FACE

Fatality Assessment and Control Evaluation Program

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Three Ironworkers Die After Heavy-lift Crane Tips Over-Wisconsin

Photo 1: Heavy-lift crane during tipover at stadium (Photo courtesy of John A. Thraen)

SUMMARY

On July 14, 1999, three male ironworkers (the victims), ages 39, 40, and 52, died after falling approximately 300 feet to the ground when the suspended personnel platform they were occupying was struck by the uncontrolled load of a heavy-lift crane. The victims were working in windy conditions during the construction of a county sports stadium. The three ironworkers were suspended about 300 feet above the ground to observe the hoisting of a 450-ton roof section. The roof section had been hoisted to about 330 feet and transported over its connection location by the heavy-lift crane crew. As the roof section was being lowered into place, the heavy-lift crane began to tip over. The crane continued tipping, and the roof section collided with the personnel platform, knocking it and the victims to the ground. Fire department and emergency medical personnel were immediately notified and responded within 5 minutes. The victims were pronounced dead on site by the county medical examiner.

NIOSH investigators concluded that to help prevent similar incidents, employers should

- ***implement specifically engineered lift plans for critical-lift hoisting operations. Such plans should be designed by registered professional engineers having specialized knowledge of critical lift operations and should be based on the following: (1) the rated capacity and operational limitations specified by the crane's load chart; (2) measured, as opposed to calculated, weights for the materials to be hoisted; (3) thorough studies of wind speed and its effect on the crane and hoisted load; and (4) consideration of the effects of ground conditions and dynamic forces on the crane's stability.***

- ***ensure that cranes and work areas are equipped with strategically located instruments to monitor wind velocity (speed and direction) at or near the elevation of hoisted loads***

- ***ensure that suspended personnel platforms are not used during weather conditions which could endanger the hoisted workers***

- ***consider alternative methods of observation when landing locations are not readily visible to ground-level observers during hoisting operations***

- ***ensure that only personnel necessary to safely complete the lift are assigned as hoisted observers***

- ***ensure that cranes are equipped with correctly calibrated instruments to accurately monitor all parameters affecting safe crane operation***

Additionally, designers and erectors should

- ***carefully evaluate worker risk when devising construction and hoisting methods for use during steel erection***

INTRODUCTION

On July 14, 1999, three male ironworkers (the victims), ages 39, 40, and 52, died after falling approximately 300 feet to the ground when the suspended personnel platform they were occupying was struck by the uncontrolled load of a heavy-lift crane. On July 15, 1999, NIOSH's Division of Safety Research (DSR) learned of the incident through news media reports. On July 20 and 21, and July 27 through 29, 1999, a DSR safety engineer accompanied the investigating OSHA compliance officers to the site and examined the wreckage. Photographs and videos of the incident were examined and witness interviews were attended. On December 15 and 16, 1999, the safety engineer met with the OSHA investigators for further discussion and to continue review of the case files, photographs, and videos. Additional information was obtained from newspaper accounts of the incident, court testimony during subsequent litigation, and from reports of engineering evaluations of the crane and external forces affecting the tipover. The incident was a complex, multifactorial event, and this report is not intended as a comprehensive documentation of all the factors involved. However, its intention is to identify and describe the major risks for crane-related injury that were present during the incident and to make recommendations to help prevent similar incidents.

The stadium construction project had been ongoing for about 3 years. The design of the stadium included a multipanel retractable roof supported by curved truss assemblies. At the time of the incident, construction had progressed to the point where the truss assemblies for the roof panels were being erected. Between 400 and 700 workers employed by various contractors and subcontractors were on site.

The general contractor for the project, a consortium of three construction firms, had been contracted by a county stadium board. The general contractor had contracted the design and construction of the stadium's retractable roof to two large multinational firms. One firm had designed the roof structure while the second had designed the transport mechanism that retracted the roof. The second firm had also been contracted to supervise the assembly and erection of the roof. This firm had in turn contracted a steel erection company (the victims' employer) to provide ironworkers and had also contracted for the use of a heavy-lift crane from a multinational crane company.

The steel erection company employed 88 ironworkers at the incident site. The company had a written safety program and conducted regular toolbox safety talks. The program contained specific procedures for safe hoist operations, including specific precautions to take when hoisting personnel platforms. The program prohibited the hoisting of personnel platforms in high-wind conditions, which could endanger employees.

The roof construction contractor also had a written safety program. This program included specific procedures for hoisting personnel platforms that prohibited their use when wind conditions exceeded 20 mph.

These were the steel erection company's first fatalities.

INVESTIGATION

The heavy-lift crane was owned by a crane rental and heavy rigging business with over 20 years experience. The business employed 250 people worldwide. It had been at the stadium construction site for 11 months before the incident and had been used to successfully hoist 10 roof sections into place. The heavy-lift crane, of a unique design, was operated by a 5-member crew under the direction of a lift superintendent (Figure 1). Its upper-works consisted of a bridge with five hoisting drums, a hoist operator's cab, and a 340-foot lattice boom with a 200-foot jib. The upper-works was supported by two crawler-tracked transporters and was attached to the front transporter by a center pin located between the boom heel pins. The rear transporter carried a 2,400-kip (1 kip = 1,000 pounds) counterweight and was connected to the bridge by an articulated joint behind the hoist operator's cab. In this configuration, the heavy-lift crane had a maximum capacity of 1,040 kips. Each diesel-powered transporter had its own operator. Two individually operated tugger winches, used to control lines attached to the hoisted load, were mounted on the bridge near the boom heel pins. Crane travel and boom swing were accomplished by the coordinated movement of the transporters under the direction of the lift superintendent. For example, to swing the boom, the transporters would be rotated at angle to the bridge. While the front transporter remained stationary, the rear transporter would continue traveling, moving the rear of the bridge and thus swinging the boom. Moving both transporters in the same direction along parallel paths moved the crane sideways. To move the crane forward or backward, the transporters would be rotated in-line with the bridge, one transporter traveling in trail with the other. Along with the heavy-lift crane, the crane rental company had supplied the services of a lift superintendent, a hoist operator, and a mechanic/ transporter operator who operated the rear transporter. The remaining crew members, two tugger winch operators and the front transporter operator, were employees of the steel erection firm.

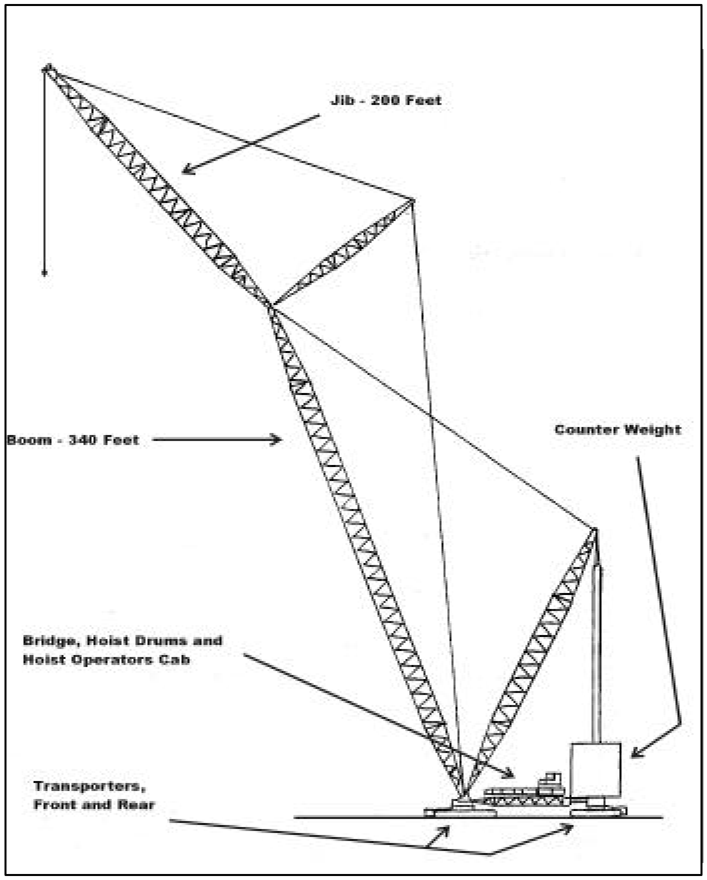

Figure 1. Side view of heavy-lift crane.

To minimize the ironworkers' exposure to fall hazards and to shorten construction time, the truss assemblies supporting the retractable roof panels were fabricated on the ground in approximately 200- to 450-ton sections. Each roof section was then hoisted over the stadium structure, landed, and connected. This operation followed specific procedures for lifting each roof section that used the heavy-lift crane and multiple observers both on the ground and in the air. The entire operation was coordinated by the lift supervisor, who was in radio contact with crane crews and observers stationed at strategic locations around the job site (Figure 2). On the day of the incident, observation locations included three suspended personnel platforms. Two of the personnel platforms were suspended from tower-configured mobile cranes set up inside the stadium. One of these personnel platforms, suspended approximately 300 feet above ground, was to be occupied by the victims. The third personnel platform, which was to have been occupied by the lift supervisor while the roof section was being lowered to its final position, was suspended from a lattice-boom crawler crane located outside of the stadium and to the north of the heavy-lift crane.

Rigging of the roof section for hoisting had been completed by the evening of July 13, 1999. This included welding lifting eyes to the roof section, attaching slings and shackles, and moving the

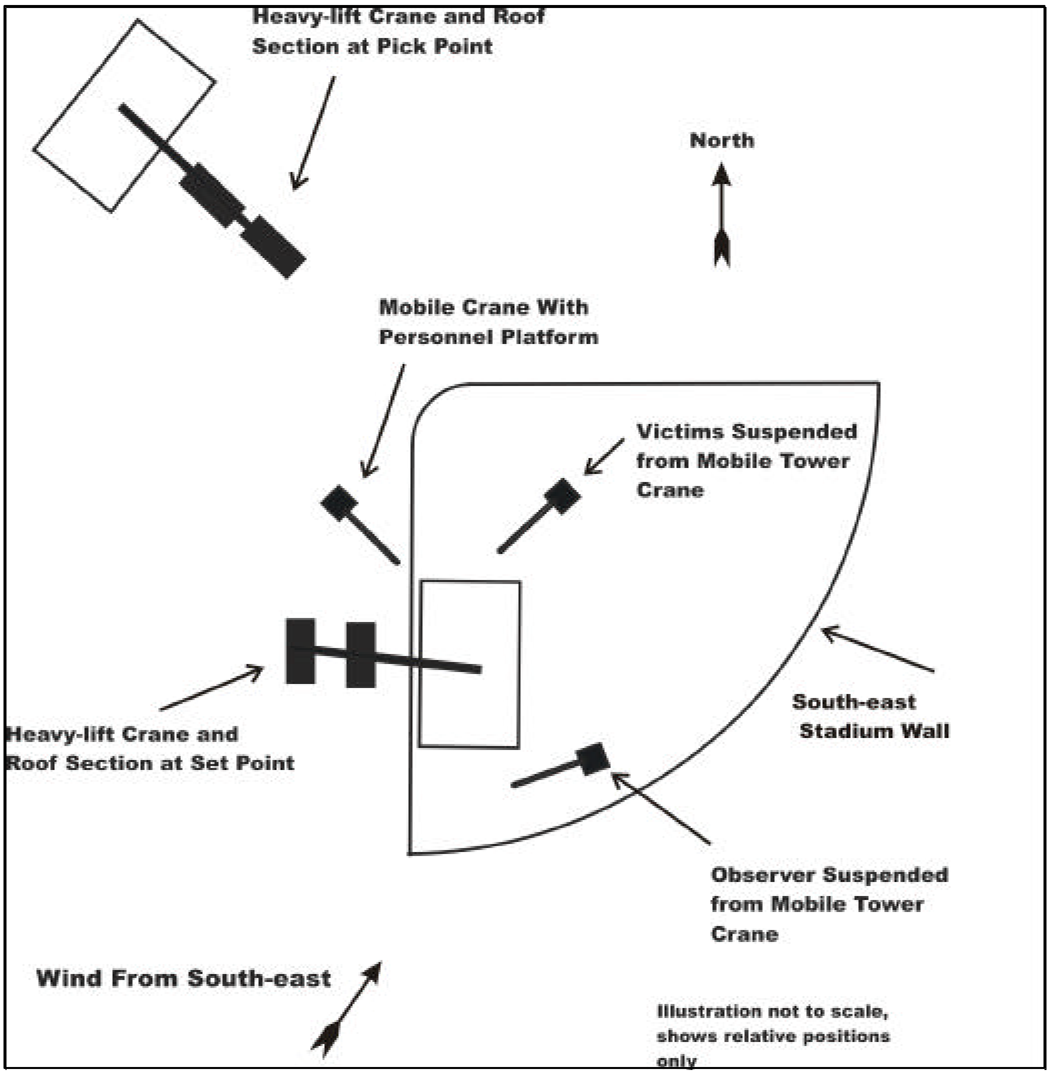

Figure 2. Plan view, heavy-lift crane and stadium.

heavy-lift crane into position. At 5 a.m. on July 14, 1999, the lift superintendent completed the lift plan. The crane crew arrived for work at 5:30 a.m. and performed routine daily crane maintenance. Other workers who would be involved in the lift arrived on site around 6 a.m. At 6:30 a.m., a prelift meeting was held which was attended by approximately 40 workers from the various employers involved in the lift. During the meeting, the lift superintendent briefed the crane operators and observers on the procedures to be used during the lift and the directions in which the crane and its load would be maneuvered. The lift would be directed by the lift superintendent while located on the ground near the heavy-lift crane. It would begin at the "pick point"(Photo 2) near the north end of

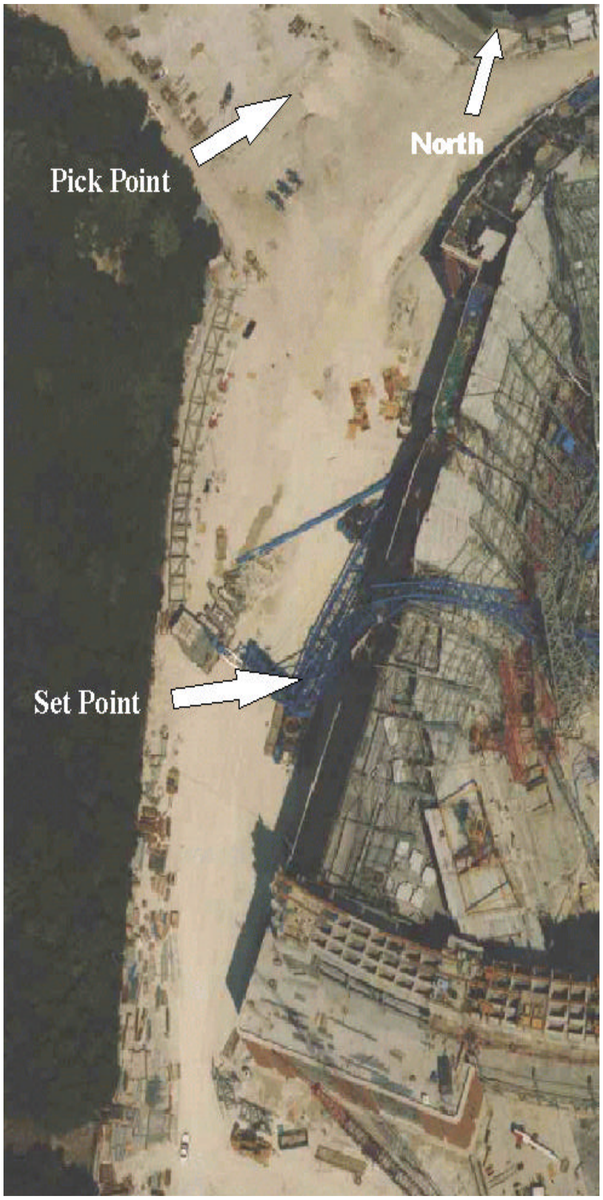

Photo 2. Travel route from pick point to set point.

the stadium where the roof section would be hoisted and checks made to be sure it was properly suspended. The roof section would then be swung to the west, hoisted over the south end of the stadium, and moved to the "set point" near the south end, where the roof section would be lowered into place. The lift superintendent would then direct the final positioning and connection while suspended from the third personnel platform. At 7 a.m., the lift superintendent examined the load and rigging and established radio communication with the crane crews and observers. Hoisting operations were begun and the 176- by 200- by 16-foot roof section, which had been resting on support blocks, was picked up. At about 9:30 a.m., after the roof section had been raised 6 to 8 feet above the blocks, the lift was halted so that the attitude of the roof section (i.e., the orientation at which the hoisted load hangs suspended) could be determined by survey. Since the roof was curved, the connections between the roof sections were at differing elevations on the stadium structure (Photo 3). To successfully connect the roof sections together, it was necessary to hoist them into place at nearly the same attitude as they would be connected. For the roof section being lifted, the south-end connections were at a lower elevation than the north-end connections. The attitude at which a suspended object hangs depends on the location of the object's center of gravity in relation to the attachment points and lengths of the lines suspending it. The attitude of a hoisted load is usually adjusted by moving attachment points, or shortening or lengthening suspension lines. In this case the attachment points (lifting eyes) had been welded to the roof section and could not easily be moved, and changing the length of the suspension lines was judged to be too time-consuming. Therefore, the attitude of the roof section was adjusted by hanging a 6,500-pound concrete block near the southeast corner. This adjustment required several trial-and-error attempts until the correct position was found. While the adjustment was being made, the lift superintendent observed that the crawlers of the front transporter were sinking into the ground, which meant that swinging the roof section to the west would put the

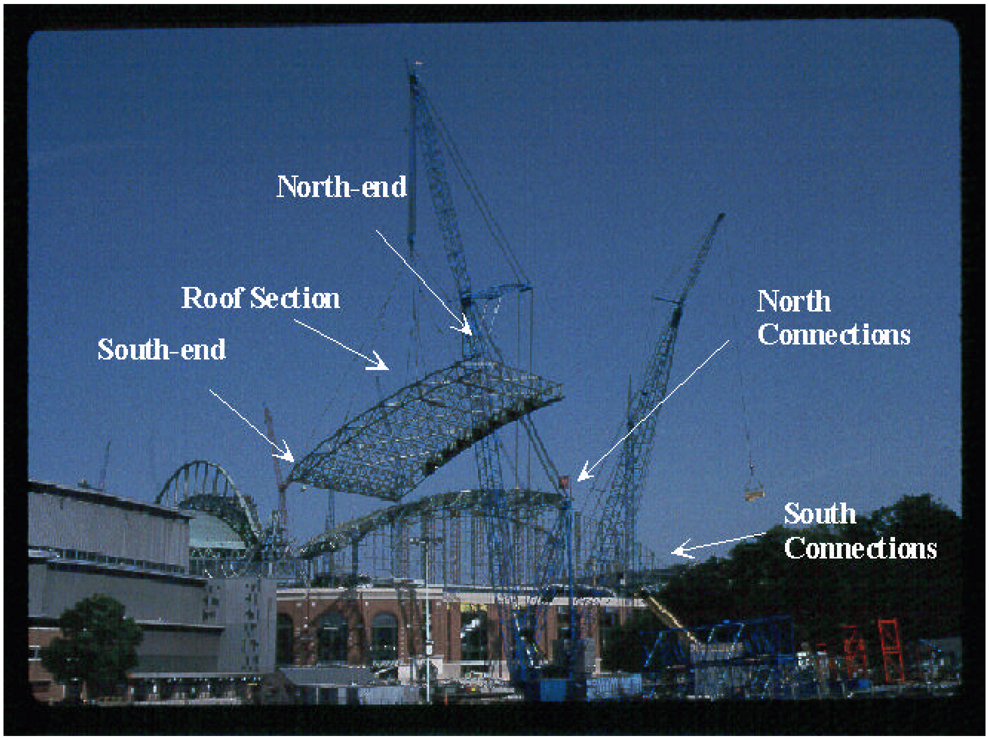

Photo 3. Heavy-lift crane with roof section before moving over.
(Photo courtesy of John A. Thraen)

crane out of level. He therefore directed the crew to move the crane southeast onto more competent ground. The lift plan was now changed. The roof section would be hoisted over the north end of the stadium, swung to the east, and moved into place. This new route required the roof section to be lifted to a higher elevation so that it would clear the roof structure that had already been constructed. After moving onto firmer ground, the crane was stopped so that the roof section could be correctly positioned for connection. This was accomplished by pulling the load with cables attached to forklifts. After the load was hanging in the correct position and attitude, it was constrained from further rotation by lines attached to the two tugger hoists. These preparations consumed several hours. Between 2:30 p.m. and 3 p.m., the roof section was hoisted to about 330 feet, and the crane was positioned for traveling by rotating the transporters. The crane then moved sideways to the set point. As the crane moved sideways, the lift superintendent requested regular updates on the wind conditions from the hoist operator. Conditions indicated by the crane's mast-mounted anemometer indicated wind speeds between 17 and 20 mph. The crane, with its suspended load, successfully traveled about 500 feet, reaching the set point toward the south end of the stadium shortly before 5:14 p.m. The crane was stopped and the crew engaged in stabilizing the roof section while the hoist operator began to lower it into place. This was necessary because, when the front and rear transporters had been stopped at the set point, the roof section, acting pendulum-fashion, continued moving, swinging to the south. To control the roof section, the lift superintendent attempted to move the crane's boom southward to center the boom tip over the roof section before it swung northward;

however, the attempt was mistimed, and the roof section began to swing back to the north. The lift superintendent told the crane crew that they would attempt to stabilize the roof section during its next swing south; however, as the roof section swung back, the crane became unstable and began tipping to the north and slightly eastward. As the crane continued to tip, the boom contacted the stadium wall parapet and buckled just below the boom midpoint. The roof section, upper half of the boom, and the jib fell inside the stadium. During the tip over, the roof section swung into the victims' personnel platform, which was suspended from the mobile tower crane located inside the stadium. The tower crane's boom collapsed and the personnel platform fell to the ground, carrying the victims with it. Fire department, emergency medical personnel and public safety units were immediately notified and responded within 5 minutes. The victims were pronounced dead on site by the county medical examiner.

Evaluation of information gathered during the investigation indicates that the weight of the hoisted load, side loads from wind forces on the crane and roof section, out-of-level ground conditions, and the pendulum motion of the roof section combined to tip the crane to the north. This combined load exceeded either the crane's resistance to overturning or its structural strength, causing the incident. Consequently, the hoisted load moved northward, uncontrolled, and collided with the crane and personnel platform of the victims.

CAUSE OF DEATH

The medical examiner attributed the deaths to blunt force trauma resulting from a fall.

RECOMMENDATIONS

Recommendation No. 1: Employers should implement specifically engineered lift plans for critical-lift hoisting operations. Such plans should be designed by registered professional engineers having specialized knowledge of critical lift operations and should be based on the following: (1) the rated capacity and operational limitations specified by the crane's load chart; (2) measured, as opposed to calculated, weights for the materials to be hoisted; (3) thorough studies of wind speed and its effect on the crane and hoisted load; and (4) consideration of the effects of ground conditions and dynamic forces on the crane's stability.

Discussion: During hoisting operations, cranes are subjected to additional loads other than the weight of the materials being lifted. Crane load charts specify maximum lifting capacities for every configuration permitted by the manufacturer and specify the limitations and conditions necessary for safe operation.[1] Knowledge of the hoisted load, wind loads, and ground conditions is basic to safe crane operation. The actual hoisted load includes the weights of the lifted materials, hook block, slings, and other lifting accessories. Additional loads may be imposed on the crane by wind forces acting on the crane structure and the lifted materials, by dynamic forces due to movement of the crane and lifted materials, and side loads due to out-of-level or unstable ground conditions.[1,3] Lifts where the hoisted load exceeds 85 to 90% of a crane's rated capacity allow little reserve to counter unanticipated loads, and are known as "critical lifts." Other situations in which hoisting operations may be considered as critical lifts include lifts made in hazardous locations, where the crane and rigging configuration is nonstandard, or when the load is unwieldy, expensive, or irreplaceable.[2]

The maximum rated capacity of the heavy-lift crane was 1,040 kips. The nominal weight of the roof section was 900 kips or 87% of the crane's rated capacity. It is generally recognized throughout the crane and rigging community that special hoisting precautions are necessary for critical[2] lifts. Critical lifts require the use of specifically engineered lift plans based on a comprehensive evaluation of the most accurate information available for all factors affecting crane stability. Because a thorough understanding of the relationship between the crane design and the dynamic effects of traveling and moving with hoisted loads is crucial to the development of these plans, the plan should be designed by a registered professional engineer specializing in hoisting operations. To prevent crane tip over, the lift plan should be based on the operational limitations specified by the crane load chart, measured as opposed to calculated weights for the materials to be hoisted, thorough studies of wind speed and its effect on the crane and hoisted load, and consideration for the effects of ground conditions and dynamic forces on the crane's stability. Further discussion of these factors follows.

Hoisted Load

The lift-plan tally completed by the lift supervisor prior to the lift indicated that the hoisted load would be 1,002.4 kips. This included the weight of the crane's headache ball, the hook block, the load rigging, 350 feet of load line, the jib and the calculated weight of the roof section. To correct the attitude of the roof section, a 6,500-pound concrete block had been added to one corner of the roof section, bringing the total hoisted load recorded on the lift plan to 1,008.9 kips. The weight of the roof section had been calculated as 913 kips by the roof contractor's engineers and was provided to the lift superintendent before the development of the lift plan. A more accurate weight for the roof section could have been obtained by weighing the roof section with calibrated load cells. After the incident, the roof contractor and the erection contractor reevaluated the roof section weight. The contractor's second calculation was 919 kips while the erection contractor calculated 895 kips for total hoisted loads of 1,015.9 kips and 991.8 kips, respectively. These values for the hoisted load range from 92% to 97.6% of the heavy-lift crane's maximum capacity.

Side Loads Due to Wind Forces

Shortly before 5 p.m. on the day of the incident, a local airport 8 miles from the site recorded winds of 20.7 mph from the southwest, gusting to 26 mph. Just before 6 p.m. the wind was from the south, southwest at 19.6 mph, gusting to 27.6 mph. (Note: The direction of the tip-over was north, northeast) The heavy-lift crane was equipped with an anemometer located on its mast at about 180 feet elevation. According to interviews with the heavy-lift crane's hoist operator, this instrument indicated a wind speed of 17 mph about 5 minutes before the incident. At this time, the south end of the roof section was about 240 feet above ground and the north end was about 300 feet above ground. Actual conditions at these elevations were not measured; however, there are indications that wind speeds near the elevation of the roof section may have been higher.

The roof construction contractor had conducted engineering evaluations of the effects of wind on the roof and its supporting structure; however, similar evaluations of wind effects on the heavy-lift crane and its load during hoisting operations had not been performed. Engineering evaluations conducted after the incident included estimates of the steady wind speed at the height of the roof section and its effect on the heavy-lift crane and load. These estimates based on standard wind assessment methods and wind tunnel studies ranged from 19 to 23 mph. Estimates of wind gusts (3-second average) ranged from 31 to 35 mph. The load chart for the heavy-lift crane lists rated capacities when steady wind speeds are 20 mph or less. No ratings for wind speeds over 20 mph are listed and gusts were not considered in developing the capacities for the chart. The OSHA Office of Engineering Services evaluated the wind forces on the suspended roof section and concluded that a 25 mph southwest wind could impose a force of 13,492 pounds in the northeast direction on the load. Other studies estimate that the side load due to the wind acting on the crane structure as approximately ½ the force acting against the roof section. The total side load due to steady wind may have been as high as 20.75 kips.

Side Load Due to Out-of-Level Ground Conditions

The load chart for the heavy-lift crane specifies that the crane shall be level to within plus or minus 0.75 inches in 30 feet. After the incident the ground under the front transporter was surveyed and found to be sloping to the north, at a rate that varied from 1.6 to 2.9 inches in 30 feet. Out-of-level crane operation induces side loads at the crane's boom tip acting in the down-slope direction. Out-of-level operation also changes the load radius, increasing the distance between the hoisted load and the crane's center pin when the crane is swung downslope and decreasing the crane's resistance to tipping toward the load.[1] Since the down-slope direction in this case was north, loads which may have resulted from out-of-level operation added to the side loads due to wind forces.

Side Load Due to Dynamic Effects

When the transporters of the heavy-lift crane had been stopped at the set point, the suspended roof section continued to move, swinging pendulum fashion to the south. The heavy-lift crane crew, directed by the lift superintendent, made an attempt to arrest the pendulum motion by swinging the boom southward to center the boom tip over the load. This attempt was mistimed and, as the pendulum motion continued, the roof section swung northward. The lift superintendent notified the crane crew that they would make a second attempt to arrest the pendulum motion after the roof section had completed its northward swing and was again swinging to the south. However, as the roof section swung northward, the crane tipped over. Forces resulting from the pendulum motion of hoisted objects cause side loading on the boom tip in the direction of swing, in this case northward.

Recommendation No. 2: Employers should ensure that cranes and work areas are equipped with strategically located instruments to monitor wind velocity (speed and direction) at or near the elevation of hoisted loads.

Discussion: The crane in this incident was equipped with an anemometer located about 170 feet above ground level on the crane's mast. Wind speed was displayed by a monitor located in the hoist operator's cab. According to interviews with the hoist operator, the wind speed approximately 5 minutes before the incident was 17 mph and had not exceeded 20 mph at any time during the day's hoisting operation. However, it should be noted that these readings may not have been indicative of the conditions at the 240- to 300-foot height of the roof section. At this location, near the south corner of the stadium, the roof section may have been subject to wind as it struck the stadium walls at lower elevations and was directed up and over the building. This could have increased the local wind speed at the elevation of the roof section. Further, the drag effect caused by the contact of moving air with the earth's surface causes wind speed to vary with height, generally resulting in increased speed at higher elevations. Additionally, topographical features present to the southwest of the setpoint may have acted to channel wind at the crane and roof section, which would also increase the wind velocity. Anemometers or similar instruments located near the elevation of the suspended roof section and at other locations, such as on the south corner of the stadium, may have provided a more accurate indication of wind conditions at the elevation of the roof section. Radio-equipped anemometer systems are available that could have been mounted on the hoisted load to provide wind speed measurements at the elevation of the roof section.

Recommendation No. 3: Employers should ensure that suspended personnel platforms are not used during weather conditions which could endanger the hoisted workers.

Discussion: The safety program implemented by the roof contractor prohibited the lifting of personnel when wind conditions exceeded 20 mph. The steel-erection-contractor's policy included prohibitions against lifting personnel during high winds that could endanger employees. The wind on the day of the incident was from the southwest with speeds measured at the local airport of 17 mph gusting to 27 mph. Additionally, the crane's mast-mounted anemometer measured speeds up to 17 mph just before the incident. The lifting of personnel should also be considered a "critical lift" requiring precautions beyond those normally used for hoisting materials only.[2] The consensus standard, ASME/ANSI B30.5b - 2000, Mobile and Locomotive Cranes, specifies that personnel platforms should not be used when wind speeds exceed 15 mph[4].

Recommendation No. 4: Employers should consider alternative methods of observation when landing locations are not readily visible to ground level observers during hoisting operations.

Discussion: At the time of the incident, there were four observers located in two personnel platforms suspended from cranes located inside the stadium (Figure 2). Three of the observers (the victims) were occupying a personnel platform to the northeast of the heavy-lift crane. One observer was in a personnel platform southeast of the heavy-lift crane. When the heavy-lift crane tipped over to the north, the roof section swung into the victims' platform, severing the load line and collapsing the boom of the crane suspending them. The victims fell to the ground along with the personnel platform. Additionally, the lift supervisor was preparing to relocate to the personnel platform located north of the heavy-lift crane near the west face of the stadium. When the heavy-lift crane tipped over, it struck and collapsed the boom of the crane intended for hoisting this platform. Had the incident occurred a few minutes later, it most likely would have struck this platform and injured the lift supervisor. Use of new technology such as strategically located television cameras could eliminate the need for hoisted observers or decrease the amount of time necessary for them to be in the air. The use of distance- and position-measuring instruments, such as laser theodolites, during hoist operations similar to those of the incident could further reduce the need for hoisted observers.

Recommendation No. 5: Employers should ensure that only personnel necessary to safely complete the lift are assigned as hoisted observers.

Discussion: The correct positioning of the roof section on the existing structure was critical to safely completing the erection and connection of the roof section. The employer had evacuated personnel from the west side of the stadium as a precaution against exposure to unplanned movement of the roof section during landing; however, the procedures relied on information from radio-equipped observers stationed at various locations in the work area. Three suspended personnel platforms, to be used as observation posts, had been located at strategic locations inside and outside the stadium. As the assigned observers (two of the victims) were boarding the platform northeast of the heavy-lift crane and inside the stadium, a third worker (the third victim) decided to accompany them. The necessity for more than one observer at this location should have been evaluated. While limiting the number of observers would not have prevented this incident, it may have decreased the severity by limiting the number of fatal injuries.

Recommendation No. 6: Employers should ensure that cranes are equipped with correctly calibrated instruments to accurately monitor all parameters affecting safe crane operation.

Discussion: The crane in this incident was equipped with instruments that provided the hoist operator with a readout of operating parameters including the weight of the hoisted load. This instrument had been incorrectly calibrated and was known to report hoisted load weights significantly lower than the calculated weights provided by the roof contractor's engineers. The instrument manufacturer's operating manual specified a detailed calibration procedure that required lifting a certified test load between 50% and 90% of the crane's rated capacity. The instrument involved in the incident had been calibrated using an uncertified weight of 86 kips, only 8% of the rated 1,040-kip capacity. According to the hoist operator, the instrument indicated a load of 843 kips when the roof section was picked up from its support blocks, 60 kips less than the weight calculated by the roof contractor's engineers before the incident.

Recommendation No. 7: Designers and erectors should carefully evaluate worker risk when devising construction and hoisting methods for use during steel erection.

Discussion: The stadium roof was erected by fabricating large sections at ground level and then hoisting them into place for connection with the building structure. This method offers several advantages over more traditional methods of hoisting individual structural components or small sub-assemblies into place for connection. Worker exposure to fall-related injury may be reduced since most of the connection work is performed at or close to ground level and the construction time is shorter. The procedure had been used for 11 months before the incident, and 10 roof sections, 200 to 400 kips each, had been successfully hoisted and connected to the stadium structure. However, as illustrated by this incident, the risk of crane-related injury must be carefully evaluated when developing this type of erection procedure. Although the method used reduced the number of lifts from several hundred to between 20 or 30, the hoisting operations became more complex and hoisting larger roof sections use more of the crane's reserve capacity, decreasing its ability to resist the effects of wind, unstable ground, and dynamic influences. Reducing the size of the roof sections so that hoisted loads are within 75% to 85% of the crane's rated capacity could significantly reduce the risk of crane-related injury while still offering the advantages of ground-level fabrication.

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INVESTIGATOR INFORMATION

This investigation was conducted by Paul H. Moore, Safety Engineer, Fatality Assessment and Control Evaluation Team, Surveillance and Field Investigations Branch, Division of Safety Research, NIOSH.

ACKNOWLEDGMENT

Photographs 1 and 3 were provided through the courtesy of John A. Thraen.