

INVESTIGATION OF THE SEPTEMBER 7, 2011 COLLAPSE OF A MOBILE CRANE AT THE NATIONAL CATHEDRAL SITE IN NORTHWEST WASHINGTON, DC

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

March 2012



This photograph was taken from the top of the cathedral building about 4 hours after the collapse (Taken from National Cathedral Twitter).

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TABLE OF CONTENTS

	Page
1. Introduction	6
2. Description of the Project	7
3. Description of the Crane and the Collapse	10
4. Review of the Crane Operation Manual	20
5. Analysis and Discussion	22
6. Conclusions	38
7. References	39
Appendix A - Backup Calculations	40

LIST OF FIGURES

- Figure 1. Project Location Plan (Taken from Google Maps).
- Figure 2. National Cathedral Building before the Earthquake Damage, Looking toward Southeast (Taken from Architecture Week).
- Figure 3. Center Tower of the Cathedral Building (Taken from Architecture Week).
- Figure 4. Seven-axle Liebherr Mobile Crane Involved in the September 7, 2011 Incident (Taken from Liebherr Operating Instructions, Page 36).
- Figure 5. Liebherr Crane in the TYSN Operation Mode, Telescopic Boom Assembled with TY Guying, TN/TF Adapter with Spacers, TN Adapter and Luffing Lattice Jib (Modified from Liebherr Mobile Crane Technical Data, Page 26).
- Figure 6. The Rear Right Outrigger Pad after the Collapse. Note the steel plates and the timber mats (Taken from KCE Structural Engineers, PC).
- Figure 7. Same as Figure 6, but Viewed in a Different Direction (Taken from KCE Structural Engineers, PC).
- Figure 8. Load Block, Synthetic Web Slings and Nylon Ropes (Taken from KCE Structural Engineers, PC).
- Figure 9. Tip of the Lattice Jib Landed on the Front Yard of the Episcopal Church House (Taken from KCE Structural Engineers, PC).
- Figure 10. Broken Lattice Jib Pieces after the Collapse (Taken from KCE Structural Engineers, PC).
- Figure 11. Herb Cottage Damaged by the Lattice Jib (Taken from KCE Structural Engineers, PC).
- Figure 12. A Parked Red Truck Crushed by the Lattice Jib (Taken from KCE Structural Engineers, PC).
- Figure 13. Another Parked Red Truck Damaged by the TY Guys of the Telescopic Boom (Taken from KCE Structural Engineers, PC).
- Figure 14. A Near Vertical Position of the Carrier and the Superstructure after the Collapse (Modified from KCE Structural Engineers, PC).

- Figure 15. The Basic Dimensions of the Carrier and the Outriggers, and the Location of the Center of the Turntable (Taken from Liebherr Mobile Crane Technical Data, Page 33).
- Figure 16. The Weight and Centroid of the Carrier, the Superstructure and the Counterweights in the Direction of the Collapse (Weight and Centroid Were Provided by Liebherr-Werk Ehingen GmbH).
- Figure 17. The Weight and Centroid of the Telescopic Boom, Lattice Jib and Load Block in the Direction and at the Time of the Collapse.
- Figure 18. The Governing Load Chart for the Operation of the Crane at the Time of the Collapse (Taken from Liebherr Load Handling Chart Book, Page II-391).
- Figure 19. Recorded angular positions of the Telescopic Boom and the Lattice Jib for the Last 16 Minutes before the Collapse (Taken from Data Logger by Crane Service Company).
- Figure 20. Recorded Reactions at Four Outrigger Pads for the Last 16 Minutes before the Crane Collapse (Taken from Data Logger by Crane Service Company).
- Figure 21. Recorded Utilization Values for the Last 16 Minutes before the Collapse (Taken from Data Logger by Liebherr-Werk Ehingen GmbH).
- Figure 22. Recorded Real (Actual) Load and the Maximum Permissible Load for the Last 16 Minutes before the Collapse (Taken from Data Logger by Liebherr-Werk Ehingen GmbH).

1. INTRODUCTION

On September 7, 2011, at approximately 11:00 a.m., a 500-ton Liebherr mobile crane suddenly collapsed at the National Cathedral in Washington, D.C., amid thunderstorms and heavy rain. The crane's telescopic boom was 152 ft. and the attached lattice jib was 276 ft. long. The crane had been working on securing the cathedral building after recent earthquake damage. The crane tipped, overturned and fell its full length along the South Road, on the south side of the building. It damaged three parked vehicles and a historic Herb Cottage. The collapse was of a catastrophic nature but fortunately did not result in any fatalities. The crane operator sustained some non-life threatening injuries.

Personnel from the Baltimore/Washington, DC Area Office (BWAO) of the Occupational Safety and Health Administration (OSHA) arrived at the scene within hours of the incident. The OSHA investigation began soon after the collapse and included interviewing witnesses, taking photographs and requesting technical information from the general contractor. On the day of the incident, the OSHA Regional Administrator for Region III asked the Directorate of Construction (DOC), in OSHA's National Office in Washington, DC, to provide engineering assistance in assessing the collapse and in determining the cause of the incident. A structural engineer and a safety and health specialist from DOC visited the incident site on September 12, 2011 to examine the collapse, inspect the damages and discuss the collapse with the general contractor, the crane owner and employees at the site.

The DOC's investigation included:

- Revisiting the incident site on September 16, September 21 and October 3, 2011, to take additional photographs and to observe the removal of the 22½ ft. long, 4 ft. wide and 12 in. thick timber mat from the pavement which sustained extensive settlement.
- Visiting the Crane Service Company's (CSC) storage yard in Upper Marlboro, MD, on October 27 and December 25, 2011, to take required measurements of the

recovered crane members and to discuss the crane operation and the load chart with the CSC personnel.

- Reviewing the crane operating instructions, the load handling chart book, the mobile crane technical data, the packing list and other related information.
- Participating in the transfer of information from the Data-Logger (commonly known as the black box) at the CSC Counsel's office on January 17, 2012, and reviewing the downloaded printed records.
- Performing necessary calculations to determine the cause of the crane failure.
- Re-interviewing the CSC crane operator on February 17, 2012, on the electronic LICCON-overload shut-off system at the time of the collapse.

2. DESCRIPTION OF THE PROJECT

The National Cathedral was built, mainly of Indiana limestone, using traditional stone masonry techniques. The cathedral is located at 3101 Wisconsin Avenue, NW, Washington, DC (See Figures 1 and 2) and is a popular attraction for both tourists and worshippers. Large stone pinnacles and other non-structural decorative elements of the cathedral sustained extensive damage during the 5.8 magnitude earthquake of August 23, 2011. The decorative stones and pinnacles were not fastened to their supports using modern techniques based on current seismic knowledge and practice.



Figure 1. Project Location Plan (Taken from Google Maps).



Figure 2. National Cathedral Building before the Earthquake Damage, Looking toward Southeast (Taken from Architecture Week).

The cathedral was anxious to undertake repairs to restore its former elegance. The cathedral retained the Universal Builders Supply, Inc. (UBS) of Cheverly, MD to stabilize the loose and hanging pieces and repair the earthquake-damaged areas. UBS was the general contractor. It decided to build a scaffold system on the roof of the center tower of the cathedral to reach to the top ornamental and decorative pieces damaged by the earthquake. As the roof of the center tower was approximately 320 feet high (Figure 3), UBS needed a crane to transport various scaffold pieces and structural beams to the roof level to build the scaffold system. For this reason, UBS retained the Crane Service Company (CSC) of Upper Marlboro, MD, to assemble a crane at the site to hoist the scaffold components and the steel support beams to the roof of the center tower of the cathedral building.

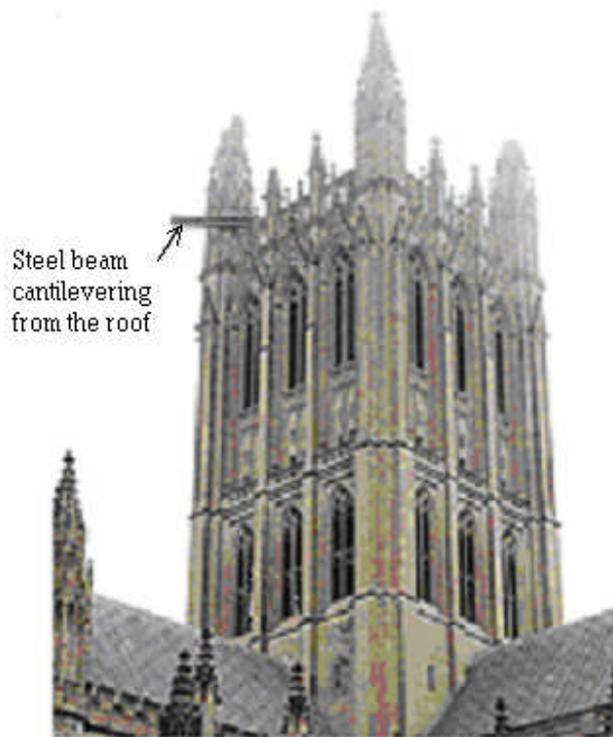


Figure 3. Center Tower of the Cathedral Building (Taken from Architecture Week). Note that a large steel beam cantilevering from the roof of the center tower was the last load delivered by the crane.

3. DESCRIPTION OF THE CRANE AND THE COLLAPSE

The Crane

CSC deployed a telescopic mobile Liebherr crane at the site, identified as LTM 1400-7.1, Serial Number 072180. It was a seven-axle mobile crane equipped with a telescopic boom and a lattice jib (Figures 4 and 5). This crane had a maximum lifting capacity of 880,000 pounds (880 kips) at 10 ft. radius, a maximum hoist height of 400 ft. and a maximum reach of 300 ft. This crane was designed and manufactured by Liebherr-Werk Ehingen GmbH of Germany. It was a new crane acquired by CSC in June 2011. This crane was load tested and certified on July 25, 2011, by Martin Enterprize, Inc. of Chesterfield, VA.

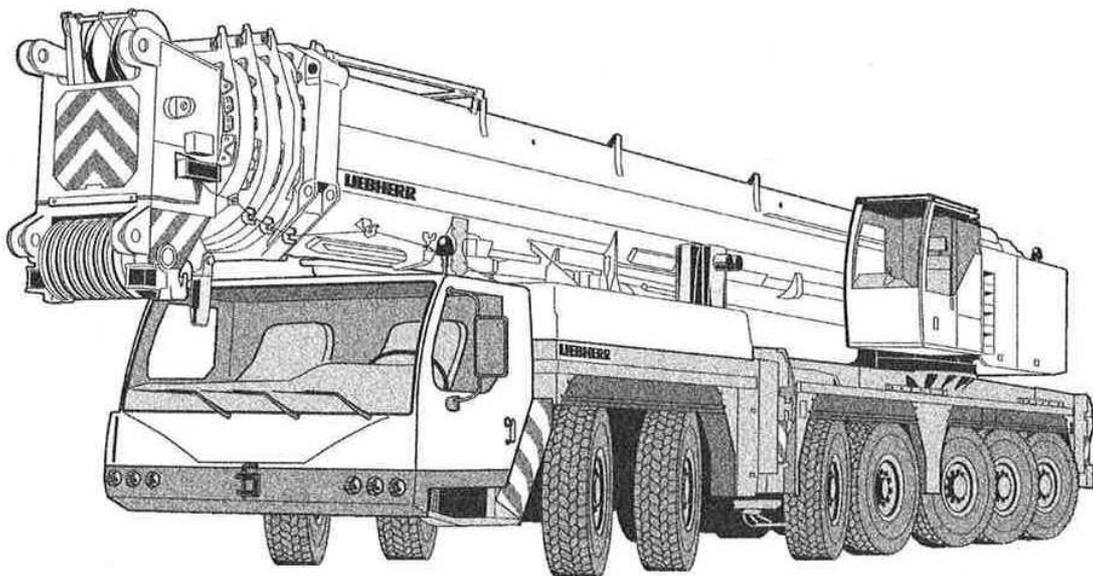


Figure 4. Seven-axle Liebherr Mobile Crane Involved in the September 7, 2011 Incident (Taken from Liebherr Operating Instructions, Page 36).

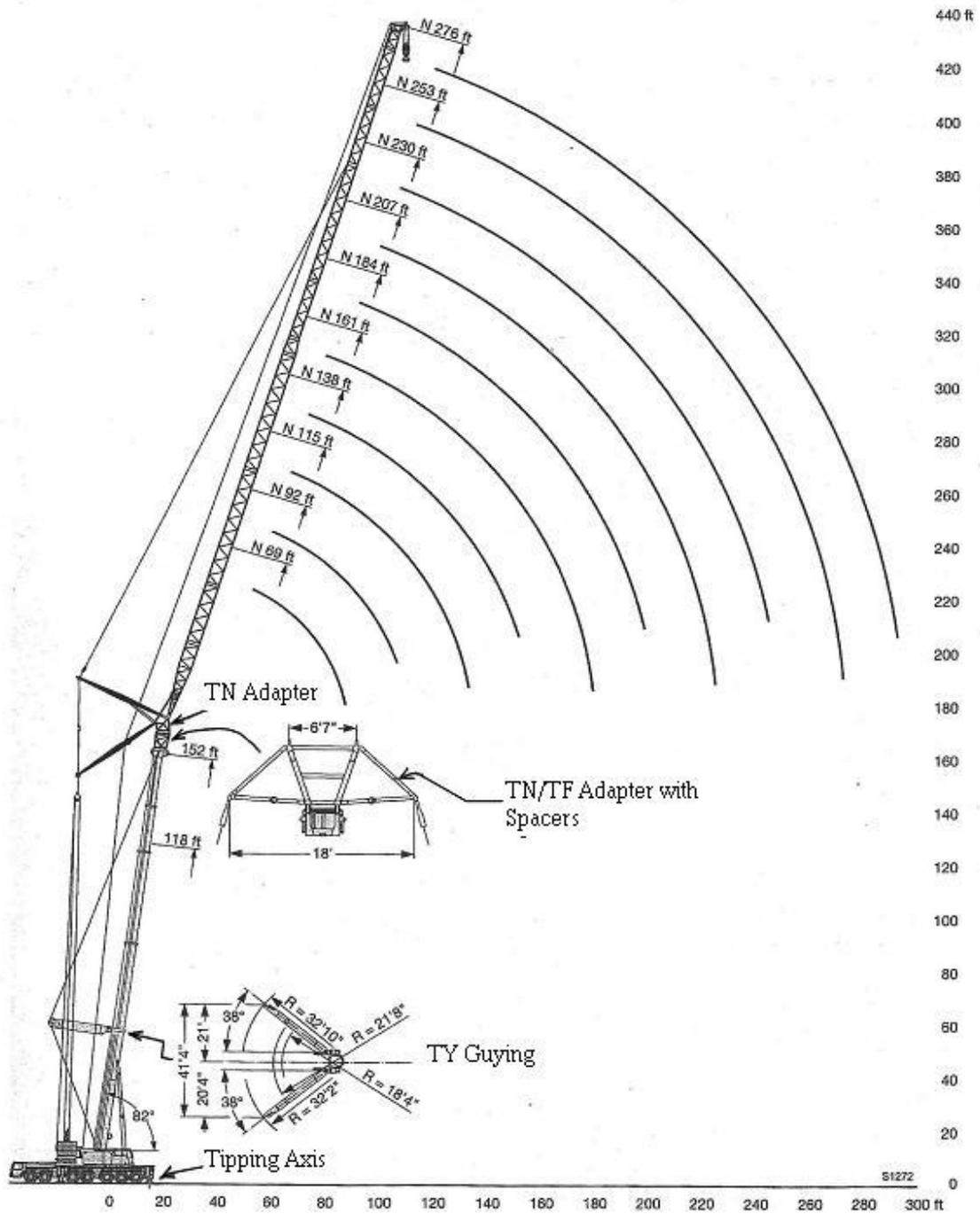


Figure 5. Liebherr Crane in the TYSN Operation Mode, Telescopic Boom Assembled with TY Guying, TN/TF Adapter with Spacers, TN Adapter and Luffing Lattice Jib (Modified from Liebherr Mobile Crane Technical Data, Page 26).

Sequence of Events Leading to the Collapse

CSC mobilized the Liebherr crane to the National Cathedral site on Sunday, September 4, 2011. The crane carrier was parked on the South Road on the backside of the main cathedral building at the designated location. The front of the carrier was toward the east and the zero degree mark on the fixed portion of the turntable was approximately towards the west. The four outriggers were extended and the pads were lowered onto the pavement. The southwest (rear right) outrigger pad happened to be near a catch basin, 15 ft. away. The size of the basin was 6 ft. long, 1½ ft. wide and 3 ft. in depth. It was a masonry structure constructed over 100 years ago. It took the entire day to assemble the crane to the intended operating mode. It included placing the counterweights on the counterweight frame, assembling the lattice jib and extending the telescopic boom.

The crane was put to work on Monday, September 5. It made a few lifts mostly in the 3,200 pounds range. In the afternoon, the crane operator and others observed a crack on the asphalt pavement at the rear right outrigger pad.

The next day, September 6, the cracking of the asphalt continued and caused a ¼ inch settlement of the rear right outrigger pad. CSC placed two 32 ft. long, 4 ft. wide and 12 in. thick timber mats side by side on the asphalt; and added an 8 ft. by 9 ft. steel pad between the mats and the rear right outrigger pad (Figures 6 and 7 indicate the pad after the collapse). The purpose of the mats and the steel pad was to uniformly spread the load over a larger area and to minimize any additional settlement. Later in the afternoon, when the wind subsided, the crane successfully made one lift of scaffold cross braces. No other activity took place and the crane was set for the night.



Figure 6. The Rear Right Outrigger Pad after the Collapse. Note the steel plates and the timber mats (Taken from KCE Structural Engineers, PC).



Figure 7. Same as Figure 6, but Viewed in a Different Direction (Taken from KCE Structural Engineers, PC).

On Wednesday, September 7, after performing the daily inspection, the crane operator set the 152 ft. long telescopic boom to 82 degrees. The attached lattice jib was 276 feet long. A lift was made carrying 3,200 pounds of scaffold components without any problem. The next load was steel I beams that weighed 8,600 pounds. The load was rigged on the northwest and delivered on the north side approximately 320 ft. high to the roof of the tower. As the load was being released on the roof, it began to rain intensely. The load was released and the operator raised up the hook to clear the cathedral tower. At this time, lightning was snapping around the top of the jib, obscuring its view from the operator's cab. The operator then swung the boom and jib to the west (the rear of the carrier), and luffing the jib down to a lower angle to let the storm pass by. At this time, the operator noted that the telescopic boom was at approximately 68 degrees and the jib was at approximately 18 to 20 degrees. Later, however, the crane operator recalled that the jib was in fact at near zero degrees to the horizontal. After a few minutes, at around 11:00 a.m., the operator felt sudden vibration of the crane. Suddenly the boom began to go down. The boom was falling, then, the counterweight was rising until it almost stood vertical at which time it rotated towards the south. The counterweights hit the pavement and the timber mats supporting the outrigger, and pierced through the pavement. The north counterweights were separated and fell off. The counterweights on the south side remained connected.

The Collapse

From the field examination of the collapsed crane:

- The tipping axis during the collapse was the rear outrigger pads of the crane (Figure 5).
- During the collapse, the load block (headache ball) hit the ground first. The load block dragged over the grass surface more than 50 ft. until the tip of the jib hit the ground on the front yard of the Episcopal Church House (Figures 8 and 9).



Figure 8. Load Block, Synthetic Web Slings and Nylon Ropes (Taken from KCE Structural Engineers, PC).



Figure 9. Tip of the Lattice Jib Landed on the Front Yard of the Episcopal Church House (Taken from KCE Structural Engineers, PC).

- The lattice jib broke at the mid transition point (between the smaller and bigger sections) when the tip hit the ground (Figure 10).



Figure 10. Broken Lattice Jib Pieces after the Collapse (Taken from KCE Structural Engineers, PC).

- The rear portion of the jib hit the roof of the Herb Cottage (Figure 11) and crushed a parked truck (Figure 12).



Figure 11. Herb Cottage Damaged by the Lattice Jib (Taken from KCE Structural Engineers, PC).



Figure 12. A Parked Red Truck Crushed by the Lattice Jib (Taken from KCE Structural Engineers, PC).

- The tip of the telescopic boom fell over a second parked truck (Figure 12) and the TY guys of the boom landed on a third truck (Figure 13).



Figure 13. Another Parked Red Truck Damaged by the TY Guys of the Telescopic Boom (Taken from KCE Structural Engineers, PC).

- The main body of the boom landed on the pavement surface (See the photograph on the cover of this report).
- Due to the overturning energy, the carrier and the attached superstructure tilted upward to a near vertical position with the rear side of the carrier supported on the pavement surface (Figure 14).



Figure 14. A Near Vertical Position of the Carrier and the Superstructure after the Collapse (Modified from KCE Structural Engineers, PC).

- At the initial stage of the tipping, the counterweight became unbalanced. It rotated southward along with the superstructure. They both rotated about 90 degrees counterclockwise (Figure 14). As a result of the rotation, the north half of the counterweights fell off of its frame and landed on the earth slope below. The south half remained connected.
- There was no payload attached to the hook (load block) at the time of the collapse.
- The settlement of the rear right outrigger pad was approximately 6 inches.
- It appeared that the impact force from the rotating south counterweight crushed the south timber mat below. The pavement at this location experienced approximately 2- to 3-feet of surface settlement. Thus, it is believed that some voids might be present under the pavement. The voids (or the ground loss) were perhaps created by the flushing off of fine grain soils by the storm water through the nearby catch basin during the thunderstorms. The investigation of the subsurface condition at this location is still on-going. Since the rotation of the counterweight occurred after the initial tipping of the crane, the finding of the subsurface investigation will not influence the conclusion of this report.

Crane Elements Installed at the Time of the Collapse

Based on the examination of the collapsed crane elements at the incident site and at the CSC storage yard, the crane was in the TYSN operating mode with TY guys and a TN adaptor installed before the collapse. At the time of the collapse, the length of the telescopic boom was 152 ft. and the length of the attached lattice jib was 276 ft. (See the photograph on the cover of this report). The total installed counterweight was 154,300 pounds (70 metric tons). It included the base plate (15 tons), the center plate (5 tons), three counterweights (25 tons) on the south side of the base plate, and identical weights (25 tons) on the north side of the base plate. All tons refer to the metric tons (2,200 pounds). It was further confirmed with the CSC personnel at the storage yard that the counterweight with its frame was fully extended and Winch 3 was mounted at the rear end of the frame. Thus, the code of the applicable Liebherr load chart was 1596. Both

CSC and the crane manufacturer were using this load chart (with Code Number 1596) for the control and operation of the crane.

4. REVIEW OF THE CRANE OPERATION MANUAL

The LICCON computer system is a system for controlling and monitoring mobile cranes. The abbreviation “LICCON” stands for Liebherr Computed CONtrolling. Some key functions of the computer controlled operation system from the crane operation manual are summarized below. Note that the sentences in italics are directly taken from the operation manual.

- *The LICCON computer system works on the principle of comparing the current / actual load with the maximum permissible load according to the load chart and reeving (Operating Instructions (OI), Page 299).*
- *The actual load and the “maximum load according to the loading chart and reeving” are compared. When they approach the specified limit, an advanced warning is issued. If the limit is exceeded, the overload stop is triggered and any crane movements which increase the load momentum are turned off (OI, Page 299).*
- *Even without a load, the boom may only be moved inside those areas for which load capacity values are stated, otherwise there is a danger of tilting (Load handling chart book (LHCB), Page I-3/58).*
- *Even without a load, the telescopic boom may only be moved within the working radius ranges for which values are listed in the load capacity table (LHCB), Page I-4/58).*
- *The “Advanced warning (Exclamation Mark)” icon appears, if the current chart capacity exceeds the (90%) limit programmed in for the advance warning (OI, Page 343).*
- *The “STOP” icon is displayed if the load chart load exceeds the 100% mark. Note: All crane movements that increase the load momentum are shut off (OI, Page 343).*

- *“Horn” icon: Acoustical signal, sounds in addition to the optical display of detected operational errors, leading to the interruption of a movement, and application errors with error number. Operational errors are: Overload, boom outside the angle range of the load chart, and boom outside radius range of the load chart. “Horn” is a beeping sound of a duration of approximately 0.5 seconds, which is repeated in one second rhythm (OI, Page 345).*
- *When the shut off of luffing the telescopic boom / attachment down is bypassed the telescopic boom / attachment is further down, then there is no load chart any longer! Crane operation with bypassed shut off luffing the telescopic boom / attachment down is prohibited, since severe accident can result! Activate the bypass of the shut off “luffing the telescopic boom / attachment down” only in emergency cases (OI, Page 625).*
- *The bypass can be activated by “Turn the set up key **D** to the right”. As a result: “The working speed is reduced for all functions and all hoist limit switches are bypassed” (OI, Page 621).*
- *The LICCON-overload limit switch is a safety device and must not be used as a shutdown device for operating purposes. The crane operator must assure himself of the weight of a load before attempting to lift it. The fact that the crane is equipped with the LICCON-overload safety device does not free the operator from responsibility with regard to operating safety (LHCB, Page I-7/58).*
- *Liccon LiftAnalyzer II is used to analyze logged data from cranes manufactured by Liebherr Ehingen GmbH. The data logger installed on the crane typically acquires data about the operational condition of the crane every 5 seconds. For example, this data includes the lifted load, boom angle, telescope length, turntable angle, etc (Liccon LiftAnalyzer II Manual, Page 3).*

5. ANALYSIS AND DISCUSSION

Stability of the Crane

Cranes usually fail either due to structural overstress at high angles of booms or due to instability at lower angles and the large radius of the boom. In this investigation, we are dealing with a case of instability that occurred at the large radius of the boom and near horizontal angle of the jib.

There are two factors related to the stability of cranes, i.e., the overturning moments and the stabilizing moments. If the overturning moment is less than the stabilizing moment, then the crane is stable. However, if the overturning moment exceeds the stabilizing moment, the unbalanced moment will cause the crane to rotate, tip-over and fail.

The stability of the crane was analyzed based on the magnitude of the stabilizing and overturning moments. The analysis was conducted to determine the overturning moment at the time of the collapse considering the orientation of the crane, boom and the jib at the time of failure. As will be discussed later, the boom was at an angle of approximately 63 degrees to the horizontal, and the jib was nearly horizontal. The boom and the jib were positioned approximately along the zero degrees of the turntable (toward the west direction). The wind speed at the time of the collapse and the settlement of one of the rear outriggers were also considered in the analysis.

The basic dimensions of the carrier and the outriggers were taken from the Liebherr manual and verified in the field (See Figure 15). The weights and center of gravity of the carrier, various components of the superstructure, and counterweights are indicated in Figure 16.

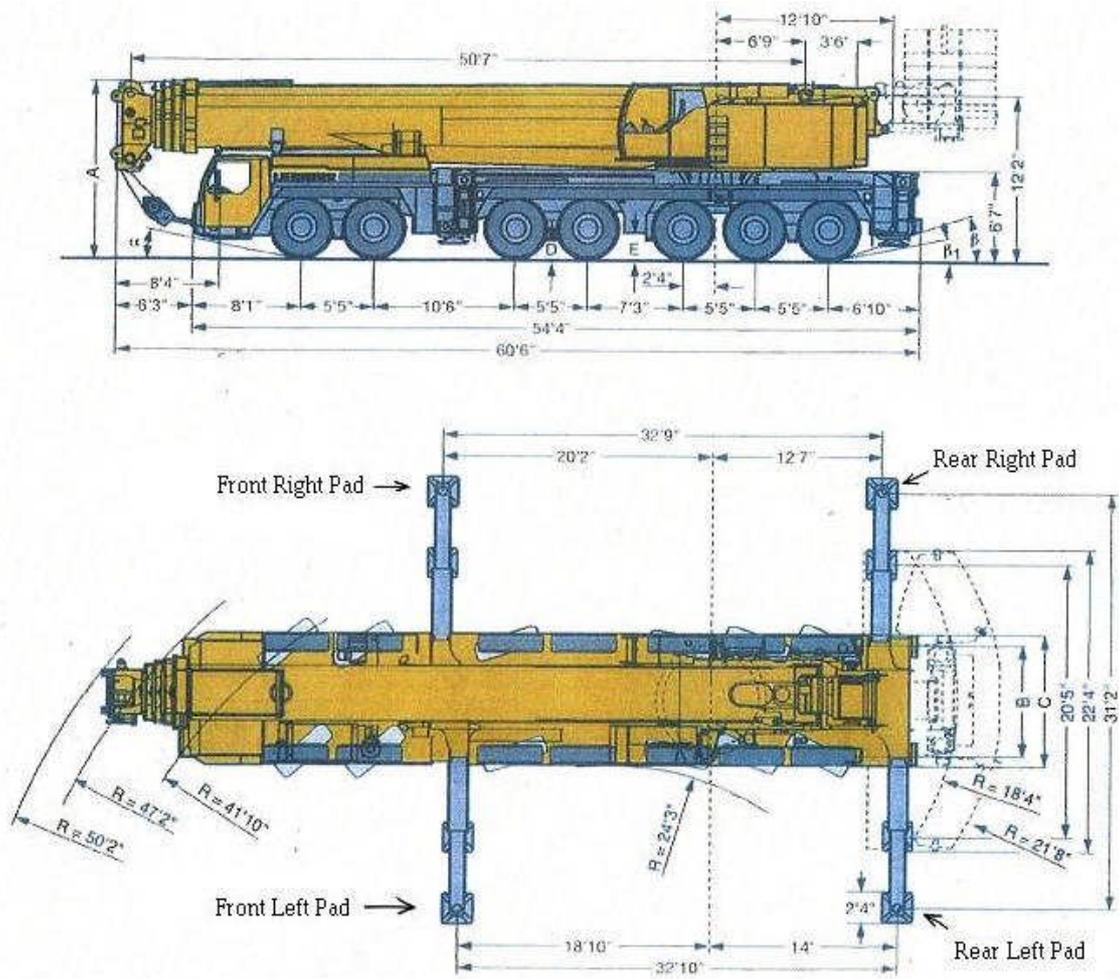


Figure 15. The Basic Dimensions of the Carrier and the Outriggers, and the Location of the Center of the Turntable (Taken from Liebherr Mobile Crane Technical Data, Page 33).

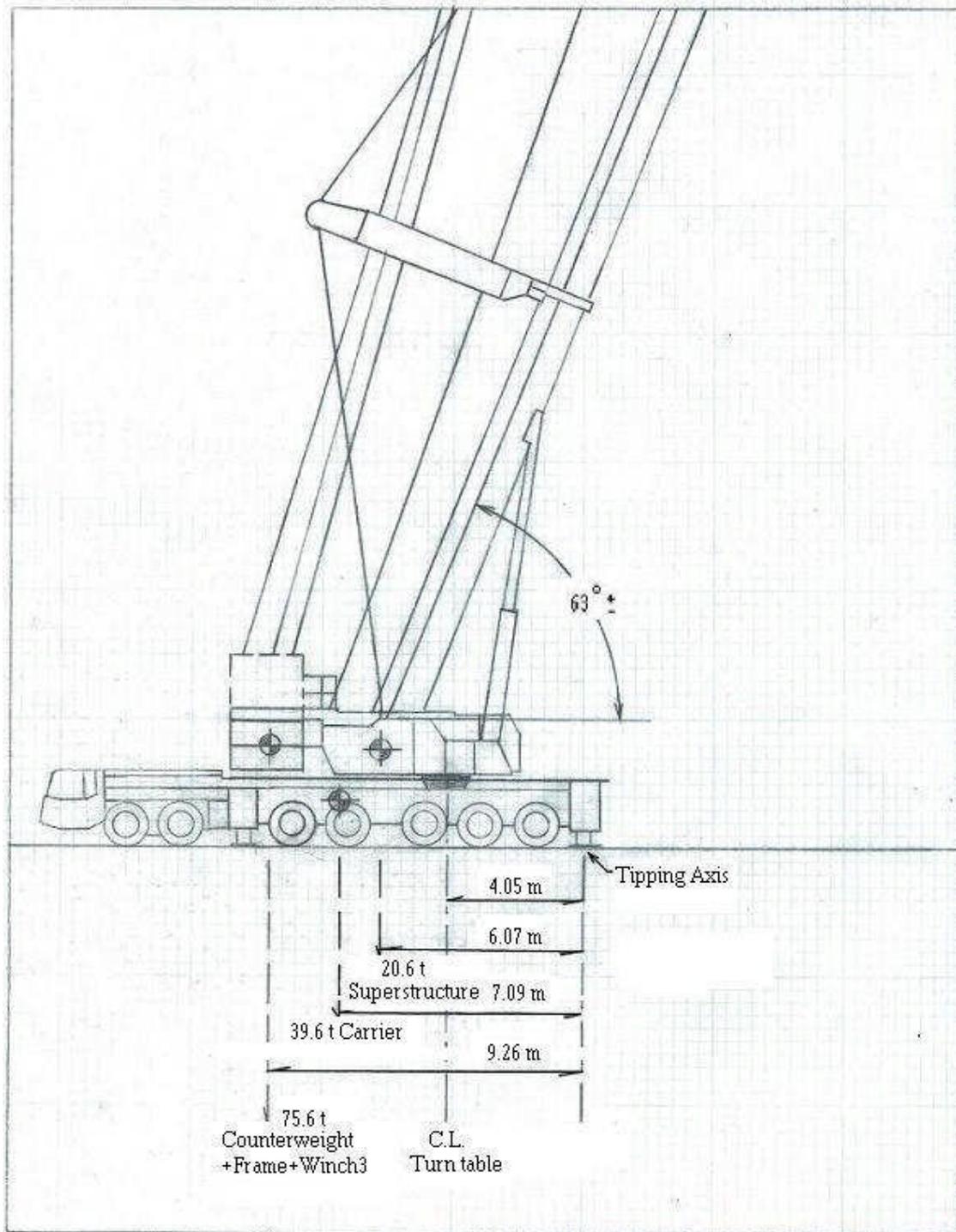


Figure 16. The Weight and Centroid of the Carrier, the Superstructure and the Counterweights in the Direction of the Collapse (Weight and Centroid Were Provided by Liebherr-Werk Ehingen GmbH).

The following items were considered in the analysis:

Crane Member	Individual Element	Individual Weight	Total Weight	Centroid to Tipping Axis *
Carrier	---	---	87,100 lbs.	-23.3 ft.
Superstructure	---	---	45,300 lbs.	-19.9 ft.
Counterweight + Frame + Winch 3	Base Plate	15 tons	166,000 lbs. (75.6 tons)	-30.4 ft.
	Center Plate	5 tons		
	10 Tons Wt. x 4	40 tons		
	5 Tons Wt. x 2	10 tons		
	Frame + Winch 3	5.6 tons		
Telescopic Boom Assembly	Base Section	6.6 tons	97,500 lbs. (44.3 tons)	7.8 ft.
	Section 1	5.3 tons		
	Section 2	4.7 tons		
	Section 3	4.1 tons		
	Section 4	3.5 tons		
	Tele. Cylinder	3.4 tons		
	½ Luff. Cylinder	1.9 tons		
	TY Guying	12.2 tons		
	TN/TF Adapter	1.9 tons		
	TN Adapter	0.7 tons		
Lattice Jib Assembly	G9	7.4 tons	41,800 lbs. (19.0 tons)	154.5 ft.
	G3	1.04 tons		
	2 x G4	2 x 1.86 tons		
	G5	0.45 tons		
	G6	1.00 tons		
	G7	1.95 tons		
	2 x G6	2 x 1.00 tons		
	G8	1.42 tons		
Load Block Assembly	Headache ball + Web Sling + Nylon Ropes	---	1,760 lbs. (0.7 tons)	330.3 ft.

* Centroid to the tipping axis is the horizontal distance from the center of gravity of the crane members to the tipping axis at the time of the collapse.

The weights of some of the above items were taken from the operating instructions for the crane (See Figure 17).

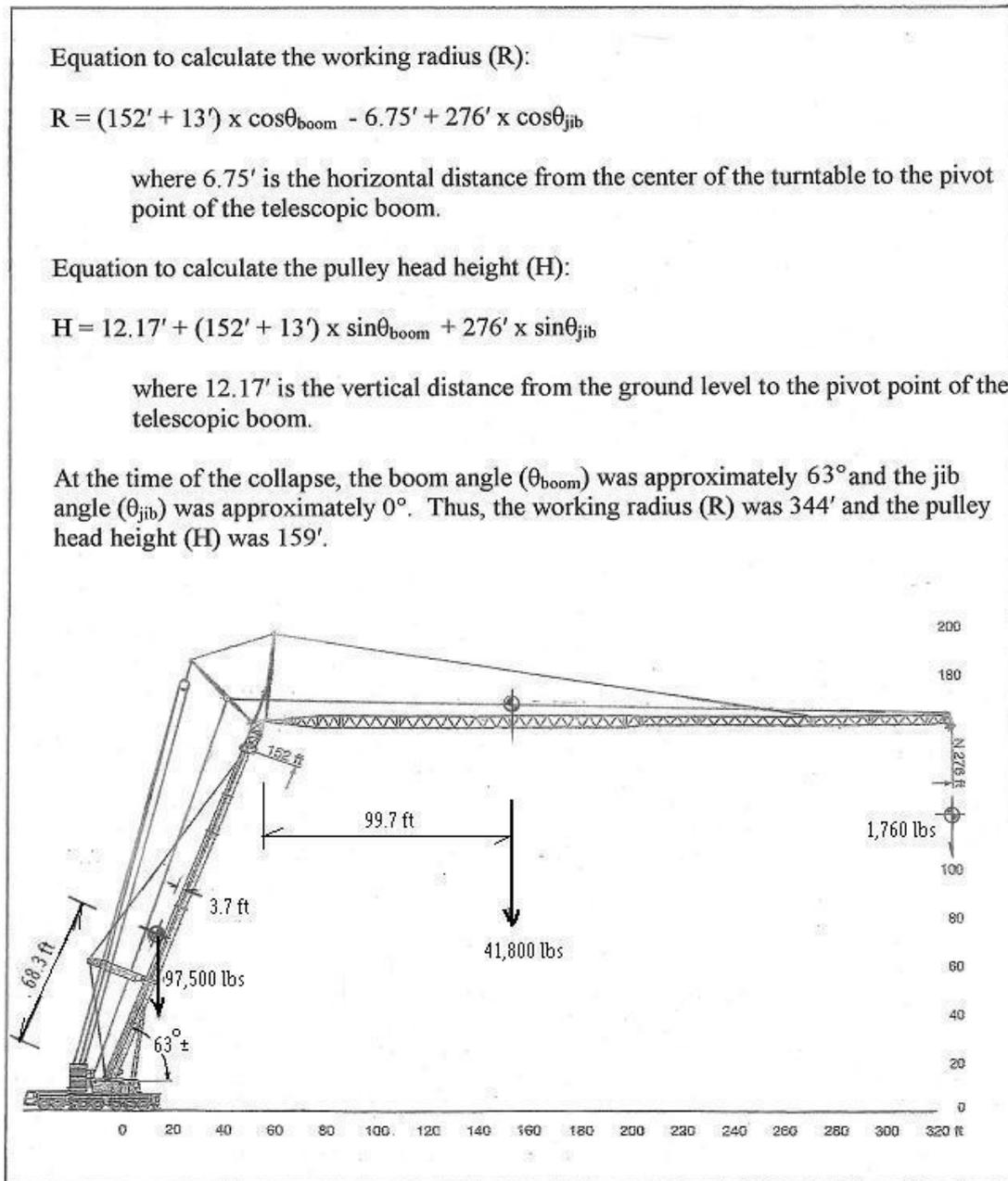


Figure 17. The Weight and Centroid of the Telescopic Boom, Lattice Jib and Load Block in the Direction and at the Time of the Collapse.

At the time of the collapse, the entire crane including all elements mentioned above weighed approximately 200 tons. This weight compared very closely to the total weight of 203 tons derived from the shipping packing lists prepared by Liebherr.

It was determined that when the telescopic boom reached an angle of 63 degrees to the horizontal, and when the jib was nearly horizontal, the overturning moment was 8,000,000 ft-pounds. The stabilizing moment at this position of the crane was computed to be 7,980,000 ft-pounds, and hence the failure. At the time of the collapse, the crane had a working radius of 344 feet which was well beyond the allowable radius provided in the load chart, discussed later.

Wind and settlement of one of the outriggers adversely impacted the stabilizing moment but their contributions were minimal. At the time of the collapse, wind speed was recorded as 15 mph. An average pressure of 0.6 psf was estimated for the exposed elements of the crane. The wind resulted in an additional overturning moment of 100,000 ft-pounds, i.e., 1.3% of the total overturning moment. The impact of the settlement of one of the rear outriggers was also considered. The settlement was assumed to be 6 inches at the rear right outrigger. This settlement resulted in an additional overturning moment of 108,000 ft-pounds, i.e., 1.4% of the total overturning moment. As mentioned the impact of the wind and settlement were minimal. If the crane was operated within the bounds of the load chart, wind and the settlement of one of the outrigger pads would not have caused the collapse of the crane.

Load Chart

The crane manual consists of several volumes. There are numerous load charts provided in the manual. The appropriate load chart is selected based upon the length of the telescoping boom, the length of the luffing boom, the magnitude of the counterweights, and the number of axles of the mobile crane carrier. The load chart for the crane which collapsed indicated the following:

- 152 ft. long telescoping boom
- 276 ft. long luffing jib
- 70 metric tons of counterweight fully extended
- Winch 3 mounted on the rear end of the counterweight frame

- Seven axles of the mobile crane

The crane's code number was determined to be 1596 (See Figure 18), and the applicability of this load chart is not in dispute.

ISO DIN		xx° TYS W3<=		N 276ft		
072180				21.03		
ft	ft >> lbs		CODE > 1596 < L146 4520 .x(x)			
	118	152	118	152	118	152
115	21,400					
120	21,400	15,600				
125	21,400	15,600				
130	21,400	15,600				
135	21,400	15,600				
140	21,400	15,600				
145	21,400	15,600				
150	21,400	15,600				
155	21,400	15,600				
160	21,400	15,600	17,200			
165	21,400	15,600	17,000			
170	21,400	15,600	16,100	11,600		
175	21,200	15,600	15,300	11,000		
180	20,500	15,600	14,500	10,300		
185	19,600	15,600	13,700	9,600		
190	18,700	15,400	13,000	9,000		
195	17,900	14,900	12,300	8,400		
200	17,100	14,300	11,600	7,800	6,100	
205	16,400	13,600	10,900	7,200	5,900	
210	15,700	12,900	10,300	6,700	5,400	
215	15,000	12,300	9,800	6,200	4,900	
220	14,300	11,700	9,200	5,700	4,500	
225	13,700	11,100	8,700	5,300	4,000	
230	13,100	10,600	8,200	4,800	3,600	
235	12,500	10,100	7,700	4,400	3,200	
240	11,900	9,600	7,200	4,000	2,800	
245	11,400	9,100	6,700	3,600		
250	10,900	8,600	6,300	3,200		
255	10,400	8,200	5,900	2,800		
260	9,900	7,700	5,500	2,500		
265	9,500	7,300	5,100			
270	9,100	6,900	4,700			
275	8,700	6,500	4,400			
280	8,300	6,200	4,000			
285		5,800	3,700			
290			3,400			
295			3,100			
300			2,800			
* n *	1	1	1	1	1	0
xx	82.0	82.0	75.0	75.0	68.0	68.0
1	92+	92+	92+	92+	92+	92+
2	46+	92+	46+	92+	46+	92+
3	46+	46+	46+	46+	46+	46+
% 4	0+	46+	0+	46+	0+	46+
ft /s	23	23	23	23	23	23
TAB ***	393	393	406	406	419	419

xx° TYS W3<=	N 276ft	154,300 lbs	33 x 31 ft	[] -> 22 ft
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Figure 18. The Governing Load Chart for the Operation of the Crane at the Time of the Collapse (Modified from Liebherr Load Handling Chart Book, Page II-391).

The load chart essentially provides the maximum permissible load that can be hoisted at various working radii. Working radius is defined as the horizontal distance from the center of the turntable to the vertical axis of the load being hoisted. Furthermore, the angles of the telescopic boom at which permissible loads are provided at different radii are also given.

Of particular interest to this investigation are seven columns in the load chart, 1 through 7 beginning from the left. Column 1 provides various working radii ranging from 115 feet to 300 feet. The next column provides permissible loads for the radii given in Column 1, but this applies to a telescopic boom length of 118 feet which is not the case here. Column 3 provides permissible loads at radii ranging from 120 feet to 285 feet, applicable to a telescopic boom length of 152 ft. which was the boom length for this crane. This set of permissible loads must also comply with another constraint which is that the telescopic boom must also have an angle of 82 degrees. So, if the 152 ft. long telescopic boom is at an angle of 82 degrees, then loads ranging from 15,600 pounds at a 120 ft. radius to 5,800 pounds at a radius of 285 ft. could be hoisted. Column 4 is applicable to a 118 ft. long boom. Column 5 is applicable to a 152 ft. long telescopic boom, and provides permissible loads at different radii, but the telescopic boom must have an angle of 75 degrees. For example, the crane could hoist a load of 11,600 pounds at a radius of 170 feet, or a load of 2,500 pounds at a radius of 260 feet, provided the boom has an angle of 75 degrees. Column 6 is applicable to a 118 ft. long boom. Column 7, although applicable for a 152 ft. long boom, does not provide any permissible load. The jib angle could vary depending upon the site demands provided that the working radius is not exceeded.

It is interesting to note that the load chart permits a load of 5,800 pounds at a radius of 285 ft. but only permits a load of 2,500 pounds at a smaller radius of 260 ft. This is because a greater load is permitted due to the steeper angle of 82 degrees, and a smaller load is permitted at a shallower angle of 75 degrees. It is well-recognized in the industry that interpolation is not permitted in the crane load charts. If the actual lifting radius lies between the two tabulated radii, then the proper practice is to use the larger radius. If the

boom angle lies between the tabulated angles, then the lower angle is used to determine the safe load-carrying capacity.

In this load chart, only two angles for the telescopic boom are provided, i.e., 82 and 75 degrees. So, the boom can only be operated between angles of 82 and 75 degrees. If the boom is at an angle greater than 82 degrees or at an angle lower than 75 degrees, then the crane would be in violation of the load chart, and a failure could be imminent. Similarly, at a boom angle of 75 degrees, if the radius of the load is greater than 260 ft., the load chart is violated and a failure could be imminent. In the present case, the boom was at an angle of 63 degrees at a radius of 344 ft., both exceeding the maximum permissible values. Although the crane was not hoisting any load, the weights of the headache ball (load block) and other accessories were enough to topple the crane.

Our structural analysis, independent of the load chart, confirmed that the crane with the boom angle of 63 degrees, and the jib at nearly horizontal angle will overturn even if there is no load at the hook other than headache ball and the weight of wire ropes, etc. The computations for overturning and stabilizing moments are included in Appendix A.

Crane's "Black Box"

The crane operator's cab is equipped with a computer that records operations of the crane at intervals of five seconds. This program is called Liccon Lift Analyzer II. The computer-stored information is generally referred to as a black box. The program is proprietary and requires special software to download data recorded during the actual operation of the crane. After several weeks of negotiations between the interested parties, CSC purchased the special software required to download the data. The data recorded in the last few minutes before the collapse provided insight into the actual configuration, i.e., the angle of the boom, the angle of the jib, the orientation of the crane platform, the load at the time of the collapse, the utilization ratio, the outrigger reactions, etc. It also graphically plotted the vertical and horizontal angles of the boom and the jib at different times (See Figure 19).

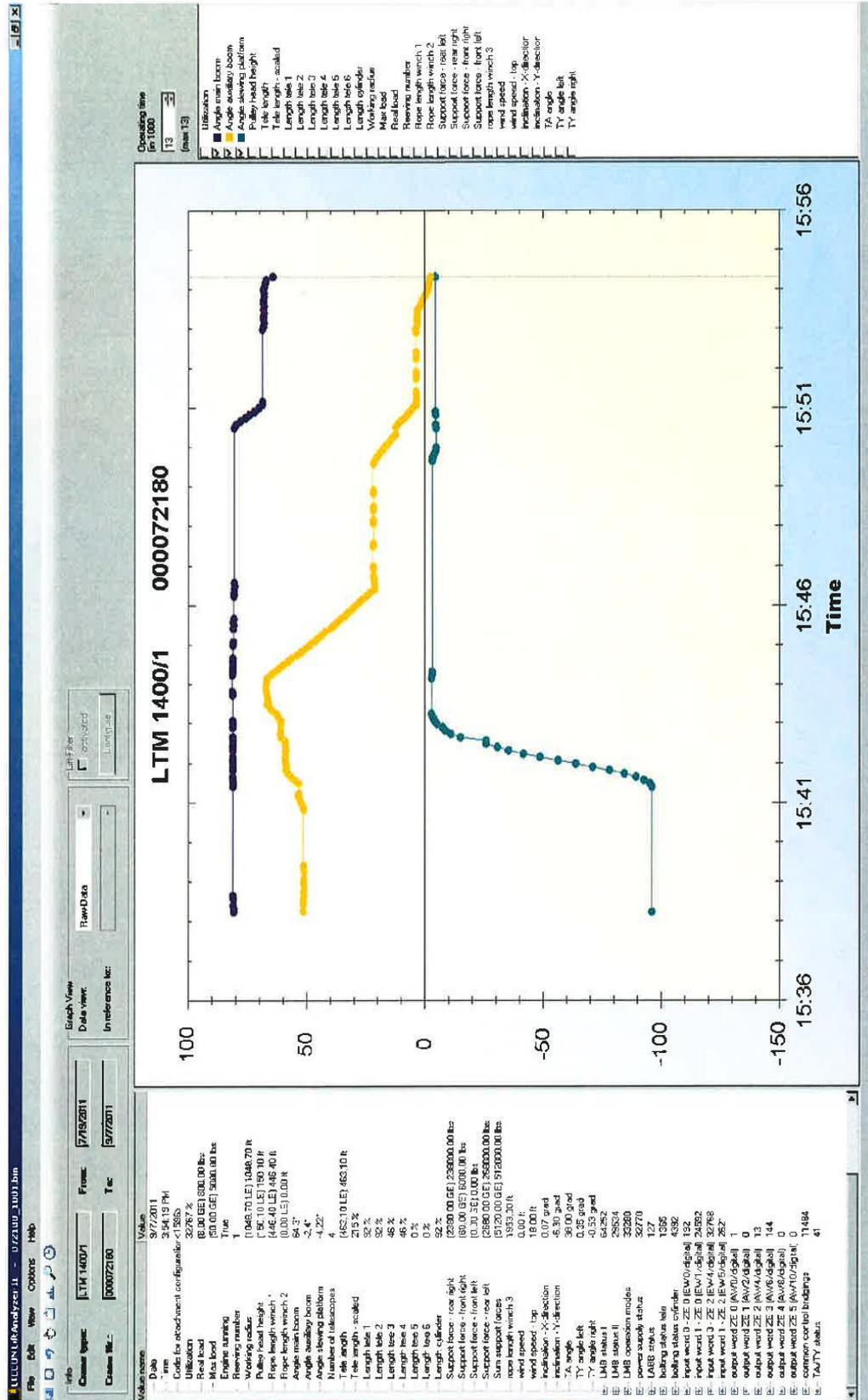


Figure 19. Recorded angular positions of the Telescopic Boom and the Lattice Jib for the Last 16 Minutes before the Collapse (Taken from Data Logger by Crane Service Company).

A typical example is provided below.

Data was downloaded for:

- September 7, 2011: Computer time from 15:38 hours to 15:54:19 hours (Actual time from 10:44 a.m. to 11:00 a.m. EDT).
- September 6, 2011: Computer time from 18:59 hours to 19:21 hours (Actual time from 14:05 p.m. to 14:27 p.m. EDT).

The computer time does not correspond to Eastern Daylight Time (EDT) nor does it correspond to German time. It is understood that the computer time is 4:54 hours ahead of US EDT. The data provided the movements of the crane boom and the jib at various times of the day of the incident, in particular the last 16 minutes before the collapse. The following information is extracted from the data logger, and tabulated below showing the orientation of the crane platform, and the vertical angles of the boom and the jib.

Computer Time	U.S. EDT AM	Horizontal Angle of the Platform	Vertical Angle of the Boom	Vertical Angle of the Jib
15:38	10:44	-96 deg	81.2 deg	51.1 deg
15:39	10:45	-96 deg	81.2 deg	51.1 deg
15:42	10:48	-90 deg	81 deg	60 deg
15:44	10:50	-50 deg	81 deg	63 deg
15:46 *	10:52	-4 deg	81 deg	23 deg
15:48	10:54	-4 deg	81 deg	23 deg
15:49	10:55	-4 deg	81 deg	23 deg
15:50	10:56	-4 deg	81 deg	16 deg
15:52	10:58	-4 deg	70 deg	4 deg
15:54	11:00	-4 deg	68 deg	0 deg
15:54:19	11:00:19	-4 deg	64.3 deg	-2.4 deg

*** Figures in bold indicate that the crane was operating outside of the safe zone, as per Liebherr Load Chart.**

The crane collapsed at approximately 11:00 a.m., corresponding to the second last row (highlighted) in the above table. The table provides information for the last 16 minutes before the collapse, providing data on the movements of the crane. It begins at 10:44

a.m. at which time the crane was positioned towards the north over the cathedral roof as the crane was unloading the cantilevered steel beam. At this time, the boom was at an angle of approximately 81 degrees to the horizontal, an angle which the crane maintained until approximately four minutes before the collapse even during its counterclockwise rotation towards the west. At 10:44 a.m., the jib was at an angle of approximately 51 degrees. The crane was then well within the load chart.

After unloading the material, rain started, and the operator swung the crane counterclockwise to the west without carrying any load in about 6 minutes until 10:50 a.m. The jib was raised to approximately 63 degrees. The crane continued to be within the load chart. However, at approximately 10:52 a.m. the crane jib was then suddenly lowered to 23 degrees, a drop of 40 degrees in the course of one minute. The crane was then operating outside the load table because our analysis indicated that the radius was approximately 273 ft., which is greater than the maximum permissible radius of 260 ft. This is confirmed by the sudden increase of the recorded utilization values from 43% to 32,767% (See Figure 21). The utilization value is the ratio of the real (actual) load over the maximum permissible load. Any utilization value above 100% indicates the crane is operating beyond the load chart. It is believed that at this time the crane was automatically shut off, and no movement of the boom or the jib could occur unless the bypass switch was activated overriding the shut off.

For the next three minutes, no movement was recorded either in the boom angle or the jib angle, which would indicate that the computer had actually shut off the operation. But, at 10:56 a.m., the operation started again. Is it possible that in the last three minutes, the bypass switch was activated? We do not know because the crane operator denies engaging the bypass switch. At 10:56 a.m., the jib was recorded to be lowered to 16 degrees, while the boom was maintained at approximately 81 degrees. At 10:58 a.m., the boom was lowered to approximately 70 degrees, and the jib was further lowered to 4 degrees. At 11:00 a.m., the boom was recorded to be at approximately 64 degrees with the jib at nearly horizontal. In fact, the recorded support reactions from the data-logger

show that the front left pad had just separated (See Figure 20). The collapse followed immediately.

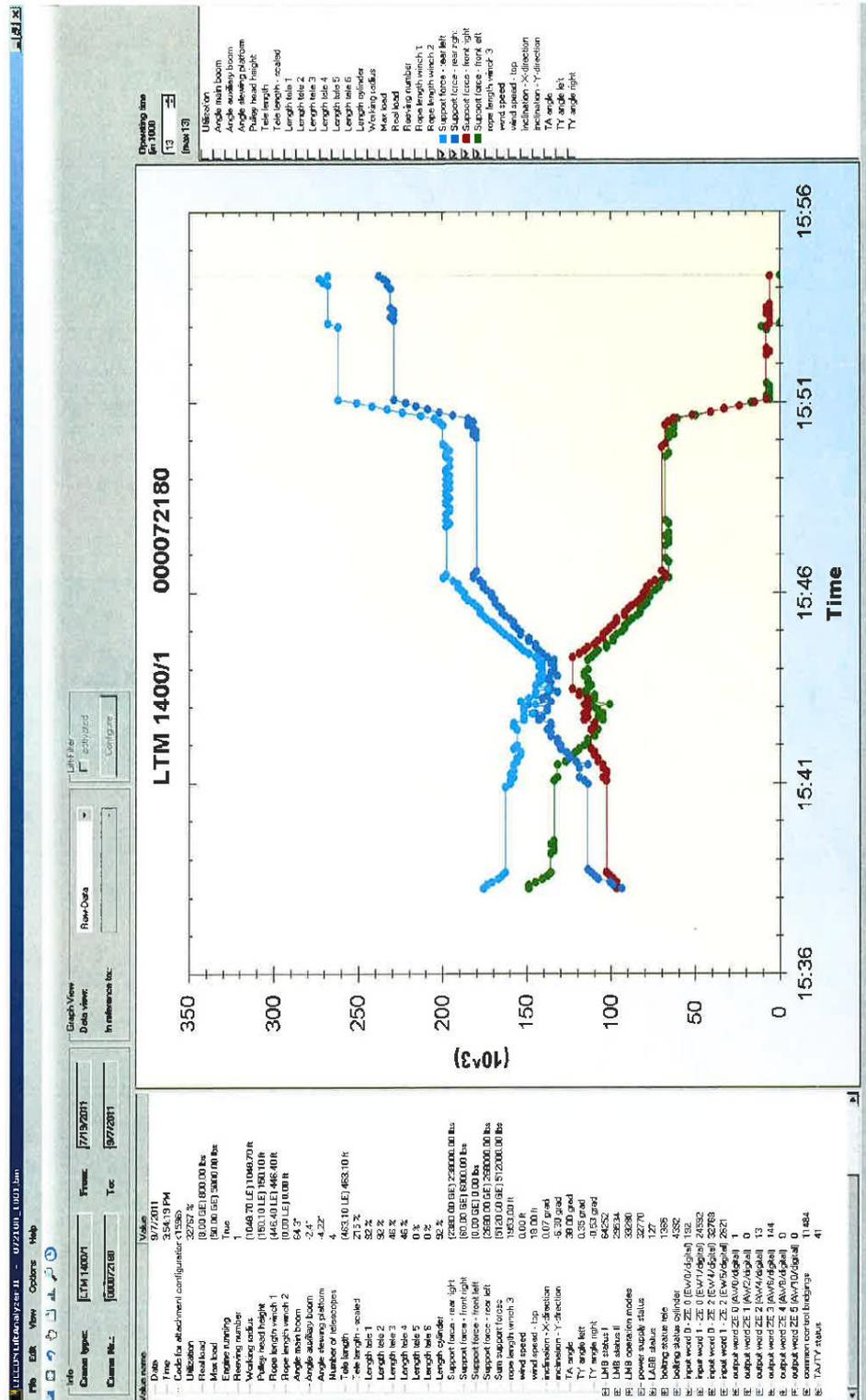


Figure 20. Recorded Reactions at Four Outrigger Pads for the Last 16 Minutes before the Crane Collapse (Taken from Data Logger by Crane Service Company).

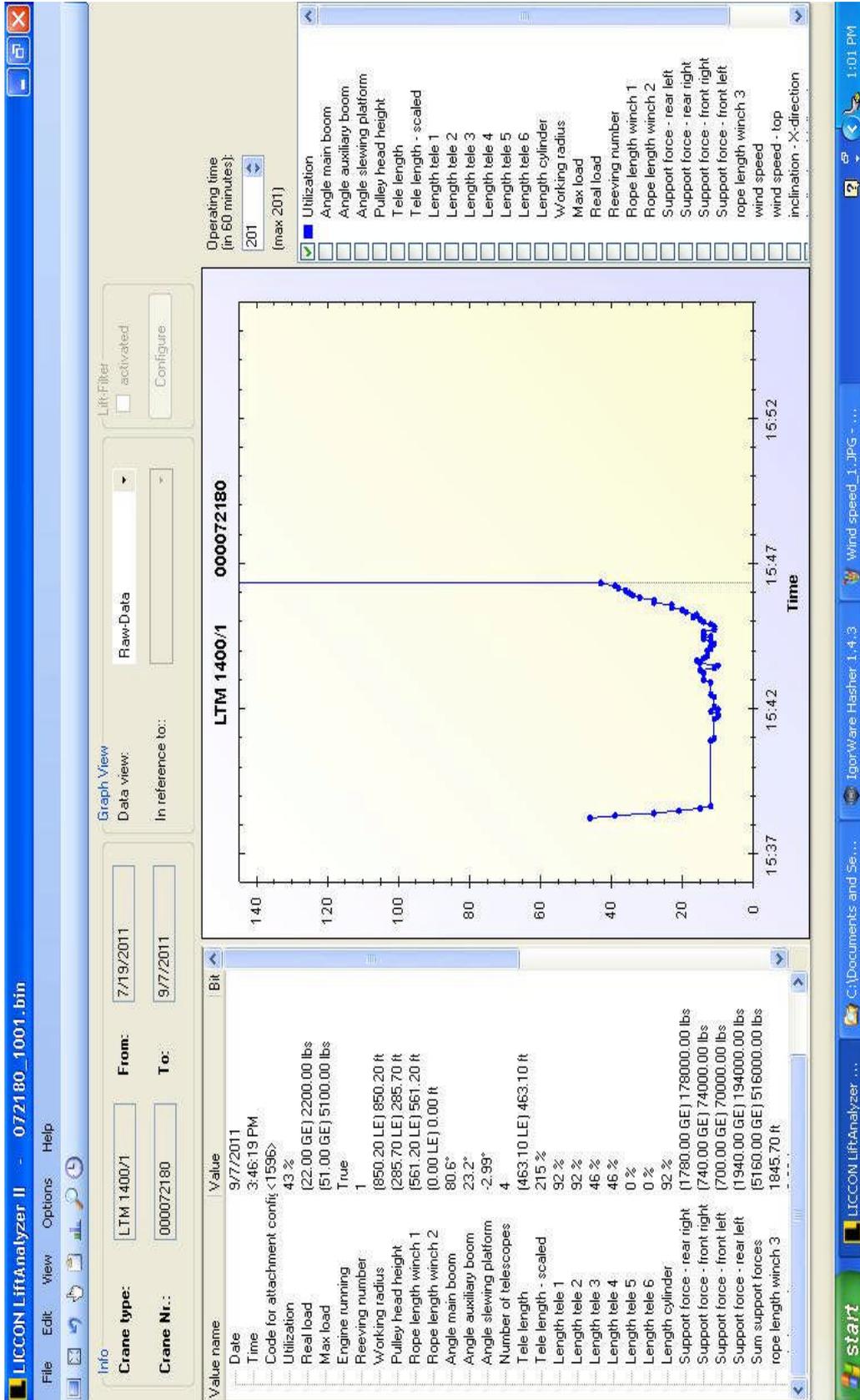


Figure 21. Recorded Utilization Values for the Last 16 Minutes before the Collapse (Taken from Data Logger by Liebherr-Werk Ehingen GmbH).

Our independent analysis indicated that the approximate angle of the boom when the overturning and stabilizing moment would be equal would be approximately 63 degrees with the jib being horizontal. This matches closely with the recorded angle of 64 degrees.

At 10:52 a.m. and thereafter, the crane was being operated beyond the load chart, and failure could be expected anytime. The reasons of how the crane became operational again after being stationary for three minutes are not clear. An obvious reason could be that the crane operator engaged the bypass switch overriding the shutoff. Another reason could be a malfunction of the shutoff.

It must be noted that certain information contained in the print out of the data logger was inaccurate in regard to the working radius, the telescopic boom length, the total support forces and the permissible load immediately prior to the collapse (see Figure 22) downloaded from the data-logger. It is uncertain whether these discrepancies occurred due to flaws in the special software used to download the data or in the crane software itself.

The crane operator indicated a scenario of a thunderstorm with heavy rain and lightning near the tip of the jib. His visibility was very limited and he could not see the tip of the jib. He argues that because it takes approximately 20 minutes to telescope the boom inward due to the 12-part pulley system, he decided not to telescope the boom inward. Instead, he lowered the jib to near zero degrees and also lowered the boom to approximately 68 degrees to avoid lightning and thunderstorm. Then, he was waiting for the storm to pass by. As he was waiting, the crane began to overturn. Our analysis indicates that if he had maintained the boom at 81 degrees and the jib at 22 degrees, this incident would not have happened, despite the raging storm.

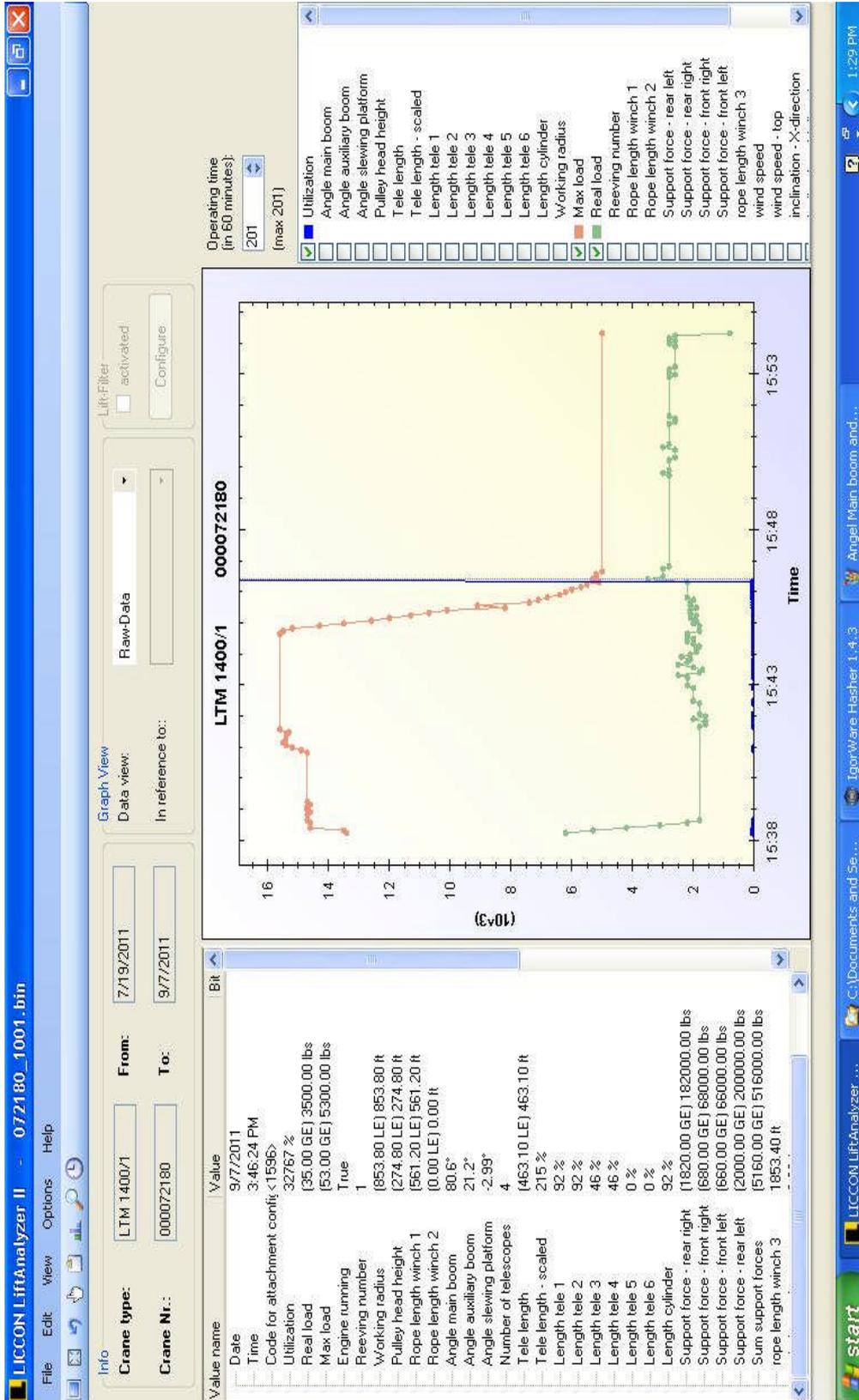


Figure 22. Recorded Real (Actual) Load and the Maximum Permissible Load for the Last 16 Minutes before the Collapse (Taken from Data Logger by Liebherr-Werk Ehingen GmbH).

6. CONCLUSIONS

1. The crane collapsed because the Crane Service Company operated the crane at a radius well beyond its load chart. At the time of the collapse, the radius of the load was approximately 344 feet, and the telescoping boom was at an angle of approximate 63 degrees. The jib attached to the telescoping boom was almost horizontal. The load chart does not go beyond 260 feet, with the boom making an angle of 75 degrees.
2. Although the crane was not hoisting any load at the time of the incident, the weight of the headache ball and the riggings were enough to create instability at a radius of 344 feet that resulted in the crane overturning.
3. The right rear support of the pad settled approximately 6 inches before the incident but did not cause the collapse. Its contribution to the collapse was minimal, approximately 1.5%. If the crane had been operated within the load chart, the collapse would not have occurred despite the settlement.
4. At the time of the collapse, the overturning moment was greater than the balancing moment due to the larger radius and lower angles of the boom and the jib.
5. The wind speed at the time of the collapse was approximately 15 miles per hour with no appreciable gusts. Wind did not cause the collapse.
6. When the crane reaches its load limit as it did in this case, an alarm is supposed to sound warning the crane operator, at which time the shut-off switch automatically comes on. The shut-off switch locks the movement of the crane unless the operator engages a bypass switch which overrides the shut-off switch. Data obtained from the crane data-logger indicated that the crane operator was able to operate the crane for at

least eight to nine minutes after it exceeded the load limit. The crane operator denied hearing any alarm or engaging the bypass switch. Because the data-logger did not appear to record the engagement of the bypass switch or the sounding of the alarm, we were unable to verify the accuracy of the operator's statements.

7. The Liebherr crane was equipped with a data-logger (commonly known as a black box). Some of the information related to the maximum permissible load, the working radius, the telescopic boom length and the sum of the support forces were in error. We can not ascertain with a high degree of accuracy whether this inconsistency arose from any potential flaw in the software used to download the data from the data-logger or the data-logger itself was recording erroneously. In addition, we recommend that the data-logger be equipped with the capability to record the engagement of the bypass switch and the activation of the alarm.

7. REFERENCES

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6. Liccon LiftAnalyzer II Manual, by Marek Wyborski, 30 Pages, July 18, 2008.
7. ASCE STANDARD ASCE/SEI 7-10 Minimum Design Loads for Buildings and Other Structures, Prepared by American Society of Civil Engineers, 608 Pages.

APPENDIX A

Backup calculations

- A-1 Summary
- A-2 Weight and Center of Gravity of the Crane Members Provided by the Crane Manufacturer for the Recovery Operation
- A-3 Estimation of the Total Weight of the Crane at the Time of the Collapse
- A-4 Estimation of the Total Resisting Moment in the Direction of the Collapse
- A-5 Estimation of the Weight and the Center of Gravity of the Telescopic Boom Assembly
- A-6 Estimation of the Weight and the Center of Gravity of the Lattice Jib Assembly
- A-7 Estimation of the Overturning Moment Due to the Telescopic Boom Assembly, Lattice Jib Assembly and Hook Block
- A-8 Estimation of the Overturning Moment Due to the Wind Force
- A-9 Estimation of the Overturning Moment Due to the Settlement of the Rear Right Support Pad
- A-10 Estimation of the Total Overturning Moment in the Direction of the Collapse

A-1 Summary

The purpose of the analysis is to estimate the required telescopic boom angle that will cause the toppling of the crane. It also estimates the amount of contributions from the wind force and the sudden settlement of the rear right support pad toward the collapse of the crane.

The weight and the center of gravity (centroid) of the carrier, the superstructure, and the counterweight frame are listed in Section A-2. This information was provided by the crane manufacturer during the recovery of the failed crane. The weight of the remaining elements was selected from the Operating Instructions of the crane. Section A-3 adds the weight of all crane elements assembled on the crane at the time of the collapse as approximately 200 tons. With the above information, the total resisting moment of the crane is calculated as 1,106 m-tons in Section A-4. Note that the moment is taken about the rear axis of the support pads, which was the rotational axis of the toppled crane.

The centroids of the telescopic boom assembly and the lattice jib assembly are computed in Sections A-5 and A-6, respectively. The overturning moment from the telescopic boom assembly, lattice jib assembly and the hook block is calculated about the rear axis of the pads in Section A-7. The overturning moments due to the wind force and the settlement of the rear right support pad are estimated in Sections A-8 and A-9, respectively. The total overturning and resisting moments are compared in Section A-10. It is found that:

- The crane toppled when the telescopic boom angle reached 63° and the lattice jib angle around 0° . The crane was operated beyond the load chart.
- The wind force and pad settlement contribution to the overturning moment that caused crane collapse were 1.3 % and 1.4 %, respectively.