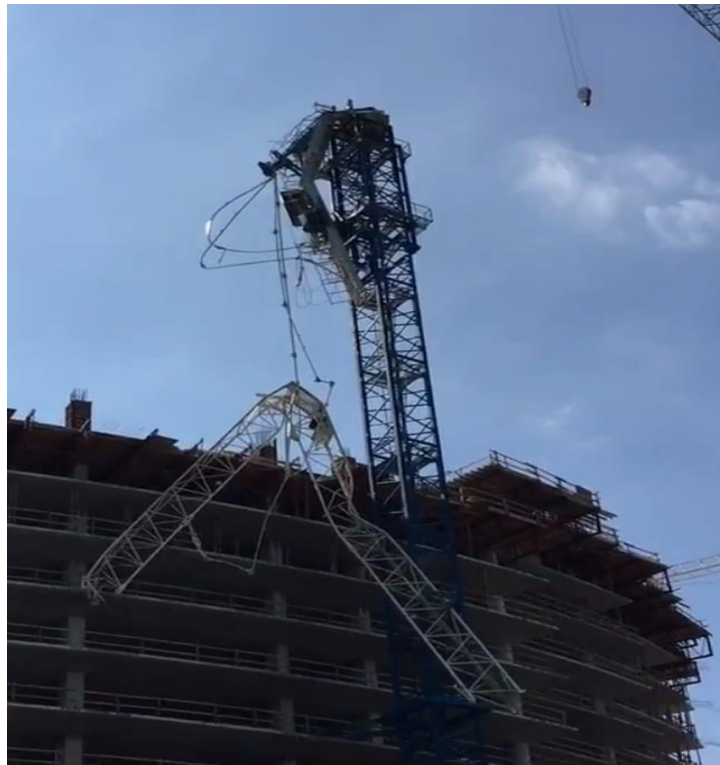




Failure of Hammerhead Cranes



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Investigation of the Failures of Three Hammerhead Cranes on September 10, 2017, in Miami and Fort Lauderdale in the Wake of Hurricane Irma

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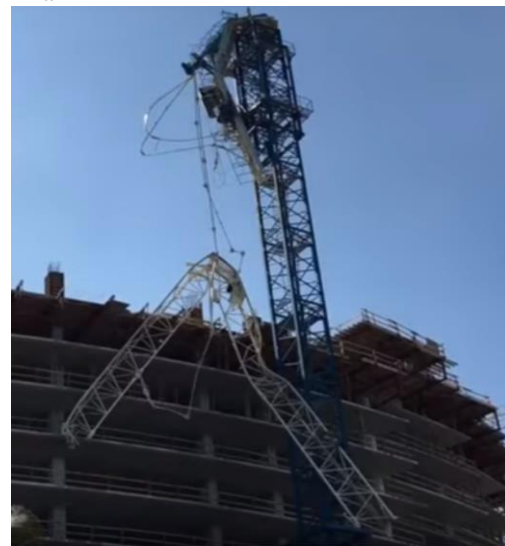
September 2018



Miami



Miami



Fort Lauderdale

Report

Investigation of the Failures of Three Hammerhead Cranes on September 10, 2017, in Miami and Fort Lauderdale in the Wake of Hurricane Irma

September 2018

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1. Executive Summary

On Sunday, September 10, 2017, three hammerhead tower cranes collapsed within hours of each other; two in Miami and one in Ft. Lauderdale, Fla., during heavy winds in the wake of Hurricane Irma. Miami and Ft. Lauderdale were experiencing tropical storm conditions as Hurricane Irma made landfall on the west coast of Florida. In these particular crane collapses, no one was injured because construction everywhere was at a standstill, and residents were either evacuated or taking shelter in their homes. There was limited property damage from the collapses at these construction sites. Terex Peiner GmbH (Terex Peiner) manufactured one of the three cranes, and the other two were manufactured by Noell Service and Maschinenetechnik GmbH (Noell). The three cranes were the same model SK-315. There were over two dozen other cranes in the bustling Miami and Fort Lauderdale area, but none of them collapsed except the SK 315 models. There was another SK 315 model crane that did not collapse which was at a much lower height and was shielded by tall structures. There were Terex manufactured cranes other than SK 315 in the area which did not fail.

OSHA initially went to the site location based on a media referral. Upon visiting the construction location, there were no employees exposed to hazards as construction activities had been ceased due to the hurricane. OSHA did not open an enforcement inspection. The Agency's involvement was limited initially to providing technical assistance in the safe dismantling of the cranes and associated equipment from the construction locations. Suspecting potential deficiencies in this model of the Terex crane, OSHA decided under the authority of the OSH Act and the Field Operations Manual (Chapter 11, Section III) to pursue an engineering investigation of the three incidents. Structural engineers from the Office of Engineering Services (OES) in OSHA's Directorate of Construction visited the incident sites, the Maxim Crane storage yard in Kentucky, and the grounds in Orlando and Miami where the remnants of the failed cranes were stored. The manufacturer and owner of the cranes cooperated and were given the opportunity and provided input throughout the process. Based on this investigation, OES concludes that:

1. The design of the crane, model SK-315 generally met the U.S. and European standards. The crane was designed for a maximum wind speed of 95 mph at the jib level for the out-of-service condition. Beyond 95 mph, failure could occur as stated in the manufacturer's

manual. The wind speed at different heights of the jib of the three cranes in Miami and Ft. Lauderdale exceeded 95 mph.

2. If the wind speed at the jib level exceeds 45 mph, the crane must be placed out of service and allowed to weathervane, as per the manufacturer's manual. On Sept. 10, 2017, all three cranes were put out of service and allowed to freely weathervane.
3. The U.S. and European codes do not require that turbulent wind, suction, or vortexes be considered in the design of the cranes. The failure of all three cranes occurred due to turbulent wind.
4. Out of more than a dozen cranes in and around Miami, only the model SK-315 failed due to an inherent weakness at the connection of the jib to the turntables.
5. The cause of the failure of the three cranes was the detachment of the crane jibs from their turntables due to turbulent wind loads. Based on our evaluation, it is believed that wind gusts, at oscillation periods corresponding to the frequencies of the dominant modes of the jibs, struck the jibs. Under the turbulent wind loads in either lateral or upward direction, the forces on the turntable cradles at the jib feet exceeded their capacities. The separation of the jibs at the turntable caused the jibs to fall in all three cases.
6. In all three crane failures, only the jibs, counterjibs, and the tower top collapsed, while the crane masts, ties and foundations remained intact.
7. The tower top collapsed due to a transient loss of the forces in the jib pendants.
8. On coastal areas with tall buildings and locations prone to frequent turbulent winds, local governing bodies should consider asking engineers to conduct simulations based on dynamic analysis to get a more realistic wind evaluation than quasi-static analysis. Instead of conducting cost-prohibitive wind tunnel tests, engineers could conduct a Computational Fluid Dynamics (CFD) analysis, which has become affordable due to the rapid advance of software and computing technology.
9. Terex, the crane manufacturer, should evaluate the design of jib-to-turntable connections to prevent possible detachment of crane jibs in high turbulent wind in the future.
10. To prevent catastrophic collapses of the crane tower top in the future, it is recommended that tower tops be evaluated and designed with a higher safety margin, and the design should also be based with loads applied from only the counterjib.

11. The jibs in all three cranes were suspended by single pendants. In the event that the jib begins to sway to the sides, the single pendants could not be expected to secure the stability of the jib. It is, therefore, recommended that two symmetric pendants or cables be considered in the design of the tower cranes. Terex should consider adding pendants to the existing SK-315 models.
12. Although the National Hurricane Centre issued warnings to the residents in South Florida that heavy Squalls with embedded tornadoes were sweeping across South Florida, no tornadoes formed at any of three failure sites on September 10, 2017. However, localized high-altitude strong vortexes cannot be ruled out.

2. Introduction

Hurricane IRMA changed its course and made its landfall on the west coast of Florida. Therefore, the east coast (i.e., Miami and Ft. Lauderdale) were spared the intense destruction of a hurricane. Nevertheless, on Sunday, September 10, 2017, Miami and Ft. Lauderdale faced a tropical storm with a turbulent wind speeds of 40 to 70 miles per hour (mph) with gusts near 80 mph. Miami was bustling with construction activities, with cranes dotting the landscape. Reportedly there were over two dozen cranes in the City of Miami alone. Anticipating the hurricane's approach, all construction activities were terminated, and all three tower cranes identified in this investigation were set to weathervane in the wind with their slewing brakes released. The cranes carried no load except their dead weight.

A hammerhead tower crane, model SK-315, manufactured by Terex Peiner, and another hammerhead tower crane, model SK-315, manufactured by Noell, collapsed in the wind on Sunday within hours of each other. Both cranes were located in the downtown Miami area approximately two miles apart (see Figure 1). No injuries were reported as all construction activities ceased the night before and the streets were deserted. A few hours later another hammerhead tower crane, also a model SK-315, failed in Ft. Lauderdale some 35 miles north of Miami (Figure 1). No other cranes failed either in Miami or Ft. Lauderdale during the tropical storm.

OSHA became involved due to reports of the crane failures through the media and proceeded to the location to see if any employees were injured and if the conditions were safe for workers. Upon visiting the site, it was apparent that the worksite was not active and that employees were not exposed to the hazards posed by the three cranes in question. An OSHA inspection was not opened for that reason. However, the three failures of the same model hammerhead cranes in a similar manner alarmed OSHA officials. The agency decided to initiate an engineering investigation of the failures to ascertain whether the particular crane model SK 315 cranes had some potential deficiencies causing them to fail in turbulent high winds while no other cranes were failing. Structural engineers from the Office of Engineering in the Directorate of Construction visited the incident sites in Miami and Ft. Lauderdale, the Maxim Crane Yard in Kentucky, and the storage yards in Orlando and Miami where the remnants of the failed cranes were stored for later inspection. Numerous photographs, videos taken by amateur videographers publicly available on

YouTube.com, and media reports were examined. Discussions with general contractors, crane owners, officials of the City of Miami Building Department, and the crane manufacturer were held over a period of several months after the incident. Structural analyses of the jib, counterjib, and the tower frame were conducted.

The following is our report:

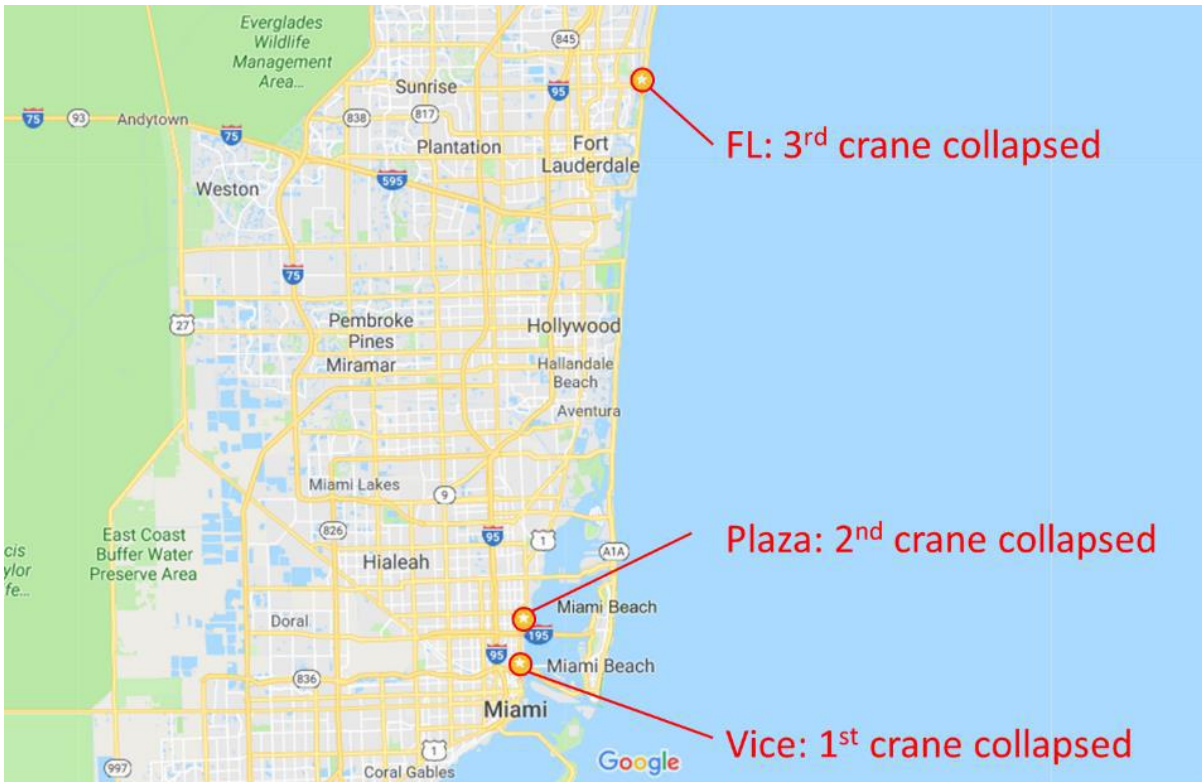


Figure 1 Locations of the three failure sites
(Courtesy of Google Map)

3. Description of the Cranes

3.1 Description of the Structures

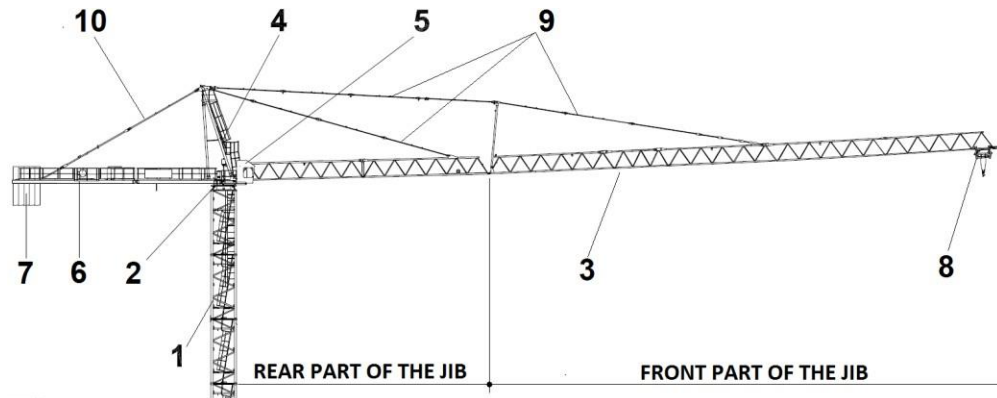
The three cranes involved in the three incidents were the same model, SK-315, one manufactured by Terex Peiner and the other two manufactured by Noell. The cranes were designed in the mid-1990s. The cranes involved in the first and the third failures were built in 1998, while the one involved in the second failure was built in 2000.

Each of the three cranes consisted of a mast, a turntable, a tower top, a jib, a counterjib, and accessories, as shown in Figure 2. The mast was fixed to crane foundations and attached to the exterior face of structures. The jib and the counterjib were mounted to the turntable, where the slewing bearing and slewing machinery were located. The counterjib carried a counterweight consisting of concrete blocks, while the jib suspended the load from the trolley. The hoist motor and transmissions were located on the mechanical deck on the counterjib, while the trolley motor was located on the jib. The operator's cabin was located at the top of the tower, attached to the turntable right next to the jib foot. There were two pendants supporting the jib: 70mm x 50mm (2.8" x 2") solid shape supporting the rear part of the jib, and 50mm x 50mm (2" x 2") solid shape supporting the front part of the jib; and there were two 90mm x 50mm x 7.1mm (3.5" x 2") hollow rectangular tube pendants supporting the counterjib, as shown in Figure 2. The long pendants consisted of several pieces interconnected with pins.

The tower top, approximately 28 ft. high, was connected to the turntable with pendants suspending the jib and the counterjib. The tower top was a tubular structure consisting of four structural tubes, two 200mm x 120mm x 12.5mm (8" x 4-1/2" x 1/2") toward the jib, and two 180mm x 100mm x 6.3mm (7" x 4" x 1/4") toward the counterjib (see Figure 3). The tubular structure of the tower top was triangular. The structural tubes on the side of the jib and the side of the counterjib were diagonally braced about the minor axis. However, the major axes were braced with a solitary horizontal brace at approximately mid-height. The bottom of the tubular framed tower top was pinned at four locations at the top of the turntable (see Figure 3).

The jib consisted of multiple sections of triangular-shaped, latticed-framed structures, and was mounted in two parts, the rear part and the front part, as shown in Figure 2. The rear part of the

jib consisted of 120mm x 120mm x 12.5mm (4.7" x 4.7") square tube bottom and top chords braced diagonally by steel pipes, and the front part of the jib consisted of 100mm x 100mm x 10mm (4" x 4") square tube bottom and top chords braced diagonally by steel pipes. The bottom chords of the jib were additionally braced by channels. The two bottom chords of the jib were pinned to the two cradles on the turntable (see details in Figure 4).



- | | |
|--------------|-------------------------|
| 1: Mast | 6: Counterjib |
| 2: Turntable | 7: Counterweight |
| 3: Jib | 8: Trolley and hook |
| 4: Tower top | 9: Jib pendants |
| 5: Cabin | 10: Counterjib pendants |

Figure 2 Terex Peiner SK-315 hammerhead tower crane

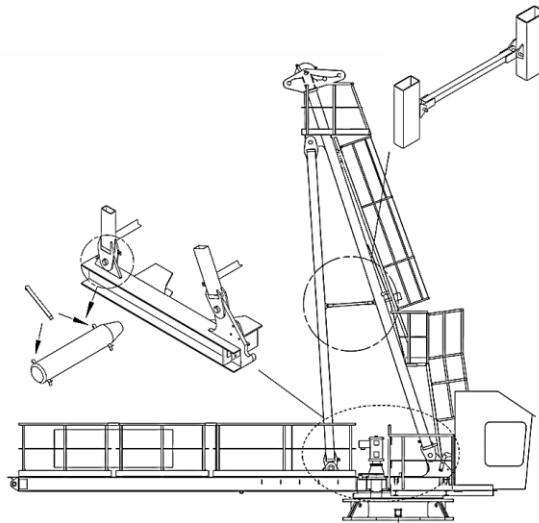


Figure 3 Terex Peiner SK-315 tower top and turntable

Two wide flange beams were welded to the top of the turntable to receive the counterjib. The counterjib, consisting of two wide flange beams braced along its length, was connected to the two wide flange beams of the turntable with pins (see Figure 5).

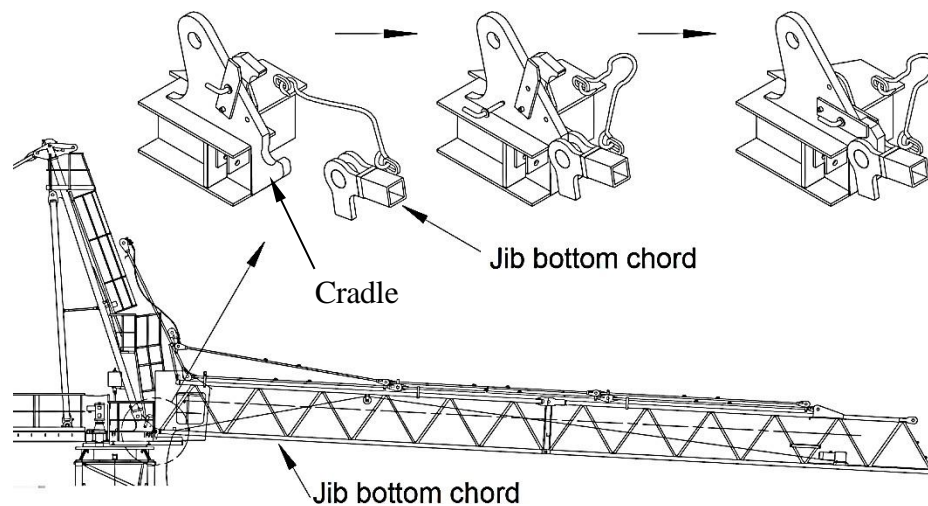


Figure 4 Jib and turntable connection

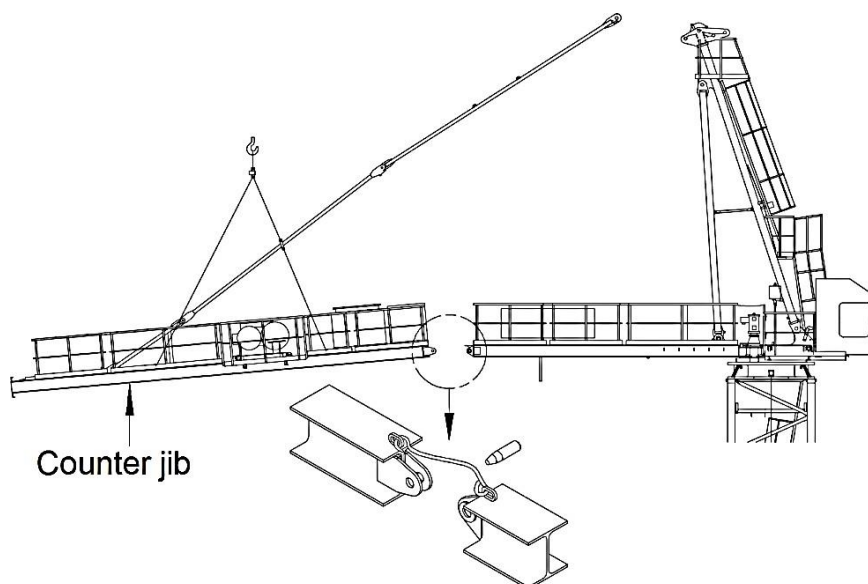


Figure 5 Counterjib and turntable connection

3.2 Slewing and Wind Release

In principle, the surface area of the jib is much larger than the counterjib. The jib will follow the wind direction, and the counterjib will point against the wind. The cranes will stay in the wind mean direction, and will follow the low-frequency fluctuations. This orientation minimizes the

surface area, thereby reducing the wind pressure exerted on the upper structure. Without surrounding environment, the cranes will be in tailwind condition, as shown in Figure 6. The jib fluctuates, and the counterweights of the jib equilibrate the aerodynamic loads.

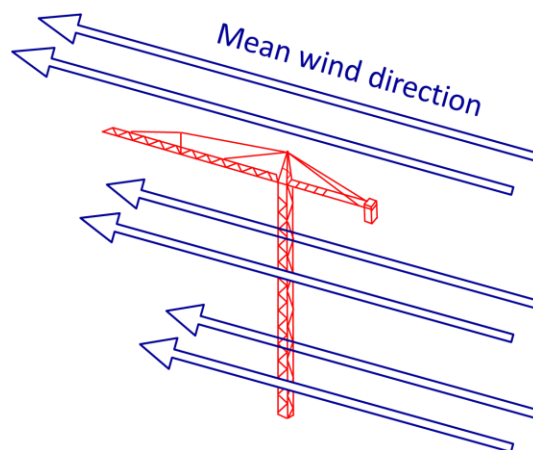


Figure 6 Tailwind condition of tower cranes

The SK315 cranes were required to weathervane when out of service. According to the SK315 Hammerhead Tower Crane Operating Manual, during the windstorm, the rotation parts of the crane shall be free to rotate. To allow the crane to rotate freely in the wind after being taken out of service, the slewing gear brakes must be bled. This could be achieved by either turning the thumb-wheel on the slewing gear brakes in the counter-clockwise direction mechanically, or pressing the pushbutton “WIND RELEASE” on the control stand if the electrical wind release was installed.

3.3 Design Wind Loads

As required in the FEM 1.001 Booklet 2: Rules for the Design of Hoisting Appliances, two design wind conditions were taken into account in calculating wind loads on the crane: in-service wind and out-of-service wind.

The in-service wind is the maximum wind in which the crane is designated to operate. As stated in the SK315 Hammerhead Tower Crane Operating Manual, the maximum permissible in-service wind speed that the SK315 cranes were designed to bear is 45 mph. Measures to take the crane out of service must be taken before this critical level is reached.

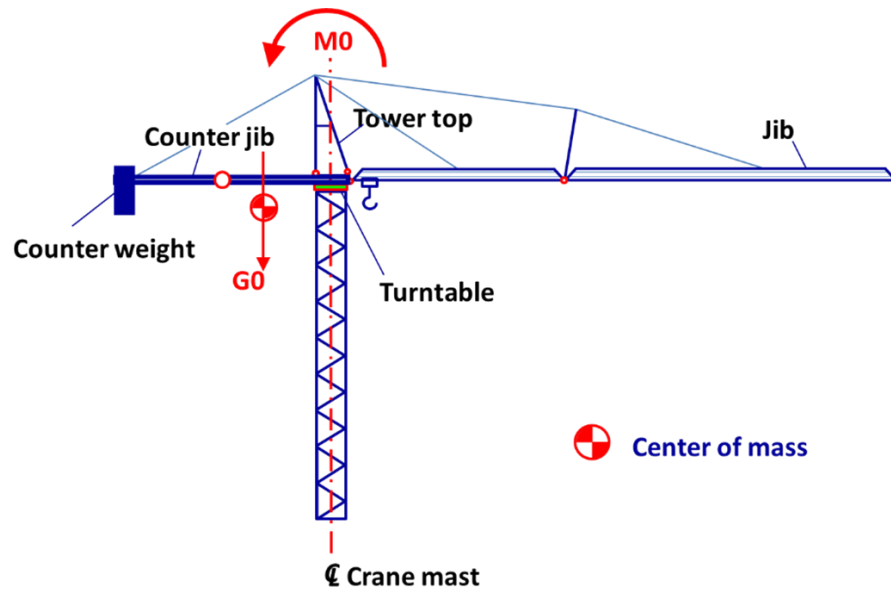
The out-of-service wind is the maximum wind for which the crane was designed to remain stable in out-of-service conditions. The speed varies with the height of the crane above the surrounding ground level—the geographical location and the degree of exposure to the prevailing winds. The out-of-service wind that the SK315 cranes were designed to withstand is 95 mph. Weather data indicates that gusts were expected to be below 95 mph at 33 ft. above ground on September 10, 2017.

3.4 Tower Top in the Out-of-Service Condition

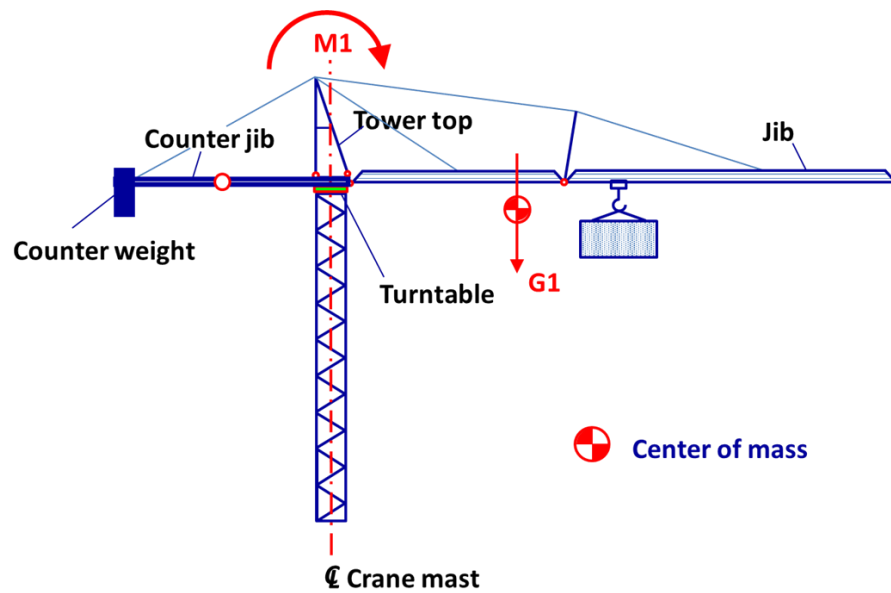
The SK315 cranes were substantially counterweighted. The cranes with zero hook load have reverse moments, compared to the forward moments when the cranes have the full design loads at the maximum radius, as shown in Figure 7. The two tower top columns toward the counterjib were under compression in the out-of-service condition.

According to the SK315 Hammerhead Tower Crane Operating Manual, before the jib can be mounted, the erection counterweight should be positioned in the rearmost insertion position (i.e., in the insertion position farthest from the tower top). After the jib is mounted and before the crane can be put into operation, the rest of the counterweight should be completed.

In the rest of this report, *right* and *left* are used from the point of view of the reader while standing on the turntable and facing the jib.



(a) Without load



(b) With load

Figure 7 Resulting moment of tower cranes

4. Description of the Collapses

Locations of the three hammerhead tower crane cranes that collapsed are shown in Figure 1. The three sites were either very close to or on the coast. The sites were expected to receive the maximum force when the wind was blowing from the ocean.

4.1 The First Failure

A 33-story concrete-framed building with post-tensioned slabs for apartments, condominiums, and parking garage was under construction at 243 NE 3rd Street, Miami. The building was called VICE building; 31 stories were already completed. The general contractor was John Moriarty & Associates of Hollywood, Fla. A hammerhead tower crane, model SK-315, erected approximately a year ago, was being used with a jib length of 180 ft., counterjib length of 64 ft., and counterweight of 39 kilopounds (kips) consisting of five individual concrete blocks. The crane was owned by Maxim Crane and leased to L&R Structural. L&R retained Diamond Back Hoist and Rigging Company to erect the tower. Prior to the storm, the height of the crane mast had been reduced by two sections, 20 ft. each. At the time of the failure, the crane was 425 ft. high, and the bottom of the jib was approximately 70 ft. above the completed structure.

The surrounding environment of the first failure site is shown in Figure 8. Jib location and wind direction were determined based on video taken when the crane collapsed.

The failure occurred at approximately 10 a.m. The counterjibs rotated 90 degrees and were hanging upright, though still connected to the turntable. The pendants remained connected to the counterjibs at both locations. The tower top structure also bent 90 degrees toward the counterjib. The two tower-top columns on the counterjib side buckled at approximately mid-height between the top pin and the brace. The jib came off the pinned connection, flipping 270 degrees, and fell over the completed structure with a 90-degree bend where the A-frame (a.k.a. queen post) was located. The last pin of the pendant connecting to the top chord of the jib, and the last pin of the other pendant connecting the A-frame, were opened as the cotter pin loosened. All five pieces of the counterweight fell over the interior of the building, damaging the already-completed floor slab; none fell outside the perimeter of the building. The engineer of record examined the building and

recommended repairs to the slabs. Refer to Figure 9 for the collapsed crane tower top after the failure.

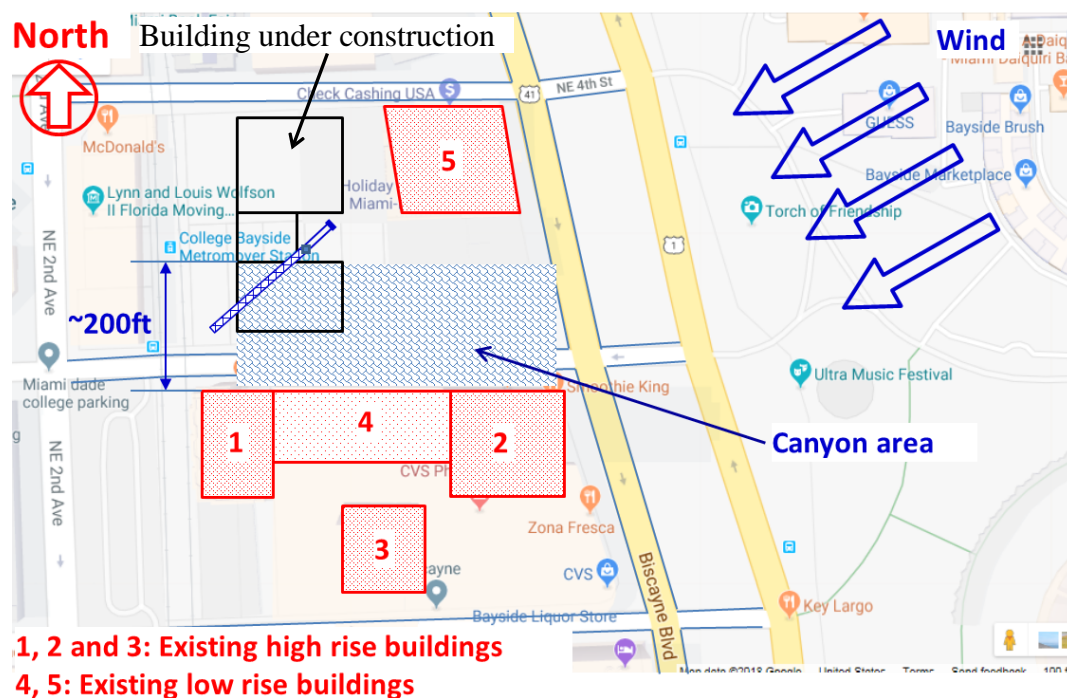


Figure 8 Surrounding environment of the first failure site
 (Courtesy of Google Map)

A YouTube video was later discovered that showed how the collapse occurred (see Figure 10 for pictures extracted from the video footage). It was discovered that the jib itself swayed toward the right, and the left bottom jib chord detached from the turntable. As the jib continued swaying toward the right, the right bottom jib chord separated suddenly from the turntable and the jib started falling. During the fall of the jib, the two jib pendants were unloaded. The tower top changed in seconds from being loaded from both sides to being loaded only from the counterjib side. Then the two tower top columns, swaying toward the counterjib, failed under the change of the transient load.

The remnants of the crane, safely stored after they were removed, were examined in Miami on December 14, 2017.



Figure 9 Tower top and counterjib after the incident – the first failure



Figure 10 Image sequence showing the crane collapse
(Courtesy of Nick Tangredi)

1. Jib started to sway to the right, and the left jib bottom chord detached from the turntable;
2. Jib kept swaying to the right, and the jib knocked the cabin;
3. Jib kept swaying to the right, and the counterjib started shaking;
4. Jib kept swaying to the right, and the right jib bottom chord detached from the jib foot. Therefore, the entire jib was no longer mounted to the turntable;
5. Jib fell, and the two jib pendants were not loaded. The tower top was loaded from the counterjib pendants only. The two tower top columns, swaying toward the counterjib side, buckled; and
6. The tower crane collapsed.

Figure 10 Image sequence showing the crane collapse – continued

4.2 The Second Failure

A 55-story concrete-framed building was under construction at 610 NE 31st Street in Miami, a couple of miles away from the VICE building. The building was called PLAZA, consisting of apartments, condominiums, and a parking garage. An SK-315 crane was erected to aid the construction. As in the case of the first failure, the crane mast was lowered 40 ft. the night before the storm to a height of approximately 600 ft. The concrete structure was already completed up to the 51st floor at the time of the failure. The crane had a 147-ft.-long jib with a 64-ft.-long counterjib. It had four pieces of counterweight with a total weight of 32 kilopounds. The general contractor was PLAZA Construction, with offices in Miami. Moss and Associates LLC was the construction manager from Ft. Lauderdale. The second failure occurred approximately between noon and 3 p.m. At the time of the failure, the bottom of the jib was approximately 100 ft. above the completed structure.

There were three other cranes at the second failure site—a CTL luffing crane, an SK 415 hammerhead tower crane, and another SK 315 crane but at a shallow height of approximately 96 ft. The shallower SK 315 did not collapse, possibly because it was shielded by buildings and its lower height.

The surrounding environment of the second failure site is shown in Figure 11. Jib location and wind direction were determined based on video taken prior to the collapse of the crane.

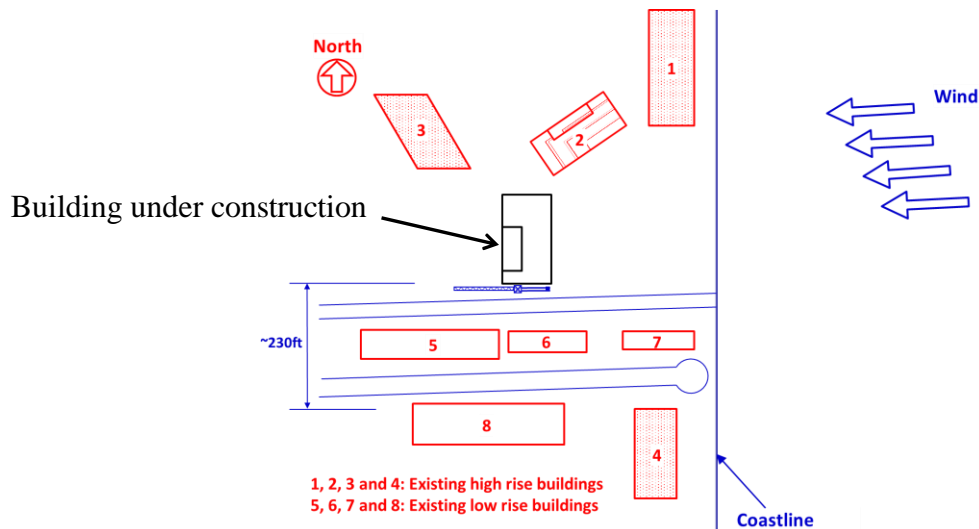


Figure 11 Surrounding environment of the second failure site

The failure of the tower top occurred in a manner similar to the first failure. The counterjib beams rotated 90 degrees and were hanging straight down by the side of the crane mast. The tower also rotated approximately 90 degrees. Again the tubular columns on the side of the counterjib buckled very distinctly between the top pin and the solitary brace about the major axis. All four counterweight pieces fell on the street below piercing the pavement. The City of Miami had ordered an evacuation of adjoining apartments and condos. The street was therefore deserted, and there were no injuries. The jib came off its pinned bearing connection and was bent in a V-shape at the location of the A-frame. During the failure, all pendants remained connected to the jib, and all pins interconnecting the pendants remained intact. A photograph of the crane tower top taken after the crane collapse is shown in Figure 12.

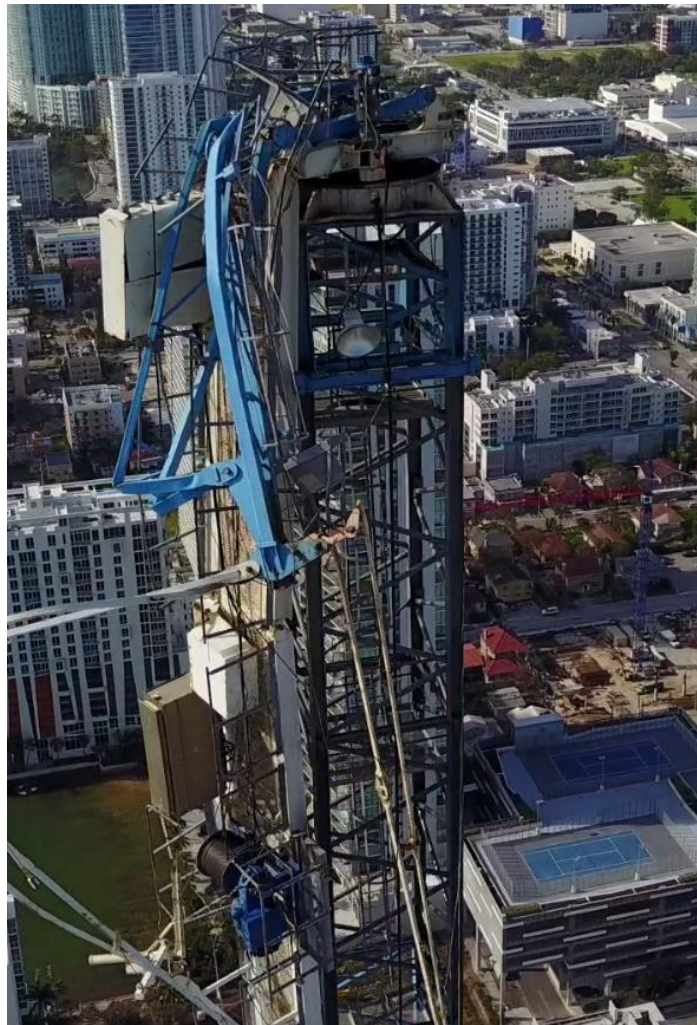


Figure 12 Tower top and counterjib after the incident – the second failure site

It is interesting to note that another crane model SK 415, also manufactured by Terex, was located some 75 ft. away from the failed SK 315. The SK 415 did not fail except that the right post of the A-frame was bent. It was approximately same height as SK 315 but had a distinct feature that the jib, the bottom and top chords of the jib had bigger sizes. Another distinction between the two models was that there were double wire rope pendants supporting the jib instead of one solid tube.

The OES structural engineers examined the remnants of the crane on December 12 and 13, 2017.

4.3 The Third Failure

Approximately 35 miles north of Miami, another failure involving model SK 315 occurred at around 4:50 pm at a construction site at 2200 N. Ocean Boulevard in Fort Lauderdale. The general contractor was Moss and Associates, LLC of Fort Lauderdale. It was a concrete framed structure for Auberge Condominiums and Spa. Maxim Crane was a sub-contractor who owned, operated, assembled and maintained the crane. Unfortunately, when the structural engineer of OES arrived at the Fort Lauderdale incident site on Monday, September 18, 2017, Maxim crane had already removed the failed crane. However, a YouTube video was later discovered that showed the failed crane jib, and counterjib during the removal phase. More pictures of the construction site were discovered during the investigation that showed the site and the crane immediately prior to and after the failure. The surrounding of the Auberge site is shown in Figures 13 and 14. Wind direction was based on the photographs taken prior to the collapse of the crane. At the time of the failure, the bottom of the jib was approximately 80 ft. above the completed structure.

The failure of the tower top occurred in a manner similar to the first two failures. The counterjib beams rotated 90 degrees and were hanging straight down by the side of the crane mast. The tower also rotated approximately 90 degrees. Again the tower top columns toward the counterjib buckled very distinctly between the top pin and the solitary brace about the major axis. All four counterweight pieces fell, but there were no injuries. The jib came off its pinned bearing connections and was bent in a V-shape at the location of the A-frame. During the failure, all pendants remained connected to the jib, and all pins interconnecting the pendants remained intact. A photograph of the crane tower top taken after the crane collapse is shown in Figure 15.



Figure 13 Surrounding environment of the third failure site
(Courtesy of Google Map)



Figure 14 Tower cranes prior to the incident – the third failure site

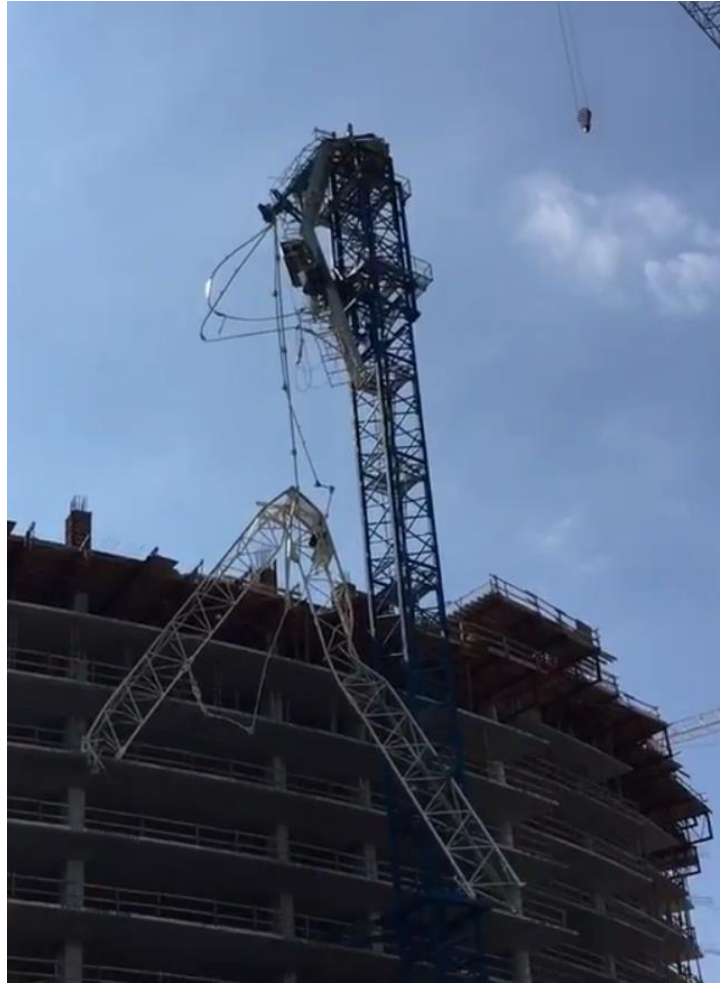


Figure 15 Collapsed crane after the incident – the third failure site

Later, the remnants of the failed crane were examined at the storage yard in Orlando on December 12 and 13, 2017 by the OES structural engineers. Interestingly the inspection indicated similar failure where the tubular frame of the tower on the counterjib side failed at about the same location. All three failures were identical, see Figures 9, 12 and 15.

The slewing rings and brakes of the three crane were examined at the storage yard in Orlando on July 9, 2018.

5. Description of the Construction Sites

5.1 Collapse Site of the First Failure

At the first failure site, the two existing high-rise buildings across the street were taller than the crane, see Figure 16. The building under construction and the existing high-rise buildings across the street formed a small open channel, see Figures 16 and 17. Within the channel area, Venturi effect is normally expected. Therefore, the speed of wind increased when it funneled through this small opening. The severity of the Venturi effect is a function of width, length, height, and size of the opening in the canyon. The local wind acceleration effects are extremely difficult to describe and to schematize. However, it is clear that the local building configuration made the wind accelerate in this restricted area. Meanwhile, the crane tower was in front of the building, facing the strong wind from the ocean. Prior to the collapse, the jib was within a shear and separation zone beside and behind the building, see Figure 18. Therefore, wind speed and aerodynamic loads at the jib side were expected to be elevated. Moreover, vortex flow beside and behind the building was expected near the jib because of the high rise buildings across the street. This was proven by the fact that upward turbulent wind was observed underneath the jib in the video footage taken when the collapse took place, see Figure 19. Since the crane's jib was approximately 70 ft. above the completed structure, it was also likely that the jib and the counterjib were above the turbulent layer, and in a more stable laminar flow.

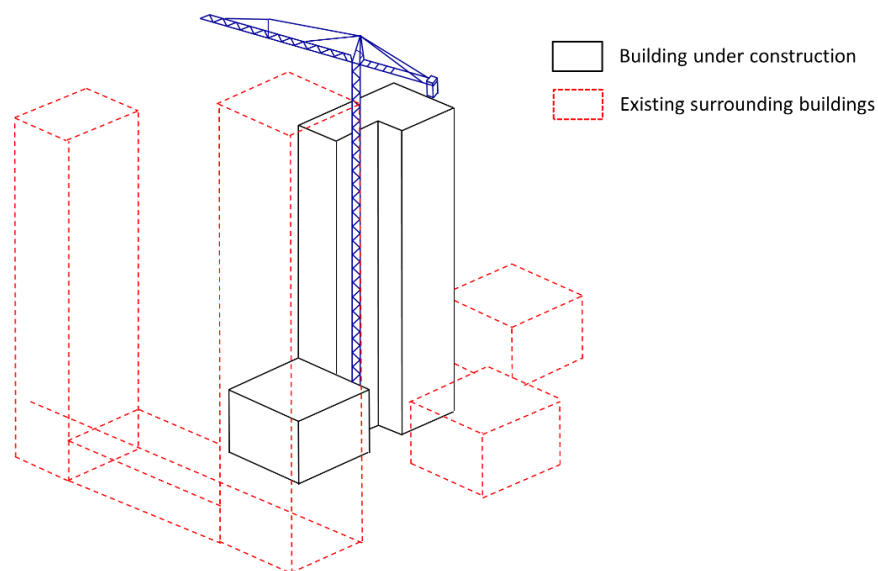


Figure 16 ISO view of the first failure site and surrounding buildings



Figure 17 Street view of the first failure site – looking west*
(Courtesy of Google Map, May 2017)

- * Note: the lower crane in the figure had been dismantled before the incident. When the incident took place, only the crane that collapsed was at the site.

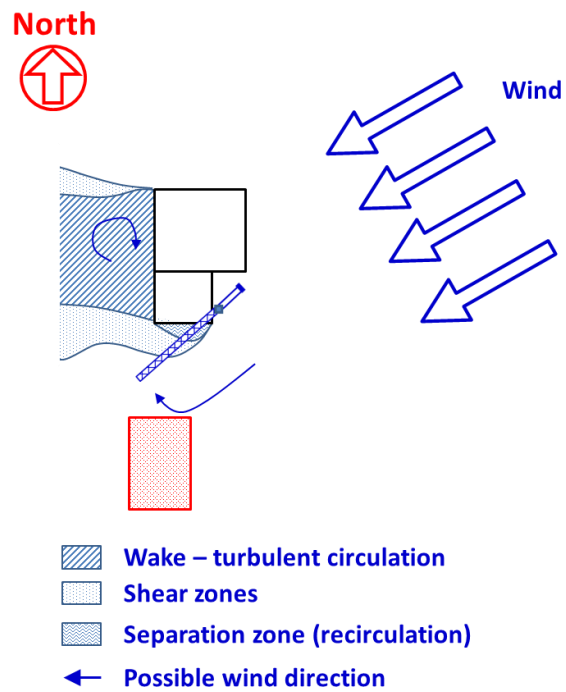


Figure 18 Surrounding environment of the first failure site
(Modified after Bodéré and Grillaud)



a) Jib jumped off the left bearing connection



b) Upward turbulence wind detected right after counterweight blocks hit the building

Figure 19 Upward turbulence wind detected when the crane collapsed at the first failure site (Courtesy of Mr. Nick Tangredi)

5.2 Collapse Site of the Second Failure

At the time of the failure, the bottom of the jib was approximately 100 ft. above the completed structure. The crane tower was against the side wall of the building, facing the strong wind from the ocean, see Figures 20 and 21. The nearest existing high-rise building in the area, which was about the same height of the completed structure, was more than 250 ft. away from the tower crane, see Figure 21. The location of the jib and the counterjib prior to the collapse was unknown. Similar to the first failure, the building under construction and the existing high-rise buildings across the street formed an open channel similar to the first failure site, as shown in Figure 21. Again, the crane was much taller than the completed structure and the nearest existing high rise building. Whether the crane was located in an area that local turbulent winds were expected was not clear. Video footage captured on September 8, 2017, showed the initial position of the two cranes less than 24 hours prior to the landfall of the storm. Compared with two other videos captured during the storm, it is confirmed that positions of the jibs of the two cranes at this site changed after the storm made landfall, as shown in Figure 22. One of the two videos captured during the storm, but prior to the crane collapse, showed the crane involved in the incident and the nearby SK415 crane,

were in tail wind condition, while the two lower cranes behind the high-rise buildings were spinning due to fluctuating winds, see Figure 23.

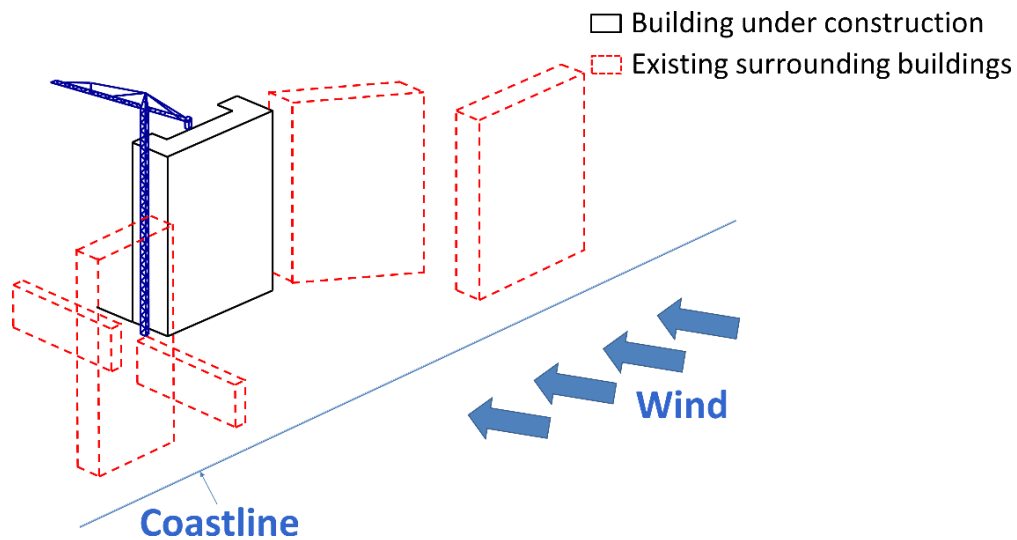
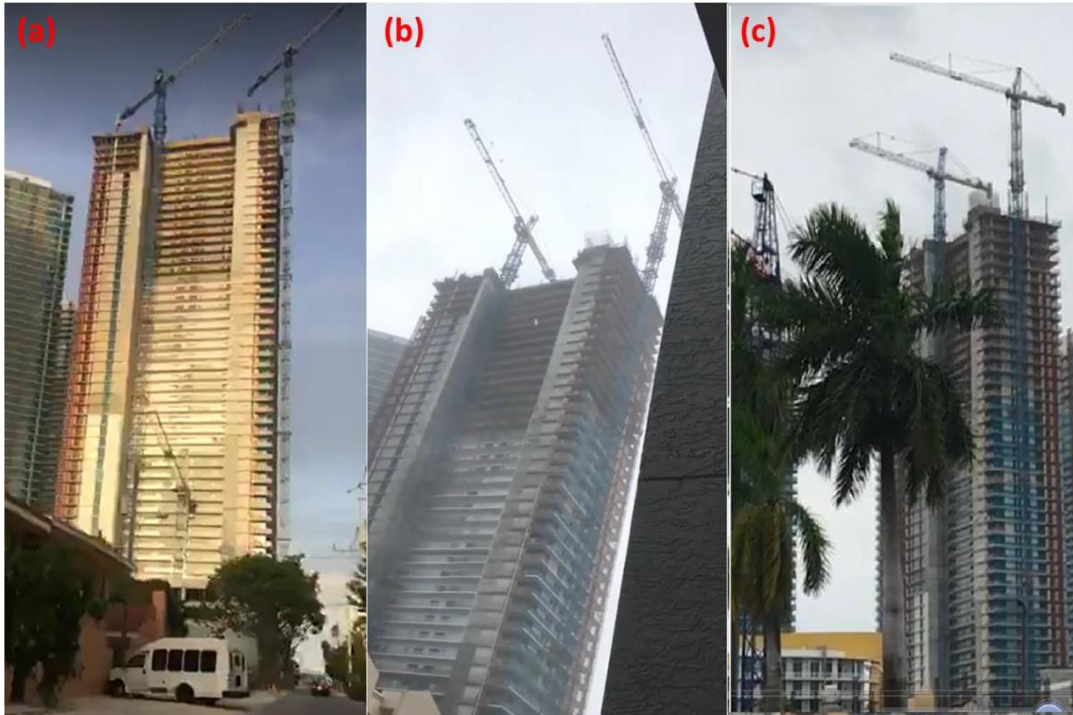


Figure 20 ISO view of the second failure site and surrounding buildings



Figure 21 Aerial view of the second failure site – looking east



(a): Captured on September 8, 2017, before Hurricane IRMA's landfall;
 (b) & (c): During Hurricane IRMA.

Figure 22 Proof of weathervane – the second failure site
 (Courtesy of Mr. Peter Zalewski and YouTube.com)

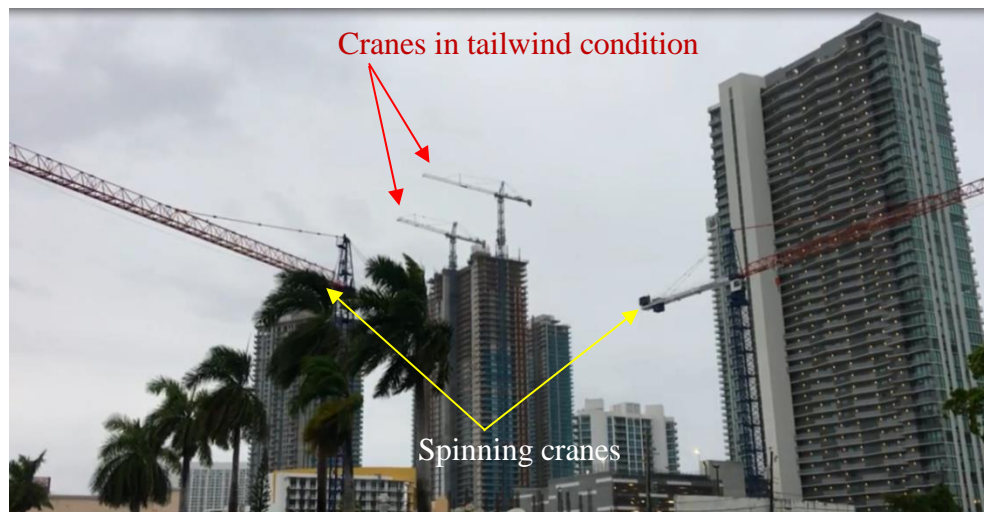


Figure 23 Tailwind condition of cranes at the second failure site – looking northeast
 (Courtesy of Mr. Peter Zalewski)

5.3 Collapse Site of the Third Failure

The built environment of the third failure site is shown in Figures 13, 14 and 24. Wind direction and probable jib location were determined based on video footages and photographs taken before and after the incident, see Figure 24.

The crane tower was in front of the building, facing the strong wind. The bottom of the jib was approximately 80 ft. above the completed structure. The buildings under construction and the nearby existing high-rise building interfered. The local surroundings created a complicated situation where the wind was not guided but accelerated in restricted areas. The local wind acceleration effects were extremely difficult to describe and to schematize. However, it is believed that the local building configuration made the wind accelerate in this restricted area. Therefore, wind speed and aerodynamic loads at the jib were expected to be elevated. The local turbulent wind had significant effect on the crane. This was proven by the construction camera photographs taken before the collapse of the crane, which showed that the crane rotated due to local turbulent winds, see Figure 25.

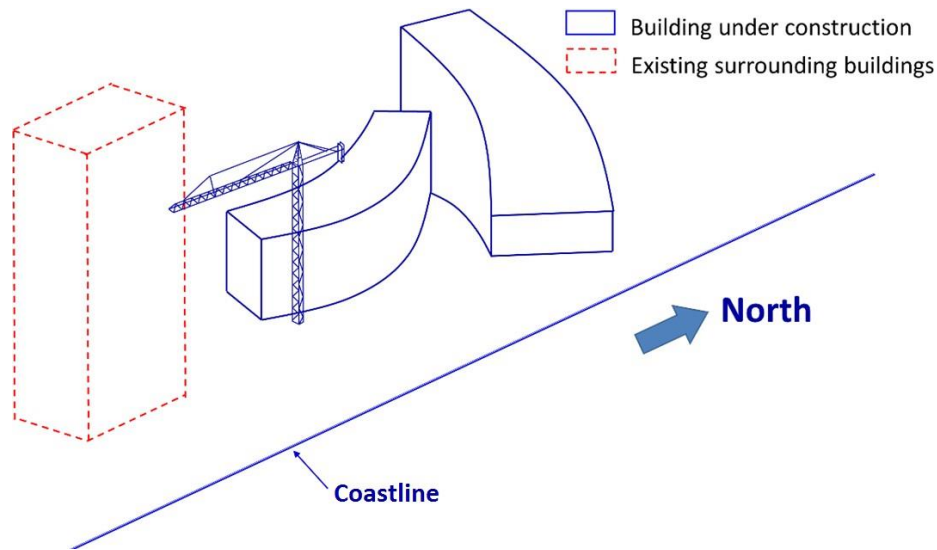


Figure 24 ISO view of the third failure site *

* Note: the lower crane behind the building is not shown in the figure. Refer the next figure for both cranes.

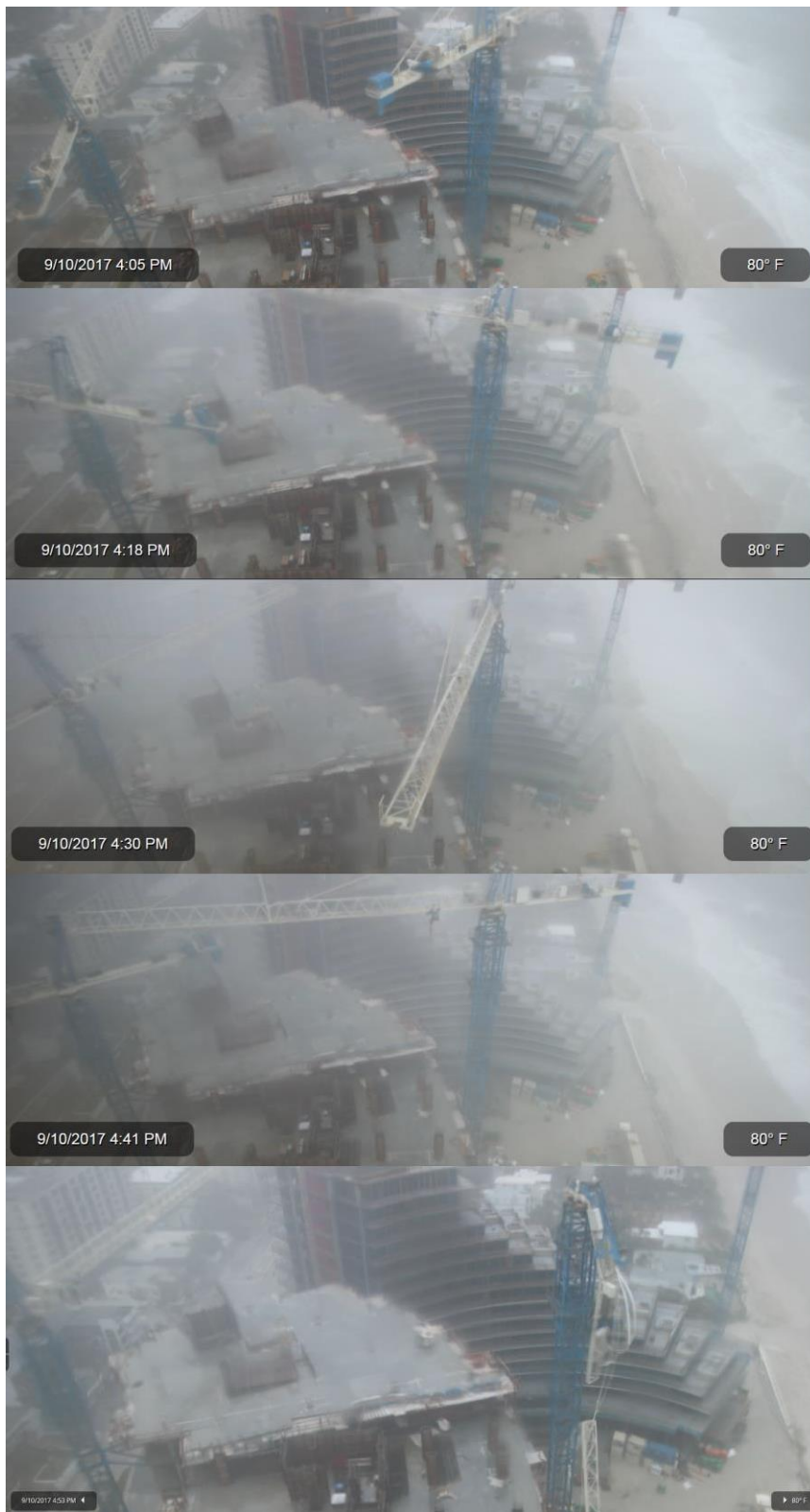


Figure 25 Spinning of the crane involved in the third failure
(Courtesy of OxBlue.com)

5.4 Actual Wind Loads

Wind data obtained from the National Weather Service was recorded at two locations—at Fort Lauderdale Executive Airport (about 5 miles from the coastline and the 3rd failure site) and at Miami-Opa Locka Executive Airport (about 9 miles from the coastline and the first two failure sites); see Appendix A.

As mentioned in previous sections, the tropical storm, with turbulent wind speeds of 40 to 70 mph and gusts near 80 mph, was observed in Miami. Since all three cranes were located on or close to the coastline, actual wind speed at the three failure sites could have been much higher than those captured at the airports miles away from the coastline. The anemometer towers are typically located at 33 ft. above ground level. The recorded wind speed at 33 ft. could be misleading, as the wind speed would be much higher at the jibs of the cranes; the crane was approximately 425 ft. tall at the first failure site, approximately 600 ft. tall at the second failure site, and approximately 200 ft. at the third failure site. Wind speeds at the jib elevations of the three cranes were obtained and tabulated below in Table 1, using the power law wind speed profile per ASCE7-10 for Exposures C and D.

Table 1 Wind speed at the jib elevations at the three failure sites

Site	Jib elevation, z (ft.)	Wind speed at 33 ft. above ground (mph)	Wind speed at z (mph)	
			Exposure C	Exposure D
1 st Failure	425	80	105	109
2 nd Failure	600	80	109	112
3 rd Failure	200	80	97	102

As mentioned in the previous section, the SK315 cranes were designed to withstand a maximum out-of-service wind speed of 95 mph. The masts and their connections to the structure and the foundation were designed for 175 mph, according to the notes provided in the drawings.

Other than increased wind speed, hurricanes often form tornadoes through the creation of well-organized thunderstorms and instability in the atmosphere, which combine to whip up the violently rotating winds. On the day of and the day before the incidents, witnesses described the natural

phenomenon as occurring near the beaches of Fort Lauderdale. The National Hurricane Center also issued warnings to the residents in South Florida that “heavy Squalls with embedded tornadoes” were “sweeping Across South Florida.” The National Weather Service (NWS) Doppler (NEXRAD) radar system at each radar site in Miami area estimated the intensity, position, velocity, and type of moisture in the atmosphere for the presence (or likelihood thereof) of various kinds of severe weather events. Numerous intense gate-to-gate azimuthal shear, associated with tornadic-scale rotation (a.k.a. Tornadic Vortex Signature (TVS)), were detected in the areas near the three incident sites. The maps of the TVS Overlay from the National Oceanic and Atmospheric Administration’s (NOAA) Severe Weather Data Inventory, an integrated database of severe weather records for the United States, were provided in APPENDIX B. No tornadoes formed at the three failure sites on September 10, 2017. However, localized high-altitude strong vortexes could have occurred at the three failure sites.

6. Observations of Collapsed Structure

Observations of the collapsed structures provided information on the failure mechanisms of the cranes. This information was correlated with the video footages captured prior to and when the cranes collapsed and was helpful in identifying the sequence of the failure. This information was also used in determining the cause of the failure.

6.1 Slewing Assembly

The slewing platform sits on the turning mechanism that consists of two concentric rings with bearing in between, as shown in Figure 26. The service platform sits on the inner slewing ring, and the outer slewing ring is mounted on the lower slewing ring support, as shown in Figure 27. Two motorized slewing gear drives rotate the outer slewing ring; therefore, the slewing ring drives the rotational movement of the slewing unit, including jib, counter-jib, cab, and tower top, as shown in Figures 26 and 27. The slewing rings have installation holes, external gear, lubricant hoses, and a sealed device. Each slewing gear drive consists of a motor, gears, and a gear brake.

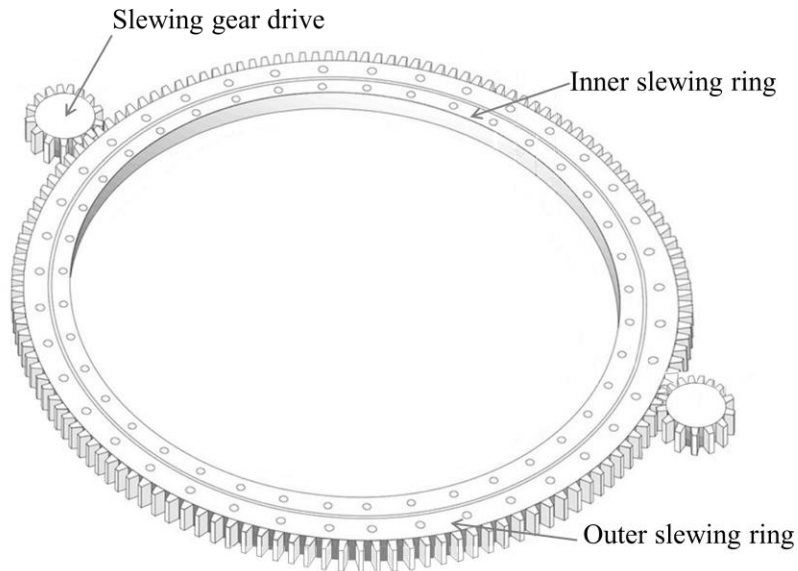


Figure 26 Slewing rings and gear drives

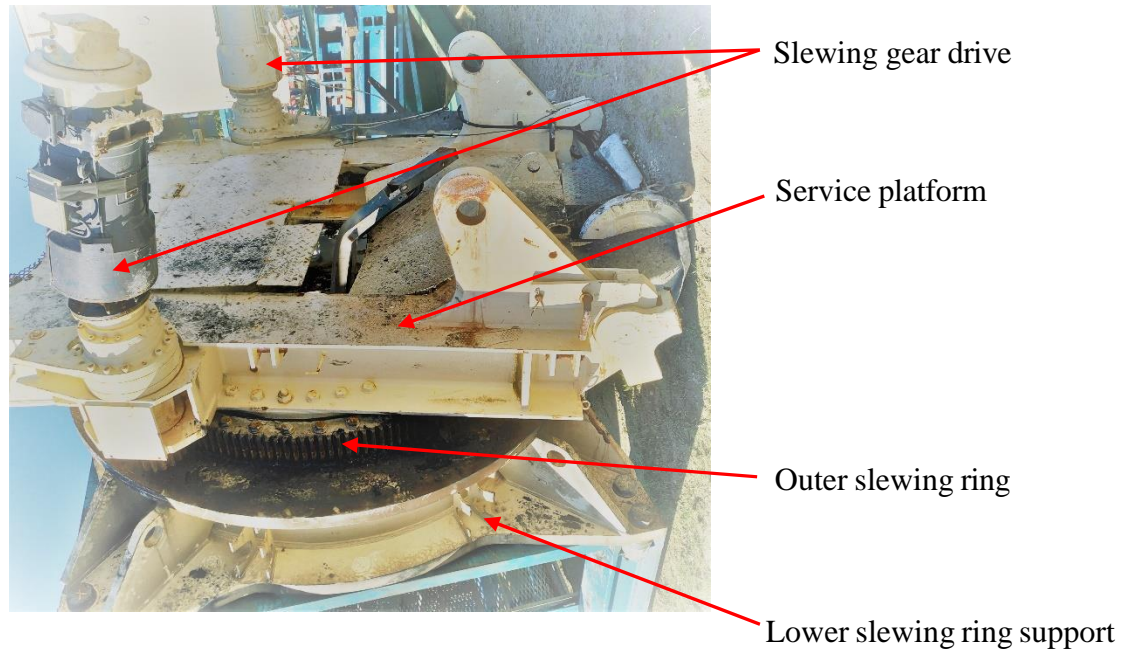


Figure 27 Slew assembly (the first failure)

The field observations of the slewing assembly focused on signs of worn slewing bearings, and on whether the slewing rings were greased and were set to weathervane as described in Section 3.2. Visual examination of the slewing bearings of the three cranes revealed that all three slewing bearings were greased, and no broken parts or missing teeth were found on the outer rings. Deadlock from debris of the slewing rings and possible jammed rings were not discovered. The wind release cases and the slewing gear brakes of the three cranes were also dismantled to verify that the cranes were set to weathervane and were able to revolve freely prior to the collapses. The disk brakes of the first and the third failure cranes were disassembled, since the wind release assemblies broke during the collapses. The brake linings of the two gear breaks had not worn down to the minimum thickness, and it was confirmed that the two cranes were set to weathervane prior to the collapses. The wind release assembly of the second failure crane was opened, and it was found that the flap was still in blocking position, which means the crane was set to weathervane.

6.2 Turntable and Jib Connections

6.2.1 The First Failure

The front part of the turntable, including the two bracket cradles, is shown in Figure 28. The jib bottom chord foots after the collapse are shown in Figures 29 and 30. It was observed in Figures

28 and 29 that the clamp of the left cradle bent vertically and, meanwhile, the left bottom jib chord foot remained intact.

The right bearing cradle and the right clamp remained intact. However, the right bottom jib chord broke at the weld between the bottom chord tube and the end plate, as shown in Figure 30. The field structural observation is consistent with the collapse of the crane shown in Figure 10. The left jib bottom chord detached from the left turntable cradle because the jib swayed to the right. Once the jib separated from the left turntable cradle, the jib was only supported at the right turntable cradle and the two jib pendants. As the jib continued rotating to the right, the right bottom chord foot broke at the weld between the tube and the end plate, and the jib started falling.



Left side jib foot



Right side jib foot



Figure 28 Jib foot bearing connections – turntable side (the first failure)

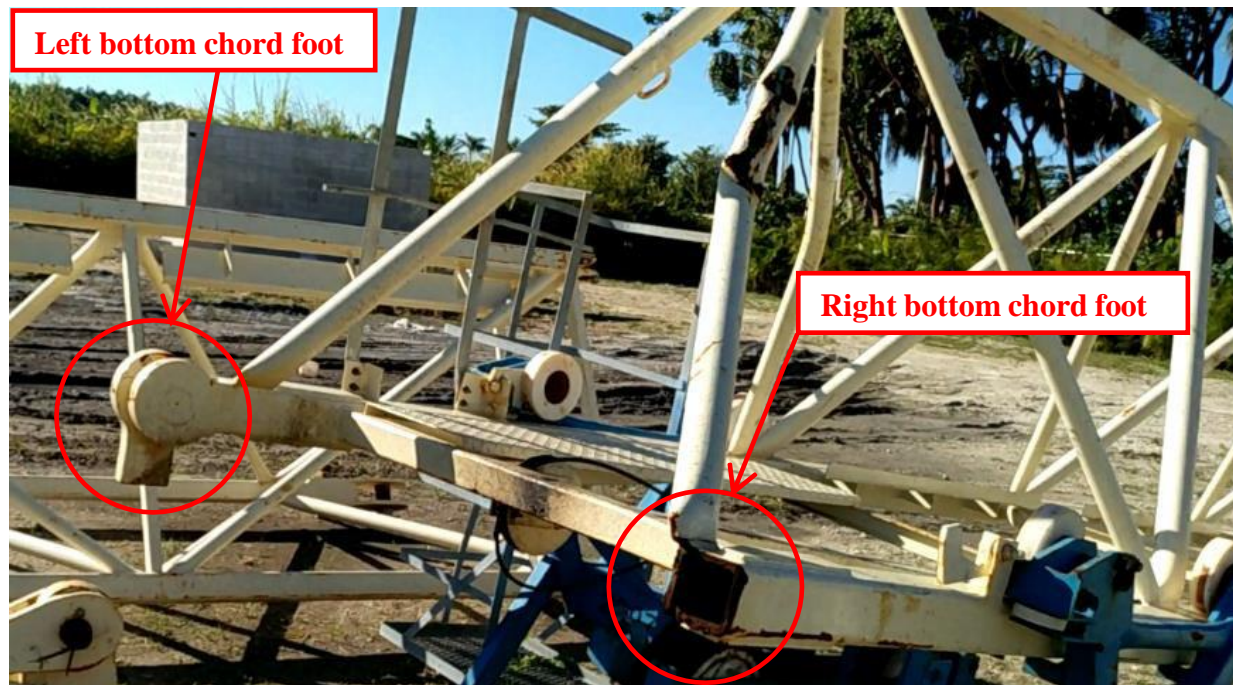
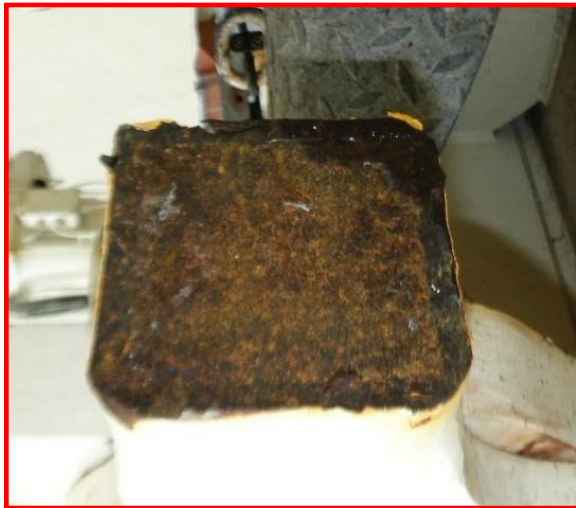
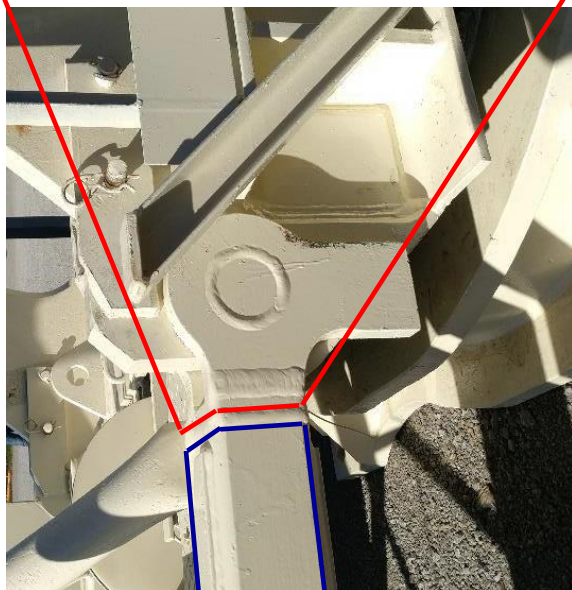


Figure 29 Jib foot bearing connections – jib side (the first failure)



Bearing plate side



Jib bottom chord side

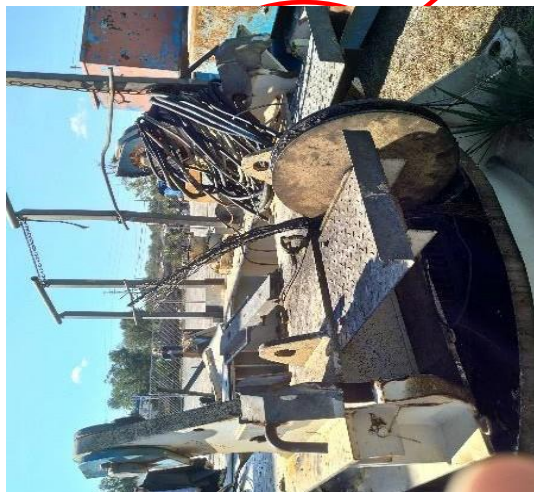
Figure 30 Right bottom chord end failure (the first failure)

6.2.2 The Second Failure

The front part of the turntable, including the two bracket cradles, is shown in Figure 31. The two jib bottom chord foots after the collapse are shown in Figure 32. It was observed in Figure 32 that the clamp of the left cradle bent vertically and meanwhile, the left bottom jib chord foot remained intact. The clamp of the right cradle bent upward and to the right, while the right bottom jib chord foot, including the end bracket, bent to the right, as shown in Figure 32. The field structural observation indicated that the left jib bottom chord detached from the left turntable cradle because the jib rotated to the right. As the jib continued rotating to the right, the right bracket cradle and the right bottom chord bent to the right till the right bottom chord detached from the right bracket cradle. Per the field observations of the damaged structures the failure modes of the first two cranes' jibs are identical.



Left side jib foot



Right side jib foot



Figure 31 Jib foot bearing connections – turntable side (the second failure)

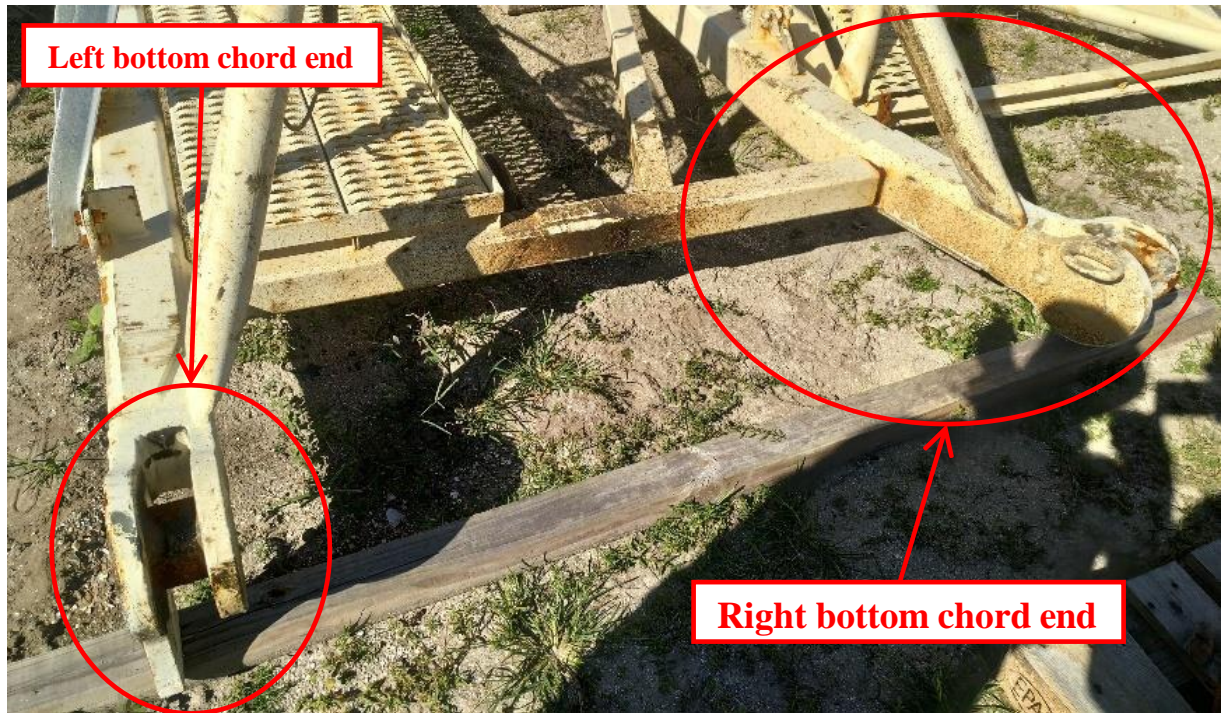


Figure 32 Jib foot bearing connections – jib side (the second failure)

6.2.3 The Third Failure

The front part of the turntable, including the two bracket cradles, is shown in Figures 33, 34, and 35. The two jib bottom chord feet after the collapse are shown in Figure 36. It was observed in Figures 33 to 35 that the clamp of the right cradle bent vertically and, meanwhile, the right bottom jib chord foot remained intact. The clamp of the left cradle bent upward and to the left, while the left bottom jib chord foot remained intact, as shown in Figure 36. The field structural observation indicated that the right jib bottom chord detached from the right turntable cradle first because the jib rotated to the left. As the jib continued rotating to the left, the left bracket cradle bent to the left until the left bottom chord detached from the left bracket cradle. According to field observations of the broken structures, the failure modes of the three cranes' jibs are similar.



Left side jib foot



Right side jib foot



Figure 33 Jib foot bearing connections – turntable side (the third failure)



Side view

Front view

Figure 34 Left cradle and clamp (the third failure)



Side view

Front view

Figure 35 Right cradle and clamp (the third failure)

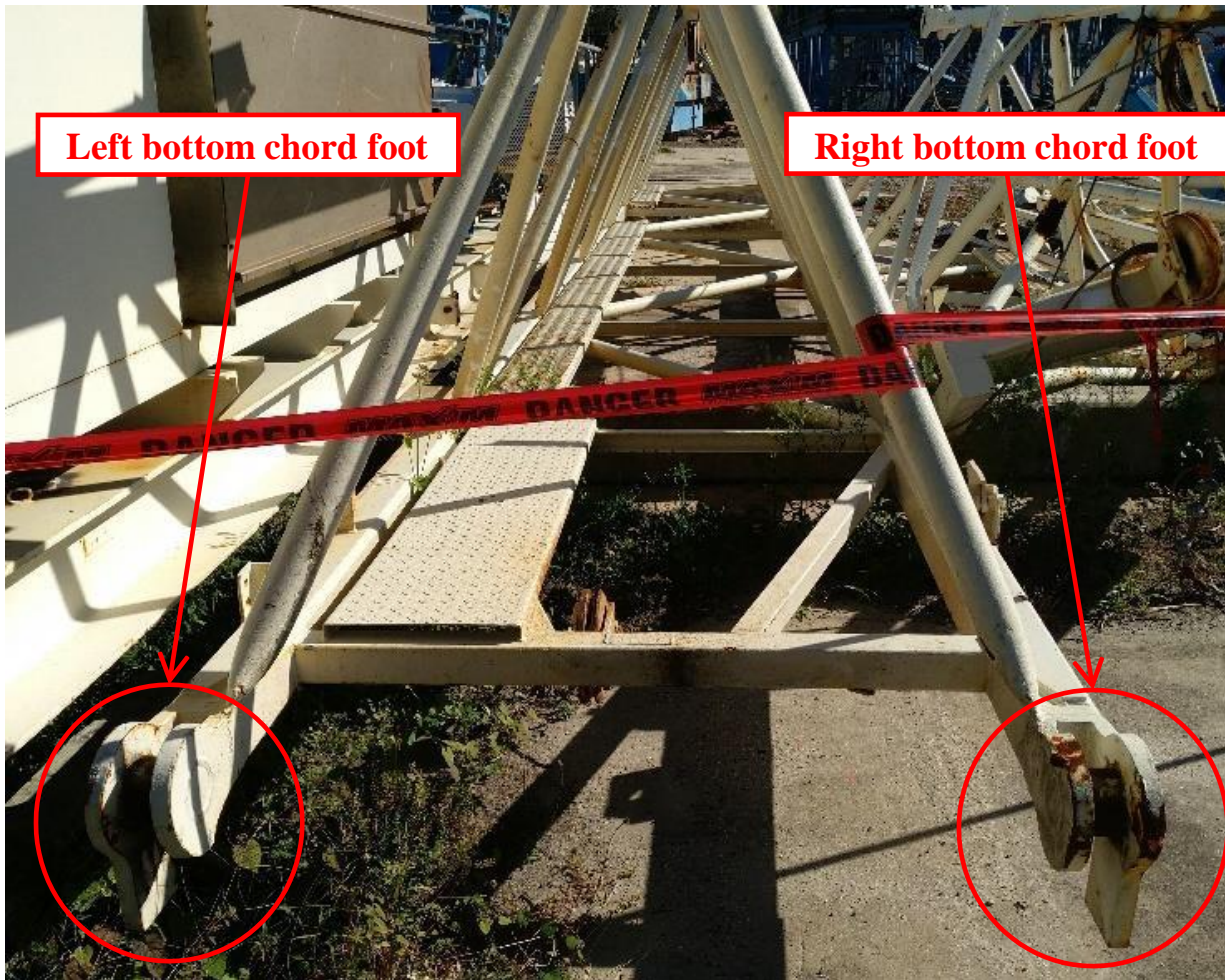


Figure 36 Jib foot bearing connections – jib side (the third failure)

6.3 Tower Top and Counterjib Failures

Figure 37 shows the collapsed tower tops from the three failures. All three tower structures bent 90 degrees toward the counterjib. The two tower top columns toward the counterjib bent at approximately mid-height between the top pin and the brace. Considering the crane tower failure of the first incident as shown in Figure 10, it is believed that the tension forces at the tower apex from the two jib pendants disappeared suddenly due to the falling of the jib, and the tower was only loaded from the counterjib pendants. Therefore, compression forces in the two columns on the counterjib side were elevated rapidly, and the two columns failed under the transient forces.



(a) The First Failure

(b) The Second Failure

(c) The Third Failure

Figure 37 Tower tops of the three cranes after the collapses

6.4 A-frame and Pendants

The A-frames of the cranes involved in the first two failures remained intact after the collapses. The two posts of the A-frames remained straight after the collapses, and no bend in the posts could be detected. The A-frame of the crane involved in the third failure was found deformed: the right hand post bent at about the mid-height. It is not clear if the post bent when the jib was falling.



The First Failure



The Second Failure



The Third Failure

Figure 38 A-frames of the three cranes after the collapses

6.5 Summary of Observations

The following summarizes the footages and photographs taken prior to and during the collapse of the cranes and the field observations of the collapsed structures:

1. No obstacles at the construction sites were found that could collide with the jibs, counterjibs or counterweights. Safety distance of at least 7 ft. as required by the operating manual was maintained.
2. Prior to the storm, the cranes were lowered by two tower sections.
3. The maximum height of the tower cranes above the uppermost tie-in was less than the maximum allowable free-standing height of the cranes.
4. Turntable slewing and swing lock mechanisms of the three cranes were inspected. The slewing ring and teeth remained intact and were lubricated. The swing lock mechanisms were at a working condition. No signs were detected showing that the swing lock pads were engaged prior to the collapses of the cranes. Evidence indicates that the three cranes were set to weathervane and were able to spin freely prior to the collapses.

5. All three crane towers remained intact after the collapses. Other than the cantilever beams that bent downward due to the falling of the counterweight ballasts, the three turntables remained intact after the collapses.
6. All sections of the three jibs remained connected after the collapses.
7. In the first two failures, the left bottom jib detached from the left cradles of the turntable first. Then, the jibs rotated to the right to either break the weld between the tube and end bracket in the first failure, or to bend the right bottom jib chord foot and the cradle in the second failure. Finally, the jibs detached from the turntable and started falling.
8. In the third failure, the right bottom jib detached from the right cradles of the turntable first, and the jib rotated to the left to bend the left cradle. Then, the jib detached from the turntable and started falling.
9. The A-frames of the tower cranes involved in the first two failures remained intact after the incidents, while the A-frame involved in the third failure deformed. It is not clear if the deformation of the A-frame was due to the falling of the jib.
10. Once the jib started falling, the two jib pendants were released. The forces on the tower top apex from the jib pendants decreased from the maximum to zero in a short time. The two tower top columns toward the counterjib failed because of the transient load change on the tower top. The failure modes of the two columns were identical in the three failures.

7. Analysis and Discussion

7.1 Introduction to Structural Analyses

To determine the probable causes of the three crane failures, comprehensive structural analyses were carried out, including static analyses, modal analyses, and dynamic analyses.

Three-dimensional (3D) finite element computer models were developed for each of the three cranes, including 1) one solid model of the clamp; 2) three models of the crane jibs with different length; 3) one model of the crane tower top; and 4) three combined models, including crane jib, counterjib, and tower top. The linear elastic program includes beam and plate elements and is capable of performing dynamic analyses, such as mode analysis and time history analysis.

In all three crane failures, the crane jibs were detached from the turntables in a similar manner: the turntable cradle clamps bent due to the tensile force the jib bottom chord. Therefore, static analyses were carried out first to determine the maximum load capacity of the connections between the turntable and the jib bottom chord.

The crane masts were properly anchored to the buildings at different floors and were found intact after the incidents. The jib and the tower top were pinned to the turntable. Since the mast and the turntable were supposed to be rigid bodies compared to the jib and the counterjib, their deformations could be neglected. Moreover, only the structures above the turntable collapsed. Based on the video footages of the first failure, no significant rocking or movement was detected in the crane mast when the jib started falling. Therefore, only the mobile part of the cranes, including jib, counterjib, and tower top, were considered in the following dynamic analyses.

Modal analysis is a study of the dynamic properties of systems in the frequency domain. Results from the modal analyses would assist in understanding structural behavior under vibrational and transient excitation. The crane's mobile part, including tower top, jib, and counterjib, has the tendency to vibrate at certain frequencies, called *natural* or *resonant* frequencies. Each natural frequency is associated with a certain shape, called *mode* shape, which the model tends to assume when vibrating at that frequency. When a jib structure is properly excited by a dynamic load with a frequency that coincides with one of its dominant frequencies, the structure undergoes large

displacements and stresses. Therefore, modal analyses were performed first on the three models of the cranes.

During the windstorm, the rotating parts of the crane were set free to rotate. If the wind direction and magnitude were fairly constant, the cranes would stay in the wind mean direction and would follow the low frequency fluctuations or the cranes would be in a tailwind condition. The jib fluctuated, and the counterweights of the jib were able to equilibrate the aerodynamic loads. However, during a hurricane or a strong tropical storm in an urban area with numerous high-rise and low-rise buildings, it is exceedingly difficult to determine local wind directions and speeds. The transient wind is critical to tall cranes in an urban area. Hence, dynamic analyses were carried out to study the structural response of the tower cranes, especially the jibs, to the excitation of the impulsive wind when the directions and magnitude could change rapidly. Transient aerodynamic load-time histories were constructed to represent possible impulse wind loads that could act on the jibs. Both vertical and lateral excitations on the jibs were studied.

The two tower top columns toward the counterjib failed in a similar manner in all three failures. The two columns bent at approximately mid-height between the top pin and the brace. Therefore, the tower tops were analyzed to determine the maximum compressive stresses in the two columns toward the counterjib, while the tension loads at the apex of the tower top from the jib pendants were suddenly reduced to zero and the towers were only loaded from the counterjib side.

7.2 Design Out-of-Service Condition – FEM 1.001 and 1.005

The design loads associated with the slewing of a crane's turntable, jib, counterjib, and other components, such as jib-turntable connections, tower top, and pendants, include:

- a) The friction moment from the slewing ring (Section 5.1, FEM 1.005).
This is the maximum friction moment from the slewing ring to guarantee weathervaning for 25 mph.
- b) The inertia effect due to slewing (Section 2.2.3, FEM 1.001).
This can be calculated in terms of the value of the acceleration and the mass of a structural component. According to FEM 1.001, the calculation shall be based on the accelerating torque applied to the motor shaft of the mechanisms for slewing

motion. For a normal crane, the rate of acceleration between 0.33 ft/sec^2 and 2.0 ft/sec^2 may be chosen for the acceleration at the jib head so that an acceleration time of from 5 to 10 seconds is achieved.

- c) The effect of centrifugal force (Section 2.2.3, FEM 1.001).

According to Section 2.2.3.2, FEM 1.001, the centrifugal force due to slewing shall be included in the design of jib cranes. In practice, it is sufficient to determine the horizontal force exerted at the jib head as a result of the inclination of the rope carrying the load and, in general, to neglect the effects of centrifugal force on the other elements of the crane. However, it is not clear whether centrifugal forces due to slewing should be included in the structural analysis when a jib crane is rotating without carrying any payload.

7.3 Static Analyses

7.3.1 Turntable Cradle Clamp Force

The turntable cradle clamp was modeled using 3d solid element in Staad Pro, as shown in Figure 39. Force was applied at the tip of the clamp to simulate the pulling of the pins on the bottom jib chord foot. The material grade for the clamp was S355J2G3, with a yield stress of 52 kilopounds per square inch (ksi). A minimum pulling force from the bottom jib chord pin to yield the clamp steel was determined to be 32 kips. It is noted that the existing clamp design is not able to secure the jib foot from separating, once the force from one jib bottom chord exceeded 32 kips. No design calculation or analysis documents or proof loading test results were made available to OSHA. Further evaluation could be required.

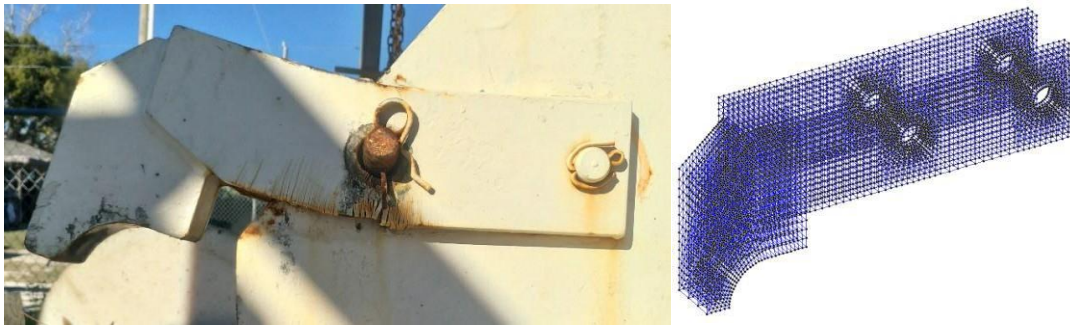


Figure 39 Turntable cradle clamp and 3D solid model

7.3.2 Jib Foot Reactions

The jib sat on the two cradles of the turntable at the end, and was suspended from two pendants. The directions of the stationary forces exerted on the turntable cradles are shown in Figure 40. The magnitudes of the forces are tabulated in Table 2.

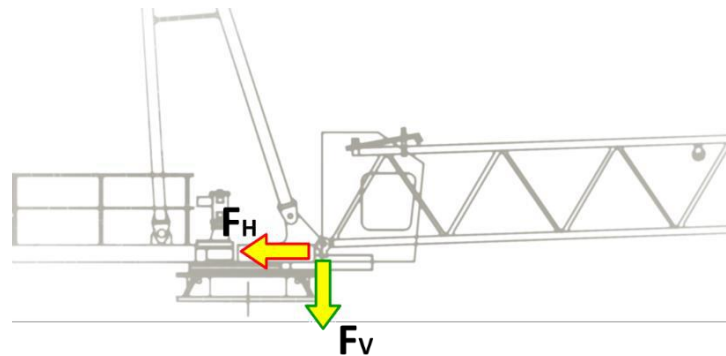


Figure 40 Jib foot loads on turntable – side view

Table 2 Jib foot loads due to self-weight of jib

	1 st failure (VICE)	2 nd failure (PLAZA)	3 rd failure (Auberge)
Jib length	181' - 0"	148' - 0"	131' - 0"
F_H	28.0 kips	20.0 kips	16.0 kips
F_V	3.0 kips	2.7 kips	2.5 kips

According to FEM 1.005, the minimum wind load to overcome the frictional moment from the slewing ring is 25 mph (40 kilometers per hour). Considering the diagrams showing in Figure 41, the coupling forces, F_{H_wind} , in the two bottom jib chord feet, where the jib was mounted to the turntable, due to the horizontal steady-state wind pressure, were determined for the three cranes, as tabulated in Table 3.

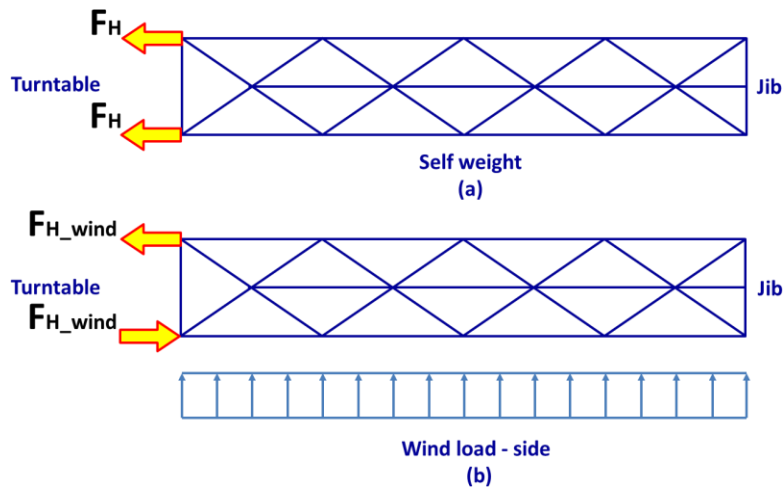


Figure 41 Jib foot loads on turntable – plan view

Table 3 Jib foot loads due to the minimum lateral wind to rotate the turntable

	1 st failure (VICE)	2 nd failure (PLAZA)	3 rd failure (Auberge)
Jib length	181' - 0"	148' - 0"	131' - 0"
Speed, steady-state wind	25 mph	25 mph	25 mph
F_{H_wind}	8.8 kips	5.9 kips	4.6 kips

7.4 Dynamic Analysis of Jib

7.4.1 Impulse Wind Effect on Tall Tower Cranes

Wind is observed as a phenomenon with a constant effect because of its large period of oscillation (sometimes refer to the term low frequency), such that it has been considered as a constant load in civil-engineering design, or static and quasi-static analyses. In previous studies and design practices related to tower cranes, the tower crane model, including both crane mast and mobile parts, had one degree of freedom. The mobile parts were fixed in the wind direction, and the only degree of freedom was the overturning angle around the tipping point. The objective was to characterize the influence of gust duration on overturning risk. In a natural turbulent wind without any environmental effect, the mobile part of the crane moves automatically in the wind direction.

It is commonly accepted that the penetration in the crane components and the continuous motion of the rotating part that alleviates critical vibratory phenomenon are additional justification to neglect dynamic effects, and to consider only the direct quasi-steady wind loads in the analysis of the overall stability of the tower crane.

However, the impact of a hurricane or strong local vortex tornado on tower cranes could directly endanger their integrity and stability. The gusts of strong wind frequently lead to galloping oscillations, resonance, and collapse of structures. During the storm, the two cranes involved in the first and the second failures were found in the tailwind condition, and the one involved in the third failure was found rotating. This is primarily because the first two cranes were the tallest structures in the construction sites and were isolated from the surrounding structures without any wind disturbances produced by the surroundings. However, the third crane rotated because of the surroundings, and the wind flow around the tower crane exhibited unexpected and dangerous aerodynamic phenomena.

The wind force may be divided into two components—the horizontal and the vertical. The horizontal component of the force is induced by the vortexing of air in the vicinity of the jib. Contrary to that, the vertical component of the wind load occurs due to the air flow with the relative speed. The vertical force component could lead to the galloping vibration effect on the observed machine. For example, galloping crane hook was observed in the video of the first collapse.

Therefore, to determine the probable causes of the three incidents, both upward and lateral transient wind loads were considered applied on the jibs at 90 degrees to represent the possible situations where crane jibs were hit by a strong vortex or impulse wind, as shown in Figures 42 and 43. In contrast to typical design practices—which considered a complete crane, including mast, tower top, jib and counterjib, to evaluate its stability and integrity—only the dynamics effects of the jib introduced by the sudden rise in wind speed (or pulse effect) were examined in this study.

It should be noted that the two analytical conditions in this section are beyond the design usual practice and are served as a study to determine the probable causes of the three crane collapses. The effects of transient wind on tower crane structures, especially on crane jibs, are not usually included in the structural design of tower cranes.

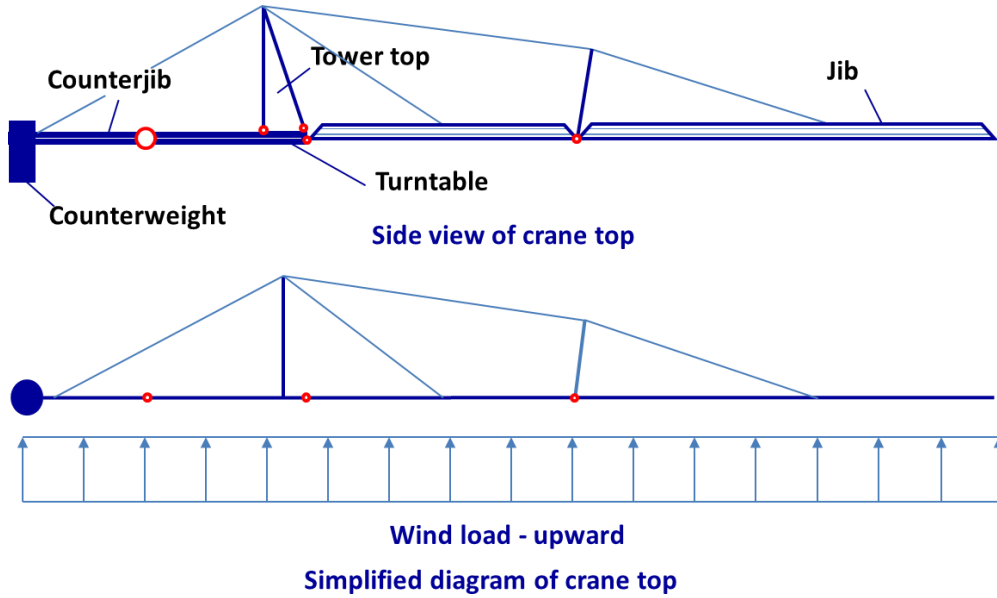


Figure 42 Tower crane top under upward transient wind

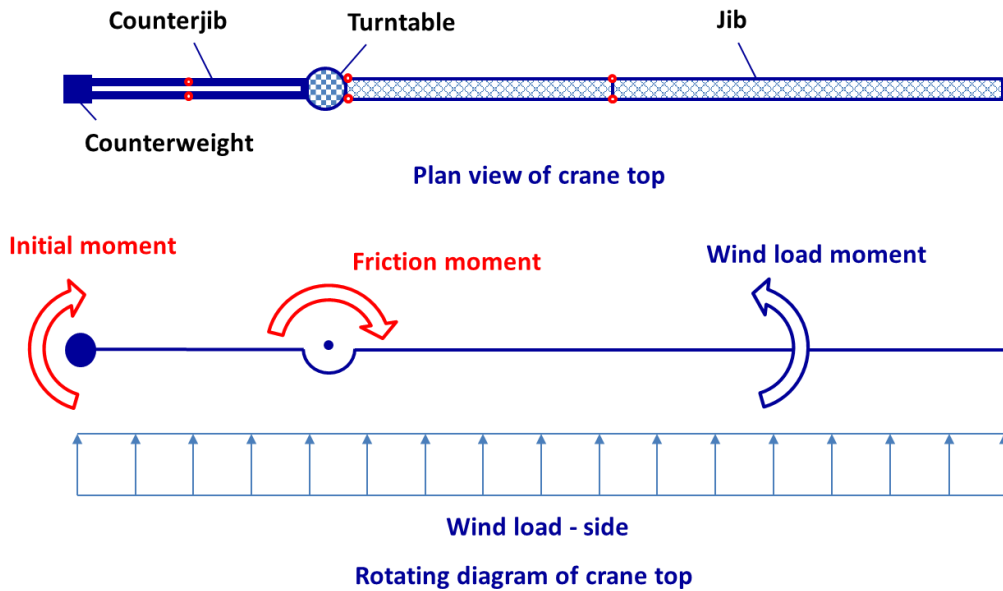


Figure 43 Tower crane top under lateral transient wind

7.4.2 Mode Analysis of Jib

The 3D structural models of the three cranes, including the tower top, jib and counterjib, were developed as shown in Figure 44.

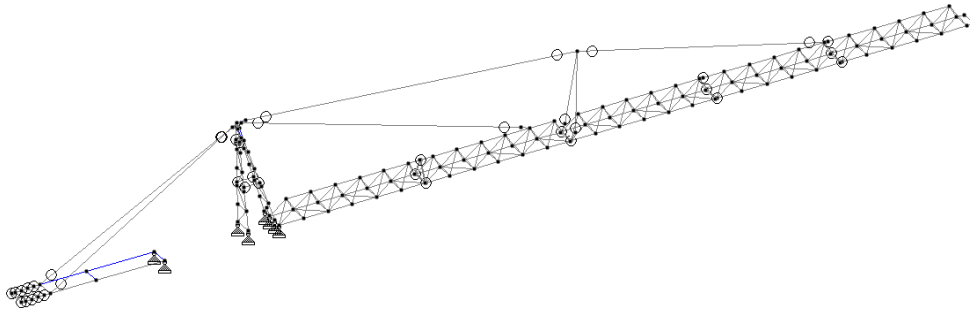


Figure 44 3D structural model of the mobile part of the crane (1st failure crane)

It was found that the dominant modes of the crane mobile parts included both transvers swaying of the jib and vertical shaking of the jib and counterjib, as shown in Figure 45.

The first three dominant modes in both transvers and vertical directions and corresponding frequencies of each crane are tabulated in Table 4. The effective mass participation factor provides a measure of the energy contained within each resonant mode, since it represents the amount of system mass participating in a particular mode. A mode with a large, effective mass is usually a significant contributor to the response of the system to dynamic excitation.

Table 4 Dominant modes of the mobile part of the three cranes

	Transvers Direction			Vertical Direction		
	Mode No.	Frequency (Hz)	Participation Factor (%)	Mode No.	Frequency (Hz)	Participation Factor (%)
1 st failure	9	3.819	53	4	1.354	81
	1	0.466	14	10	4.349	6
	22	12.083	10	7	3.033	2
2 nd failure	8	3.906	52	4	1.423	82
	1	0.67	13	10	4.516	6
	22	14.329	10	15	8.956	2
3 rd failure	6	4.051	52	4	1.462	82
	1	0.759	11	8	4.39	6
	22	14.341	11	17	10.466	3

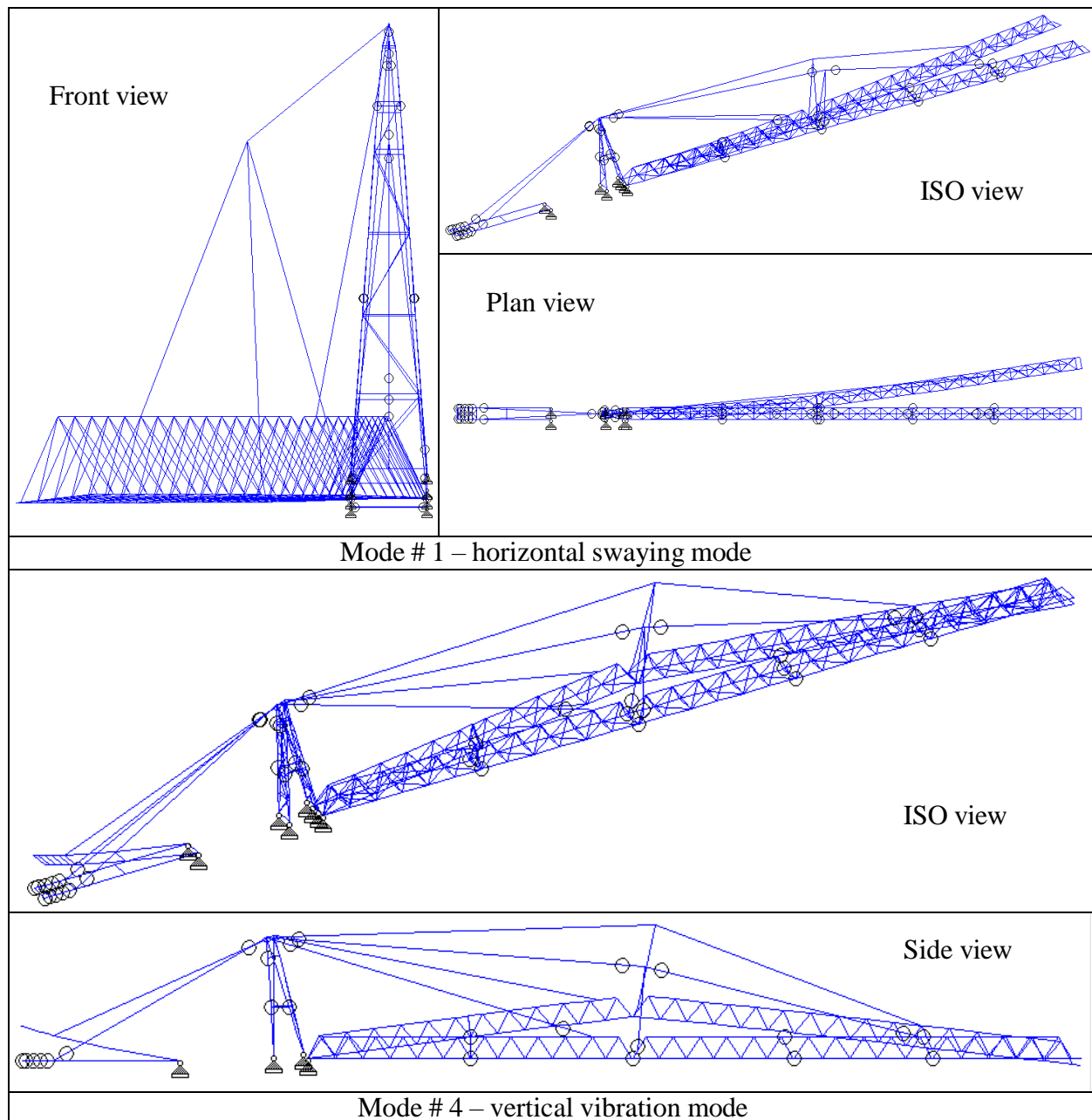


Figure 45 First two dominant modes of the crane mobile parts (1st failure crane)

The wind speed fluctuates in all the frequencies between 0.0005 and 5 Hz. The first two dominant modes of both horizontal and vertical vibrations of the three cranes were within the frequency range of the typical frequencies of a wind. Therefore, the choice of the impulsive wind frequencies in this study aims to study the middle-range wind frequencies in a scale from 0.5 to 1.5 Hz, excluding the extremes of very low or very high frequencies.

As mentioned previously, the cranes involved in the first two collapses were in tailwind condition prior to the collapses; and, for the third failure, jib rotation speed prior to the collapse was not known. Whether the rotational frequency is able to excite the jib structure's natural modes, especially the transverse mode, as shown in Figure 45, is not clear.

7.4.3 Upward Transient Wind Load

The upward wind load is not included in current design criteria. However, upward wind load applied on tower crane jib is likely to happen, especially in an urban area or during a windstorm or hurricane. When the upward wind is strong enough, the wind may lift the jib up. The tower top is only loaded from the counterjib side since the jib pendants become unloaded. When the wind disappears, the jib falls, and a dynamic load will be applied on the jib pendants, A-frame, and the tower top. This analysis was performed on the crane involved in the third failure in Section 7.4.5 since the A-frame of the tower was found deformed. Due to the non-stationary and highly transient upward wind, the dynamic response of a crane jib could be different from the static one.

A time-force function representing a harmonic gust of wind was developed based on sinusoidal forcing function. The frequency of the gust was close to the frequency of the first dominant vertical mode of the crane mobile parts as discussed in the previous section. To simulate the possible rapidly increasing upward wind load acting on the bottom chords of the jibs, a short ascending part of the forcing function was adopted as the transient wind force in the dynamic time history analysis. The total duration of the force was one second. Dynamic time-history analyses were then carried out on the three 3D models as used in the mode analyses. The dynamic analysis results indicated that when a crane jib was loaded from the bottom in a very short period by a transient wind load, the load from both jib bottom chords changed the direction. In other words, the jib could detach from the turntable if the upward transient wind load was high enough.

7.4.4 Horizontal Transient Wind Load

In current design practices, the wind load is considered to be applied horizontally from any direction, and the wind is considered at a constant velocity. There is a static reaction to the wind loads it applied to the crane structure, including the jib (FEM 1.001). This is true when the wind is stationary. Since the crane jib is gradually loaded by the horizontal wind, the wind load moment

is able to overcome the frictional moment to rotate the turntable, see Figure 43. During this process, the rotational acceleration is very small, and the initial effects due to the mass of the counterweight and other rotational components are limited. However, if the wind load is transient, pulse effect must be considered. When the transient wind strikes the jib, the inertial moments due to the mass of the counterweight and other rotational components, as well as the friction moment, would resist the rotation of the turntable due to the horizontal wind. The equation of motion of the rotating part of the crane is given as:

$$I\dot{\theta} + \mu_{Friction}\theta = T_{wind}(t)$$

In this equation $\dot{\theta}$ and θ are jib angular rotational speed and acceleration, respectively, I is the mass moment of inertia of the whole mobile part about its rotating vertical axis, $\mu_{Friction}$ is the friction coefficient between the turntable slewing ring and gears, and $T_{wind}(t)$ is the instantaneous aerodynamic torque acting on the jib (only consider aerodynamic load on the jib).

The magnitude of the dynamic moment on the jib, including the initial moment ($I\dot{\theta}$) and the friction moment ($\mu_{Friction}\theta$), depends on the angular acceleration of the turntable ($\dot{\theta}$), or the acting time duration of the wind load. Therefore, the jib foot reactions, as discussed in Section 7.3.2, under transient horizontal wind load may be increased due to the dynamic response of the jib structure, compared to the static case. For a short period after application of the transient wind load on the crane jib; the turntable may remain still due to inertia effect. Therefore, it is reasonable to perform a time history analysis on the mobile part of a tower crane, including crane jib, counterjib, counterweight and tower top, where a transient horizontal wind load acts on the jib only, while the complete system remains still.

Similar to the time-history analyses on the crane mobile parts under the upward wind, a time-force function representing a horizontal harmonic gust of wind was developed based on sinusoidal forcing function. The frequencies of the gusts for the three cranes were from 0.5 to 1.0 Hz as discussed in Section 7.4.2. To simulate the possible rapidly increasing lateral wind load acting on the side face of the jibs, a short ascending part of the forcing function was adopted as the transient wind force in the dynamic time history analysis. The total duration of the force is one second. The results from this transient analysis indicate that the tension load at the bottom jib chord foot increased significantly compared to the force found from the static analyses in Section 7.3.2. It is

confirmed that under the transient horizontal wind, the windward side bottom jib chord would detach from the turntable cradle in a very short period if the wind speed were 80 mph or more.

7.4.5 Jib Dropping due to Upward Wind

Static analyses were conducted to determine the minimum vertical wind speed to overcome the self-weight of the front part of the jib involved in the third collapse, and the minimum wind speed is about 173 miles per hour. Then, impact loads in the front pendants and the two posts of the A-frame were determined by assuming the front part of the jib as a rigid body dropping from different heights. It was found that the pendants and the A-frame would fail due to the impact force of the dropping of the front part jib if the front part of the jib were lifted up about 2° ($\alpha=2^\circ$ in Figure 46).

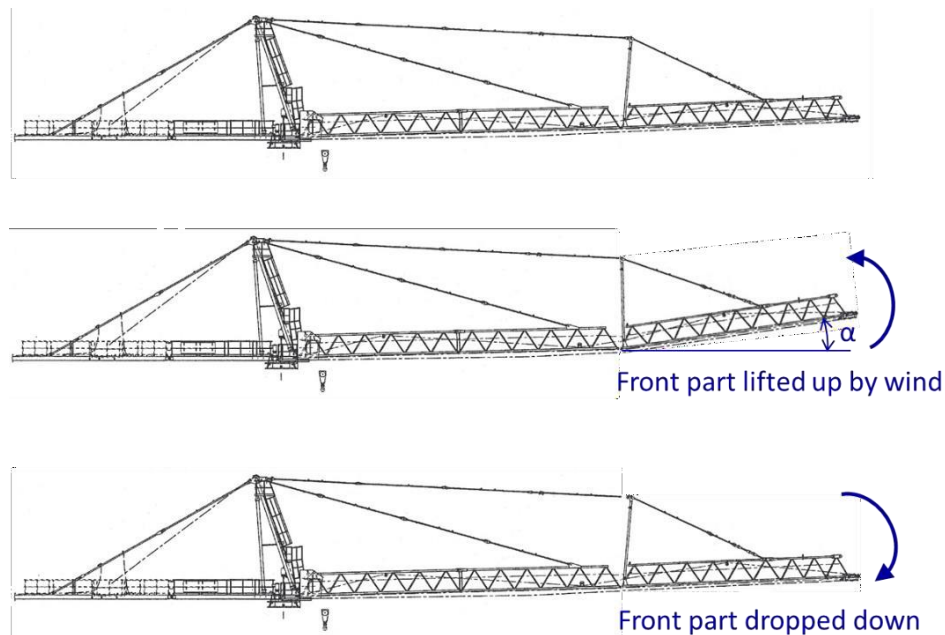


Figure 46 Front jib dropping failure

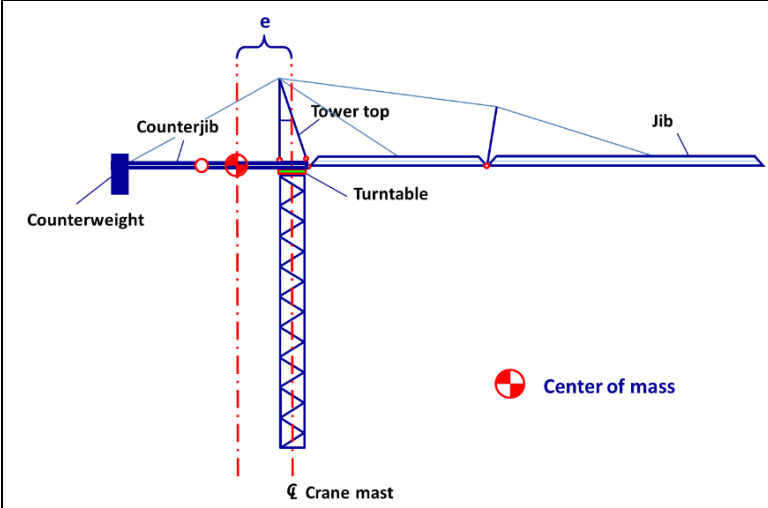
Therefore, it is possible that the front part of the jib involved in the third collapse was lifted by a strong vertical wind when the wind disappeared the jib section dropped down, and a significant impact force acted on and failed the A-frame. Once the jib started swaying to the side due to unbalanced suspension forces, the collapse of the jib, counterjib and tower top occurred.

Since the A-frames of the first two collapse were found intact after the collapses, the probable cause discussed in this section is only applicable to the crane involved in the third failure.

7.5 Design Conditions of Tower Top

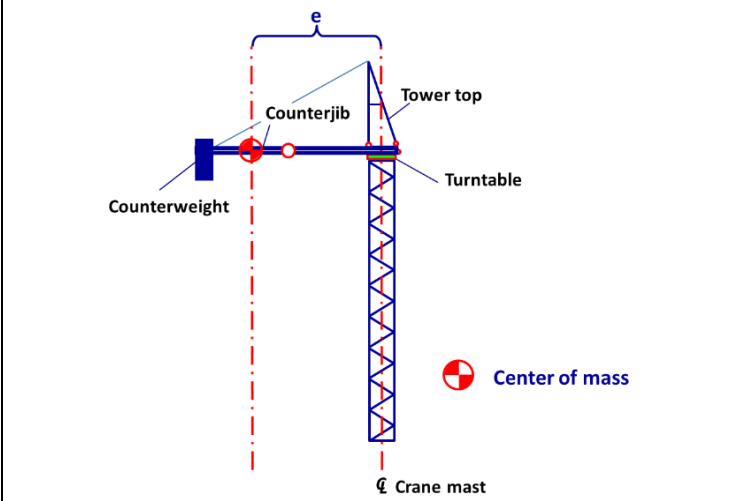
The centers of mass of the crane top, including jib, turntable, tower top and counterjib of the three cranes were located at the counterjib side. Locations of the center of the mass of the three cranes without any payloads are summarized in Table 5. The two columns of the crane tower top on the counterjib side were under compression if the cranes were set out-of-service or without any payloads. The maximum compressive load (F) and compressive stress (σ) in the two columns are tabulated in Table 5. When the tower top is statically loaded from the counterjib side only, the compressive loads in the two tower columns toward the counterjib increased as tabulated in Table 6.

Table 5 Loading conditions of the counterjib side tower top columns – out-of-service

		1 st Failure	2 nd Failure	3 rd Failure
	e (ft.)	22	25	27
	F (kips)	115	119	119
	σ (ksi)	22	23	23

The material grade for the columns was S355J2H, with a yield stress of 52 ksi. The governing critical load for the buckling was 984 kips on the major axis. This critical load would cause uniform stress of 197 ksi, which exceeded the yield stress of the steel (52 ksi), and the two columns would yield before buckling. Therefore, dynamics analyses are necessary to determine the possible failure mode of the tower top under transient loads, as provided in the following section.

Table 6 Loading conditions of the counterjib side tower top columns – without jib

		1 st Failure	2 nd Failure	3 rd Failure
	e (ft.)	59	58	58
	F (kips)	207	177	167
	σ (ksi)	40	34	33

When the tower top is loaded from the counterjib only, the maximum compressive stress in the two columns toward the counterjib is about 77% of the yield strength of the steel for the crane involved in the first failure, and about 65% for the crane involved in the second failure and 63% for crane involved in the third failure.

7.6 Tower Top Failure under Transient Loads

As discussed in previous sections, the jib pendants were released in a short period due to the falling of the jib once it detached from the turntable. Per the video footage taken at the first failure site as discussed in Section 4.1, the time duration of the entire process could be less than 0.1 seconds. Dynamic time history analyses were carried out on 3D frame model of the tower top only, as shown in Figure 47. A linear time-history function to simulate the sudden disappearance of the pendant tension from the jib side was adopted in the analyses, as shown in Figure 47. Results indicate that the two tower top columns towards the counterjib side were overstressed and failed due to the sudden release in tension in the jib pendants. The maximum combined compressive stresses in the upper sections of the two columns toward the counterjib are 63 ksi for the crane involved in the first failure, and 59 ksi for the cranes involved in the rest two failures.

The diagram of the governing bending moment in the upper sections of the two columns toward the counterjib is shown in Figure 48. It is found that the maximum compressive stress occurred at

the side of the column section toward the jib. The deformed columns of the tower top toward the counterjib are consistent with the bending moment diagrams, as shown in Figure 48.

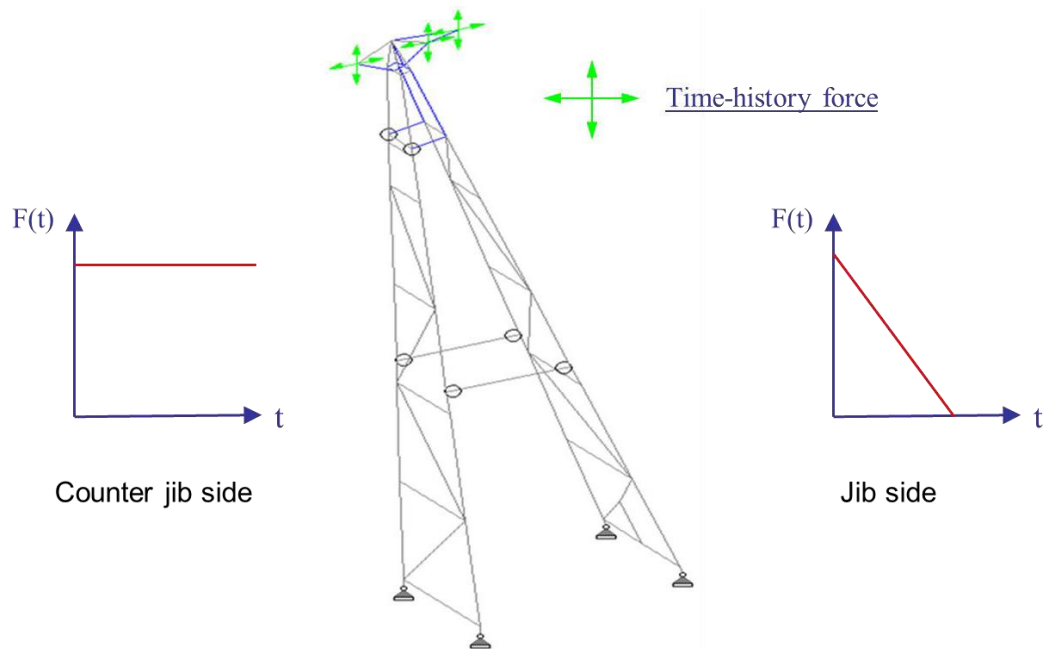


Figure 47 Frame model of tower top for dynamic analysis

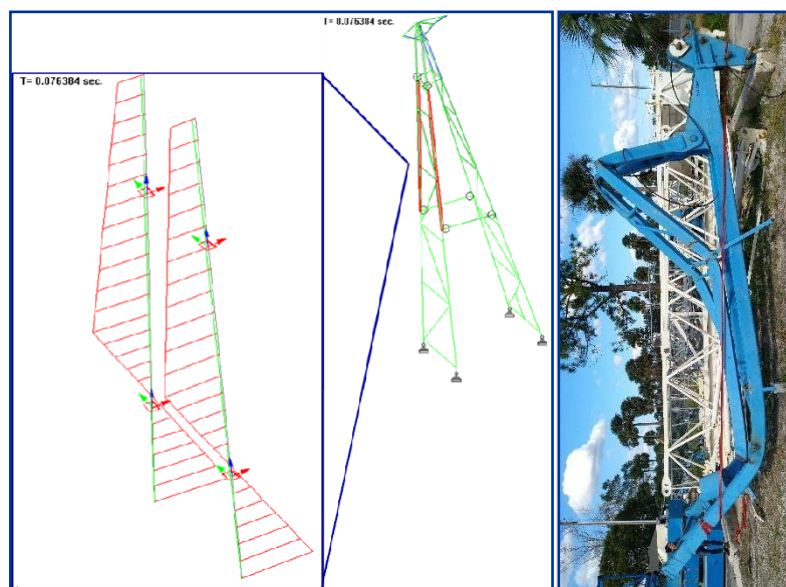


Figure 48 Strong axis bending moment diagram of the columns vs. deformed columns

7.7 Failure Scenario

The ultimate cause of the collapses, as indicated by the structural analysis in this section and video footage shown in Section 3, was the detachment of the crane jibs from the crane turntables. The video footage captured at the first failure site indicated that first, the left bottom chord of the jib disengaged from the left cradle on the turntable. The entire jib swayed to the right, and the right bottom chord of the jib then disengaged from the turntable. Once the jib separated from the turntable and started falling, the tower top could either be loaded from both the counterweight and the falling jib or the counterweight alone. The observation of the collapsed structural members retrieved after the incidents for the first two failures, as well as the video footage showing the first failure, corroborated that the tower tops were mainly loaded from the counterjib side due to loss of the tensions of the jib pendants. For the third failure the two jib bottom chords were also found detached from the turntable in the same manner, and no bottom chord end was bent due to the swaying of the jib as found in the first two failure. The two tower top columns at the counterjib side were buckled in the same plane of the jib, tower top, and the counterjib. This observation corroborated that in the third failure the tower top was loaded from the counterjib side.

Following steps were taken to address the cause of the rotation of the jib while out-of-service:

- a. The cranes were examined for any commercial banners attached to the cranes that could add significantly to the wind pressure. No such banners were found on the crane.
- b. The cranes were examined for add-on structures that were not engineered on the cranes. No add-on structures were found on the crane.
- c. The turntable bearing and the lock mechanism of each crane were examined after the incidents to verify the cranes were set to weathervane prior to the Hurricane Irma. Field inspections, video footages taken near the second failure site and photographs taken by the construction camera at the third failure site confirmed the weathervane conditions of all three cranes.

Therefore, any of the above factors could not be the cause of the rotation of the jibs and subsequent failures. Therefore, the most probable cause is the turbulent lateral and/or vertical wind on the jibs that could cause the rotation of the jibs and their detachments from the crane turntables.

8. Conclusions

The following conclusions by the Occupational Safety and Health Administration are based on the examination of the collapsed structure, a review of the manuals for the SK-315, the review of video footages taken at the incident sites and structural analysis discussed in this report.

1. The design of the crane, model SK-315 generally met the U.S. and European standards. The crane was designed for a maximum wind speed of 95 mph at the jib level for the out-of-service condition. Beyond 95 mph, failure could occur as stated in the manufacturer's manual. The wind speed at different heights of the jib of the three cranes in Miami and Ft. Lauderdale exceeded 95 mph.
2. If the wind speed at the jib level exceeds 45 mph, the crane must be placed out of service and allowed to weathervane, as per the manufacturer's manual. On Sept. 10, 2017, all three cranes were put out of service and allowed to freely weathervane.
3. The U.S. and European codes do not require that turbulent wind, suction, or vortexes be considered in the design of the cranes. The failure of all three cranes occurred due to turbulent wind.
4. Out of more than a dozen cranes in and around Miami, only the model SK-315 failed due to an inherent weakness at the connection of the jib to the turntables.
5. The cause of the failure of the three cranes was the detachment of the crane jibs from their turntables due to turbulent wind loads. Based on our evaluation, it is believed that wind gusts, at oscillation periods corresponding to the frequencies of the dominant modes of the jibs, struck the jibs. Under the turbulent wind loads in either lateral or upward direction, the forces on the turntable cradles at the jib feet exceeded their capacities. The separation of the jibs at the turntable caused the jibs to fall in all three cases.
6. In all three crane failures, only the jibs, counterjibs, and the tower top collapsed, while the crane masts, ties and foundations remained intact.
7. The tower top collapsed due to a transient loss of the forces in the jib pendants.
8. On coastal areas with tall buildings and locations prone to frequent turbulent winds, local governing bodies should consider asking engineers to conduct simulations based on dynamic analysis to get a more realistic wind evaluation than quasi-static analysis. Instead of conducting cost-prohibitive wind tunnel tests, engineers could conduct a Computational

Fluid Dynamics (CFD) analysis, which has become affordable due to the rapid advance of software and computing technology.

9. Terex, the crane manufacturer, should evaluate the design of jib-to-turnstile connections to prevent possible detachment of crane jibs in high turbulent wind in the future.
10. To prevent catastrophic collapses of the crane tower top in the future, it is recommended that tower tops be evaluated and designed with a higher safety margin, and the design should also be based with loads applied from only the counterjib.
11. The jibs in all three cranes were suspended by single pendants. In the event that the jib begins to sway to the sides, the single pendants could not be expected to secure the stability of the jib. It is, therefore, recommended that two symmetric pendants or cables be considered in the design of the tower cranes. Terex should consider adding pendants to the existing SK-315 models.
12. Although the National Hurricane Centre issued warnings to the residents in South Florida that heavy Squalls with embedded tornadoes were sweeping across South Florida, no tornadoes formed at any of three failure sites on September 10, 2017. However, localized high-altitude strong vortexes cannot be ruled out.

9. References

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APPENDIX A – Local Climatological Data

U.S. Department of Commerce
 National Oceanic & Atmospheric Administration
 National Environmental Satellite, Data, and Information Service
 Current Location: Elev: 10 ft. Lat: 25.5069° N Lon: -80.2803° W
 Station: MIAMI OPA LOCKA AIRPORT, FL US 42882

Local Climatological Data
 Daily Summary
 September 2017
 Generated on 12/22/2017

National Centers for Environmental Information
 151 Patton Avenue
 Asheville, North Carolina 28801

Date	Temperature (F)				Degree Days (base 65F)				Sun (LST)		Weather Weather Type	Precipitation (in)		Pressure (inHg)		Wind		Maximum Wind Speed = MPH Direction = Degrees			
	Max	Min	Avg	Dep	ARH	ADP	AWB	Heat	Cool	Rise		Set	TLC	Snow Fall	Snow Depth	Avg Stn	Avg SL	Avg Speed	Peak Speed	Peak Dir	Sust. Speed
1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23
01	84	80	87	3.9				0	22	0601	1841	TS	0.02	0.0	0	30.01	7.6	22	180	17	180
02	91	74	82	-1.1				0	17	0602	1840	TS RA BR	0.44	0.0	0	30.04	6.7	30	210	24	200
03	92	79	86	2.0				0	21	0602	1839		0.00	0.0	0	30.08	4.2	19	340	14	340
04	92	79	86	3.0				0	21	0602	1838		T	0.0	0	30.02	8.6	20	100	17	080
05	92	80	86	3.0				0	21	0603	1838	RA	T	0.0	0	29.98	7.3	20	100	16	080
06	91	80	86	3.0				0	21	0603	1835	RA	0.01	0.0	0	29.93	4.1	22	140	17	130
07	94	79	86	3.0				0	21	0604	1834		T	0.0	0	29.93	6.4	20	100	16	080
08	94*	83	88	5.1				0	23	0604	1833	RA	0.01	0.0	0	29.87	14.3	33	080	25	080
09	98	75	82	-0.9				0	17	0604	1832	TS RA BR	3.06	0.0	0	29.88	22.3	55	110	45	090
10								0	19	0605	1831	RA BR	4.87	0.0	0	29.34	40.7	85	110	55	140
11	88	79	84	1.1				0	19	0605	1830	RA	0.00	0.0	0	29.85	15.2	37	200	30	200
12	90	76	83	0.2				0	18	0606	1829		0.00	0.0	0	29.85	5.8	19	270	14	280
13	90	78	84	1.2				0	19	0606	1828	TS RA BR	1.82	0.0	0	29.92	4.8	16	140	14	140
14	91	77	84	1.2				0	19	0606	1827		0.00	0.0	0	29.95	4.6	18	100	15	100
15	91	79	85	2.2				0	20	0607	1826		0.00	0.0	0	29.96	6.6	17	089	14	080
16	92	80	86	3.2				0	21	0607	1824		T	0.0	0	29.95	8.9	28	070	20	060
17	91	78	84	1.3				0	19	0608	1823		0.00	0.0	0	29.84	7.9	18	340	15	340
18	90	76	83	0.3				0	18	0608	1822		0.00	0.0	0	29.91	7.4	21s	280s	14	280
19	93	79	86	3.3				0	21	0608	1821	TS RA	T	0.0	0	29.90	5.9	20	140	17	140
20	92	78	85	2.4				0	20	0609	1820	TS	0.00	0.0	0	29.95	4.1	16	130	13	120
21	91	78	84	1.4				0	19	0609	1819	TS RA BR	0.85	0.0	0	29.93	4.9	19	050	15	080
22	86	77	82	-0.6				0	17	0610	1818	TS RA BR	1.00	0.0	0	29.87	3.9	26	080	21	080
23	90	76	83	0.5				0	18	0610	1817	RA	0.07	0.0	0	29.82	6.1	22	080	20	080
24	90	77	84	1.5				0	19	0610	1816	TS	0.18	0.0	0	29.84	4.9	26	360	21	350
25	91	78	84	1.6				0	19	0611	1814	TS	0.00	0.0	0	29.88	3.3	15	200	13	200
26	87	73*	80	-2.3				0	16	0611	1813	TS RA FG BR	1.96	0.0	0	29.90	6.0	24	240	20	260
27	87	76	82	-0.3				0	17	0612	1812	TS RA BR	0.93	0.0	0	29.88	2.4	27s	190s	22	210
28	90	76	83	0.8				0	18	0612	1811	RA BR	0.21	0.0	0	29.88	4.6	21	100	16	120
29	85	76	80	-2.1				0	15	0612	1810	TS RA BR	1.98	0.0	0	29.91	4.7	28	200	21	200
30	90.2	77.5	83.9					0	17	0613	1809		0.00	0.0	0	29.93	4.8	20	160	16	130
0.7	1.6	1.2										18.91s				29.89	29.90	8.1			
Departure from Normal (1981-2010)																					
8.46s																					

Heating Cooling	Degree Days		Season-to-date		Temperature		Precipitation		Snow		Weather	
	Total	Departure	Total	Departure	Max	Min	>=0.01"	>=0.1"	>=1"	T-Storms	Heavy Fog	
552	21	3771	0	0	0	0	0	11	0			
Date of 5-sec to 3-sec wind equipment change												
2009-07-08		Date		Sea Level Pressure		Time		24-Hr...		Snow Depth		
		Maximum		30.14		0906		Precip		Snowfall		
		Minimum		29.20		1612		7.51s		Date		
				02				09-10				
				10								
Station Augmentation												
Name: N/A Lat: N/A Lon: N/A Elevation: N/A Distance: N/A Elements: N/A Equipment: N/A												

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service
Current Location: Elev: 10 ft. Lat: 25.9069° N Lon: -80.2803° W
Station: MIAMI OPA LOCKA AIRPORT, FL US 12882

Local Climatological Data
Hourly Observations
September 2017
Generated on 12/22/2017

National Centers for Environmental Information
151 Patton Avenue
Asheville, North Carolina 28801

Date	Time (LST)	Station Type	Sky Conditions	Visi- bility	Weather Type (see documentation)		Dry Bulb Temp		Wet Bulb Temp		Dew Point Temp		Rel Hum %	Wind Speed (MPH)	Wind Dir (Deg)	Wind Gusts (MPH)	Station Press (inHg)	Press. Tend	Net 3- Hr. Change (inHg)	Sea Level Press. (inHg)	Report Type	Precip Total (in)	Alti- meter Setting (inHg)
					AU AW MW	6	(F)	(C)	(F)	(C)	(F)	(C)											
10	0053	7	BKN07 26 BKN07 55 OVC08 120	8.00	-RA RA	79	26.1	78	25.7	78	25.6	97	29	100	41	29.58	8	+0.04	29.59	FM-15	0.04	29.59	
10	0108	7	SCT04 24 BKN07 50 OVC08 90	10.00	-RA RA	79	26.1	78	25.7	78	25.6	97	30	110	41	29.58				FM-16	T	29.59	
10	0153	7	FEW02 20 BKN07 59 OVC08 70	4.00	RA BR RA	79	26.1	79	26.1	79	26.1	100	24	100	40	29.57			29.59	FM-15	0.09	29.58	
10	0253	7	FEW02 15 OVC08 23	3.00	+RA BR RA	77	25.0	77	25.0	77	25.0	100	28	100	38	29.55			29.57	FM-15	0.18	29.56	
10	0307	7	OVC08 20	2.50	+RA BR RA	76	24.4	76	24.4	76	24.4	100	32	090	43	29.53				FM-16	0.08	29.54	
10	0316	7	OVC08 18	6.00	-RA BR RA	76	24.4	76	24.4	76	24.4	100	25	080	38	29.52				FM-16	0.09	29.53	
10	0353	7	BKN07 38 BKN07 90 BKN07 110	10.00	-RA RA	82	27.8	79	26.2	78	25.6	88	37	110	51	29.48	8	+0.10	29.49	FM-15	0.14	29.49	
10	0453	7	FEW02 29 BKN07 45 OVC08 95	7.00	-RA RA	80	26.7	79	25.9	78	25.6	94	30	110	47	29.47			29.48	FM-15	0.08	29.48	
10	0553	7	FEW02 25 BKN07 36 OVC08 42	4.00	RA BR RA	80	26.7	79	26.3	79	26.1	97	34	110	60	29.44			29.45	FM-15	0.10	29.45	
10	0606	7	FEW02 24 OVC08 32	2.50V	+RA BR RA	79	26.1	79	26.1	79	26.1	100	34	100	60	29.42				FM-16	0.07	29.43	
10	0618	7	FEW02 24 OVC08 34	3.00	+RA BR RA	80	26.7	79	26.3	79	26.1	97	33	110	61	29.43				FM-16	0.10	29.44	
10	0626	7	FEW02 21 OVC08 32	1.75V	+RA BR RA	77	25.0	77	25.0	77	25.0	100	44	110	62	29.44				FM-16	0.14	29.45	
10	0632	7	OVC08 26	0.75	+RA BR RA	77	25.0	77	25.0	77	25.0	100	44	110	68	29.44				FM-16	0.22	29.45	
10	0644	7	FEW02 17 OVC08 24	1.25	+RA BR RA	75	23.9	75	23.9	75	23.9	100	41	110	68	29.44				FM-16	0.28	29.45	
10	0653	7	FEW02 15 OVC08 21	1.00	+RA BR RA	76	24.4	76	24.4	76	24.4	100	34	100	57	29.43	6	+0.05	29.44	FM-15	0.36	29.44	
10	0722	7	BKN07 14 BKN07 25	1.75	+RA BR RA	77	25.0	77	25.0	77	25.0	100	41	110	63	29.41				FM-16	0.18	29.42	
10	0734	7	BKN07 16	1.25	+RA BR RA	78	25.6	78	25.6	78	25.6	100	51	120	62	29.42				FM-16	0.25	29.43	
10	0750	7	SCT04 16 SCT04 23 OVC08 27	2.00	RA BR RA	79	26.0	79	26.1	79	26.0	100	41	110	63	29.42				FM-16	0.31	29.43	
10	0753	7	FEW02 14 SCT04 21 OVC08 27	2.00	+RA BR RA	77	25.0	77	25.0	77	25.0	100	38	110	61	29.42			29.43	FM-15	0.32	29.43	
10	0804	7	FEW02 14 SCT04 21 OVC08 27	1.50	+RA BR RA	78	25.6	78	25.6	78	25.6	100	40	110	68	29.42				FM-16	0.07	29.43	
10	0827	7	FEW02 17 BKN07 30 OVC08 60	2.50	RA RA								41	100	62	29.38				FM-16	0.15	29.39	
10	0853	7	SCT04 19 BKN07 26 OVC08 34	2.00	+RA RA								47	110	64	29.37			29.39	FM-15	0.21	29.38	

10	0916	7	FEW:02 16 SCT:04 21 OVC:08 31	1.75	+RA RA																46	110	64	29.36					FM-16	0.08	29.37	
10	0923	7	FEW:02 16 BKN:07 29 OVC:08 35	1.75	+RA RA																	43	110	64	29.36					FM-16	0.10	29.37
10	0953	7	SCT:04 19 OVC:08 28	1.75	+RA RA																	44	120	66	29.35	8	+0.06	29.37	FM-15	0.23	29.36	
10	1016	7	FEW:02 20 BKN:07 26 OVC:08 35	2.00	RA RA																	45	120	69	29.36					FM-16	0.10	29.37
10	1048	7	SCT:04 17 BKN:07 24 OVC:08 31	3.00	RA BR RA	79	26.0	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	53	120	68	29.34					FM-16	0.17	29.35
10	1053	7	BKN:07 17 OVC:08 31	4.00	-RA BR RA	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	55	120	76	29.35			29.36		FM-15	0.19	29.36
10	1111	7	BKN:07 19 OVC:08 34	2.00	+RA BR RA	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	52	120	69	29.33					FM-16	0.05	29.34
10	1153	7	SCT:04 17 BKN:07 24 OVC:08 36	2.50	RA BR RA	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	52	120	68	29.30			29.31		FM-15	0.20	29.31
10	1236	7	SCT:04 16 BKN:07 21 OVC:08 35	1.00	+RA BR RA	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	52	120	68	29.28					FM-16	0.20	29.29
10	1244	7	SCT:04 18 SCT:04 23 OVC:08 31	0.75	+RA BR RA	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	63	120	84	29.28					FM-16	0.31	29.29
10	1253	7	SCT:04 16 OVC:08 25	0.75	+RA BR RA	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	53	130	76	29.27	8	+0.07	29.28		FM-15	0.46	29.28
10	1333	7	OVC:08 14	0.50s	+RA s RA s	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	55	140	82	29.23			29.24		FM-15	1.02	29.24
10	1422	7	BKN:07 9 OVC:08 15	0.25s	+RA s RA s	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	45	150	74	29.21					FM-16	0.71	29.22
10	1431	7	BKN:07 11 OVC:08 15	0.50s	+RA s RA s	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	41	150	59	29.23					FM-16	0.86	29.24
10	1437	7	BKN:07 14	2.50	-RA RA	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	45	160	62	29.23					FM-16	0.86	29.24
10	1444	7	FEW:02 10 BKN:07 16 OVC:08 30	1.50	RA RA	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	53	150	71	29.23					FM-16	0.90	29.24
10	1453	7	SCT:04 14 OVC:08 23	1.75	-RA RA	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	52	150	68	29.23			29.24		FM-15	0.93	29.24
10	1513	7	FEW:02 18 SCT:04 26 OVC:08 34	2.00	RA RA	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	77	25.0	47	150	77	29.22					FM-16	0.09	29.23
10	1530	7	SCT:04 16 BKN:07 25 OVC:08 36	3.00	-RA RA	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	53	150	68	29.21					FM-16	0.12	29.22
10	1545	7	BKN:07 16 BKN:07 22 OVC:08 33	2.00V	-RA RA	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	78	25.6	62	150	75	29.21					FM-16	0.16	29.22
10	1553	7	BKN:07 15 BKN:07 22 OVC:08 30	2.50V	-RA BR RA	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	49	150	75	29.20	6	+0.06	29.21		FM-15	0.17	29.21
10	1605	7	BKN:07 18 OVC:08 28	1.25	RA BR RA	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	49	160	71	29.20					FM-16	0.05	29.21
10	1613	7	BKN:07 18 OVC:08 27	3.00	-RA BR RA	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	79	26.1	53	150	72	29.20					FM-16	0.05	29.21
10	1636	7	BKN:07 20 OVC:08 28	1.75	-RA BR RA	80	26.7	80	26.7	80	26.7	80	26.7	80	26.7	80	26.7	80	26.7	80	26.7	47	160	68	29.20					FM-16	0.10	29.21
10	1648	7	BKN:07 20 BKN:07 26 OVC:08 37	3.00	-RA BR RA	81	27.0	81	27.0	81	27.0	81	27.0	81	27.0	81	27.0	81	27.0	81	27.0	45	170	66	29.22					FM-16	0.15	29.23

Local Climatological Data
Daily Summary
September 2017
 Generated on 12/22/2017

National Centers for Environmental Information
 151 Patton Avenue
 Asheville, North Carolina 28801

U.S. Department of Commerce
 National Oceanic & Atmospheric Administration
 National Environmental Satellite, Data, and Information Service
 Current Location: Elev: 14 ft. Lat: 26.1969° N Lon: -80.1708° W
 Station: FORT LAUDERDALE EXECUTIVE AIRPORT, FL US 12885

Date	Temperature (F)				Degree Days (base 65F)				Sun (LST)		Weather Weather Type	Precipitation (in)		Pressure (inHg)		Wind		Maximum Wind Speed = MPH				
	Max	Min	Avg	Dep	ARH	ADP	AWB	Heat	Cool	Rise		Set	TLC	Snow Fall	Snow Depth	Avg	SL	Avg	Dir	Peak	Sust.	
01	94*	78	86	3.3	0	21	0601	1840	12	12	13	0.08	0.0	0	30.00	7.8	19	20	21	22	23	
02	91	77	84	1.4	0	19	0601	1839	TS RA			0.02	0.0	0	30.03	6.0	19	170	14	130		
03	92	76	84	1.4	0	19	0601	1838				0.00	0.0	0	30.04	3.6	17	110	14	110		
04	90	77	84	1.5	0	19	0602	1837				0.00	0.0	0	30.01	7.5	21	080	15	080		
05	92	77	84	1.5	0	19	0602	1836	RA BR			0.34	0.0	0	29.95	7.8	22	130	18	080		
06	92	77	84	1.5	0	19	0603	1835	TS RA BR			1.40	0.0	0	29.91	3.8	23	180	17	160		
07	92	77	84	1.6	0	19	0603	1834	RA			0.01	0.0	0	29.93	6.1	20	080	17	060		
08	92	82	87	4.6	0	22	0603	1833				T	0.0	0	29.88	12.5	31	050	22	050		
09	88	75	82	-0.3	0	17	0604	1832	TS RA BR			1.57	0.0	0	29.68	20.2	51s	070s	39	110		
10							0604	1831	TS RA FG BR			8.00	0.0	0	29.41	37.2	75s	100s	53	110		
11	90	79	84	1.7	0	19	0605	1830				0.00	0.0	0	29.63	13.1	32	230	20	220		
12	91	76	84	1.8	0	19	0605	1829				0.00	0.0	0	29.83	4.4	18	310	14	270		
13	91	77	84	1.9	0	19	0605	1827	TS RA			T	0.0	0	29.91	5.7	18	120	14	120		
14	91	76	84	1.9	0	19	0606	1826				0.00	0.0	0	29.64	6.7	18	070	14	060		
15	91	77	84	1.9	0	19	0606	1825				0.00	0.0	0	29.96	7.1	22	080	15	070		
16	91	78	84	1.9	0	19	0607	1824	RA			0.02	0.0	0	29.64	7.5	25	060	17	060		
17	92	77	84	2.0	0	19	0607	1823				0.00	0.0	0	29.93	6.2	23	280	14	010		
18	91	73	82	0.0	0	17	0607	1822	TS			0.00	0.0	0	29.90	5.6	21	360	15	270		
19	91	76	84	2.1	0	19	0608	1821	RA BR			0.16	0.0	0	29.89	6.4	20	080	16	100		
20	90	76	83	1.1	0	18	0608	1820	RA HZ			0.03	0.0	0	29.93	5.1	19s	110s	14	060		
21	88	77	82	0.1	0	17	0609	1818	TS RA			0.01	0.0	0	29.91	5.8	18	050	14	050		
22	88	75	82	0.2	0	17	0609	1817	TS RA			0.03	0.0	0	29.86	6.7	24	060	18	060		
23	91	75	83	1.2	0	18	0610	1816				T	0.0	0	29.80	6.8	22s	060s	16	050		
24	86	76	82	0.3	0	17	0610	1815	TS RA BR			0.62	0.0	0	29.83	5.2	18	110	15	120		
25	93	77	85	3.4	0	20	0610	1814				0.09	0.0	0	29.84	5.1	17	120	15	120		
26	89	73	81	-0.6	0	16	0611	1813	TS RA BR			0.69	0.0	0	29.88	6.2	24	180	18	180		
27	87	76	82	0.5	0	17	0611	1812	TS			T	0.0	0	29.86	3.0	16	230	12	230		
28	90	76	83	1.6	0	18	0612	1811	RA			0.06	0.0	0	29.87	5.4	29	110	16	120		
29	85	74	80	-1.3	0	15	0612	1810	TS RA BR			0.31	0.0	0	29.89	6.5	24	190	18	160		
30	89	73*	81	-0.3	0	16	0612	1808				0.00s	0.0	0	29.91	5.3	26	140	15	150		
90.4	76.2	83.3					Monthly Averages Totals					13.12s			29.88	29.90	7.8					
1.7	0.8	1.2					Departure from Normal (1981-2010)					4.86s										
Number of days with...																						
Heating		Total		Season-to-date		Departure		Temperature		Precipitation		Snow		Weather								
Cooling	0	0	0	0	0	0	0	0	<=32°	<=0°	>=0.01"	>=0.1"	>=1"	T-Storms	Heavy Fog							
	532	21	3889								17	8	0									
Date of 5-sec to 3-sec wind equipment change		Sea Level Pressure		Date		Time		24-Hr...		Snowfall		Snow Depth										
2009-07-30		30.10		03		1037		Precip		8.42s		Snowfall										
		29.22		10		1702		Date		09-10		Date										
Station Augmentation																						
Name: N/A Lat: N/A Lon: N/A Elevation: N/A Distance: N/A Elements: N/A Equipment: N/A																						

U.S. Department of Commerce
 National Oceanic & Atmospheric Administration
 National Environmental Satellite, Data, and Information Service
 Current Location: Elev: 14 ft. Lat: 26.1969° N Lon: -80.1708° W
 Station: FORT LAUDERDALE EXECUTIVE AIRPORT, FL US 12885

Local Climatological Data
Hourly Observations
September 2017
 Generated on 12/22/2017

National Centers for Environmental Information
 151 Patton Avenue
 Asheville, North Carolina 28801

Date	Time (LST)	Station Type	Sky Conditions	Visi- bility	Weather Type (see documentation)	Dry Bulb Temp		Wet Bulb Temp		Dew Point Temp		Rel Hum %	Wind Speed (MPH)	Wind Dir (Deg)	Wind Gusts (MPH)	Station Press (inHg)	Press. Tend	Net 3-Hr Change (inHg)	Sea Level Press. (inHg)	Report Type	Precip Total (in)	Alti- meter Setting (inHg)	
						(F)	(C)	(F)	(C)	(F)	(C)												
1	2	3	4	5	AU AW MW	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
10	0053	7	FEW02 30 BKN07 100 BKN07 120	10.00	-RA RA		79	26.1	76	24.6	75	23.9	88	29	090	38	29.62	8	+0.04	29.64	FM-15	T	29.63
10	0153	7	FEW02 23 SCT04 65 BKN07 110	10.00	-RA RA		78	25.6	77	24.8	76	24.4	93	29	090	38	29.61			29.62	FM-15	0.02	29.62
10	0245	7	BKN07 29 BKN07 47 OVC08 90	1.75	+RA BR RA		74	23.3	73	23.0	73	22.8	97	25	100	33	29.58				FM-16	0.36	29.59
10	0253	7	BKN07 16 BKN07 27 OVC08 90	1.00	+RA BR RA		73	22.8	73	22.8	73	22.8	100	22	100	33	29.59			29.61	FM-15	1.07	29.60
10	0301	7	BKN07 14 BKN07 25 OVC08 70	1.00	+RA BR RA		74	23.3	74	23.3	74	23.3	100	22	110	34	29.59				FM-16	0.37	29.61
10	0322	7	OVC08 25	2.00V	+RA BR RA		76	24.4	76	24.4	76	24.4	100	17	140	33	29.54				FM-16	0.77	29.56
10	0333	7	VV09 19	0.75	+RA BR RA		74	23.3	74	23.3	74	23.3	100	30	150	54	29.56				FM-16	1.19	29.57
10	0341	7	VV09 16	0.50	VC+RA FG FG RA		74	23.3	74	23.3	74	23.3	100	37	140	48	29.56				FM-16	1.60	29.57
10	0350	7	VV09 11	1.00	+RA BR RA		75	24.0	75	23.9	75	24.0	100	46	090	63	29.52				FM-16	1.97	29.53
10	0351	7	VV09 11	1.00	VC+RA BR RA		75	24.0	75	23.9	75	24.0	100	36	090	63	29.54				FM-16	1.97	29.55
10	0353	7	BKN07 12 OVC08 70	1.25	VC+RA BR RA		74	23.3	74	23.3	74	23.3	100	36	100	63	29.53	6	+0.07	29.55	FM-15	1.84	29.54
10	0412	7	BKN07 13 OVC08 23	1.00	+RA BR RA		74	23.3	74	23.3	74	23.3	100	22	130	38	29.53				FM-16	0.74	29.54
10	0427	7	VV09 8	0.75	+RA BR RA		76	24.4	76	24.4	76	24.4	100	48s	110	60	29.54				FM-16	1.29	29.55
10	0437	7	BKN07 9 BKN07 20 OVC08 100	2.00	-RA BR RA		76	24.4	76	24.4	76	24.4	100	36	100	62	29.53				FM-16	1.37	29.54
10	0442	7	FEW02 9 BKN07 18 OVC08 100	7.00	-RA RA		76	24.4	76	24.4	76	24.4	100	39	100	56	29.52				FM-16	1.37	29.53
10	0448	7	SCT04 18 BKN07 46 OVC08 110	7.00	VC-RA RA		75	24.0	75	23.9	75	24.0	100	34	100	56	29.52				FM-16	1.37	29.53
10	0453	7	SCT04 24 BKN07 80 OVC08 110	7.00	VC-RA RA		78	25.6	77	25.2	77	25.0	97	25	100	48	29.51			29.53	FM-15	1.23	29.52
10	0506	7	FEW02 50 BKN07 110	7.00	-RA RA		80	26.7	79	25.9	78	25.6	94	33	110	48	29.49				FM-16	0.01	29.51
10	0553	7	BKN07 29 BKN07 50 OVC08 100	7.00	-RA RA		81	27.2	79	26.0	78	25.6	91	38	090	52	29.49			29.51	FM-15	0.06	29.50
10	0601	7	SCT04 27 BKN07 37 OVC08 110	7.00	-RA RA		81	27.2	79	26.0	78	25.6	91	38	090	55	29.48				FM-16	T	29.49
10	0651	7	FEW02 18 SCT04 28 OVC08 34	2.00	+RA BR RA		79	26.0	79	26.1	79	26.0	100	37	120	57	29.49				FM-16	0.17	29.50
10	0653	7	FEW02 18 SCT04 26 OVC08 37	2.50	+RA BR RA		78	25.6	78	25.6	78	25.6	100	36	110	57	29.48	6	+0.03	29.50	FM-15	0.18	29.49

10	0701	7	FEW:02 18 BKN:07 43 OVC:08 90	6.00	-RA BR RA	79	26.1	78	25.3	77	25.0	94	34	110	53	29.47				FM-16	0.01	29.48
10	0710	7	FEW:02 24 BKN:07 43 OVC:08 75	4.00	RA BR SQ SQ RA	77	25.0	76	24.6	76	24.4	96	44	120	70	29.49				FM-16	0.03	29.50
10	0751	6	FEW:02 22 BKN:07 39 OVC:08 80	2.50	+RA BR RA	81	27.0	80	26.4	79	26.0	94	38	110	71	29.46				FM-16		29.47
10	0753	7	FEW:02 22 BKN:07 39 OVC:08 75	2.00	+RA BR RA	79	26.1	78	25.7	78	25.6	97	43	100	71	29.46			29.48	FM-15	0.15	29.47
10	0755	7	SCT:04 26 BKN:07 39 OVC:08 75	1.75	+RA BR SQ SQ RA	79	26.1	78	25.3	77	25.0	94	56	110	71	29.46				FM-16	0.01	29.47
10	0811	7		2.50	RA BR RA	79	26.1	77	24.9	76	24.4	90	46	100	59	29.46				FM-16	0.06	29.47
10	0826	7		4.00	RA BR RA	79	26.1	78	25.3	77	25.0	94	47	100	67	29.45				FM-16	0.09	29.46
10	0853	7		3.00	RA BR RA	80	26.7	78	25.5	77	25.0	90	41	100	59	29.44			29.45	FM-15	0.14	29.45
10	0953	7	SCT:04 25 BKN:07 34 OVC:08 70	4.00	-RA BR RA	80	26.7	79	25.9	78	25.6	94	45	100	63	29.41			29.44	FM-15	0.04	29.43
10	1031	7	FEW:02 22 BKN:07 29 OVC:08 38	3.00	RA BR RA	81	27.2	79	26.0	78	25.6	91	46	110	66	29.41				FM-16	0.02	29.42
10	1040	7	FEW:02 20 BKN:07 33 OVC:08 43	2.00	RA BR RA	80	26.7	79	26.3	79	26.1	97	47	110	62	29.40				FM-16	0.05	29.41
10	1051	6	SCT:04 20 BKN:07 28 OVC:08 38	2.50	RA BR RA	81	27.0	80	26.4	79	26.0	94	46	110	67	29.40				FM-16		29.41
10	1053	7	FEW:02 20 BKN:07 26 OVC:08 50	2.50	RA BR RA	80	26.7	79	26.3	79	26.1	97	51	110	67	29.40			29.42	FM-15	0.09	29.41
10	1103	7	FEW:02 19 BKN:07 35 OVC:08 48	2.00	RA BR RA	80	26.7	79	26.3	79	26.1	97	44	100	70	29.39				FM-16	0.03	29.40
10	1107	7	FEW:02 19 BKN:07 27 OVC:08 35	1.75v	RA BR RA	80	26.7	79	26.3	79	26.1	97	45	110	62	29.39				FM-16	0.06	29.40
10	1134	7	SCT:04 18 BKN:07 23 OVC:08 28	2.00	RA BR RA	79	26.1	79	26.1	79	26.1	100	48	110	63	29.38				FM-16	0.21	29.39
10	1153	7	SCT:04 21 BKN:07 20 OVC:08 55	3.00	RA BR RA	80	26.7	79	26.3	79	26.1	97	41	120	63	29.36			29.39	FM-15	0.27	29.38
10	1208	7	SCT:04 20 BKN:07 27 OVC:08 50	2.50	RA BR RA	80	26.7	79	26.3	79	26.1	97	48	120	64	29.35				FM-16	0.05	29.36
10	1228	7	SCT:04 16 BKN:07 22 OVC:08 26	1.25	+RA BR RA	79	26.1	79	26.1	79	26.1	100	51	110	72	29.34				FM-16	0.17	29.35
10	1253	7	SCT:04 15 BKN:07 22 OVC:08 27	1.25	+RA BR RA	80	26.7	80	26.7	80	26.7	100	53	110	74	29.30	8	+0.12	29.31	FM-15	0.35	29.31
10	1311	7	FEW:02 9 OVC:08 17	0.75	+RA BR RA	78	25.6	78	25.6	78	25.6	100	28s	130	67	29.28				FM-16	0.29	29.30
10	1322	7			+RA RA	79	26.1						54s	120	84	29.28				FM-16	0.40	29.29
10	1331	7		1.25	+RA RA	79	26.1						52	120	74	29.28				FM-16	0.46	29.29
10	1405	7		1.25	BR	79	26.1	79	26.1	79	26.1	100	45	120	74	29.25				FM-16	0.72	29.26
10	1421	7		0.50s	+RA s RA s	79	26.1						46	130	69	29.27				FM-16	1.04	29.28
10	1503	7		1.50	-RA RA	79	26.1						38	130	66	29.23				FM-16	1.30	29.24
10	1521	7				79	26.1									29.22				FM-16	1.39	29.23
10	1532	7		0.50	+RA FG FG RA	77	25.0	77	25.0	77	25.0	100	33s	140	63	29.23				FM-16	1.74	29.25

10	1549	7	BKN:07 10 OVC:08 26	1.50	RA BR RA	79	26.0	78	25.3	77	25.0	94	38	140	63	29.23				FM-16	1.91	29.25
10	1551	6	BKN:07 10 OVC:08 22	2.00	RA BR RA	79	26.0	78	25.3	77	25.0	94	43	140	63	29.23				FM-16		29.25
10	1553	7	BKN:07 10 OVC:08 50	2.50	-RA BR RA	78	25.6	77	25.2	77	25.0	97	44	140	63	29.23		29.25	FM-15	0.65	29.24	
10	1559	7	SCT:04 12 BKN:07 20 OVC:08 55	4.00	-RA BR RA	79	26.1	78	25.3	77	25.0	94	41	140	61	29.23			FM-16	T	29.24	
10	1612	7	SCT:04 19 BKN:07 36 OVC:08 75	7.00		80	26.7	78	25.5	77	25.0	90	40	130	59	29.23			FM-16	T	29.24	
10	1636	7	SCT:04 21 BKN:07 28 OVC:08 36	6.00	-RA RA	81	27.2	77	25.3	76	24.4	85	45	140	67	29.21			FM-16	0.01	29.22	
10	1651	6	FEW:02 21 SCT:04 26 OVC:08 34	6.00	-RA BR RA	81	27.0	78	25.6	77	25.0	89	44	140	66	29.21			FM-16		29.22	
10	1653	7	SCT:04 21 BKN:07 31 OVC:08 36	6.00	-RA BR RA	81	27.2	78	25.6	77	25.0	88	46	140	66	29.21		29.23	FM-15	0.01	29.22	
10	1723	7		2.00V	-RA BR RA	80	26.7	78	25.5	77	25.0	90	40	150	63	29.23			FM-16	0.06	29.24	
10	1729	7	SCT:04 18 BKN:07 24 OVC:08 39	3.00	-RA BR RA	80	26.7	78	25.5	77	25.0	90	34	150	67	29.23			FM-16	0.06	29.24	
10	1751	7				79	26.0	76	24.6	75	24.0	89				29.23			FM-16	0.07	29.25	
10	1753	7				79	26.1	77	24.9	76	24.4	90				29.23			FM-15	0.07	29.25	
10	1853	6														29.27	3	-0.06	FM-15		29.28	
10	1953	7														29.31			FM-15	0.00	29.32	
10	2053	7														29.35			FM-15	0.00	29.36	
10	2153	7														29.39	2	-0.12	FM-15	0.00	29.40	
10	2253	7														29.44			FM-15	0.00	29.45	
10	2353	7														29.48			FM-15	0.00	29.49	

APPENDIX B - NOAA's Severe Weather Data Inventory TVS Data

1st Failure Site

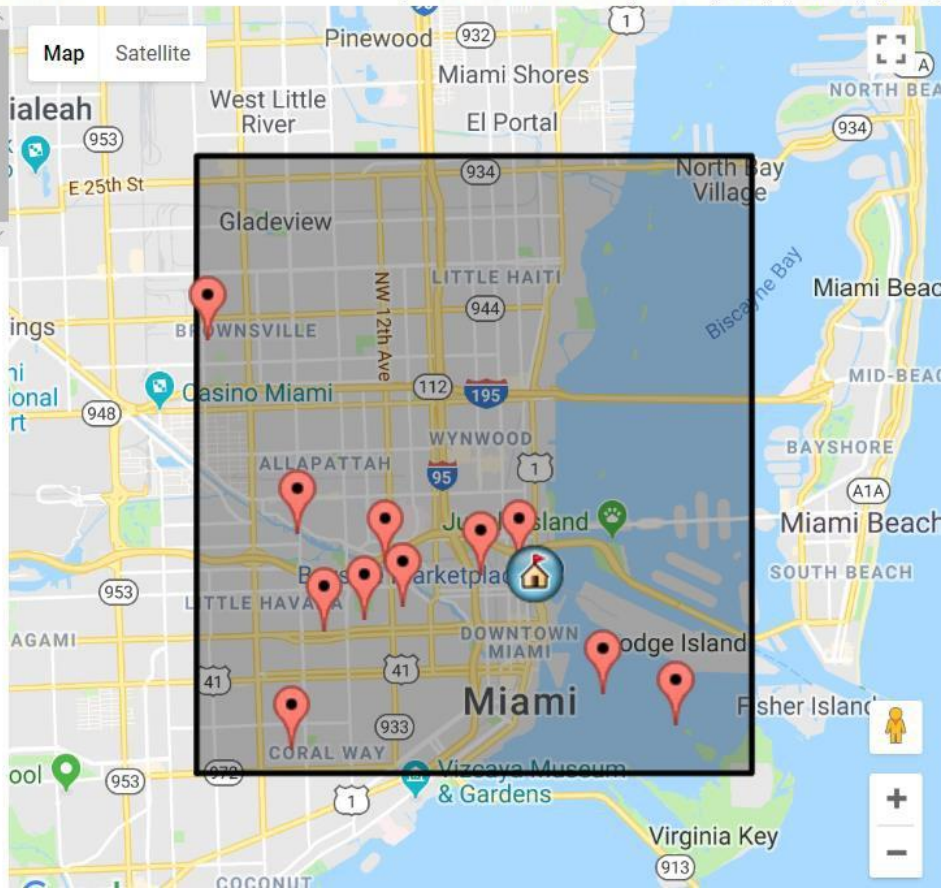
243 NE 3rd Street, Miami, fl
Select Year and Dataset
2017 Tornado Signatures from NEXRAD (Level-III TVS Product)

Data Table and Map Timeline Graph

- Click on map to select new tile -

[Download Summary Data: [CSV](#) / [JSON](#) / [XML](#)]

DATE (UTC)	NUM
Aug 11, 2017	1
Sep 9, 2017	1
Jul 20, 2017	3
Sep 10, 2017	11
May 14, 2017	1



2nd Failure Site

610 NE 31st Street in Miami, fl

Select Year and Dataset

2017 ▼ Tornado Signatures from NEXRAD (Level-III TVS Product) ▼

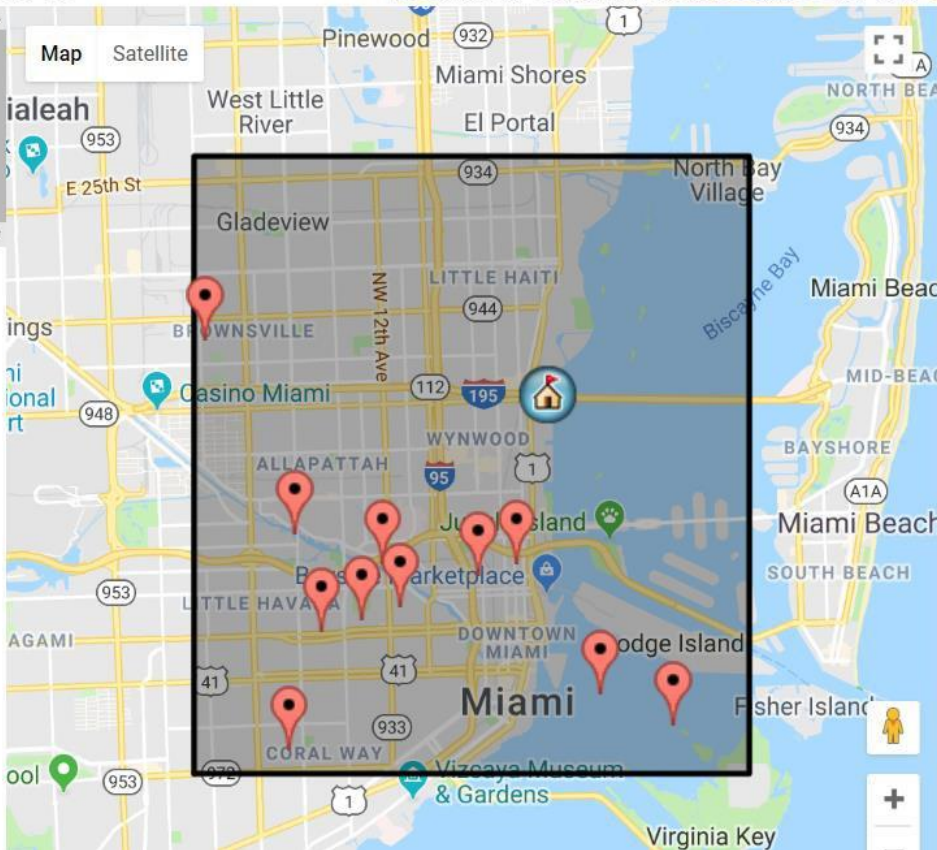
Data Table and Map

Timeline Graph

- Click on map to select new tile -

[Download Summary Data: [CSV](#) / [JSON](#) / [XML](#)]

DATE (UTC)	NUM
Aug 11, 2017	1
Sep 9, 2017	1
Jul 20, 2017	3
May 14, 2017	1
Sep 10, 2017	11



3rd Failure Site

2200 N. Ocean Boulevard, Fort Lauderdale, fl

Select Year and Dataset

2017 Tornado Signatures from NEXRAD (Level-III TVS Product)

Data Table and Map

Timeline Graph

- Click on map to select new tile -

[Download Summary Data: [CSV](#) / [JSON](#) / [XML](#)]

DATE (UTC)	NUM
Jun 5, 2017	1
Sep 9, 2017	1
Jan 23, 2017	2
Jun 7, 2017	2
Jun 6, 2017	5
Sep 10, 2017	25
Aug 11, 2017	2

