Investigation of a Tower Crane Collapse in San Francisco, California- November 28, 1989

U.S. Department of Labor
Occupational Safety and Health Administration

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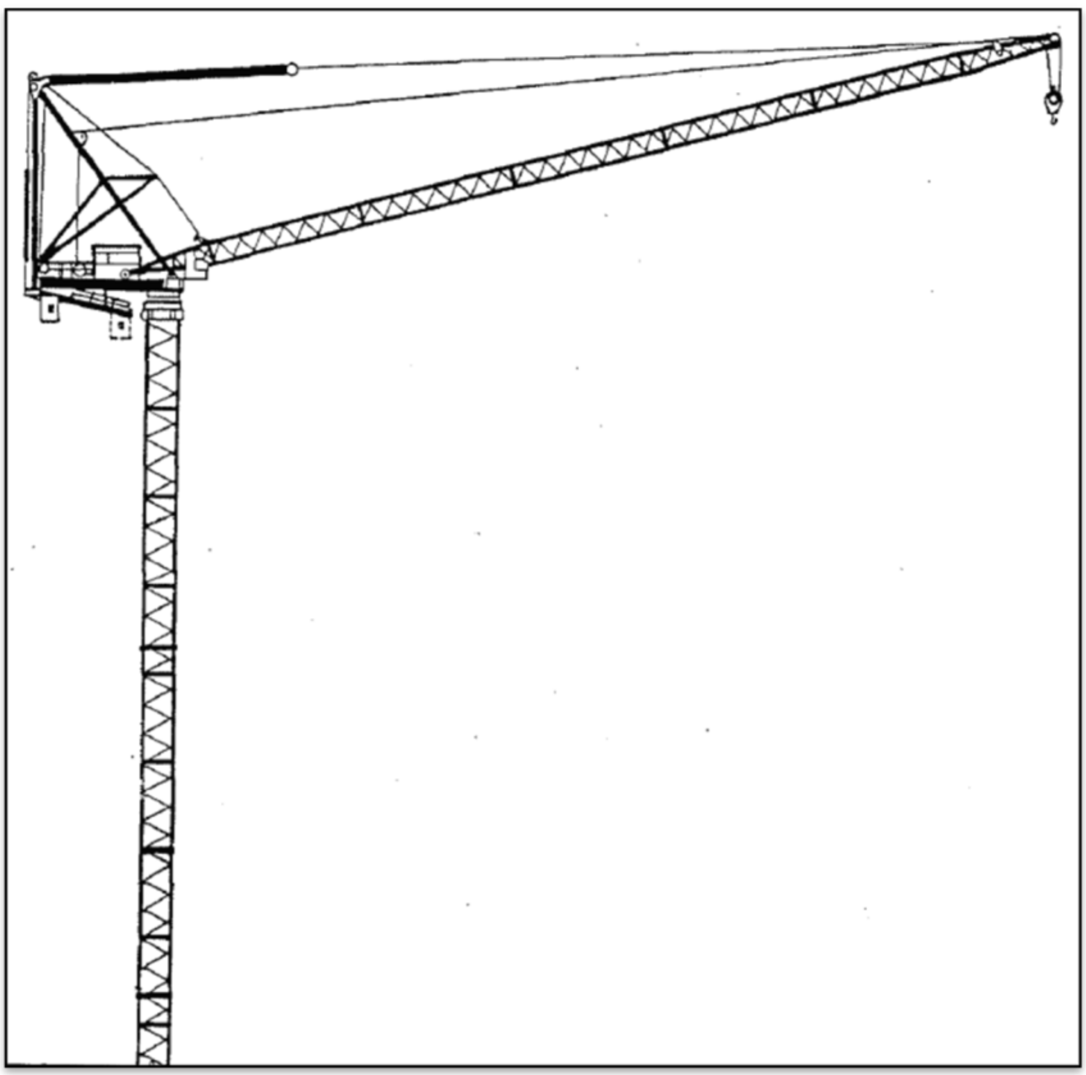

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ABSTRACT

This report presents the results of an investigation to determine the cause of the collapse of a tower crane in San Francisco, California on November 28, 1989. The failure occurred when the crane was being raised or "climbed" to increase its working height. The investigation included a detailed inspection of the collapsed structure, review of eyewitness accounts of the collapse, laboratory tests and computer analyses of the structure. The cause of the failure was overloading of structural members in the tower due to rotation of the crane during the climbing operation. The rotation was likely due to adjustments being made to the climbing section that involved powered slewing of the crane. The computer analysis indicated the structure was sensitive to rotation of the superstructure during the climbing operation. The results of the computer analysis were consistent with the mode of failure of the structure. A preexisting crack in a connection plate and a structural member and brittle behavior of the materials associated with the welding details may have contributed to the failure.

Keywords: Accident; collapse; crane; construction failure; steel structure.

PREFACE

In January 1990, the Division of Occupational Safety and Health, Department of Industrial Relations of the State of California (CalOSHA) requested assistance from the U.S. Department of Labor, Occupational Safety and Health Administration (OSHA) in their investigation of the collapse of a tower crane that occurred on November 28, 1989, in San Francisco, California. The purpose of the assistance was to provide technical support in determining the cause of the collapse. This report presents the results of the analysis of the cause of the collapse conducted by the OSHA Office of Construction and Engineering.

The OSHA analysis was conducted in cooperation with CalOSHA. Statements obtained from the witness interviews conducted by the Bureau of Investigation, Department of Industrial Relations and CalOSHA staff were provided to the OSHA investigation team. The OSHA team and CalOSHA staff worked together in collecting data on the collapsed structure and in planning the laboratory tests.

Roy Berg, Ralph Allen, Jerry Lombardo, CalOSHA staff and John Tennison, Regional Manager, CalOSHA made important contributions in the conduct of this investigation.

EXECUTIVE SUMMARY

On November 28, 1989, shortly after 8:00 a.m., a tower crane collapsed in the center of the financial district in San Francisco, California. Four construction workers engaged in the climbing operation of the crane and one person on the street below the crane were killed. Given the time of day and the location in a busy urban setting, the catastrophic potential of this accident was substantial.

At the request of the Division of Occupational Safety and Health, Department of Industrial Relations of the State of California (CalOSHA), the Occupational Safety and Health Administration (OSHA), U.S. Department of Labor, participated in the investigation of the accident. The purpose of the OSHA participation was to determine the cause of the accident. Evaluation of compliance with safety regulations and enforcement actions relating to the accident were the sole responsibility of CalOSHA.

The OSHA investigation began in early January 1990. The investigation included a detailed inspection of the collapsed structure, a review of eyewitness accounts of the collapse, laboratory tests to determine the mechanical properties of the structure and computer analyses of the crane structure. This work was carried out in cooperation with CalOSHA.

At the time of the collapse, a climbing operation was underway which involved raising the superstructure or operating portion of the crane. The sensitivity of the structure to a variety of loading conditions that could have existed during this climbing operation was evaluated. The loading considered related to: (1) luffing of the boom, (2) loss of roller support of the climbing section and (3) rotation of the superstructure. The results of this evaluation together with physical evidence of the behavior of the structure in the collapse and eyewitness observations of the work underway at the time of the collapse were used to determine the cause of the failure.

Based on the results of the investigation, OSHA concludes that:

1. The likely cause of the failure was overloading of structural members in the tower due to rotation of the crane during the climbing operation. The rotation was likely due to adjustments being made to the climbing section that involved powered slewing of the crane.

2. A preexisting crack in a connection plate and a structural member and brittle behavior of the materials associated with welding details may have contributed to the failure.

3. The climbing section was not correctly positioned with respect to tower section 15, particularly, in the third climbing step.

4. The forces on certain rollers of the climbing section are very sensitive to rotations of the crane superstructure.

5. Failure of the crane in terms of exceeding the load carrying capacity during the climbing operation occurs at a counterclockwise rotation of approximately 45 degrees.

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1. INTRODUCTION

1.1 Background

On November 28, 1989, shortly after 8:00 a.m., a tower crane collapsed in the center of the financial district in San Francisco, California. Four construction workers engaged in the climbing operation of the crane and one person on the street below the crane were killed. Given the time of day and the location in a busy urban setting, the catastrophic potential of this accident was significant.

The tower crane was being raised or "climbed" at the time of the collapse. Climbing involves raising the superstructure or operating portion of the crane, i.e., the turntable, operator's cab, machinery and boom and installing additional supporting elements or tower sections to raise the working height of the crane to the desired elevation as the building construction progresses. Special procedures, as outlined by the manufacturer of the crane, are followed during this climbing operation to control the behavior of the portion of the crane being raised and maintain the structural integrity of the supporting structure.

A sketch of the tower crane is shown in figure 1.1.1. The figure illustrates the configuration of the crane at the time of the collapse. Figure 1.1.2 illustrates the various operating elements. Figure 1.1.3 is a photograph taken during the climbing operation three weeks prior to the collapse, the last time the crane was raised. The crane was designed and manufactured by Peiner Maschinen und Schraubenwerke for the American Pecco Corporation headquartered in Millwood, New York. The crane is a climbing, luffing boom, tower crane. The tower was tied to the building under construction at two locations for lateral support as shown in figure 1.1.1 .

Representatives from the Division of Occupational Safety and Health, Department of Industrial Relations of the State of California (CalOSHA) and from the U.S. Department of Labor, Occupational Safety and Health Administration (OSHA), were on the scene within approximately one hour of the accident. The State of California has its own occupational safety and health program. CalOSHA, therefore, was responsible for investigating the accident. Evidence in the form of photographs and a videotape of the accident scene collected by OSHA regional office staff, on November 28, 1989, was turned over to CalOSHA immediately following cleanup of the accident site.

In early January 1990, CalOSHA requested OSHA provide assistance in their investigation of the accident. The purpose of this assistance was to provide technical support in determining the cause of the accident.

One of the functions of the OSHA Office of Construction and Engineering headquartered in Washington, D.C., is to provide technical assistance to State government agencies. Accordingly, on January 3, 1990, a team of engineers from the Office of Construction and Engineering met with CalOSHA staff in California to begin this work. The assistance provided by OSHA was limited to determining the cause of the accident. Evaluation of compliance with safety regulations and enforcement actions relating to the accident were the sole responsibility of CalOSHA.

1.2 OSHA Investigation

The OSHA investigation included a detailed inspection of the collapsed structure, a review of eyewitness accounts of the collapse, laboratory tests to determine the mechanical properties of the structure and computer analyses of the crane structure. The work was carried out in cooperation with CalOSHA. Eyewitness interviews obtained by CalOSHA immediately following the accident were provided to the OSHA investigating team. Inspection of the collapsed structure and collection of relevant data were done jointly. Both groups planned the laboratory testing program. The laboratory tests were conducted by a private firm under contract to CalOSHA. Throughout the course of the investigation, both groups worked together sharing information and jointly developing perspectives on the various aspects of the accident and the cause.

1.3 Organization of the Report

This report is organized in nine Chapters and Appendices:

Chapter 2 describes the procedures followed by OSHA in conducting the investigation.

Chapter 3 describes the tower crane structure, the brakes and the climbing operation used to raise the crane.

Chapter 4 provides background information on the crane prior to the collapse and activities underway at the time of the collapse. Eyewitness accounts of the collapse are reviewed. Detailed observations of the collapsed structure and performance of the components of the structure are also presented.

Chapter 5 describes the results of the laboratory tests conducted to determine the material properties and evaluate the behavior of the structural components of the tower including the slewing brakes.

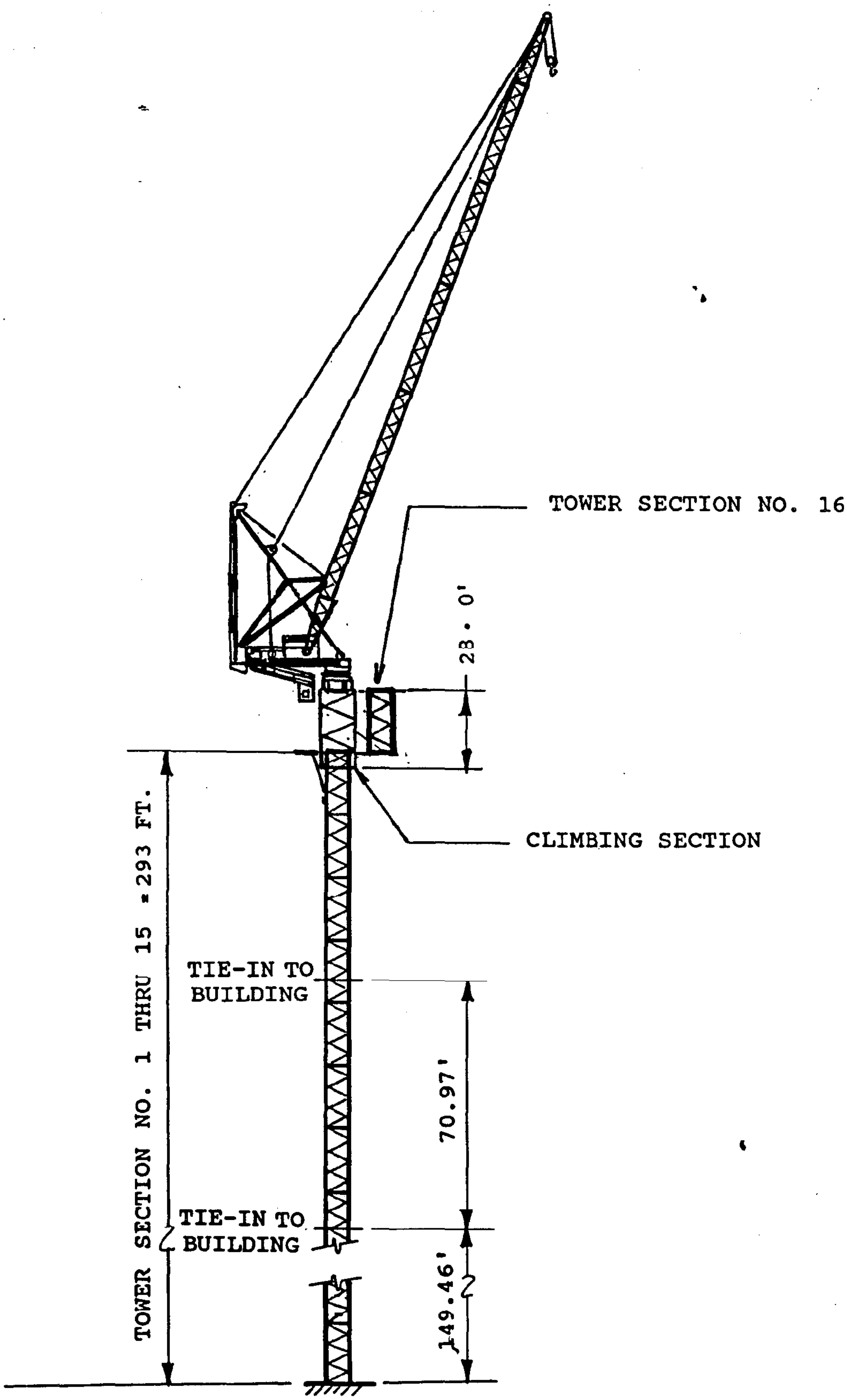
Chapter 6 presents the results of analytical studies conducted to evaluate the response of the tower and climbing section to a variety of loading conditions. Forces and stresses in the structural members and the forces on the rollers of the climbing section were determined. Failure mechanisms and associated loading conditions were also determined.

Chapter 7 presents the results of the investigation. The information obtained in the investigation is used to identify the cause of the failure.

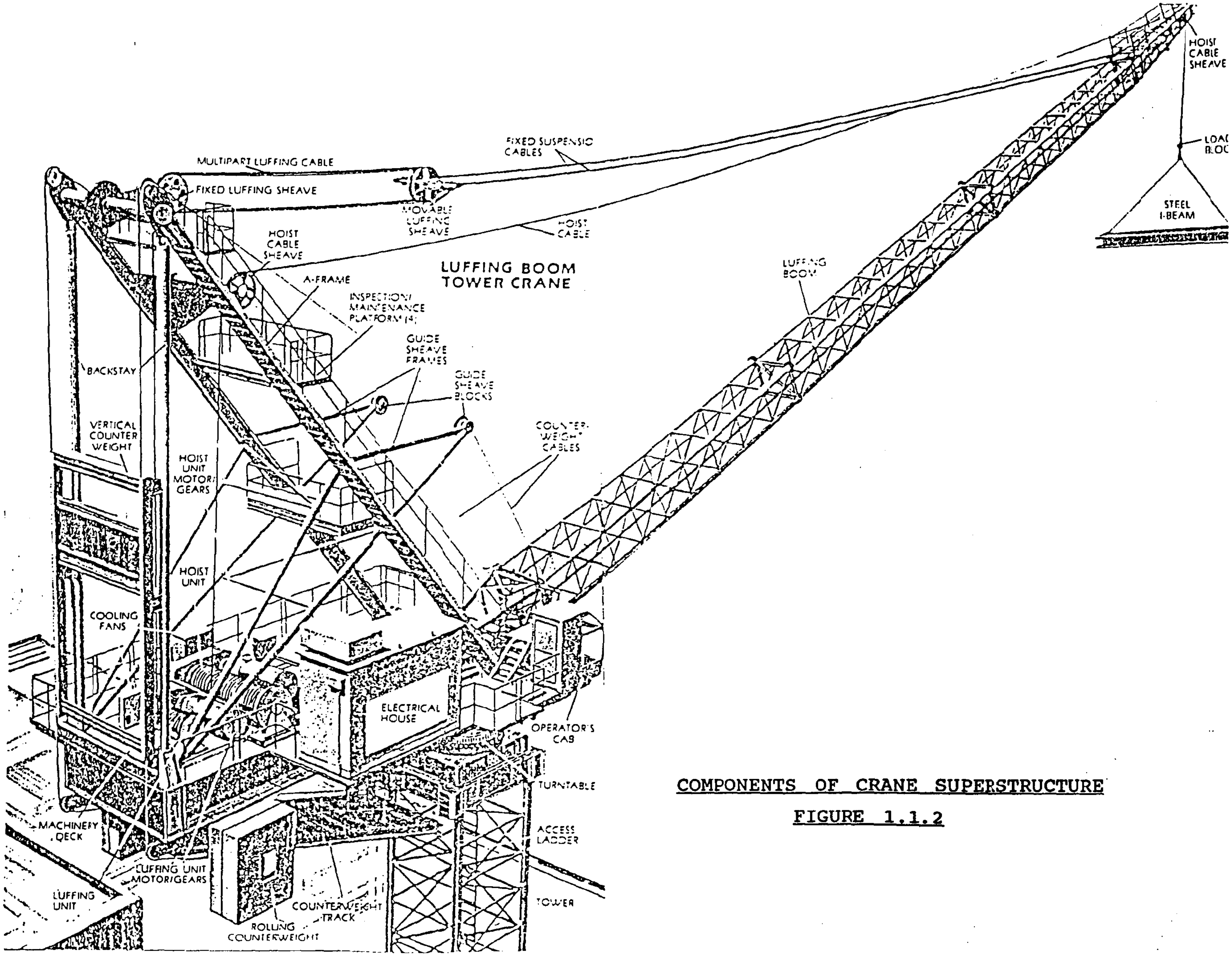
Chapter 8 presents the conclusions reached in the OSHA investigation.

Chapter 9 lists the references cited in the text.

The Appendixes include a description of the climbing procedure and the calculations of the limit states for the structural components.

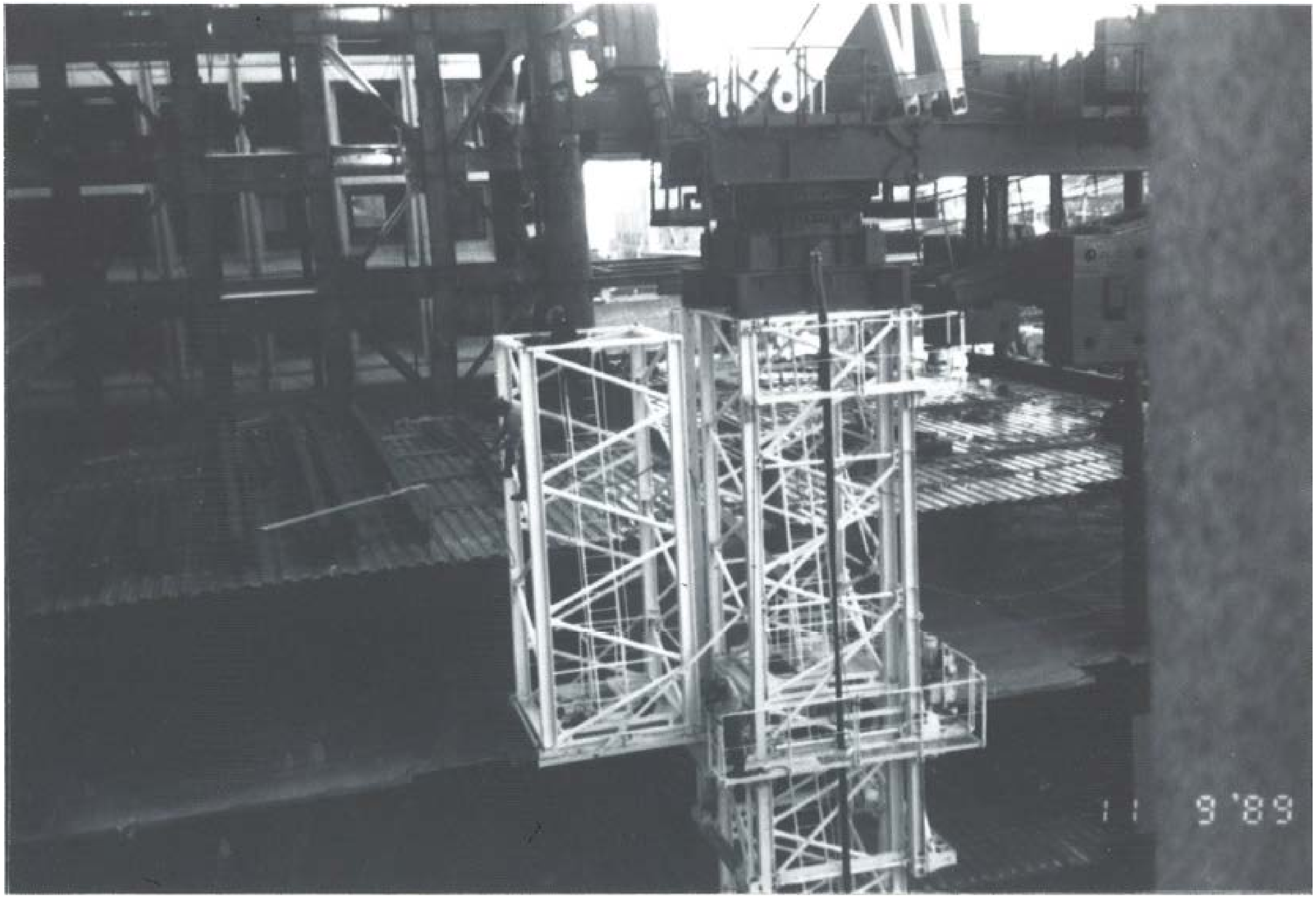


TOWER CRANE CONFIGURATION PRIOR TO COLLAPSE
FIGURE 1.1.1



COMPONENTS OF CRANE SUPERSTRUCTURE

FIGURE 1.1.2



Climbing operation on 11-9-89. Turntable on top of climbing section, new section on platform at left.

Figure 1.1.3

2. CONDUCT OF THE INVESTIGATION

2.1 Structural Observations

The collapsed structure was removed from the construction site in downtown San Francisco following the accident, to a storage yard of the Sheedy Crane and Rigging Company, 1215 Michigan Street, San Francisco, California. Photographs, videotapes and accounts of the location of the parts of the collapsed structure obtained by CalOSHA immediately following the accident were provided to the OSHA investigation team. The OSHA team's initial visit to the Sheedy Crane and Rigging Company storage yard to collect data on the collapsed structure was on January 3, 1990. The team made six visits to the storage yard over the next four months to collect additional data as the investigation proceeded. Detailed measurements, photographs, and sketches were made of the pattern of deformation of the tower sections, climbing traverse and climbing section. Data on other components of the crane including the brakes and the electrical system were also collected. The OSHA team also visited the Pecco Corporation storage yard in Oakland, California, where some parts of the collapsed structure were stored, to examine their structural integrity. OSHA staff visited a construction site in San Francisco in February 1990, to observe the operation of a tower crane of the same type as the one that collapsed.

2.2 Crane Information

General background information was collected on the structural details and operating procedures of this model of crane. Most of this information was obtained from the operating manual of the crane provided by the American Pecco Corporation [1]. Information was also obtained from American Pecco Corporation engineers during a visit by OSHA and CalOSHA staff to the corporation headquarters in Millwood, New York on March 21, 1990. This visit also provided an opportunity to operate a similar demonstration model tower crane and become familiar with the control panel cabin, operator's cab, the mechanical and electrical systems and the crane's operating characteristics.

Information was also sought on the performance history of the collapsed crane. This included: (1) the maintenance log which contained details of past usage and repairs, (2) reports on the results of the inspection of the crane by American Pecco Corporation staff following the October 17, 1989, Loma Prieta, California earthquake, and (3) operating practices by the company responsible for erection and operation of the crane at the time of failure.

2.3 Laboratory Tests

Laboratory tests were conducted to determine the chemical composition and mechanical properties of the structural steel. Chemical analyses, standard tensile tests and energy absorption tests were used for this purpose. Metallographic and fractography tests were conducted to evaluate the characteristics of the fracture surfaces in the components of the structure. Examinations were also conducted on the components of the crane brakes. Indentations and deformations of the four columns in tower section 15 were examined, in detail, to evaluate their characteristics.

2.4 Analytical Studies

Structural analysis of the crane tower and the climbing section was conducted, using a three dimensional computer program, to determine the response of the structure to a variety of loading conditions. This included loading conditions during normal climbing operations and those that occurred prior to the collapse. The forces in the members of the climbing section, the rollers and the members of the crane tower were computed at several locations of the boom during the climbing process and at various degrees of rotation of the boom and compared with their failure loads. The sensitivity of the structure to the loss of the roller supports of the climbing section was also determined. In elastic response of members and P Delta effects were included in the analysis.

3. DESCRIPTION OF THE CRANE AND THE CLIMBING OPERATION

3.1 Description of the Structure

Figure 1.1.1 is a sketch of the structure. This was the configuration of the crane on the morning of November 28, 1989 at the time of the collapse. This model SN 355 crane, a climbing, luffing boom tower crane had a maximum reach of 192 feet-6 inches and a maximum lift capacity of 17,100 pounds with two wire ropes. The crane was reported to have been manufactured in 1982 and had been in use at various construction sites. Table 3.1.1 indicates the locations and details of its prior use, as obtained from American Pecco Corporation.

The erection chronology and erection crew members involved in the climbing operation are given in figure 3.1.1. Note the erection crew on the day of the collapse were involved in climbing the crane on November 9 and November 27, 1989. The crane had been certified and placed in operation on August 22, 1989. The height of the crane consisting of nine identical sections, nos. 1 through 9, at this time was 185 feet above the footings and was free standing. On November 9, 1989, three additional tower sections, nos. 10, 11 and 12, were added. The height then became 247 feet. Lateral support was provided by the structural steel frame of the building under construction as shown in figure 1.1.1. On November 27, 1989, three sections, nos. 13, 14 and 15, were added. The height then became 298 feet. A second lateral support was provided by a tieing into the building under construction. On the morning of November 28, 1989, the climbing process was underway to add another tower section no. 16. The accident occurred during this process.

The tower sections consist of rolled structural shapes for the columns and round structural tubing for the diagonal bracing members. The diagonals are welded to the columns. One tower section consists of four identical columns and twenty-four identical diagonals. The horizontal members at the top and bottom of each tower consist of channel sections and angles. The north face columns are provided with welded lugs, three in each column, to support the climbing traverse and the climbing section during the climbing process. The dimensions for a tower section are given in figure 3.1.2.

The climbing section consists of rolled structural shapes for the columns, one size for the two north columns and one size for the two south columns. The diagonals are round structural tubing pin-connected to the columns. In addition, there are rigid stiffening beams at the location of upper level rollers and lower level rollers. The dimensions for the climbing section are given in figure 3.1.3. There are sixteen guide rollers attached to the climbing section, eight located at the upper set of stiffening beams and eight located at the lower set of stiffening beams.

These rollers guide the climbing section as it moves up the tower section and provide lateral support.

The climbing traverse consists of a frame comprised of structural shapes and a hydraulic ram or "hoist cylinder". The climbing traverse is supported on the lugs of the north face columns of the tower. Applying hydraulic pressure extends the ram sliding the climbing section vertically over the uppermost tower section. The guide rollers on the climbing section roll on the flanges of the tower section to guide the climbing section as the climbing section and crane superstructure are raised.

The cross sectional dimensions and section properties of the structural members of the tower section and climbing section are given in table 3.1.2. At the beginning of the investigation, attempts to obtain the dimensions and structural designations for these members from the crane manufacturer were not successful. The cross sectional dimensions listed, therefore, are measured values from the collapsed structure. The section properties in the tables were calculated from the measured dimensions. These values were used in the structural analysis in Chapter 6. Figures 3.1.4, 3.1.5, 3.1.6 and 3.1.7 show a typical bolted connection between tower sections, a tower section viewed from the bottom, typical connection plates between tower sections and the turntable support frame.

3.2 Slewing Brakes

Two drive motors and reduction gear sets were used to control slewing of the boom on the crane. Each motor incorporated an eddy current brake and a double shoe friction brake. The friction brakes function by pressure of two shoes against a rotating brake drum on the slewing motor gear set. The pressure is provide by a compression spring and release is achieved by counteracting the force of the compression spring by a spreading magnet, an electromagnetic device. The spreading magnet is energized, releasing the friction brakes, whenever the slewing motor is running under operator control via the joystick. The magnet is deenergized, applying the friction brakes, when the brake pedal is fully depressed. The friction slewing brakes are also applied when the electric power is off. The friction brakes can also be released manually by a hand lever located outside the cab and attached to an eccentric cam on the spreading magnet.

The resisting torque applied to the superstructure by the slewing brakes is determined by the torque and rotational speed of the brake motor. The slewing brake had a torque of 74 ft-lbs and a rotational speed of 1,820 rpm. The torque applied to the superstructure by the two brakes, therefore, equaled 269 ft- kip (74 x 1820 x 2 ÷ 1000).

Under some circumstances of operation, the function of the two slewing brakes is altered. For example, during service with a hook reach of more than 65 feet, both slewing motors and slewing brakes are used. If the hook reach is less than 65 feet, one of the slewing motors is automatically switched off, and its friction brake is opened electrically by the spreading magnet. The slewing action is then controlled by one motor and one slewing brake.

According to the maintenance instructions, the slewing brakes are adjusted for a deceleration time of 10.1 seconds, from full slewing speed (Section 1.3.13 of the owners manual). The friction brakes are not intended to cause a sudden deceleration because of the danger of overturning, however, they can serve to lock the turntable when slewing is not desired. During climbing up or climbing down, for example, slewing is not permitted.

It is interesting to note, that during climbing, the boom is normally adjusted to a hook reach of 70 feet in order to attain a balance of the boom, hoist and counterweight over the climbing frame. Minor adjustments of the balance are permitted by luffing of the boom. However, from the discussion above, it is apparent that if the boom is luffed back (upward) to a hook reach of less than 65 feet, one slewing friction brake will automatically be released. Slewing during the climb is then prevented only by one slewing brake.

3.3 <u>Climbing Operation</u>

The working height of the crane is increased by climbing the crane or using the climbing section to raise the superstructure above the uppermost tower section and adding another tower section. The climbing procedure is described in the crane operations manual and is included in Appendix A.

Referring to Appendix A, the climbing operation can be separated into three phases. The first phase (Sections 3.4.2 through 3.4.5) involves preparing the structure. Adjusting the guide rollers, placing the new tower section on the erection platform and balancing the crane are key steps in this phase. As noted, in Section 3.4.2, the crane should not slew or rotate after the initial preparations have been made for climbing.

The following method was used by the erection crew to place tower section 16 on the platform of the climbing section. The method differed from that described in the operating manual:

- The new section was hoisted on the load line of the crane and elevated to a height of few feet above the elevation of the platform of the climbing section

- The crane was slewed toward the building - pointing the new section close to the building at the 17th floor level.

- The erection crew reached out to the new section and secured the end of cable to the new section as shown in figures 3.3.1 and 3.3.2.

- The air-activated wrench - located on the 15th floor pulled the cable. The cable passed through a pulley secured to a perimeter beam on the 15th floor, went through the north and south faces of the climbing section and the uppermost installed tower section and was tied to the new section.

- The new section was pulled toward the platform in an inclined fashion since the minimum hook distance is 23 feet.

- As the south legs of the new section approach the interior of the platform, the load line was lowered to allow the south legs to sit on the platform. Simultaneously, cable was pulled in to tilt the new section from its inclined position into a vertical position.

- The north legs of the new section bear on the platform.

- The cable was disengaged from the new section and tied to the north face of the climbing section with enough slack in the cable to allow unobstructed upward movement by the climbing section.

The second phase (Section 3.4.6) or the actual climbing involves raising the superstructure. This is carried out in three lifts or "steps" as illustrated in figure 3.3.3. In each lift the climbing section is raised approximately 6 feet-6 inches. A final lift of 1 foot-5-1/2 inches is required prior to inserting the new tower section. Between lifts the climbing section is supported on lugs on the north tower section columns as the hydraulic ram is retracted and repositioned for the next lift. The third phase (Section 3.4.7) involves installation of the new tower section and securing it in place.

The climbing process is clearly a hazardous operation. During this time, portions of the structure are no longer positively connected together and proper load transfer between these portions requires maintaining a specific alignment or relative orientation of the components. Transfer of the superstructure load through the climbing section into the tower of the crane in figure 1.1.1, for example, depends on the alignment of the rollers on the climbing section.
This load transfer will be discussed further in Chapter 6. Many firms perform the climbing operation for tower cranes on weekends

or other special times in order to minimize the risk to workers and others on or near the construction site in the event of an accident. Some jurisdictions require notification prior to climbing tower cranes and that the work be done at special times.

3.4 Climbing Section Rollers

There were sixteen guide rollers attached to the climbing section which controlled vertical and horizontal alignment of the climbing section during the climbing process. Eight rollers were located at the upper level about 7 feet from the bottom and eight rollers were at the lower level, at the bottom of the climbing section. At each level, four guide rollers were positioned to roll against the edge of the flanges of the tower legs and the other four rollers against the face of the flange of the tower legs. Figures 4.3.17 and 4.3.18 indicate the location of the guide rollers. The rollers for the flange edges were bevelled with the exception of the lower southeast edge roller. A typical edge and flange roller is shown on figure 3.4.1. The rollers contained a brass bushing inside the hole to provide a smooth surface for rolling over the shaft. The bushing was held in place by press fit only. The bushings were of uniform thickness.

The rollers were held in place by means of a round retaining steel plate, 1/4 inch thick, connected to the shaft by two 1/4 inch ϕ threaded bolts 3/4 inch long. There was a common steel washer under the two bolt heads. The diameter of the retaining plate, was slightly larger than the outside diameter of the bushing. Figure 3.4.2 shows the typical diameter of the retaining plate. The intent of the design of the plate and the bolts appeared to be to keep the roller in place in a normal climbing procedure. The size of the bolts were such that each bolt had an ultimate capacity of 1.4 kips, assuming an ultimate tensile stress of 50 ksi. An axial force of 2.8 kips would be able to push the roller off the shaft regardless of the size of the retaining plate. Evidently the retaining plate and the two retaining bolts were not designed for situations where axial forces along the axis of the shaft were present. Such forces would be present when the rollers are applying forces to the flanges at angles other than 90 degrees to the bearing surface.

Table 3.1.1
History of Crane Usage

Usage Dates			Vendor	Site	Type of Climber
Erection	Dismantling	Total Usage			
8/19/89	11/28/89 (accident)	3 mos.	The Erection Co. 600 Cal. Street San Francisco	600 Cal. San Francisco	Top Climber
3/1/88	8/30/88	5 mos.	Mellon Stuart Co. Orlando, FL	Gateway Ctr. Orlando, FL	Top Climber
7/18/86	8/14/87 NOTE: Same crane for both contractors	13 mos.	A & S Structures 1144 Zerega Ave., Bronx New York ----------- Chase Concrete 1144 Zerega Ave. Bronx, NY	4 Columbus Circle, N.Y.C. 4 Columbus Circle N.Y.C.	Jacking-inside building
9/1/85	5/28/86	8 mos.	American Bridge Chicago, IL	190 S. LaSalle Chicago	Top Climber
			Carlisle Construction Newport, KY	Cincinnati, Ohio	

Note: Manufactured in 1983.

TABLE 3.1.2

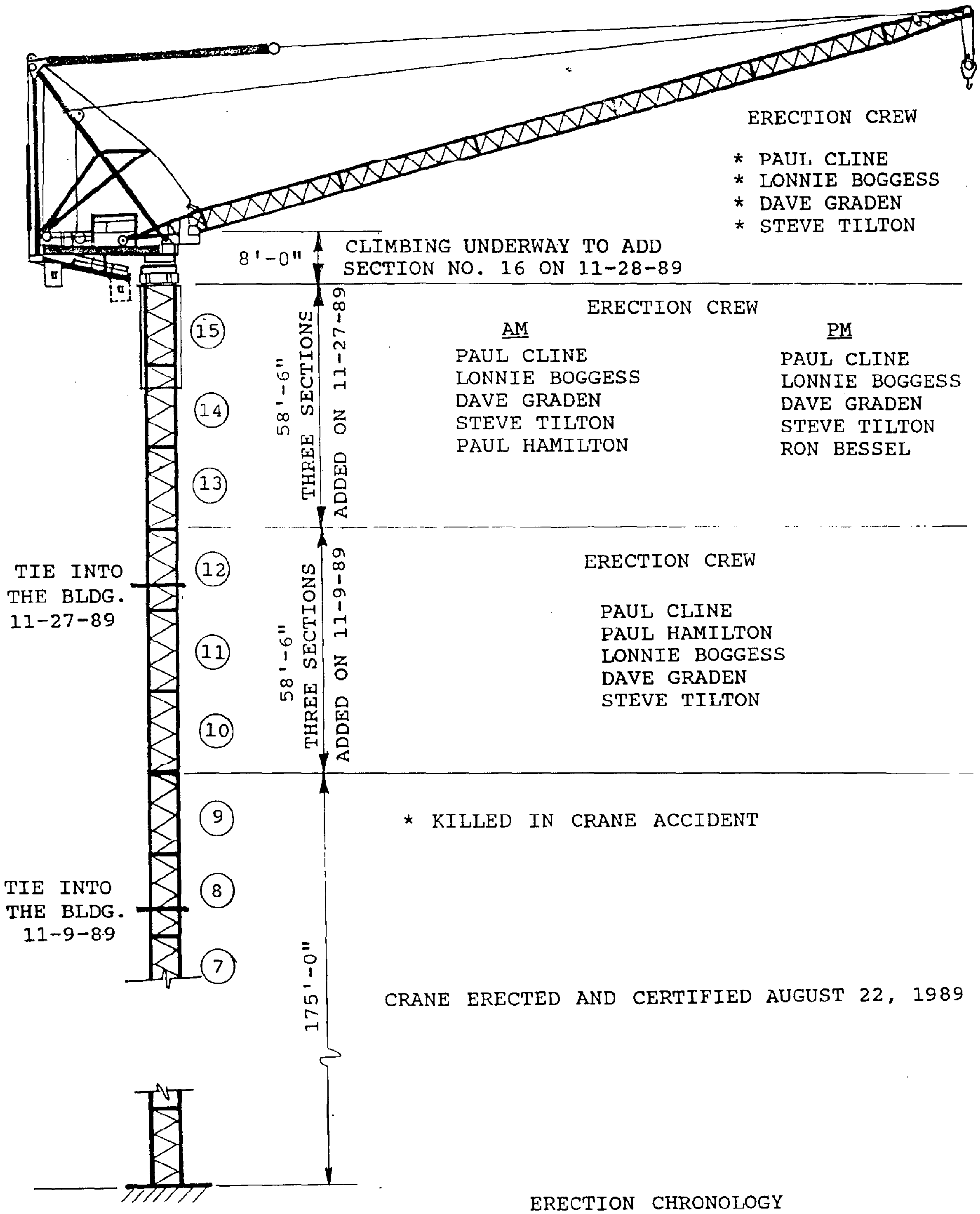
DIMENSIONS AND STRUCTURAL PROPERTIES
OF THE COLUMN MEMBERS

	Web		Flange		Area	Axis x-x		Axis y-y	
	Depth	Thickness	Width	Average Thickness		I	Z	I	Z
Location	in.	in.	in.	in.	in^2	in^4	in^3	in^4	in^3
Tower Section	8.66	0.59	8.11	0.98	20.31	255.63	67.65	87.69	32.74
Climbing Section SE & SW Legs	6.30	0.31	6.30	0.51	8.42	59.82	20.79	21.36	10.26
Climbing Section NE & NW Legs	7.87	0.35	7.87	0.59	12.11	136.94	37.88	48.05	18.53

TABLE 3.1.2 (Continued)

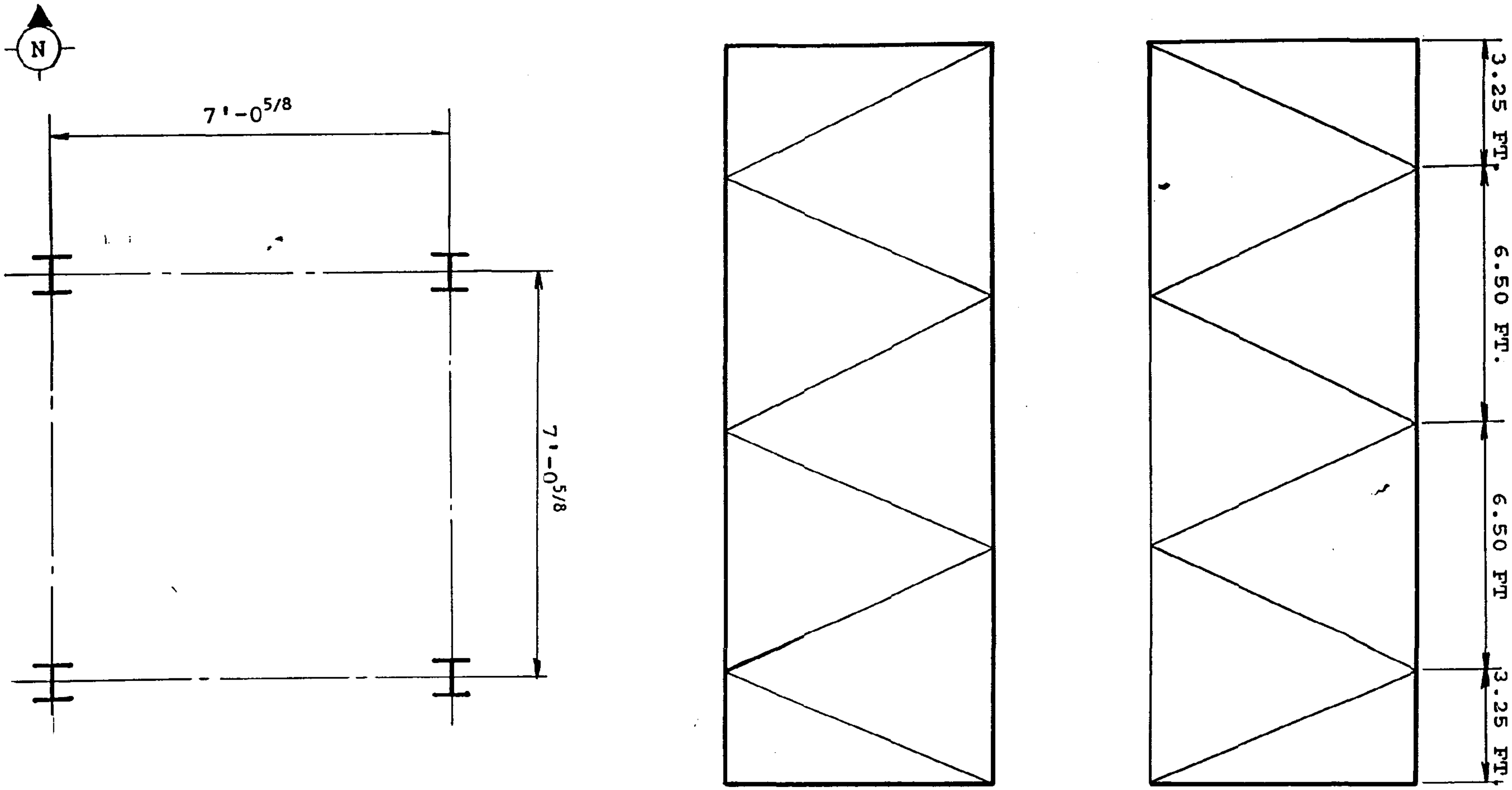
DIMENSIONS AND STRUCTURAL PROPERTIES OF THE DIAGONAL BRACING MEMBERS

Location	Inside Diameter (in)	Outside Diameter (in)	Area (in^2)	I (in^4)	Z (in^3)
Tower Section	2.64	3.43	3.76	4.41	3.66
Climbing Section OD = 3.0"	2.50	3.00	2.16	2.06	1.90
Climbing Section OD = 3.5"	3.00	3.50	2.55	3.39	2.65
Climbing Section OD = 4.2"	3.58	4.20	3.79	7.21	4.70



ERECTION CHRONOLOGY

FIGURE 3.1.1

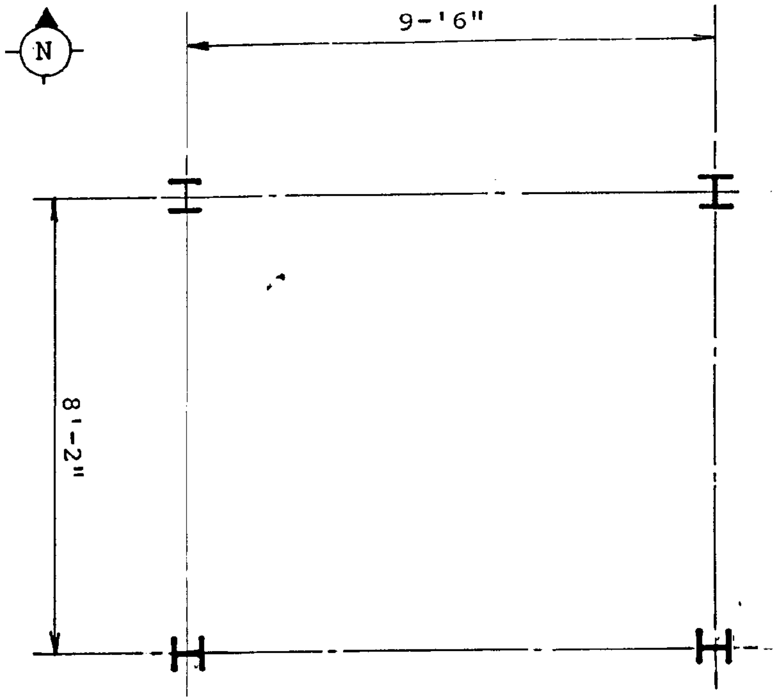


PLAN OF TOWER

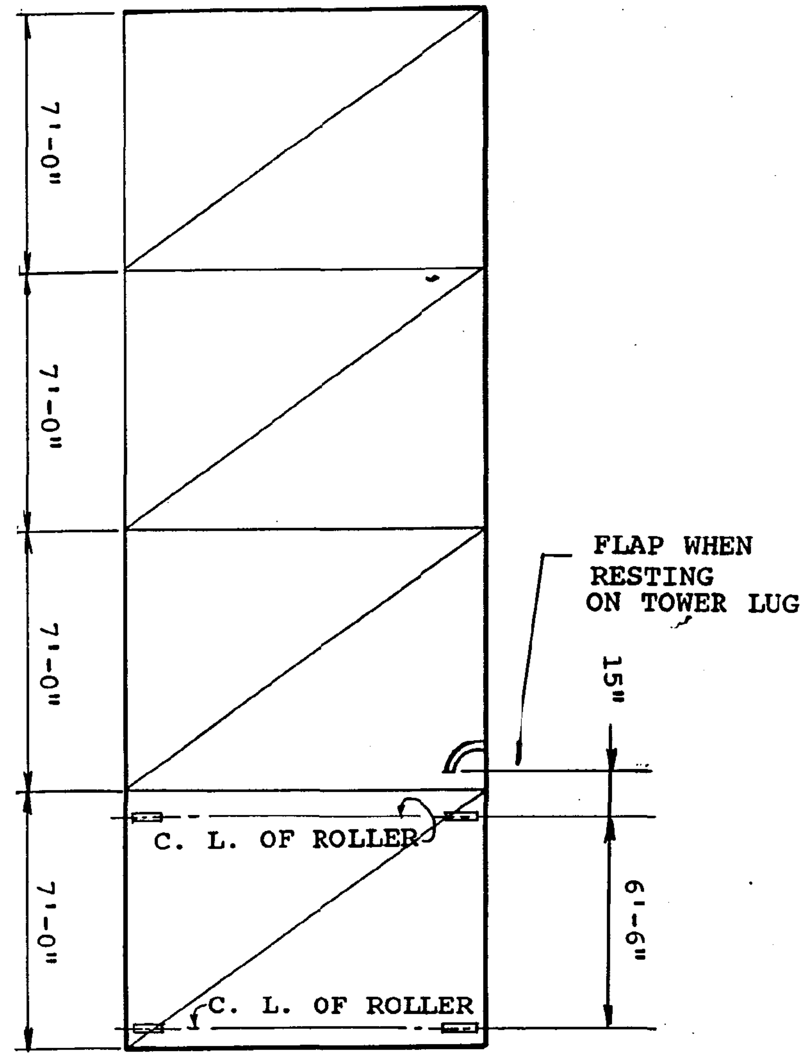
ELEVATION
SOUTH AND WEST FACES
TYPICAL TOWER SECTION

ELEVATION
NORTH AND EAST FACES
TYPICAL TOWER SECTION

FIGURE 3.1.2

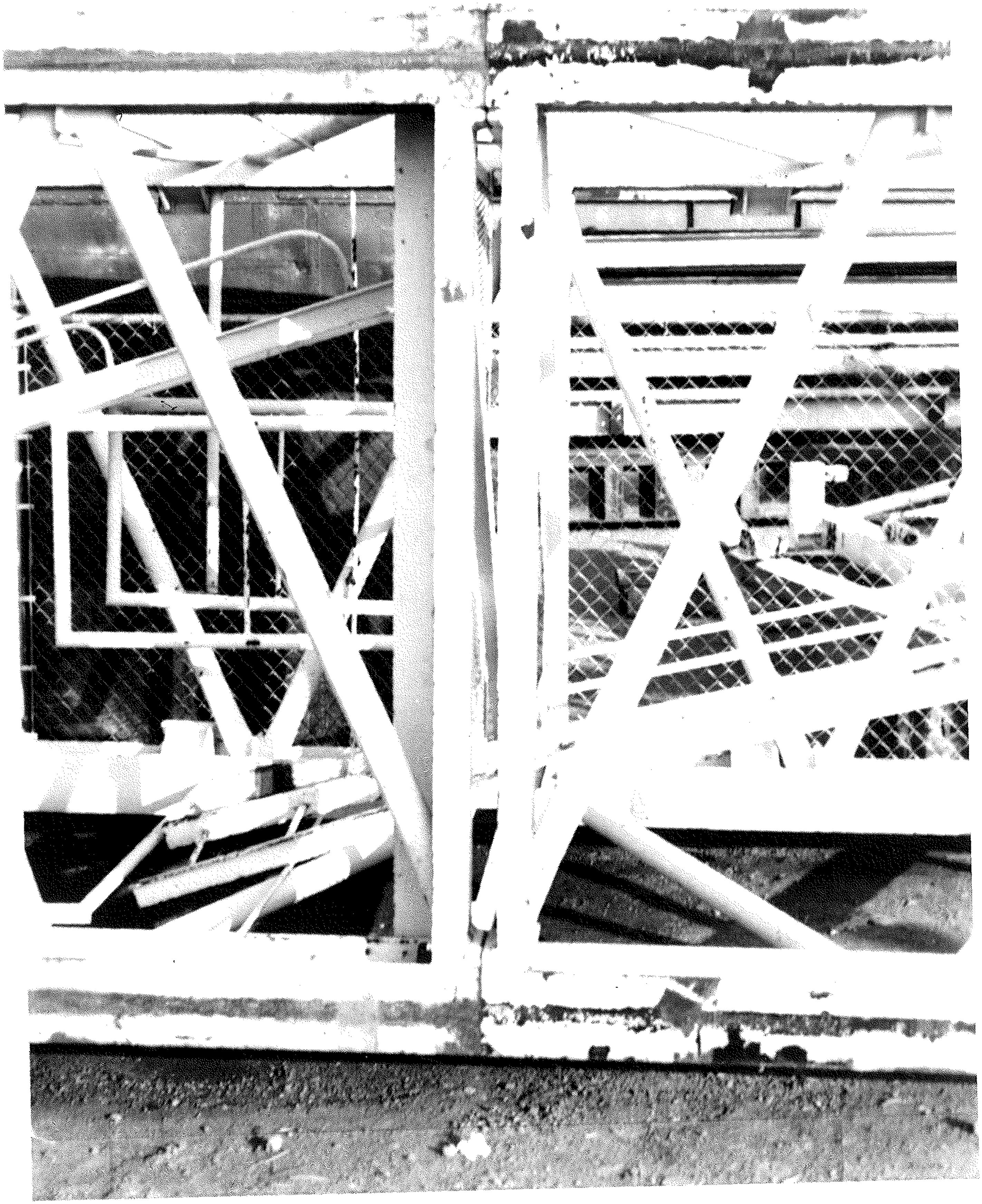


PLAN OF CLIMBING SECTION



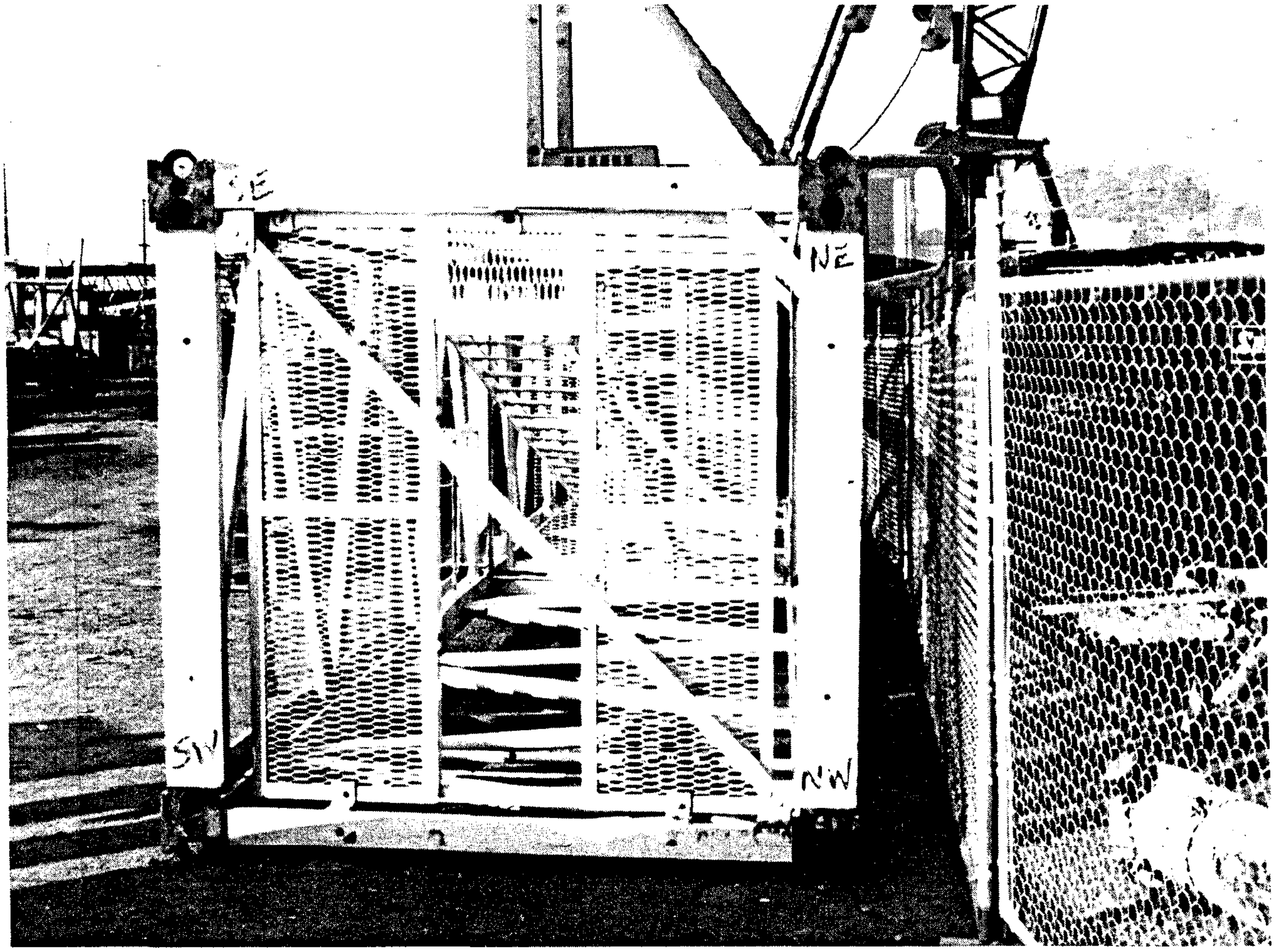
ELEVATION OF THE CLIMBING SECTION
EAST FACE

FIGURE 3.1.3



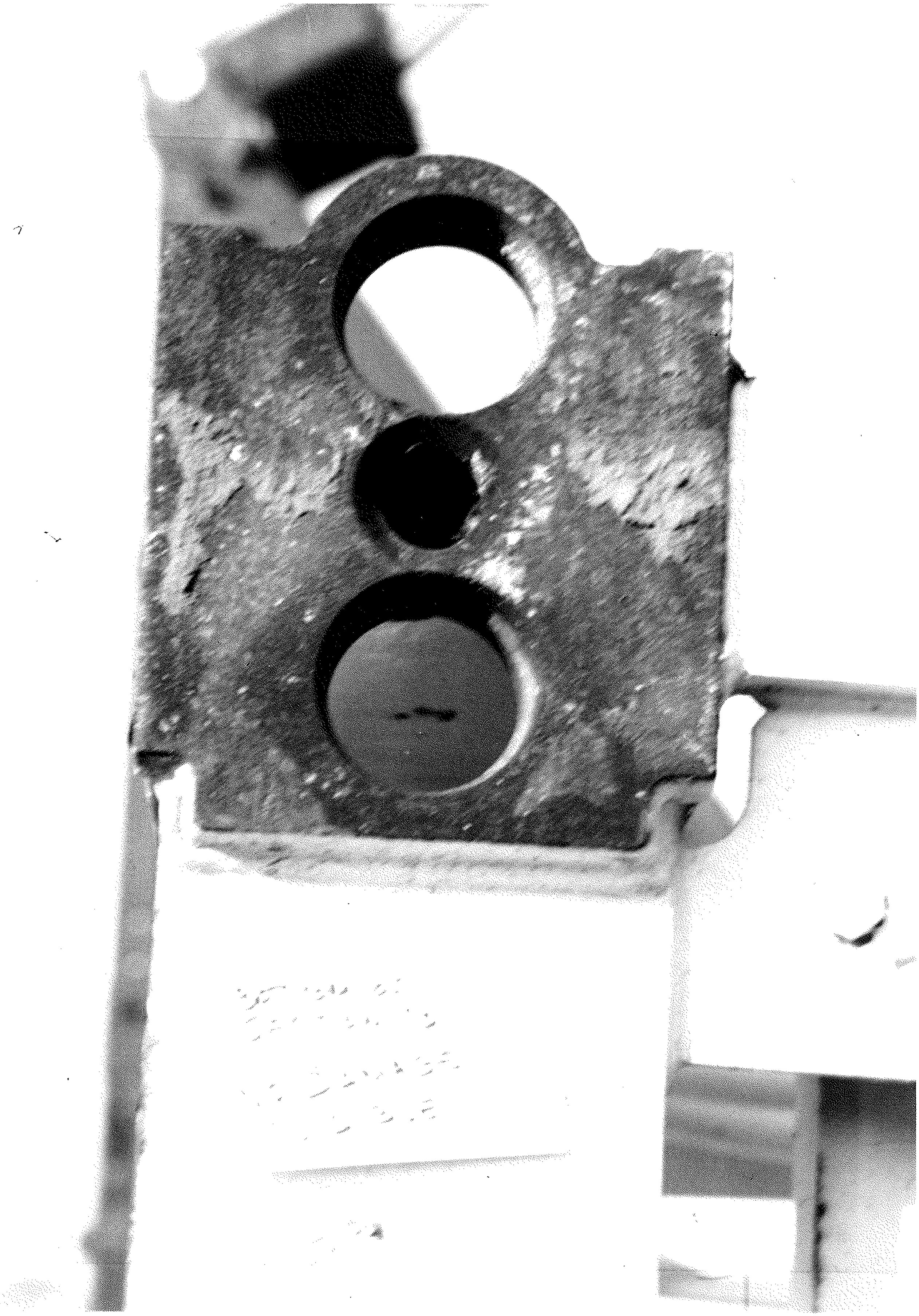
Typical bolted connection between two tower sections.

Figure 3.1.4



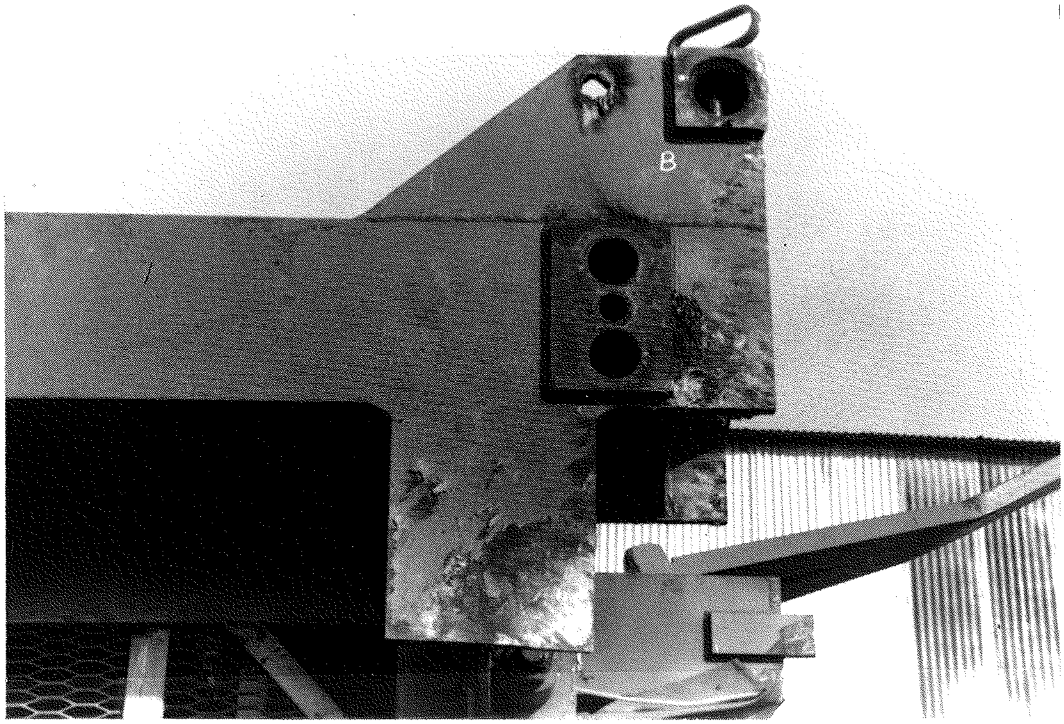
Typical tower section — viewed from the bottom.

Figure 3.1.5

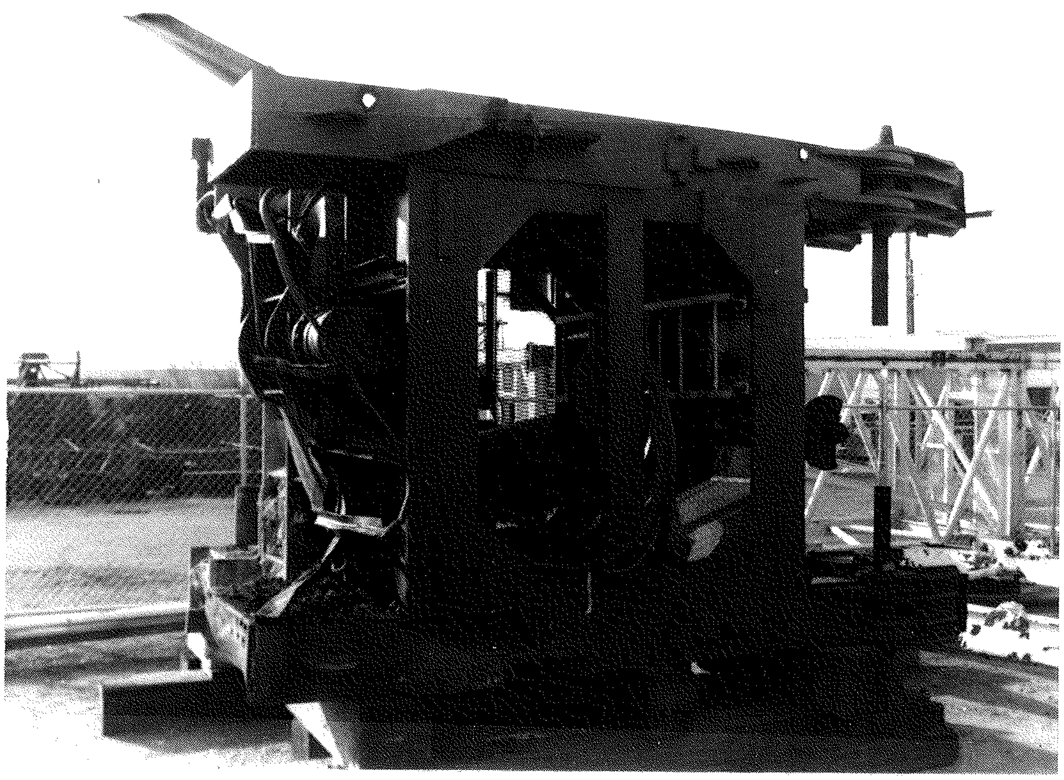


Typical bottom end plate of tower section.

Figure 3.1.6

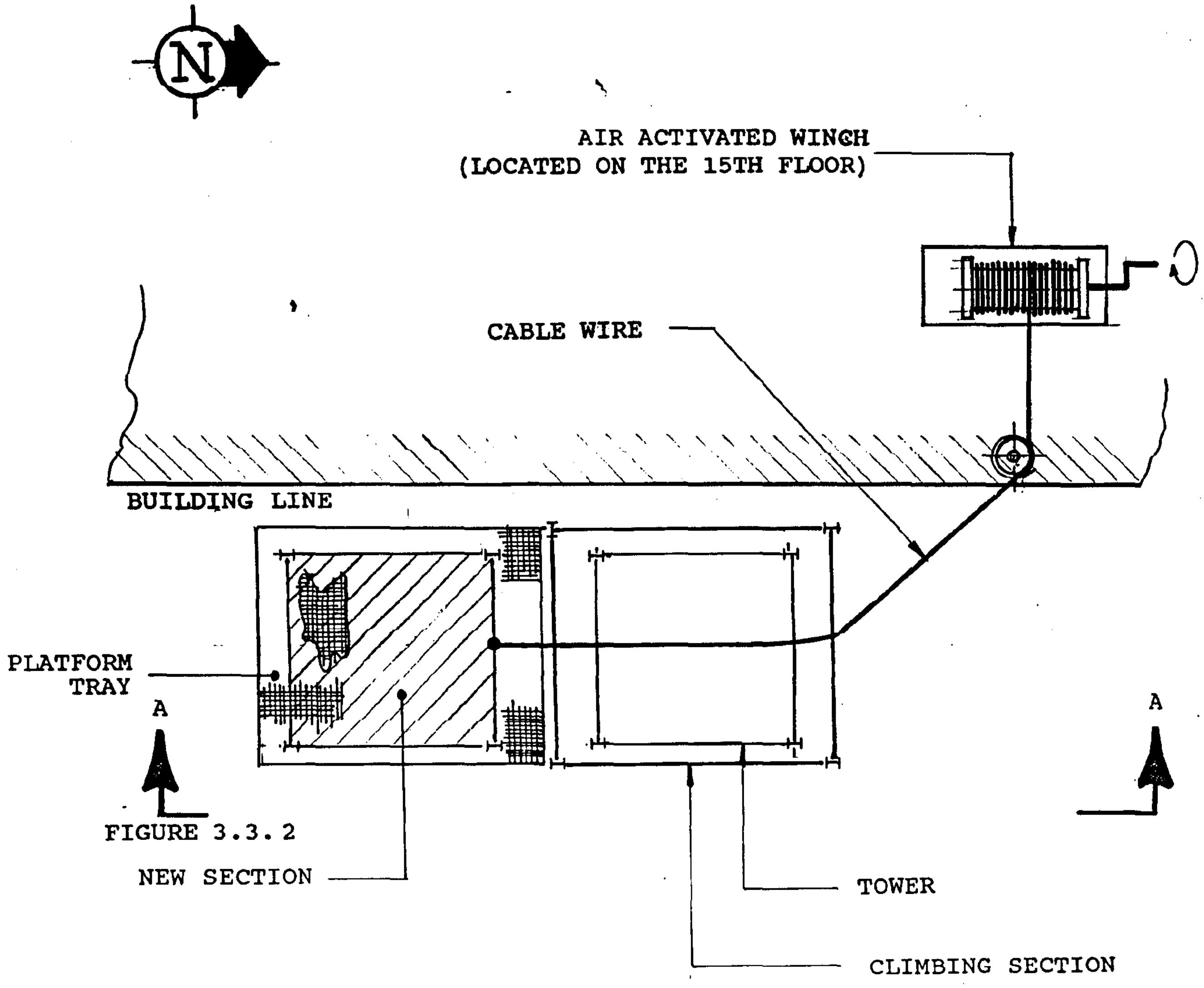


Underside of turntable. Single pin-hole for climbing section, double pin-hole for tower section.



Turntable — viewed from the top.

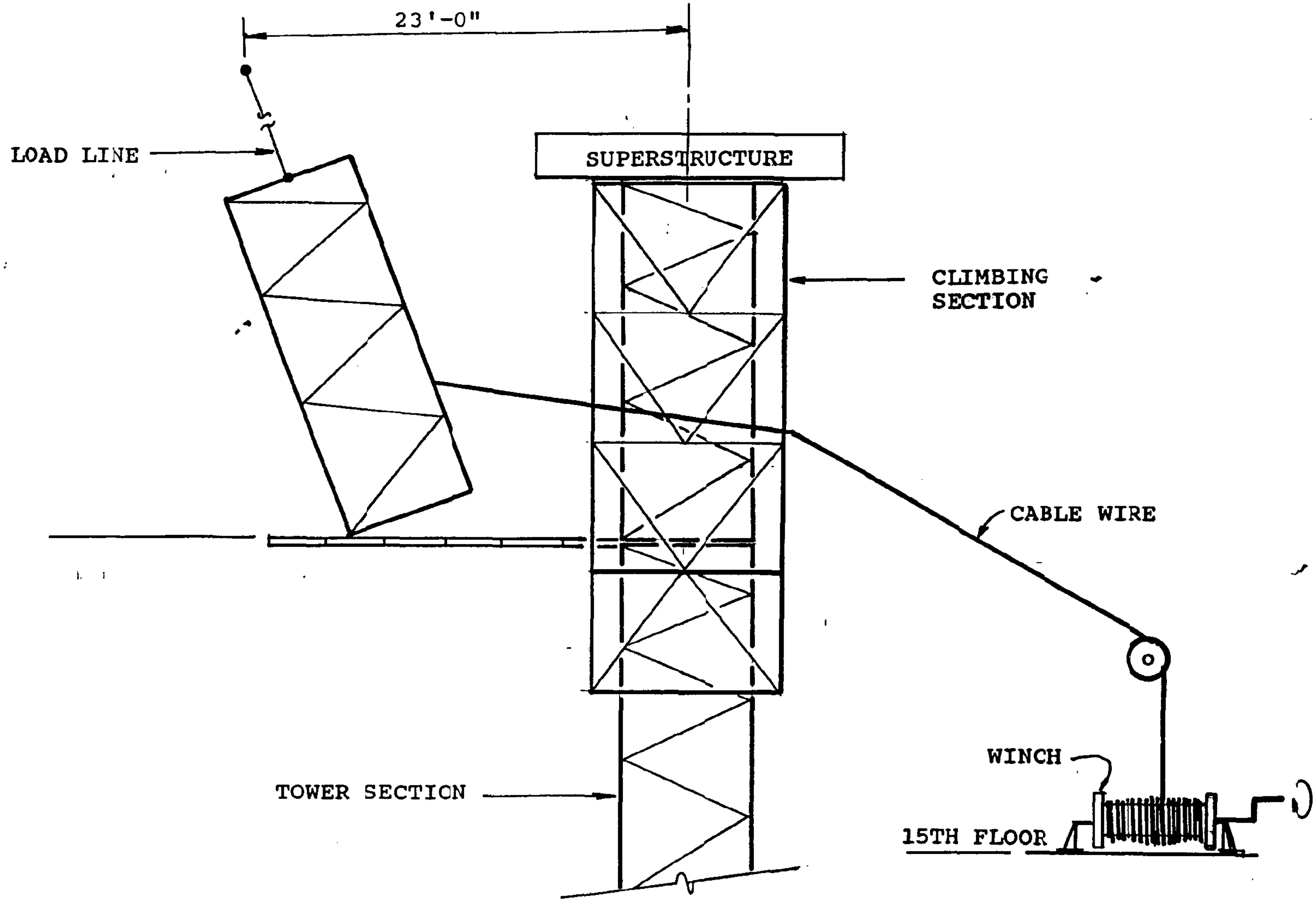
Figure 3.1.7



PLAN VIEW

THE NEW SECTION ON THE CLIMBING PLATFORM

FIGURE 3.3. 1

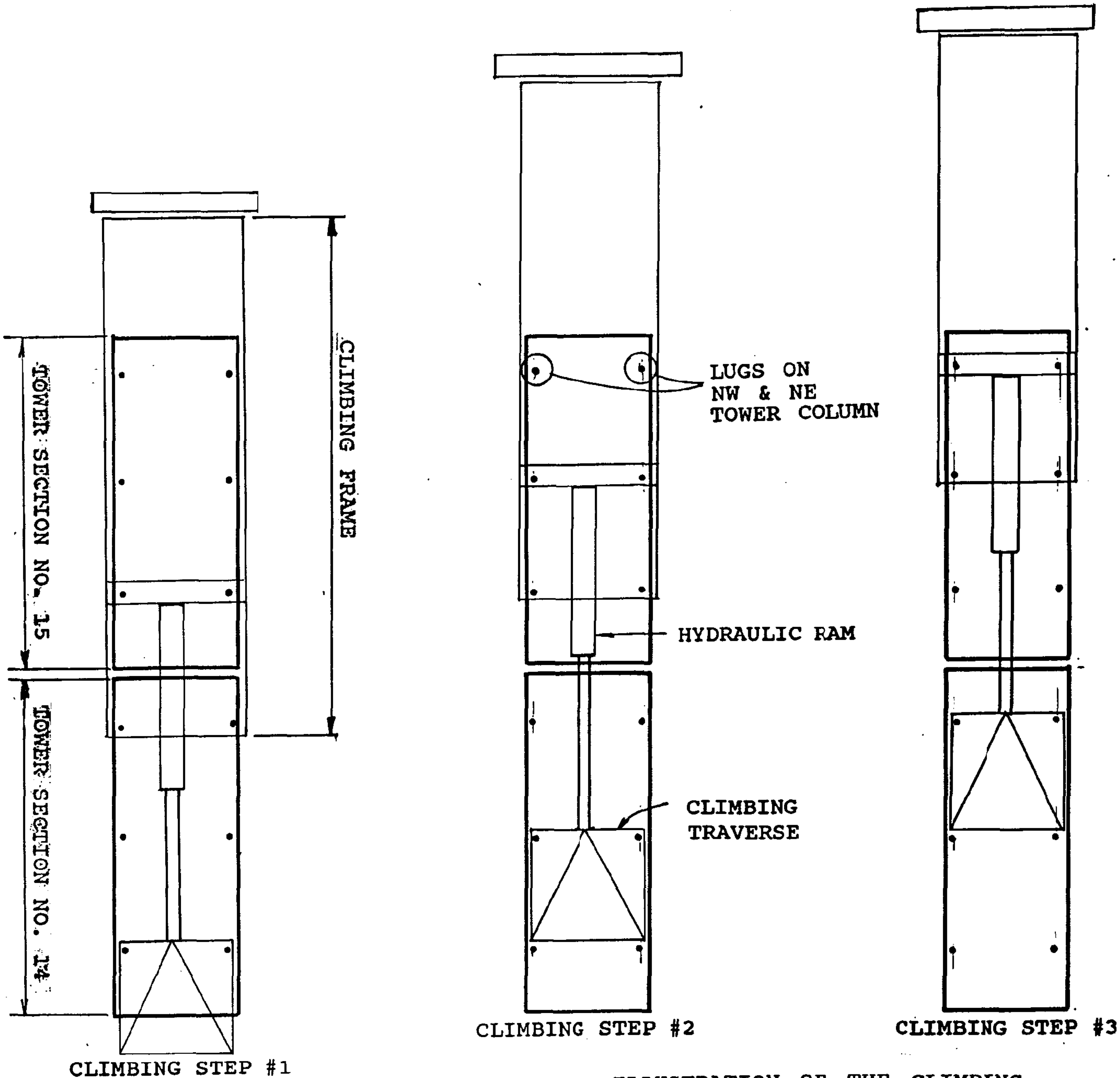


ELEVATION A-A

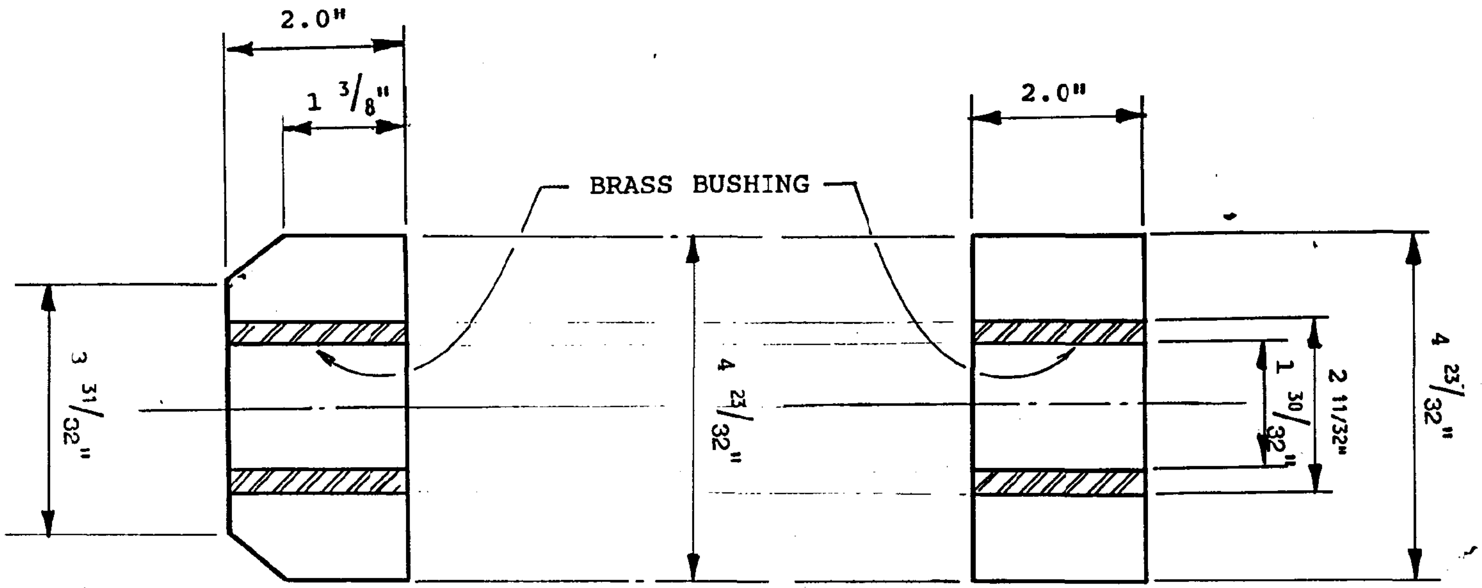
POSITIONING OF NEW SECTION ON THE CLIMBING SECTION PLATFORM

LOOKING WEST

FIGURE 3.3.2



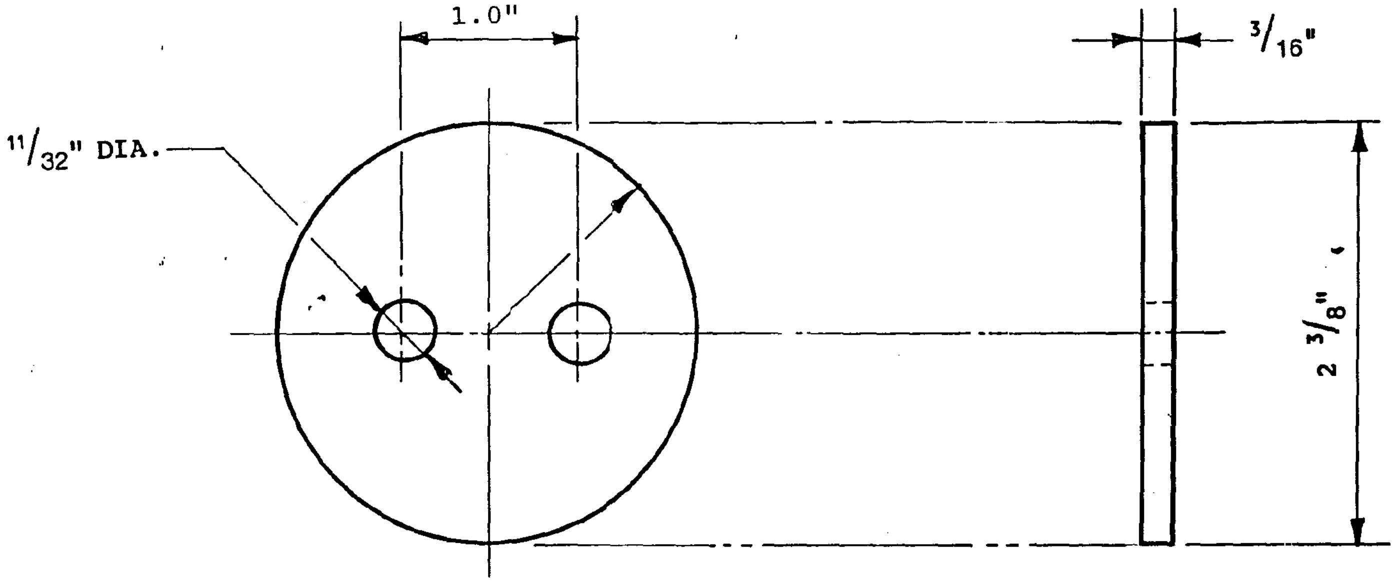
SCHEMATIC ILLUSTRATION OF THE CLIMBING
PROCESS ON 11-28-89
FIGURE 3.3.3



TYPICAL EDGE ROLLER
CROSS SECTION

TYPICAL FLANGE ROLLER
CROSS SECTION

FIGURE 3.4.1



TYPICAL RETAINING PLATE AND BOLT FOR THE ROLLERS

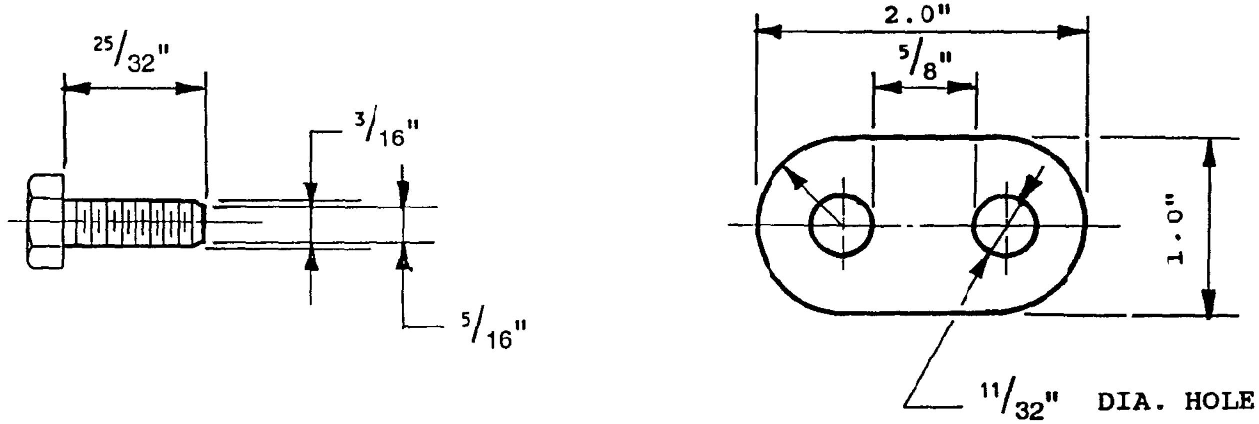


FIGURE 3.4.2

4. DESCRIPTION OF THE FAILURE

4.1 Background

Eyewitness accounts of the sequence of events associated with the collapse and descriptions of the collapsed structure are presented in this chapter. This information was used in determining the cause of the collapse as described in Chapter 7.

4.2 Eyewitness Accounts of Failure

A total of 96 persons were interviewed to obtain information about the failure. This included workers on the site, individuals on the street or in adjacent office buildings and others not at the site who had knowledge of the tower crane and work practices followed in operating the crane. Most of the interviews were conducted within one month of the accident. These interviews were conducted by the Bureau of Investigation, Department of Industrial Relations, State of California and some of the eyewitnesses were later reinterviewed by OSHA staff to obtain additional information and clarify portions of their original statements. This section summarizes the witness observations.

Some witnesses were casually observing the crane operations prior to the failure, others began to observe it when it became clear that something out of the ordinary was happening. Many of the witnesses, however, did not observe the events immediately preceding the failure or the initial stages of the collapse. Also, they were only able to provide general descriptions of the collapse and not details useful in determining the cause of the failure. Eighteen individuals were able to describe the event in some detail. The locations of these individuals are shown in figure 4.2.1. Most of the eyewitnesses were in office buildings adjacent to the site. A summary of their statements is presented in table 4.2.1. The dates the interviews were conducted are also given in the table.

The ten eyewitnesses in table 4.2.1 in adjacent buildings had unobstructed views of the upper portion of the crane, the turntable, climbing section and tower structure. Using an assumed average story height of 12 feet for the office buildings, the elevation of each witness relative to the top of the crane (top of the turntable) which was 285 feet above street level can be determined. Witness no. 2 in table 4.2.1, for example, on the 30th floor, was approximately 75 feet above the level of the turntable looking down on the structure. Witness no. 4, on the other hand, was approximately 55 feet below the turntable looking up at the top of the structure. The estimated line of sight distance in table 4.2.1 is the distance measured along a straight line from the witness location to the turntable or top of the structure.
The remaining seven witnesses listed in table 4.2.1 were on the construction site and had varying views of the crane at the time of

the failure. Witness no. 4 involved with the climbing procedure was the closest person to the crane at the time of the accident and was able to provide important information on the activities underway and the behavior of the structure.

The summary of the key eyewitness statements in table 4.2.1 presents the highlights of the interviews. It includes information on the activities immediately preceding the collapse and the behavior of the structure during failure. The highlights presented were taken directly from the witness statements. No attempt was made to interpret the witnesses remarks. An attempt was made, however, to determine the sequence in which the witnesses observed the events. In some cases, this was not clear from the interview and some witnesses were reinterviewed. In reviewing the statements in table 4.2.1, the time period referred to by the witness is important. Witness no 2, for example, was observing the operations over a period of time preceding the collapse. The statement by witness no. 5, however, refers to the events at the time of failure.

The witness statements provide information on: (1) the activities underway on the crane prior to the collapse, (2) the behavior of the structure during the time leading up to the collapse, and (3) the mode of failure of the tower structure. Activities underway on the crane were described by witnesses nos. 2 and 25. Witness no. 2, noted the boom was initially parallel to the building under construction pointing south with counterweights on the north side of the tower. The boom had been raised and there was no load on the hook. A number of witnesses confirmed this orientation of the boom. Witness no. 2, then noted that someone climbed up to the turntable and after looking in the cab went to the control panel cabin (relay room). An individual came out of the control panel cabin (presumably the crane operator), they talked briefly, the workman climbed down to the climbing section and the operator went back to the control panel cabin and then to the cab.

Witness no. 2 places the operator in the cab before the crane started to rotate. Three witnesses, nos. 17, 19 and 25, place the operator in the cab during the rotation. Witness no. 5 did not see anyone in the cab during the rotation. Witness no. 17 notes that he was moving his hands while in the cab. At some time prior to the collapse, he was observed trying to push his way out of the cab. Witness no. 25 also saw him seated in the cab, then stand up quickly after looking down at something the workmen on the climbing section were observing. One witness, no. 31, not listed in table 4.2.1 placed the operator in the cab prior to the failure. Two witnesses, nos. 8 and 45, indicated they did not see anyone in the cab. Unfortunately, they did not indicate at what point during the rotation of the crane they observed this. Witnesses nos. 6 and 45 place the operator on the turntable holding onto a rail as the crane was collapsing. These observations are not necessarily contradictory since the operator could have left the cab at some time during the crane's rotation, probably after sensing some problem.

Witness no. 4 was on the 16th or the 17th floor of the building under construction and was in direct communication with the crane operator through the two-way radio and with the climbing crew on the climbing section platform. He was about 85 feet from the operator's cab and 55 feet from the climbing section platform. This witness reported a hydraulic leak on one of the top fittings of the ram before the climbing operation started. This leak also occurred the day before during climbing. He indicated that a metallic sound indicative of "rubbing" of metal surfaces was coming from the climbing section during the climbing of the tower. This sound gradually increased and became intense during the last climbing step. He indicated that the crew raised the tower to the desired elevation and the lift was almost complete. He indicated that a few minutes before the completion of the third climbing step, the operator luffed the boom up to correct the "leaning of the tower towards the south". This witness, at the time of the collapse, did not talk to the crane operator or the climbing crew on the platform as he was engaged in conversation on the radio with a different party on the ground.

There was general agreement among the witnesses on the behavior of the crane leading up to the collapse. Nine witnesses indicated they observed the crane rotating counterclockwise, one witness observed it rotating clockwise. Witness no. 25 indicated he observed no rotation. It is possible that his observation of the crane was limited to the time just prior to the collapse when the boom had rotated around and struck tower section 16 which was resting on the climbing section. Six eyewitnesses indicated they observed the counterweights striking the new tower section. The rotation of the crane was a steady, normal, uniform movement. No one observed any acceleration or deceleration of the turntable. In addition, the turntable appeared to remain horizontal during rotation. Given the witnesses were all at least 80 feet from the crane, the turntable could have tilted and gone unnoticed.

Six witnesses provided details of the collapse. All six indicated the crane fell in a southerly direction after the counterweights struck tower section 16 resting on the climbing section. Some statements were made about the southwesterly column failing first and the crane tilting in a southerly direction acting like it was hinged. Also, that there was a tension failure of two north face legs, e.g., witness no. 6. Witness no. 22 noticed a "piece of iron" flying through the air at the time of the failure and saw one of the erection crew falling with the debris at the same time. The piece of iron, which was later determined to be a roller guide from the climbing section, landed on the 17th floor.

One witness, no. 32, not listed in table 4.2.1 as an eyewitness, indicated that the slewing brakes were adjusted by the personnel of the steel erection company a week before the collapse because they were "overheating, too tight and grabbing." He said that Pecco's representative came and checked the adjustment.

4.3 Observations of Collapsed Structure

Observations of the collapsed structure provided information on the failure mechanisms of the structure. This information was correlated with the witness observations and was helpful in identifying the sequence of the failure. This information was also used in determining the cause of the failure.

4.3.1 Overall Collapse

The failure of the tower crane occurred at about 8:10 a.m on November 28, 1989. The entire crane superstructure fell in the southeasterly direction. A general view of the debris after the collapse is shown in figure 4.3.1. The location of various pieces of the structure is shown in figure 4.3.2. The locations in figure 4.3.2 are based on early photographs of the accident scene, before any clearing of the debris. A portion of the crane tower, e.g., climbing section, tower section 15, some components of tower section 14, tower section 16 and the climbing traverse fell on Kearny Street. A majority of the crane superstructure also landed on Kearny Street. Some parts of the crane superstructure landed on California Street and on the 18th level of 600 California Street and the roof of 601 California Street.

During the collapse, a number of buildings were damaged due to the impact of portions of the collapsing structure. The cornice of the building at 601 California Street was damaged by the luffing boom tip and load blocks; the building at 580 California Street was damaged by the climbing section, the structural steel frame of the building under construction was damaged by various parts of the crane superstructure. In addition, the paving of Kearny Street and the roof of the underground garage on Kearny Street were damaged.

Five bodies were recovered from the debris which included the body of the driver of a bus hit by the falling heel section and lower gantry support. Four bodies were from the erection crew. The body of the crane operator was recovered in the vicinity of the smashed operator's cab. It could not be ascertained whether the body was removed from inside the operator's cab or outside the cab.

4.3.2 Tower Structure

The locations of the failures in the tower structure, tower sections 15 and 14, are shown in figure 4.3.3. The remaining portion of the failed tower is shown in figures 4.3.4 and 4.3.5. Section 14 is the uppermost section in these photographs. The southwest leg of tower section 14 was fractured about 3 feet-4 inches below the top while the southeast, northwest and northeast legs fractured through the four inch thick plate welded to the top of the legs of section 14. These plates serve as connection plates between two tower sections. Figure 4.3.6 shows the fracture surfaces for this southwest leg. The top lug of the northwest leg of tower section 14 showed signs of bearing type deformation. Similar distress was observed in the northwest dog of the climbing traverse and will be discussed later in this section.

Figures 4.3.7, 4.3.8 and 4.3.9 show the fracture surfaces for the southeast, northeast and northwest legs. The location of the failed diagonals of tower section 15 and 14 are shown in figure 4.3.10. The other diagonals in tower section 15 and 14 remained intact.

The tower sections below section 14 were examined to determine if any permanent deformation occurred due to the collapse. All the sections appeared to have remained elastic. The two lateral ties to the building under construction and their connections were reportedly free from any signs of distress prior to disassembly and removal to the storage yard.

4.3.3 Tower Section 16

Tower section 16, located on the platform of the climbing section prior to collapse, landed on Kearny Street with its top facing in a northerly direction. The north face of tower section 16 was in contact with the paving. Figure 4.3.11 shows the deformed shape of tower section 16 subsequent to the collapse.

Most witnesses indicated that the counterweights hit tower section 16 as the crane rotated prior to the collapse.

There was a deep indentation on the southeast corner of the south flange of the northeast leg of tower section 16 and there was blue paint over it. The crane superstructure was painted blue. This indentation was located about nine feet above the base of the section. This could not have been made by the counterweights as the west face of tower section 16 would come in contact with the counterweights. This indentation is believed to have been made on the street by the edge of the turntable. The edge of the turntable was lying very close to the northeast leg of tower section 16.

Tower section 16, as shown in figure 4.3.11, has been deformed with the diagonals buckling predominately in the east and west faces. No significant mark with blue color was observed on the west face of the tower section 16 where the witnesses reported seeing the counterweights strike the section.

4.3.4 Climbing Section

The climbing section landed on the east sidewalk of Kearny Street, leaning against 580 California Street in an upright position. The west face of the climbing section was parallel to the 580 California Street building and the north face was towards California Street, i.e., the climbing section rotated approximately

180 degrees. During the fall, the climbing section hit the facade of 580 California Street but damage was limited to breakage of window glass, deformation of window framing and the building facade. The climbing traverse and the hydraulic ram were no longer attached to the climbing section. They were lying near the climbing section.

None of the four columns of the climbing section were fractured. The northwest and southwest columns were bent substantially. The southwest column was torsionally deformed. The northeast and southeast columns also showed signs of twisting and bending. Figures 4.3.12, 4.3.13, 4.3.14, and 4.3.15 show the deformed shape of the northeast, southeast, southwest, and northwest columns of the climbing section. The four guide pins at the top of the columns of the climbing section were sheared and bent toward the north as shown in Figure 4.3.16. All 1-1/2 inch ϕ pins were found in place except one which was sheared off.

The horizontal member at the upper level of rollers on the south face of the climbing section was deflected downward. The horizontal member at the lower level of rollers remained essentially straight. On the east face, the horizontal member at the upper level of rollers had an outward deflection away from the center of the climbing section of about one inch measured in a horizontal plane. The member at the bottom level of rollers on the east face had deformations believed to have been caused by impact. On the west face, the horizontal member at the upper level of rollers remained essentially straight but the horizontal member at the lower level of rollers had an upward deflection of about three inches. This deflection could have been due to impact. On the north face, the horizontal member at the upper level of rollers did not deform. The horizontal member at the lower level of rollers on the north face, however, had deformed in a vertical plane. Figure 4.3.44 shows the deformed climbing section after the collapse.

4.3.5 Climbing Section Rollers

Out of the sixteen rollers, four were not attached to the climbing section after the collapse. All four rollers were the edge rollers meant to roll on the edge of the flanges of the tower columns. One of the rollers was found on the 17th floor by Witness no. 22. The other three rollers were found among the debris on Kearny Street. Figure 4.3.17 provides a description of the marks and deformations of the upper level rollers. Figure 4.3.18 describes the lower level rollers. Figures 4.3.19, 4.3.20, 4.3.21, 4.3.22 and 4.3.23 show the marks and indentation on the rollers detached from the climbing section. Figures 4.3.24, 4.3.25 and 4.3.26 indicate the marks and indentations of the rollers found in place on the climbing section. Further discussion of the rollers is contained in Section 4.3.6 and in Chapter 7.

4.3.6 Tower Section 15

Tower section 15 was found lying on Kearny Street in close proximity to the climbing frame. The top of tower section 15 was underneath the climbing frame, pointing towards the east and the bottom part of tower section 15 was towards the building under construction. The south face was up and the west face was facing north. Section 15 separated from section 14 by fractures through the plates welded to the top of the tower section 14 columns at the northeast, northwest and southeast corners. The fracture at the southwest corner in the leg of tower section 14 was about 3 feet-4 inches below the top of the section.

Figures 4.3.27, 4.3.28 and 4.3.29 and 4.3.30 show the fractures in the tower legs. The northeast, southeast and southwest legs of the tower section fractured at different locations. The southeast and southwest legs fractured at the location where two diagonal members are welded to the flange. The northeast leg sustained a partial fracture through the south flange and the web only. This fracture also occurred at a section where the two diagonals are welded to the south flange of the northwest leg. The northwest leg did not fracture.

Figure 4.3.3 indicates the points of failure in the legs of tower section 15. Most of the diagonals in the east and west face of tower section 15 fractured. A few fractured on the north and south face. Figure 4.3.10 shows the location of the fractured diagonals of tower section 15. The northwest leg of tower section 15 deformed toward the south bending uniformly along the length about the major axis. The deflected shape, based on the field measurement is shown in figure 4.3.31. The northeast leg also deformed below the fracture toward the south. The deflected shape, based on the field measurement is shown in figure 4.3.32. The deformations of the southeast and southwest legs are shown in figures 4.3.33 and 4.3.34. Figure 4.3.45 shows the diagonal failures.

There was extensive damage to the edges of the flanges of the legs of tower section 15. All four legs sustained damage. Figures 4.3.35, 4.3.36, 4.3.37 and 4.3.38 show the deformations observed on the edge and the face of the flanges of tower section 15.

The west edge of the south flange of the southwest leg had an indentation beginning at 2 feet-6 inches from the bottom and ending at about 9 feet-6 inches from the bottom. This indentation is marked (A) on figure 4.3.35. The depth of this smooth bearing type deformation increased with the height along the section. The last six inches exhibited the greatest deformation. The nature of the indentation was such that it indicated a uniform increase in bearing stress from the bottom to the top. The smooth uniform indentation was an indication it occurred while the climbing section was ascending. The surface was free of any scaling or galling, indicating that the identation was caused by rolling and not sliding. Further, one of the detached edge rollers had a profile matching the indentation at the point of maximum deformation of this leg and, therefore, could be identified as the lower southwest edge roller. The upper southwest edge roller did not have any markings that were clearly correlated with these deformations. These deformations, therefore, could have only been made only by the lower southwest edge roller. Because of the continuity of the deformation on either side of the fracture, it was clear the fracture of the southwest leg of tower section 15 took place after the deformations were made.

Other damage to the edge of the flange of the southwest leg occurred at about 9 feet-9 inches from the top marked (B) in figure 4.3.35. There was flattening of the flange edge and a cut extending downward. A portion of the flange sheared in a downward direction toward the web side. The indentations on the flange edge are close to the web of the section. This marking was very similar to the deformation found on the lower southwest edge roller. The direction of the cut was such that it could only have been made while the roller was forced downward. A similar marking was not found on the upper southwest edge roller. It was, therefore, concluded that markings (A) and (B) were made by the lower southwest edge roller. Additional marks pertaining to the southwest leg of section 15 are explained in figure 4.3.35. Figure 4.3.37 shows the marks (A) and (B). The roller came off the shaft at the end of mark (B) after the downward motion of about three inches at a distance of 10 feet from the top of section 15.

Figure 4.3.36 shows the deformation of the northwest leg of section 15. The north flange of the northwest leg also sustained damage indicative of a bearing type failure at the west edge.

At eleven feet from the top, on the deformation on the west edge of the flange towards the web occurred. A bearing type depression and indentations was noticed on the underside of the flange, see figure 4.3.48. The form of this deformation corresponded to the configuration of markings on one of the detached rollers. Consequently, the lower northwest edge roller was positively identified. Further, the bushing inside the roller was noticed to have shearing and galling marks in the longitudinal direction indicating that damage was due to axial movement and not rotation of the roller. The marks on the bushing suggested that load was applied to the roller along its shaft resulting in failure of the bolts securing the retaining plate of the roller. This deformation on the flange edge is indicative of the location where the lower southwest edge roller came off the shaft. This deformation toward the web is indicative of counterclockwise movement of the turntable. Another deformation of the flange at about ten feet from the top of the section (see figure 4.3.49) occurred. This deformation indicated that the lower northwest edge roller was applying a high intensity force at an elevation of 10 feet from the top before being displaced at a point 12 inches below following a downward motion.

A number of deformed areas were found on the east edge of the north flange of the northeast leg of tower section 15. Figure 4.3.37 shows these deformations. About 2 feet-8 inches from the top, a flattened surface toward the web occurred on the flange edge extending for about four inches (see figure 4.3.50). The greatest deformation occurred slightly below the top and the severity appeared to decrease toward the bottom. Markings on the upper northeast edge roller conformed to the configuration of the flange edge deformation and could be positively identified as the source of the extreme load applied to the flange edge. Further, this was the only detached roller without a brass bushing. The brass bushing remained on the shaft. A few inches above this location, a semicircular bearing type impression occurred on the north flange. There were other smooth deformations on the flange in a direction away from the web, indicative of counterclockwise movement. There are no indications on the flanges that show either of the two rollers were displaced.

The southeast leg also sustained indentations on the edge of the flange. Figure 4.3.38 shows these indentations. At a section 3 feet-2 inches from the top, a bearing type deformation occurred on the east edge indicative of counterclockwise movement (see figure 4.3.51). This indentation was towards the web. The deformation matched very closely with markings on the upper southeast edge roller. This was at the level where the upper edge roller would be located at the end of the third lift of the climbing frame. At about 4 feet-9 inches from the top for a length of 6 feet-9 inches, there is a linear flange distortion on the east edge. Further discussion of the deformations are contained in Chapter 7.

4.3.7 Climbing Traverse

The climbing traverse and the hydraulic ram hit the bus in the east curb lane of Kearny Street during the collapse. They landed on the east sidewalk of Kearny Street at an angle of 45 degrees with the traverse towards the southeast direction. No sign of any leaking fluid was found on the street or on the hydraulic ram. Figure 4.3.39 shows the climbing traverse and the hydraulic ram. The ram was fully extended and measured 18 feet from the center of the pin at the top and underside of the climbing traverse dog. The structural frame of the climbing traverse did not show any sign of distress. The northeast dog of the climbing traverse was undamaged but the northwest dog was bent away from the frame. The hydraulic ram was inclined about 7 degrees to the west due to the deformation of the plate connecting the hydraulic ram to the bottom pin of the climbing traverse (see figure 4.3.39). These deformations of the plate and the northwest dog were not likely due to the impact of the fall. Figure 4.3.40 shows the climbing traverse, the hydraulic ram and the elevation of the two lugs.

4.3.8 Boom

The boom fell backwards and broke into three pieces. The heel and section L1 remained connected with the turntable and landed on Kearny Street. The middle portion, sections L2, L3 and L4 hit the roofs of 600 California Street and 601 California Street and then fell on California Street at an angle of about 45 degrees. Figure 4.3.41 shows the boom and approximate location of the points of separation. Figure 4.3.42 shows the middle sections L2, L3 and L4 on the street. The tip and section L5 were connected together and were hanging with the wire rope from the roof of 600 California Street on the side of California Street. Figure 4.3.42 shows the tip and the boom section L5.

4.3.9 Turntable

The main turntable landed on Kearny Street in a southeast direction. The slewing assembly and the support frame was facing southwest. The tip of the turntable where the operator's cab is located was facing in southeast direction. The heel and section L1 of the boom remained connected to the turntable. The bottom part of the A-frame remained bolted to the turntable as well as the guide sheave frame. The turntable support frame is shown in figure 3.1.7.

4.3.10 A-Frame

The A-frame was found in two pieces. The first piece consisting of the vertical members and the top half length of the sloping members was found embedded on the 18th and 19th floor of the building under construction. The other piece consisting of the bottom half length of the sloping member was found on Kearny Street. The separation occurred at six places. The two connections of the vertical members of the A-frame to the turntable, the two connections of the sloping members to the turntable failed during the collapse. Also, the two sloping members separated at about midlength.

4.3.11 Guide Sheave Frames

The two guide sheave frames were generally intact and found on Kearny Street in close proximity of the turntable.

4.3.12 Miscellaneous

Figure 4.3.2 indicates the location of other parts. Figure 4.3.43 shows the damaged electrical control room.

4.4 Summary

The following summarizes the eyewitness accounts of the collapse and observations of the collapsed structure:

1. The climbing operation was underway and was nearly completed at the time of the collapse.

2. There was considerable noise coming from the climbing section during the last stages of the climbing operation prior to the collapse.

3. The crane operator was in the cab prior to, at the initiation of, and during some portion of the rotation of the crane that preceded the collapse.

4. The crane rotated counterclockwise prior to the collapse. The speed of rotation was reasonably uniform and the turntable appeared to remain horizontal.

5. The crane counterweights struck tower section 16 on the climbing section platform immediately prior to the collapse.

6. The tower leaned to the south and the northeast and northwest columns pulled apart.

7. All the fractures in the tower legs, i.e., section 14 southwest, section 15 southeast and section 15 northeast, occurred at sections where the diagonals were welded to the flange of the column. All fractures were brittle and showed no ductility.

8. The fracture in the top connection plates at section 14 southeast, section 14 northeast and section 14 northwest, lies in the plane containing the guide pins welded to the plate.

9. The collapse of the structure occurred generally in a southerly direction.

10. An extremely high load was applied by the edge rollers to the flange edges to create inelastic deformation during the third climbing step of the climbing section.

11. The climbing frame was not correctly positioned with respect to tower section 15, particularly, in the third jump. Bearing type deformations on the edges of the flanges were produced resulting in loud sounds heard by Witness no. 4, located closest to the climbing section. The sound, increased as climbing proceeded and became worse towards the end of the third jump.

12. The crane operator was asked to luff the boom up according to Witness no. 4 during or prior to the third jump to correct leaning of the superstructure toward the south.

13. The northwest and southwest columns of the climbing section were bent substantially toward the west.

14. The hydraulic ram was inclined about 7 degrees to the west due to the deformation of the connection plate to the bottom pin of the climbing traverse.

15. The northeast dog of the climbing traverse showed no signs of deformation. The corresponding northeast top dog of tower section 14 also showed no signs of distress.

16. The northeast dog of the climbing traverse showed flexural deformation. The corresponding northwest top dog of tower section 15 also showed a bearing type distress.

17. An extremely high load was applied by the upper southeast edge roller to the east edge of the south flange of the southeasterly leg of section 15 about 3 feet-2 inches from the top deforming the flange edge towards the web. This would be the general area where the upper roller would be located at or near the completion of the third jump.

18. An extremely high load was applied by the upper northeast edge roller to the east edge of the north flange of the northeast leg of section 15 deforming the flanges for about two inches toward the web at a height of 2 feet-8 inches from the top.

19. The missing upper northeast edge roller could be easily identified because its bushing remained on the upper northeast shaft. All other rollers were separated with their bushings. The configuration of the marks on the roller closely matched the flange deformation on the east edge of the north flange of the northeast leg of tower section 15 at 2 feet-8 inches from the top.

20. At another location, ten feet from the top, extremely high loads were applied by a roller to the west edge of the north flange of the northwest leg of section 15 causing deformation toward the flange. This would be in the vicinity of the location of the lower edge roller at or near completion of the third climbing step.

21. Extremely high loads were applied the lower northwest edge roller to the west edge of the north flange of the northwest leg of section 15 at eleven feet from the top causing indentations and deformation toward the west. The roller was forced off at this elevation after a downward motion of 12 inches from the elevation of 10 feet-0 inches from the top.

22. There were signs of axial movement along the shaft of the lower northwest edge roller because of longitudinal shearing marks and galling on the surface of the bushing at the elevation of 10 feet-0 inches from the top when the roller was forced off.

23. The lower northwest edge roller was positively identified by matching the configuration of the markings on the roller and the flange edge deformations at eleven feet from the top.

24. An extremely high load was applied by the lower southwest edge roller at about 9 feet-9 inches below the top causing deep bearing type deformation and a cut in the west edge of the south flange of the southwest leg of section 15. The roller was forced off of the shaft at the elevation of 10 feet-0 inches from the top after a downward motion of 3 inches from the elevation of 9 feet-9 inches. The deformation closely matched with the distress on the lower southwest edge roller and could only have been made while the climbing section was descending. This would be in the vicinity of the location of the lower edge roller at or near completion of the third jump.

25. A linear indentation on the west edge of the south flange of the southwest leg of tower section 15 was made by the lower southwest edge roller. The bearing type deformation occurred with height and became severe in the last six inches. The matching marks were found on the lower southwest edge roller. The deformations were made while ascending. This would be in the vicinity of the location of lower edge roller at or near the completion of the third jump.

26. The missing lower southwest edge roller could be identified due to the matching marks on the flange edge.

27. The fracture of the southwest leg of tower section 15 occurred after the deformation of the flange edge had taken place.

28. The lower southwest edge roller and the lower northwest edge roller were dislodged from the shafts at different elevations. The southwest roller came off at 10 feet-0 inches from the top and the northwest roller at 11 feet-0 inches from the top. Both rollers were forced off after a downward motion. It was also established that the southwest edge roller came off first.

29. The upper northeast edge roller and lower northeast edge roller came off when the rollers were not in contact with the tower legs.

TABLE 4.2.1

SUMMARY OF EYEWITNESS STATEMENTS

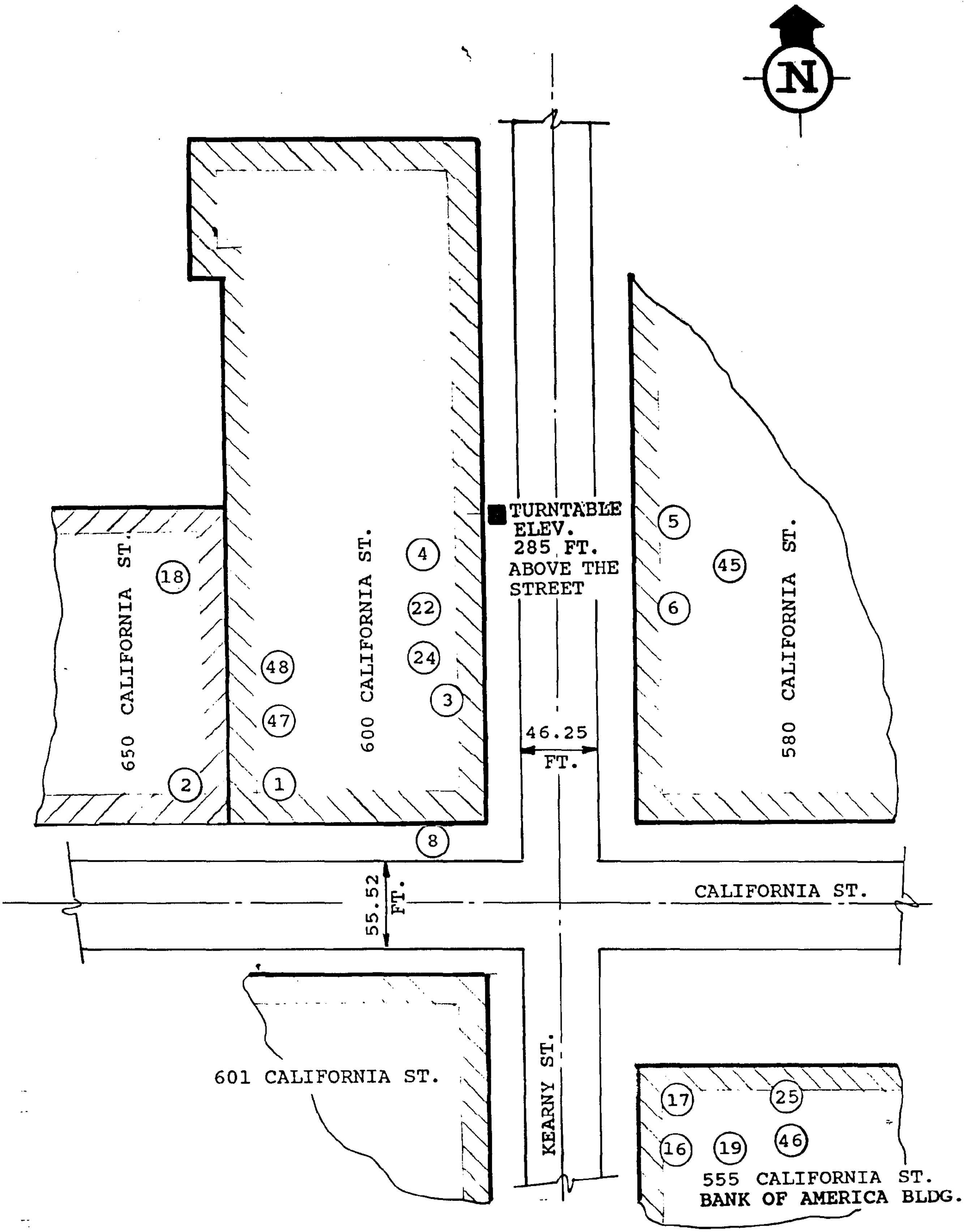
Witness Number Occupation Interview Date	Plan Location	Location Level	Estimated Line of Sight (ft)	Highlights of Eyewitness Statements
1. Ironworker Apprentice 12/14/89	600 California St.	19th Floor SW, Corner	170	• Initially had back to crane. • Heard loud pop; looked toward crane. • Saw crane turning counterclockwise. • Saw part of crane strike new section on platform and pushed it eastward. • Crew started down the tower.
2. Attorney 12/11/89 01/10/90 03/14/90	650 California St.	30th Floor	160	• Watching crane operation about 8:00 a.m. • Boom pointed in southerly direction, no load on boom. • One person climbed onto machine deck, went to cab and looked in, then went to relay room and opened door; second person came out of relay room and they talked, first person descended to climbing platform, second went back to relay room then left relay room and went to cab; this happened before the crane started to swing. • Crane starts rotation counterclockwise up to 160 degrees at uniform speed and steady. • Turntable remained balanced horizontally during rotation. • Counterweight hit section on tray and appeared to bend it. • Two persons on northside of climbing platform on catwalk during rotation, third person on platform of climbing platform near tower section 16 (i.e., third person under counterweight when they struck tower section). • Tower itself appeared to twist as it bent backwards toward the south.
3. Carpenter 12/07/89 02/02/90	600 California St. at edge near crane	14th Floor	125	• Appeared crew was ready to move section into opening. • Crane rotated counterclockwise in a normal and uniform speed. • Counterweights strike tower section on platform. • Crane started to fall toward building.
4. Ironworker 12/06/89 04/19/90	600 California St.	16th or 17th Floor	55	• Climbing frame leaning to south. • Climbing frame was bent and had seen a lot of use. • Hydraulic leak on gage fitting at top of ram. • Wheels were digging on the way up. The sound was like dragging on metal, hard drag sound. The sound started on Section 14 but got worse the next day on last section. Horrible screeching sound on last section. • Ram at full extension, prior to accident. • 5 to 10 minutes before collapse, operator was in process of touching up the boom for a couple of minutes. • Ready to pull new section in. • When the crane started to slew, it never stopped. It got faster.

TABLE 4.2.1 (Continued)

Witness Number Occupation Interview Date	Plan Location	Location Level	Estimated Line of Sight (ft)	Highlights of Eyewitness Statements
5. Stockbroker 12/12/89 01/10/90	580 California St.	21st Floor	80	• Attention directed to crane rotating. • Saw no one in cab while crane was rotating. • Crane rotated counterclockwise about 160 degrees in steady, normal speed. • Counterweights hit the new section on platform. • Turntable remained balanced horizontally during rotation.
6. Stockbroker 12/12/89 01/10/90	580 California St.	21st Floor	80	• Coworker called his attention to crane as it was rotating. • Rotation was counterclockwise. • Turntable remained horizontal during rotation. • Counterweight hit new section on platform; rotation stopped. • First (NE) vertical member and (NW) vertical member pulled apart. • South face vertical members failed last. • Man with facial hair and no hard hat clinging to rail of the deck of crane as crane was going down.
8. Labor Steward 12/11/89	Corner of Kearney & California St.	Street Level	285	• Crane turned counterclockwise. • No one near operator's cab. • Part of crane hit tower section. • Saw a man without a hard hat about 10 feet above platform level -- above top of cab and went down with boom.
16.Stockbroker 12/04/89	555 California St.	22nd Floor	280	• Turntable was not leaning while turning. • It was rapid movement under power. • After rotation, it began to tilt southward.
17.Stockbroker 02/15/90	555 California St.	22nd Floor	280	• No load on boom. • Boom rotating clockwise in a jerky wobbly motion. • Prior to pushing on the door, it looked as if he was operating the crane and he was making the crane move. He was concentrating on moving the controls. • Rotation was jerky, wobbling. • It was not a full power rotation.
18.Stockbroker 12/04/90	650 California St.	18th Floor	140	• Counterweights were facing north and south and new section facing south. • Jumping frame jacked-up one-half to two-thirds of new section's height. • Crane began to list to the right (i.e., south). • The entire top of the crane went to the south -- it started slowly and reached maybe 30 degrees or 40 degrees and then accelerated. • The new section sitting on the tray was one of the first items to tip over towards south. • Failure occurred like a hinge -- 10 to 20 feet below catwalk.

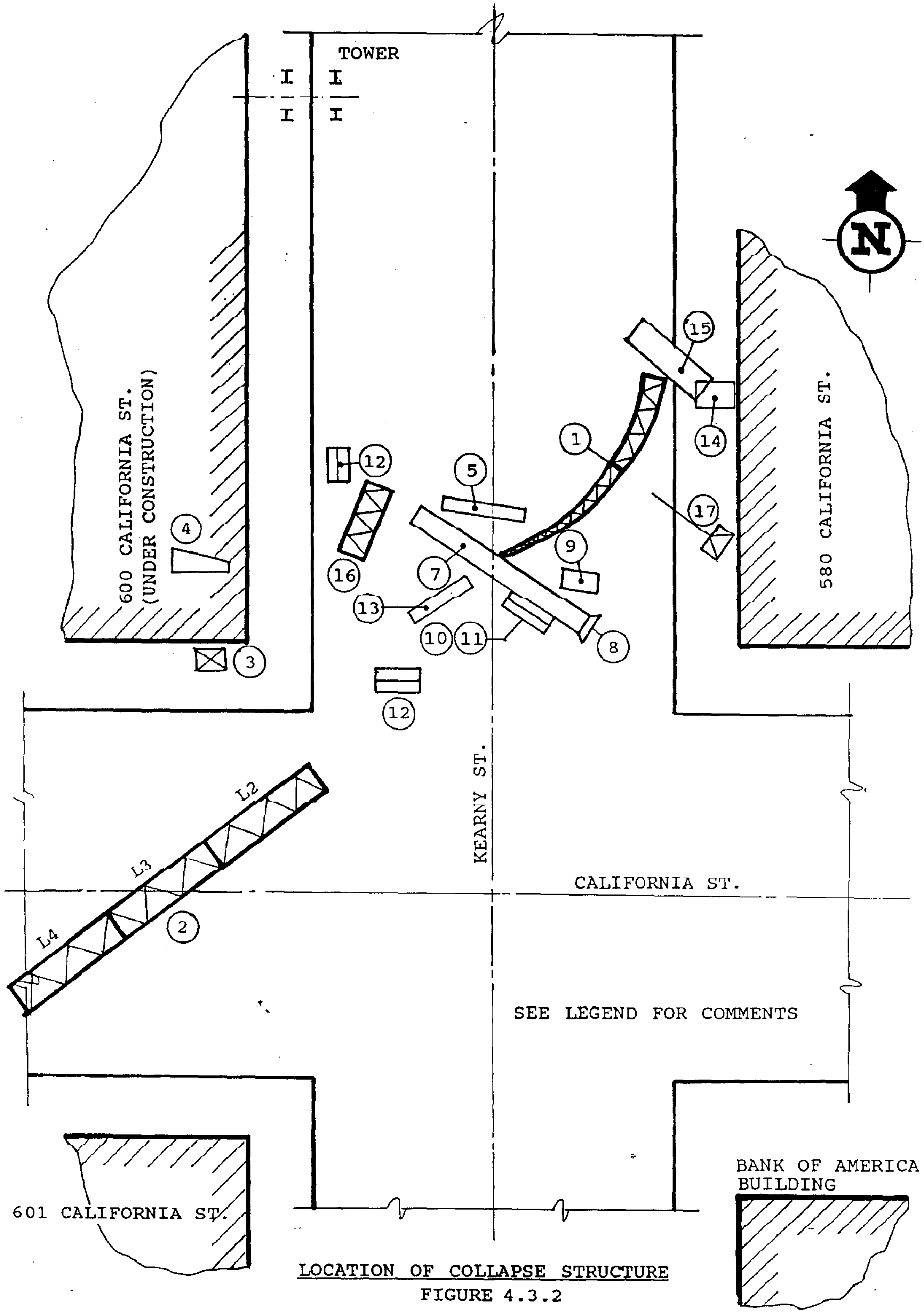
TABLE 4.2.1 (Continued)

Witness Number Occupation Interview Date	Plan Location	Location Level	Estimated Line of Sight (ft)	Highlights of Eyewitness Statements
19. Elevator Company Employee	555 California St. Bank of America	33rd Floor	290	• Crane started rotating counterclockwise. • Counterweight strikes section on tray and crane starts to fall. • Operator still in the cab as crane fell on Kearney Street. • Tip of boom hit 601 California Street and part of upper crane landed on top of 600 California Street.
22. Ironworker 11/29/89	600 California St.	18th Floor	75	• Heard explosior type sound. • Saw piece of iron flying through air and Dave Gradin falling down through the tower. • Roller guide landed on 17th floor.
24. Ironworker (No date)	600 California St.	18th Floor	75	• Heard explosior like a rifle, looked up and saw crew trying to run down the tower.
25. Stockbroker 12/05/90 02/14/90 03/01/90	555 California St.	17th Floor NE	280	• Operator in the cab, stood up from sitting position and looked down below before rotation. • Boom did not move just before accident. • New tower section not plumb.
45. Stockbroker (No date)	580 California St.	21st Floor	80	• Saw someone in blue shirt crouching near "powerhouse" holding to something as crane was going down. • Did not see anyone in cab.
46. Elevator Company Employee (No date)	555 California St.	33rd Floor	290	• Saw counterclockwise rotation prior to failure.
47. Employee of Erection Company (No date)	600 California St.	19th Floor	60	• Crane swung counterclockwise more than 90 degrees but less than 180 degrees. • Rotation was continuous. • There was no braking. • Counterweights hit section #16 and 15 seconds later observed failure below climber.
48. Ironworker (No date)	600 California St.	19th or 20th Floor	60	• Lacing on tower or climber began buckling -- saw paint popping off climber. • Southwest leg of tower or climber was first to fail.



LOCATION OF THE WITNESSES
FIGURE 4.2.1

General view of debris after collapse -photo taken before any debris removed.
Figure 4.3.1



LOCATION OF COLLAPSE STRUCTURE
FIGURE 4.3.2

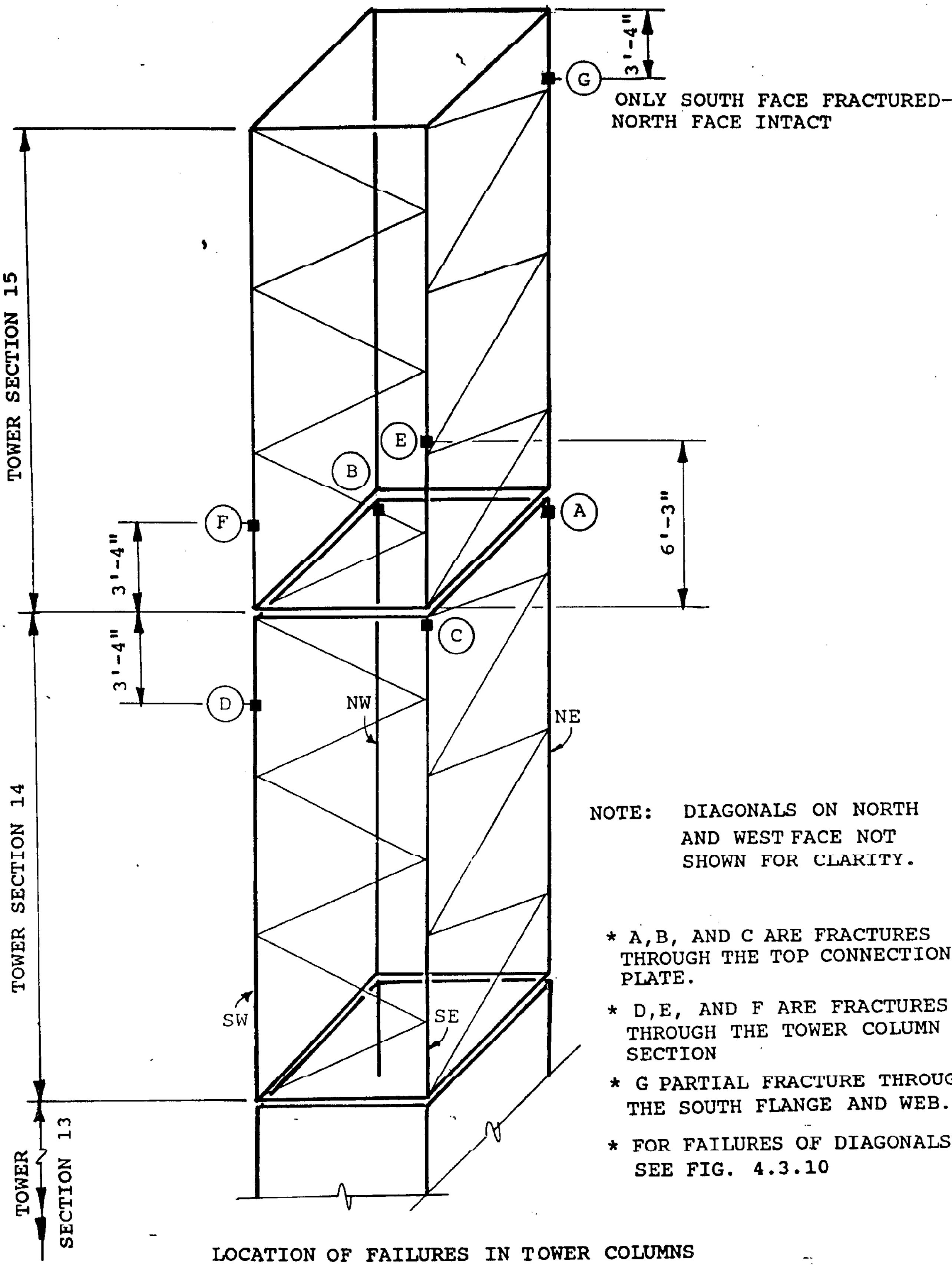
Location of Collapsed Crane Parts

PARTS	COMMENT	LOCATION FOUND
Luffing Boom		
#1 Heel	Remained attached to the turntable	Kearny St.-SE of tower base
#2 Section L1	Remained attached to the heel and the turntable	Kearny St.-SE of tower base
L2 L3 L4	L2 thru L4 in one piece connected to each other	California St. - lying at 45°
#3 L5 and Tip	L5 and tip of the luffing boom connected to each other were hanging from wire rope of the A-frame.	Hanging on the California St. side of 600 California St.
A-Frame		
#4 Vertical members plus the top half inclined member	The A-frame was found in two pieces. The sloping member sheared in two halves. The top half of the sloping member remained attached to the vertical member.	17th floor of 600 California St.
Other Parts		
#5 Bottom half of sloping member of the A-frame		Kearny St.-SW of tower base
#6 Guide Sheave Frames		Kearny St.-SW of tower base
#7 Turntable Frame	Lying sideways on the ground with slewing ring facing south	Kearny St.-SW of tower base
#8 Operators' Cab	Smashed lying next to the turntable frame	Kearny St.-SW of tower base
#9 Control Panel Cabin	Separated from turntable frame and distorted	Kearny St.-SW of tower base
#10 Slewing Ring	Attached to the turntable frame	Kearny St.-SW of tower base
#11 Turntable Support	Attached to the turntable frame	Kearny St.-SW of tower base
#12 Counterweights	Separated from the frame	Junction of California & Kearny St
#13 Counterweight Tray	Separated	Kearny St.-SW of tower base

FIGURE 4.3.2 (Legend)

#14 Climbing Frame	Hit the face of the 580 California St. building on Kearny St. and then landed on the sidewalk leaning against 580 California St. Upright condition. West face leaning against the bldg. North face towards California St.	Leaning against the 580 California Street on Kearny Street side.
#15 Tower Section 15	Partially underneath the climbing frame. West face up. South face towards California St. SE leg sheared, SW leg sheared, NE leg sheared, NW leg partially fractured.	Kearny Street
#16 Tower Section 16	South face up. Top towards north	Kearny Street
#17 Climbing Traverse	Hydraulic ram pointing to NW	Kearny Street

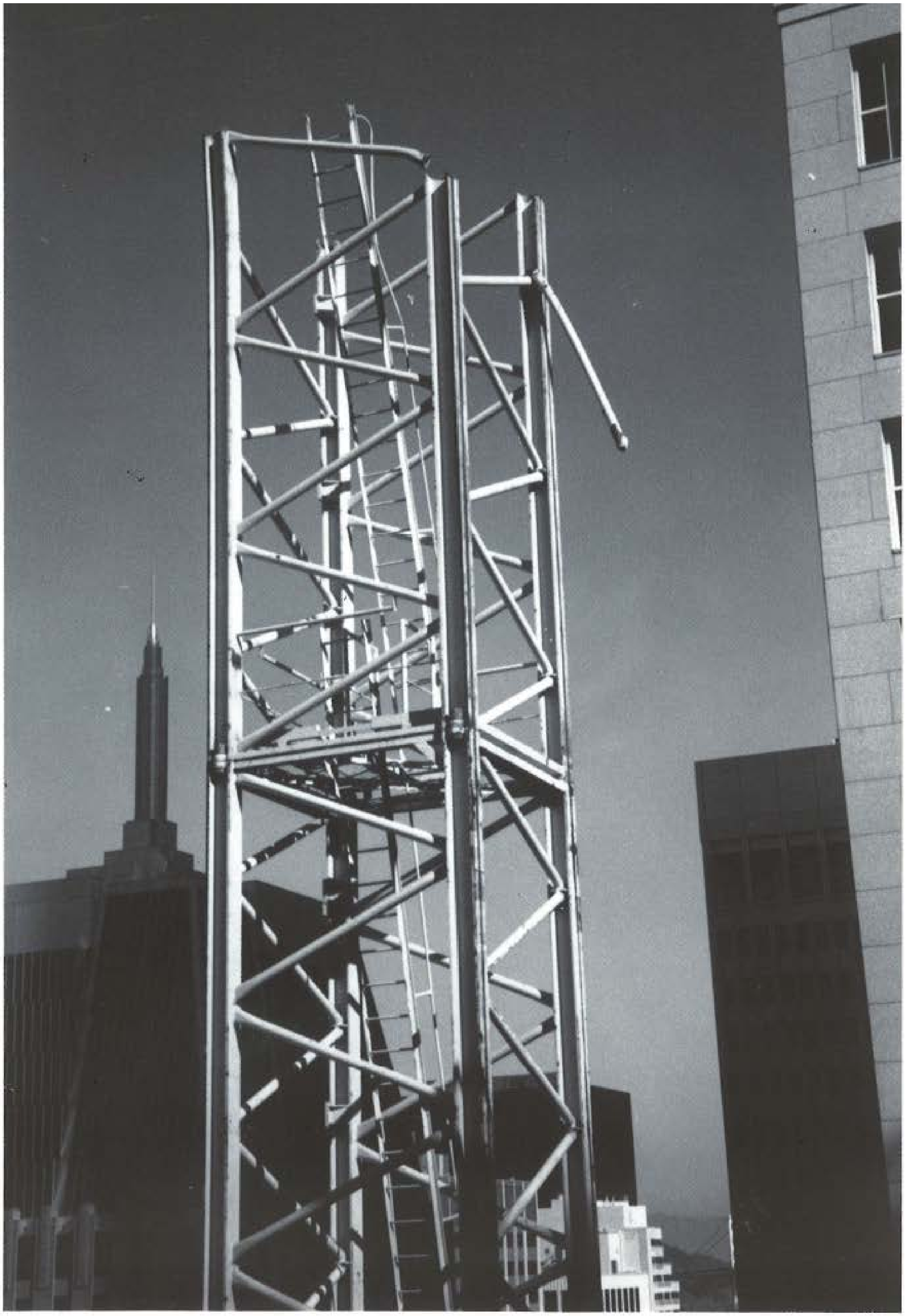
FIGURE 4.3.2 (Legend - cont.)



NOTE: DIAGONALS ON NORTH AND WEST FACE NOT SHOWN FOR CLARITY.

* A, B, AND C ARE FRACTURES THROUGH THE TOP CONNECTION PLATE.
* D, E, AND F ARE FRACTURES THROUGH THE TOWER COLUMN SECTION
* G PARTIAL FRACTURE THROUGH THE SOUTH FLANGE AND WEB.
* FOR FAILURES OF DIAGONALS, SEE FIG. 4.3.10

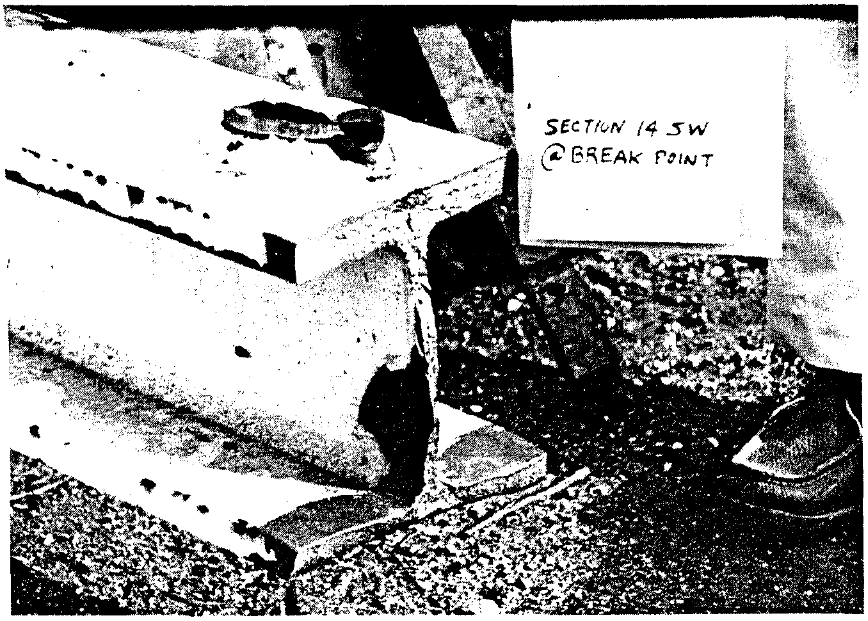
LOCATION OF FAILURES IN TOWER COLUMNS
FIGURE 4.3.3



Remaining portion of failed tower -damaged building under construction shown to the left of tower.
Figure 4.3.4

Remaining portion of failed tower -view to Northeast. Top section in photo is remaining part of Section 14.

Figure 4.3.5



Failure at Section 14 SW leg.

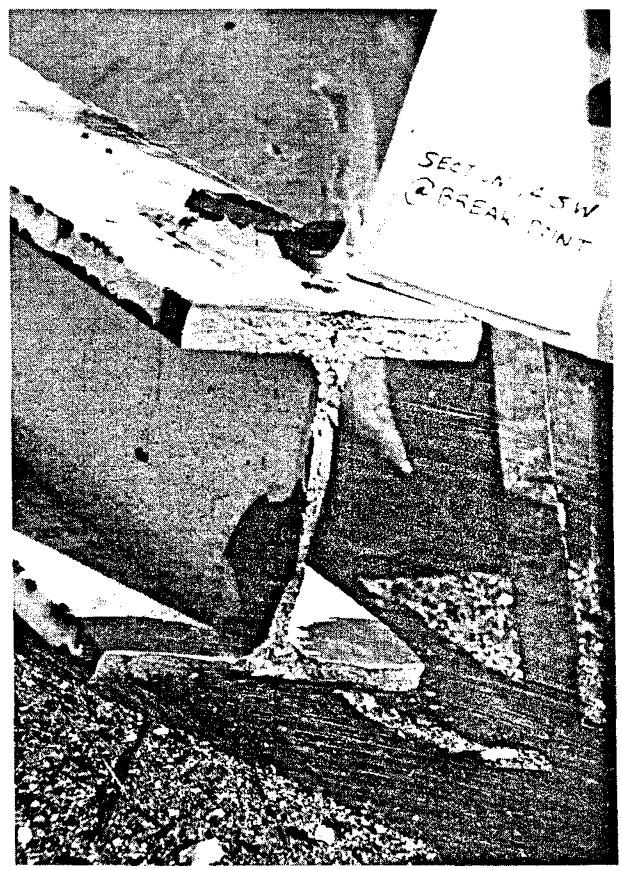
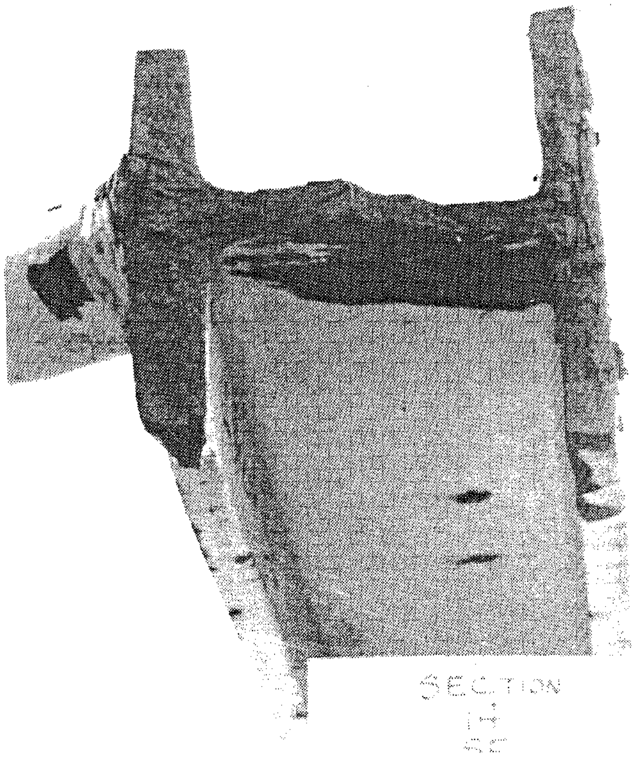


Figure 4.3.6



Failure of Section 14 SE leg viewed toward bottom of the section.

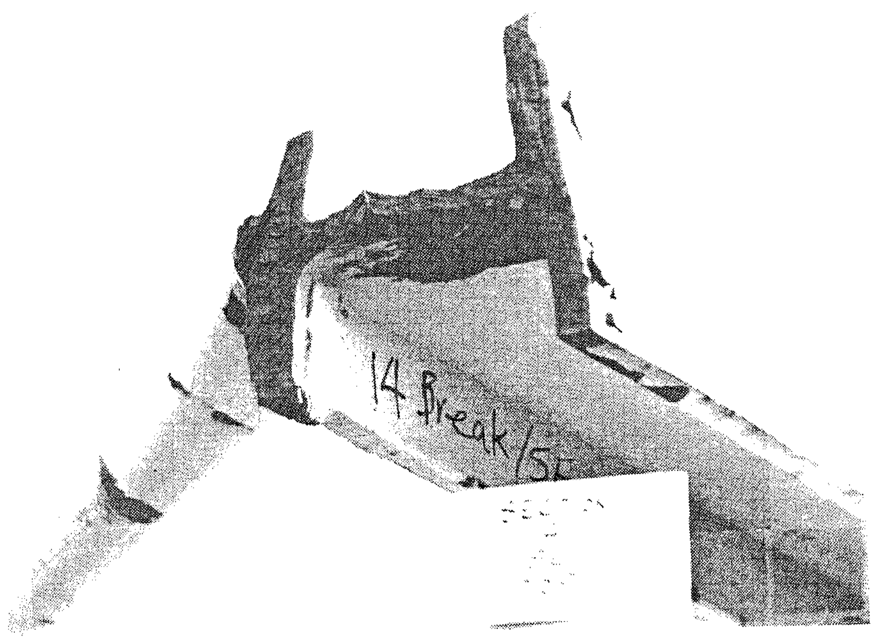
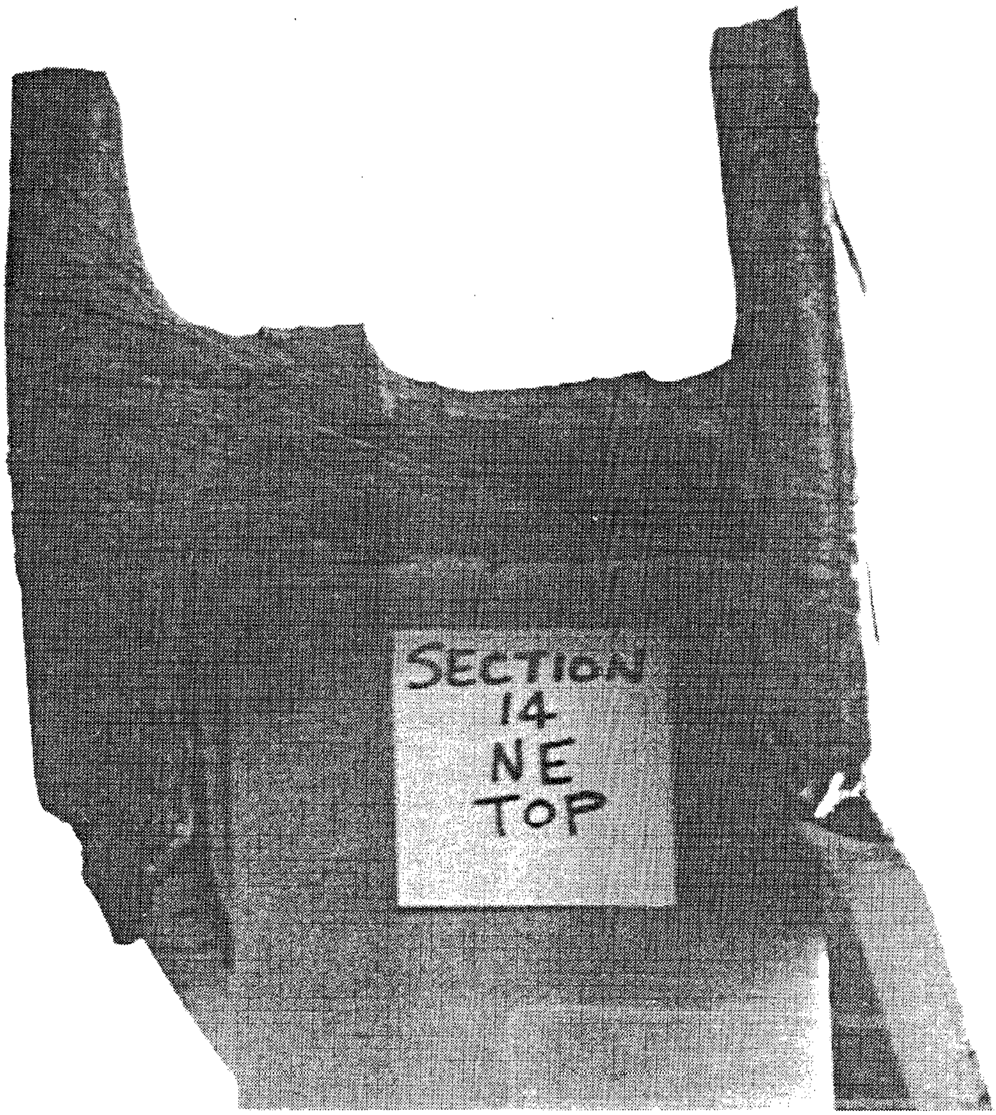
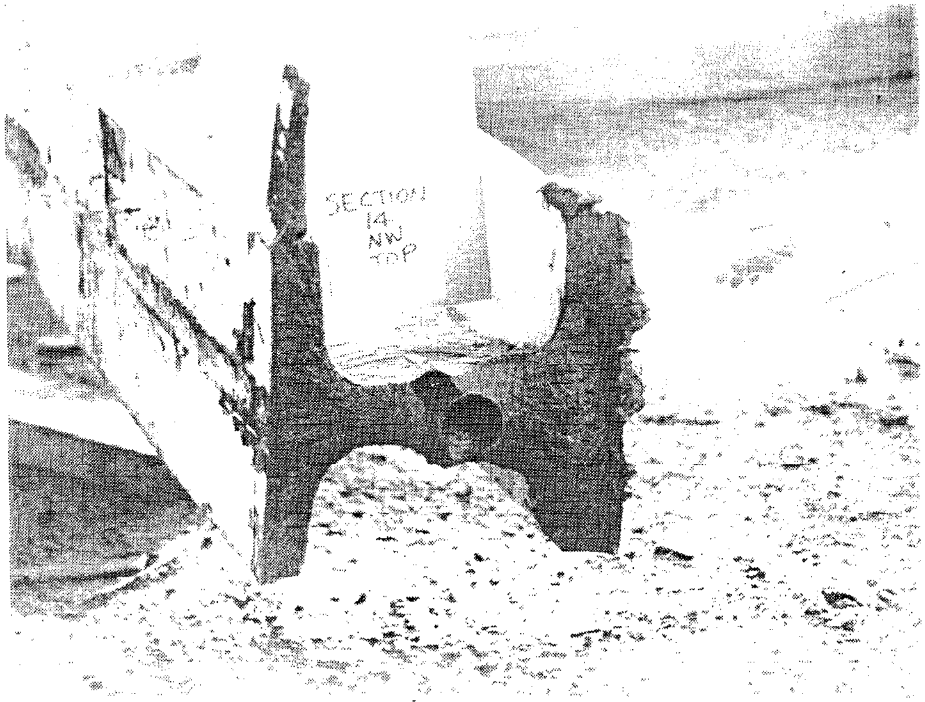


Figure 4.3.7

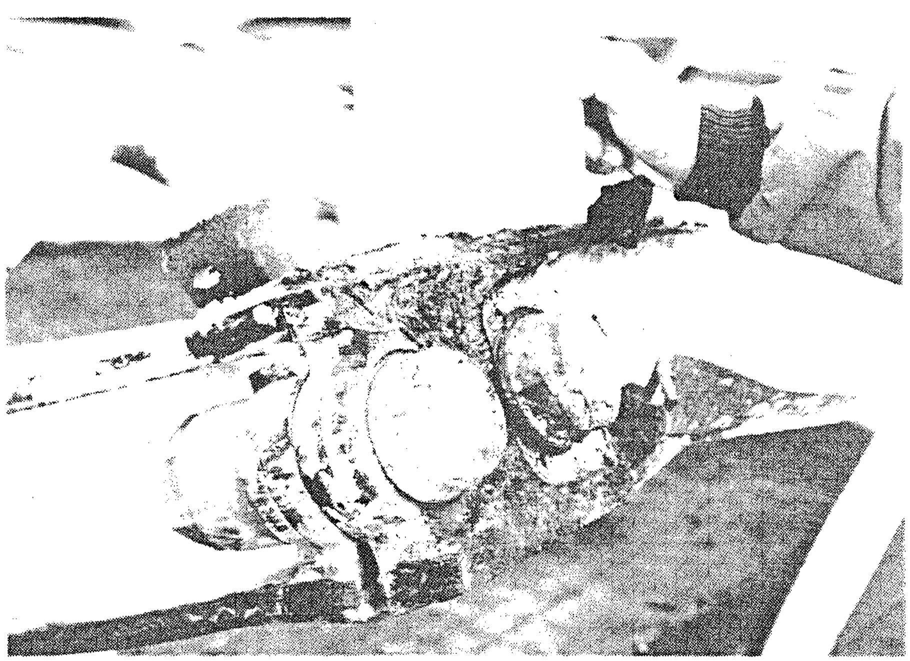


Failure of Section 14 NE leg -- at top of section.

Figure 4.3.8

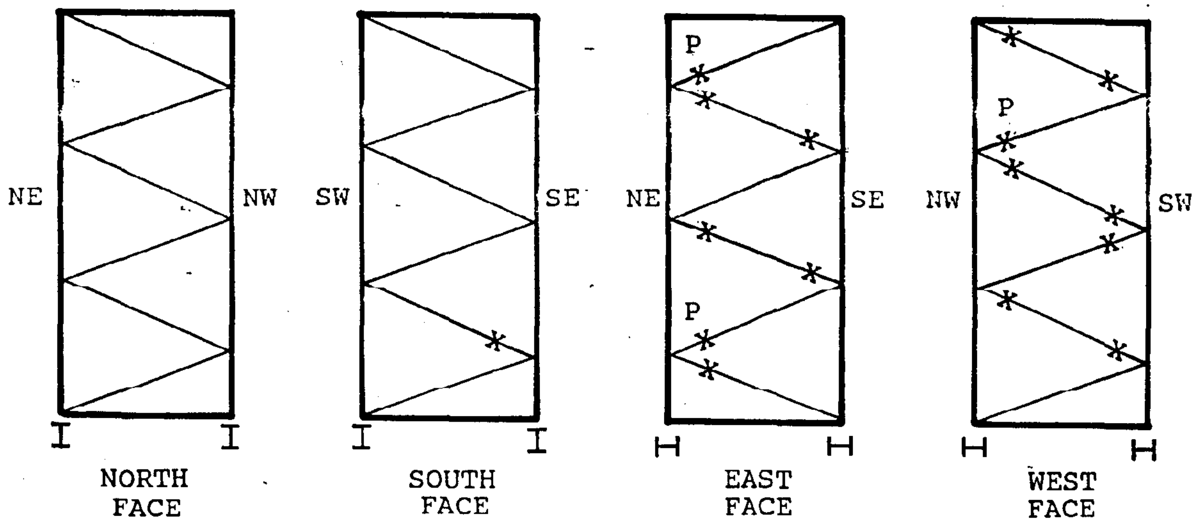


Failure at Section 14 NW leg — viewed from top toward bottom.



Failure at Section 14 NW leg — viewed from bottom toward top.

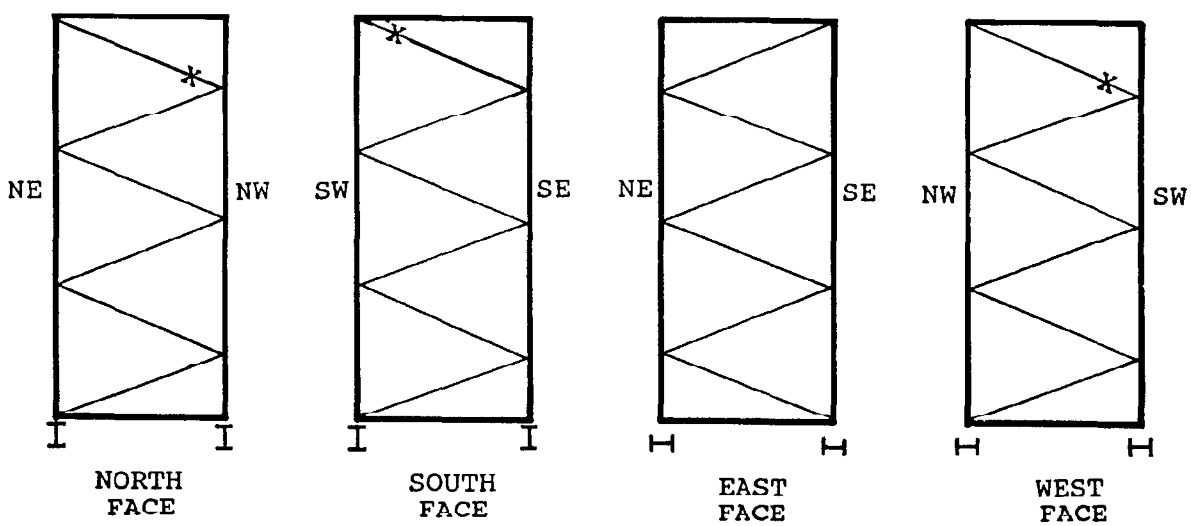
Figure 4.3.9



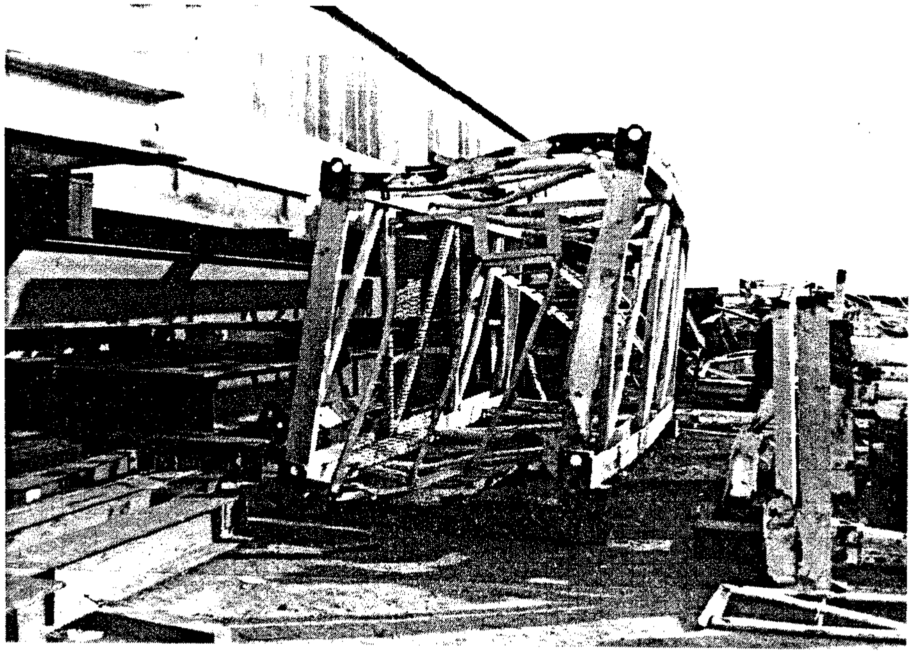
ELEVATION OF FRACTURED DIAGONALS OF TOWER SECTION 15
AFTER COLLAPSE

X – LOCATION OF FRACTURE
THRU ENTIRE SECTION

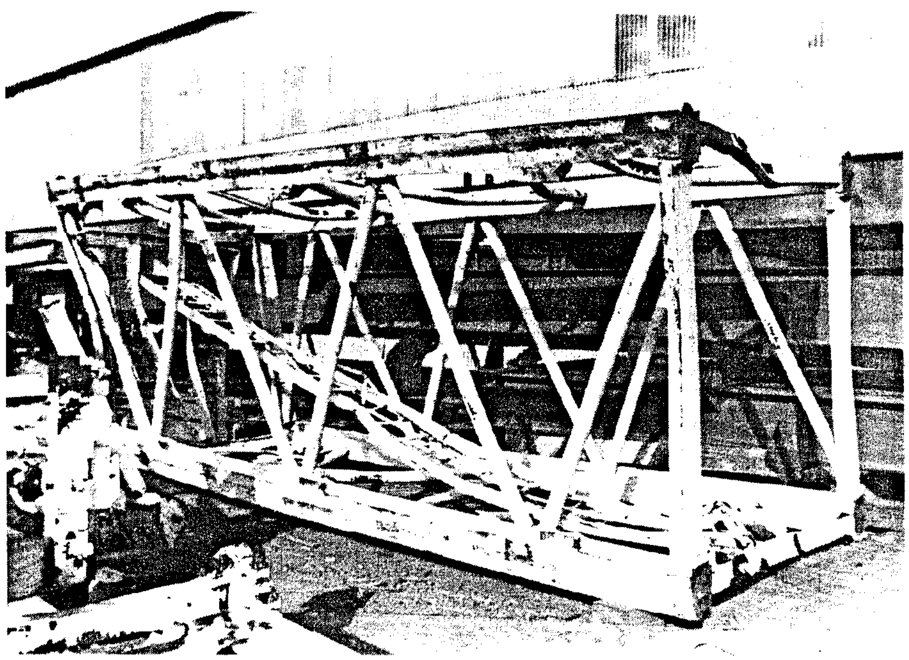
P = LOCATION OF PARTIAL
FRACTURE



ELEVATION OF FRACTURED DIAGONALS OF TOWER SECTION 14
AFTER COLLAPSE
FIGURE 4.3.10

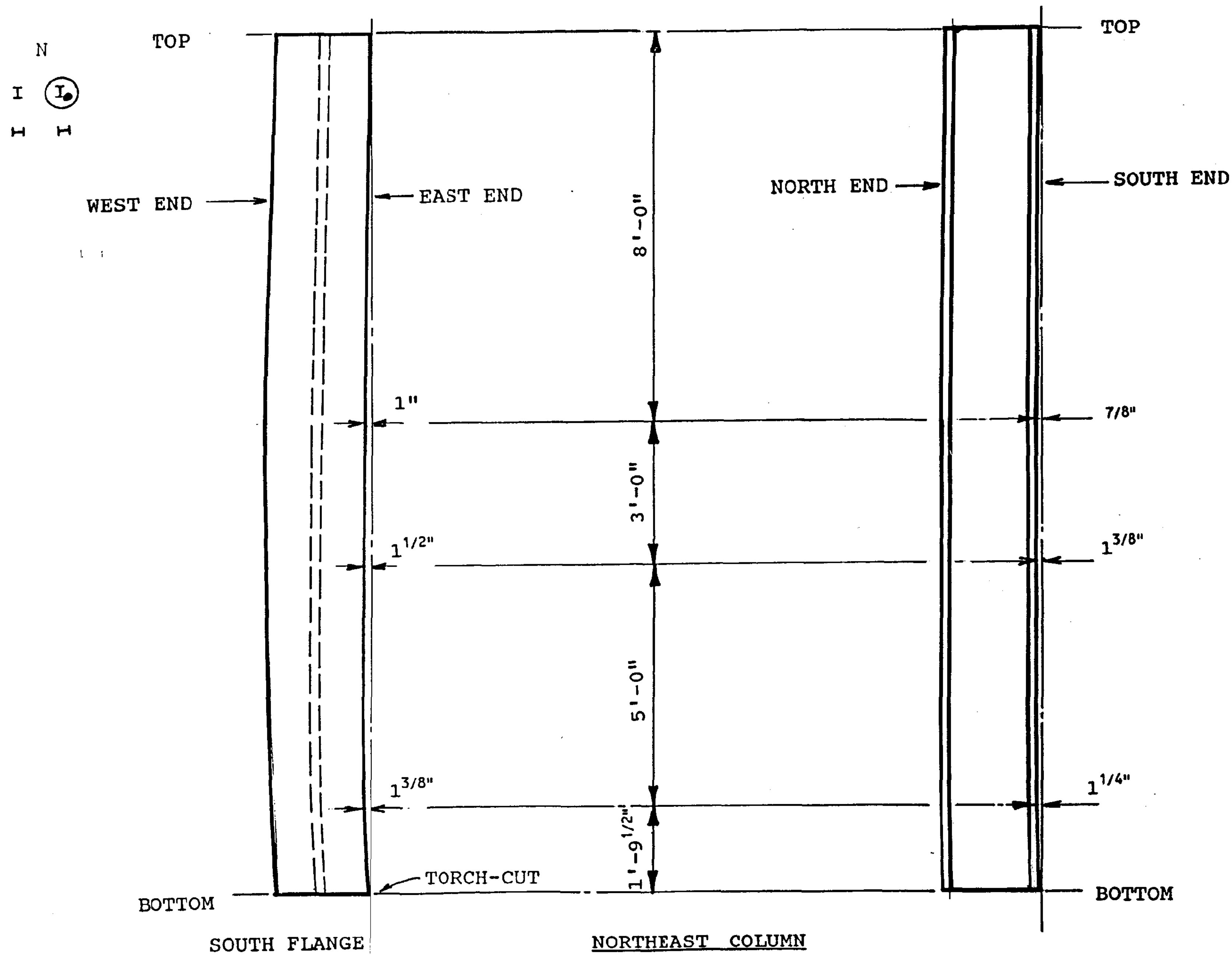


Tower Section 16 — viewed from the bottom — the West face is on the ground.

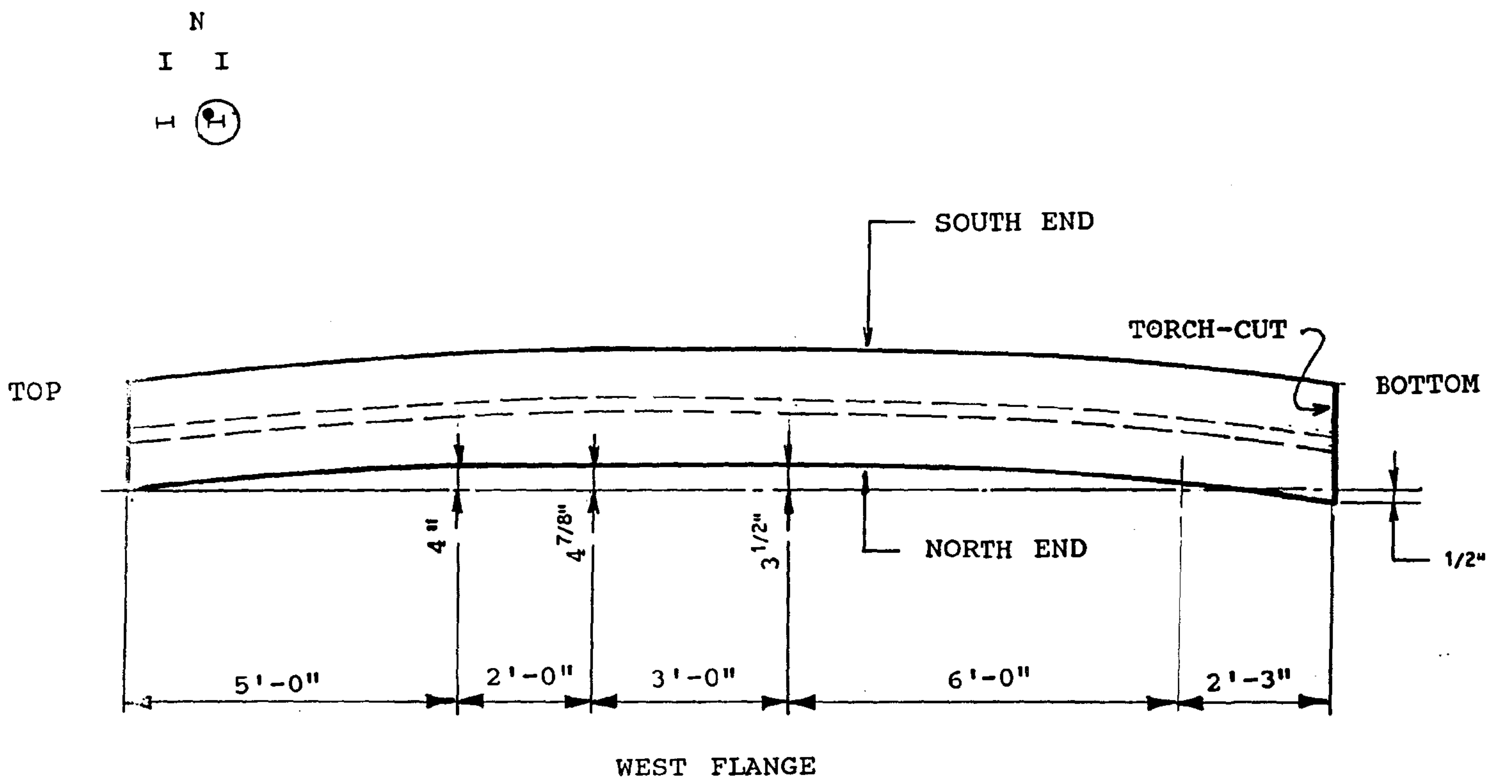


Tower Section 16 — view of North face.

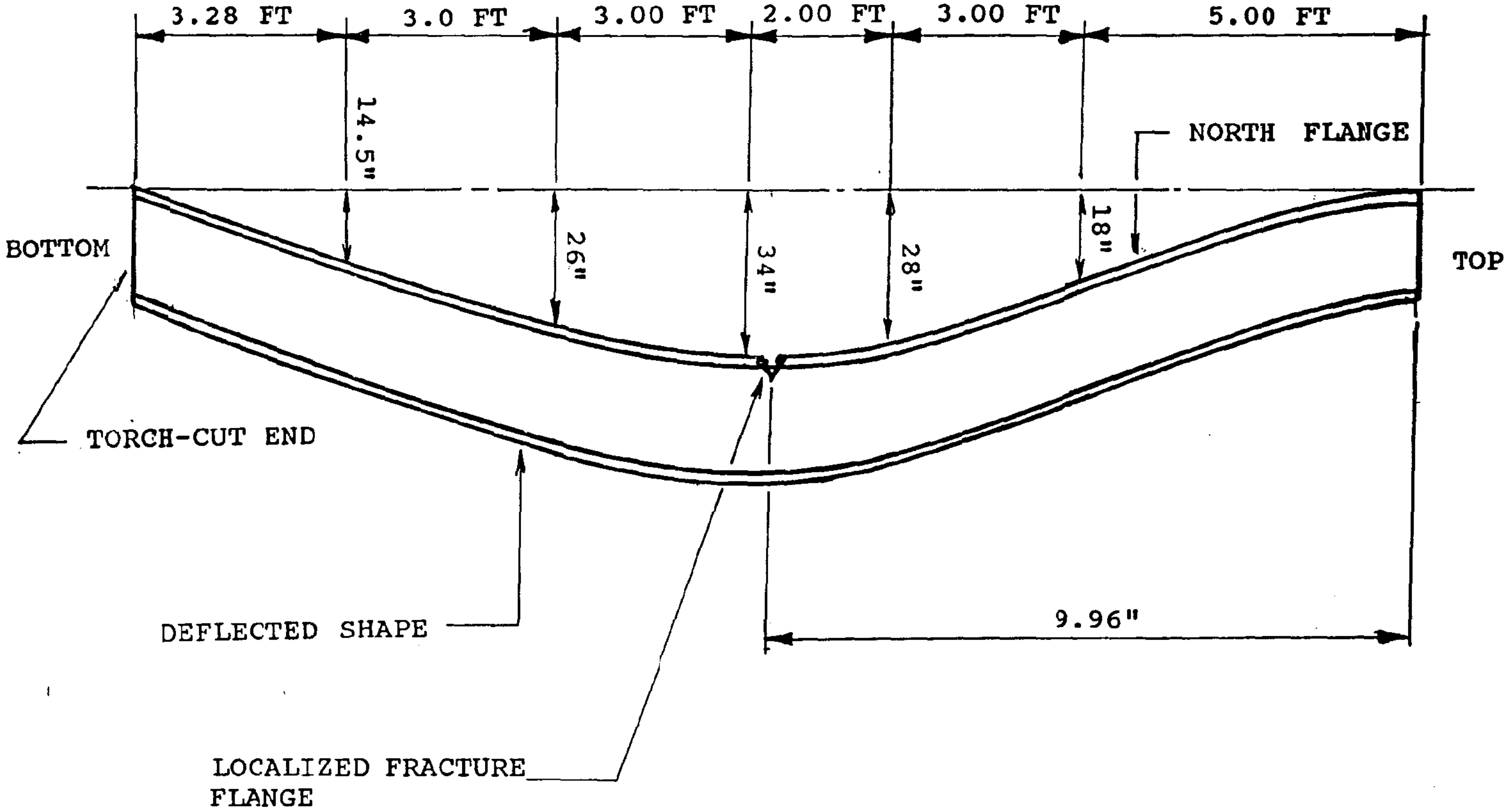
Figure 4.3.11



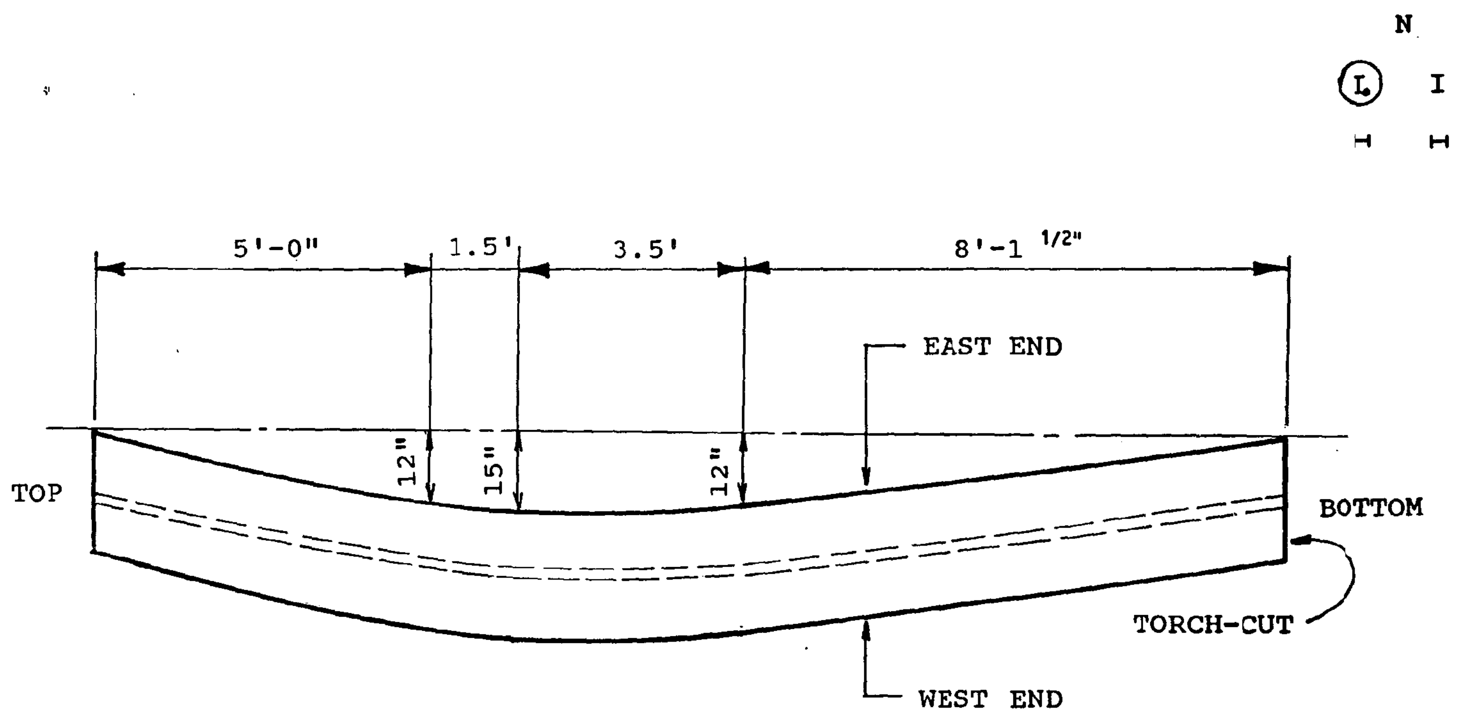
NORTHEAST COLUMN
CLIMBING SECTION
FIGURE 4.3.12



<u>SOUTHEAST</u> <u>COLUMN</u>
CLIMBING SECTION
FIGURE 4.3.13



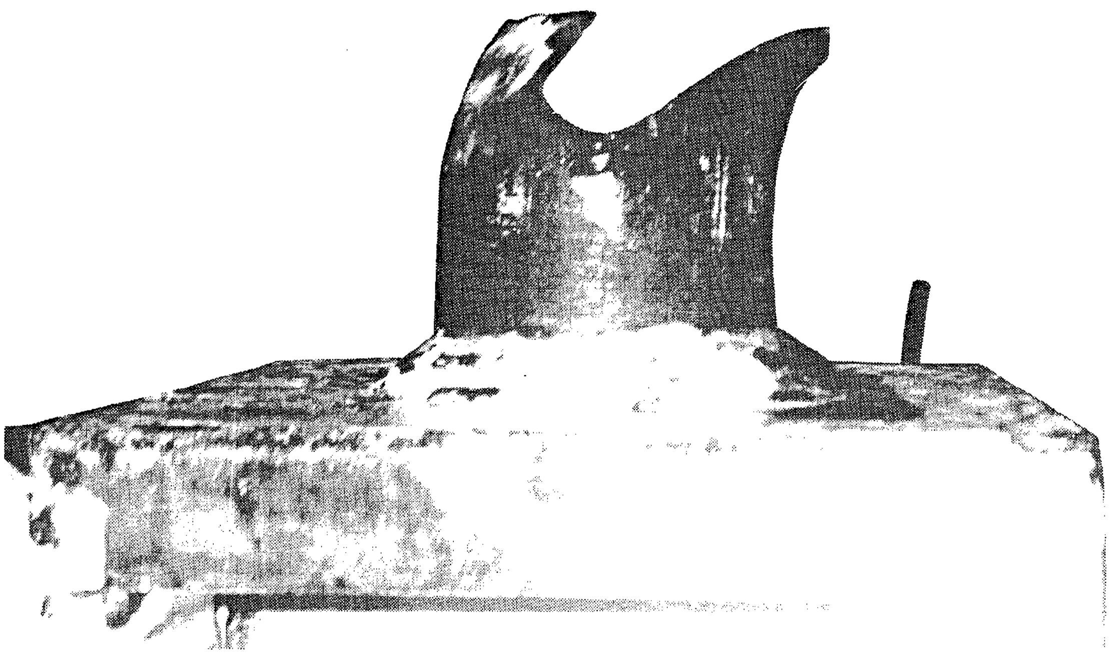
<u>CLIMBING SECTION; SOUTHWEST LEG</u>
LOOKING EAST
FIGURE 4.3.14



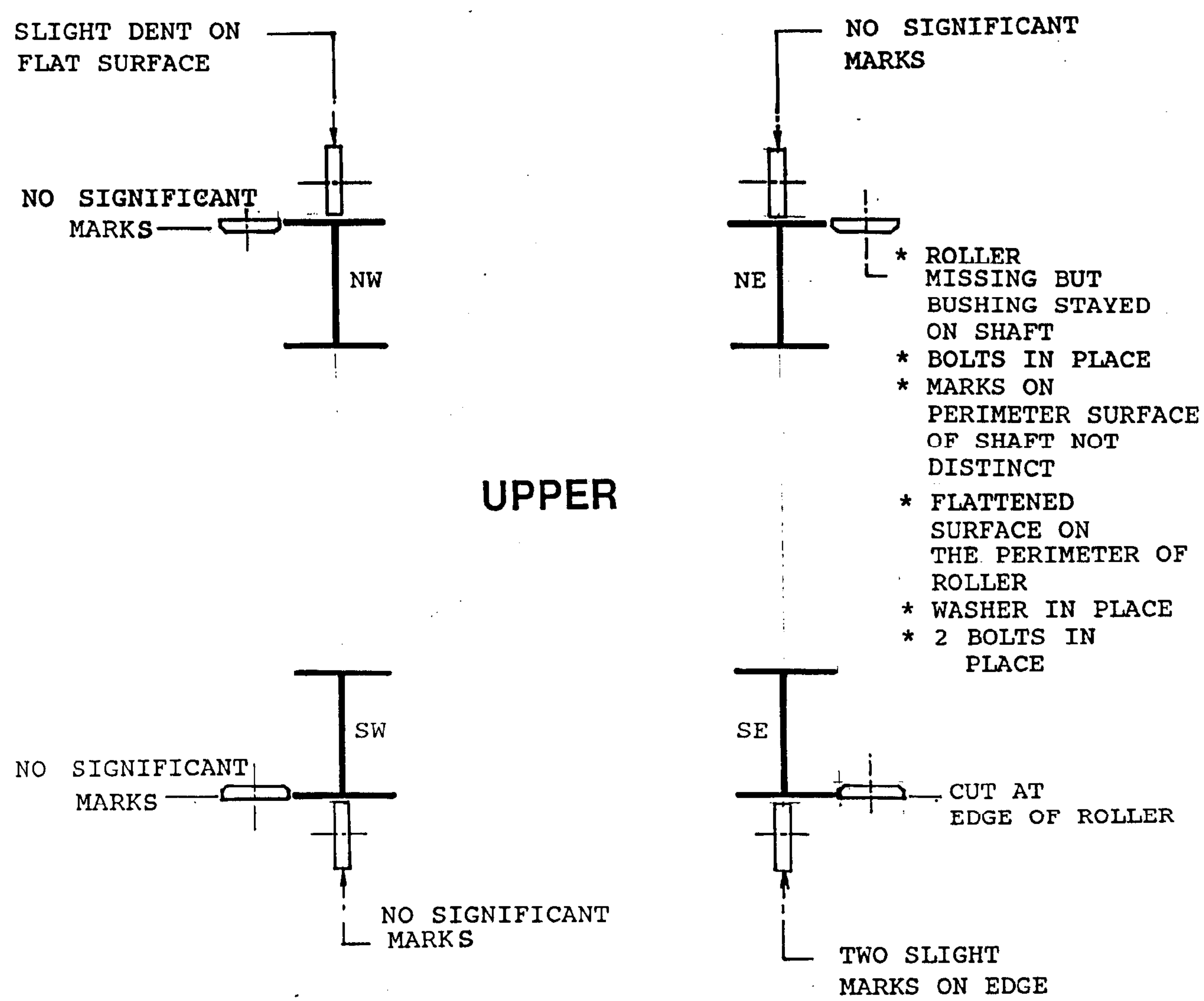
SOUTH FLANGE

CLIMBING SECTION
NORTHWEST COLUMN
LOOKING NORTH

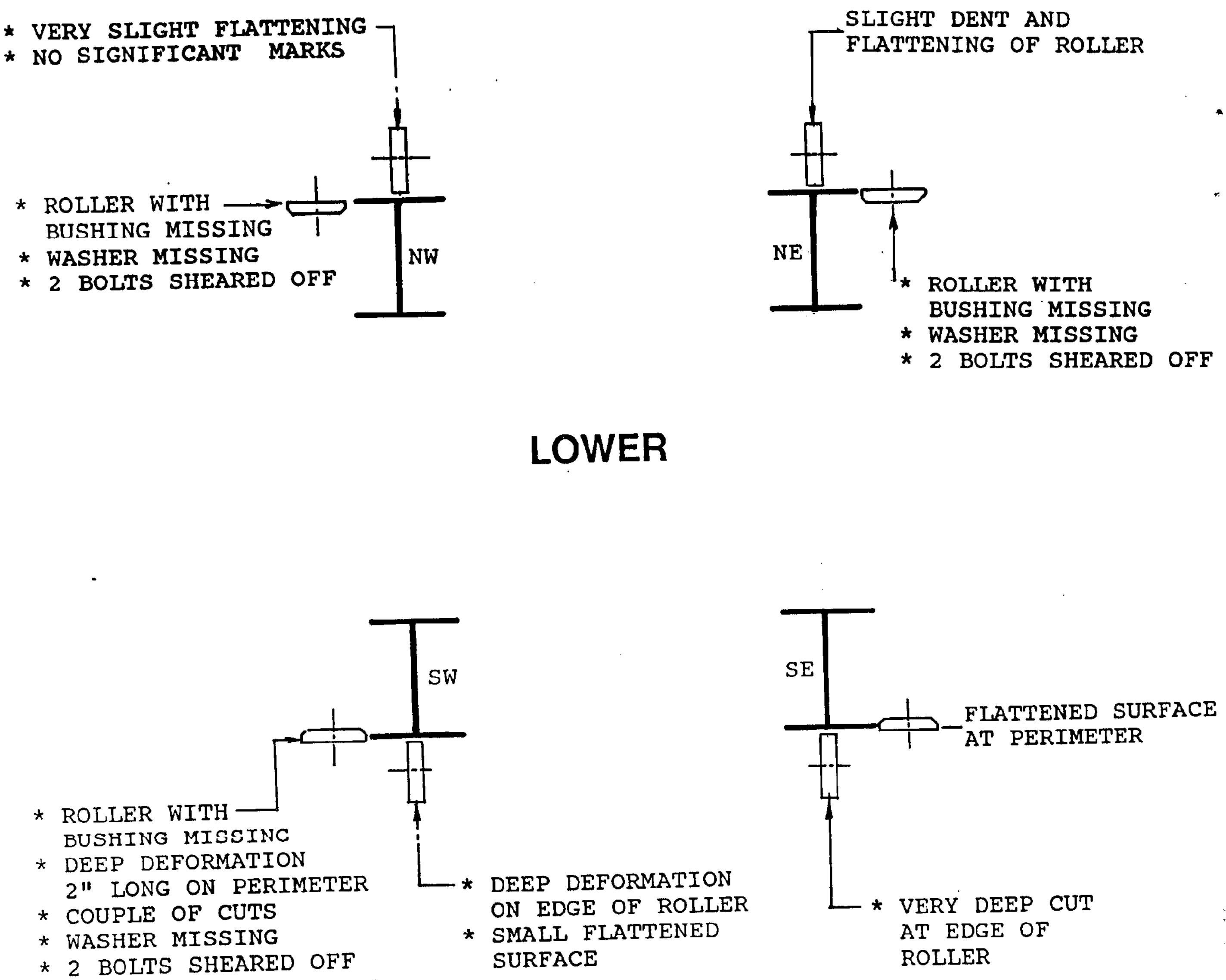
FIGURE 4.3.15



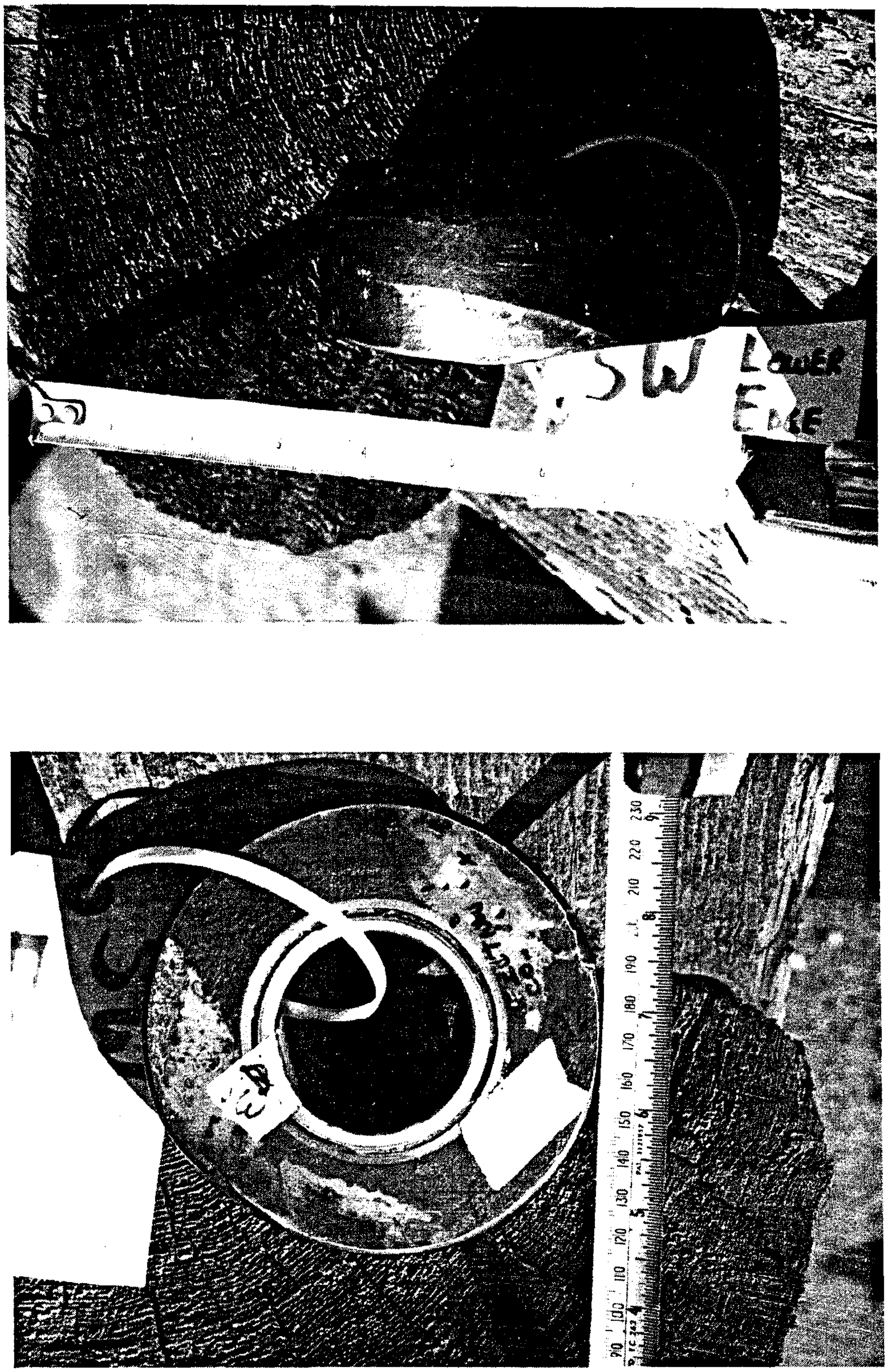
Failure of guide pin of climbing section.
Figure 4.3.16



DESCRIPTION OF UPPER ROLLERS
AFTER COLLAPSE
FIGURE 4.3.17



DESCRIPTION OF LOWER ROLLERS
AFTER COLLAPSE
FIGURE 4.3.18

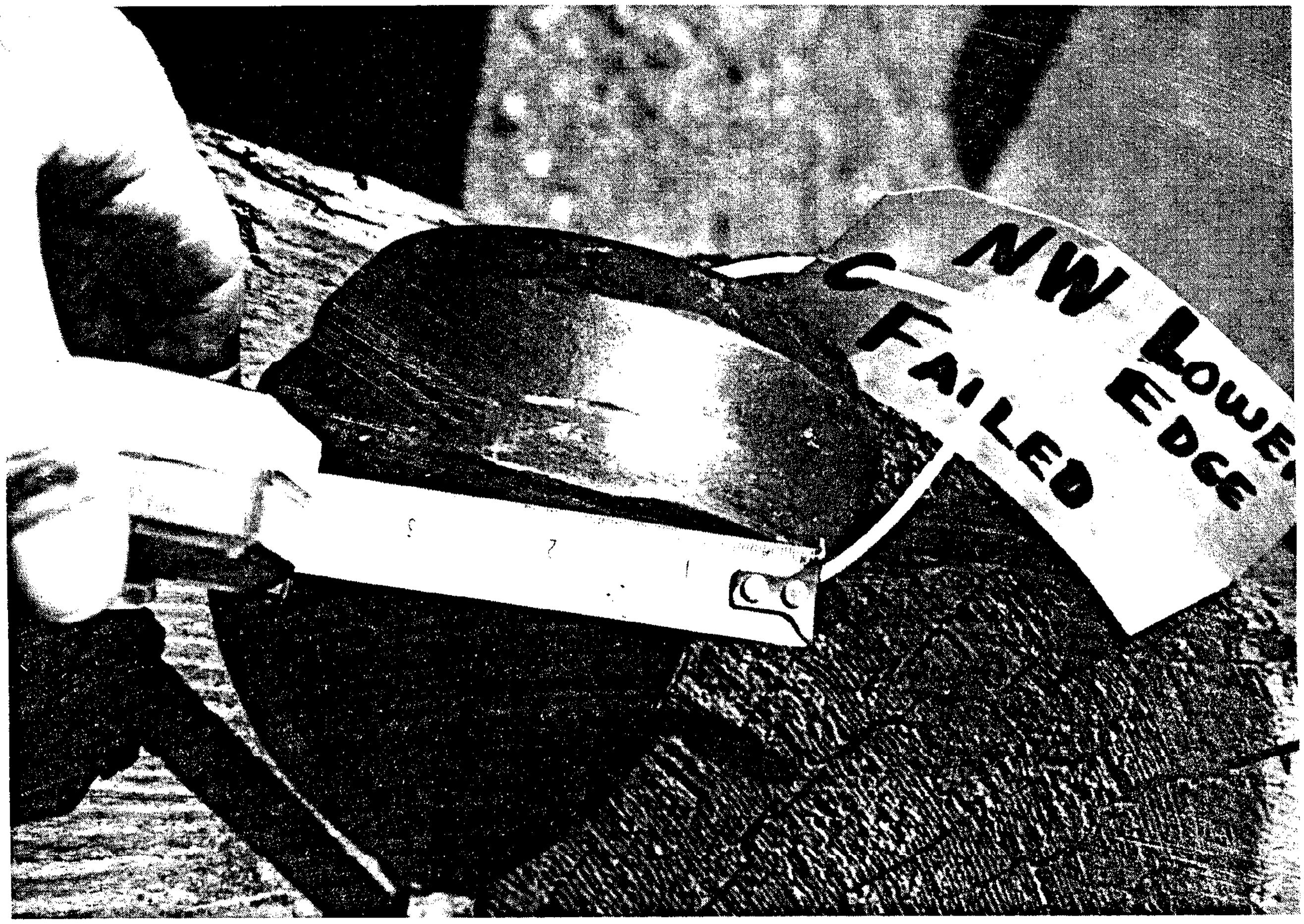


Missing lower SW edge roller.

Figure 4.3.19

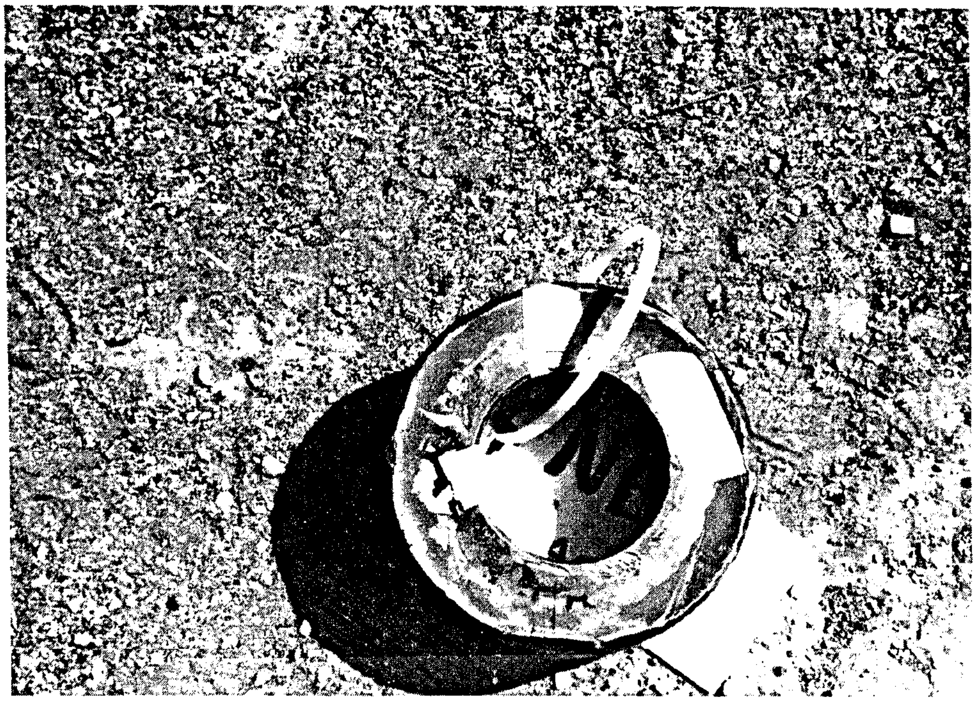
Lower SW edge roller.

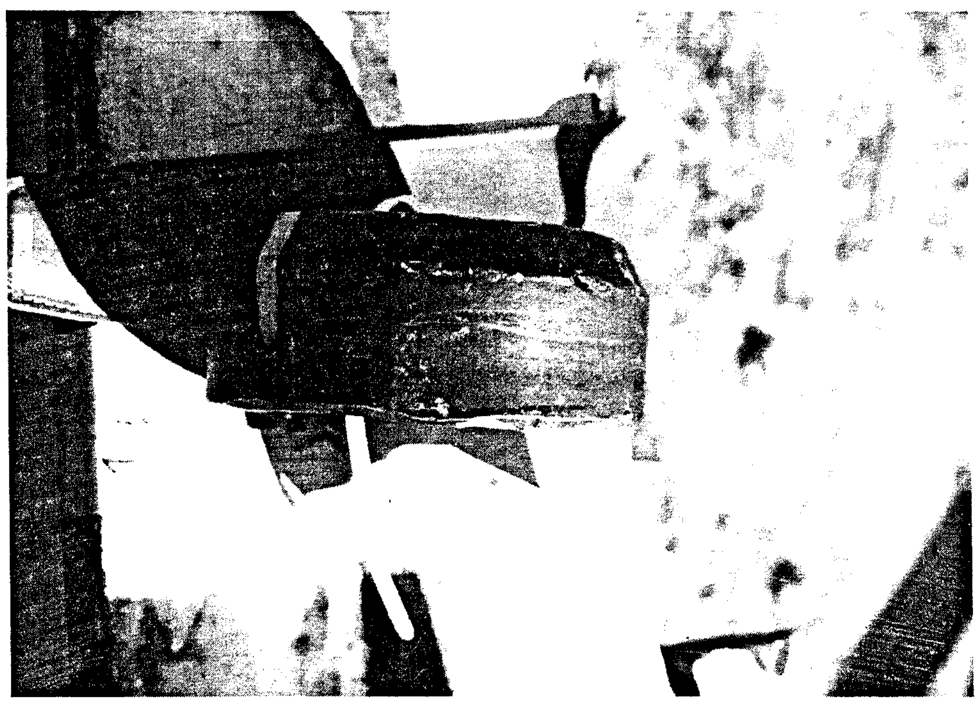
Figure 4.3.20



Missing lower NW edge roller.

Figure 4.3.21



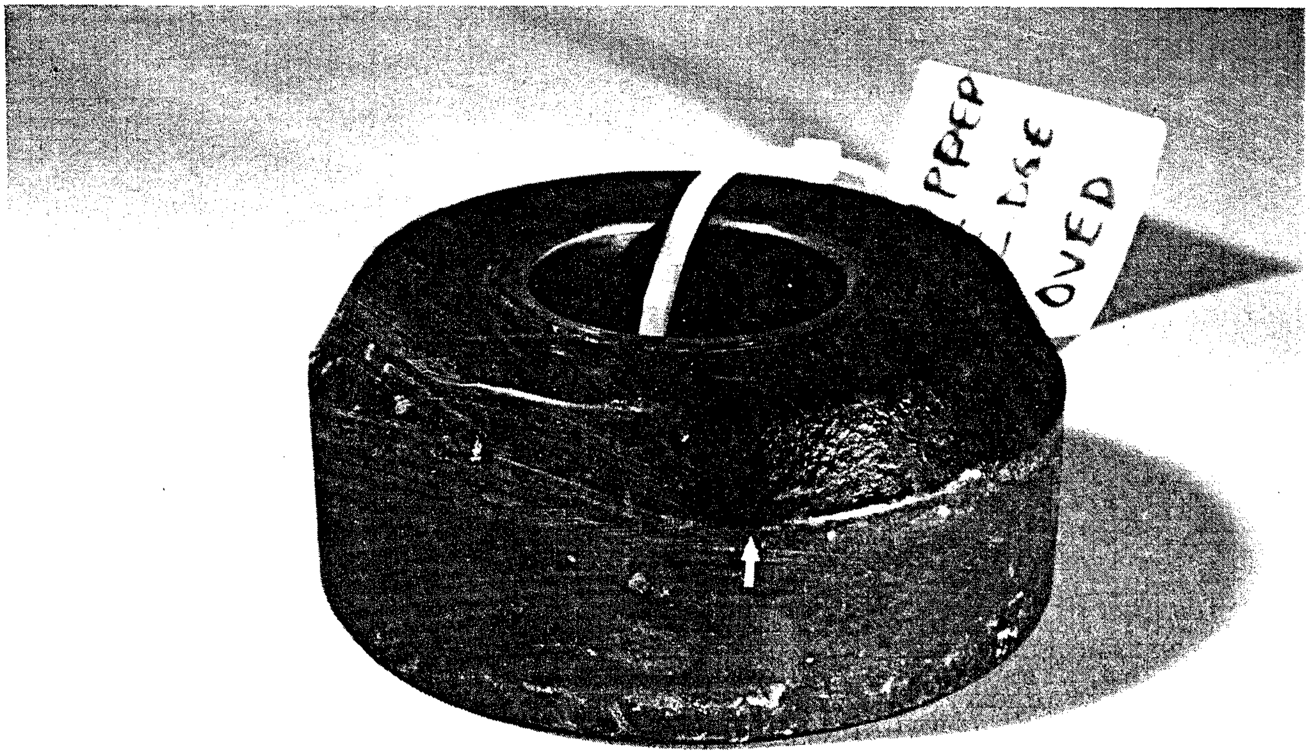


Missing upper NE edge roller.

Figure 4.3.22

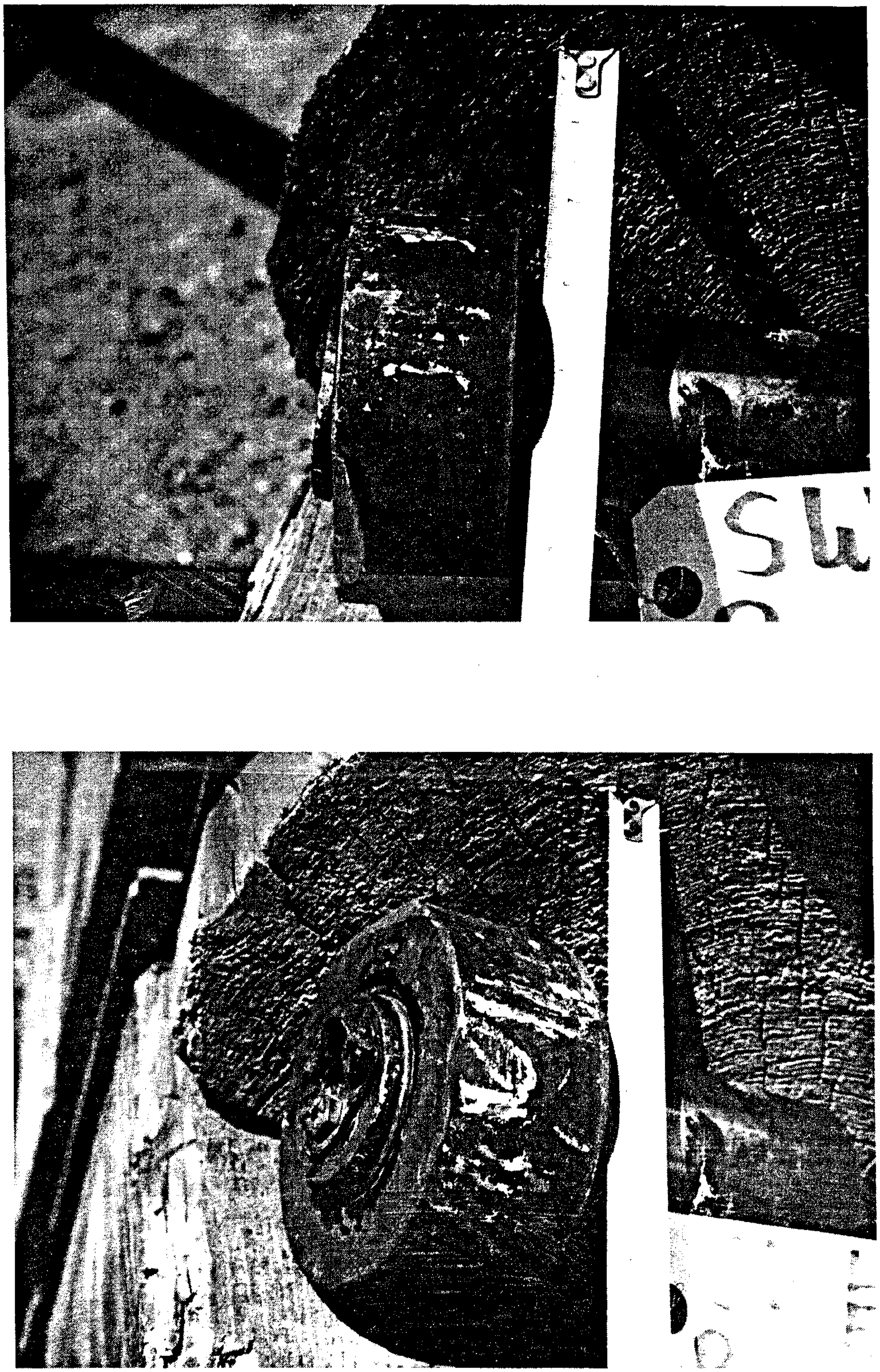
Missing NE lower edge roller.

Figure 4.3.23



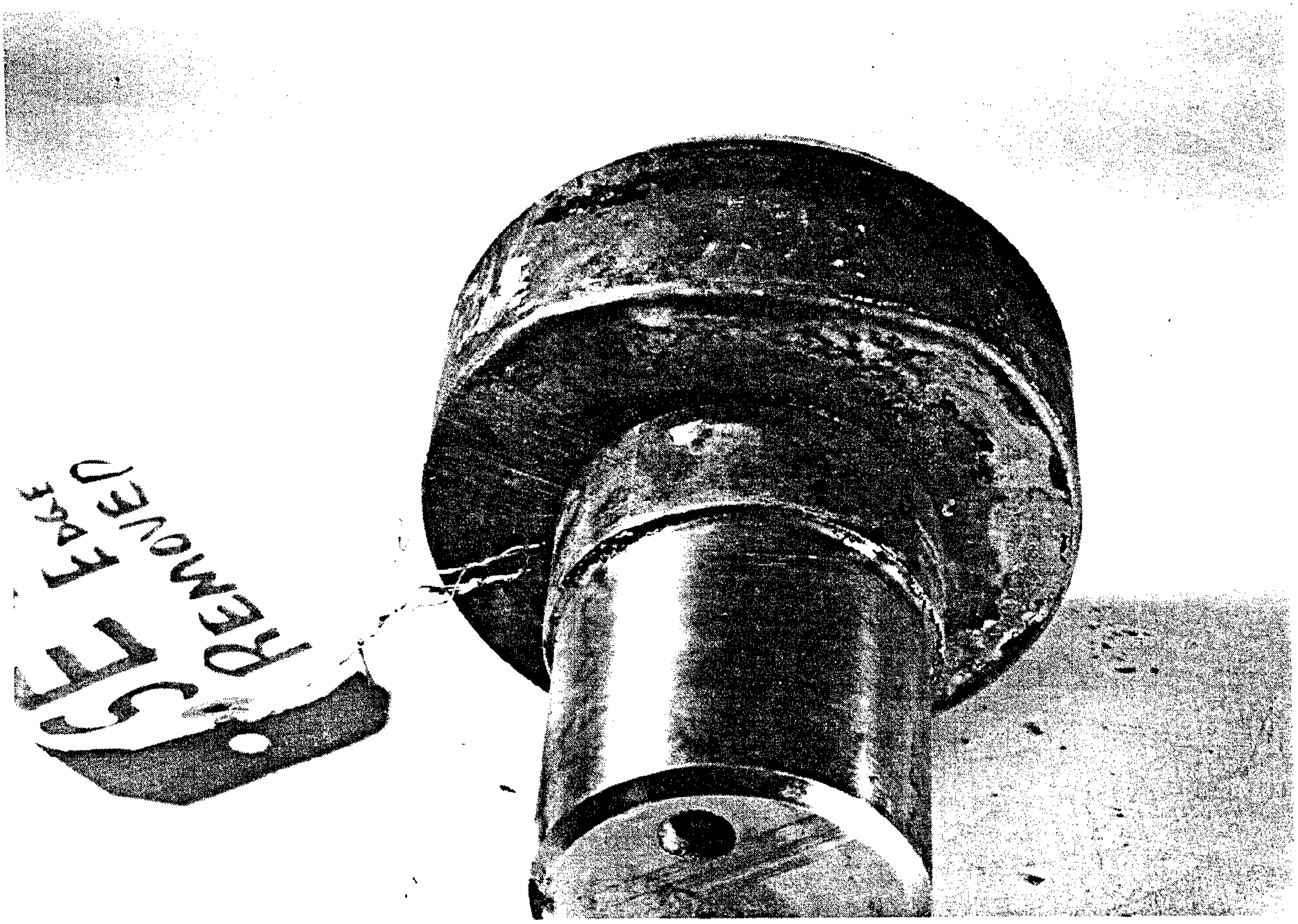
Upper SW edge roller.

Figure 4.3.24



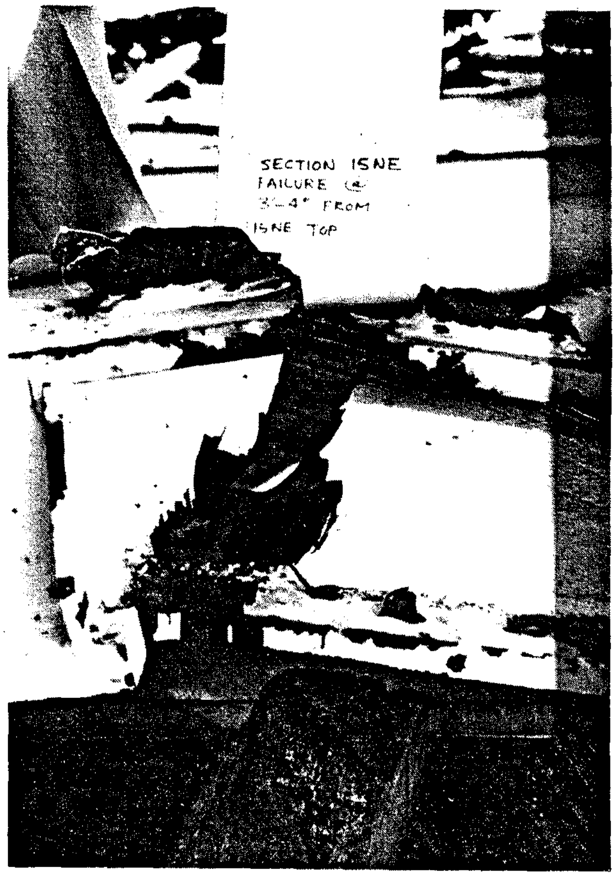
Damaged lower SW flange roller.

Figure 4.3.25



Deformation of upper SE edge roller.

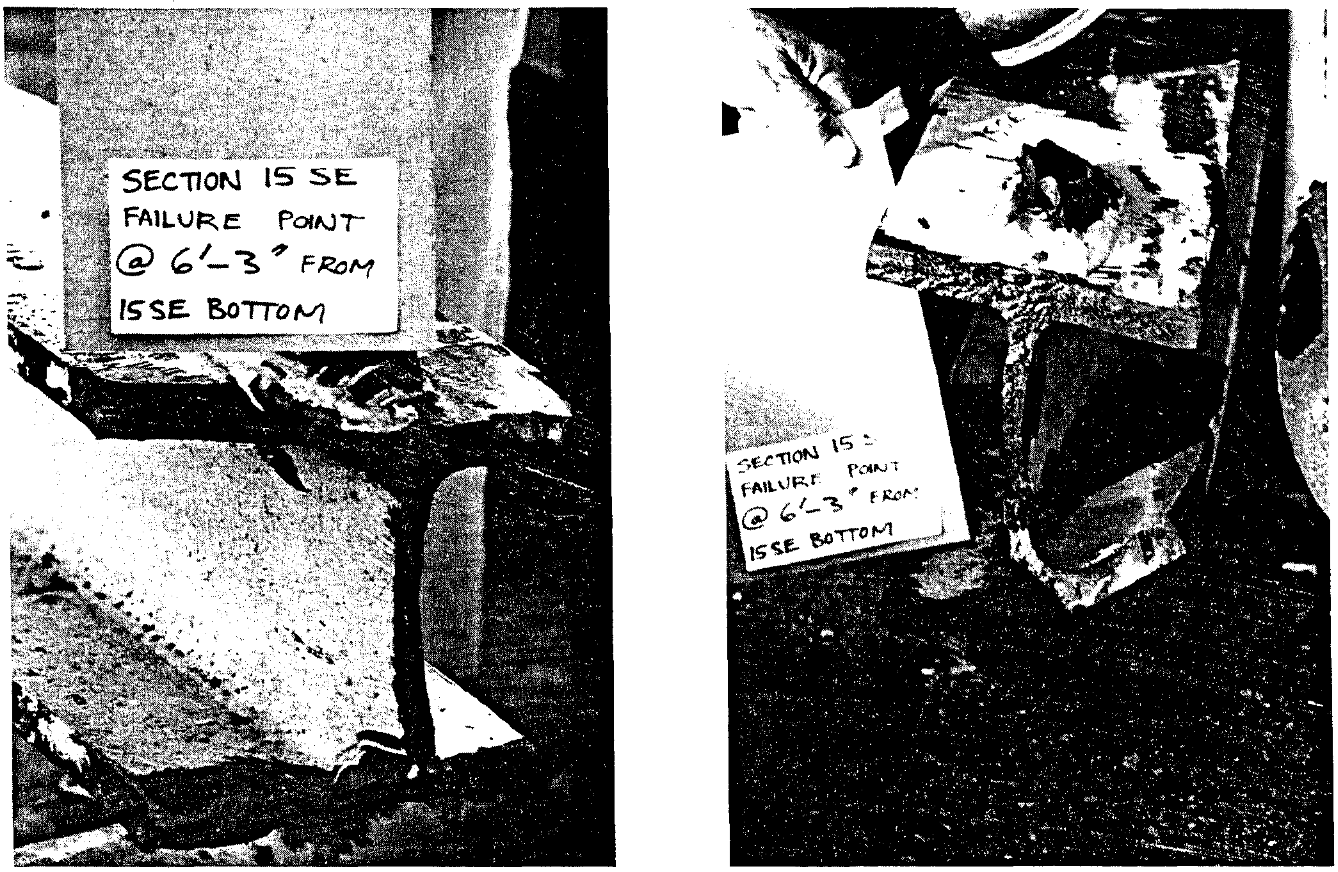
Figure 4.3.26



Failure of Section 15 NE leg at 3'-4" from top of member.

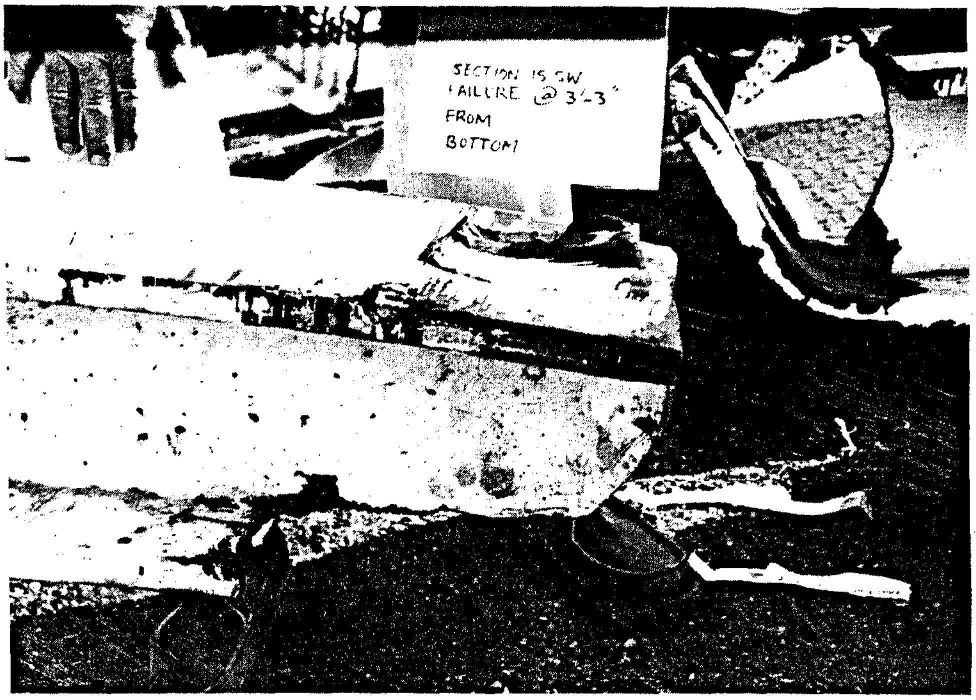
Failure of Section 15 NE leg at 6'-3" from bottom of member.

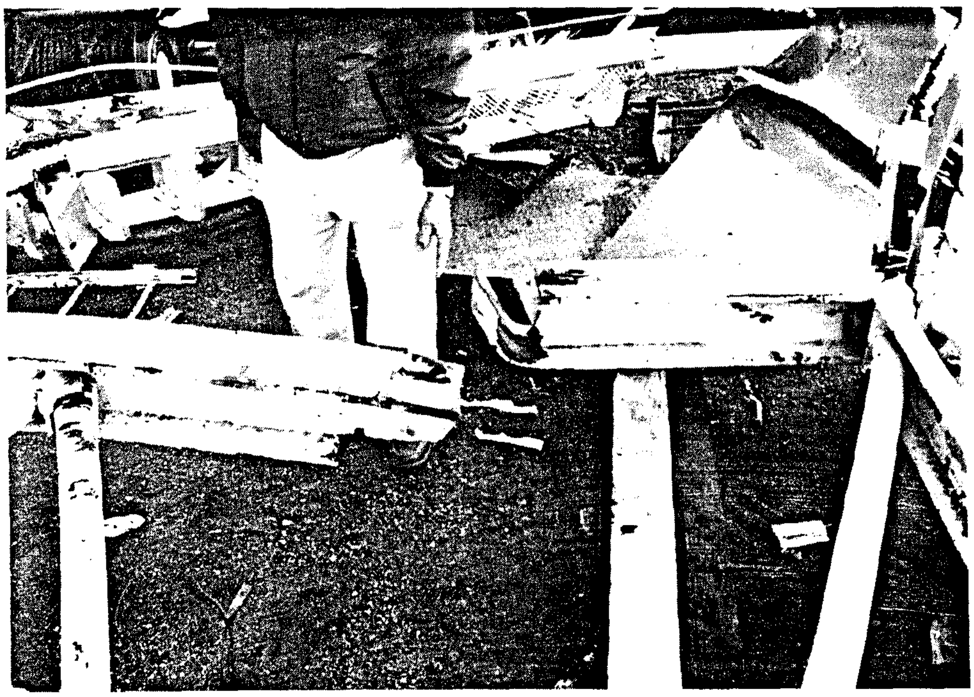
Figure 4.3.27



Failure of Section 15 SE leg at 6′-3″ from top of section.

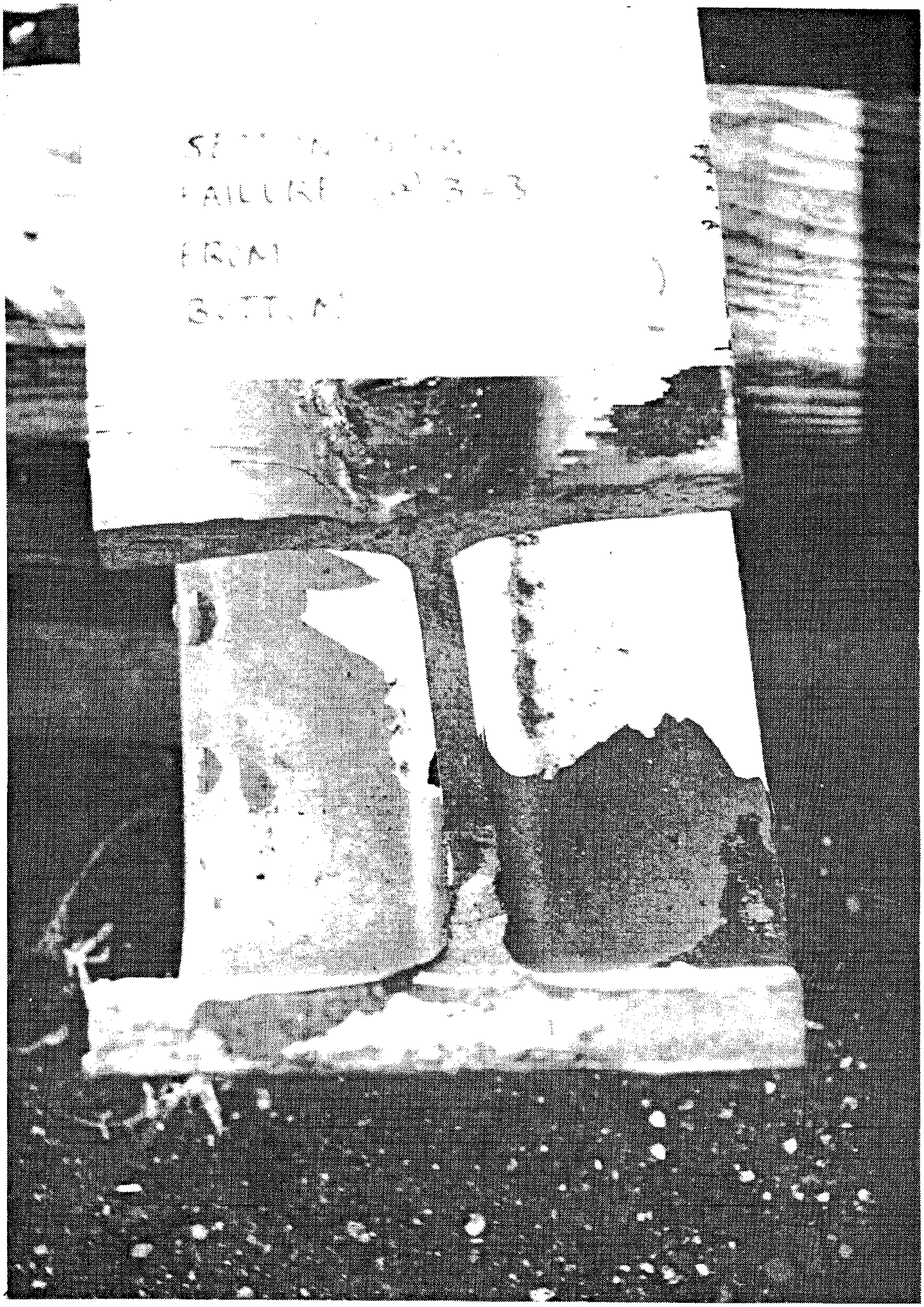
Figure 4.3.28



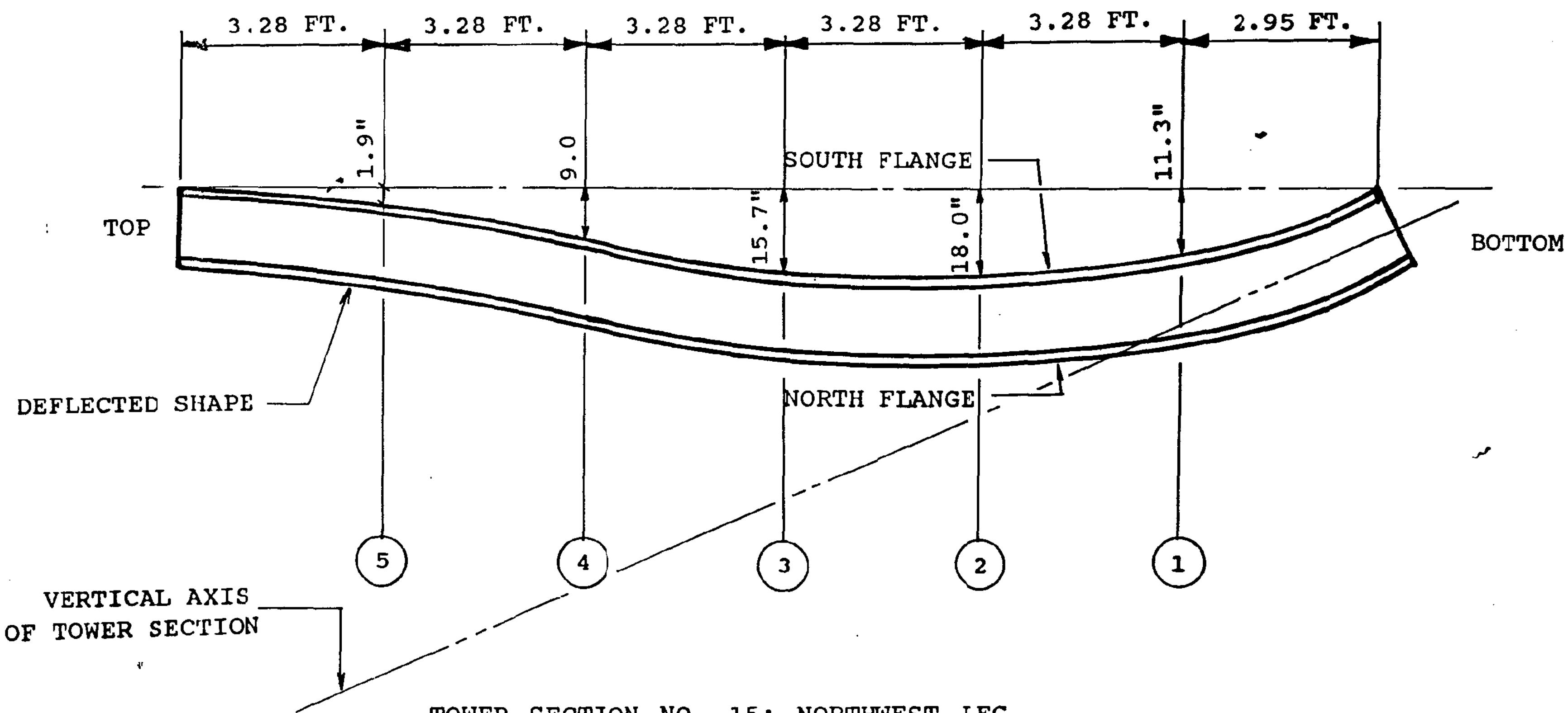


Failure of Section 15 SW leg — at 3′–4″ from bottom of member.

Figure 4.3.29



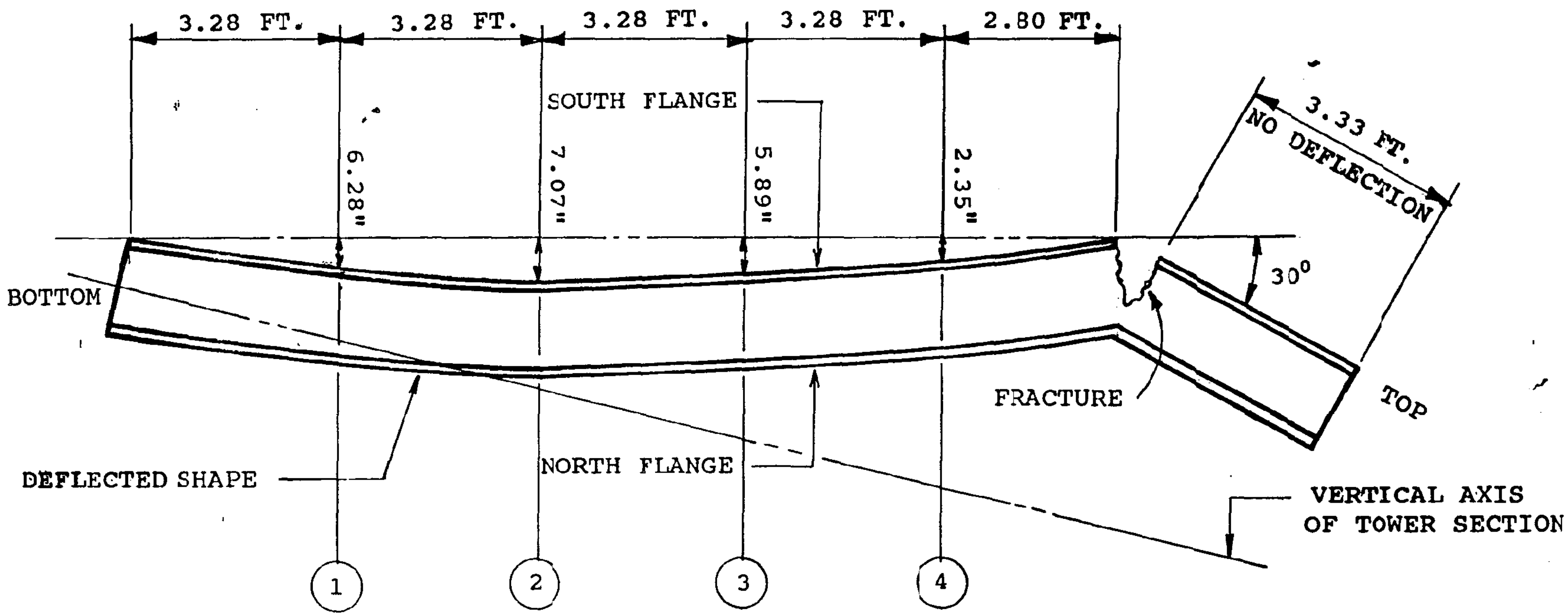
Failure of Section 15 SW leg at 3'-4" from the bottom of member — viewed toward the bottom of member.
Figure 4.3.30



TOWER SECTION NO. 15; NORTHWEST LEG

LOOKING EAST

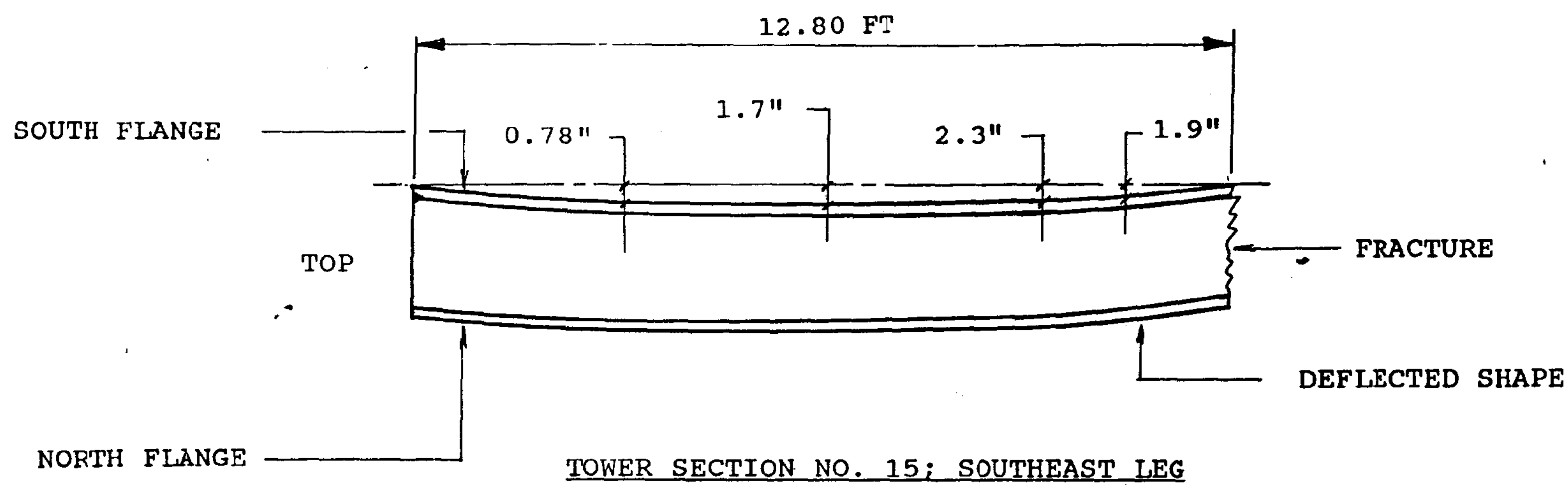
FIGURE 4.3.31



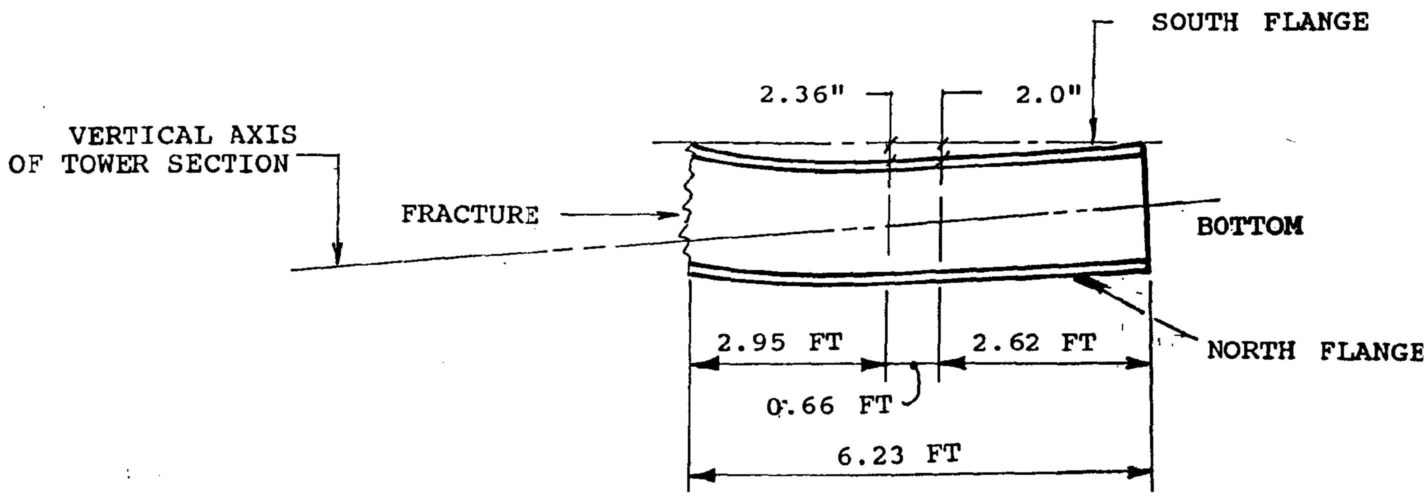
TOWER SECTION NO. 15; NORTHEAST LEG

LOOKING WEST

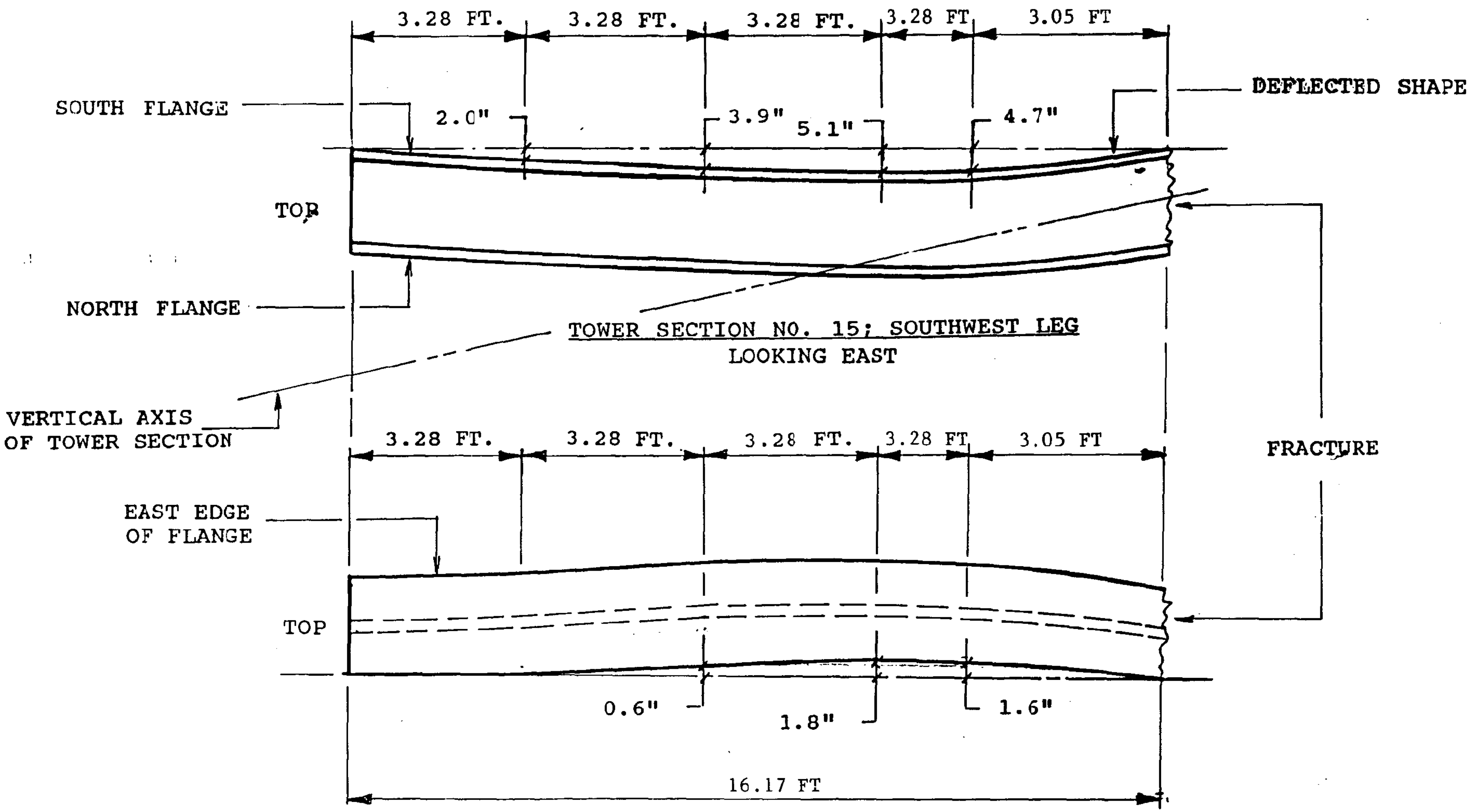
FIGURE 4.3.32



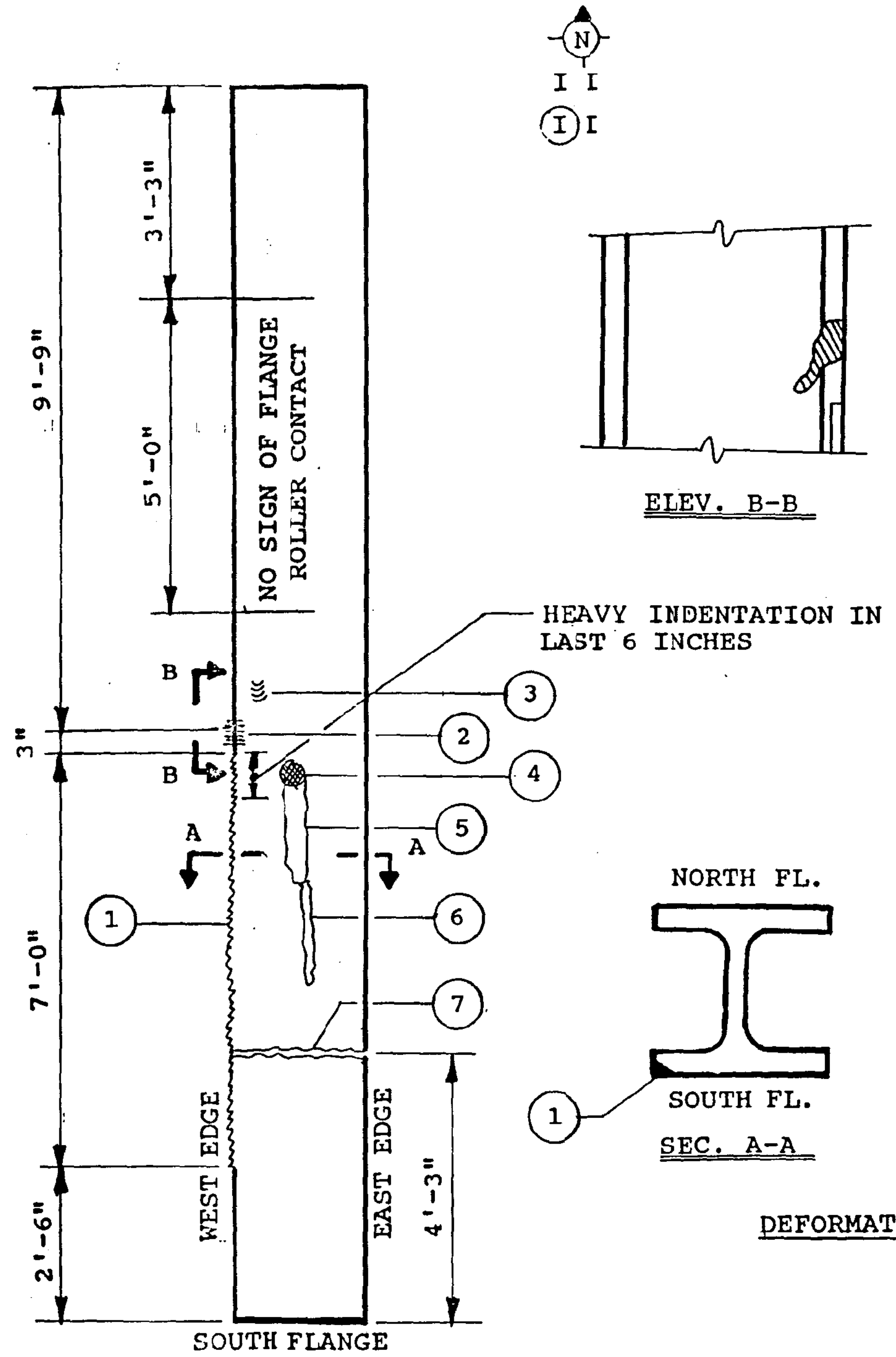
TOWER SECTION NO. 15; SOUTHEAST LEG
LOOKING EAST



TOWER SECTION NO. 15; SOUTHEAST LEG
LOOKING EAST
FIGURE 4.3.33



TOWER SECTION NO. 15; SOUTHWEST LEG
LOOKING NORTH
FIGURE 4.3.34

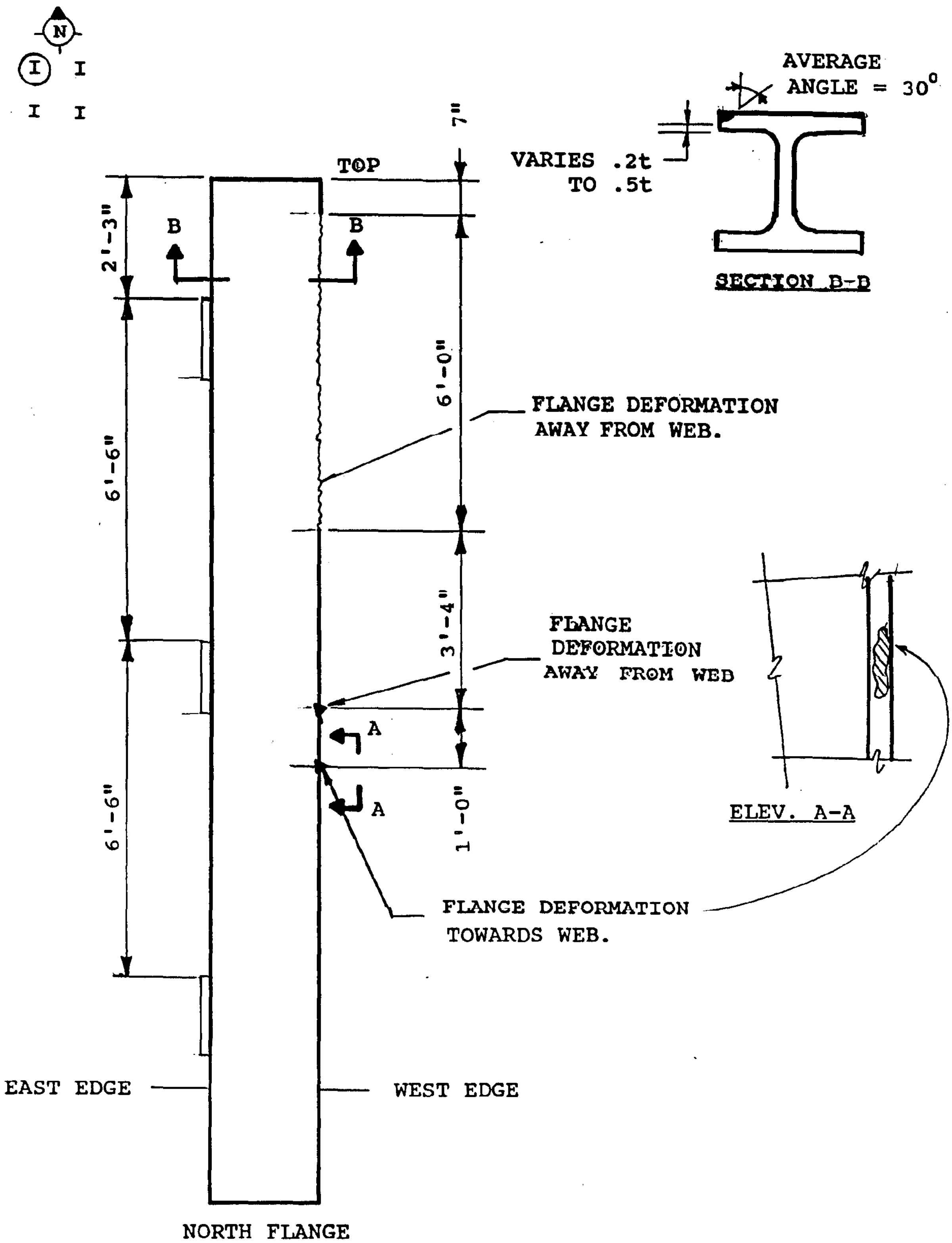


KEY TO SYMBOLS ON SW TOWER NO. 15 LEG.

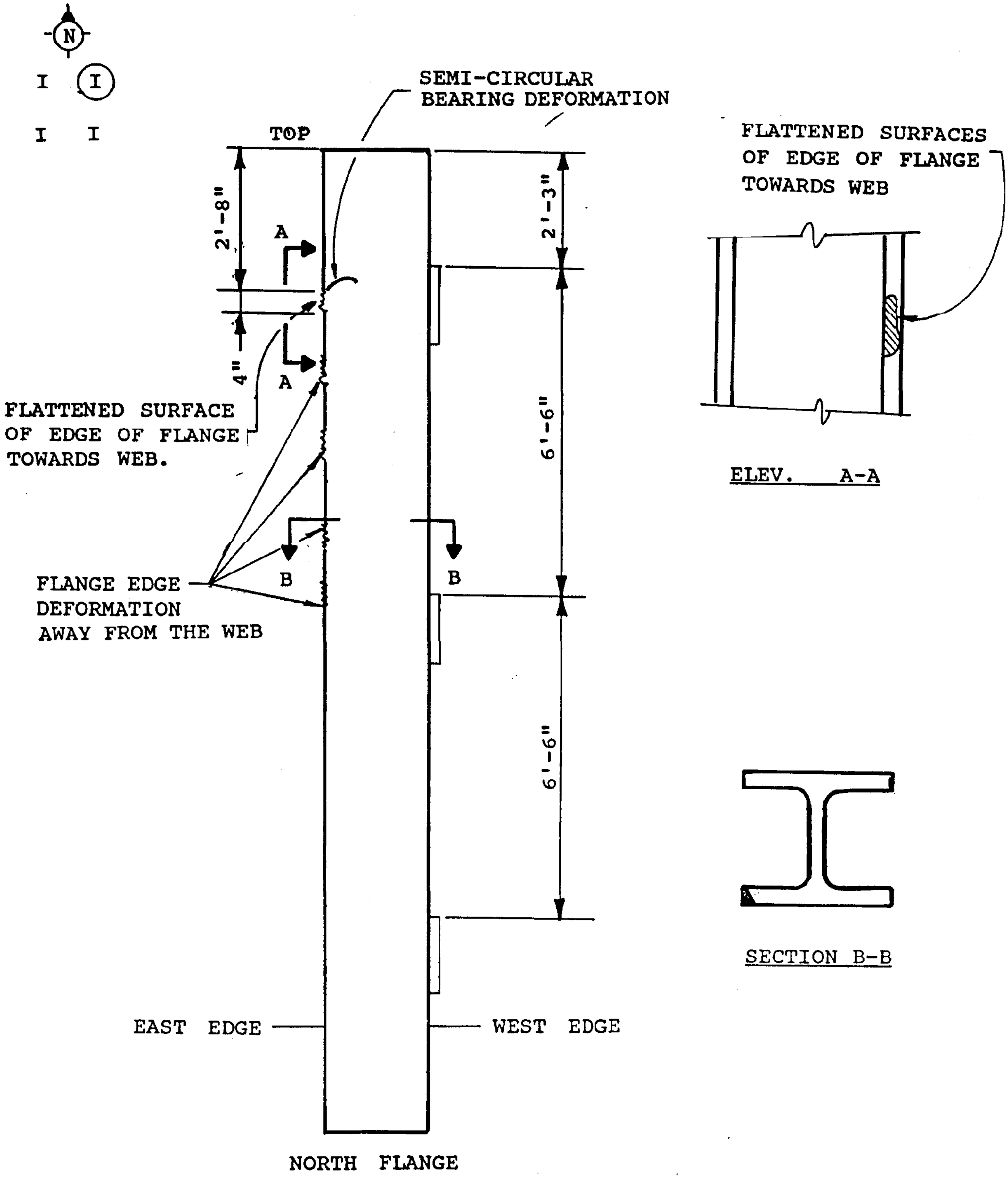
1. ROUGH METAL SCARS AND DEFORMATION AT THE EDGE OF THE FLANGE AS SHOWN IN SEC. 1-1. STARTING WITH ROUGH SCARS AT THE BOTTOM CHANGING TO DEFORMATION TOWARDS THE TOP. DEFORMATION INCREASING ALONG THE LENGTH TOWARDS THE TOP. LAST 6 TO 8 INCHES OF DEFORMATION IS DEEPER. ALL MARKS ON DEFORMATIONS AWAY FROM THE WEB. EXCEPT AT CENTER WHERE IT COVERED THE ENTIRE EDGE
2. DEFORMATION, FLATTENING AND DEEP CUT AS SHOWN IN ELEVATION B-B, TOWARDS THE WEB.
3. MULTIPLE SEMI-CIRCULAR AND GOUGES AND FLATTENING ABOUT 2" INSIDE FROM THE WEST EDGE.
4. SMALL FLATTENED SURFACE.
5. WIDE PAINT SCAR.
6. NARROW PAINT SCAR.
7. FRACTURE

DEFORMATION AND MARKS ON TOWER SECTION NO. 15 SW LEG

FIGURE 4.3.35

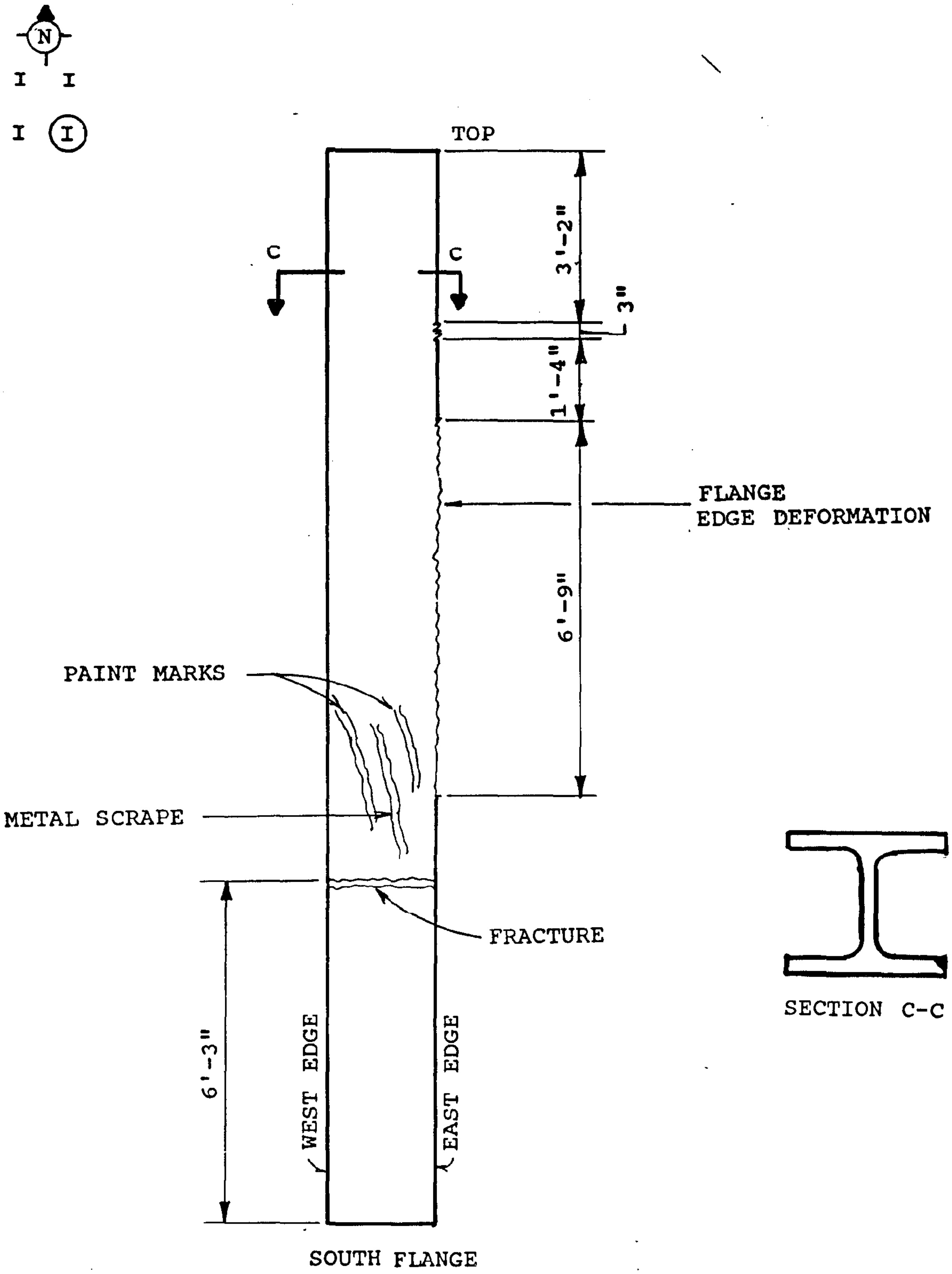


DEFORMATION AND MARKS ON TOWER SECTION NO. 15 NW LEG
FIGURE 4.3.36



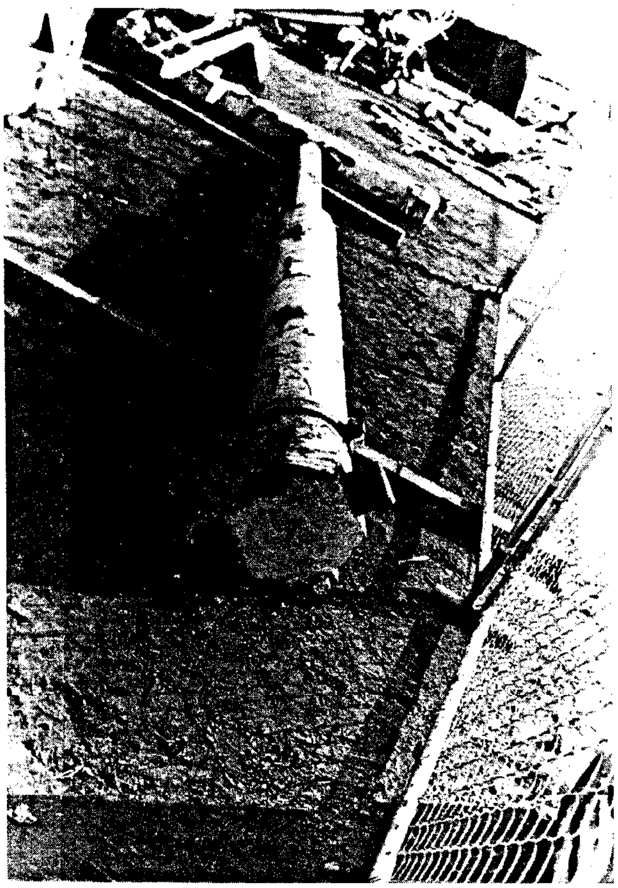
DEFORMATION AND MARKS ON TOWER SECTION NO. 15 NE LEG.

FIGURE 4.3.37



DEFORMATION AND MARKS ON TOWER SECTION NO. 15 SE LEG.

FIGURE 4.3.38



Hydraulic ram — viewed from the top.

Hydraulic ram and climbing transverse — looking from bottom.

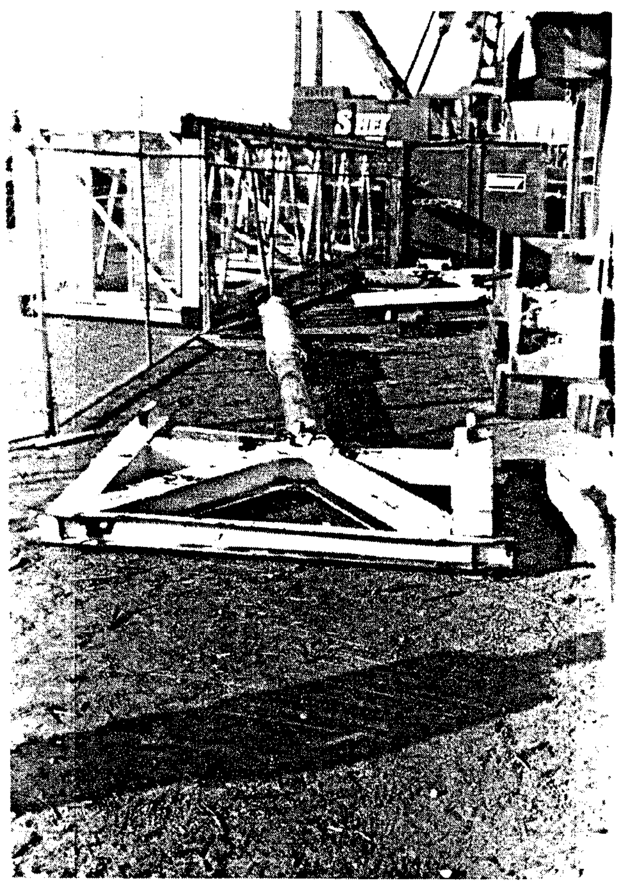
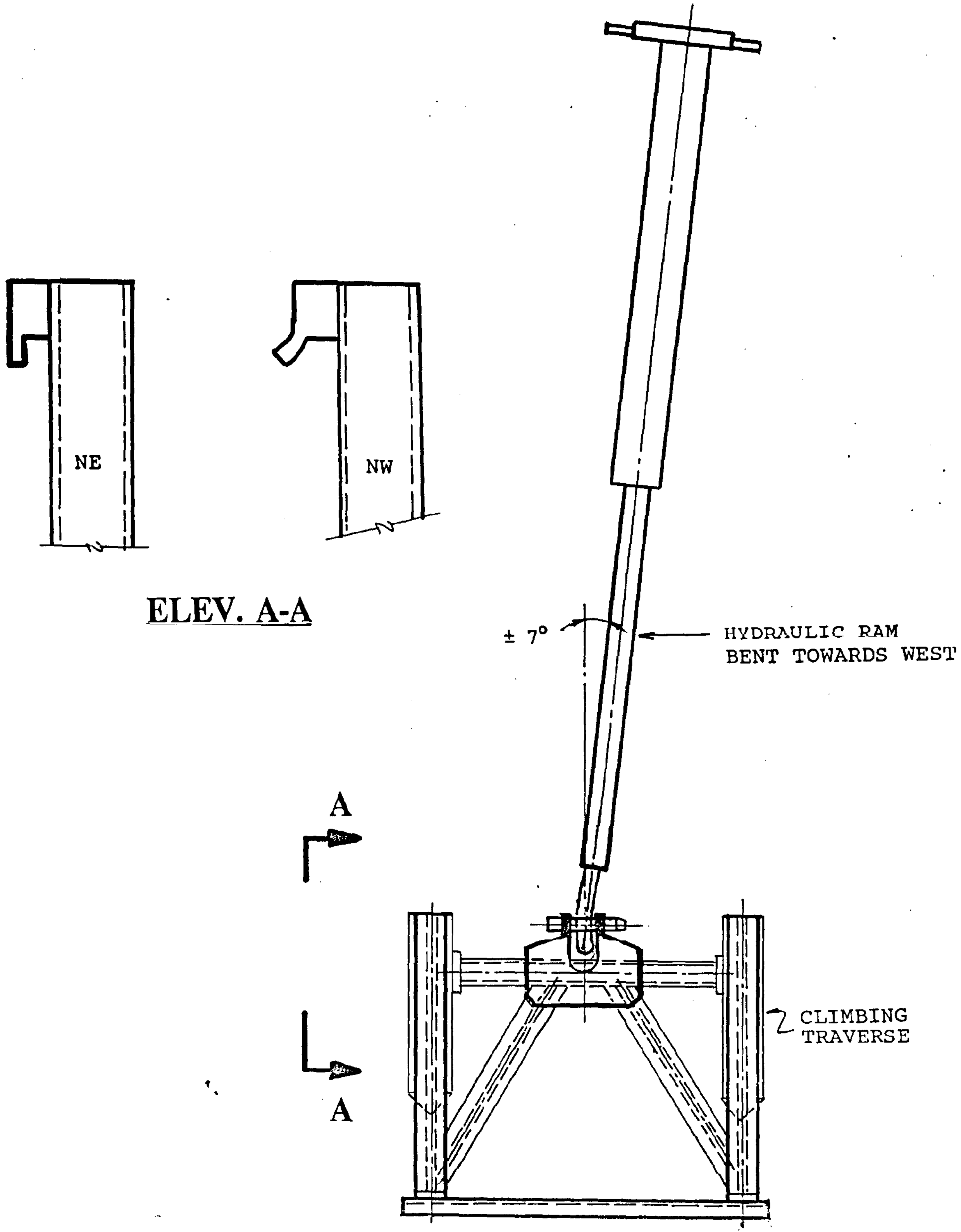
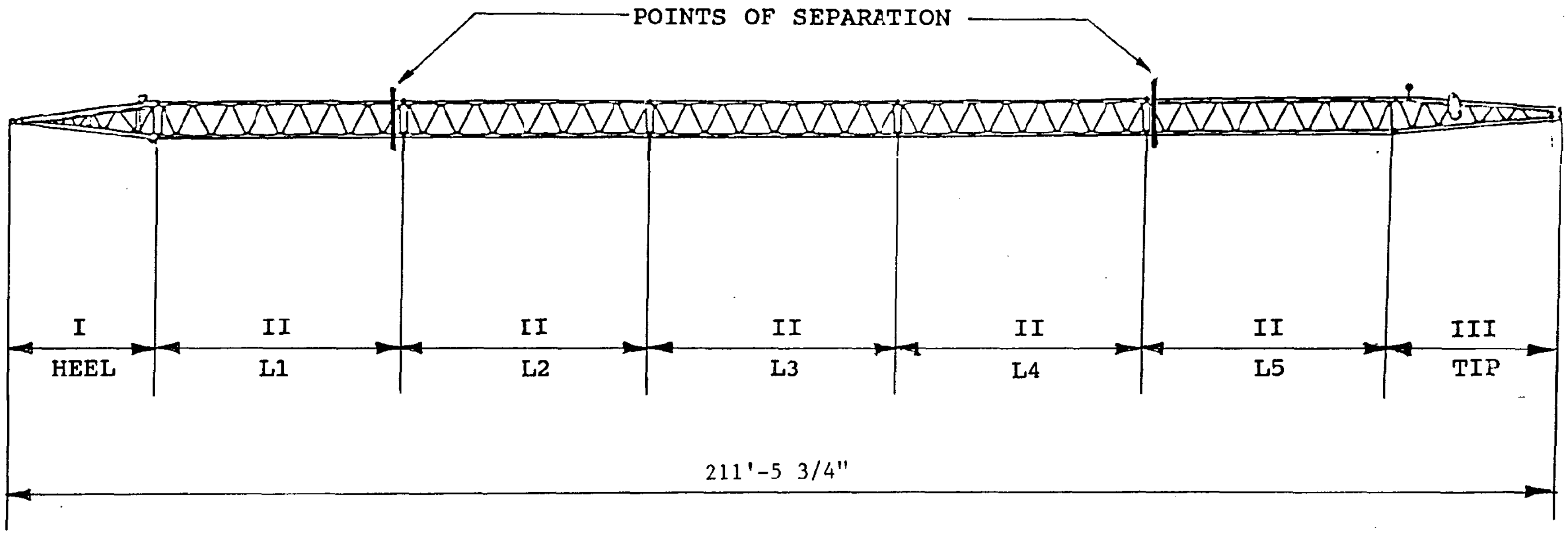


Figure 4.3.39



CLIMBING TRAVERSE AND HYDRAULIC RAM

FIGURE 4.3.40



LUFFING BOOM
ELEVATION
FIGURE 4.3.41

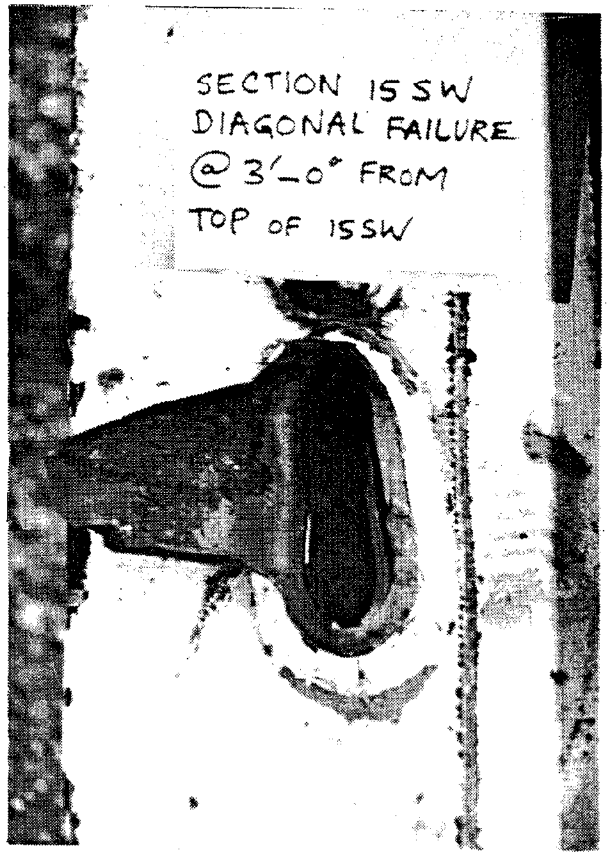
Portion of collapsed boom hanging from the building under construction onto California Street.

Main part of the collapsed boom - laying on California Street.

Figure 4.3.42

Deformed climbing section after collapse -- leaning on 580 California Street.

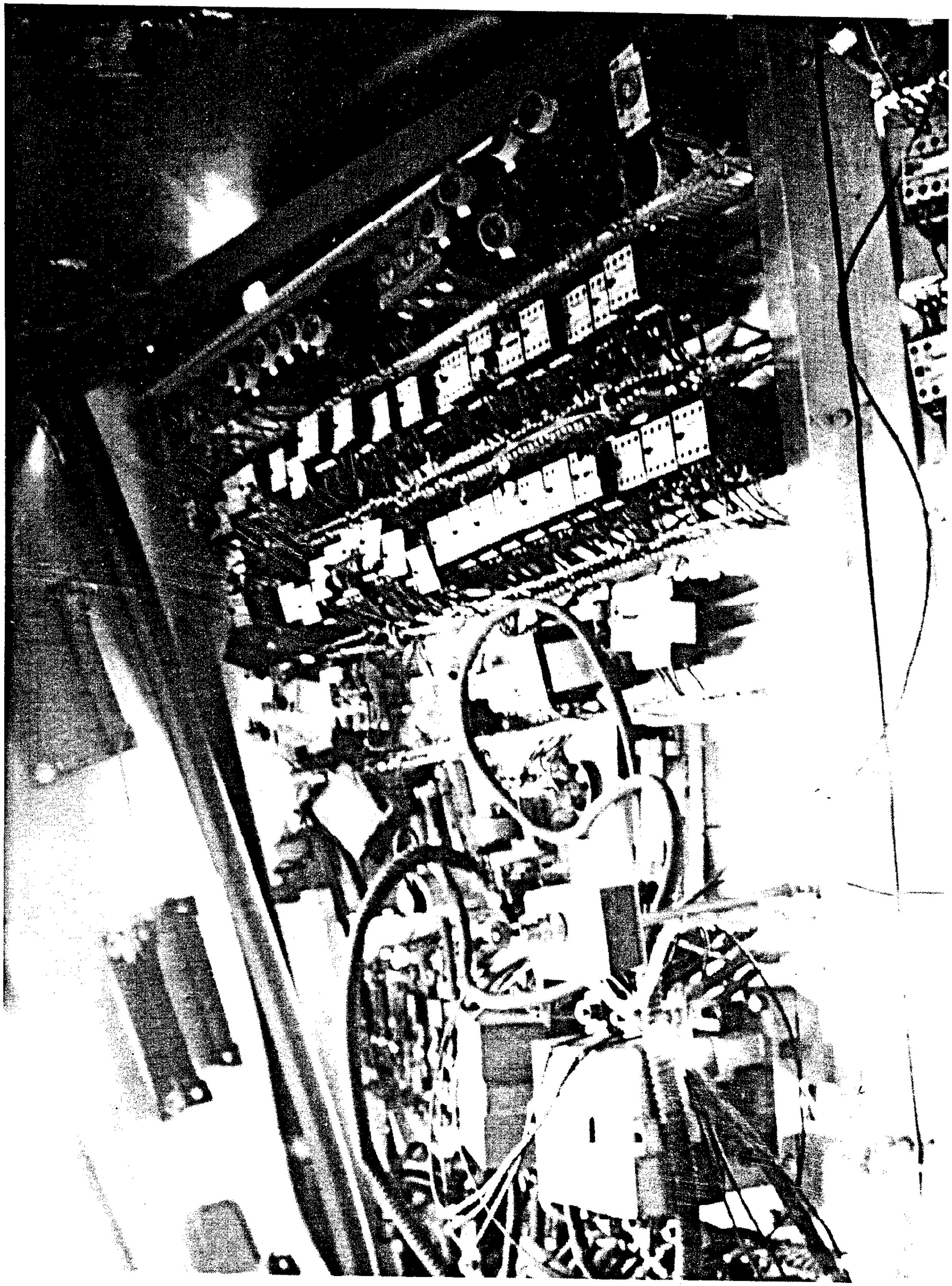
Figure 4.3.44



Failure of Section 15 SW diagonal at 3'-0" from top of section.

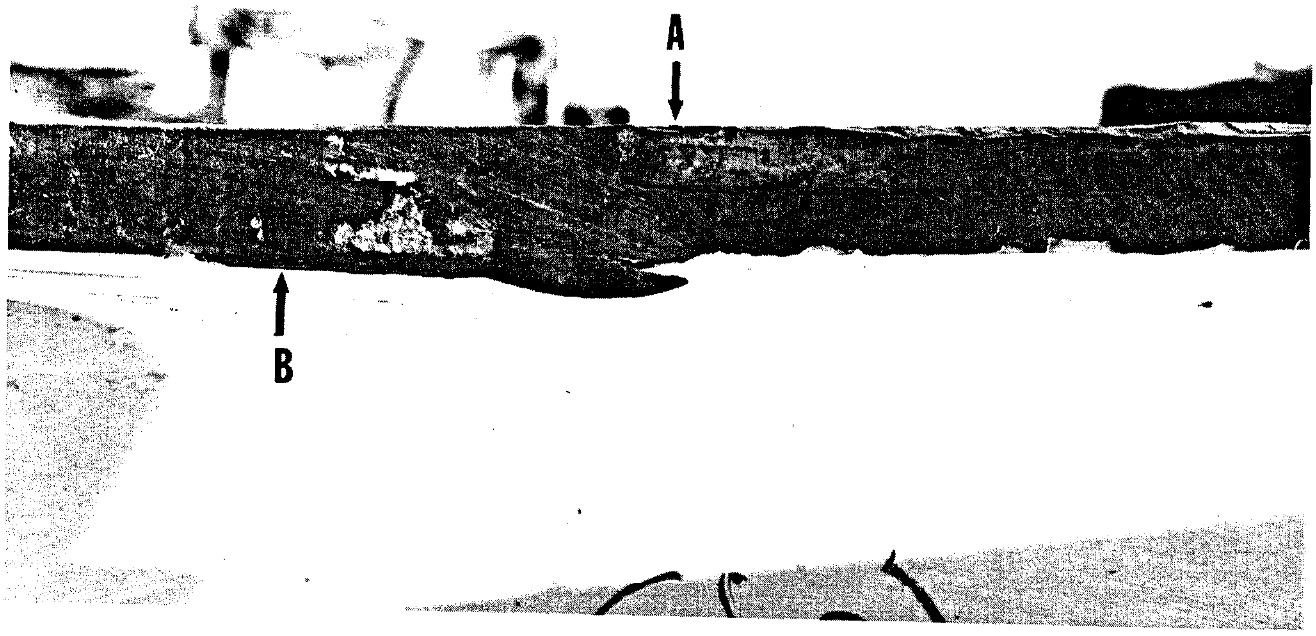
Failure of Section 15 SE diagonal at bottom of section.

Figure 4.3.45



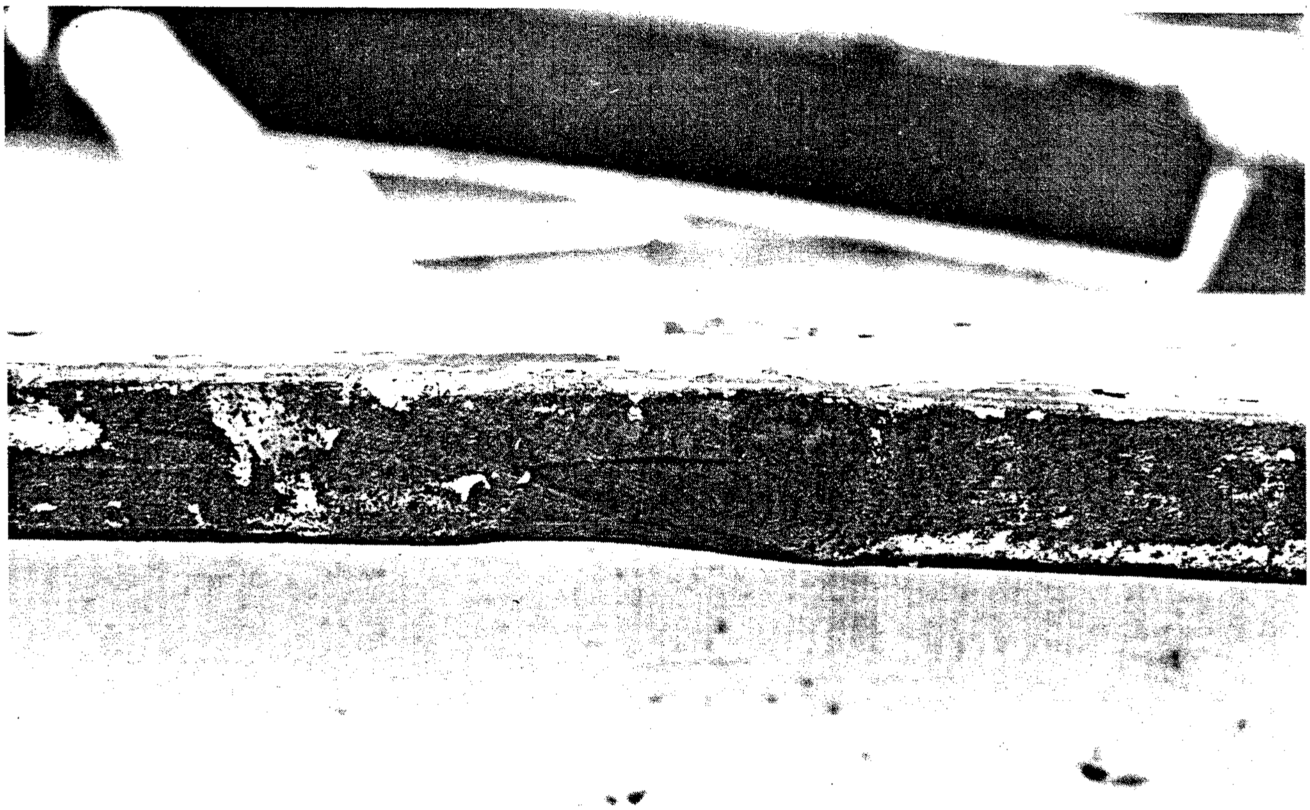
View of damaged electrical control room.

Figure 4.3.46



Flange deformations - marked as 1 and 2 - on the West edge of South flange of tower Section 15 SW leg.

Figure 4.3.47

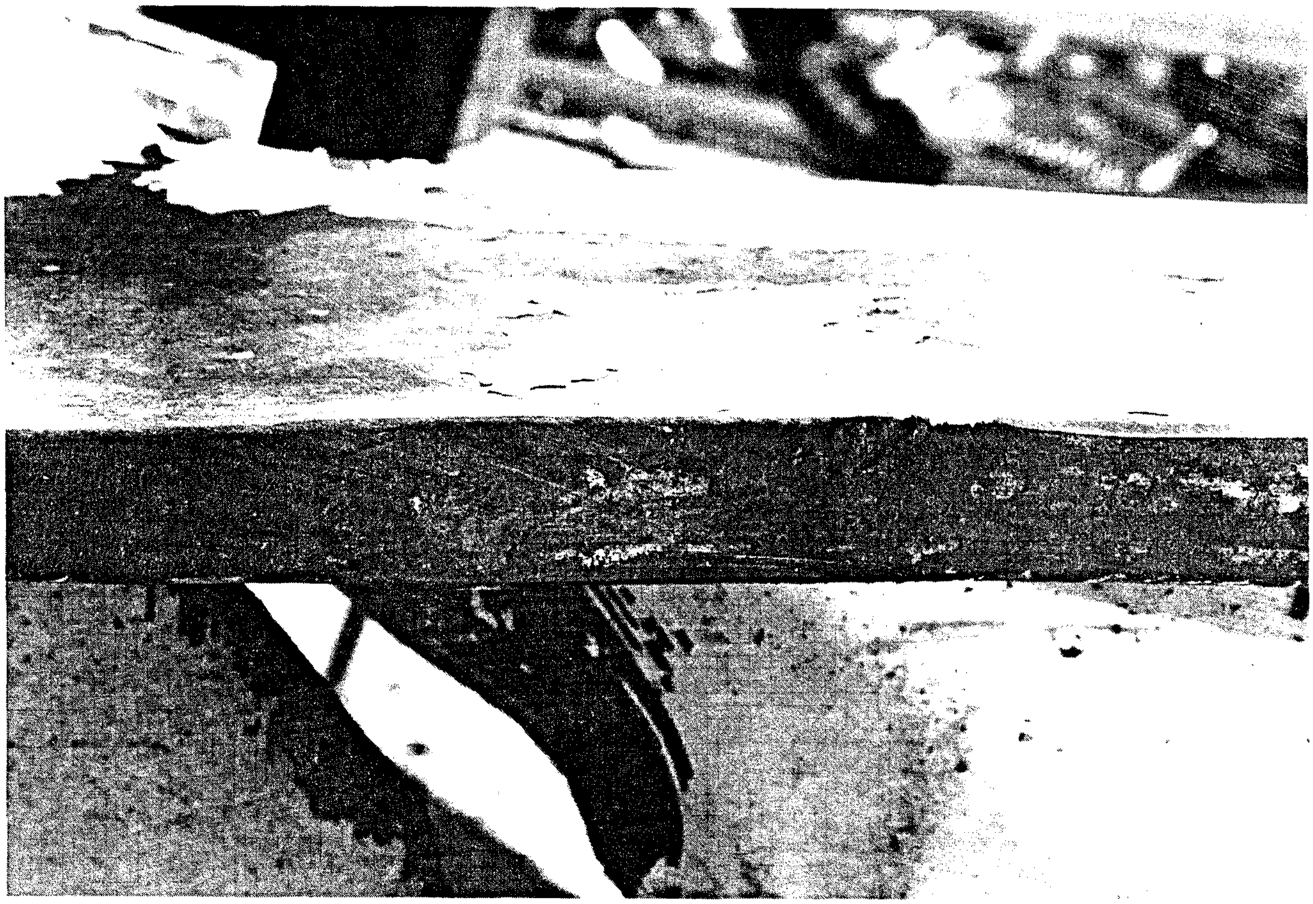


Deformation at 11'-0" from top on the West edge of North flange of tower Section 15 NW leg.

Figure 4.3.48

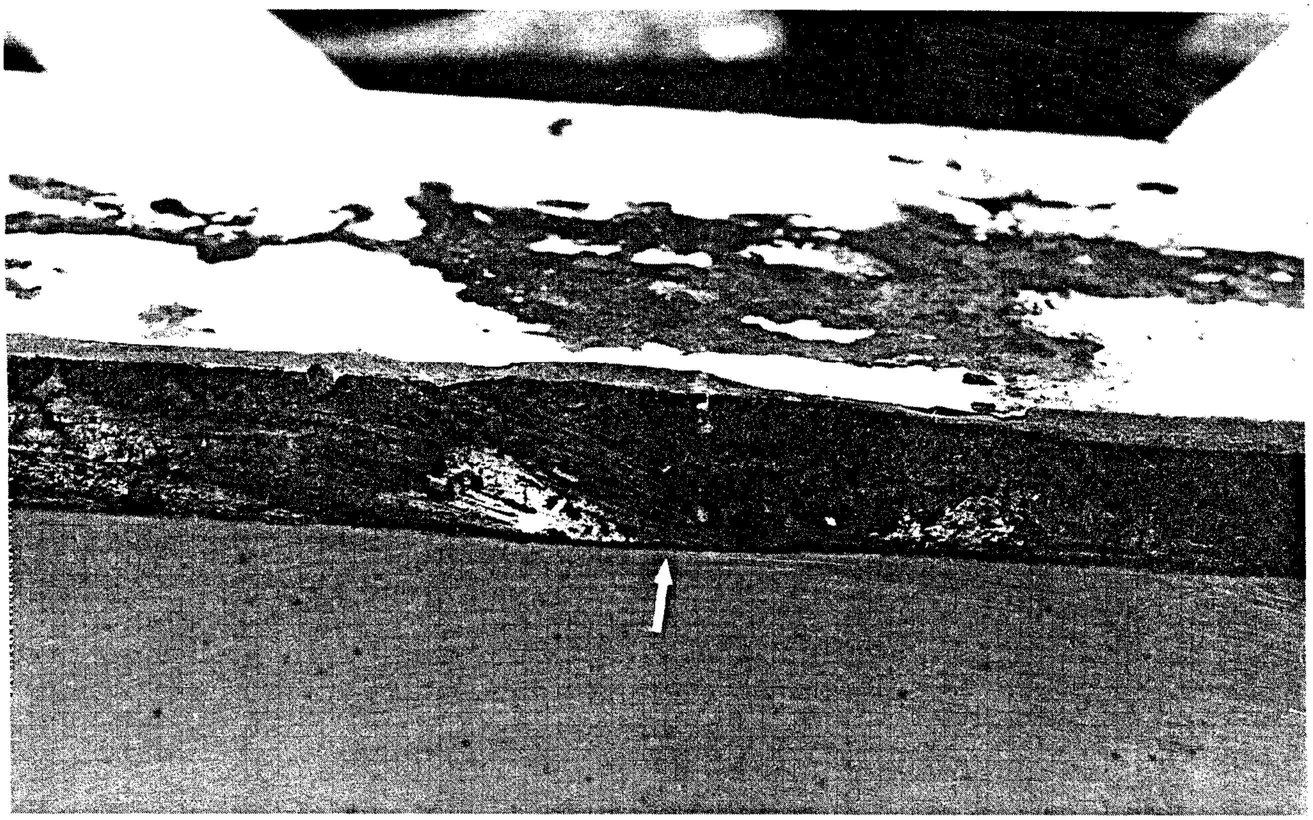
Deformation at 10'-0" from top on the West edge of North flange of tower Section 15 NW leg.

Figure 4.3.49



Flange deformation at 2'-8'' from top on East edge of North flange to tower Section 15 NE leg.

Figure 4.3.50



Flange deformation at 3'-2" from top on East edge of South flange of tower Section 15 SE leg.

Figure 4.3.51

5 LABORATORY TESTS

5.1 Introduction

The laboratory tests carried out as part of this investigation were conducted by a private testing laboratory under contract to CalOSHA. The complete results from these tests are included in the contractor's report to CalOSHA [2]. The following sections summarize the highlights of these tests.

5.2 Material Properties

Tests were conducted to determine the chemical composition and mechanical properties of the steel used for the tower sections and the climbing section. The tests were conducted on samples taken from the columns and connection plate of tower section 14, the southwest and northwest legs of the climbing section and the diagonal bracing in the climbing section and tower sections 14 and 15. In order to preserve the deformation pattern of tower section 15 for future reference, no specimens were taken from the columns of this section. The location of the samples taken from the structure are given in table 5.2.1.

Chemical Composition

Results of the analysis of the chemical composition of the steel members are presented in table 5.2.2. The results may be compared with requirements specified in DIN 71 100 for ST 52-3 steel the material specified for the structural members according to engineers from American Pecco Corporation. This comparison indicates the chemical composition of the specimens met these requirements.

Tensile Tests

Tensile test specimens for the columns of the climbing section and tower section 14 were cut from both the flange and web of the segments removed from the structure. For each column, two coupons were cut from the flange and one from the web. Only minimal surface cleaning was performed to remove paint or rust from these specimens in order to permit testing a specimen representing the full section thickness. The specimens had an overall length of 18 inches. For the diagonal bracing, the coupons were cut parallel to the longitudinal axis of the bracing at three locations about 120 degrees apart around the circumference of the tubular cross section.

A tensile specimen was also cut from the connecting plate of the southeast column of tower section 14. The axis of the specimen was perpendicular to the vertical fracture that occurred in this plate which connected tower sections 14 and 15. The specimen had a one inch gage length and a gage section diameter of 0.25 inch. All specimens conformed to ASTM E 8-89, "Standard Methods for Tension Testing of Metallic Materials," and were tested in accordance with this specification. The yield point was determined as the stress at 0.5 percent total extension.

The tensile test results are summarized in table 5.2.3. The yield point of all the specimens except for the connecting plate of tower section 14, exceed the minimum required for ST 52-3 steel. The percent elongation values are indicative of ductile structural steel. The average values and standard deviation for the mechanical properties for each of the sections are:

Tower Section 14

Column

- Yield point (ksi) - 50.1, 2.8
- Ultimate tensile strength (ksi) - 81.8, 2.1
- Percent elongation - 27.0, 3.8

Diagonal Bracing

- Yield point (ksi) -61.3, 0.7
- Ultimate tensile strength (ksi) - 86.5, 0.4
- Percent elongation - 33.0, 0.4

Tower Section 15

Diagonal Bracing

- Yield point (ksi) -63.8, 6.1
- Ultimate tensile strength (ksi) - 89.9, 0.7
- Percent elongation - 31.3, 3.7

Climbing Section

Column

- Yield point (ksi) - 60.5, 2.4
- Ultimate tensile strength (ksi) - 77.2, 1.9
- Percent elongation - 26.2, 5.5

Diagonal Bracing

- Yield point (ksi) - 57.6, 0.3
- Ultimate tensile strength (ksi) - 85.4, 0.8
- Percent elongation - 33.5, 0.4

Charpy Impact Tests

Charpy V-notch impact tests were conducted to determine the fracture toughness of the steel in the tower and climbing section and the connecting plates of the columns. The purpose of these tests was to determine the fracture toughness at the temperature on the site at the time of the collapse. No attempt was made to evaluate fracture toughness over a range of temperatures and determine the transition temperature. Three Charpy specimens were machined in accordance with ASTM E23-88, "Standard Method for Notched Impact Testing of Metallic Materials," from the same column and diagonal bracing segments from which the tensile coupons were obtained. Because of the limited wall thickness of the diagonal bracing, specimens that were three-fourths of the standard size, i.e., 7.5 mm in width compared to the standard width of 10 mm were used. The specimens from the column segments were taken from the flanges with each specimen oriented parallel to web of the member. The specimens from the diagonal bracing were parallel to the longitudinal axis of the member. The specimens from the connecting plate were perpendicular to the plate thickness. Thus, the impact test fractures in all the specimens were in planes parallel to the fracture planes in the tensile specimen. Since the low temperature reading on the morning of the crane accident based on surface weather observations by the National Weather Service Office for the City of San Francisco was 45°F, the tests were performed at 45°F.

The results of the Charpy V-notch impact tests are presented in table 5.2.4. The impact energies obtained for all the specimens were relatively high. The lowest energies reported for column of tower section 14 are well above the value of 15 ft·lbf considered desirable for steels in structural applications.

5.3 Analysis of Fracture Surfaces

The fracture surfaces in tower sections 14 and 15 (locations A through G, in figure 4.3.3) were examined using a scanning electron microscope and optical microscopy and microhardness tests were also performed on these surfaces. The objective of the testing was to determine the characteristics and microstructure of these fractures.

Examination of the fracture surfaces showed that major portions of the fractures were macroscopically brittle. The fractures resulted from single overload failure with no evidence of progressive crack growth due to fatigue loading.

Two of the fractures showed evidence of prior cracks. One of these two fractures was in the southwest leg of tower section 14 at about 40 inches from the top surface of the connection plate at the top of the leg (location D in figure 4.3.3). The prior crack from which the final fracture initiated was at the common toe of two circumferential welds joining the diagonal bracing to the northwest leg. The other prior crack was part of the vertical fracture at the top of the top connection plate of the northwest leg (location B in figure 4.3.3).

Microstructural examination and microhardness testing of weld regions in tower section 14 indicated that the heat affected zones had high hardness and exhibited microstructures that would be expected to promote brittle failure.

These observations indicated that the weld areas in legs of the tower sections were regions that were prone to prior cracks and/or brittle failure.

5.4 Slewing Brake

Portions of both friction slewing brakes were examined after the accident by the testing laboratory. The purpose of this examination was to document the condition of the brakes and determine, if possible, the condition and state of assembly prior to the crane collapse.

The drum, brakeshoes, brakearms and spreading magnet from the one slewing brake displayed substantial damage attributable to the impact after the collapse as well as wear and tear from service. The outer surface of the drum appeared to be chromium plated across the full width of the friction surface; the contact area with the brakeshoes was about three quarters of the width. The thickness of the brake pads was about 0.30 inch and 0.32 inch. The friction surface of the drum of one slewing brake was discolored by brown deposits. A closeup view of some of these deposits suggests that the friction forces on the drum were minimal since heavy friction would wipe the surface clean. It is possible, however, that these deposits occurred after the collapse.

Only the brakepad and brakearm attached to the spreading magnet armature were recovered from the second slewing brake assembly. The thickness of the available brakepad was about 0.34 inch.

None of the fractures in the slewing brake components displayed any areas of altered texture or discoloration that would indicate that a crack or fracture existed prior to the accident. All of the fractures were bright and clean and generally associated with impressions or gouges attributed to impact during the accident. Similarly, the various bends and abrasions appeared to be due to collision with other structures or objects during the accident, and there was no evidence to suggest that components that were missing, were missing before the accident. From the present condition of the brakes, it was not possible to determine whether either of the brakes had been applied or not just prior to the accident.

TABLE 5.2.1

IDENTIFICATION OF SAMPLES OF STRUCTURAL MEMBERS
FOR LABORATORY TESTS

1. Top portion, containing a fracture, from the southeast leg of tower section 14.
2. Top portion, containing a fracture, from the southwest leg of tower section 14.
3. Top portion, containing a fracture, from the northwest leg of tower section 14.
4. Top portion, containing a fracture, from the northeast leg of tower section 14.
5. Bottom portion of the southeast leg of tower section 14, containing the mating fracture for sample 1.
6. Bottom portion of the southwest leg of tower section 14, containing the mating fracture for sample 2.
7. Bottom portion of the northwest leg of tower section 14, containing the mating fracture for sample 3.
8. Bottom portion of the northeast leg of tower section 14, containing the mating fracture for sample 4.
9. Southwest leg of climbing section, minor member.
10. Northwest leg of climbing section, major member.
11. Segment of diagonal from the climbing section.
12. Segment of diagonal from tower section 15.
13. Segment of diagonal from tower section 14.

TABLE 5.2.2

CHEMICAL ANALYSIS OF STEEL MEMBERS
(PERCENT)

Location		C	P	S	Mn	Si	Ni	Cr	V	Mo	Cu
Tower Section 14	Southeast Leg	0.19	0.027	0.015	1.54	0.46	0.03	0.02	<0.005	<0.005	0.01
Connection Plate of Tower Section 14	Southeast Leg	0.17	0.025	0.022	1.25	0.44	0.16	0.24	<0.005	<0.005	0.13
Climbing Section	Southwest Leg	0.14	0.020	0.023	1.26	0.36	0.02	0.06	<0.005	<0.005	0.008
	Northwest Leg	0.15	0.015	0.012	1.29	0.34	0.02	0.04	<0.005	<0.005	<0.005
Diagonals	Climbing Section	0.20	0.011	0.014	1.35	0.23	0.02	0.01	0.06	<0.005	0.01
	Tower Section 15	0.18	0.006	0.011	1.30	0.33	0.20	0.30	<0.005	0.03	0.30
ST 52-3 Steel requirements (1)		0.22 max.	0.050 max.	0.050 max.	1.70 max.	0.60 max.					

(1) In accordance with DIN 17 100.

TABLE 5.2.3

TENSILE TEST RESULTS

		Specimen	Yield Point (ksi)	Ultimate Tensile Strength (ksi)	Percent Elongation (%)
Tower Section 14	Southeast Leg (connection plate)	1-1	45.3	78.2	32
	Southeast Leg	5-1	51.9	82.9	26.5
		5-2	52.3	83.5	21.5
		5-3	50.9	82.7	28
Climbing Section	Southwest Leg	9-1	58.0	75.0	28.5
		9-2	64.4	79.7	22.5
		9-3	57.3	74.7	28.5
	Northwest Leg	10-1	60.6	77.2	27
		10-2	62.0	74.4	23.5
		10-3	60.4	77.1	27
	Diagonals	11-1	57.7	84.8	34
		11-2	57.3	84.8	33.5
		11-3	57.9	86.5	33
Tower Section 15	Diagonals	12-1	72.0	90.7	28
		12-2	61.8	89.9	29.5
		12-3	57.6	89.0	36.5
Tower Section 14	Diagonals	13-1	61.9	86.5	32.5
		13-2	61.7	86.9	33.5
		13-3	60.4	86.0	33
ST 52-3 Steel requirements (1)			51.5 (3) 50.0 (5)	71.7-91.4 (2)	22 (4)

(1) In accordance with DIN 71 100.
(2) Section thickness 3 to 100 mm.
(3) Section thickness less than 16 mm.
(4) Section thickness 3 to 40 mm.
(5) Section thickness greater than 16 mm but less than 40 mm.

TABLE 5.2.4

CHARPY V NOTCH TEST RESULTS

		Specimen	Energy Absorption (ft/lbs)
Tower Section 14	Southeast Leg	1	41
		2	40.5
		3	45.5
	Southwest Leg	1	53.5
		2	38
		3	35.5
		4	52
Climbing Section	Southwest Leg	1	107
		2	183
		3	176
	Northwest Leg	1	207
		2	245
		3	194
Diagonal Bracing	Climbing Section	1	79
		2	63
		3	59
	Tower Section 15	1	84
		2	84
		3	85
	Tower Section 14	1	96
		2	125
		3	92

TABLE 5.2.4 (Continued)

CHARPY V NOTCH TEST RESULTS

		Specimen	Energy Absorption (ft/lbs)
Connection Plates	Tower Section 14 Southeast	1	73
		2	150
		3	153
	Tower Section 14 Northeast	1	94
		2	67
		3	71.5
	Tower Section 14 Northeast	1	63
		2	66
		3	64

connections of the four inch thick plates welded to the ends of the tower columns were assumed to be capable of transmitting moment and were modelled accordingly. The connections between the diagonal bracing and the columns in the climbing section were assumed to be pinned and in the tower section were assumed to be fixed. The base of the columns of tower section 12 were assumed to be pinned.

The applied loads are shown in figure 6.2.2. The weights for the climbing section and the tower section on the climbing section platform were taken from the owners manual [1]. Note the climbing section is not symmetric and its center of gravity, therefore, is eccentric with respect to the centerline of the tower. The exact weights of all the components comprising the superstructure were not known and the values for each crane differ somewhat from nominal values tabulated in the manufacturer's catalogue. A value of 237 kips was an approximate value recommended by engineers from American Pecco Corporation. The plate used to model the superstructure had a weight of 9.5 kips as indicated in figure 6.2.2. This load is less than one-half the weight of 25.5 kips for the turntable and slewing motors, i.e., the stationary portion of the superstructure. It was therefore decided to use the full 237 kips load to represent the weight of the movable portion of the superstructure, i.e., the load that will change position as the crane rotates on slews.

The section properties for the members given in table 3.1.2 were used in the analysis. The value of the yield stress for all structural members was assumed to be 50 ksi. The values used for modulus of elasticity of these members was 29,000 ksi. This nominal value for ST 52-3 was used in lieu of average values for the various members based on the tensile test results in Chapter 5. Limit state values calculated using the measured cross section dimensions are given in table 6.2.1.

The behavior of the guide rollers on the climbing section required special consideration. The model incorporated a nodal point at the bearing locations of the climbing section rollers on the tower columns. Short truss members capable of transmitting axial loads only were used to model each roller individually at these locations. For a given loading condition, the forces in these truss members were determined. A tensile force in a truss member indicated the roller was not bearing on the flange or the edge of the flange of the tower section, i.e., had lifted off in the actual structure and the results of the analysis were not correct. When this occurred the model was modified by eliminating the truss member, i.e., eliminating any force transmission by the roller since it lifted off, and the loading condition was rerun until all the rollers exhibited compressive forces. The compatibility of deflections of the joints were then examined to ensure that the eliminated rollers did not come in contact with the tower section due to the resulting deflection. For each external loading condition, a number of computer runs were made to satisfy these conditions.

An iterative procedure was used to account for inelastic behavior. If the combined stress (bending about both principal axes and axial load) exceeded the yield stress, an iterative approach was required. For a given loading condition, the external load required to cause the combined stress to reach the yield stress at the most highly stressed point in the structure was determined. It was assumed that as the external load increased beyond this value, the relationship or relative distribution of the internal forces at this point in the structure remained constant, i.e., the internal forces followed the same load path until a plastic hinge formed at the cross section. The combination of internal forces required for this to occur was determined from the following interaction equation [4]:

$$P/P_y + M_x/M_{Px} + M_y/M_{Py} = 1 \qquad (1)$$

Assuming linear elastic behavior from initial yield to the formation of this hinge, the external load associated with the plastic hinge forming was determined by multiplying the external load at initial yield by the ratio of the internal forces associated with equation (1) to the values at initial yield. The model was then modified assuming a pin joint at this plastic hinge location and the remaining portion of the external load applied to this modified structure. The internal forces and displacements were combined for the two cases to obtain the final values for the particular loading condition.

In some cases, the external load caused more than one plastic hinge to form and the solution procedure noted was used for the various load increments as each hinge formed. In the actual structure, the externally applied load remained constant. The superposition procedure noted was based on a piecewise linear approximation of the actual nonlinear structural behavior.

6.3 Results of the Analysis

The internal member forces and maximum combined stresses (axial stress plus stress due to bending about both principal axes), in the climbing section and tower sections 14 and 15 are shown in figure 6.3.1a and b, for the balanced condition. Only combined stresses in excess of 10 ksi are shown. For the loads shown in figure 6.2.2, the center of gravity of the superstructure load is 10.5 inches from the top of the hydraulic ram for the balanced condition. The reactions of the rollers of the climbing section are shown in figure 6.3.1c. Second order effects (P Delta effects) were not included in this analysis.

It was assumed in the analysis that all sixteen rollers were initially in contact with tower section 15. The roller adjustment procedure described in Appendix A (Section 3.4.2) indicates that some of the rollers should have a 3/16 inch clearance at the beginning of the climbing process. It is not known whether these adjustments were made prior to climbing the crane on the day of the collapse. Also, any imperfections in tower section 15 or the climbing section would alter these clearance by the time the climbing section was at the top of section 15. The assumption that all rollers were in contact, therefore, appears reasonable. The effect of this assumption was evaluated and will be discussed subsequently.

Referring to figure 6.3.1a, as expected the largest internal member forces occur in the north face of the climbing section. The northeast and northwest columns each have a compressive force of 146 kips. Tensile forces of 22 kips exist in the southeast and southwest columns. Note that the axial forces vary along the length of the column due to the frame action caused by the diagonal bracing. The maximum combined stresses exceed 10 ksi only in the members in the north face of the climbing section. The maximum combined stress is approximately 23 ksi.

The member forces and combined stress are quite small for tower section 15 as is shown in figure 6.3.1b. The column loads are also quite small since the major portion of the weight of the superstructure is transferred to the tower into tower section 14 by the hydraulic ram. The column loads in the north face of tower section 14 below this load transfer point are similar to those in the upper portion of the north face columns of the climbing section.

The forces exerted by the climbing section rollers on tower section 15 are shown in figure 6.3.1c. Note that the upper roller forces on the northerly columns and the lower roller forces on the lower southerly columns are zero. The maximum roller forces occur on the lower rollers on the edge of the flanges of the northerly columns. The reason for these high forces is evident when the load path through the north face of the climbing section is considered. The reaction at the hydraulic ram in figure 6.2.1 is resisted primarily by truss action of the north face of the climbing section. The vertical load pushing upward tends to deform the bottom of the climbing section inward or perpendicular to the direction of this vertical load. The lower rollers on the edges of the flanges on the north side of the climbing section resist this movement producing the large loads shown.

The influence of a number of variables on the results obtained for the balanced position was evaluated. This included second order effects (P Delta effects), luffing of the boom, loss of roller support and rotation of the superstructure. The results are presented below.

Second Order Effects

The influence of including second order P Delta effects in the analysis for the balanced position is given in figure 6.3.2a, b and

6. STRUCTURAL ANALYSIS

6.1 Introduction

The objective of the structural analysis was to determine the internal member forces under the loading conditions encountered during the climbing operation and compare these forces with limit state values to determine whether the loading would cause failure. Several loading cases were considered. One case involved the loading associated with the balanced position recommended in the owners manual for climbing the crane (see Appendix A). In this position, the boom is oriented directly south and elevated so that the moments about the point of contact between the hydraulic ram and the climbing section produced by the superstructure load, the load due to the climbing section and the load due to the tower section supported on the platform of the climbing section are zero. The other cases involved loadings associated with luffing of the boom or rotation or slewing of the crane superstructure from this balanced position.

A three dimensional finite element computer model was used for the analysis [3]. The linear elastic program includes beam and plate elements. The program is capable of including second order P Delta effects in the analysis. The program was used to analyze the structure in the inelastic range using an iteration process based on piecewise linear approximation of the nonlinear response.

Results presented in this chapter were compared with eyewitness accounts of the structural behavior and observations of the collapsed structure presented in Chapter 4 and used to identify the cause of the collapse. This comparison is presented in Chapter 7.

6.2 Computer Model and Analysis Procedure

The three dimensional model of the climbing section top plate and tower used in the analysis is shown in figure 6.2.1. Only the portion of the tower consisting of sections 12 through 15 and the climbing section were modelled. Field measurements indicated the tower sections below section 12 remained elastic and were unaffected by the collapse. It was assumed, therefore, that the tower below section 12 would have a limited influence on the structural behavior of the sections that failed and this model was adopted.

The model in figure 6.2.1 included 359 structural members for sections 12 through 15, the climbing section, structural tie-in, the hydraulic ram and the climbing traverse. The superstructure above the climbing section consisting of the turntable, counterweights, machinery, etc., was modelled as a very stiff plate supported by the four climbing section columns. Two hundred and twenty four plate elements with an elastic modulus 100 times the value of that for the structural members were used. The bolted

c. The member forces in the climbing section in figure 6.3.2a are similar to those in figure 6.3.1a neglecting second order effects. The same is true for the forces in tower sections 14 and 15 (figure 6.3.2b versus 6.3.1b). The same is generally true for the roller forces although the lower roller forces on the face of the flanges on the northerly columns do increase by an order of magnitude when the second order effects are considered. Note that the loads on the northwest and northeast columns of the climbing section are no longer equal. The same is true for the two southerly columns of the climbing section. The column loads in tower section 14 illustrate the same behavior. This is due to the location of the diagonal bracing members in the east and west face of tower section 15 relative to the location of the rollers of the climbing section. On the east face, the diagonal bracing intersect the column at the lower roller location (figure 6.3.2b). On the west surface the rollers load the column between the braces. The resulting lateral displacements of the columns are not equal and correspondingly the P Delta effects are not the same for the two columns.

The remainder of the results in this chapter were obtained including second order P-Delta effects.

Luffing of Boom

If the boom is luffed (upward or downward) from the balance position, the location of the center of gravity of the superstructure loads will change and the member forces will be affected. To evaluate this effect it was assumed the boom was lowered from the balanced position a sufficient amount to move the center of gravity of the superstructure load toward the center of the tower until it was directly over the north face of the climbing section. As shown in figure 6.2.2, the center of gravity of the superstructure loads moved inward or south by 20.3 inches for this case. The results are shown in figure 6.3.3a, b and c. The results are as expected. The compressive loads in the northerly columns of the climbing section and tower section 14 were reduced. The loads in the southerly columns of the climbing section and tower section 14 changed from tension to compression. Luffing the boom had little effect on the forces on the rollers along the edge of the flange. It had a considerable effect on the forces on the rollers on the flange width as can be seen by comparing figure 6.3.2c and 6.3.3c. This is understandable since the center of gravity of the superstructure was moved from a point north or outboard of the hydraulic ram to a point south or inboard of the ram. The counterbalancing moment required to be produced by the rollers is clearly different for the two cases.

Loss of Roller Support

There has been speculation that failure of the crane was triggered by loss of one of the roller supports along the edge of a flange. The effect of loss of a roller was therefore evaluated. For the balanced position, loss of an upper or lower roller along the edge of the flange of one of the southerly columns would have no effect since these roller forces are zero for this load case. The same is true for the upper rollers along the edge of the flange of the northwest and northeast columns. Therefore, with the crane in the balanced position the lower roller on the edge of the flange of the northwest column was removed. The initial computer analysis for this case indicated excessive deflections and several locations at which the maximum combined stress exceeded 100 ksi, i.e., was considerably above the yield stress. For the linear elastic computer program used in this analysis, excessive deflections indicate an unstable solution or an ill-conditioned stiffness matrix. No attempt was made to solve this case in the inelastic range since adding plastic hinges would only make the structure more unstable. Similar results were obtained for a loading case in which the superstructure was rotated counterclockwise by 8 degrees.

The computer analysis, thus, indicated the structure is sensitive to loss of one of the load carrying roller supports along the edge of the flange for the balance condition and small angels of rotation. The possibility that loss of roller support was the cause of the failure of the crane will be considered in Chapter 7.

Rotation of Superstructure

The crane did rotate counterclockwise prior to collapse. The effect, therefore, of rotation of the superstructure on member forces and stresses in the climbing section and the tower and on the roller forces was evaluated. The influence of rotating the crane 8 degrees counterclockwise is shown in figure 6.3.4a, b and c. Note that only the 237 kip superstructure load shown in figure 6.2.2 moves due to this rotation. The rotation was assumed to be along a circular path with a radius equal to the distance between the center of rotation and the balance position location in figure 6.2.2 (5.79 feet). The value of 8 degrees was selected since this corresponded to coincidence of a nodal point of the finite element grid used for the superstructure model and this circular path. Comparing figures 6.3.4 and 6.3.1 indicates some changes in the forces. The forces in the column sections on the south face of the climbing section are no longer equal. A similar effect occurs in the columns on the south face of tower section 14. The roller forces change significantly as seen by comparing figures 6.3.4c and 6.3.1c. The roller forces in the north-south direction, i.e., the rollers on the flange width do not change a great deal. The roller forces on the edges of the flange, however, increase substantially. The lower roller on the edge of the flange of the southwest column which had no force on it when the crane was in the balanced position is subjected to 31.8 kips due to the 8 degree rotation. The upper roller on the southeast column behaves the same way.

Several additional cases of rotation were considered. The results for a counterclockwise rotation of 30 degrees are shown in figure

6.3.5a, b and c. Inelastic action occurred for this loading and a plastic hinge formed in the southwest column of tower section 15 at the location of the lower roller of the climbing section. This plastic hinge was due primarily to bending of the column due to the high roller force exerted on the column. The force in one column on the south face of the climbing section is now tension, the other is compression. The same is true for the columns on the south face of tower section 14. Note also that the compressive force of 132 kips in the diagonal bracing member in the upper portion of the south face of tower section 15 slightly exceeds the calculated buckling load of 121.6 kips in table 6.2.1. The maximum combined stress in this member is also at the yield stress. The roller forces also change significantly. Some of the rollers which were not exerting any force when the crane was at 8 degrees have now come in contact and are exerting forces on the columns of tower section 15. The force on the upper roller on the flange width of the northeast column has increased from zero at 8 degrees to 25 kips at 30 degrees. The force on the lower southwest roller and the upper southeast roller on the edge of the flange has increased by 400 percent.

Results for a counterclockwise rotation of 45 degrees are shown in figure 6.3.6a, b and c. The compressive force in the diagonal bracing on the south face of the climbing section exceeds the buckling load for this rotation. Also, the other diagonal has yielded in tension. Three plastic hinges have now formed in the southwest leg of tower section 15 as shown in figure 6.3.6b. Note also that the tension forces at the connection between tower sections 14 and 15 at the southeast column and northeast column are close to 100 kips. Also, the maximum combined stress, primarily due to bending, in four diagonal bracing members on the west face of tower section 15 far exceed the yield stress. These diagonal bracing members correspond to several of those that were fractured in the collapse as can be seen by referring to figure 6.3.10. It is clear that the load carrying capacity of the structure is essentially exhausted at this rotation of 45 degrees.

As the crane rotates, the superstructure will tilt as shown in figure 6.3.7. A component of the superstructure load then acts in the plane of the turntable producing a torque which tends to rotate the crane. It is of interest to compare this torque with the capacity of the crane's slewing brakes. The amount of tilting of the superstructure, the resulting torque due to the component of the 237 kip weight of the superstructure acting at 5.79 feet from the center of rotation and the vertical deflection at the edge of the superstructure shown in figure 6.3.7 were calculated for several angles of counterclockwise rotation of the crane. The results obtained are as follows:

Angle of Rotation of Crane (degrees)	Tilt of Turntable (degrees)	Edge Deflection (in)	Resulting Torque (ft-kips)
8	0.3	0.59	7.1
16	1.0	1.98	24.0
22	1.2	2.4	28.8
30	1.35	2.7	32.5
45	8.0	15.8	191.0

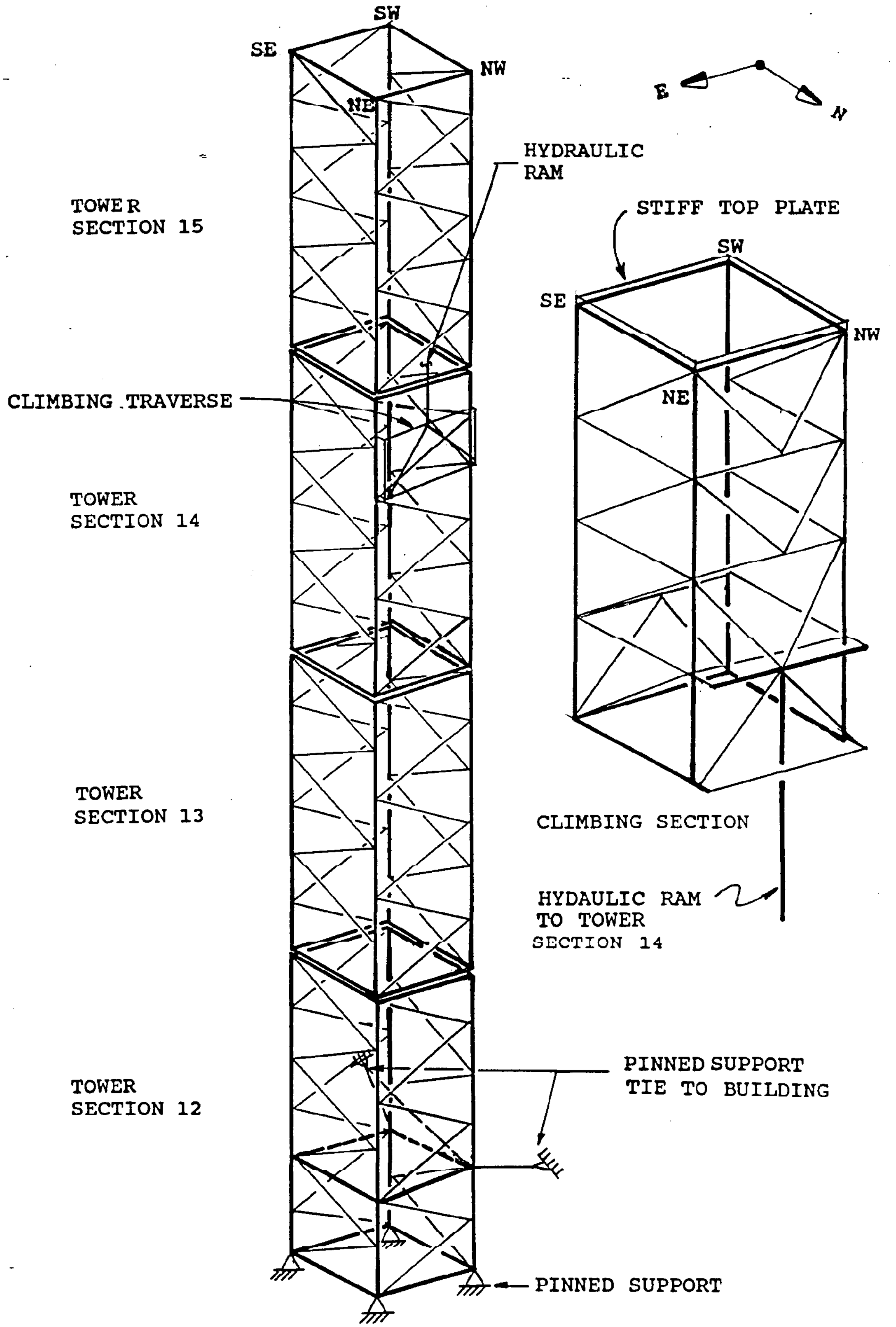
The torque capacity of the slewing brakes as determined in Chapter 3 was 269 ft-kips for the two brakes. The resulting torque due to tilting of the superstructure is less than the slewing brake capacity for all the angles considered. If, however, only one slewing brake were functioning due to the boom being luffed such that the hook reach was less than 65 feet as noted in Section 3.2, the torque exceeds the brake capacity at a 45 degree rotation.

The reactions of the rollers and the member forces obtained from the above analysis for those loading conditions in which the structure remained elastic were compared with results obtained from another analysis in which the climbing section was modelled as an independent structure, without the tower structure. The sixteen guide rollers in this case were modelled as lateral supports free to move vertically. The roller reactions and member forces from the two analyses were in general agreement.

TABLE 6.2.1

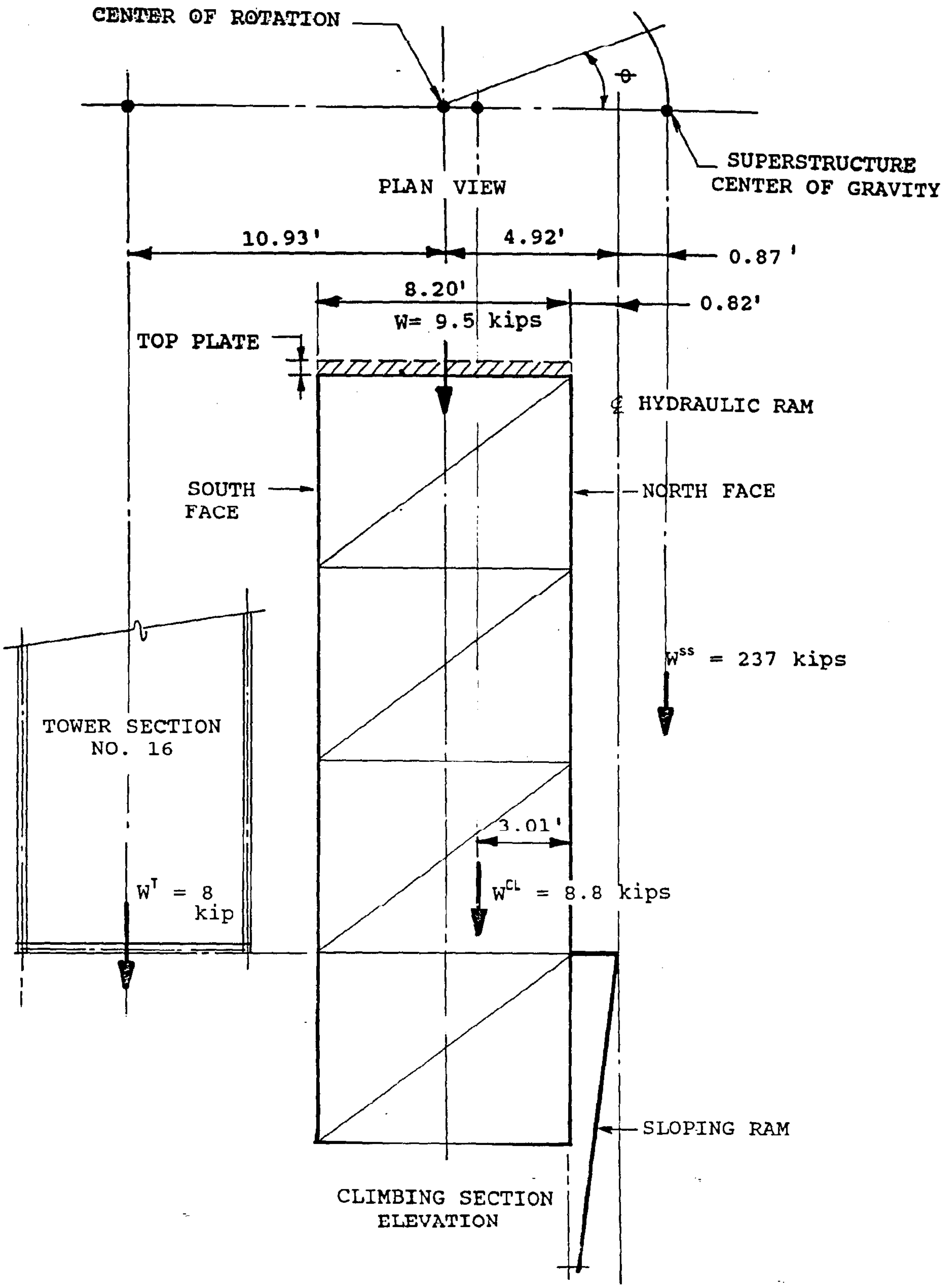
LIMIT STATE VALUES FOR STRUCTURAL MEMBERS

Item	Structural Member		Axial Load P_y kip	Length ft.	Buckling Load		Plastic Moment	
					P_{crx} kip	P_{cry} kip	M_{px} kip-ft	M_{py} kip-ft
Tower Section 15	Column		1,016.5	6.50	989.9	947.7	281.9	136.4
	Diagonal Bracing		188.0	7.71	121.6	121.7	15.3	15.3
Climbing Section	NE & NW Columns		605.5	7.00	583.1	545.3	157.8	77.2
	SE & SW Columns		421.0	Lx=21 Ly=7	249.5	356.9	86.6	42.8
	Diagonal Bracing	OD = 3.0"	108.0	3.76	92.5	92.5	7.9	7.9
			108.0	7.05	62.6	62.6	7.9	7.9
			108.0	7.20	60.9	60.9	7.9	7.9
			108.0	7.46	58.2	58.2	7.9	7.9
		OD =3.5"	127.5	9.78	59.5	59.5	11.0	11.0
		OD = 4.2"	189.5	7.05	143.9	143.9	19.6	19.6
			189.5	7.46	139.3	139.3	19.6	19.6



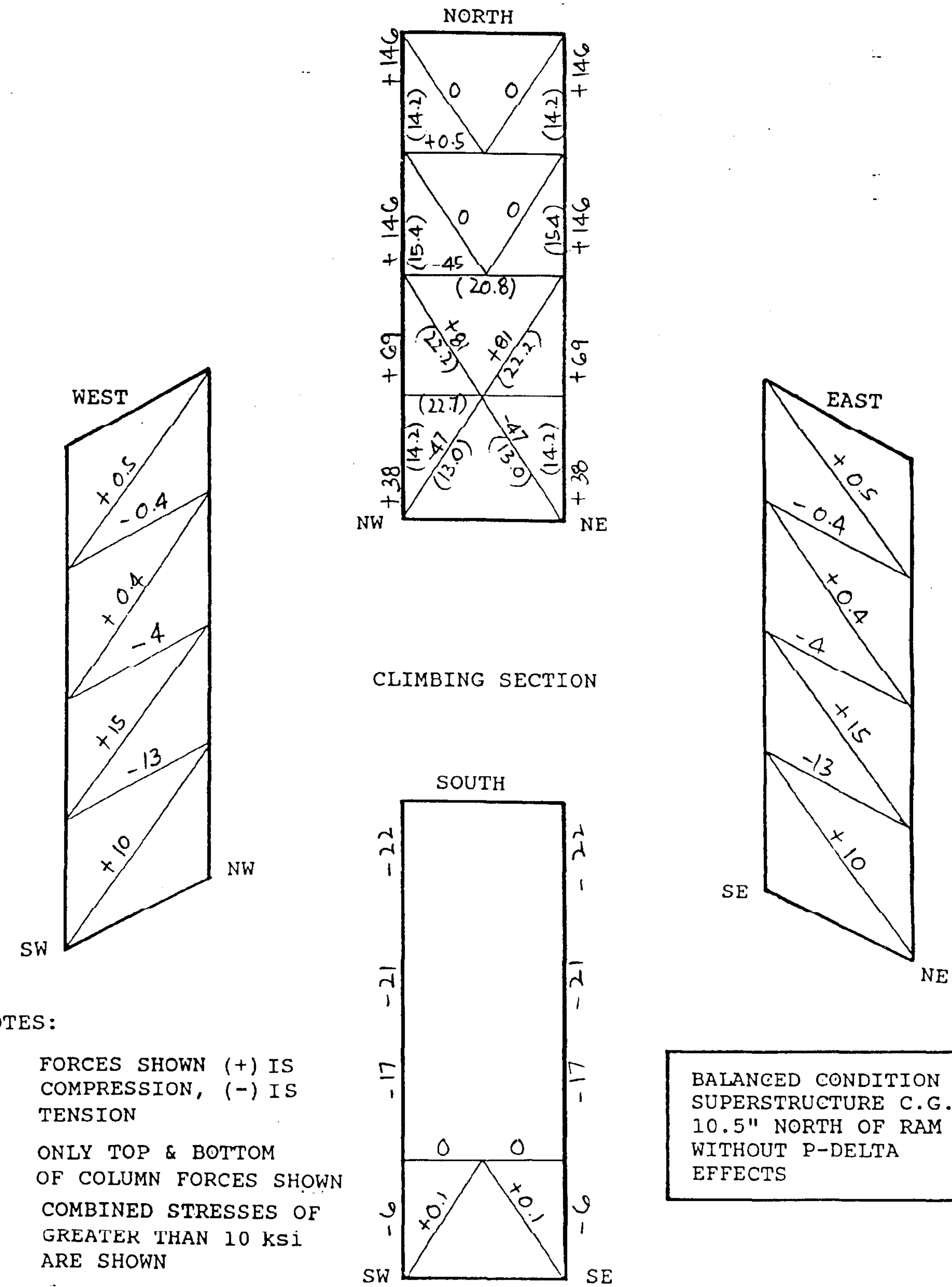
STRUCTURAL ANALYSIS MODEL OF TOWER AND CLIMBING SECTION

FIGURE 6.2.1



LOCATION OF APPLIED LOADS

FIGURE 6.2.2



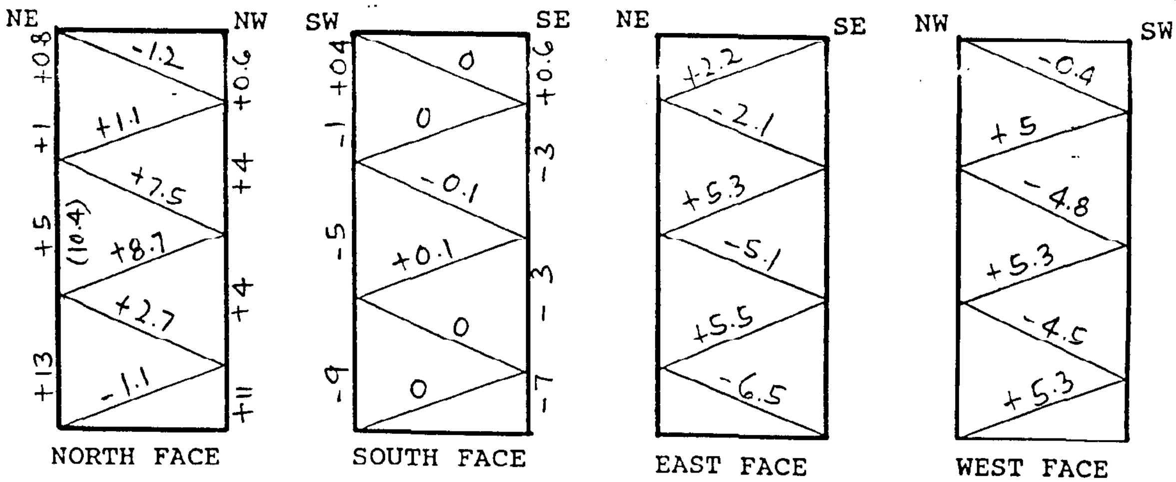
NOTES:

1. FORCES SHOWN (+) IS COMPRESSION, (-) IS TENSION
2. ONLY TOP & BOTTOM OF COLUMN FORCES SHOWN
3. COMBINED STRESSES OF GREATER THAN 10 ksi ARE SHOWN
4. COMBINED STRESSES ARE SHOWN IN PARENTHESIS (XXX).
5. FORCES SHOWN ARE IN kips

BALANCED CONDITION
SUPERSTRUCTURE C.G.
10.5" NORTH OF RAM
WITHOUT P-DELTA
EFFECTS

FORCES AND STRESSES IN CLIMBING SECTION AT ~~θ~~ = 0°

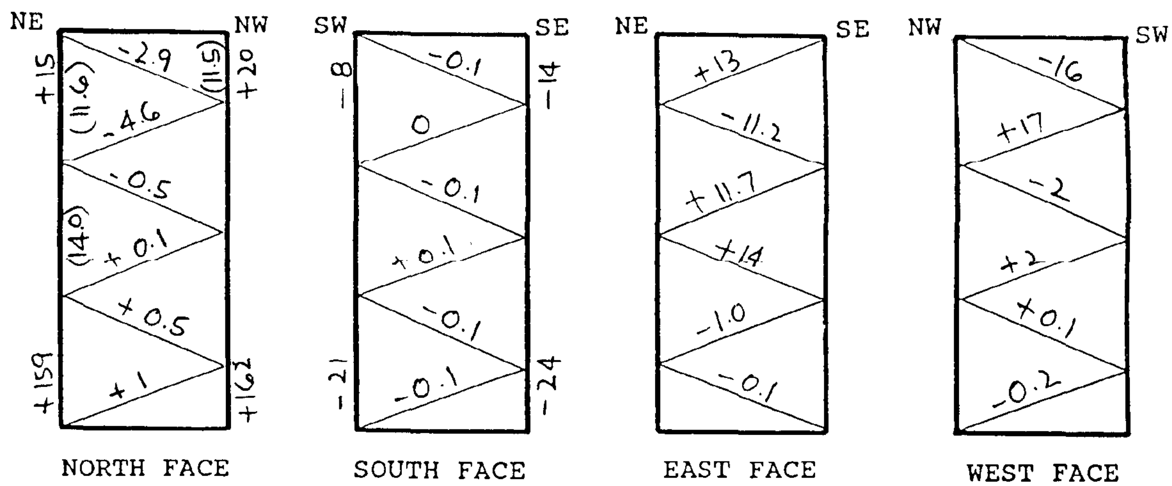
FIGURE 6.3.1a



TOWER SECTION NO. 15

Notes:

1. FORCES SHOWN (+) IS COMPRESSION, (-) IS TENSION
2. ONLY TOP & BOTTOM OF COLUMN FORCES SHOWN
3. COMBINED STRESSES OF GREATER THAN 10 ksi ARE SHOWN
4. COMBINED STRESSES ARE SHOWN IN PARENTHESIS (XXX).
5. FORCES SHOWN ARE IN kips

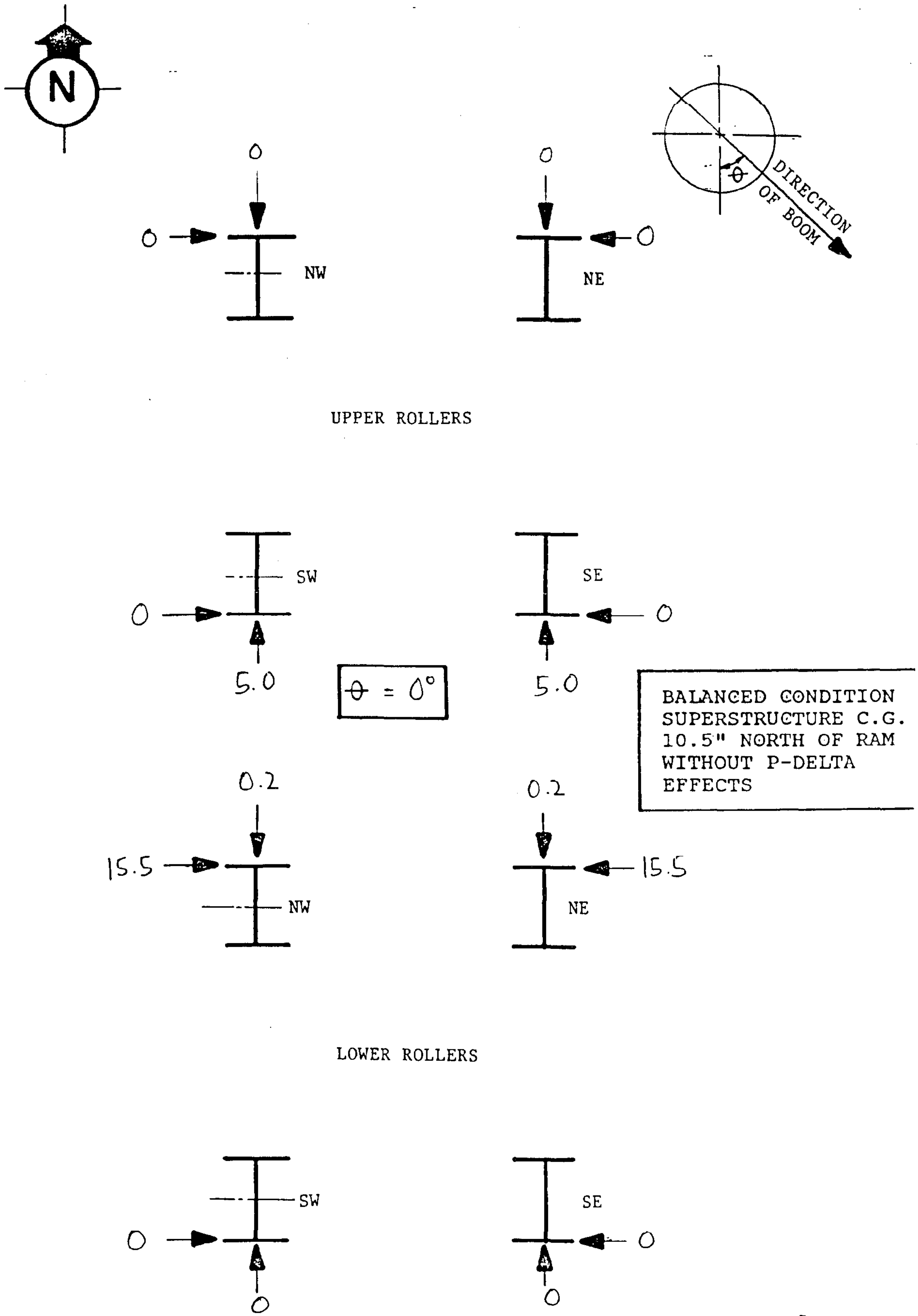


TOWER SECTION NO. 14

BALANCED CONDITION
SUPERSTRUCTURE C.G.
10.5" NORTH OF RAM
WITHOUT P-DELTA
EFFECTS

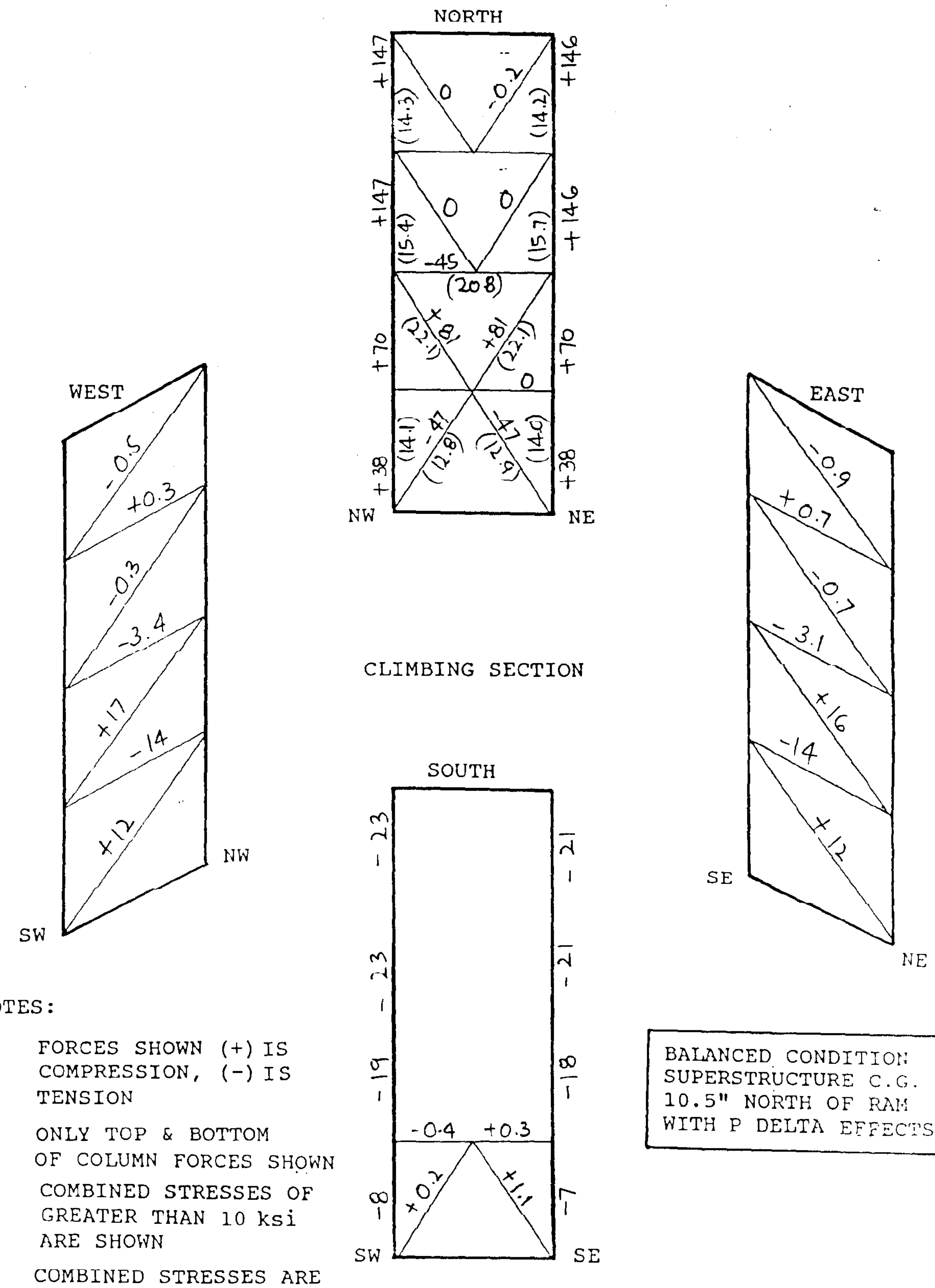
FORCES AND STRESSES IN TOWER SECTIONS ~~θ~~ = 0°

FIGURE 6.3.1b



<u>ROLLER FORCES ON TOWER LEGS</u> (KIPS)

FIGURE 6.3.1c



NOTES:

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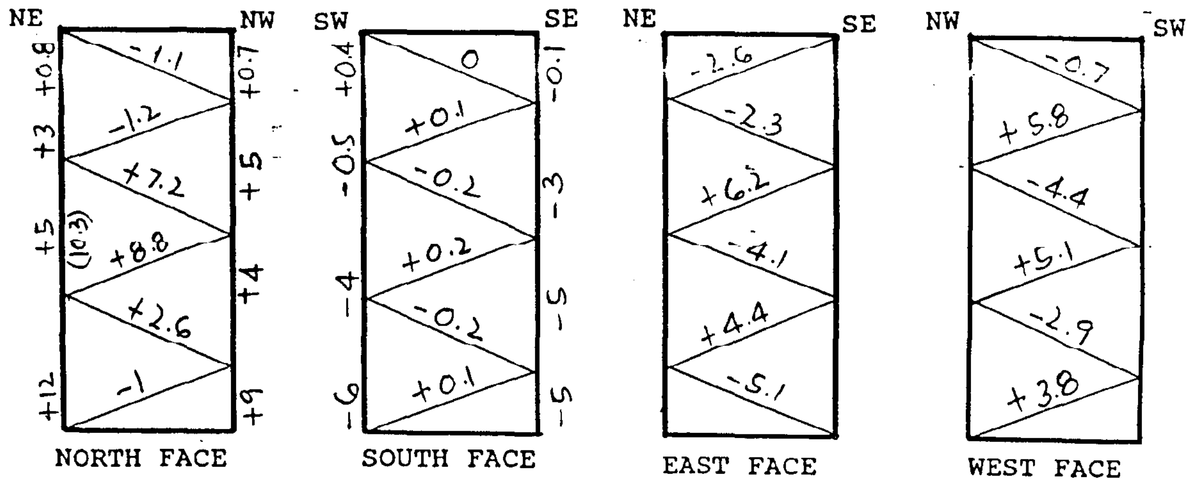
2. ONLY TOP & BOTTOM OF COLUMN FORCES SHOWN
3. COMBINED STRESSES OF GREATER THAN 10 ksi ARE SHOWN
4. COMBINED STRESSES ARE SHOWN IN PARENTHESIS (XXX).
5. FORCES SHOWN ARE IN kips

BALANCED CONDITION
SUPERSTRUCTURE C.G.
10.5" NORTH OF RAM
WITH P DELTA EFFECTS

FORCES AND STRESSES IN CLIMBING SECTION AT $\theta = 0°$

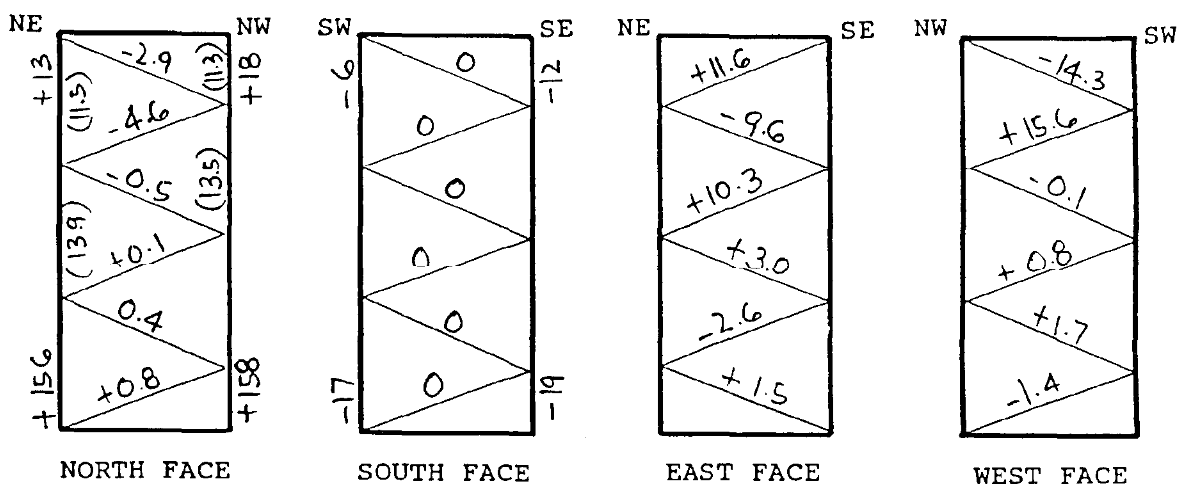
FIGURE 6.3.2a



TOWER SECTION NO. 15

Notes:

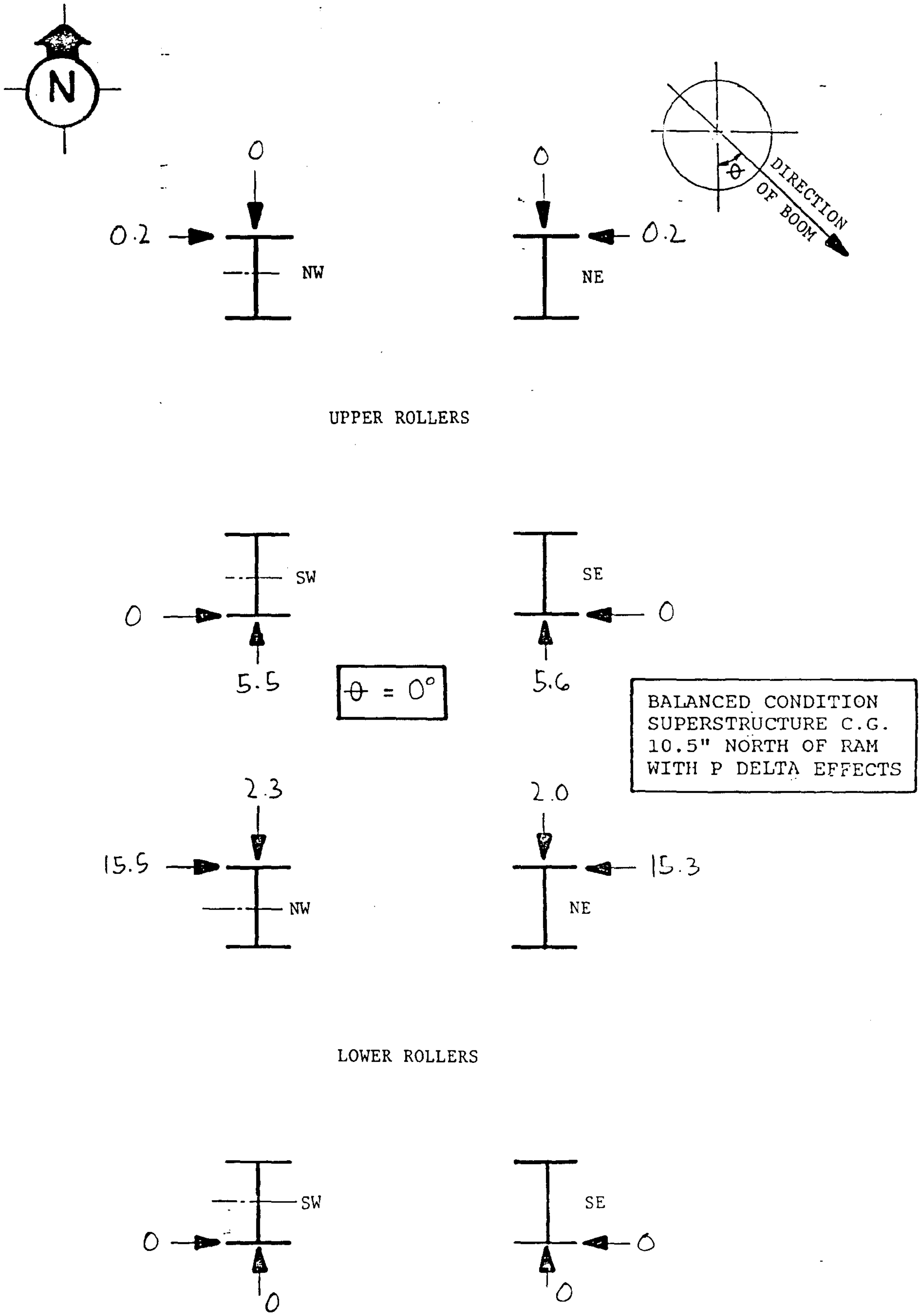
1. FORCES SHOWN (+) IS COMPRESSION, (-) IS TENSION
2. ONLY TOP & BOTTOM OF COLUMN FORCES SHOWN
3. COMBINED STRESSES OF GREATER THAN 10.ksi ARE SHOWN
4. COMBINED STRESSES ARE SHOWN IN PARENTHESIS (XXX).
5. FORCES SHOWN ARE IN kips



TOWER SECTION NO. 14

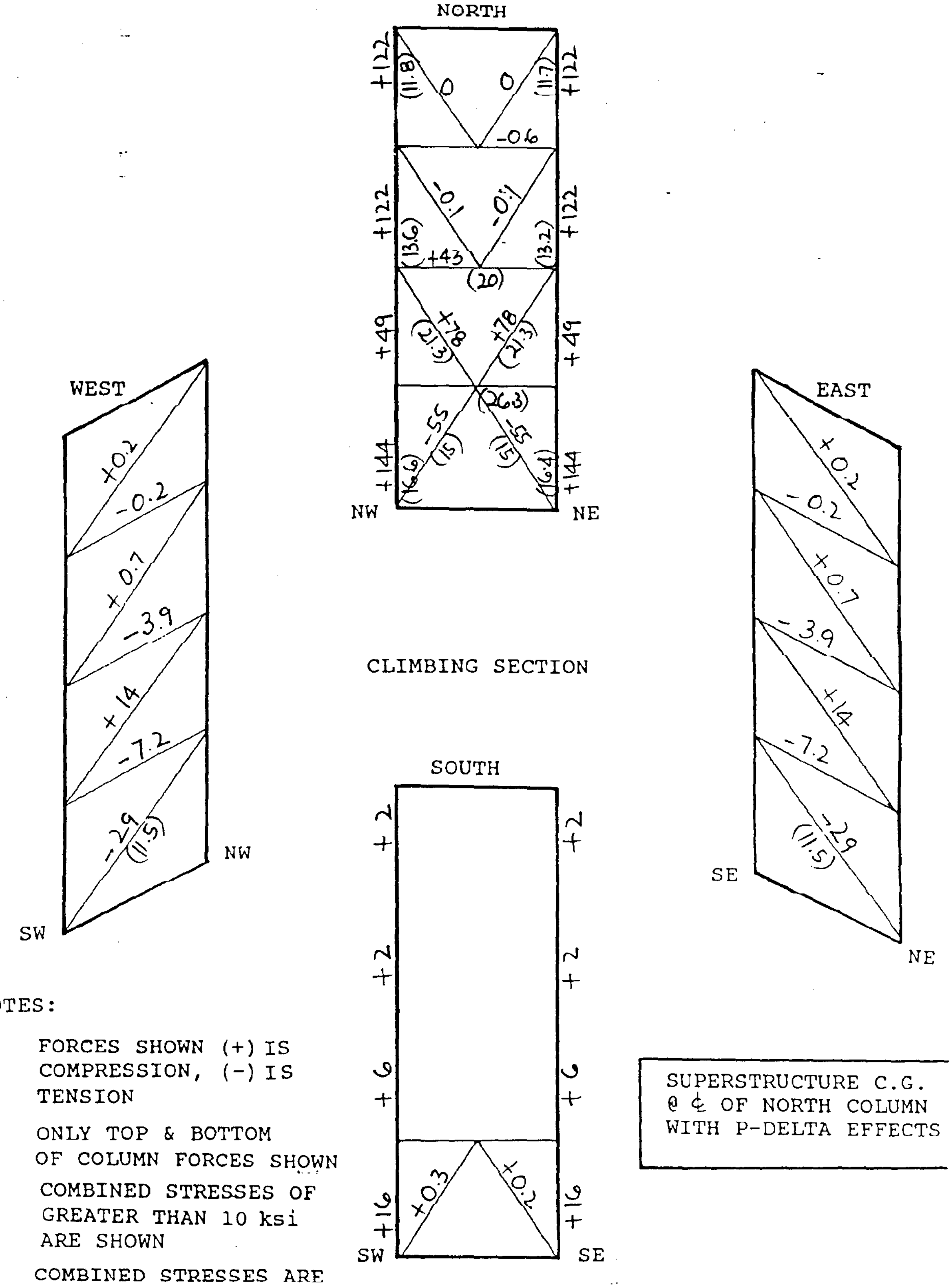
BALANCED CONDITION
SUPERSTRUCTURE C.G.
10.5" NORTH OF RAM
WITH P DELTA EFFECTS

FORCES AND STRESSES IN TOWER SECTIONS $\cancel{\theta}$ = 0°
FIGURE 6.3.2b



ROLLER FORCES ON TOWER LEGS (KIPS)

FIGURE 6.3.2c



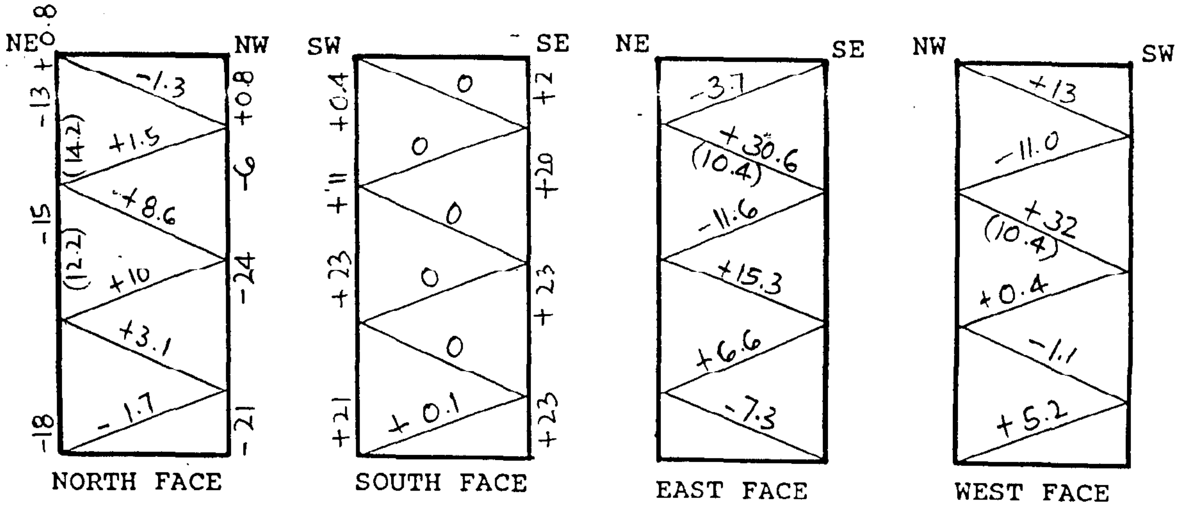
NOTES:

1. FORCES SHOWN (+) IS COMPRESSION, (-) IS TENSION
2. ONLY TOP & BOTTOM OF COLUMN FORCES SHOWN
3. COMBINED STRESSES OF GREATER THAN 10 ksi ARE SHOWN
4. COMBINED STRESSES ARE SHOWN IN PARENTHESIS (XXX).
5. FORCES SHOWN ARE IN kips

SUPERSTRUCTURE C.G. @ ℄ OF NORTH COLUMN WITH P-DELTA EFFECTS

FORCES AND STRESSES IN CLIMBING SECTION AT $\theta = 0^{o}$

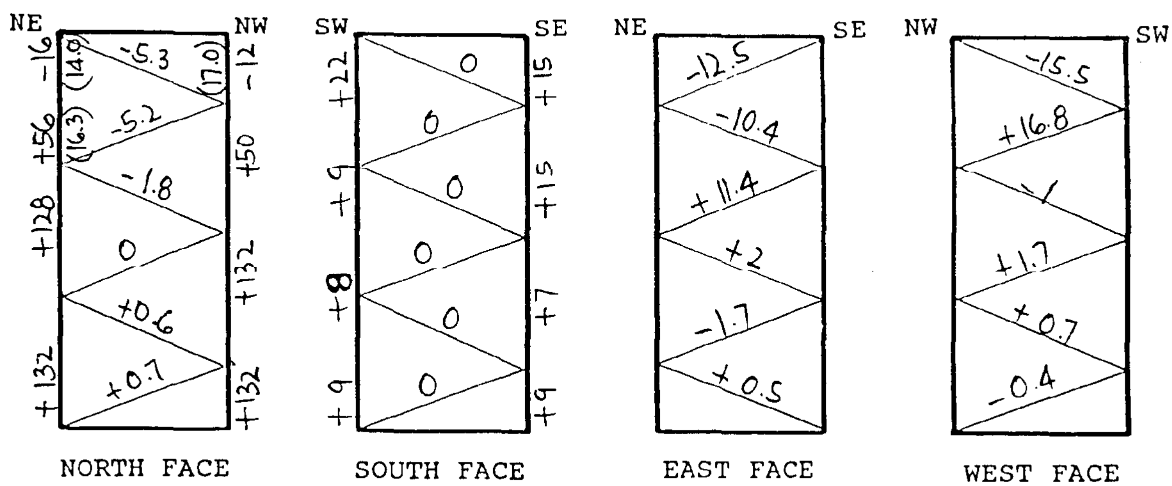
FIGURE 6.3.3a



TOWER SECTION NO. 15

Notes:

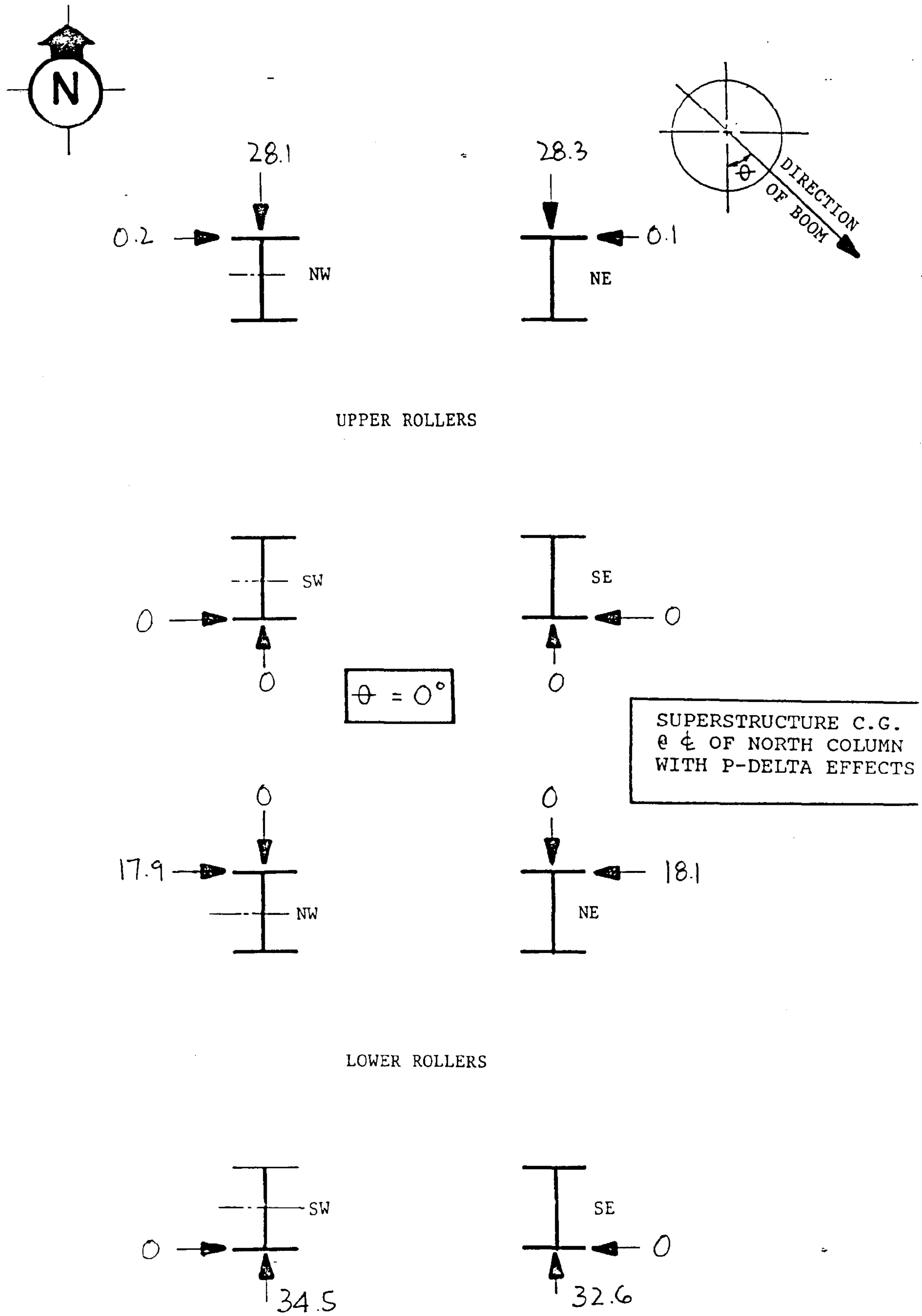
1. FORCES SHOWN (+) IS COMPRESSION, (-) IS TENSION
2. ONLY TOP & BOTTOM OF COLUMN FORCES SHOWN
3. COMBINED STRESSES OF GREATER THAN 10 ksi ARE SHOWN
4. COMBINED STRESSES ARE SHOWN IN PARENTHESIS (XXX).
5. FORCES SHOWN ARE IN kips



TOWER SECTION NO. 14

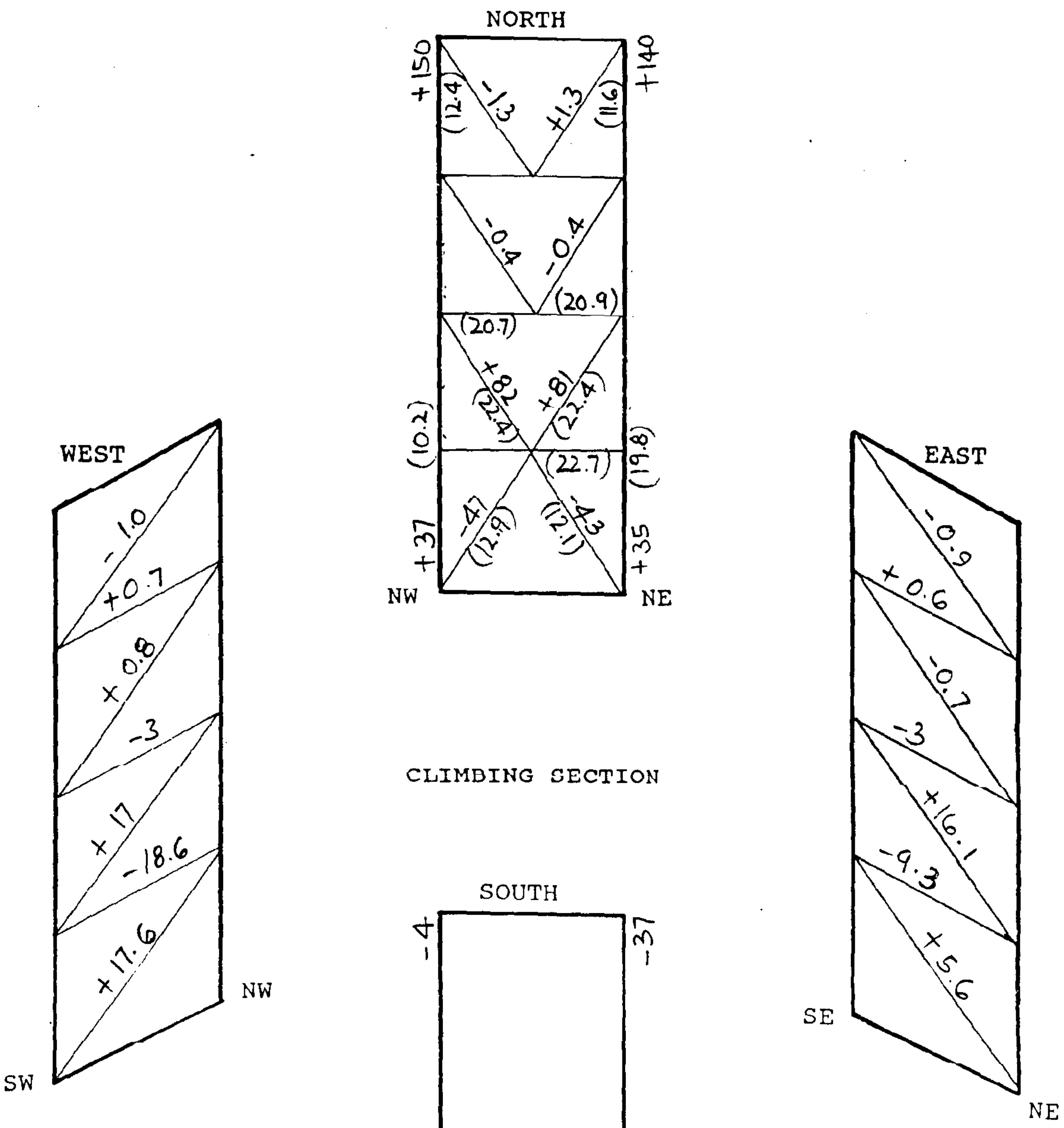
SUPERSTRUCTURE C.G.
@ ℄ OF NORTH COLUMN
WITH P-DELTA EFFECT

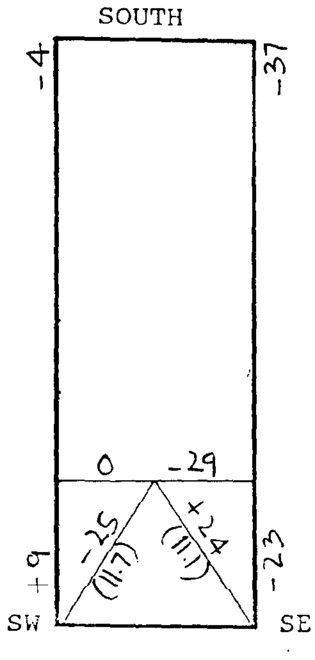
FORCES AND STRESSES IN TOWER SECTIONS θ = 0°
FIGURE 6.3.3b



ROLLER FORCES ON TOWER LEGS (KIPS)

FIGURE 6.3.3c





NOTES:

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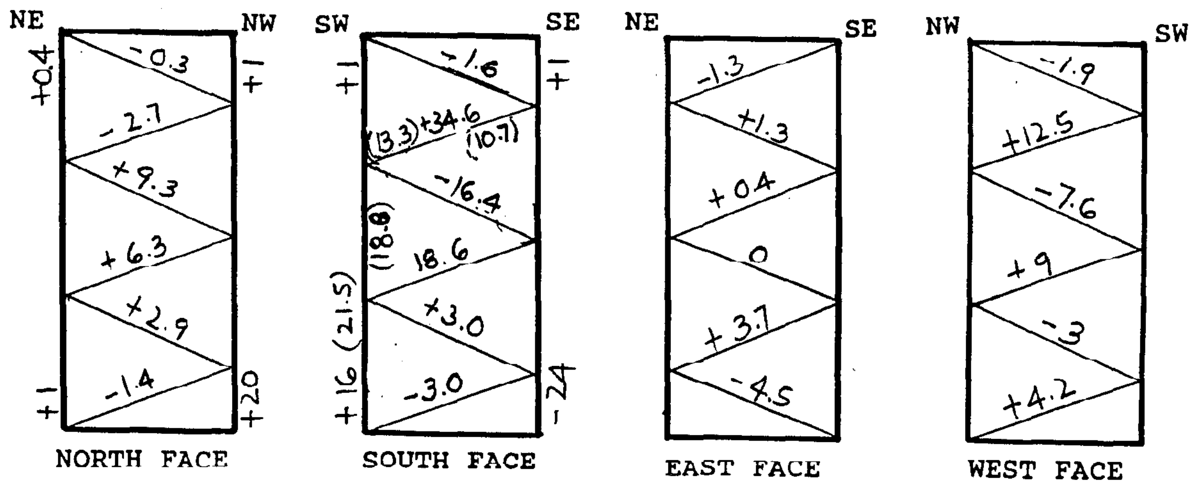
3. COMBINED STRESSES OF GREATER THAN 10 ksi ARE SHOWN
4. COMBINED STRESSES ARE SHOWN IN PARENTHESIS (XXX).
5. FORCES SHOWN ARE IN kips

WITH P-DELTA

FORCES AND STRESSES IN CLIMBING SECTION AT ~~θ~~ = 8°

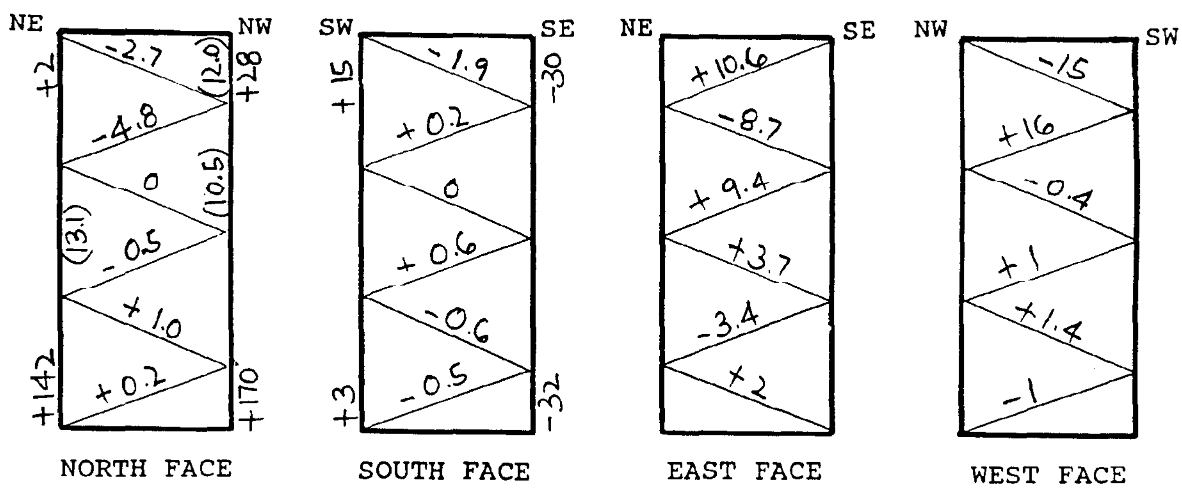
FIGURE 6.3.4a



TOWER SECTION NO. 15

Notes:

1. FORCES SHOWN (+) IS COMPRESSION, (-) IS TENSION
2. ONLY TOP & BOTTOM OF COLUMN FORCES SHOWN
3. COMBINED STRESSES OF GREATER THAN 10 ksi ARE SHOWN
4. COMBINED STRESSES ARE SHOWN IN PARENTHESIS (XXX).
5. FORCES SHOWN ARE IN kips

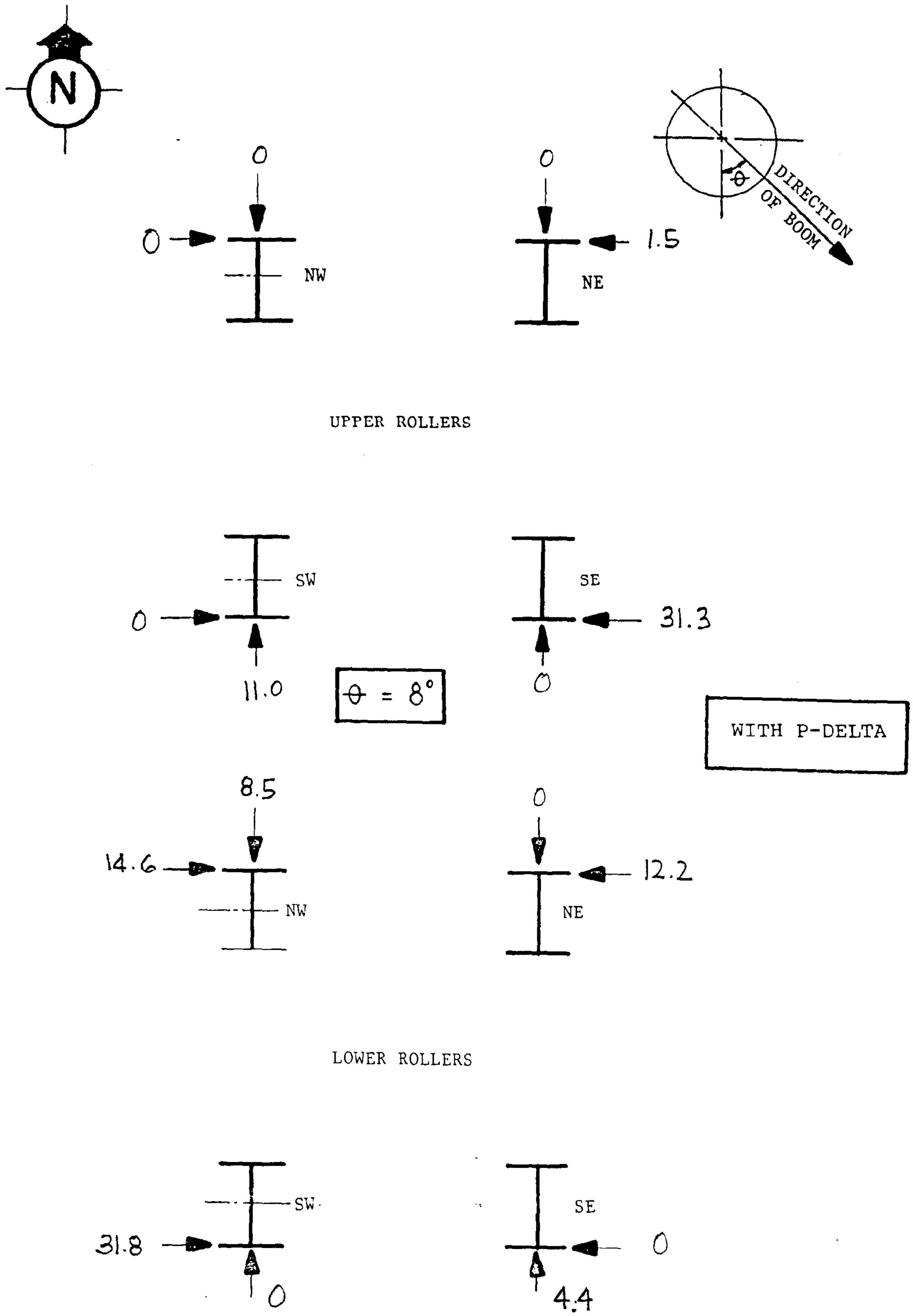


TOWER SECTION NO. 14

WITH P-DELTA

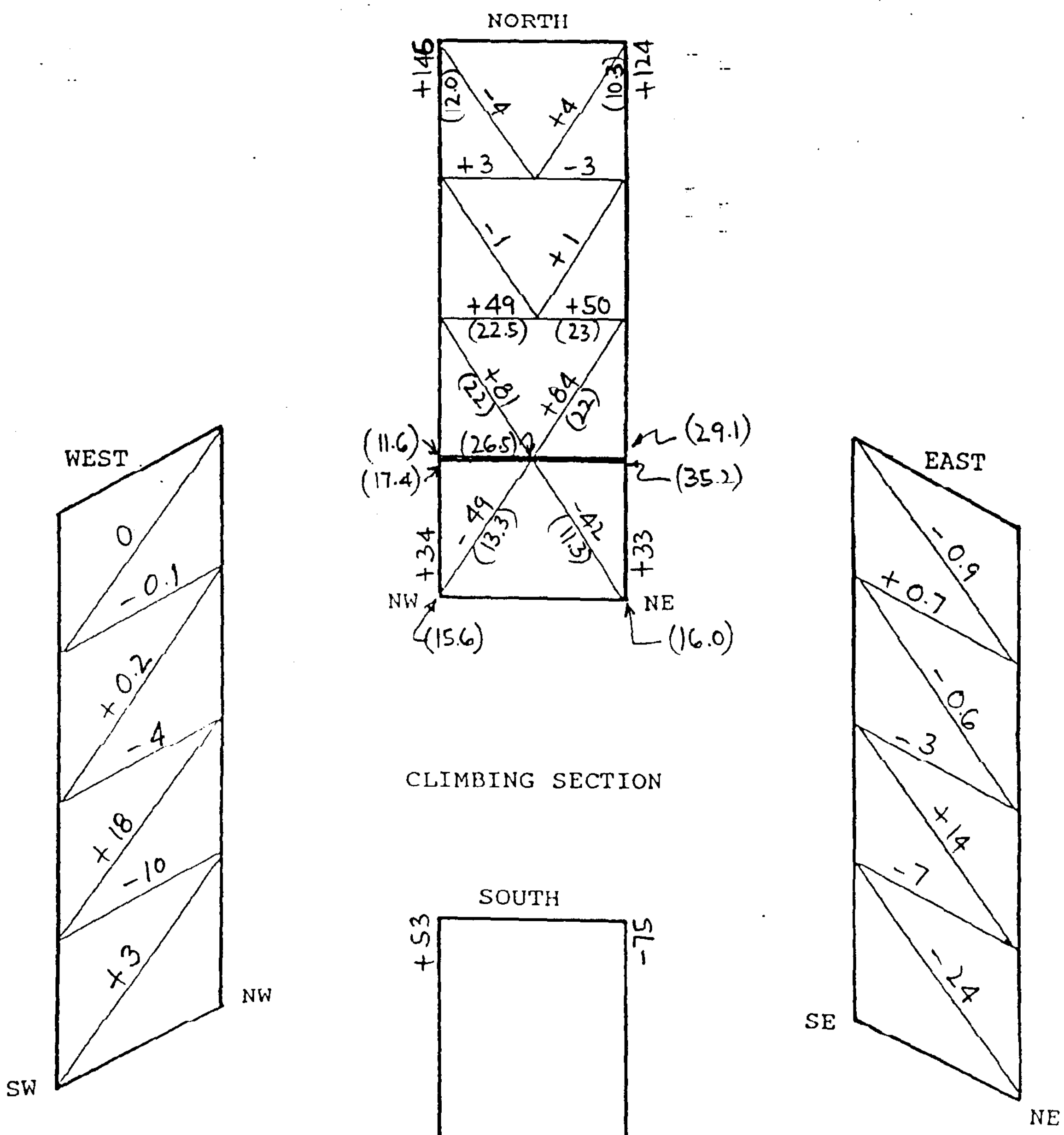
FORCES AND STRESSES IN TOWER SECTIONS ~~θ~~ = 8°

FIGURE 6.3.4b



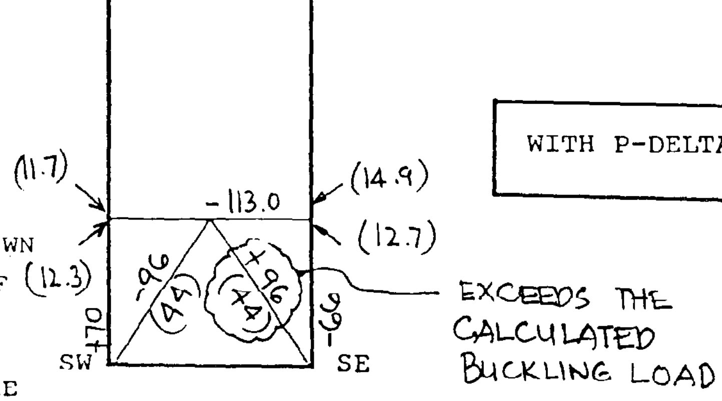
ROLLER FORCES ON TOWER LEGS (KIPS)

FIGURE 6.3.4C



NOTES:

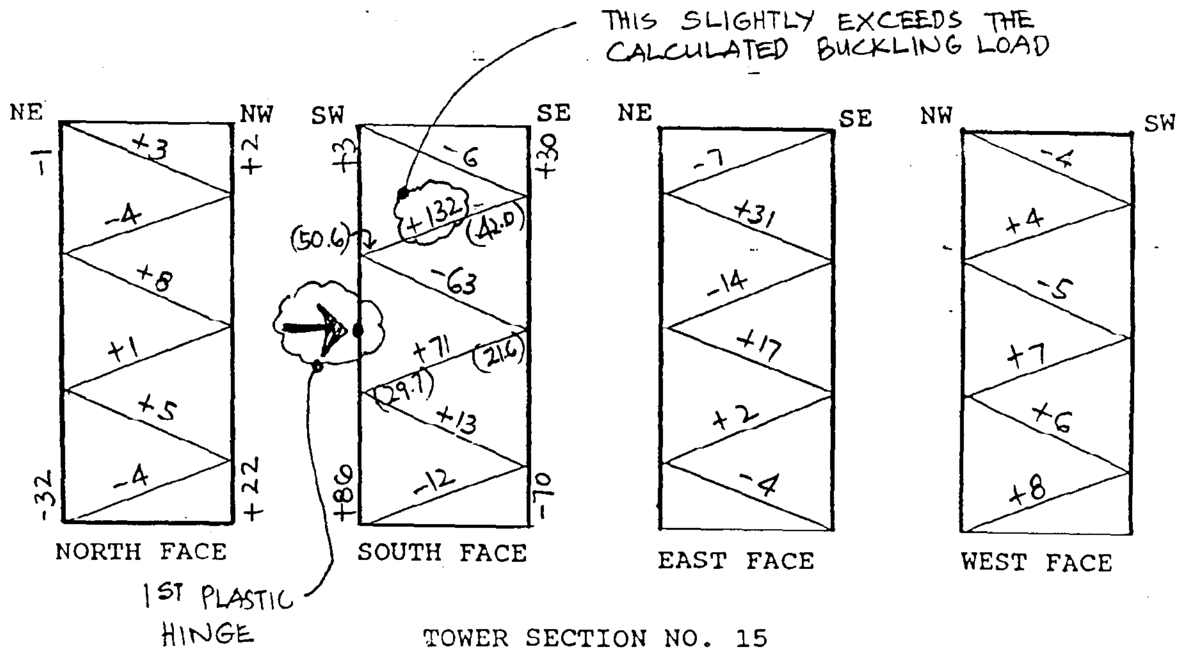
1. FORCES SHOWN (+) IS COMPRESSION, (-) IS TENSION
2. ONLY TOP & BOTTOM OF COLUMN FORCES SHOWN
3. COMBINED STRESSES OF GREATER THAN 10 ksi ARE SHOWN
4. COMBINED STRESSES ARE SHOWN IN PARENTHESIS (XXX).
5. FORCES SHOWN ARE IN kips



WITH P-DELTA

FORCES AND STRESSES IN CLIMBING SECTION AT ~~θ~~ = 30°

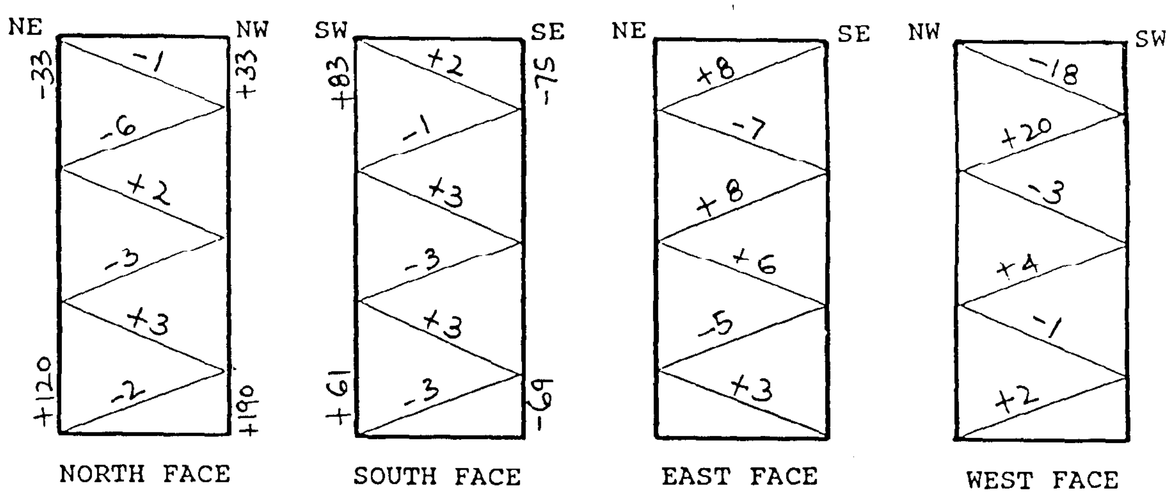
FIGURE 6.3.5a



TOWER SECTION NO. 15

Notes:

1. FORCES SHOWN (+) IS COMPRESSION, (-) IS TENSION
2. ONLY TOP & BOTTOM OF COLUMN FORCES SHOWN
3. COMBINED STRESSES OF GREATER THAN 20 ksi ARE SHOWN
4. COMBINED STRESSES ARE SHOWN IN PARENTHESIS (XXX).
5. FORCES SHOWN ARE IN kips

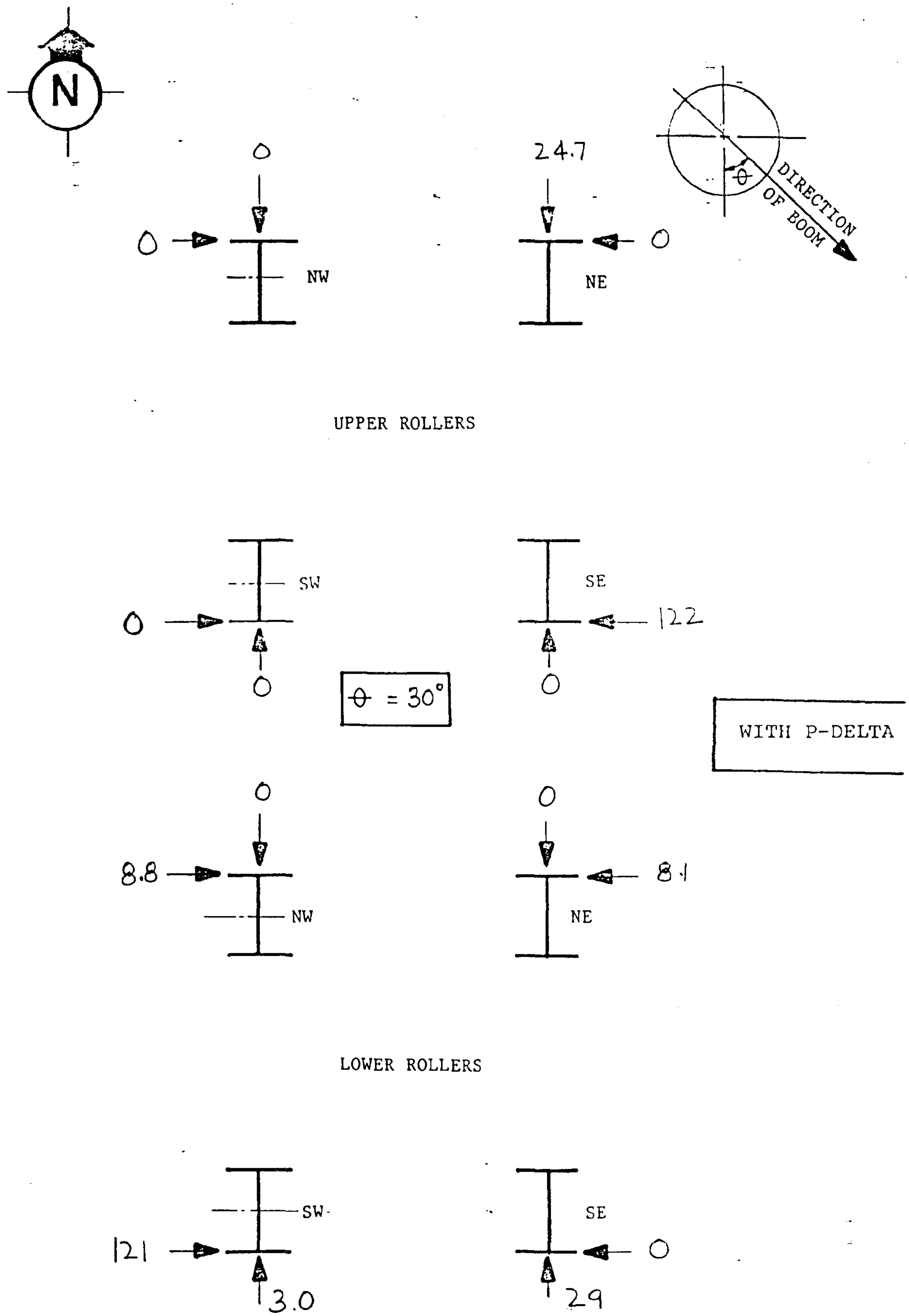


TOWER SECTION NO. 14

WITH P-DELTA

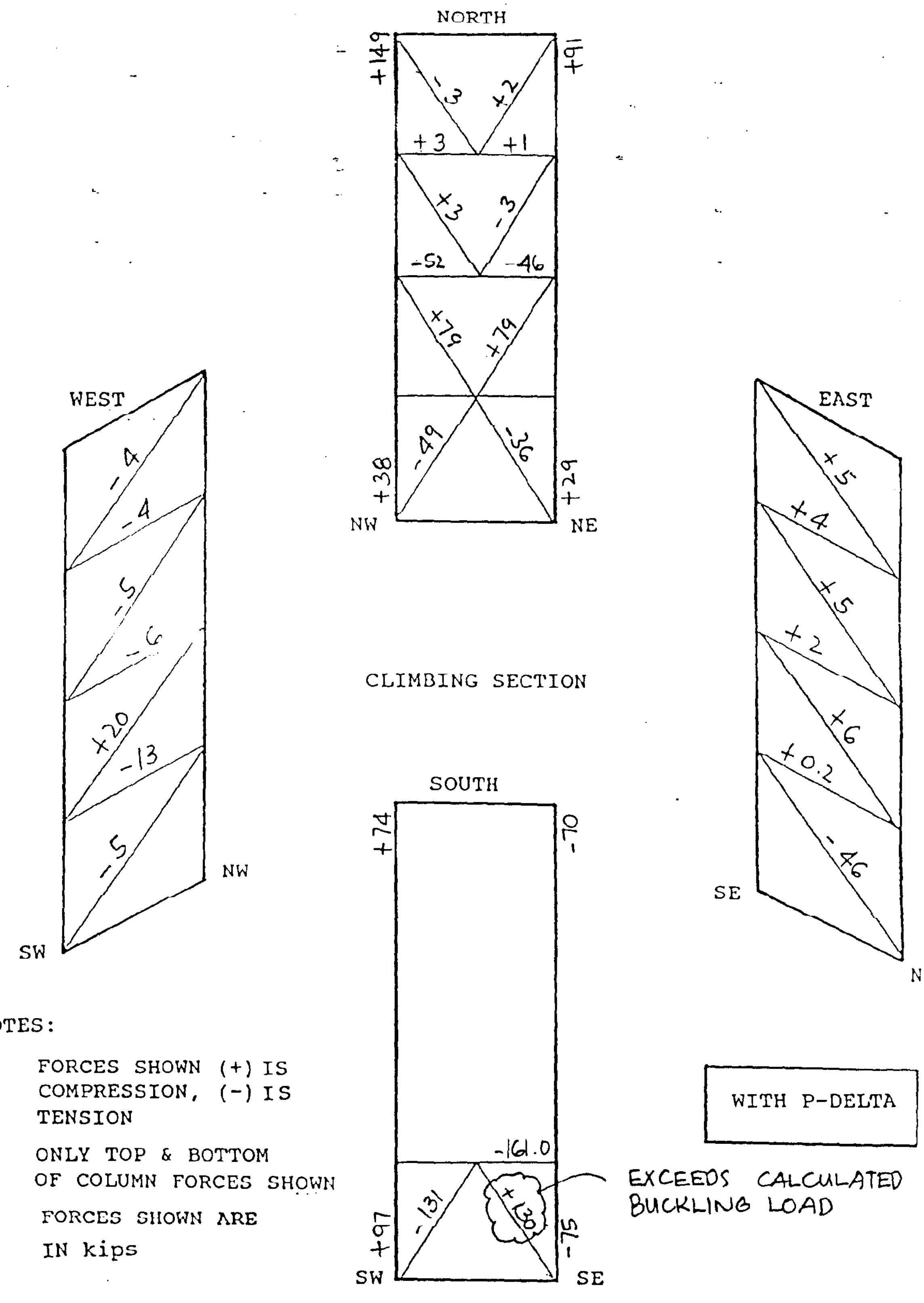
FORCES AND STRESSES IN TOWER SECTIONS ~~θ~~ = 30°

FIGURE 6.3.5b



<u>ROLLER FORCES ON TOWER LEGS</u> (KIPS)

FIGURE 6.3.5c

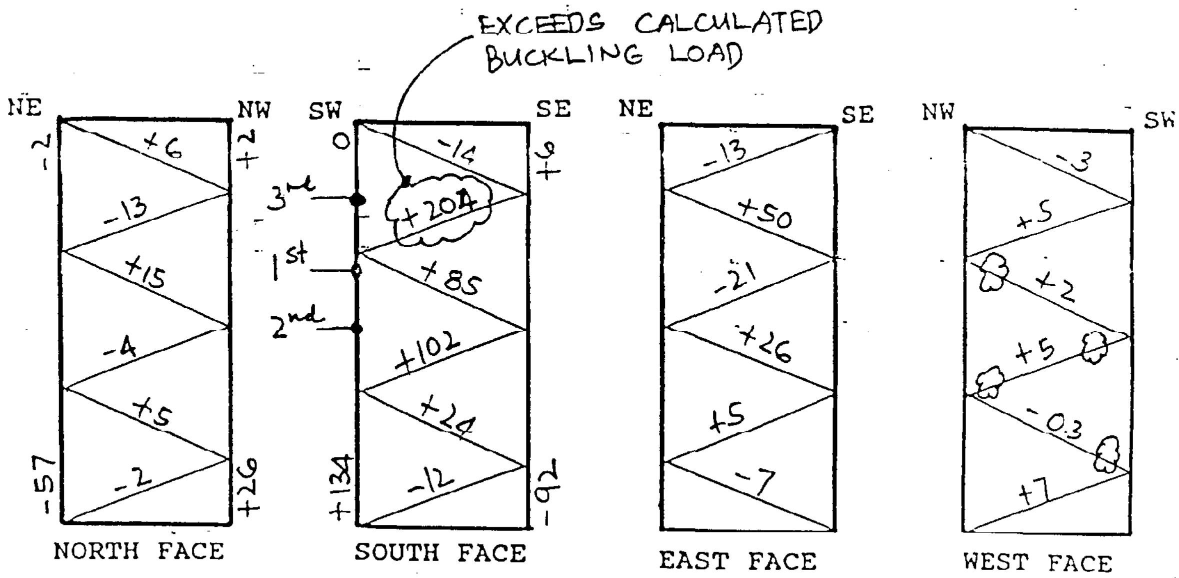


NOTES:

1. FORCES SHOWN (+) IS COMPRESSION, (-) IS TENSION
2. ONLY TOP & BOTTOM OF COLUMN FORCES SHOWN
3. FORCES SHOWN ARE IN kips

FORCES AND STRESSES IN CLIMBING SECTION AT θ = 45°

FIGURE 6.3.6a

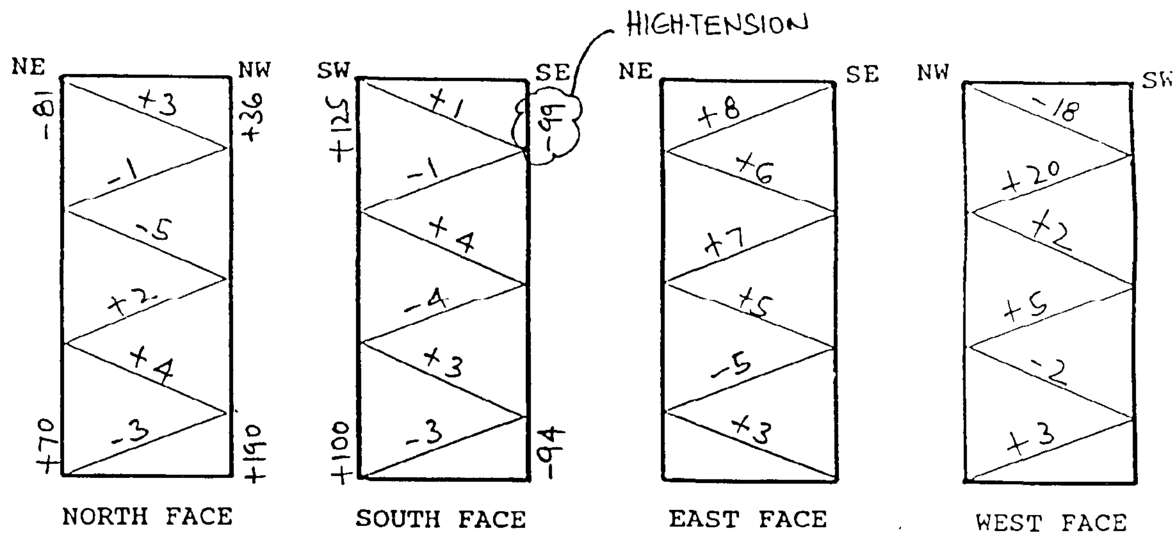


TOWER SECTION NO. 15

(cloud symbol) = LOCATIONS OF HIGH COMBIN STRESSES

Notes:

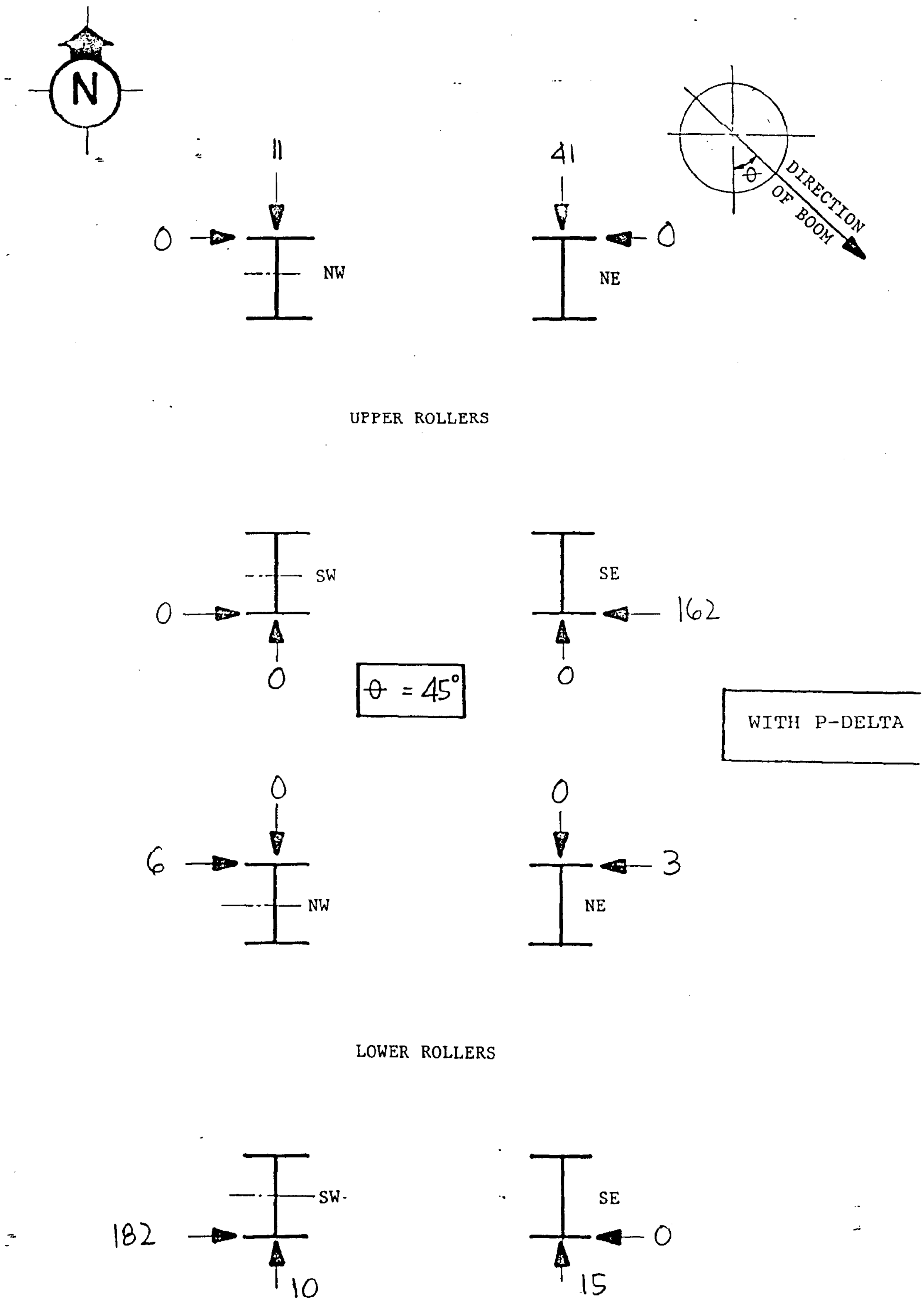
1. FORCES SHOWN (+) IS COMPRESSION, (-) IS TENSION
2. ONLY TOP & BOTTOM OF COLUMN FORCES SHOWN
3. FORCES SHOWN ARE IN kips



TOWER SECTION NO. 14

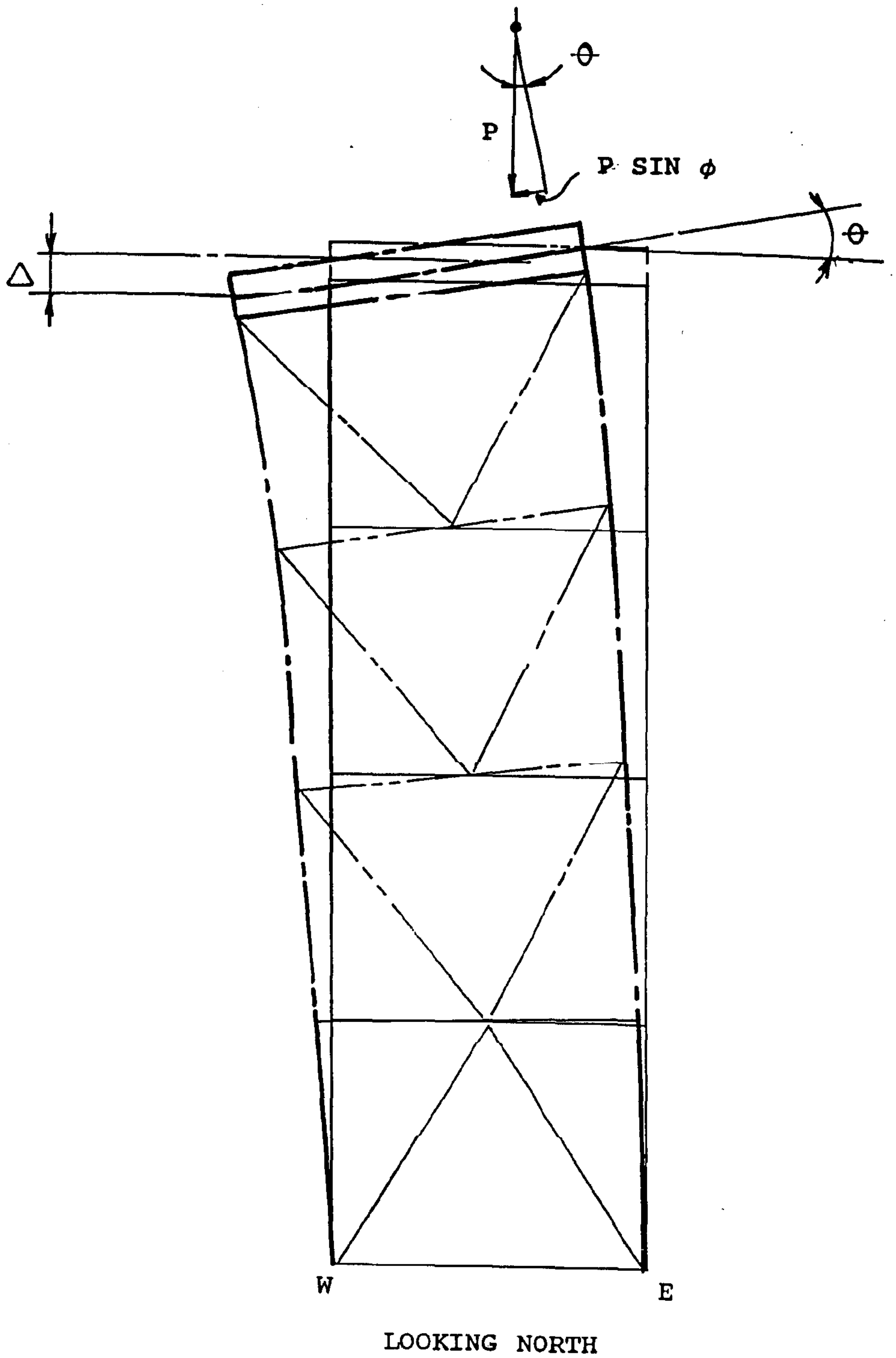
WITH P-DELTA

FORCES AND STRESSES IN TOWER SECTIONS ~~θ~~ = 45°
FIGURE 6.3.6b



<u>ROLLER FORCES ON TOWER LEGS</u> (KIPS)

FIGURE 6.3.6c



ROTATION OF CRANE SUPERSTRUCTURE

FIGURE 6.3.7

7. ANALYSIS OF COLLAPSE

7.1 Introduction

It is important in determining the cause of the failure to consider all the available information from the investigation. For example, in discussing the witness statements in Chapter 4, there was some apparent disagreements as to where the operator was at the time of the collapse. Considering this information alone, therefore, could affect conclusions as to whether the rotation of the crane, possibly by the operator, was the initial cause of the failure or the rotation occurred without control by the operator as a result of some other failure. Considering only portions of the collapsed structure such as the rollers displaced from the climbing section could also be misleading. Prior to presenting the failure scenario, therefore, key elements of the eyewitness testimony will be reviewed and relevant observations of the collapsed structure will be discussed in Section 7.2. The failure scenario presented in Section 7.3 will be based on all the information obtained in the course of the investigation.

7.2 Summary of Significant Data

Location of Crane Operator

The location of the cab operator immediately prior to rotation of the crane is important in determining the likely mechanism which led to the collapse. Witness no. 2 placed the operator in the cab before the movement started. The witness was at an elevation which provided a clear view looking down on the crane. Witness no. 17 saw the operator in the cab moving his hands and prior to the collapse this witness saw him trying to push his way out of the cab. Witness no. 25 also saw him seated in the cab, then stand up to observe something near the southwest leg. Other witnesses e.g., nos. 19 and 31, place the operator in the cab. Two witnesses saw him standing on the turntable holding onto a rail on the turntable, as the crane was collapsing. There were other witnesses who indicated that they did not notice the operator in the cab but they were not specific about the timing of their observation. The overall indications are that the operator was in the cab immediately prior to the initiation of the rotation of the crane. At some time, he came out of the cab and was holding onto the railing of the turntable as the collapse progressed.

Status of Climbing Operation

Physical evidence indicates that the climbing section was raised very close to the highest elevation in the third climbing step immediately before initiation of rotation of the crane.

This is supported by witnesses including Witness no. 4 who was closest to the climbing section platform and was in direct communication with the crane operator. The climbing section, however, were not resting on the tower lugs but were supported on the hydraulic ram before and during the rotation of the crane. This is supported by physical evidence including the length of the hydraulic ram, the bending of the hydraulic ram towards the west, the bending of the northwest dog of the climbing traverse and deformation found on the top of the northwest lug of tower section no. 14. These deformations could not have occurred due to impact from the collapse. All these deformations took place during the rotation of the turntable.

The hydraulic ram was fully extended when found on the street. The measured length between the pins at the top of the ram and underside of the climbing traverse was 18 feet-3 inches. The indentations on the flanges of tower section no. 15 also indicate that the ram was fully extended. The longitudinal axis of the ram was bent about 7 degrees to the west due to bending of the bottom connection plate. This deformation could not take place if the climbing section's flaps were resting on the top lugs of section no. 15 since the climbing traverse and the hydraulic ram would have been relieved of load. Further, the nature of the deformation of the northwest dog of the climbing section confirmed that the load of the superstructure was supported by the hydraulic ram during collapse. This deformation of the northwest dog of the climbing traverse could only have occurred when the crane superstructure was collapsing in a southerly direction.

Crane Rotation and Collapse

The counterclockwise rotation of the crane is supported by most of the witnesses who indicate that the collapse occurred at the end of the rotation when the counterweights appeared to strike section 16 on the climbing section platform. This corresponds to a rotation of about 140 degrees, although structural failure may have begun before the rotation reached 140 degrees. Most witnesses indicate that the movement of the turntable was steady and uniform. The location of the parts of the crane after the collapses confirmed that the crane superstructure fell in a southerly direction.

External Loading

None of the witnesses interviewed indicated that they noticed any load being lifted by the crane during the time the climbing process was underway. There was also no appreciable wind at the time of the collapse. Data from the National Oceanic and Atmospheric Administration indicated a wind speed of 5.8 mph at 8:00 a.m. on the day of the collapse at the San Francisco Airport.

Previous Climbing Operation

On the day before the accident, three tower sections, nos. 13, 14 and 15, were added. The witnesses did not indicate any unusual problems during the climbing operations. Tower sections nos. 12, 13 and 14 were inspected in this accident investigation and found to be free from any significant deformations. One eyewitness indicated he heard a metal screeching sound at the end of the climbing operation on tower section 14. The sound was similar but less pronounced than the sound heard during the third climbing step of the climbing operation preceding the collapse. It was also reported that a hydraulic leak at a gage fitting on the ram was fixed and did not affect the climbing operation.

The method employed to raise tower sections 13, 14 and 15, to the climbing section platform on November 27, 1989, was identical to the method employed to raise tower section 16 on November 28, 1989. This method differed, however, from the recommended method outlined in the operating manual [1]. The actual method used was described in Section 3.3.

Witness no. 4 indicated hearing a screeching sound of metal bearing against metal during the climbing operation on the morning of the collapse. This sound became louder as the climbing operation progressed and was worse during the third climbing step. This is supported by physical evidence of indentations of the flange edges of the legs of tower section 15.

Luffing of Boom During Climbing Operation

Witness no. 4 who was in direct communication with the crane operator, through a two-way radio indicated the boom was luffed up approximately 5 to 8 minutes before the collapse. He reported that the crane was leaning towards the south and the erection crew instructed the operator to "trim" up the crane. This may have had a significant effect on the braking capacity in the event of any subsequent rotation of the crane. The ideal location of the hook in the balanced position is 70 feet-6 inches from the center line of the tower. However, if the hook is luffed back to a hook reach of 65 feet or less, one of the two slewing brakes is cut off and braking is achieved by only one slewing brake. The angle of the boom at the ideal balanced position is 70 degrees and by luffing the boom by 2 degrees or more, the braking capacity is reduced by 50 percent. The amount the boom had been raised could not be determined in the investigation. It is certain, however, that the operator moved the boom up prior to or during the third climbing step.

Condition of Slewing Brakes

It can be reasonably concluded that the slewing brakes were not in the open position when the climbing process began due to the eccentric cam on the spreading magnet being engaged. The operator had raised section 16 to the climbing section platform on the morning of the accident and he would have more than likely had to use the slewing brakes during that operation.

Witness no. 32 reported the slewing brakes were "overheating, grabbing and were too tight," and had been adjusted by the steel erection company a week before the accident. This witness also indicated the Pecco Corporation representative checked the adjustment.

Tower Section 15 Flange Deformations

There were a number of indentations on the edges of the flanges of tower section 15. The loading producing these marks was accompanied by the screeching sound discussed previously. These deformations could have been caused by one of the following conditions:

(a) Before or during the climbing operation, the flange and edge rollers were improperly adjusted. There is no physical evidence available to confirm or support this. If the rollers on the face of the flanges are adjusted improperly, the edge rollers may be only partially bearing on the edges of the flanges. It was not possible to determine what adjustments were made prior to the climbing process on the day of the collapse. The same erection crew, however, had successfully climbed six sections previously.

(b) The climbing section beams at the level of the upper and lower rollers were skewed and out of adjustment. This was considered unlikely because there are rigid beams at both levels providing a stiffened structure at and below the upper level of rollers.

(c) The tower section 15 legs were out of plumb and exceeded normal tolerances. The history of usage of tower section 15 could not be determined. It could not be established, therefore, whether there were any preexisting deformations of the columns of tower section 15.

(d) The boom had been slewed after the crane was balanced. This would certainly create excessive forces on some of the rollers and they could have moved out of adjustment causing deformations during climbing. None of the witnesses reported that the crane was slewed during the climbing operation. Witness no. 4, however, said the crane operator luffed the boom up at the beginning or during the third climbing step. The deformations on tower section 15 appear to have occurred during the third climbing step. The edge rollers had to apply very high forces to produce these deep indentations. A force in the range of 2.5 to 3.0 times the ultimate tensile strength of the steel would be needed to create the inelastic bearing type deformations observed. The bearing area of the rollers when properly aligned was about 0.125 in^2. If the rollers were offset such that they were bearing on only half the flange width, a force of 30 kips would produce bearing stresses sufficient to cause the observed deformations.

Displaced Guide Rollers

Four rollers were displaced from the climbing section. They were the lower southwest edge roller, the lower northwest edge roller, the lower northeast edge roller and the upper northeast edge roller. These four rollers came off their shafts. The probability of one or more of the rollers being dislodged preceding the collapse and causing events leading to the rotation of the turntable was considered. The possible dislodging of each roller was examined in light of the deformation on the roller and on the edge of the flanges of the tower section 15 legs. It was helpful to first determine the location of the displaced rollers prior to the collapse and also the direction of their movement before being dislodged.

Lower Southwest Edge Roller

An examination of the deformed surface of the edge of the flange revealed that a high bearing force was applied to a portion of the edge of the flange while the climbing section was ascending in the third climbing step. There is a smooth, linear indentation beginning at 30 inches from the bottom of section 15 and ending at about 9 feet-6 inches from the bottom. The amount of deformation increased with distance along the tower leg and covered most of the flange for the upper half. The upper six inches was considerably deformed. The deformation of the edge of the flange was away from the web for the lower half of the length . The deepest indentation occurred at the upper most point which is about 10 feet from the top. The surface of the indentation was smooth and no galling was noticed. This deformation was formed by the southwest edge roller rolling and not sliding on the flange while the climbing section was ascending. The load on the roller increased as it moved upward. The markings on all the displaced rollers were compared with this deformation. The profile of the edge of the rolling surface of one of the displaced rollers closely matched the deformation of the flange edge at the point of maximum indentation. No other missing roller matched this profile.

At a distance of 9 feet-9 inches from the top, another deformation was observed which gave conclusive evidence of the direction of movement of the roller when it came off. The indentation consisted of a flattened area on the flange edge and the deformation extended downward for three inches and it shifted toward the web. The amount of deformation increased toward the bottom and penetrated into the flange edge. A portion of the flange edge sheared away towards the web. When the lower southwest edge roller was placed on this penetration, it closely matched the deformation of the roller while moving the roller in a downward direction. It was concluded that the roller created a flattened area on the flange then moved downward under increasing pressure and rolled off the flange. The roller movement was towards the web. Thus, the lower southwest edge roller dislodged at a distance of 10 feet-0 inches from the top of section 15 while moving downward a distance of three inches from its highest point of bearing on tower section 15. The highest point of bearing of this roller, based upon the flattened area of the flange edge is 9 feet-9 inches from the top of the southwest column. This corresponds to the location of the lower edge roller when the flap of the climbing section is close to the tower lugs. Therefore, the climbing section was at or very near the final position for the climbing operation.

Lower Northwest Edge Roller

There was an indentation on the flange edge towards the web at a distance of eleven feet from the top of the northwest leg of section 15. The underside of the flange at this location was also deformed. The configuration of the deformation on the surface of one of the displaced rollers very closely matched the indentations on the edge and underside of the west flange of the northwest leg of section 15. This roller, therefore, was conclusively identified as the lower northwest edge roller. The inside surface of the bushing was galled in the axial direction indicating that the roller was forced off the shaft. No other significant marks were present below this indentation on the flange of the leg. The deformation of the roller and the flange edge indicated that the roller shifted towards the web side of the flange edge. The mark on the flange is very short indicating that the roller came off with little movement. Another mark was observed on this roller. The deepest portion of this mark was aligned with the center of the mark on the flange edge but offset to the bevel side of the roller. The indentation consisted of a flattened area with the depth of indentation decreasing in a counterclockwise direction. This suggested the applied force was decreasing as the roller descended. It is therefore concluded that the lower northeast edge roller came off at a distance of 11 feet from the top of section 15.

Twelve inches above this mark, there was another indentation on the flange edge, away from the web. The deformations on the lower roller did not match the configuration of the flange deformation at this location. The deformations of the upper northwest edge roller also did not match with this indentation. The marking on the roller associated with this indentation might have been masked, however, by the marking which the roller sustained when it was forced off the shaft at the location twelve inches below. This deformation on the flange edge indicated that the lower roller have ascended to a height of 9 feet-11 inches from the top. It was concluded therefore, that the roller had descended from a height of 9 feet-11 inches to the height of 11 feet before being forced out. The 10 foot location for the lower northwest edge roller matches the location of the deformation of at 10 feet from top on section 15 when the lower southwest edge roller came off. The markings indicate that the roller may have been forced downward before being dislodged. The absence of markings on the flange edge between the height of 10 feet and 11 feet from the top might indicate that the roller did not apply high forces to the edge of the flange while it was ascending or descending before it was finally pushed out.

Upper Northeast Edge Roller

An indentation was observed at a height of three feet from the top on the east edge of the northeast leg of section 15 for a length of four inches. The depth of the indentation decreased towards the bottom of the section. The most severe deformation was just below the upper terminus of the mark and consisted of a flattened area on the flange edge. The upper northeast edge roller, which was easily identified because of the absence of a brass bushing, had a matching configuration including a flattened region at one end of the markings and an indentation extending about four inches around the circumference. The configuration suggested that the upper northeast edge roller moved downward for a distance of about four inches under decreasing load. The indentation indicates that the roller was bearing on the flange edge with a high intensity of force but was not dislodged from the shaft. The roller must have came off during the collapse when the roller was not in contact with section 15 legs which is why it left no mark of being forced out. There are other indentations on the surface and edge of the flange which might have occurred during the collapse. The deep indentation consisting of a flattened area on the flange edge and matching marks on the roller indicated that the upper edge roller had ascended to a maximum height of 3 feet from the top. This is approximately the location of the upper edge roller during climbing at the end of the third climbing step.

Lower Northeast Edge Roller

No indentations of significance were observed on the edges of the flanges of the legs to indicate of excessive applied load. Also, there were no signs indicating the location of the dislodgement of the roller.

Based on the above, only two of the four displaced rollers came off when in contact with tower section 15. They were the lower southwest edge roller and lower northwest edge roller. The lower southwest edge roller came off at an elevation of 10 feet-0 inches from top of section 15 where as the lower northwest edge roller came off at an elevation of 11 feet-0 inches from the top. This would indicate that the lower southwest edge roller came off first. The lower northwest edge roller did not come off until a downward motion of the climber of 12 inches after the first roller came off. The other two displaced rollers, e.g., the upper northeast edge roller and lower northeast edge roller came off when the roller was not in contact with tower section 15. This would have happened during the collapse. There is no evidence to indicate the climbing section moved downward prior to rotation of the crane, thus, the rollers were all in place when this rotation started.

Witness no. 4, the closest to the climbing section platform, indicated that the climbing section was at about its highest elevation. There was no loss of support of the hydraulic ram causing the climbing section to move downward, at least prior to rotation of the crane. Measurements following the collapse indicated the ram was fully extended. Once the ram is extended, it can be retracted only by letting hydraulic fluid out of the piston chamber of the cylinder. The piston is fitted with a "locking brake valve" at the entrance orifice of the piston chamber. This valve is configured so that fluid under pressure can flow into the piston chamber through the valve without restriction. However, in case of a broken hydraulic line, the valve acts as a check valve preventing the escape of oil from the chamber. The valve has a pilot valve which will only allow oil to escape from the piston chamber by operation of the main controls. The valve is fitted with a hand control device to allow the ram to be retracted in case of hydraulic failure. After the accident, the locking brake valve was inspected and it was undamaged and in place on the piston. The hand control device had not been damaged or used. Thus, no external leakage could have caused the ram to retract and lower the climbing section. The downward motion of the rollers was not due to malfunction of the hydraulic ram.

7.3 Failure Scenario

The ultimate cause of the collapse, as indicated by the structural analysis in Chapter 6, was overloading of the structural members in the tower due to rotation of the crane. The witnesses indicated that the rotation of the turntable preceded the failure. Witness no. 4 stated that the climbing section was raised almost to the desired elevation and the climbing section 15 flap was near the lug of the tower. A few seconds later, he reported that the turntable started to rotate and then the crew yelled to the crane operator to stop the movement of the crane. After a counterclockwise rotation of about 140 degrees, the collapse occurred. A number of witnesses corroborated this.

The cause of the rotation of the turntable, therefore, needs to be addressed. What initiated the rotation? Was it due to motion induced by the crane operator or was there a failure in the structure which caused the rotation? One of the following factors could have initiated the rotation:

1. Loss of a guide roller
2. Structural failure of the climbing frame or the tower
3. Powered slewing of the crane

The likelihood of each of these factors being the cause of the rotation and subsequent failure is examined below.

Loss of Guide Rollers

Of the four displaced guide rollers, the structure is sensitive to loss of the lower northwest edge roller or the lower northeast edge roller due to their critical location in the load path to the hydraulic ram. The loss of the lower southwest edge roller or the upper northeast edge roller do not affect the structural integrity of the climbing section at the balanced condition. This was considered in Chapter 6.

It does not appear likely that loss of a roller occurred before the rotation started and, therefore, they did not cause the rotation. The loss of the rollers before initiation of the rotation was not supported by any physical evidence of the eyewitnesses. The loss of a roller could only have occurred prior to the failure if it was preceded by a downward motion of the climbing section. This downward motion would only be possible, before the rotation of the turntable, by either retracting or losing support of the hydraulic ram. There is no evidence to establish that either the hydraulic ram was retracted or there was a loss of support of the hydraulic ram. The rollers were probably forced off due to excessive horizontal and vertical displacement of the climbing section some time after the rotation began.

The upper northeast edge roller and the lower northeast edge roller did not cause the type of deformations on the edge of the flanges of the tower legs that would indicate that they had been forced off their shafts while bearing on the tower. The lower southwest edge roller and the lower northwest edge roller show signs of being forced off the flange but only after a downward motion of the climbing section. This downward motion is not probable unless the turntable had already started to rotate and excessive displacements taken place. It can be reasonably concluded that all four rollers were displaced off their shafts after the rotation had started.

Eyewitness no. 22 heard an explosion type sound and saw a piece of iron flying which was later identified to be one of the displaced rollers. At the same time he saw a member of the crew falling with the debris. This would also indicate that the roller was displaced when the motion of the turntable was well underway.

Further, the lower southwest edge roller came off at an elevation of 10 feet from the top of section 15 and the lower northwest edge roller came off at 11 feet. This confirms that the lower southwest edge roller came off first. The structure is not sensitive to the loss of the southwest edge roller if it is in the balanced condition.

Structural Failure of the Climbing Frame or the Tower

The laboratory tests of the climbing section and the tower section indicate the materials had adequate strength, ductility and toughness for structural purposes. Two preexisting cracks were found, however. One preexisting crack was found in the north flange of the southwest leg of tower section 14 at the junction of the weld of two diagonals. The other crack was found in the vertical plane where the guide pin was welded to the connection plate. These cracks created weak points in the structure and could have precipitated failure. Given the brittle nature of the observed fractures, they probably occurred at the same time the failure stress state was reached. The climbing operation ceased, however, and the crane was in a state of equilibrium immediately prior to the collapse. Witnesses indicated that the rotation did not start until some time after reaching this point. It is therefore, not likely that these failures caused the rotation.

Powered Slewing of the Crane

It is likely that the rotation of the crane occurred under power. This was possible since the crane operator was in the cab at the time the rotation started. One possible reason for slewing the crane would be to facilitate setting of the flaps of the climbing section on the top lugs of tower section 15 at the end of the third climbing step. The marks on the edge of the flanges of the tower section columns indicated the rollers were offset from their ideal position in both directions. The climbing section was distorted, therefore, and not properly aligned with the tower section. In this situation, a decision may have been made to rotate the crane in an attempt to reorient the rollers so that the flaps could rest on the lugs and the climbing step completed. The only alternative would be to gradually retract the hydraulic ram and lower the climbing section to the second set of lugs and then correct the roller alignment. The physical evidence and witnesses do not indicate that this occurred.

With rotation of the turntable, the forces on the rollers increase as discussed in Chapter 6. This is also accompanied by tilting of the turntable toward the west. The evidence indicates that the lower southwest edge roller "rolled" off the shaft under increasing load. This was probably due to the downward motion of the climbing section. This is supported by the physical evidence on the flange of the column and markings on the lower southwest edge rollers. The turntable which is connected to the four climbing section columns swayed to the west and the vertical displacements of the columns were such that the turntable tilted a significant amount. The computed tilt of the turntable at an angle of rotation of 45 degrees when all the rollers are intact and functioning was 8 degrees. With a tilt of 8 degrees, the west side of the turntable would deflect downward 15 inches. The vertical and horizontal displacement of the turntable will cause the climbing section to slide down the west side of the tower section a few inches, causing the southwest edge roller to be dislodged. With the release of the lower southwest edge roller, the remaining rollers experience greater forces and the displacement of the climbing section becomes larger and larger.

The hydraulic ram, which continued to support the load of the entire superstructure, was also subjected to large displacements. The hydraulic ram is connected at the top to the box shape beam located at the level of the upper rollers and to the climbing traverse at the bottom. The bottom connection was made with a plate which has a pin attached to the climbing traverse. The stiffness of the hydraulic ram is several times greater than the stiffness of the bottom connecting plates. Therefore, when the hydraulic ram was subjected to such large displacements, the bottom connection plate yielded and inelastic bending deformations resulted. Figure 4.3.39 shows the hydraulic ram and the climbing traverse after the collapse.

The gravity load of the superstructure is transferred to the tower through the two dogs of the climbing traverse shown in figure 4.3.40. These two dogs bear on the tower lugs. In this case, they were supported by the top lugs of tower section 14. There is no positive connection between the dogs and the tower lugs. The load is transferred in bearing only. In view of the large displacements of the turntable and the in elastic deformation of the connection plate at the bottom of the hydraulic ram, the northeast lug of the traverse separated from its seat and rotated toward the west. This is the reason the northeast dog of the climbing traverse and the northeast lug of tower section 14 did not show any sign of distress. Subsequently, all the load of the tower was transferred to the northwest lug. As the rotation continued, the structural deformation and formation of a series of plastic hinges took place. With the rotation of the boom at 45 degrees, the structure became unstable with three plastic hinges in the southwest leg of tower section 15 as discussed in Chapter 6. If one or more of the rollers came off as the crane rotated, the instability was magnified.

The final collapse occurred at a rotation of about 140 degrees. Immediately before the collapse, the hydraulic ram continued to be supported on the northwest lug of tower section 14. During the southerly fall of the superstructure, the northwest dog of the climbing traverse was subjected to an extremely high flexural stress resulting in the deformation as shown in figure 4.3.40.

The slewing brakes are not designed to stop rotation of the crane instantaneously. Rather, they are designed to gradually stop the motion to prevent overturning the crane. It takes 10.1 seconds or a rotation of 60 degrees to bring the crane to a stop if it is rotating at the maximum speed of one revolution per minute, provided both brakes are properly adjusted. A powered rotation will continue for a few seconds, therefore, as the brakes gradually decelerate the crane. Given that the boom was luffed during the climbing operation and only one slewing brake may have been functioning, the time required to stop the rotation would have been increased. With increasing rotation, tilting of the turntable increased resulting in a torque due to the horizontal component of the superstructure load as discussed in Chapter 6. This torque also causes the crane to rotate and must be resisted by the brakes. These two effects combined, may have prevented the operator from stopping the rotation of the crane before reaching 45 degrees. Once this rotation is reached, the load carrying capacity of the structure is exceeded and the torque causing the crane to rotate exceeds the capacity of one slewing brake. Rotation continues and at some point, in this case, at 140 degrees when the counterweights struck tower section 16, total collapse occurred.

8. CONCLUSIONS

The following conclusions by the Occupational Safety and Health Administration are based on the examination of the collapsed structure, the review of witness interviews, the laboratory tests and structural analysis discussed in this report.

1. The likely cause of the failure was overloading of structural members in the tower due to rotation of the crane during the climbing operation. The rotation was likely due to adjustments being made to the climbing section that involved powered slewing of the crane.

   (a) Eyewitnesses indicated the crane operator was in the cab prior to, at the initiation of and during some portion of the rotation of the crane that preceded the collapse.

   (b) Eyewitnesses indicated the crane rotated counter-clockwise prior to the collapse.

2. A preexisting crack in a connection plate and a structural member and brittle behavior of the materials associated with welding details may have contributed to the failure.

3. The climbing section was not correctly positioned with respect to tower section 15, particularly, in the third lift.

   (a) Bearing type deformations were produced on the edges of the flanges of tower section 15 due to misalignment of some of the rollers on the climbing section.

   (b) A member of the erection crew reported a metallic sound indicative of rubbing of metal surfaces was coming from the climbing section during the climbing operation.

4. The forces in the climbing section and tower members are sensitive to loss of support of a highly loaded climbing section roller.

   (a) The structural analysis showed large displacements and overstress of many of the structural members occur with loss of a roller with no rotation or a small amount of rotation of the crane superstructure.

5. The forces on the rollers of the climbing section are very sensitive to rotations of the crane superstructure.

   (a) For a rotation of only 8 degrees from the balanced climbing position, the force on a roller on the edge of a flange increased from zero to 32 kips.

6. Failure of the crane in terms of exceeding the load carrying capacity during the climbing operation occurs at a counterclockwise rotation of approximately 45 degrees.

9. REFERENCES

1. Pecco Operating Manual - Slewing Tower Crane SN 355, American Pecco Corporation, Millwood, NY.

2. "Examination of Components from a Failed Tower Crane," Anamet Laboratories, Inc., 3400 Investment Blvd., Hayward, California, Laboratory No. 390.044, April 30, 1990.

3. "STAAD-III/ISDS Program User's Manual," Research Engineers, Inc., 590 Lippincott Drive, Marlton, NJ.

4. Load and Resistance Factor Design Specification for Structural Steel Buildings, American Institute of Steel Construction, 1st Edition, Chicago, IL, September 1, 1986.

APPENDIX A

CLIMBING PROCEDURE

The following procedure is taken verbatim from pages 36 to 42 of the American Pecco Corporation, Operating Manual for Slewing Tower Crane SN 355. Photographs and sketches in the manual are not included. The manual is undated and was reported to be the same manual provided to the operator and erection crew on the construction site at 600 California Street, San Francisco, California. The manual was obtained from American Pecco Corporation by CalOSHA.

3.4.2 **Preparation for Climbing.**

Climbing or adding tower sections to the tower is only permitted up to the following wind speeds:

° **Permissible wind speed, nearly constant and not gusty, 26'/s (17 mph) = Beaufort 4.**

° Before climbing, check oil level in hydraulic tank.

° Place the tower sections to be installed at disposat.

° Move the climbing section towards the intermediate frame and secure the pin with alligator pins.

° Adjust the guide track for the assembly carriage at the suspension in such a way, that the assembly carriage is inclined upwards.

In this way the break-in of the assembly carriage is made easier.

Attention:

° Rearrange the railing on the top erection platform of the climbing section, so that it has the required height. The crane must then not slew any more.

° Adjust the guide rollers.

The four front guide rollers must touch the tower section. The four rear guide rollers should have a play of 3/16".

The two left hand top guide rollers should touch the tower section.

The two left hand bottom guide rollers should have a play of approx. 3/16".

The two right hand bottom guide rollers should touch the tower section.

This is only a basic adjustment which must be changed according to wind influence and weight tolerances.

3.4.3 Installation of the tower section pulling device for use when top climbing.

- Pin the auxiliary rope (1/4" dia x 256' long) with thimble and rope clamp to the protective bracket one the boom tip.
- With booms L_1 and L_2 the unused piece of the rope is coiled up and stored here.
- The auxiliary rope is kept closed to the boom by way of rope eyes.
- The rope eyes are clamped on to the diagonal members on the outside of the boom in distances of 16'-5".
- The other end of the auxiliary rope is clamped and coiled onto the rope winch, until it is hanging tensioned underneath the boom.
- Clamp the rope clamp well with the auxiliary rope tensioned (approx. 1'-8" above the rope winch).
- Coil the auxiliary rope (approx. 10') off the rope winch.
- Lower the boom to widest hook reach.
- Run the load block to its top position.
- Move the guide sheave via catwalk in the boom to the platform on the boom tip.
- Undo the wing bolt and swing out the side plate on the guide sheave.
- Insert the hoist rope in the guide sheave, underneath the fixed point of hoist rope.
- Then insert the auxiliary rope in the guideway of the guide sheave and bolt the side plate with the wing bolt again.
- The guide sheave is now placed upon the load block in such a way that the guideway for the auxiliary rope points towards the crane tower.
- Hook the auxiliary rope off the rope eyes on the boom.

- Raise the boom to its top position.
- Lower the load block to shortly underneath the rope winch for the auxiliary rope. In this way the guide sheave is also lowered.
- The deflection thus created in hoist and auxiliary rope prevents the guide sheave from twisting.
- When the auxiliary rope is coiled off further, the guide sheave is pushed against the rope clamp and kept at this height.

3.4.4 Placing the tower section with run-in-device upon the erection platform of the climbing section.

- Raise the boom to 49'-3", 70° and pick up the tower section with the load block.
- When doing so, coil the auxiliary rope off the rope winch only so far that it is always tensioned.
- Pull the tower section to above the erection platform.
- Raise the boom to its steepest position.
- The auxiliary rope is kept tensioned by coiling it onto the rope winch.
- Thereafter the tower section is pulled horizontally towards the tower to the erection stage.
- Place the tower section on the assembly carriage.
- Bolt the assembly carriage with the guide track.

Dismantling of the auxiliary rope coil

- Move load block and guide sheave to their top position.
- Coil the auxiliary rope up on the drum and remove rope clamp from the auxiliary rope.
- Lower the boom to widest hook reach.
- Undo wing bolt on the guide sheave, swing out the side plate and remove auxiliary rope and hoist rope from the guideway.
- Remove guide sheave from the load block and carry it away over the catwalk.
- Remove the auxiliary rope (rope clamp) from the boom tip.

Diagonal Bracing Members of the Tower Section

P_{cr} = 121.65 kips

M_p = 15.2 kip-ft.

P_y = 188 kips

3 Inch Diameter Diagonal Bracing Members of the Climbing Section

P_y = 108 kips

M_p = 7.9 kip-ft.

Length = 3.76' : P_{cr} = 92.5 kips

Length = 7.05' : P_{cr} = 62.6 kips

Length = 7.20' : P_{cr} = 60.9 kips

Length = 7.46 : P_{cr} = 58.2 kips

3.5 Inch Diameter Diagonal Bracing Members of the Climbing Section

P_y = 1127.5 kips

M_p = 11.0 kip-ft.

P_{cr} = 59.5 kips

4.2 Inch Diameter Diagonal Bracing Members of the Climbing Section

P_y = 189.5 kips

M_p = 19.6 kip-ft.

Length = 7.05' : P_{cr} = 143.9 kips

Length = 7.46' : P_{cr} = 139.3 kips

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