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Forensic Engineering Investigation and Analysis of a Tower Crane Collapse

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Abstract

Tower cranes are popular and one of the predominant methods of material handling in high rise building construction. When there is a collapse of a tower crane in a city like New York, it is very visible, receives intense scrutiny, and becomes potentially political. This paper examines a 250-foot-tall tower crane collapse during the jumping phase of the crane to increase its height in support of a multi-level building construction. The author's investigation examines the "defective sling" claim as the primary cause of the crane collapse along with some key findings and opinions regarding the slings used to rig the collar tie to the tower section of the crane.

Keywords

Ultraviolet, isothermal, slings, tower crane, adiabatic, brittleness, shock load, synthetic

Introduction

This incident investigation looked at the claims made by the People of New York versus the accused master rigger that the 303 51st Street crane collapse (which occurred on 03/15/2008) was a result of an ultraviolet (UV)-degraded sling used to rig a critical 18th floor collar tie. The implication of the UV degradation was the sling did not have the capacity to support the collar tie to which it was attached. In turn, it was implied that the lack of lift capacity in the degraded sling resulted in overload failure. As alleged, this degraded sling failure caused the three remaining slings to fail, resulting in the 18th floor collar tie sliding down the crane tower and rupturing the lower collar ties' rigging on the ninth and third floors. The loss of the rigged collar tie attachments between the building and the crane tower caused the crane to collapse catastrophically.

The following analysis of the rigging associated with the collar tie was accomplished in three categories:

a. Sling inspection findings
b. Sling ultraviolet degradation and load carrying capacity
c. Defense sling test findings

The findings of the investigation did not support the claim that the sling was defective due to ultraviolet degradation. Analysis showed that even if the sling was UV degraded, the loss in lift capacity was insufficient to result in sling failure and ultimately the collapse of the crane.

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Tower Crane Configuration Change, Jumping Process

During building construction, as the height of the building changes, there is a requirement to increase the tower sections of the crane. Increasing the crane tower sections (or lowering the crane tower sections) is called "jumping" the crane. **Figure 1** shows the tower sections of the crane going from 18 stories on the left to 28 stories on the right. The jumping process is made up of several steps that can be categorized principally by two phases. The first phase increases the number of sections in the crane tower to a specific height as determined by the engineer of record. The second phase addresses the installation of the collar tie to the crane tower and secures the collar tie and crane to the building. **Figure 1** also shows three highlighted sections where the crane tower is attached to the building.

Typically, tower cranes are configured for one of two jumping methods — internal or external to the building. This case involves the external jumping process. **Figure 2** below gives a typical climbing arrangement and description of the jumping process to increase or decrease the number of tower sections. Phase 1 of the jumping process is as described:

a. Install climbing collars and ladder. Balance the crane upper, remove the base bolts, and raise the crane using hydraulic rams attached between collar and tower, allowing the climbing supports to skid past and then rest on a ladder rung. Repeat climbing the ladder in this manner, as required.

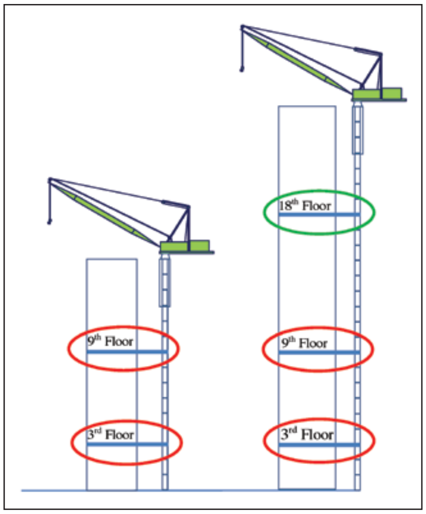

Figure 1
Diagram of tower crane at different elevated heights.

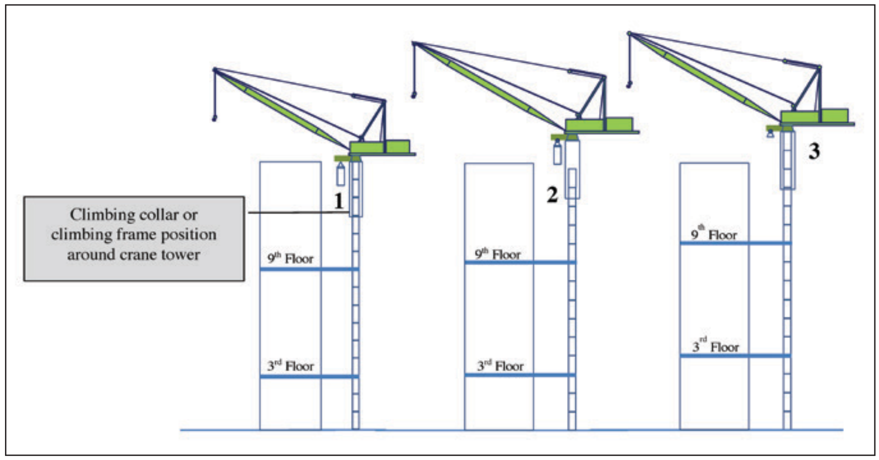

Figure 2
Diagrammatic jumping setup used to change the tower crane height.

b. Climb through the first collar, and allow the crane supports to rest on the collar. Engage collar chocks to support the crane laterally.

c. Move the ladder to the second collar, and install a third collar.

Once the crane has been extended to the specified height in phase one, the next phase commences. Phase 2 is shown in **Figure 3**, securing the crane tower to the building. **Figure 3** is a diagrammatic layout of the collar tie and tie beam setup with respect to the crane, and building. This arrangement is typically used at the three locations highlighted in **Figure 1** above.

Phase 2 of jumping the crane includes the installation of the collar tie to the tower of the crane followed by the installation of the tie beams. The collar tie is installed at the predetermined locations in two symmetrical halves using the crane, slings, lever hoist, shackles, and taglines. It was during the installation of the tie beams that the crane collapsed, which occurred some 40 minutes after the collar tie was suspended from the crane tower.

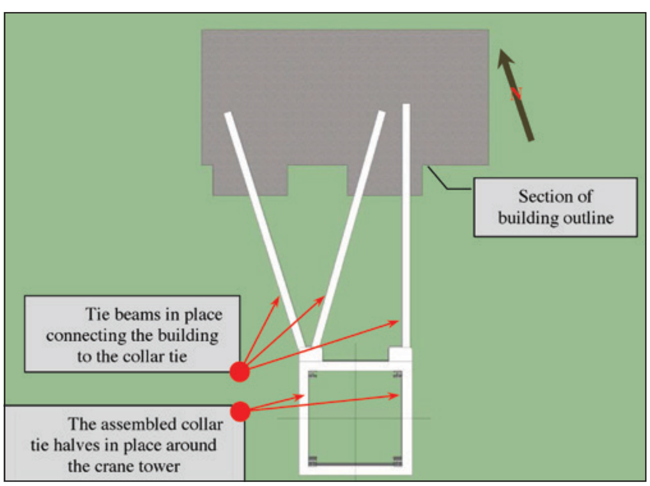

Figure 3
Collar tie and the three tie beams used to secure the crane tower to the building under construction.

There were four slings used in Phase 2 of the jumping process. The sling that was alleged to have caused the incident is described in the following analysis as "Ex_Lift." The other three slings involved in the incident were new, and are described as "All_Lift" slings.

Sling Inspection Finds Melted Fibers and No UV Degradation

Synthetic Sling Inspection

The claim made by many experts was that the defective Ex_Lift sling failed, resulting in the failure of three other slings. The 18th floor collar tie fell, triggering the crane collapse. The author's investigation focused around this allegation made against the company performing the rigging of the collar tie.

Synthetic sling inspection is governed by the Occupational Safety and Health Administration (OSHA). In addition, some key national and industry standards specify inspection requirements. Inspection criteria for polyester synthetic slings are identified in **Figure 4**. A review and comparison of these criteria across the listed organizations show that they are very similar, and the area of focus is highlighted in bold.

Synthetic Web Sling Inspection and Removal from Service Criteria			
REGULATORY AGENCY, OSHA	**ASME B30.9 2006 Edition**	**Manufacturer**	**Web Sling & Tie Down Association (WSTDA) WS-1 2004 Revision, Compiled**
Where any such damage or deterioration is present, remove the sling or attachment from service immediately.	A synthetic webbing sling shall be removed from service if conditions such as the following are present:	The web sling shall be removed from service if any of the following are visible:	A web sling shall be removed from service if any of the following are visible:
Missing or illegible sling identification	Missing or illegible sling identification	Missing or illegible tag	If sling rated capacity or sling material identification is missing or not readable
Acid or caustic burns,	Acid or caustic burns	Acid or caustic burns	Acid or alkalis burn,
Melting or charring of any part of the sling,	Melting or charring of any part of the sling	Melting or charring of any part of the sling	Melting. charring or weld spatters on any part of the web sling
Holes, tears, cuts, or snags,	Holes, tears, cuts, or snags	Holes, tears, cuts, snags or embedded articles	Holes, tears, cut, snags or embedded particles
Broken or worn stitching in load bearing splices,	Broken or worn stitching in load bearing splices	Broken or worn stitching in load bearing splices	Broken or worn stitching in load bearing splices
Excessive abrasive wear,	Excessive abrasive wear	Excessive abrasive wear	Excessive abrasive wear
Knots in any part of the sling,	Knots in any part of the sling	Knots in any part of the sling	Knots in any part of the web sling
Discoloration and brittle or stiff areas on any part of the sling,	**Discoloration and brittle or stiff areas on any part of the sling, which may mean chemical or ultraviolet/ sunlight damage**	**Discoloration and brittle or stiff areas on any part of the sling, which may indicate chemical or ultraviolet/ sunlight damage**	**Some visual indications of sunlight or ultraviolet degradation are:** 1. **Bleaching out of web sling color** 2. **Increased stiffness of web sling material** 3. **Surface abrasion in areas not normally in contact with the load**
Pitted, corroded, cracked, bent, twisted, gouged, or broken fittings, and	Fittings that are pitted, corroded, cracked, bent, twisted, gouged, or broken	Fittings that display excessive pitting, corrosion, or are cracked, bent, twisted, gouged or broken	Excessive pitting or corrosion or cracked, distorted, or broken fittings.
	For hooks, removal criteria as stated in ASME B30.10	For hooks – see ASME B30.10 for removal criteria	
	For rigging hardware, removal criteria as stated in ASME B30.26	For fittings – see ASME B30.26 for removal criteria	
Other conditions that cause doubt as to continued use of a sling.	Other conditions, including visible damage, that cause doubt as to the continued use of the sling	Other conditions and/or visible damage that cause doubt as to the continued use of the sling.	Any other visible damage that causes doubt as to the strength of the sling.
			Proof Testing Warning: Slings used in environments where they are subject to continuous exposure to sunlight or ultraviolet light shall be proof tested to twice the rated capacity semi-annually or more frequently depending on severity of exposure.

Figure 4
Inspection criteria for synthetic polyester sling.

Correctly applying any of the specified inspection requirements is expected to lead to a consistent outcome with regard to sling usability. Thus, the application of these specific criteria and the Web Sling & Tie Down Association (WSTDA) 1994 video resulted in the findings below.

Using **Figure 4** criteria, the inspection of the sling was conducted around May 2010. Following are the findings. **Figures 5** through **8** highlight aspects of the visual inspection conducted on the Ex_Lift sling.

a. Sling color was uniform, consistent with normal usage, wear, and tear.

b. The sling surface was dirty, consistent with a construction environment, such as the incident site where the sling was retrieved.

c. The sling showed two key distinct areas of damage.
   i. One sling eye was missing. The sling eye was completely severed at stitched location of the three-ply load-bearing splice.
   ii. There were contact abrasion lines on the face of the sling diagonal to the sling's longitudinal axis.

d. When the eye of the sling at the stitching was opened up and inspected, the color was consistent with the rest of the sling. A bleached sling typically shows drastic color and texture contrast between the body of the sling and the location where ply of the eyes are sewn together. None was observed.

e. Bleaching of the sling was not observed or consistent with published standards:
   i. Regulatory agency
   ii. ASME
   iii. Manufacturer
   iv. WSTDA

f. The sling stiffness and or brittleness showed no discernable difference when compared to the All_Lift slings that were regarded as new at the time of the incident.
   i. A brittleness check was conducted on the Ex_Lift sling by rubbing the sling surfaces to dislodge its fibers. No signs of brittleness were detected.

g. The sheared ends of the sling sections showed a substantial melting of the material fibers.

A similar inspection was done on the All_Lift slings. Besides the structural damage to slings, the findings were unremarkable, including the comparative fading of several of the retrieved sections. The Ex_Lift sling did not show any clear visual signs of UV degradation as claimed by the city's building department report.

Ex_Lift Sling Inspection Findings

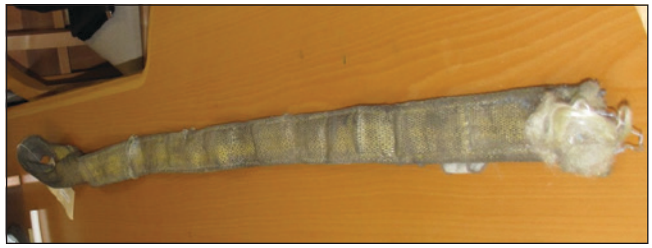

Figure 5
Ex_Lift sling section retrieved after crane incident.

Figure 6
Label of the sling is intact, and information is readable.

Figure 7
The intact eye of sling showing wear pad and color consistent with other photos.

Figure 8
Abrasion contact mark on the sling face.

A leading authority on synthetic slings, the WSTDA has produced several publications and videos on slings, including an educational video that shows an inspection protocol for polyester slings with tips for recognition of UV-degraded slings. The excerpts in **Figure 9** and **Figure 10** are examples from the video identifying UV-degraded slings. **Figure 10** shows a comparison of the Ex_Lift sling and a WSTDA UV-degraded sling. Note the distinct bleached appearance of the WSTDA sling versus the intact color of the Ex_Lift sling. The most significant finding from the Ex_Lift sling inspection was that the stiffness and brittleness was comparable to the All_Lift slings that were regarded as newer.

The review and comparison of the Ex_Lift sling to both the WSTDA sling inspection protocol for UV-degraded slings and the newer All_Lift slings showed no UV degradation present, surface abrasion, stiffness, bleaching, or brittleness.

Sling Inspection Inconsistency, New Slings Show Signs of Fading

An inspection of two of the All_Lift sling sections, 2A and 4A, showed similar characteristics to the Ex_Lift sling — color fading, which could have resulted from exposure to water followed by drying. See **Figure 11** through **Figure 13** (items labeled 7A and #11). Of particular interest were two sections of the sling that were faded. Had the larger matching sections not been retrieved, would the inspectors also conclude UV degradation? Bleaching condition of the sling rather than color fading is one measure of UV degradation. To conclude that the two highlighted sections were UV degraded, the other factors would need to be present, including increased stiffness, brittleness, and abrasion. Of course, the obvious fact that the slings were new at the time of the incident excludes the UV findings.

WSTDA 1994 Video Inspection of Ultraviolet-Degraded Slings

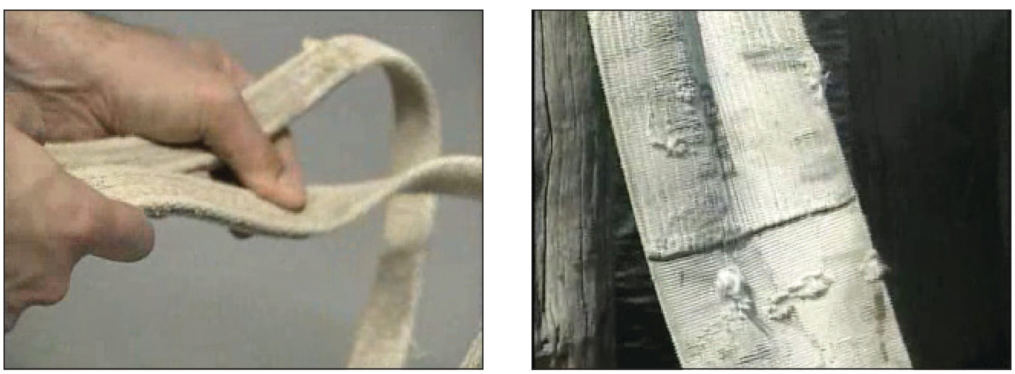

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Figure 9
Signs of bleaching, abrasions, stiffness, and brittleness indicated by UV degradation.

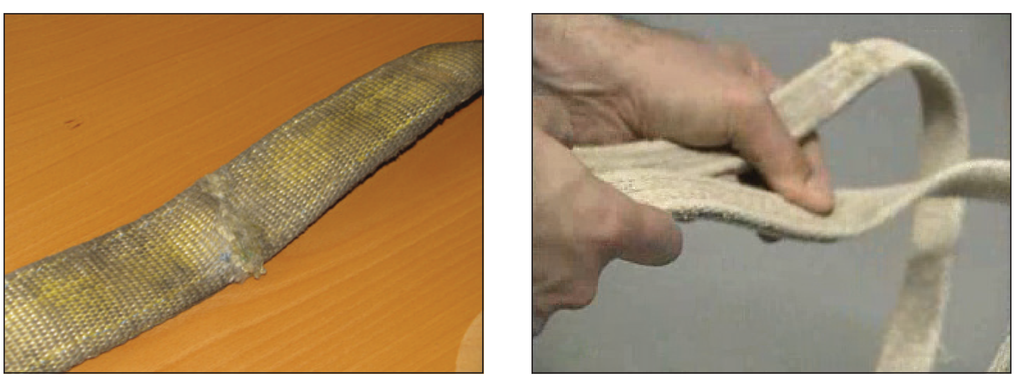

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Figure 10
Shows a side-by-side comparison of Ex_Lift sling on the left and bleached UV-degraded sling on the right.

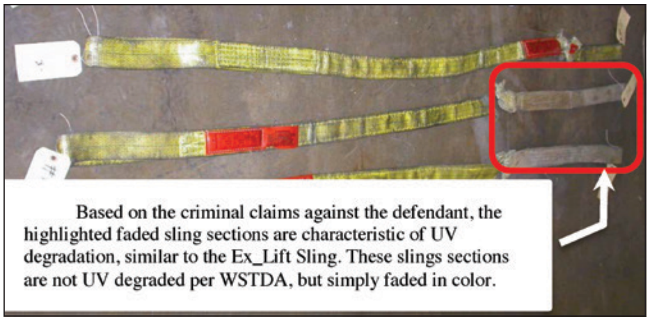


Figure 11
The highlighted faded sections should be regarded as UV-degraded based on the report's criteria. Color fading was used to evaluate the Ex_Lift.

Figure 12
The retrieved section of the All_Lift slings showing the faded characteristics versus bleaching of the sling.

Figure 13
The faded color of the All_Lift slings, 7A, #12, and #13 shown above did not experience the texture change of stiffness and brittleness that typically accompanies UV degradation.

Sling Inspection Conclusion

Evaluation of synthetic sling failures is very much predicated on several factors laid out by regulatory bodies, consensus standards, and manufacturer associations. Sling fading — used as a criterion to assess the Ex_Lift sling as being UV degraded — is not supported by any of the reviewed documents, including those from the WSTDA. Additional factors would need to be present at the time of inspection and evaluation of the sling to indicate UV degradation conclusively. In **Figure 13,** two of the three All_Lift slings (considered new at the time of the incident) had failed sections that were faded compared to their longer sections. These slings were considered to have been properly stored after the incident. These All_Lift slings were not deemed UV degraded. Slings that are UV degraded not only undergo bleaching, but that bleaching is also typically accompanied by a textural change of the polyester material: stiffness and brittleness. The inspection performed on the slings' sections that failed showed no visible UV degradation based on the prevailing standards and regulations.

Sling UV Degradation, Regulatory Agency Test Results, and Sling Load Carrying Capacity

Ex_Lift Sling Construction and Data

Figure 14 includes the data from the Ex_Lift sling used in lifting the 11,280-pound collar tie on the crane tower. The Ex_Lift sling is one of four slings used in lifting the collar tie at the time of the tower crane collapse.

One of the key characteristics to be noted is that the polyester webbing used to fabricate the sling is rated at 9,800 pounds/inch minimum — based on the number 9 in the EE292 number in line item 1 of **Figure 14**. The sling webbing is two ply — with each ply 2 inches wide — so the maximum rated strength of the two-ply webbing is 39,200 pounds. This capacity assumes the efficiency of the load bearing three-ply splice stitching and fabrication of the sling to be 100%.

Sling Properties and Characteristics, Manufactured by Ex_Lift		
1	Model	
2	Manufacture Date	07/03/2006
	Sling Load Bearing Capacities, Design	
	Hitch	**Rated Capacities per Tag, Pounds**
3	Vertical	6,400
4	Choke	5,100
5	Basket	12,800
6	Minimum Breaking Strength, 5:1 Safety Factor	32,000 = (5 x 6,400)
7	Ply, minimum number of plies (Splice ply = 3)	2
8	Webbing	Polyester
	Sling Rating Based on WSTDA	
8	WSTDA Ply Rating for Class 7 Polyester, Ex_Lift Sling	9,800 pounds/inch
9	Polyester Webbing Design Breaking Strength for Class 7—9,800 pounds/inch width. Total (4 inch x 9,800) =	39,200 pounds, (4 x 9,800 = 39,200 pounds)
10	Fabrication efficiency = 32,000/39,200	~82%

Figure 14
Listing of some properties of the Ex_Lift sling reported to be UV degraded.

Line item 3 of **Figure 14**, the sling strength is 32,000 (6,400 x 5) pounds or a fabrication efficiency of approximately 82% under tensile failure. It is important to note there are no other failure modes, such as shear or compression, identified for the sling. **Figure 15** provides the three lift capacity ratings for the sling in three configurations.

The Ex_Lift sling exceeds the WSTDA WS-1 standard rated capacity for Class 7 polyester sling shown in **Figure 15**. It is important to note that the slings' working load limit (WLL) is based on the webbing material tensile strength and fabrication efficiency. However, there are no equivalent documented shear properties for synthetic slings published. Most slings subjected to shear are based on the sling's configuration and use that is not a characteristic of the synthetic polyester webbing.

Two-Inch Polyester Synthetic Sling-Rated Capacity by Hitch, Tensile Loads in Pounds, WSTDA Comparison			
Sling Manufacturer	Vertical	Choker = 80% of Vertical	Basket
Ex_Lift	6,400	5,100	12,800
WSTDA WS-1 2005 Table 7A	6,200	4,920	12,400

Figure 15
Sling tensile-rated capacity by hitch.

Ultraviolet Degradation

The WSTDA conducted an extensive ultraviolet degradation study of synthetic slings in 1981. Excerpts of the findings are presented below. **Figure 16** shows the UVB radiation by city. Of the U.S. cities shown, Miami has the highest radiation level, which is some 40% greater than New York City.

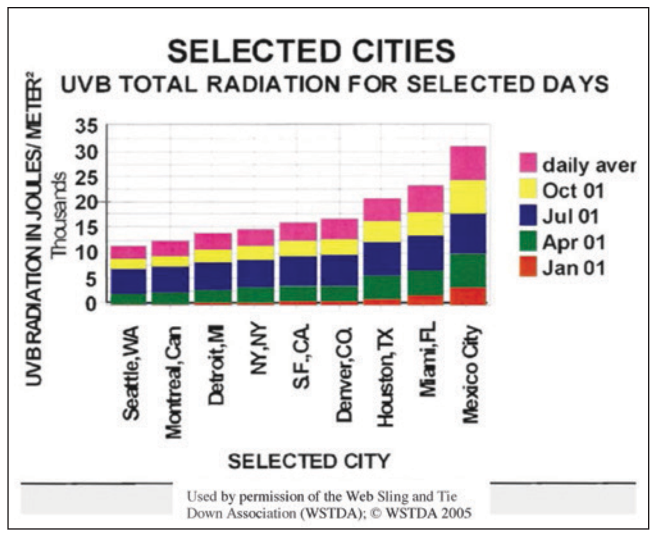


Figure 16
UV energy radiation by location in United States and Mexico. NYC UV radiation energy is approximately 60% of that in Miami.

Based on the WSTDA study, the Ex_Lift sling would have had to be sitting in the New York City sunlight for some 20 continuous months to have an equivalent 12-month UV exposure to Miami radiation or in some equivalent environment.

Figure 17 shows the reduction in breaking strength measured in WLL versus months of UV exposure. The maximum loss in WLL occurs around 12 months of exposure for polyester slings. Further exposure to UV radiation did not show any appreciable degradation below 3.7 times the WLL in 36 months. After 12 months of UV exposure, the breaking strength of the sling has been reduced by approximately 26%. The WSTDA test establishes a relationship between UV exposure and reduction in sling strength for polyester synthetic slings through destructive testing. Because the subject sling was manufactured on 07/03/2006 — and the incident occurred on 03/15/2008 — the worst-case UV exposure can be estimated at approximately 20 months in New York. Given this worst-case assumption, the reduction in tensile strength can be estimated. The decline in design factor can be estimated from 5 to 1 — to a safety factor of approximately 3.7 to 1. The breaking strength of the Ex_Lift polyester slings exposed to UV radiation can be estimated from **Figure 17** as 3.7 times WLL, which is equal to 3.7 x 6,400 pounds or 23,680 pounds. The strength retained by the assumed UV-exposed sling exceeds the proof load test of 200% of the WLL or 12,800 pounds required by manufacturers and the WSTDA for slings consistently used in a UV environment. The proof load testing of slings used in a UV environment confirms that there is no clear non-destructive method of establishing any level of UV degradation for a synthetic sling.

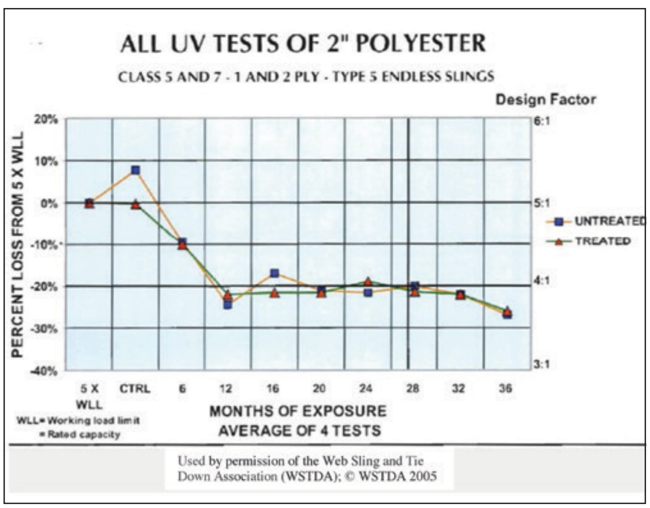


Figure 17
WSTDA graph of breaking strength loss versus months of continuous UV exposure.

A review of the manufacturer's documentation notes that slings used in environments where they are subject to continuous exposure of ultraviolet light should be tested to two times their rated capacities annually — or more often, as required. The test requirement recommended by manufacturers recognizes that UV degradation presented in **Figure 17** primarily affects the breaking strength of the sling and not necessarily the WLL. Any sling in use that is successfully tested to twice its WLL does not validate or verify UV degradation in that sling. However, the tested sling does have a lift capacity sufficient to handle loads up to (and including) its WLL. UV degradation in exposed slings is confirmed through destructive pull testing. To that end, UV degradation claims must address the following findings as well as the residual strength of the sling noted above. A list of UV degradation issues that were not directly addressed in the crane incident by experts were as follows:

a. The length of time the Ex_Lift sling was exposed to UV degradation.

b. UV radiation exposure by geographic location (New York versus Miami) are not all equal.

c. Polyester slings experience a 26% reduction in breaking strength (maximum).

d. UV-degraded polyester slings are tested to tensile failure and not shear failure.

e. UV degradation in slings is verified through destructive load testing.

f. Manufacturers and industry standards recommend load testing of slings subjected to UV degradation.

The UV degradation claim against the Ex_Lift sling was virtually silent on the above items.

Collar Tie Sling Load Distribution Upper and Lower Limits for Ex_Lift Sling

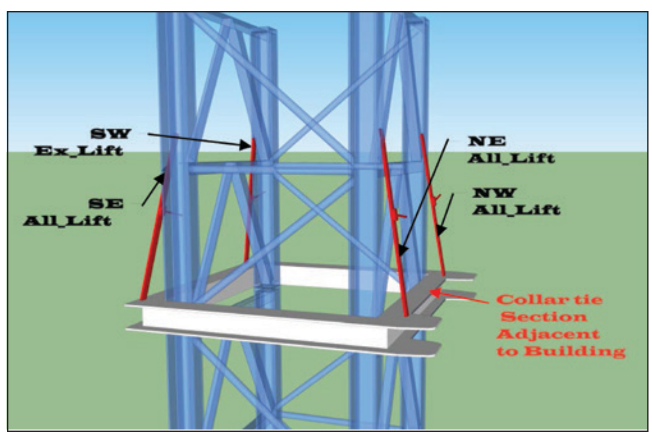


Figure 18
The arrangement of the 11,280-pound collar tie, crane tower, and rigging.

Based on **Figure 18**, the distribution of collar tie weight (11,280 pounds per the manufacturer) on the four slings was unknown at the time of failure. However, an upper and lower limit to the sling loads could be established for the sling in the SW location. The ideal load configuration assumes the total weight of the collar is distributed on the four slings based on the center of gravity and the collar tie symmetry about the center of gravity. The second sling load configuration addressed was based on industry practice where two slings are predominantly carrying the weight of the collar tie. **Figure 19** summarizes the sling load estimates for the two configurations.

Estimated Sling Load Distribution by Crane Tower Location, Pounds				
Sling Location	NW	NE	SW	SE
Ideal Load Configuration	3013	3013	2627	2627
Industry Practice	407	5631	5242	Sling Detached

Figure 19
The load limits on the slings for two configurations.

For ideal load configuration, the SW sling sees a load of approximately 2,627 pounds — much less than the 5,100 pounds the sling is rated for in a choker hitch. For the worst-case load condition, the Ex_Lift choker hitch saw a load of 5,242 pounds or 142 pounds in excess of the sling's rated capacity in a choker hitch. The Ex_Lift sling was reported to be positioned in the SW location on the crane tower. The loads experienced by the Ex_Lift in either configuration did not approach the UV-degraded failure loads: 3.7 x 6,400 or 23,680 pounds, noting the weight of the collar was only 11,280 pounds.

Deficiency of Regulatory Agency-Sponsored Sling Test

The regulatory agency sling test was designed to evaluate the actual configuration the slings were used in lifting the collar tie and the actual tower crane section involved in the incident. The test evaluated nine new All_Lift polyester slings and three new Ex_Lift polyester slings. The test configured the polyester sling in a choker hitch around the tower crane leg and between the support structures as the sling was used on the day of the incident. Absent from the test setup used to pull test the slings was the lever hoist that was an actual part of the collar tie lifting arrangement at the time of the incident. The regulatory agency-sponsored test setup is shown in **Figure 20**.

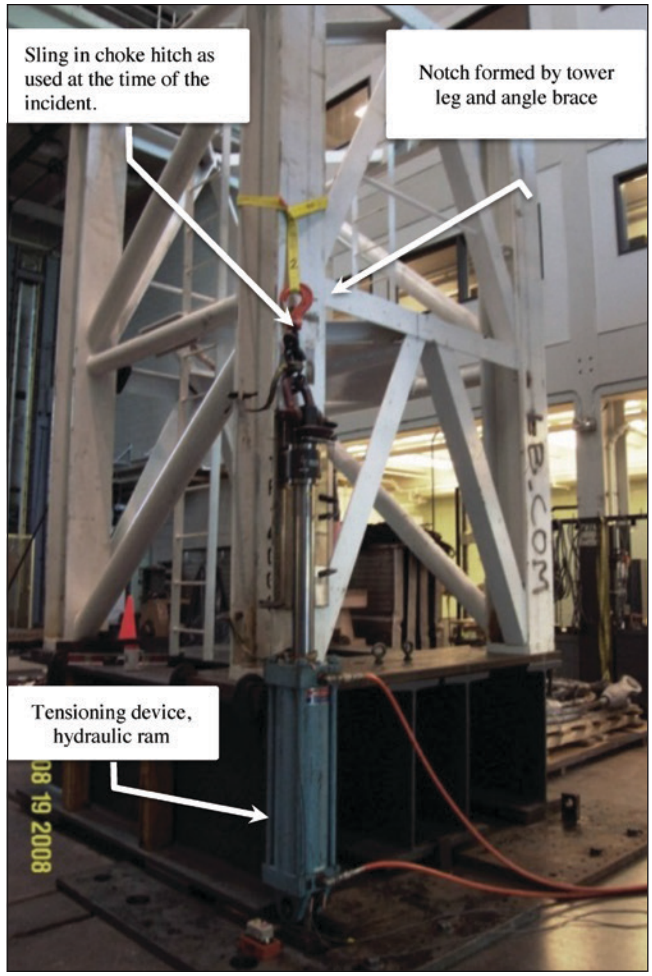


Figure 20
The setup used in the regulatory agency-sponsored test.

Figure 21
Typical sling pulled to failure. The slings failed at the stress riser, as expected.

Figure 20 shows the sling arranged in a choke hitch around the leg of tower section. The sling transits a notch formed by the leg of the crane and the angle brace. The notch is a stress riser on the sling as a load is applied to the sling. The inspection completed on the tower by the testing lab was silent on defects that would contribute to additional stress risers on the EX_Lift sling. An observation to point out here is that the sling tests utilized the same tower section and sling locations as at the time of the incident. Hence, the effects of any stress riser anomalies would be consistent between the sling tests and the incident. The tests were conducted on different corners of the tower, which ruled out any anomalies in the notch of the SW corner.

A summary of sling test results conducted under regulatory agency sponsorship is presented in **Figure 22**. Test number 4, 5, and 7 are the results from exemplar Ex_Lift slings. In each case, the test load exceeded the rated capacity of 5,100 pounds. More importantly, test 7 showed the Ex_Lift sling was able to sustain a minimum of 9,887 pounds. This failure load would have exceeded its share of the collar weight by more than 4,000 pounds if only three slings were used to support the collar tie per industry rigging practice.

Figure 23 presents the load comparison for the subject sling. The test loads obtained by the regulatory agency-sponsored test exceeds the loads the sling experienced lifting the collar tie. In addition, the capacity of the assumed UV-degraded Ex_Lift sling exceeded the regulatory agency test load by more than a factor of two.

However, the test failed to capture one key characteristic that was very evident at the time of the sling inspections and discussed in the textile expert's report — the substantial melting of the fibers found at the sheared or abraded surfaces of the slings.

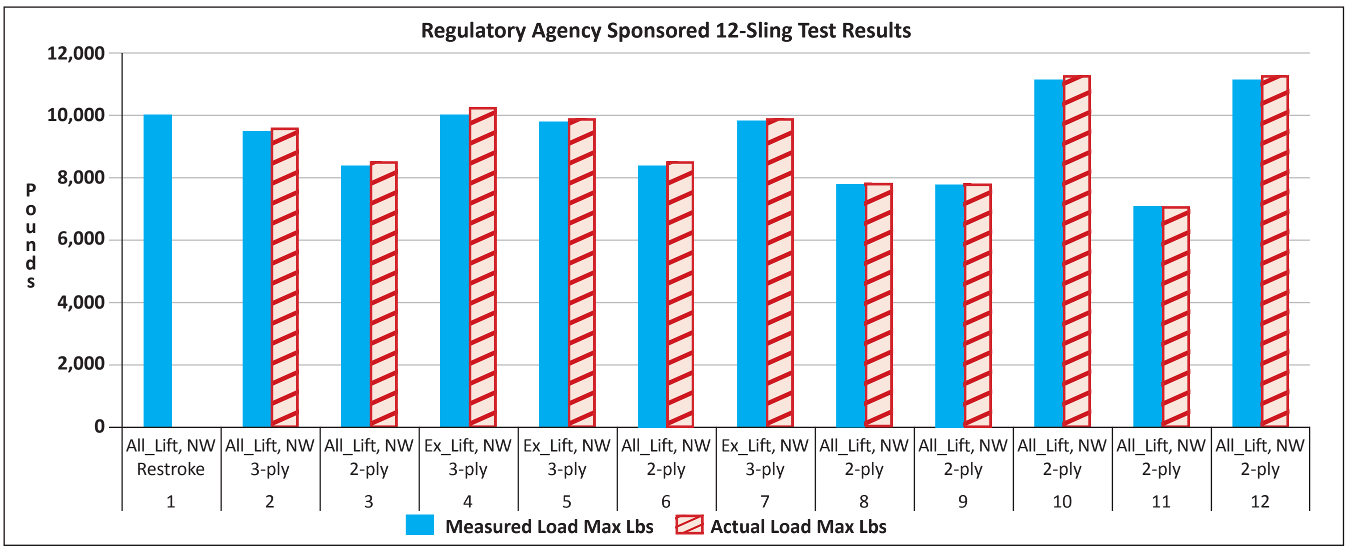


Figure 22
Results of the regulatory agency-sponsored test.

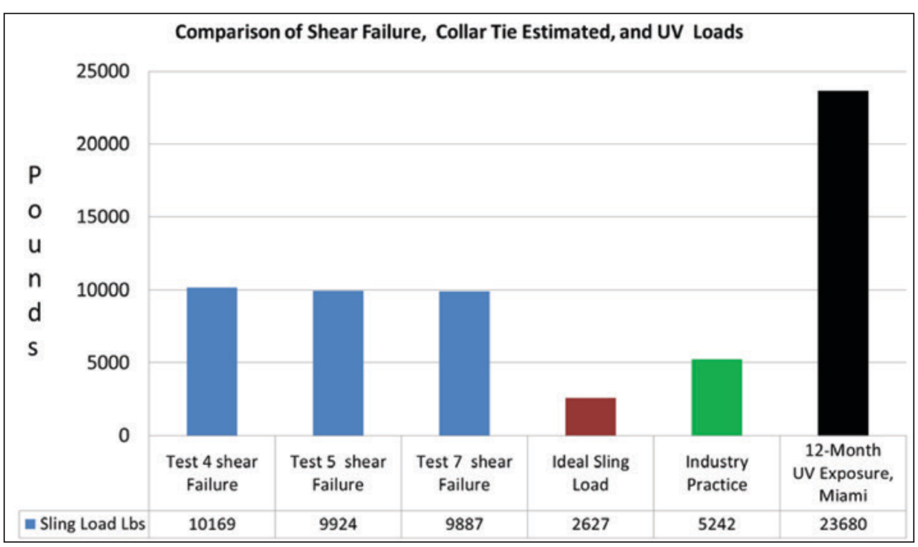


Figure 23
Test load comparison versus slings loads and UV-degraded sling safety factor.

Regulatory Agency-Sponsored Sling Test Limitations

Pictures of sling tests 2 and 4 are presented in **Figure 24** and **Figure 25**, respectively. In each case, the failed surfaces show distress from contact with the crane tower leg and the notch. The abraded and sheared surfaces are consistent with the mechanical failures of the slings retrieved at the incident site. However, neither of the tested slings shows any melted fibers consistent with the slings retrieved at the incident site. The lack of melted fibers across all tested slings suggests that the regulatory agency-sponsored test did not capture the sling's failure process at the time of the incident.

The regulatory agency-sponsored sling test results captured in these photos are regarded as slow-speed failures. These tensile tests were on the order of 10 to 15 minutes in duration in some cases.

The Ex_Lift sling test 4 and 5 conducted on behalf of the regulatory agency had recorded failure times of 1,083 and 1,041 seconds, respectively — a failure rate that is a couple of thousand times slower than a nominal failure time to produce melting of the sling fibers. This failure process that results in melting of the fibers (as noted at the time of the inspection) is called the adiabatic process (defined below).

Adiabatic process: *A thermodynamic process in which there is no transfer of heat between the working substance and the surroundings. An adiabatic process is one that is so rapid that no heat is lost, and the temperature rises accordingly.*

The slings' melted fibers are the strongest evidence that the crane failure is unrelated to the slings and sling configuration used on the collar tie.

In the inspection of the sling designated 2A melted fibers were easily visible, as shown in **Figure 26**. None of the tests conducted on behalf of the regulatory agency showed any level of melted fibers on the sheared ends.

#2, All_Lift Sling Test Visual Results

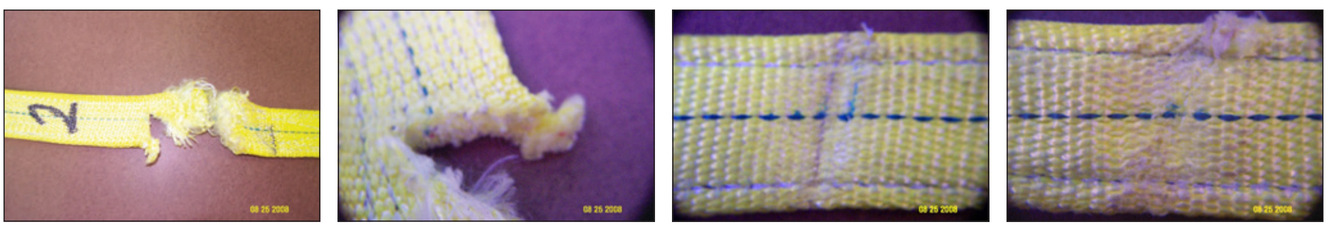


Figure 24
Pictures of the sheared or abraded surfaces of All_Lift Sling #2 test. Note no visible signs of melting on the surfaces.

#4, Ex_Lift Sling Test Visual Results

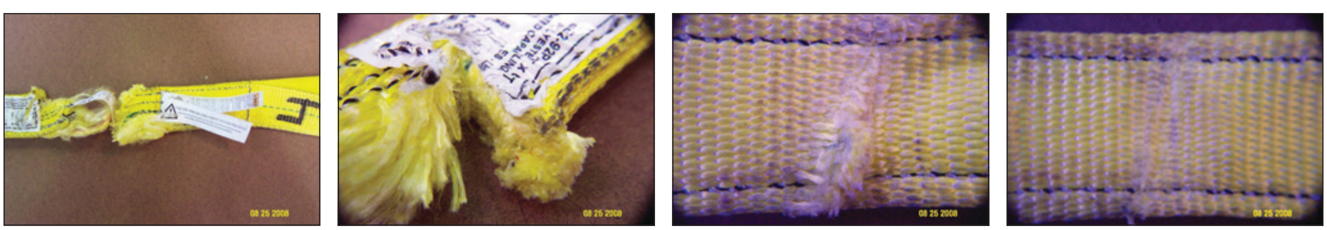


Figure 25
Pictures of the sheared and abraded surfaces of Ex_Lift sling #4 test. Note no visible signs of melting on the surfaces.

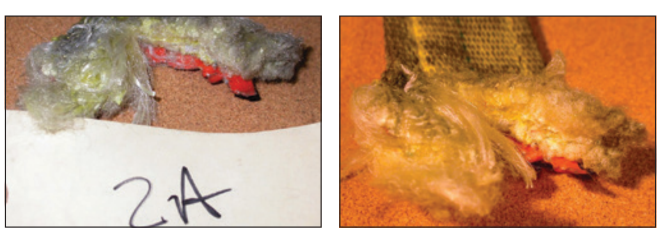


Figure 26
All_Lift Sling 2A sheared surface showing some melted fibers as well as frayed fibers that are a result of tensile failure.

Inspection of All_Lift sling section 4A in **Figure 27** was one of two sections with the greatest amount of visible melted fibers across the sheared surface. Failures of the type shown are typically characterized by rapid application of a tensile load while the material is subject to shear or abrasion. The entire process lasts a fraction of a second, and the melted fibers are a result of the thermodynamic adiabatic process.

The actual sling failure mechanism is similar to the regulatory agency-sponsored test in that they are both shear failures. However, the failure process for the actual slings is thermodynamically different in the application rate of the failure-inducing load. The regulatory agency-sponsored test of the 12 slings is regarded as an isothermal process (constant-temperature process). The rate of application of the test load is more than several minutes, such that the sling temperature remains at or close to ambient. In the case of the sling section 4A, the entire failure process shown in **Figure 27** may be less than a millisecond. In the rigging industry, this type of rapid loading of slings and equipment is called shock loading.

Figure 27 shows the sheared failure surfaces of All_Lift sling sections 4A and 7A. The failure process is similar to that of **Figure 26**, sling section 2A.

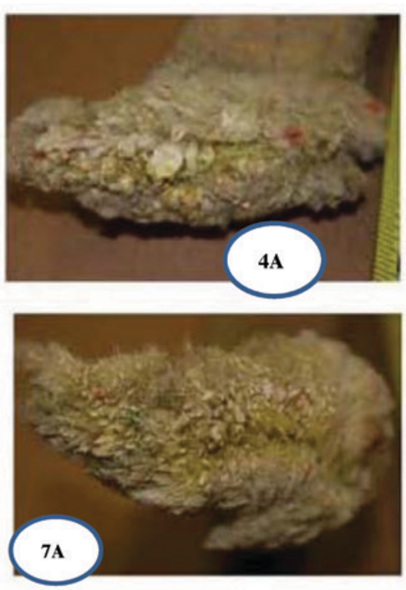


Figure 27
Sheared surfaces of All_Lift sling pieces 4A and 7A.

Figure 28 below shows section #12 and #13. The melted fibers are visible and stands in contrast to the frayed fibers located toward the edge of the sling sections.

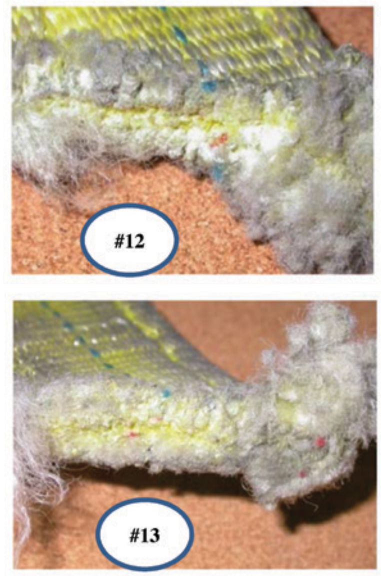
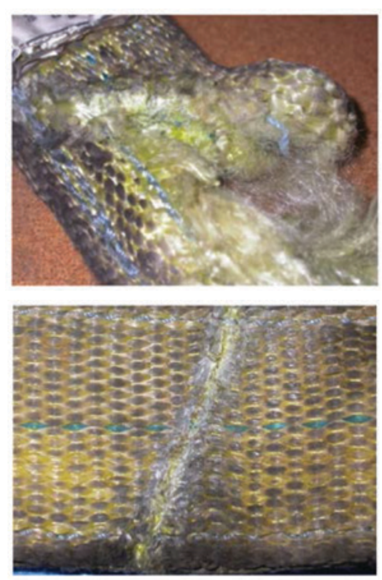


Figure 28
Two All_Lift sling sections #12 and #13. High-speed shear failure process is predominant in both sections.

Finally, **Figure 29** shows two failed sections of the Ex_Lift sling. The top section is the three-ply shear failure surface, and the bottom section is the high-speed abrasion resulting from contact between the sling



Ex_Lift sling section 1A sheared three-ply Ex_Lift sling section 1A abraded

Figure 29
Above is the Ex_Lift sling section 1A, a three-ply adiabatic shear failure with melted fibers. Below is the Ex_Lift sling section 1A with adiabatic abrasion damage.

surface and the edge crane tower leg. The melted fibers are clearly visible to the unaided eye. At the time of inspection, the melted fibers covered more than 70% to 75% of the sheared surface. The common failure process across sling sections 2A, 4A, 7A, #12, and #13 is adiabatic. The long extended frayed fibers are evidence of slow-speed tensile failure that is considered to be a less relevant failure mode based on the amount of material frayed — and one that followed the high-speed failure.

Position of Sling Sections on the Collar Tie and Tower, Rigging Setup

Several incident site photographs were reviewed to determine where sling sections were located just prior to the incident. **Figure 30** shows the SW (southwest) corner of the collapsed crane tower. Suspended from the crane tower section is the Ex_Lift sling 1A attached to the lever hoist.

Figure 30
SW corner with Ex_Lift sling 1A. Visibly extended fibers are evidence of slow-speed failure.

In **Figure 31,** All_Lift sling section 2A is suspended from the collapsed tower. This section combines with All_Lift section 11 to form a complete sling. Note: This sling was the only All_Lift to have been damaged at the red identification tag. In **Figure 32,** sling #12 and #13 identification tags are intact and undamaged.

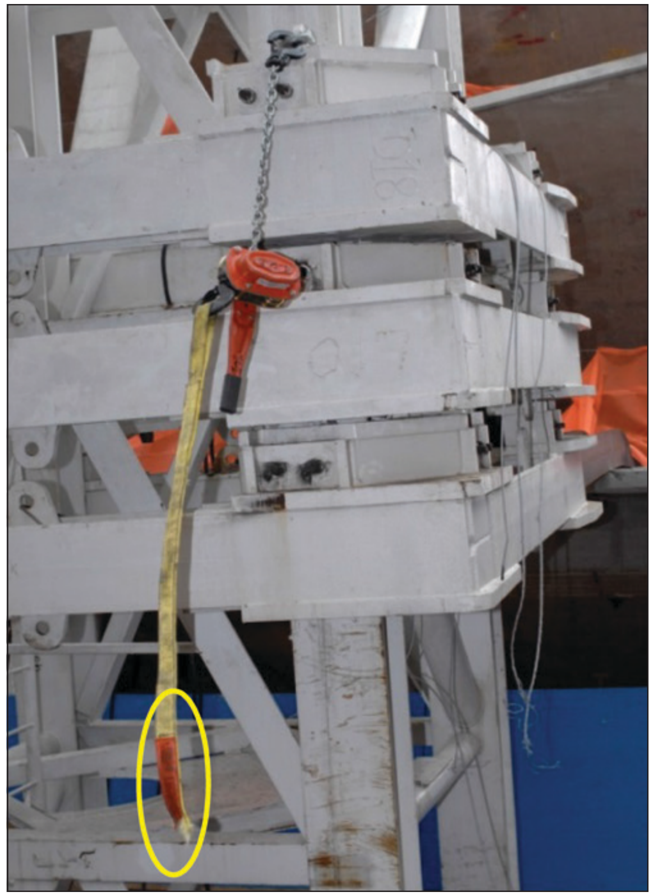


Figure 31
SE corner with All_Lift sling 2A. Extended fibers are evidence of some slow-speed failure as well.

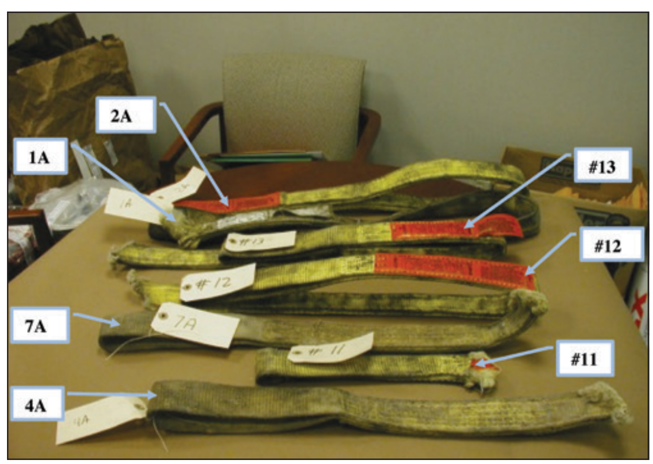


Figure 32
Sling sections retrieved from the incident site. A total of seven sections were retrieved. The Ex_Lift sling 1A, All_Lift slings 2A, 4A, 7A, #11, #12, & #13 tagged and labeled.

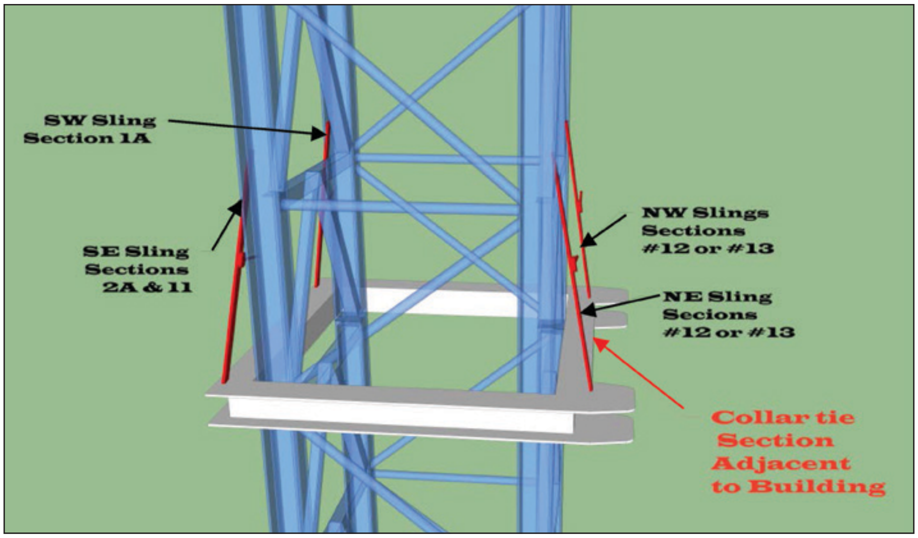


Figure 33
Diagrammatic representation of a section of the crane tower, the collar tie, and sling-lever hoist combination used to rig the collar tie.

Sling + Lever hoist	Manufacturer	Slings Marked	Matching Section	Tower Reference	Leading Failure Mode
NW Sling	All_Lift Sling	#12 or #13	4A or 7A	Building	Shear, high speed, adiabatic
NE Sling	All_Lift Sling	#13 or #12	7A or 4A	Building	Shear, high speed, adiabatic
SW Sling	Ex_Lift Sling	1A	Not retrieved	Road	Shear, high speed, adiabatic, tensile min
SE Sling	All_Lift Sling	2A	#11	Road	Shear, high speed, adiabatic, tensile min

Figure 34
The sling sections retrieved from the incident site, predominant failure modes, and their relative location on the crane tower.

The remaining sling sections #12, #13, 4A and 7A are located on the north side of the crane tower closest to the building to which the crane was attached. In other words, these sling sections were rigged to the collar tie and crane tower closest to the building. The sling section arrangements are shown in **Figure 33** and **Figure 34**.

Based on the adiabatic failure process experienced by the slings that rigged the collar tie to the crane tower, the NW, NE, and SE slings failed before the SW sling. The SW Ex_Lift sling showed substantial slow-speed tensile failure, as can be seen by the frayed extended fibers circled in **Figure 28**.

The analysis presented in foregoing sections shows the following findings: UV degradation (if it were to exist) had no effect on the sling capacity compared to the load imposed by the collar tie; the regulatory agency sling test showed that the capacity of the exemplar Ex_Lift sling exceeded the load imposed by the collar tie; the regulatory agency sling test reproduced the mechanical failures of the slings but did not reproduce the adiabatic failure process experienced by slings at the time of the crane collapse; and the adiabatic failures analysis established that the slings' failure began on the side of the crane tower closest to the building under construction.

Defense Test Supports Sling Strength Findings

The defense conducted a sling test using the following exemplars: a collar tie, crane tower section, and sample of three new All_Lift slings and a used Ex_Lift sling — manufactured on the same date as the one used on the day of the incident. The scope of the test was to produce the failure modes and failure process the slings experienced at the time of the incident and reconcile the regulatory agency-sponsored test results, the textile expert's report, and the simulation of UV degradation in one of slings. The test used a section of the crane tower similar to the regulatory agency-sponsored test and the collar tie from the 18th floor. The collar tie was rigged in a similar manner as the day of the incident.

The test examined the following rigging configurations:

a. Four slings supporting the collar tie for a specified duration — the actual rigging arrangement at the time of the incident.

b. Three slings supporting the collar tie to assess whether or not the slings had the capacity to support the collar tie in this configuration for a specified duration.

c. Four sling supporting the collar with a greater than a 50% cut in the width of Ex_Lift sling to replicate the effects of the UV degradation that were alleged at the time of the incident.

d. Finally, cutting the Ex_Lift sling 100%, simulating the alleged sling failure that resulted in catastrophic collapse of the crane.

Tests c and d were completed on the heavier end of the collar tie, hence using a more severe approach than the claim that the sling on the SW corner of the crane tower failed first.

a. Collar Tie Sling Test Demonstration Setup

Figure 35 through **Figure 45** show the assembly and setup of the crane tower as well as the installation of the collar tie halves in preparation of the first test.

Standing up tower section vertically.

Figure 35
The setup process, tower section.

Installation of sling lever hoist to crane tower leg.

Figure 36
Sling arrangement used to support collar tie.

Load transferred from crane to the slings and lever hoist.

Figure 37
Installation of the collar tie half.

Crane slings slack carrying no load of collar.

Figure 38
Collar tie half transferred from the crane to slings.

Slings from support crane removed from collar tie.

Figure 39
Support crane sling disconnected, and test slings carry the collar tie half.

Collar tie section completely supported on crane tower.

Figure 40
Collar tie half supported by the slings.

Adjusting lever hoist in place to align bolted faces of collar tie.

Figure 41
Two additional slings attached to level the collar tie half.

Second collar tie being setup for bolt up alignment.

Figure 42
Second collar tie being rigged for alignment.

Not a clear view of two of four lever hoist required to assemble the bolted faces of collar tie.

Figure 43
Second collar tie rigged with slings for alignment.

The assembled collar tie bolted out with one of two lever hoist sling combination attached at the bolted face, a manufacturer requirement.

Figure 44
Alignment completed with additional slings disconnected.

Fully assembled collar tie suspended from the crane tower per report.

Figure 45
Collar tie rigged and suspended by four slings.

b. Testing Demonstration

Figure 46
Collar tie test in progress.

Figure 46 shows the completed assembly of rigging and collar tie suspended for approximately 40 minutes to match the elapsed time to failure of the actual setup on the day of the incident. The elapsed time contradicts regulatory agency conclusions that once the collar tie is rigged, the continuous elongation of the polyester slings would require adjustment, hence making synthetic slings incorrect for this rigging operation — no violation of Hooke's law here.

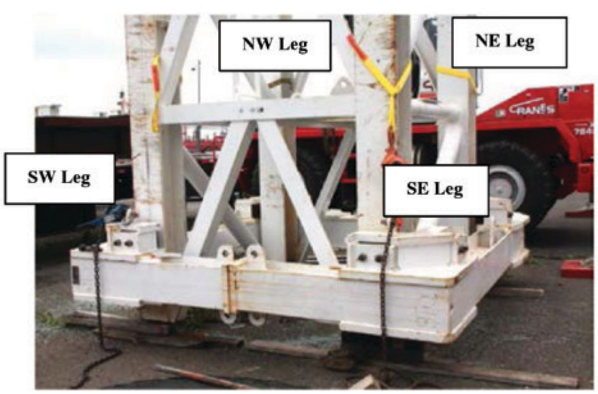


Figure 47
Collar tie suspended from three slings with the SW sling disconnected.

Figure 47 shows the disconnected sling at the SW leg of crane tower. The removal of this sling from the collar tie corresponds to the sling that allegedly failed first, resulting in the failure of the remaining three slings followed by crane collapse. This configuration results in the slings (Ex_Lift sling and All_Lift sling) adjacent to the disconnected slings carrying close to 90% of the collar tie load. This test condition was sustained for more than 20 minutes. The sling directly opposite of the disconnected sling carries a few hundred pounds to balance the collar tie. Based on the geometry of the collar tie, the center of gravity is toward the mobile crane in the background of **Figure 45**.

This test confirmed no catastrophic failure resulted because two slings are capable of carrying the weight of the collar tie with substantial reserve in lifting capacity in the remaining three slings. The industry practice for handling indeterminate load distribution on slings in **Figure 19** predicted this test result.

c. Sling Cut Test

The sling cut test was designed to simulate a sling that was impaired due to UV degradation. The WSTDA sling tests showed slings exposed to UV degradation up to 36 months experienced a reduction of the design

Figure 48
Loaded sling being weakened by cutting.

Figure 49
Weakened sling was cut beyond half its width, weakening more than 50%.

factor of safety. The factor of safety goes from a 5 to 1 on the WLL (ideal) to approximately 3.70 to 1.

The Ex_Lift sling shown in **Figure 48** and **Figure 49** was cut more than 50% of its width (the double blue tread along the width of the sling is regarded as the sling's center line) using a utility knife. The collar tie remained suspended in equilibrium after more than 20 minutes.

Figure 50
Ground clearance is maintained during the static tests using four sling and subsequent three slings.

During the tests performed on the sling, collar tie, and tower, the clearance between the rigged collar tie and the ground was maintained, as shown in **Figure 50**. The clearance between the ground and the collar tie was estimated to be between 14 to 18 inches. Maintaining clearance between the ground and collar tie was essential to ensure the four slings were carrying the total weight of the collar tie. The situation was continuously monitored during each phase of the test.

d. Dynamic Test

Finally, the dynamic test was completed. The initially cut section of the Ex_Lift was cut through the remainder of the way. A sudden drop of the collar tie was experienced, though the three remaining slings did not catastrophically fail. The key factor associated with this test was not only to determine whether the remaining slings would fail in shear but also to assess the failure process.

Figure 51
Shock load being applied to the collar tie rigging.

Figure 52
Post shock load configuration of the suspended collar tie. The collar dropped an estimated 8 inches.

The sling cut, as shown in **Figure 51,** resulted in a dynamic load to the entire system of remaining slings. Additionally, the northwest corner of the collar tie dropped some 8.5 inches, remaining clear above the ground as shown in **Figure 52**. This equilibrium condition was sustained for more than 15 minutes. During the 15 minutes of equilibrium, the remaining slings showed no further elongation.

Sling Test Results

The dynamic test where one sling was cut to replicate a weak, UV-degraded sling was incorrectly performed. The sling that was to be cut was the All_Lift sling located diagonally opposite the Ex_Lift sling. However, by cutting the Ex_Lift sling, the effect was more severe because the Ex_Lift was located on the heavier end of the collar tie. The cutting of this sling dynamically imparted a larger shock load into the remainder of the three slings. The results of the collar tie dynamic test are shown in the photographs. Compared to the regulatory agency-sponsored sling tests and the actual sling failures, the results are unremarkable. The Ex_Lift sling was sheared less than 1/5 its width for the section placed in the notch area after being cut by the utility knife. The All_Lift sling A, as shown in **Figure 53,** adjacent to the Ex_Lift sling B, is on the heavier end of the collar tie. This sling experienced the worst damage of all the slings. This result is expected because the All_Lift sling is one of the two slings carrying the total load of the collar tie. This sling carried about 55% of the total weight of the collar tie after the shock load — it should be noted that shock loads increase loads shared by the slings conservatively by an order of magnitude of 2, minimally.

The results, though expected, are far less remarkable when the failure process is considered. None of the partially sheared surfaces showed visible signs of melted fibers. The melted fibers are the by-product of synthetic fibers undergoing rapid failure that last for milliseconds perhaps — consistent with no heat transfer between the failure surfaces and the environment.

Post Test Results and Conclusions

The following five pictures show the damage to the slings that resulted from the dynamic test. The cuts are less than 50% of the sling width. The damage to the slings was a result of the slings being placed in the notch. The Ex_Lift sling damage in the three-ply area was restricted to shear.

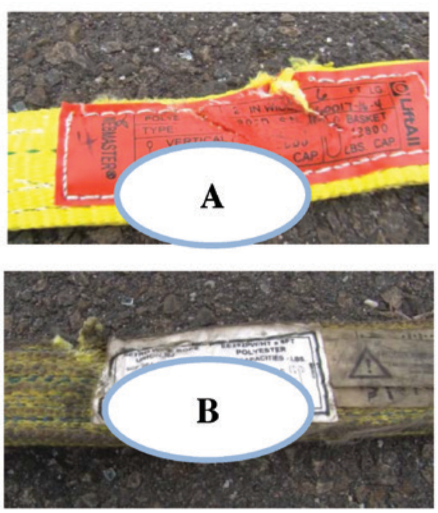


Figure 53
Damage sustained by tested slings. No ultimate slings' failure occurred after one sling was completely cut.

The conclusions of the defense collar tie test were:

a. The slings were capable of supporting the collar tie with reserve capacity.

b. The disconnection of one sling (this equates to a bad sling) from the collar tie showed the remaining three slings had the capacity to carry the weight of the collar tie.

c. The dynamic shock load was less conservative than the New York Department of Buildings' report non-linear analysis. The resulting failure was not enough to cause catastrophic failure of three remaining slings and the ultimate collapse of the crane.

d. Most importantly, the damage to the slings showed no visible adiabatic failures that are predominant in the actual sling failures.

e. The slings showed no appreciable elongation after the shock load; the length measured approximately 72 inches. This finding is contrary to the regulatory agency's expert who noted that these synthetic slings would continue to stretch (violation of Hooke's Law), given their application of lifting the collar tie (a fixed weight).

Conclusions

The findings of the investigation and analysis did not support the claims that the Ex_Lift sling was defective (due to prolonged UV degradation) and lost its lift capacity to support its share of the collar tie weight. The conclusions are as follows:

a. The sling inspection confirmed no visible indications of UV degradation were present.

b. A 36-month, UV-degraded polyester sling had an estimated breaking strength of 3.7 times WLL, which was 4.5 times the worst-case loading of the failed sling.

c. The regulatory agency-sponsored load test confirmed the All_Lift slings alone had more than adequate lift capacity to support the collar tie — had there been a compromise to the Ex_Lift sling.

d. The regulatory agency-sponsored test adequately showed that mechanical failure modes of the tested slings were similar to the slings recovered from the incident.

e. The regulatory agency-sponsored tests were isothermal, and they failed to replicate the adiabatic failure process of the slings involved in the incident.

f. The defense sling test confirmed the regulatory agency-sponsored test:

i. Four slings supported the collar tie.

ii. Three slings supported the collar tie with one sling carrying as little as 407 pounds.

g. The defense sling test showed that shock loading the collar tie and slings did not cause the collar tie to fall and the likely collapse of the tower crane.

h. The defense sling test confirmed that the imparted shock load to the collar tie slings was insufficient to cause the melting of the sling fibers at the sheared surfaces.

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