFOLD. Structure BENT consists of 24 nodes and 31 elements. Structure FRAME consists of 17 nodes and 19 elements. Each frame was statically condensed to form a new structure each consisting of 1 element and 8 nodes. Figure B.3 shows BENT-CONDENSED, the condensed version of the structure BENT where nodes 3,8,16 and 20 are shared with cross bracing elements and 1,9,14 and 22 are shared with other frames when assembled to form the higher level structure (see Figure B.7). It is noted that structure BENT-CONDENSED represents the idealized structural stiffness characteristics of structure BENT but the number of nodes and elements has been reduced which leads to computational efficiency during solution of the higher level structure, SCAFFOLD.

Structure SCAFFOLD is a higher level structure formed by assembling four copies of BENT-CONDENSED three times vertically and interconnecting them with previously defined 'planetruss' bracing elements as shown in Figure B.7. 'Spaceframe' elements were used for the initial formulation of structure BENT since the cross bracing elements connect at unique nodes not common to the frame connections 1,9,14 and 22 and out-of-plane lateral forces are introduced in the three-dimensional structure SCAFFOLD.

B.3.2 Analysis of Top Ledger Loading for Planeframes

The Steel Shoring and Scaffolding Institute (SSSI) and the scaffolding manufacturers had determined the ultimate capacity of 'tubular frame' tower assemblies by concentrically loading the frame column legs until buckling occurred (see chapter 3). Unless the scaffold tower is used as shoring or falsework, this loading scheme does not represent the manner in which scaffold systems are normally loaded. Instead, load carrying platforms bring uniformly distributed or pattern type loads onto the top frame ledger (elements 24-26, 29 of Figure B.1). Information in the SSSI studies revealed that the ledger loading scheme could result in a capacity reduction of as high as 44 percent compared with column loading. Therefore, a planeframe finite element analysis is performed to assess the effects of both loading schemes.

For comparison, the frames are subjected to a total load of 8.9kN (2 kip), either concentrated at the columns or uniformly distributed along the top ledger (see Figures B.4 through B.6). The exaggerated deflections of the frames subjected to each loading are shown in the same figures. Although no scale is used, the deflected shapes are relative to each other and indicate the overall displacement mode.

As expected, most of the applied column loads were transferred directly to the supports modeled as pinned connections. However, ledger loading introduces true frame bending action. Many of the intermediate elements are required to transfer significant forces. Horizontal reactions developed at the supports are considerably larger for the ledger loading. These reactions will often be transferred to adjoining frames and not necessarily to foundations. It is interesting to note the order of magnitude by which the 'step-type frame' sidesways under the ledger loading due to the nonsymmetrical geometry (see Figure B.6). Further investigation of this behavior is recommended since it may prove to be advantageous to alternate the ladder side when vertically stacking these frames. However, any tradeoff with accessway safety must first be studied.

B.3.3 Analysis of a Scaffold Tower for Anchor and Foundation Effects

For the system described above and shown in Figure B.7, a model analysis is performed. The purpose of this analysis is to demonstrate an approach for modeling an assembled scaffolding system using finite element analysis and to gain insight on the overall response of the system modeled under various loading and support conditions.

Two live loading conditions are used in conjunction with the system dead loads. The first consisted of uniformly distributed ledger loads of 2.6 N/mm (14.6 lb/in) on the top three frames. These loads are based on the OSHA specified 2.4 kN/m^2 (50 psf) maximum platform loading and represent the resulting reactions transferred to the support system. The second loading condition consisted of a 12.8 N/mm (73.5 lb/in) uniformly distributed load along one half of the top ledgers. This loading condition represents the pattern determined from the initial field studies as well as its location on the platforms.

For both loading conditions, spring elements are used to model the anchorages at nodes 73 and 77 (see Figure B.7). The anchor locations are based on the OSHA requirements for "ties" at vertical spacings of 8 m (26 ft) and horizontal spacings of 9 m (30 ft) for the 'tubular frame' system. Although the model studied is only 4.2 m (14 ft) wide, two anchors are employed. Two-dimensional spring elements are used to model the anchorages.

The final parameter investigated addresses the foundation constraints. The field study has shown that numerous foundation conditions encountered with the 'tubular frame' scaffold are not representative of pinned or fixed conditions. Often, base plates are not used and the open-ended tubular columns rest directly on planks, soft earth, concrete floors, etc. A common condition encountered is mudsills or planks with the supporting earth partially or completely washed out.

Under these conditions, the support is capable of rotating as well as translating with varying degrees of resistance. Therefore, rather than model the supports as pinned or fixed, stiff spring elements are placed in the x-y-z directions at four of the six supports (see Figure B.7). Two supports, nodes 2 and 6, are left totally unrestrained to represent the condition of complete foundation wash-out. Absolute (rigid) constraints are not not employed because the scaffold foundations studied are incapable of such behavior. That is, if a foundation were to wash out or settle appreciably, the scaffolding column leg, base plate or screw jack would not be forced to displace by an equivalent amount because a fixed mechanism does not exist.

Figure B.7 and B.11 depict the scaffolding models subjected to the two loading conditions. The support reactions and the forces developed in the anchorages are shown in Table B.1. For the field loading case, the forces developed in the anchorages were about three times greater than those developed under the OSHA allowable loads, .8 kN versus .3 kN (176 versus 57 lb). In addition, the support reactions are considerably larger for the field loading case and therefore the individual system support elements function differently. Figures B.8-B.10 and B.12-B.14 show selected portions of the scaffolding system and the representative axial forces developed in each member for both loading cases.

Figures B.8 and B.12 show the axial forces developed in the bottom two outside frames (elements 1 and 9) for each loading condition. Both frames developed equivalent forces due to symmetry about the central frames. The overall tension and compression behavior is similar for both loading cases; however, the order of magnitude and distribution of forces is quite different. Figures B.9 and B.13 show the axial forces developed in the bottom center frame (element 5) for both loading conditions. Once again, the general behavior of each frame is similar but the magnitude of the forces is quite different.

Figures B.10 and B.14 show the axial forces in the plane truss cross-bracing members for those members in the plane containing nodes 2-6-78 of structure SCAFFOLD. Only these members are shown because they are the most critically loaded, being above the unsupported foundations 2 and 6. The compression and tension patterns are the same for both loading cases and the magnitude is larger for the second loading case. The compression and tension behavior of the cross-bracing is a result of nodes 2 and 6 settling and forcing the cross-bracings (sloped down toward the center) to undergo compression. The nodal displacements for the top and bottom nodes are shown in the same figures. The exaggerated deflected shapes of the outside column legs represent the same mode shapes portrayed in the SSSI tests (see chapter 3) at the time of failure.

B.4 SUMMARY

The 'tubular frame' type scaffold (type 3 appendix A) is modeled using a general purpose finite element program. Individual tubular frames are modeled as plane frames subjected to concentrated column loads and uniformly distributed ledger loads. The general displacement modes for each condition are then compared. It is concluded that the two loading schemes cause different structural behavior for each frame type studied and this behavior warrants further investigation.

An assembled 'tubular frame' system, 4 tiers high and 2 bays wide, is modeled under OSHA specified loads and actual field loads. Foundation and anchorage parameters are modeled for both loading cases. The overall performance of the systems is discussed by graphically displaying critical axial forces and certain deflected mode shapes.

The analysis performed on the 'tubular frame' scaffold served the purpose of demonstrating an approach by which these systems could be analyzed. Also, insight was gained on the overall response of the system modeled under various parameters. It is intended that the approach presented here be carried out in more detail in future analytical scaffolding research efforts.

FIGURES AND TABLES

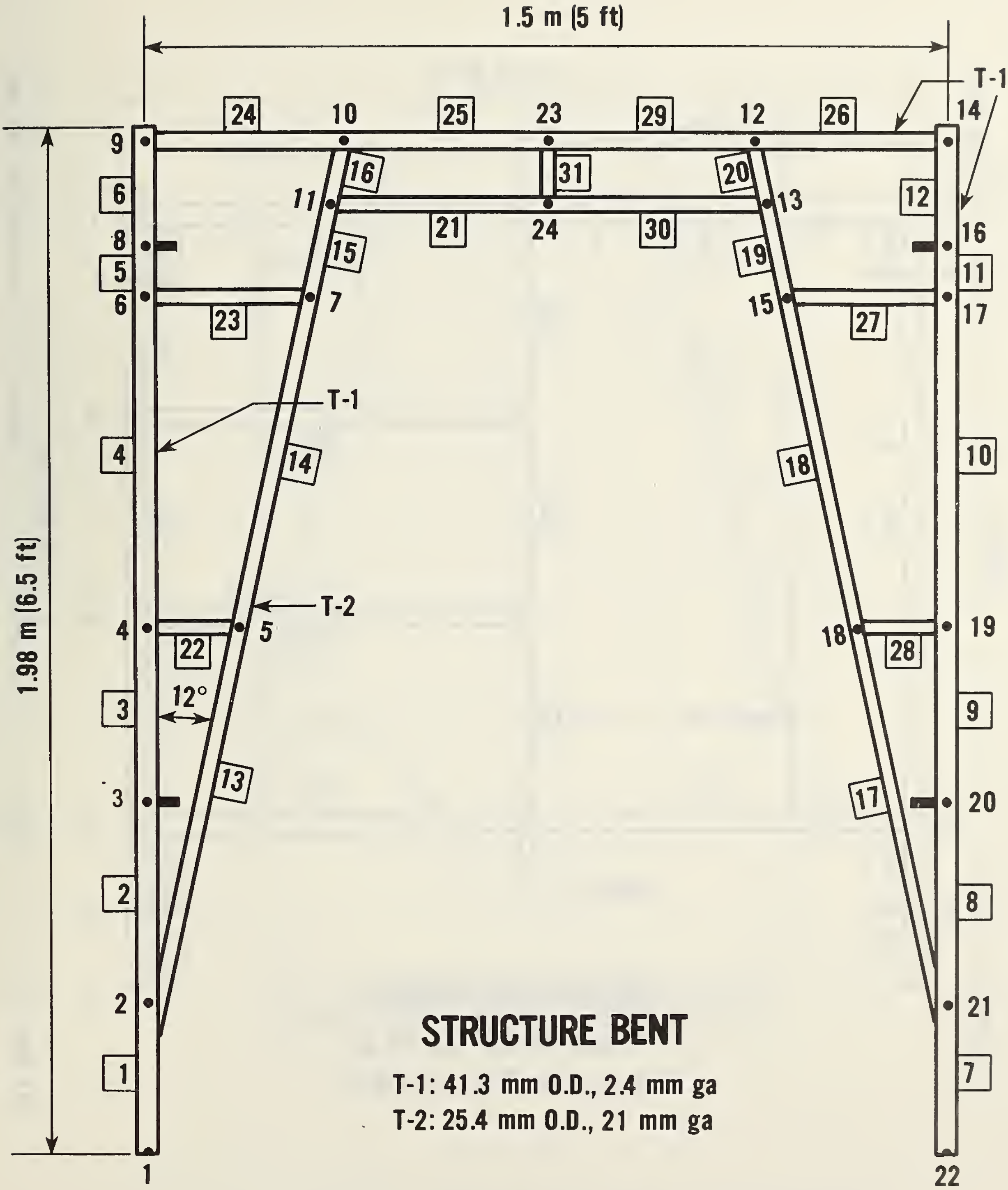


Figure B.1 Open-ended tubular frame scaffold structure 'bent' with 24 nodes and 31 elements.

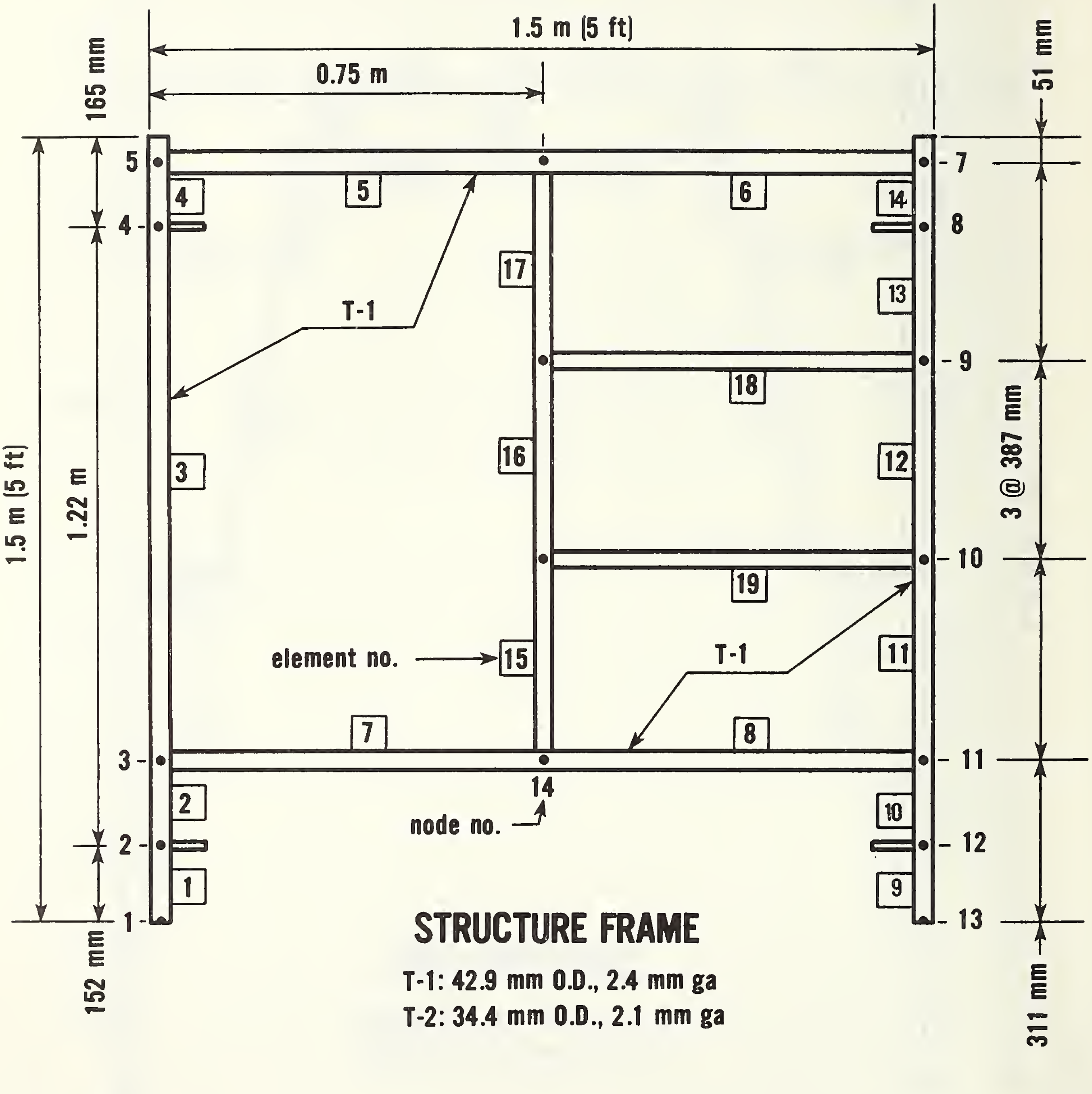


Figure B.2 Step-type tubular frame scaffold structure 'frame' with 17 nodes and 19 elements.

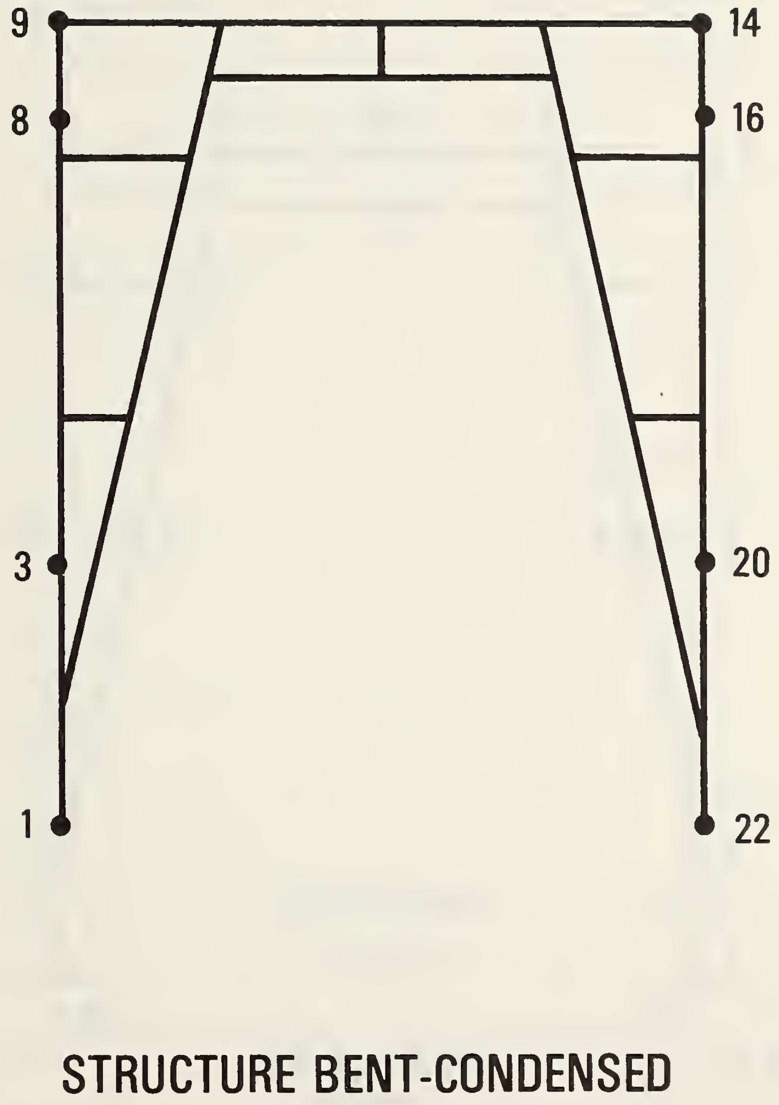


Figure B.3 Statically condensed structure 'bent' with 8 nodes and 1 element.

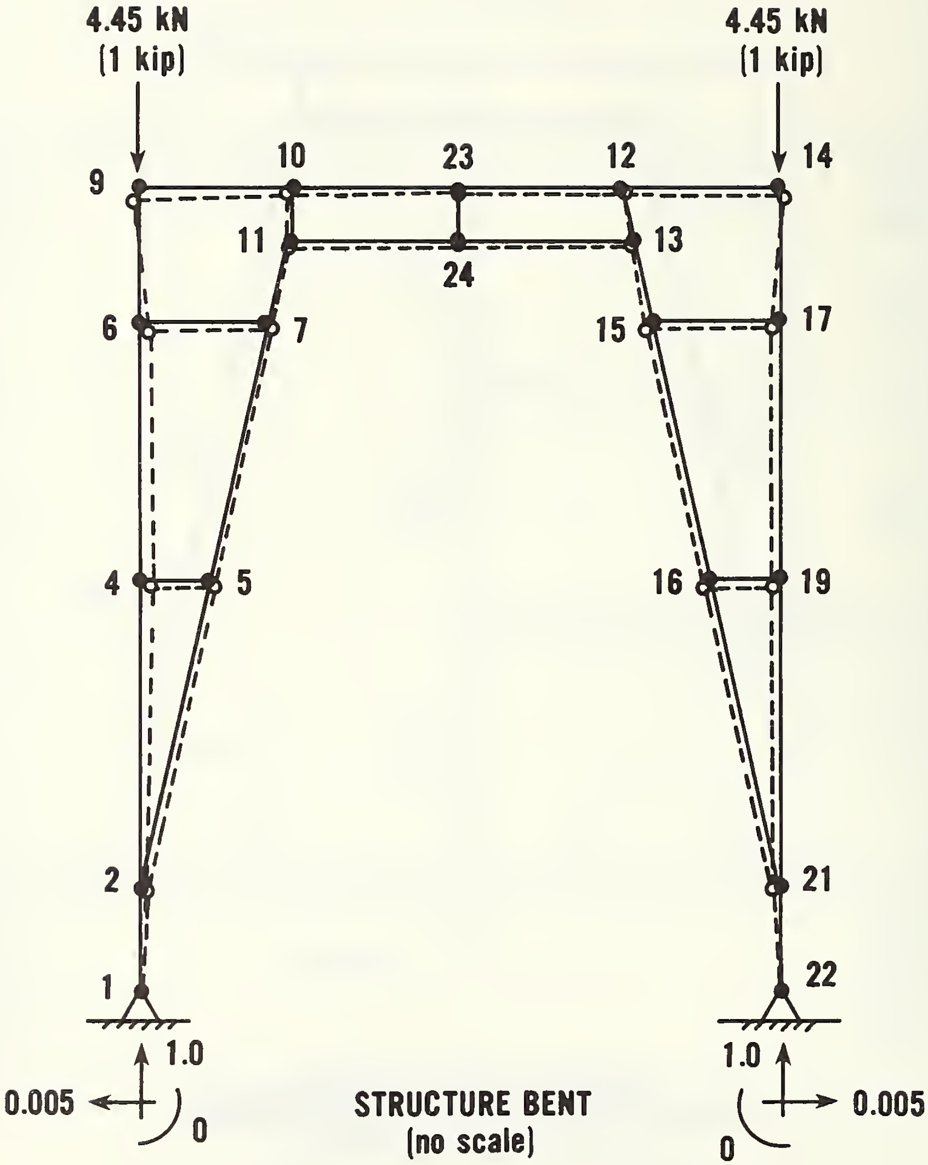


Figure B.4 Structure 'bent' deflected shape under concentrated column loads.

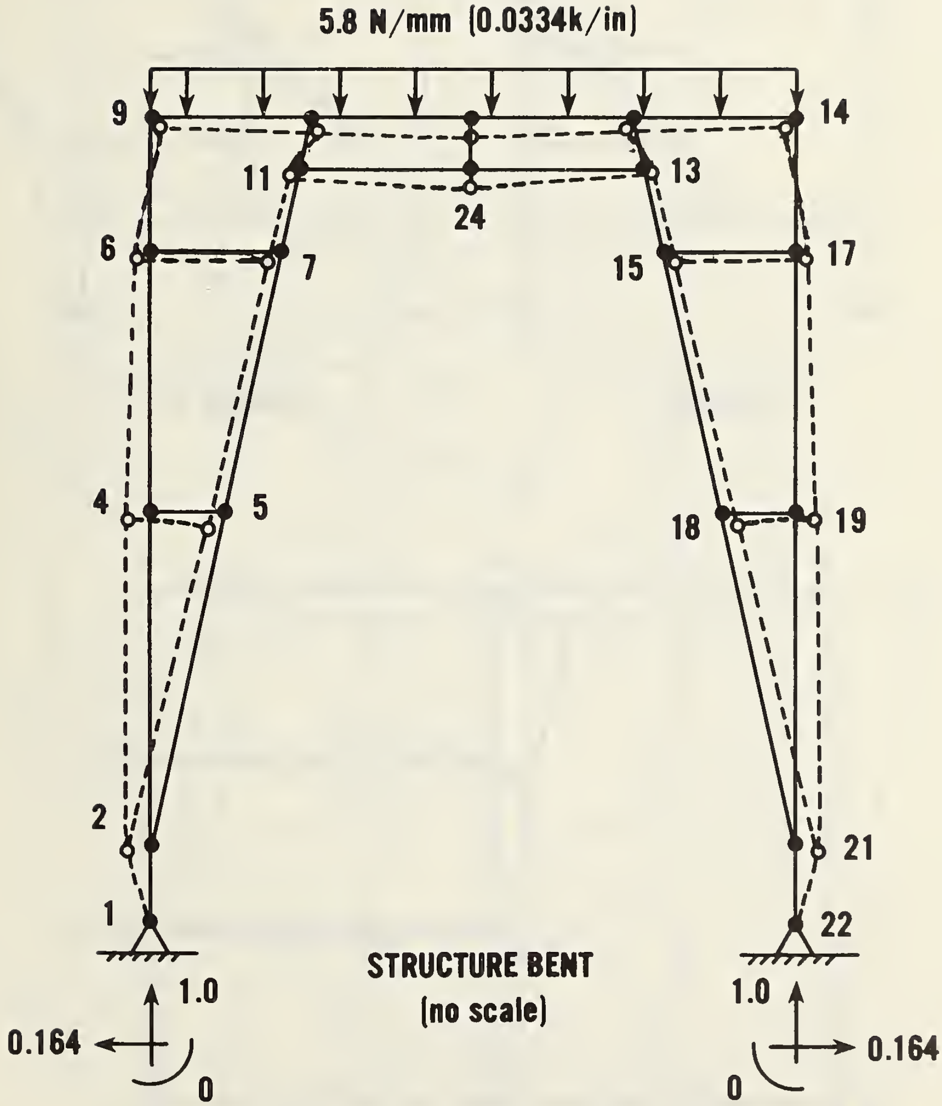


Figure B.5 Structure 'bent' deflected shape under uniform ledger load.

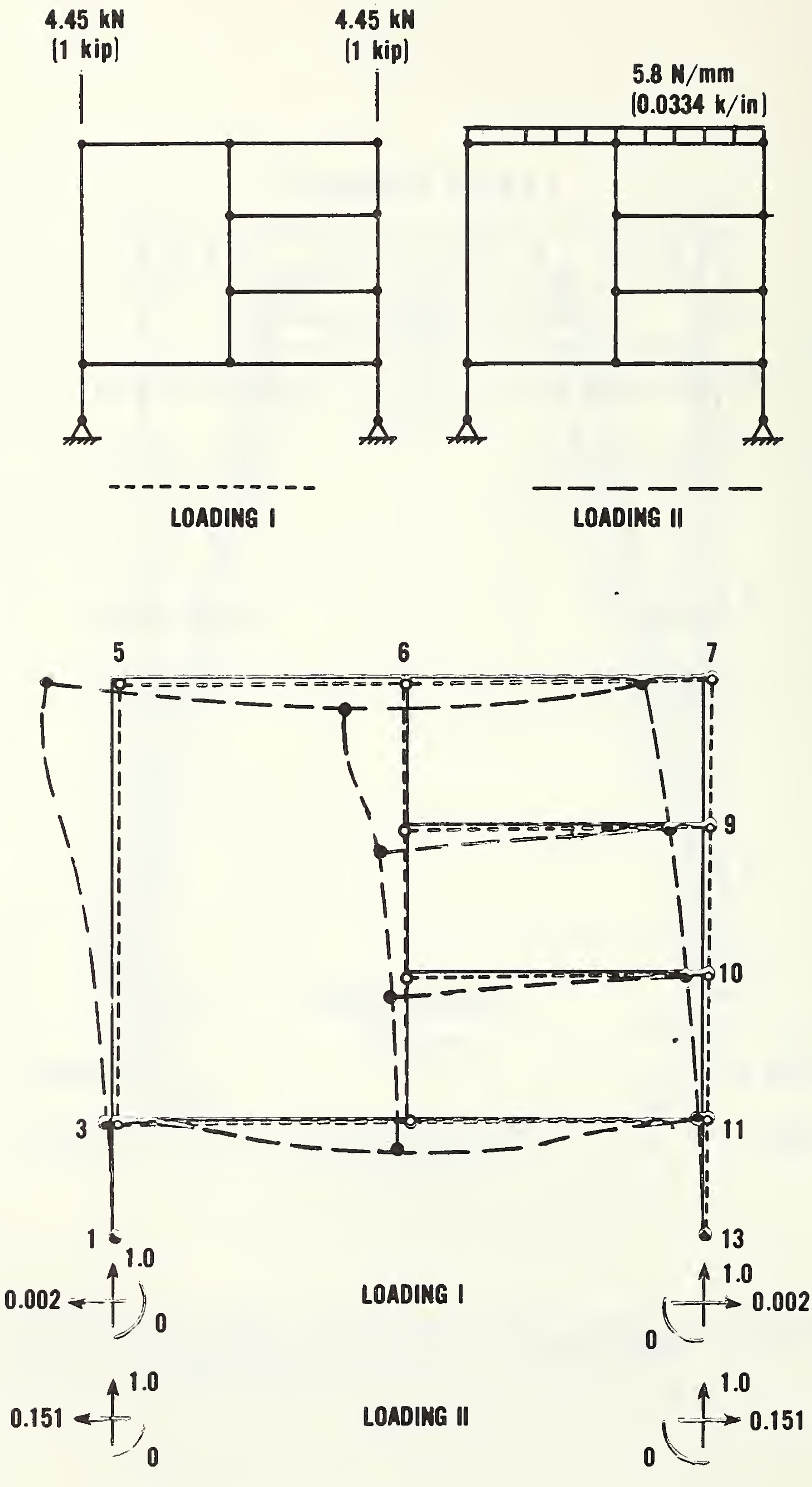
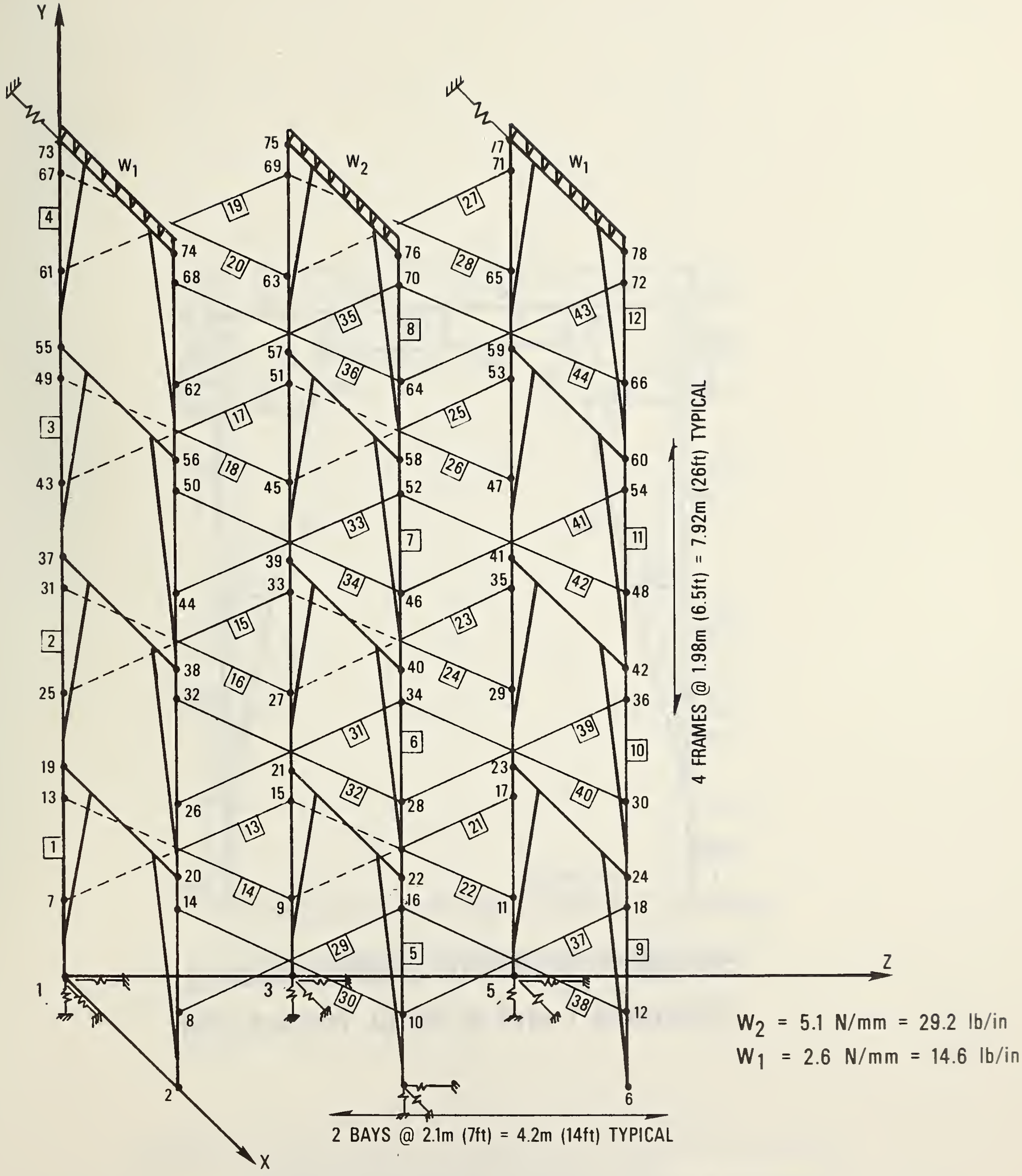


Figure B.6 Structure 'frame' deflected shapes under concentrated column and uniform ledger loads.



STRUCTURE SCAFFOLD

Figure B.7 Structure 'scaffold' with 78 nodes and 44 elements under OSHA specified 2.4 kN/m^2 (50 psf) loading.

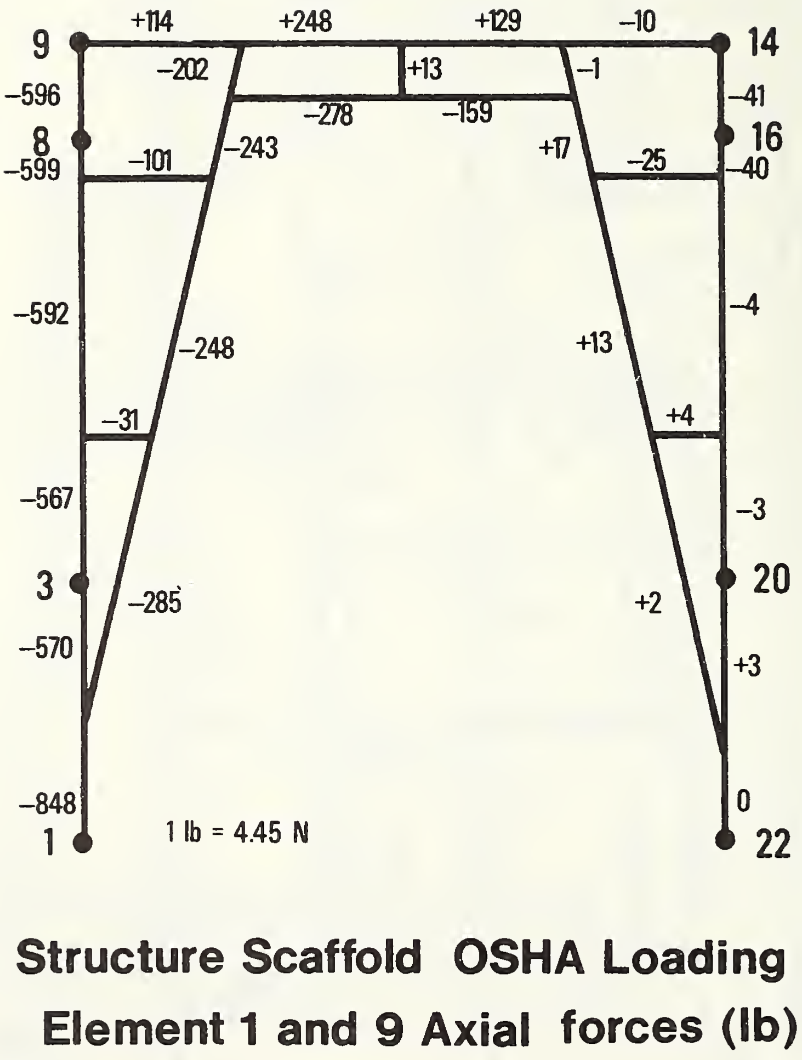


Figure B.8 Axial forces in elements 1 and 9 of structure 'scaffold' under OSHA specified loads.

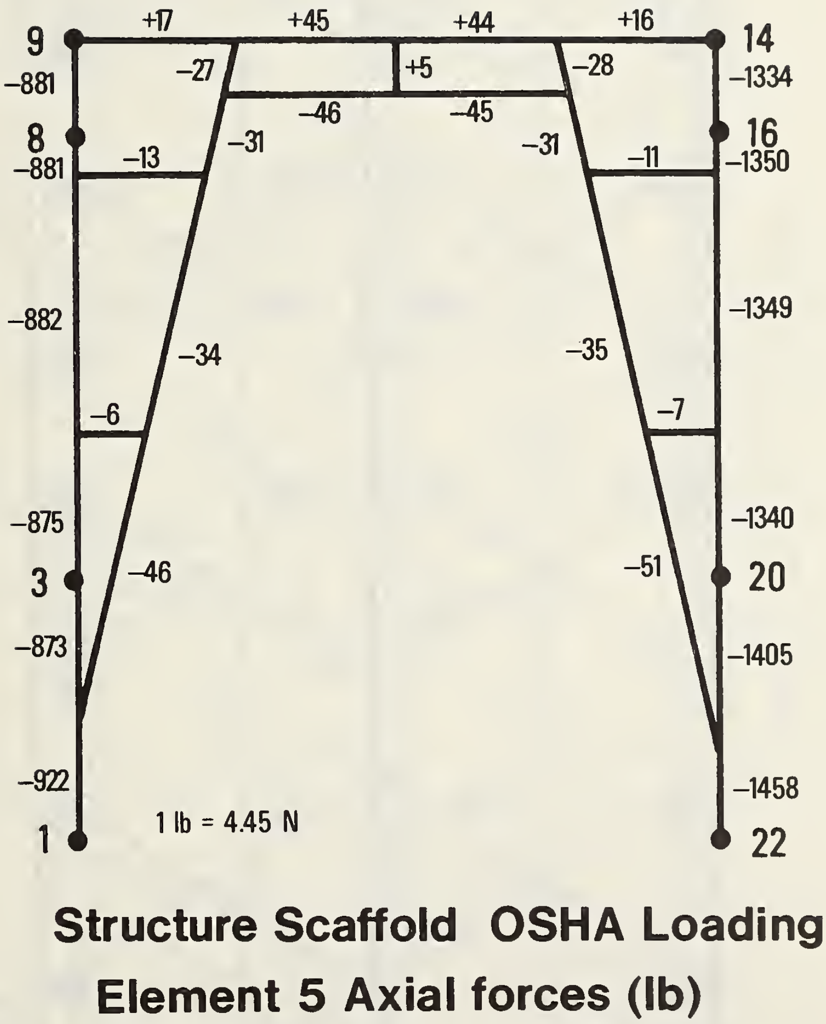


Figure B.9 Axial forces in element 5 of structure 'scaffold' under OSHA specified loads.

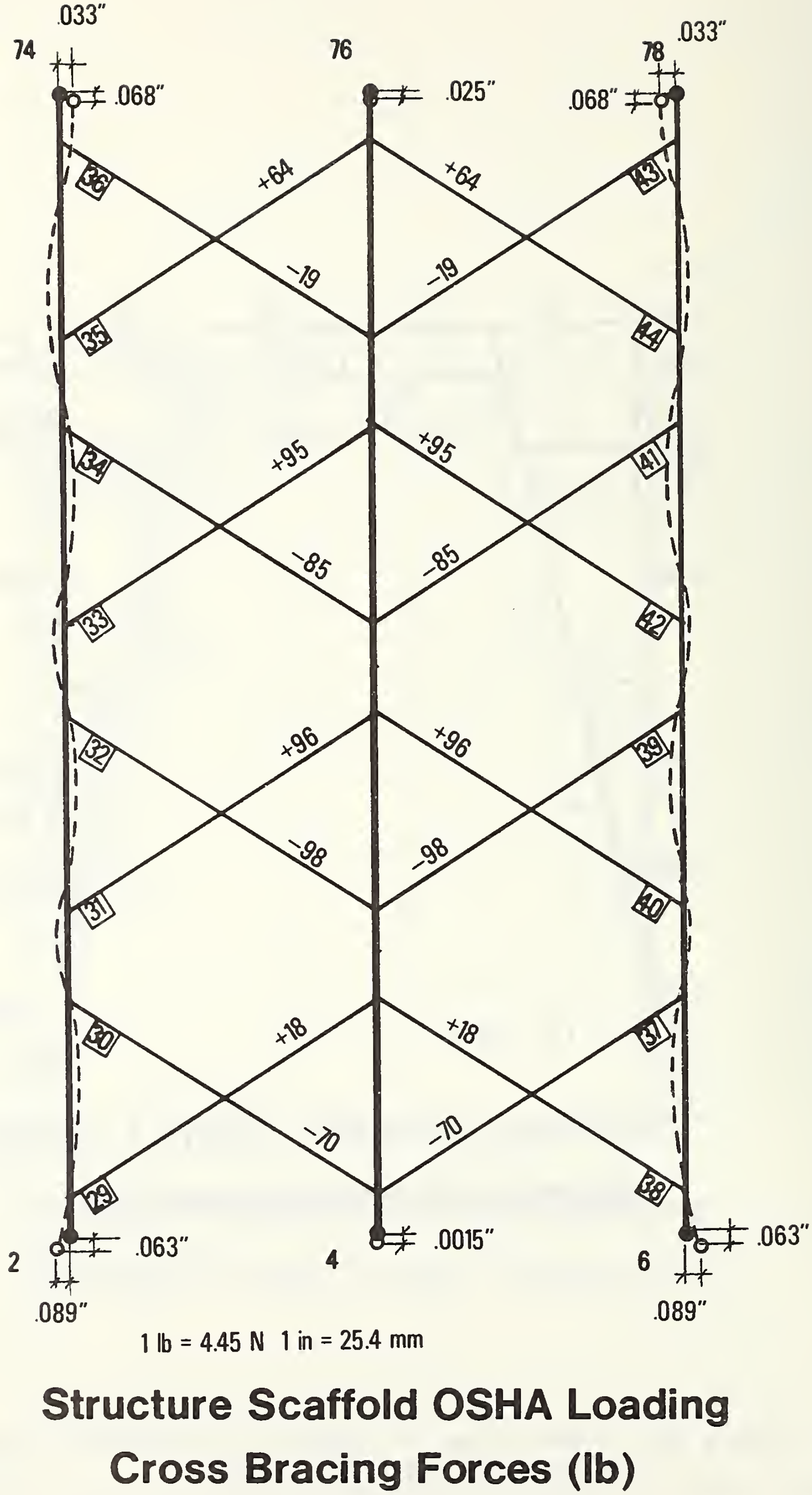


Figure B.10 Structure 'scaffold' cross-bracing forces and deflected shape for OSHA specified loads.

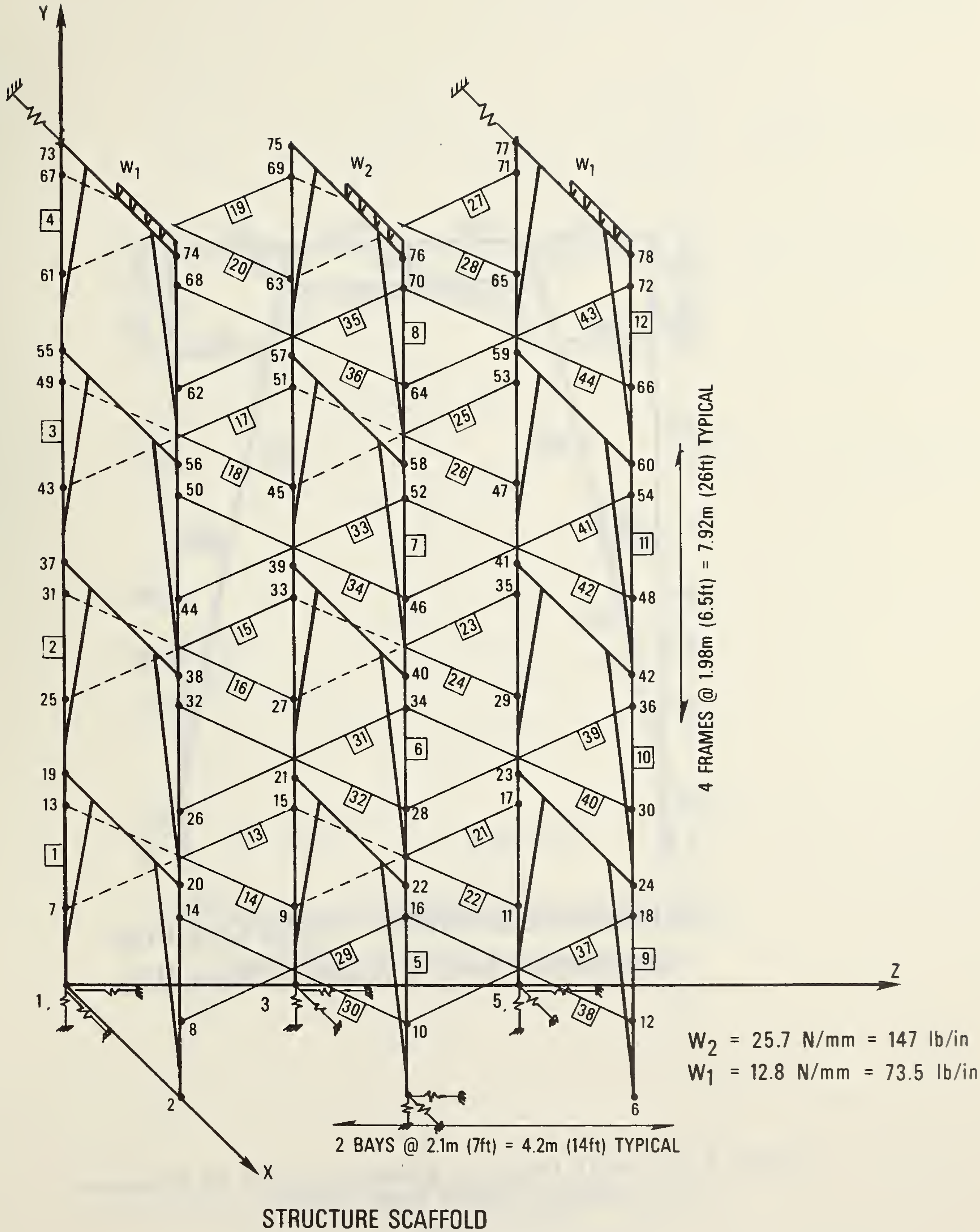


Figure B.11 Structure 'scaffold' with 78 nodes and 44 elements under field loading conditions.

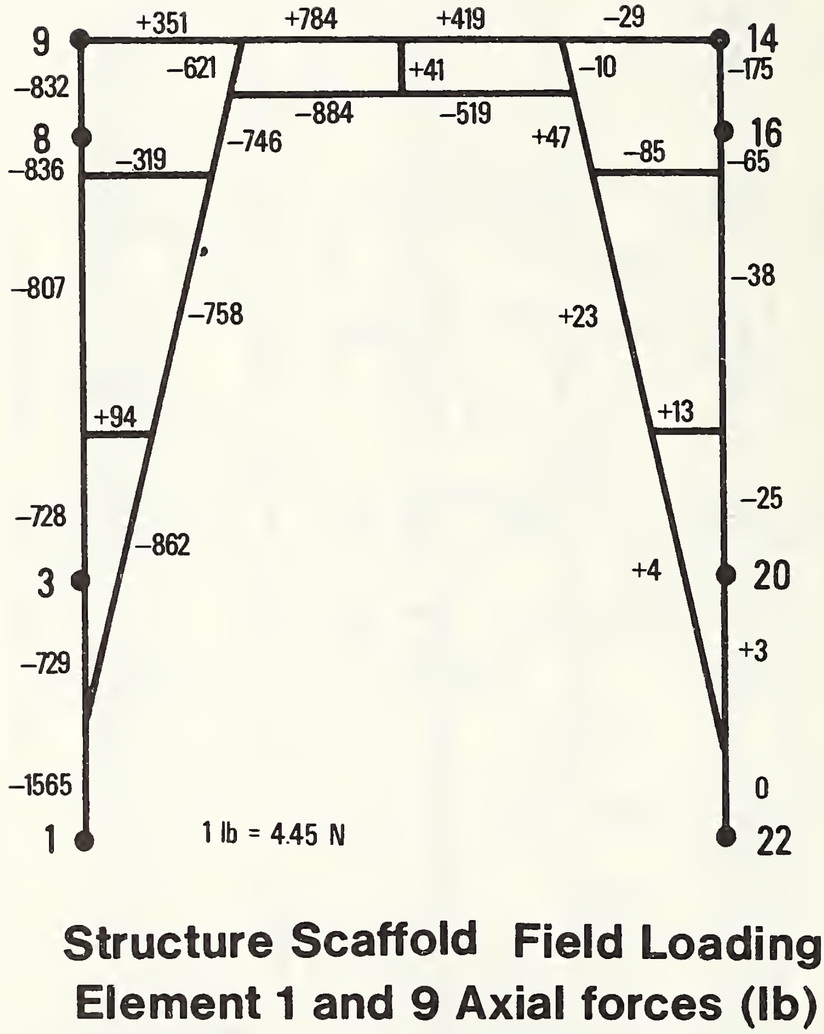


Figure B.12 Axial forces in elements 1 and 9 of structure 'scaffold' under field loads.

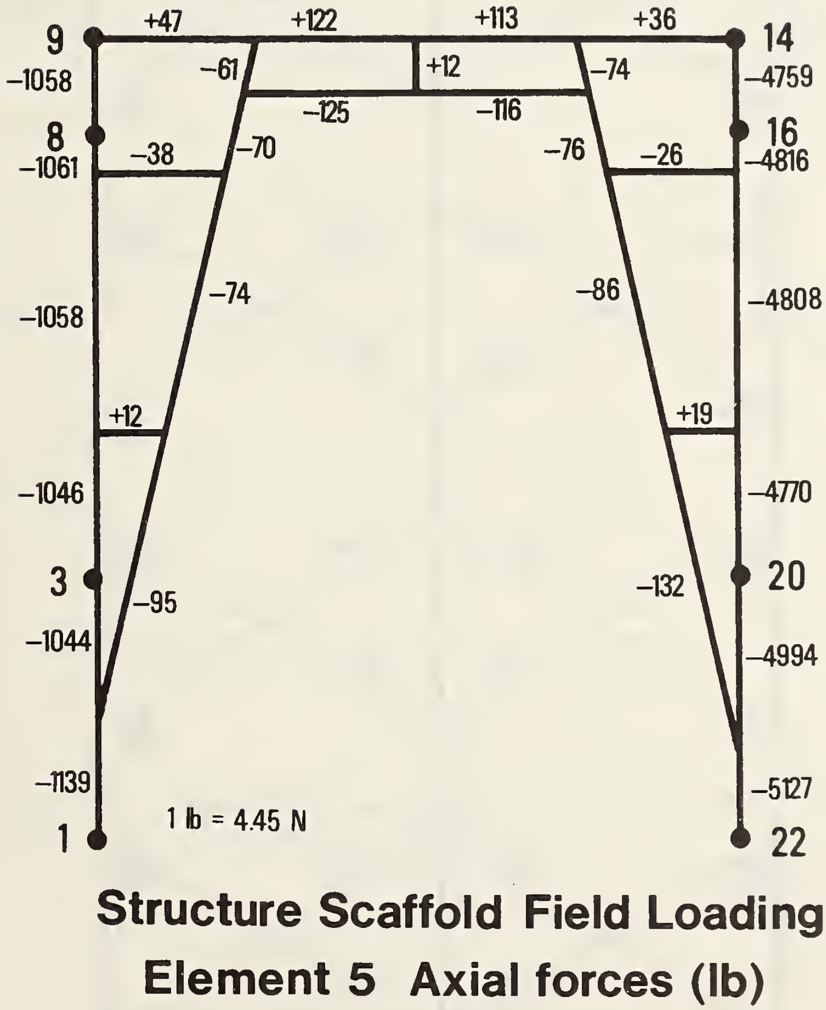
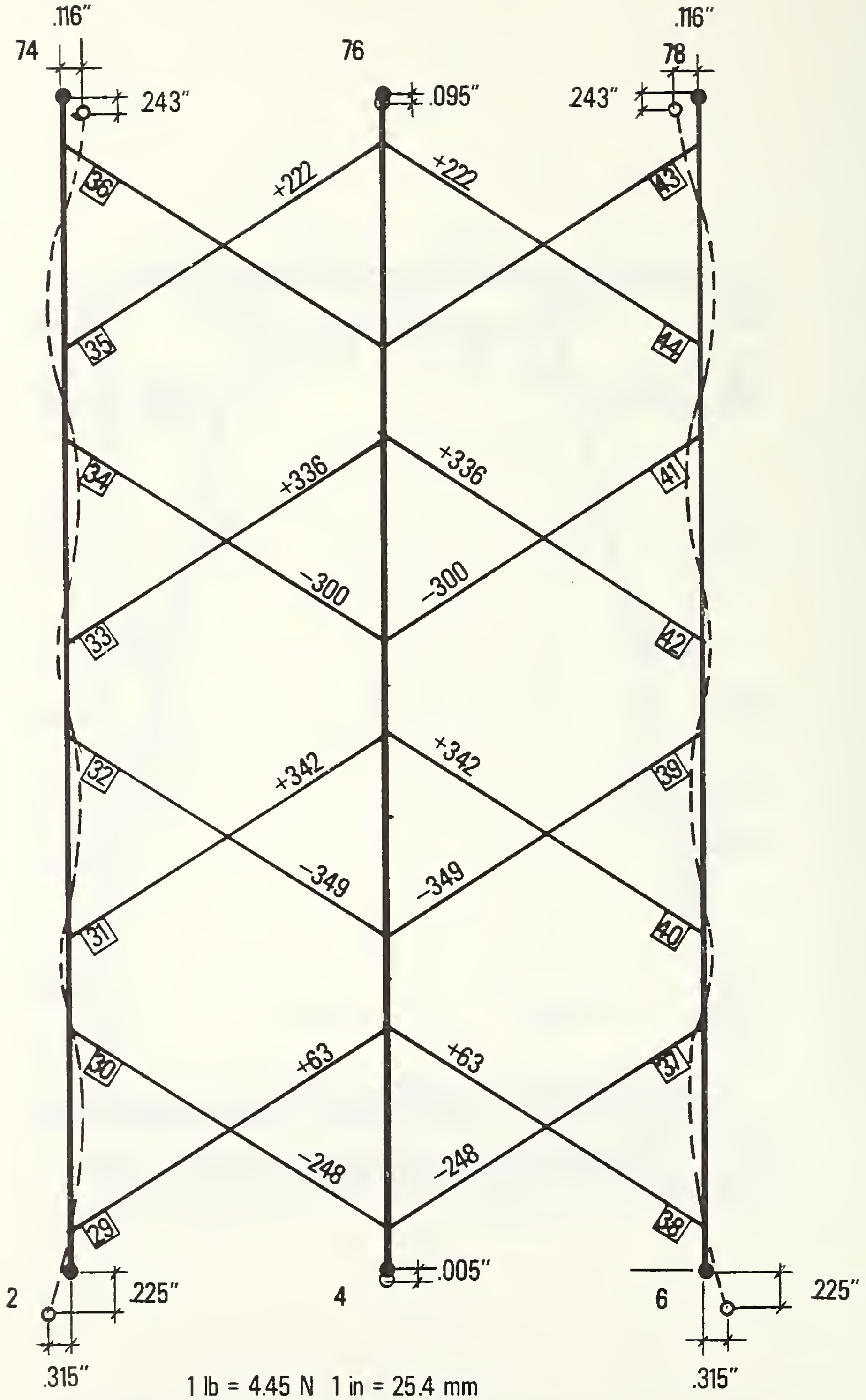


Figure B.13 Axial forces in element 5 of structure scaffold under field loads.



Structure Scaffold Field Loading
Cross Bracing Forces (lb)

Figure B.14 Structure scaffold cross-bracing forces and deflected shape for field loads.

	OSHA LOADING			FIELD LOADING		
	Force lb*			Force lb		
Node	x	y	z	x	y	z
1	57	848	1	174	1565	.4
2	-	-	-	-	-	-
3	8	922	-	17	1139	-
4	-8	1458	-	-17	5127	-
5	57	848	-1	174	1565	-.4
6	-	-	-	-	-	-
73	-57	-	-	-174	-	-
77	-57	-	-	-174	-	-

* 1 lb_f = 4.45 N

Table B.1 Foundation and anchor reaction forces for both loading cases.

B.5 References

1. Lopez, L.A., FINITE: An Approach to Structural Mechanics Systems, International Journal of Numerical Methods in Engineering, v. 11, n. 5, 1977.

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			14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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.)*

This report presents a review of the available literature on scaffolds and is the third of several inter-related studies of a scaffolding research program at the National Bureau of Standards (NBS). This study was sponsored by the National Institute for Occupational Safety and Health (NIOSH) to improve scaffolding system performance and reduce the work related injuries and losses.

A computerized search of the published literature was performed and technical information that could serve to upgrade existing codes and standards for scaffolds or offer direction to future analytical research has been presented. This information concerned the design, erection, operation or maintenance of scaffolding systems. Appendix A presents the 22 types of scaffolds under study. In addition, U.S. scaffold patent claims and the manufacturers' literature was reviewed and discussed. Appendix B presents selective model analyses of scaffolds.

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)*

Codes and standards; construction safety; design; finite element; loads; scaffolds; stability; stiffness; strength; structural safety; work surfaces.

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