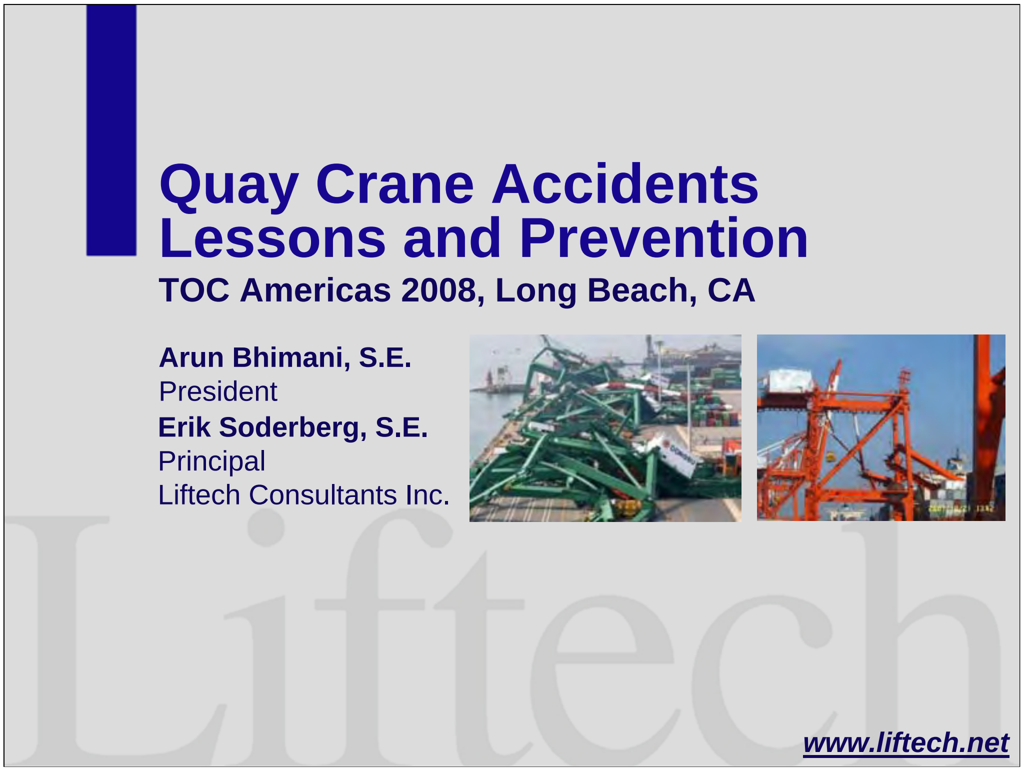

Liftech engineers have been providing structural engineering services to the container crane industry for over 45 years and have experience in many crane failures.

Several catastrophic failures have occurred this year and several others nearly occurred reminding the industry of the risks.

Accidents Related To:

1. Operations
2. Transport
3. Wind
4. Earthquakes
5. Structural Fatigue

We have organized the accidents into the five categories shown. Some overlap.

Agenda

Arun Bhimani

- Operations
- Transport

Erik Soderberg

- Wind
- Earthquake
- Structural Fatigue

Audience

Due to the amount of content we will present, please hold comments and questions until after the presentation.

Details

Incident

Probable Cause

Repairs

Prevention and Mitigation

Generally we will explain an incident, discuss the causes or probable causes, discuss how repairs were made, and suggest prevention and mitigation.

Sources

Liftech Investigations

Industry Media

Industry Contacts

Our sources include investigations we have made, accidents reported in the industry's media, and reports from our industry contacts.

Section One: Operations Accidents

We will start with some accidents that have occurred during operations.

Operation Failures

Collisions With Vessels

Boom Hoist Accidents

Boom Support System Failures - Section 5

Lifting Failures

Runaway Cranes – Section 3

We will discuss five operation failures.

Collisions with Vessels

Boom Collisions

Frame Collisions

Collisions with vessels are broken down into collisions with the crane boom and the crane frame.

Boom Collision Damage

Box Girder Boom

The most common vessel collision is between the ship and crane boom.

The typical damage for a box girder boom with cross framing is presented first.

This collision occurred in New Jersey when a vessel berthed out of control. This type of collision causes severe damage.

The ship impacted the right girder pushing the boom laterally. Despite the severity of the damage, the crane frame was undamaged and the crane did not derail.

The right girder is bent plastically at the impact location. The landside cross beam buckled plastically on either end.

In this instance, the forestay connection plates on the boom and at the apex had permanent lateral deformations.

This slide shows a close up of the buckled portions of the landside cross tie, and the residual rotation at the upper boom hinge (lower left).

Repair Steps: Documentation

Document Damage

- Measure and plot deformed geometry
- Analyze deformed geometry & strains
- Inspect suspect areas

The first step in repair is to document the damage carefully to understand what happened, identify potential damage to other areas, and inspect the damage.

Repair Steps: Restoration

Develop Method and Analyze Options

- Repair members
  - Heat flatten
  - Stiffen
- Replace members
- Repair & Replace

Align Boom

Continually Evaluate Geometry

It is worthwhile to analyze the structure to estimate the loading that caused the damage. This understanding will aid in checking the extent of damage as well as in developing repair procedures.

Repairs typically consist of heat flattening plates, heat straightening entire members, stiffening plates, and replacing sections of members. The repair method depends on the availability of construction cranes and the type of damage. In this example, the contractor preferred to lower the boom on the ground for repairs. The contractor selected to replace the buckled plates instead of heat flattening them. In regions where the construction cranes are not readily available, the repairs may be made in-situ. Heat flattening the plates may be the appropriate choice.

The geometry of the boom must be continually evaluated throughout the repair process to ensure proper alignment.

Remove Damaged Girder Web

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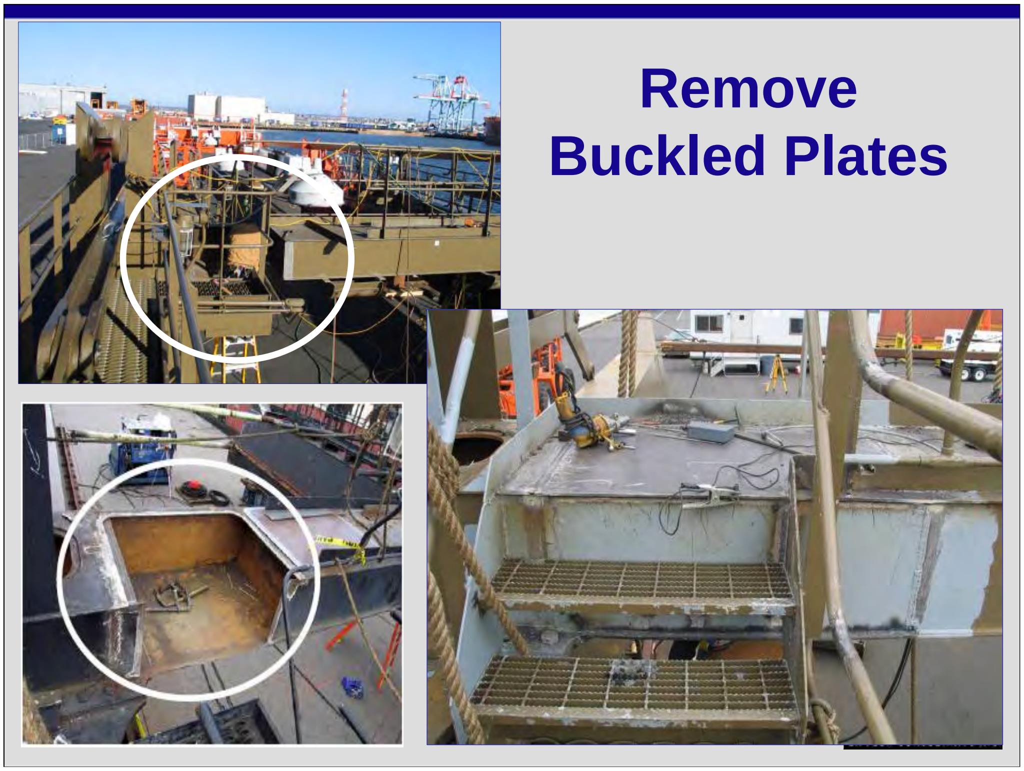
This is an example of replacing a web plate of the main boom girder.



These are examples of replacing buckled plates at the landside boom tie.

Align Boom

Replace Plates

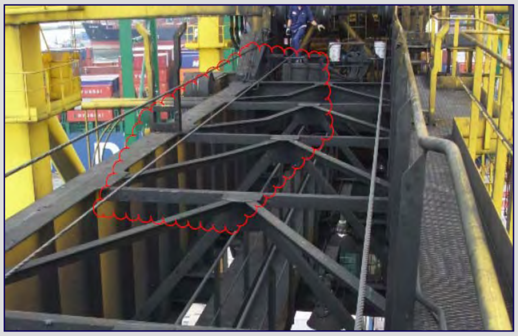
Remove damaged plates for ease in aligning the boom.

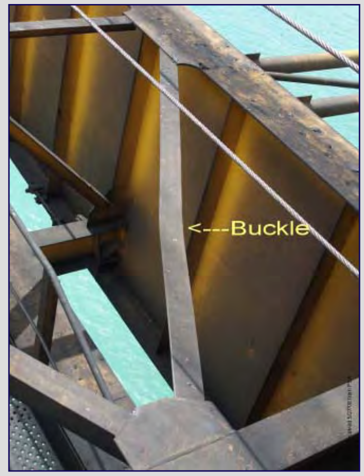
The tie system shown in the left photo was used to rack the boom in plan to realign. The pipe strut was used with a hydraulic jack to separate the boom girders.

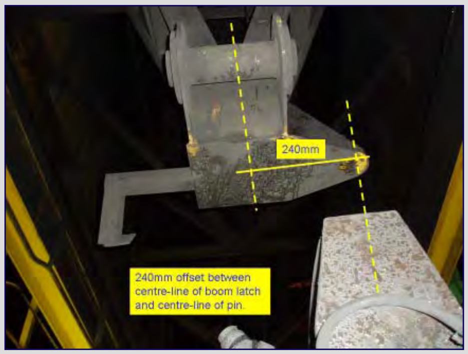
After alignment is complete, plates are replaced.

Truss Boom Damage

Truss boom damage requires a different approach.



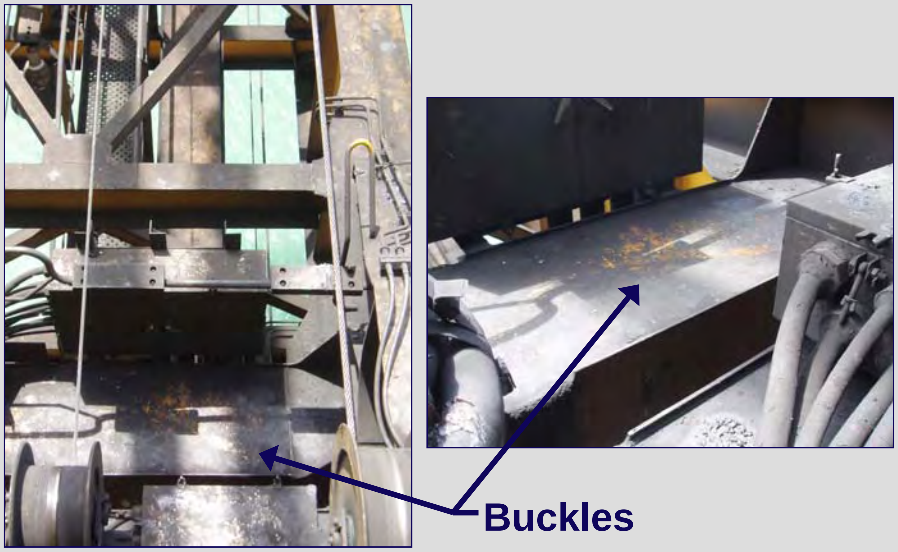




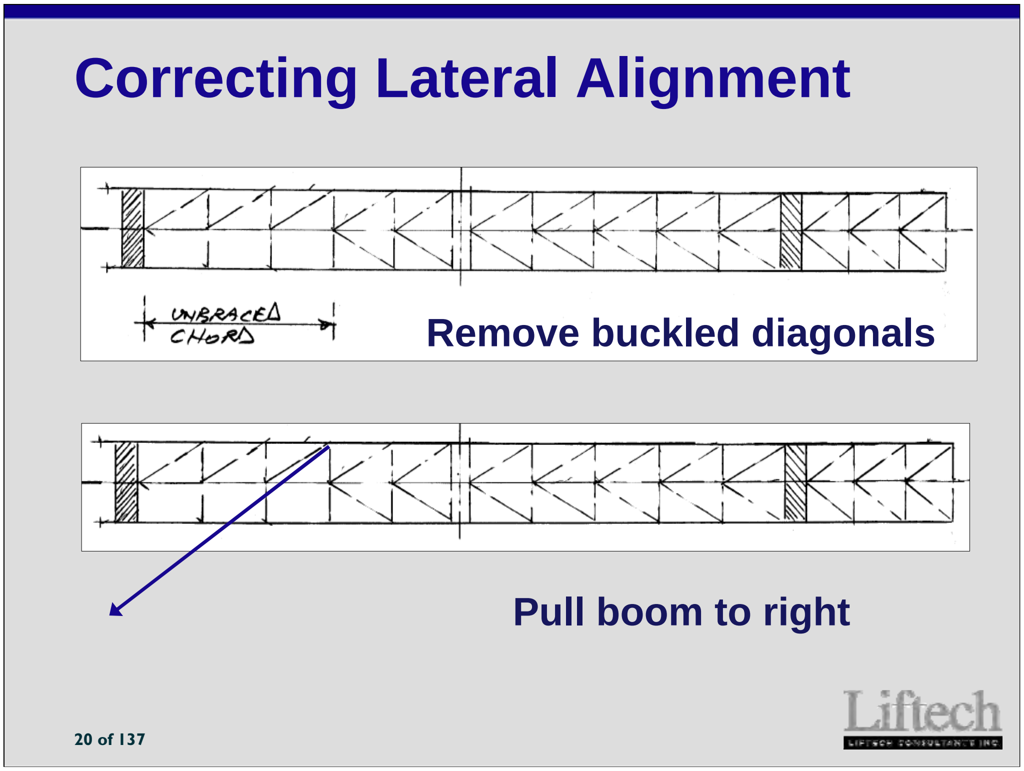
Latch Misaligned

The compression members of the trusswork between the boom girders buckled in the first three bays from the boom hinge. The boom twisted causing a vertical differential between the two sides and the latch to go out of alignment.

Buckled Tie Plates



The tie plates at the boom hinge also buckled.



Repairs involved removing the buckled truss members, pulling the boom to correct lateral alignment, and installing new truss members.

It is important to check the strength and stability of the upper chord of the boom before removing the buckled diagonals. For this repair, the right girder is unbraced for three bays, and a significant aligning load is applied.

Repair Results

Horizontal Alignment Corrected

Vertical Alignment Partially Corrected

- Operationally acceptable
- No further repairs

Repairs restored the horizontal alignment to a satisfactory level. The desired vertical alignment of the trolley runway was not obtained.

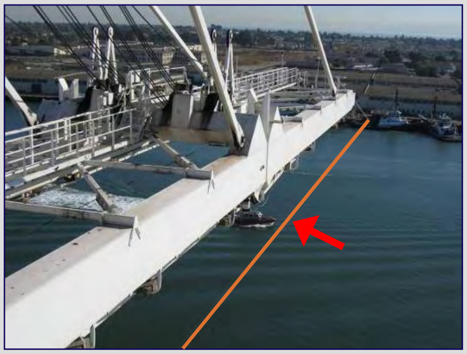
It was determined that the repairs were operationally acceptable. No further repairs were made. The vertical misalignment will cause the boom to twist and introduce additional fatigue stresses in the members. The owner was advised to inspect the boom structure at regular intervals and repair any cracks.

Boom Collision Prevention

Use wire or laser: not 100% reliable

Effectiveness depends on collision speed and detection system

Does not protect against moving vessel



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To mitigate boom collisions, we suggest using a trip wire or a laser system.

Be aware that these systems will not guarantee that collisions will not occur. For example, when vessels move into booms, the system cannot stop the vessel and a collision will still occur. Also, the trip wire may not protect a fast moving crane from collision.

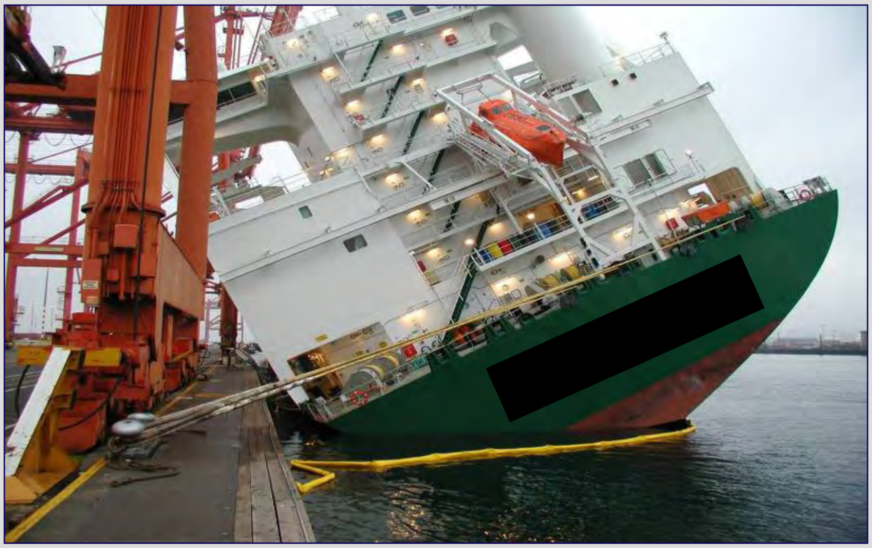
The trip wires require regular maintenance in order to be effective.

Frame Collision – Moving Vessels

Frame collisions are less frequent, but often cause significant damage.

Many collisions occur due to vessels berthing in inclement weather.

Ballast System Failure



A ballasting system failure caused the vessel to list. Fortunately, the ship structure missed the adjacent cranes and caused only minor damage.

Not Catastrophic

Many collisions are not catastrophic. In these instances, the gantrying system broke from the crane but the cranes did not collapse.

Catastrophic

Sometimes the collisions are catastrophic.

Prevention and Mitigation

Difficult to prevent ship accidents

Set waterside gantry rail back from rail face if practical

It is difficult to prevent and mitigate vessel collisions to the frame.

One way is to set the waterside gantry rails back from the face of the wharf to provide additional clearance.

Summary - Collisions

Boom collisions are common

Use boom anti-collision system

Maintain anti-collision system

Important to repair boom alignment

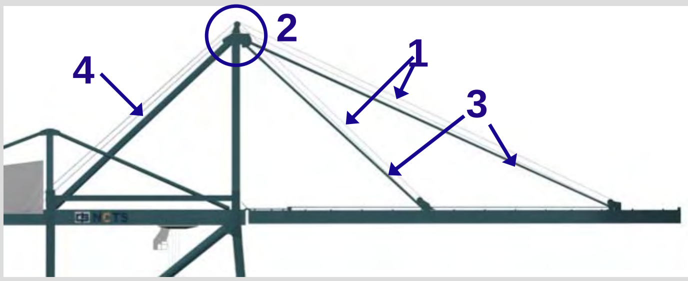
Set waterside rail back from wharf face

In summary, vessel collisions are difficult to prevent. Boom collisions are most common. To mitigate collisions, maintain boom anti-collision systems and set the crane back from the face of the fender if practical.

If damage does occur, it is important to restore the alignment of the trolley runway.

Several boom hoist accidents occurred recently.

Failure Elements



1. Boom hoist reeving
2. Apex structural
3. Forestay system
4. Backstay system

Section 5

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Common failure elements include the hoist reeving, the structure at the apex, and the forestay and backstay systems.

Boom Hoist Reeving Failures

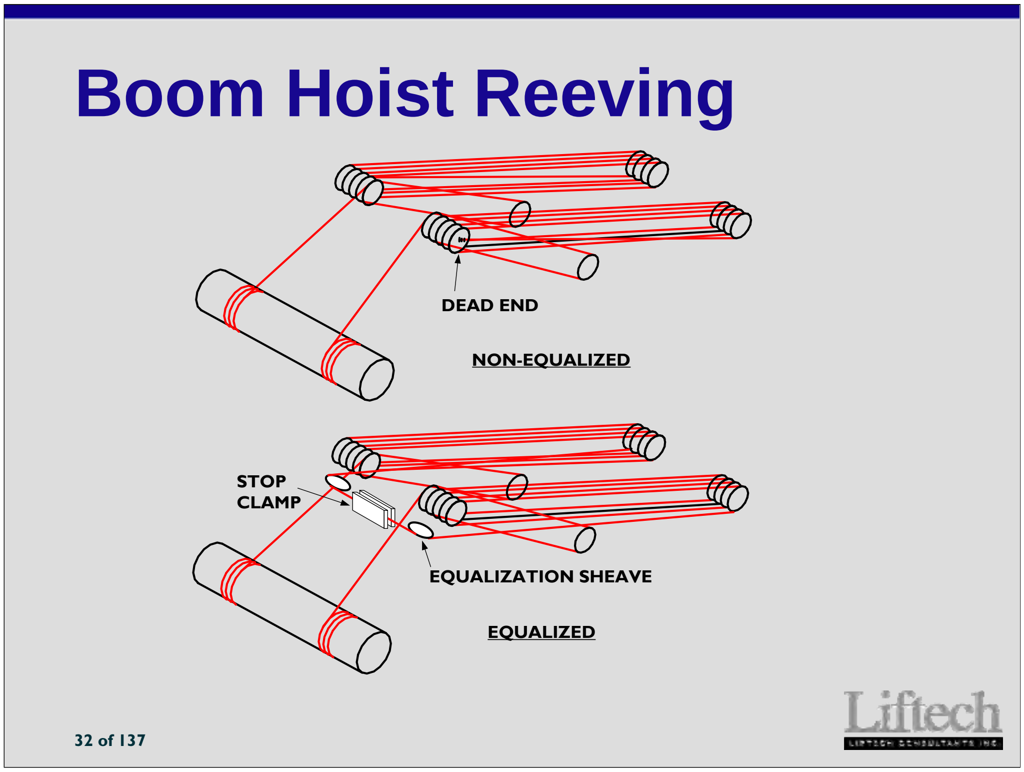
Boom latch malfunction

Rope jumping sheaves

Rope damage

Inadequate rope clamp

Boom hoist system failures have occurred for a variety of reasons. Some include latch malfunctions, ropes jumping sheaves, damage to the rope, and inadequate rope attachments.



Two common hoist reeving methods are shown.

The upper is not equalized; the two sides are independent. The tensions are adjusted using turnbuckles for some cases. The system provides redundancy.

The lower is equalized by using one rope. This is more common. A stop clamp and stops are provided in case one side breaks. If the clamp does not hold the rope, the rope slips through and provides no redundancy.

Recent Failure

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This recent failure occurred with the boom mostly raised. The forestays could not catch the falling boom. The boom landed on the ship and pulled the upper A-frame members.

Boom Hoist + Clamp Failure

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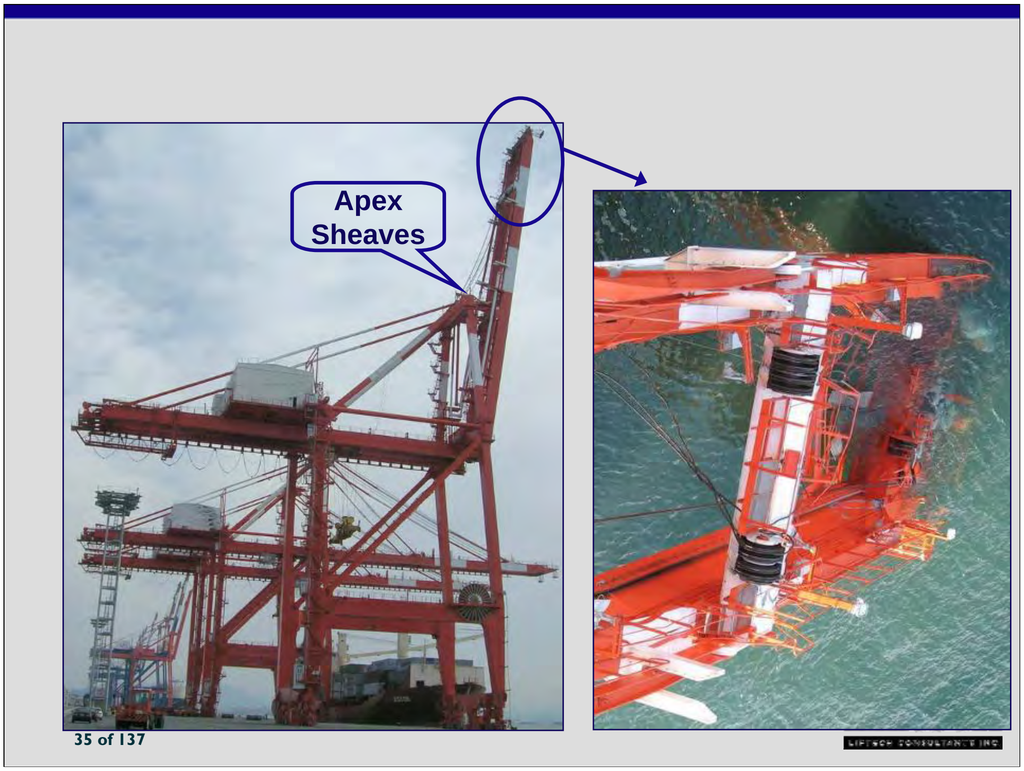
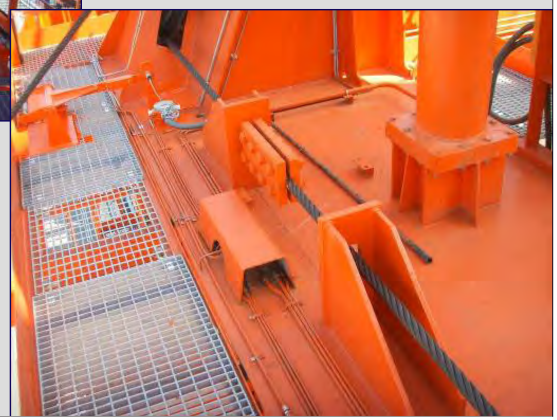
This is the same crane after the failure. The boom and A-frame members separated from the frame.



The photo on the left is of an adjacent crane. Notice the apex sheave.

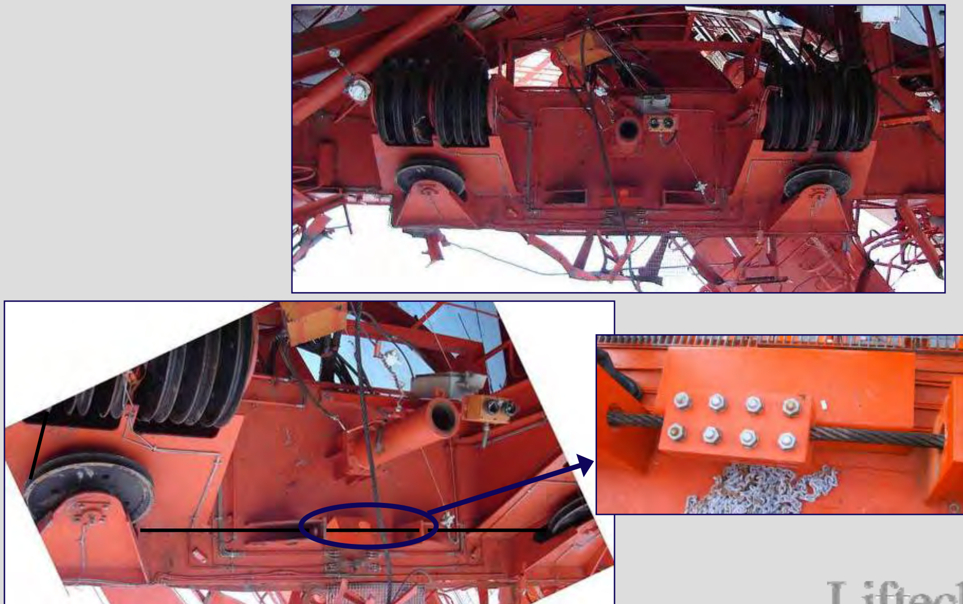
The hoist sheaves on the boom are shown on the failed boom nearly in the water. There was no damage to the sheaves. The rope is damaged.

Apex Sheaves: Adjacent Crane



This photo shows reeving at the apex of the adjacent crane including the stop clamp and stops.

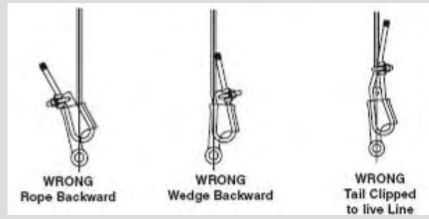
Apex Sheaves: Damaged



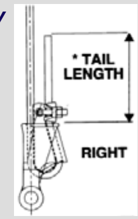
On the failed crane, the rope on the side of the reeving failed. The exact cause of the rope failure is unknown. The rope may have jumped the sheave for some reason. The stop clamp did not hold the rope after the rope broke. The clamp was likely not installed properly.

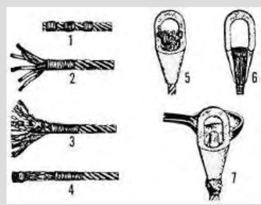
Rope Failures

- Overload
- Connections
  - Sharp edges
  - Improper assembly
  - Corrosion
- Bird-nesting on drum resulting in impact
- Damage from adjacent work, e.g. welding



Source: Crosby





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Ropes fail for many reasons. They can be overloaded from impacts, connections can fail, and they can be compromised from wear and damage.

It is very common to see rope connections improperly installed.

Prevention

Stow Boom on Ropes

Use Stow Pin Instead of Latch

Provide Limit Switch and Slack Rope Detection

Lower Boom from Boom Operating Station

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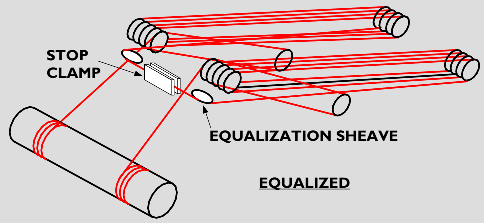
To prevent hoist failures, we suggest stowing the boom on the ropes. If stowing at the apex, use pins instead of latches. Provide limit switches for boom location and for slack rope conditions, and lower booms from the operating station.

Prevention

- Provide redundancy for boom hoist reeving
- Equalize two sides of boom hoist ropes
- Use properly designed clamp and stop
- Design crane structure for one rope breaking
- Inspect connections
- Use inspectable fittings
- Inspect after overload



To prevent failures provide redundant systems, equalize hoist ropes, properly design clamps and stops, design the crane structure for impact from failure of one side of the reeving system, inspect connections, and inspect the rope after overload or after work near the rope that may compromise it, e.g., welding.

Clamp Test

Test clamp before installation

Check bolt torque at installation

Limit clamp movement

Test rope clamps before installation, check bolt torques when installing, and limit the clamp movement to limit how far the boom will drop if one side of the reeving fails. This will limit the impact loading.

Lifting Failures

Snag

Stall

Improper Load Handling

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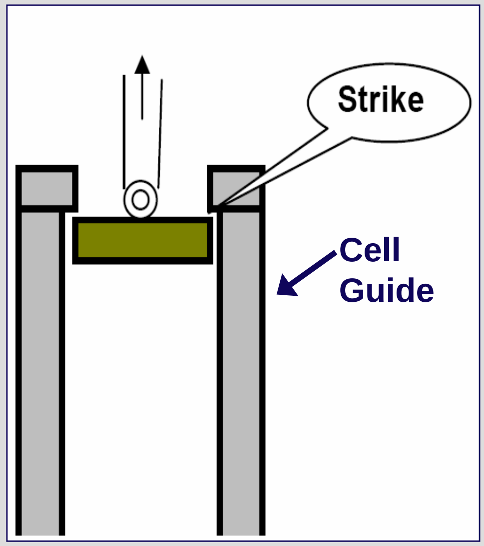
Failures have occurred due to an empty spreader snagging, lifting a dogged down container or hatch cover, and jerking a load.

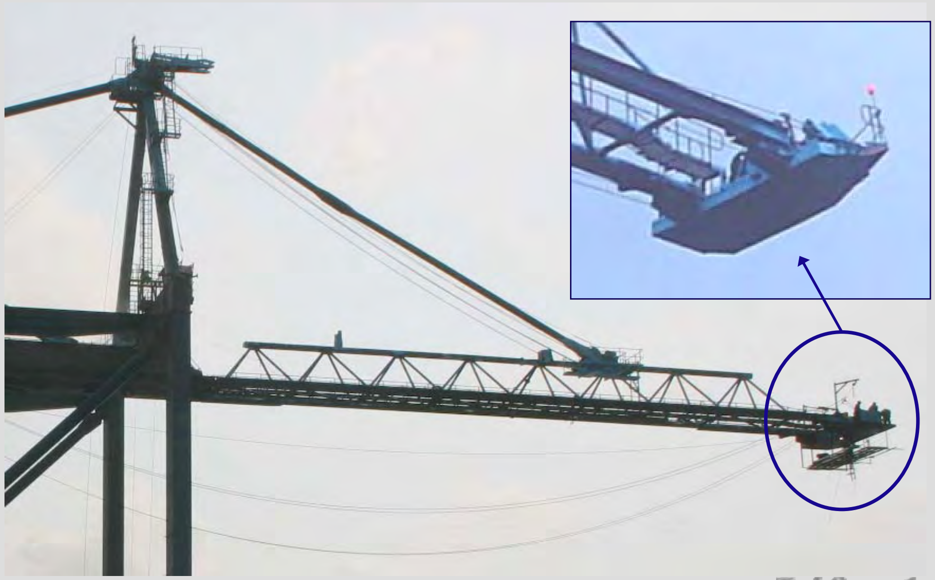
Snag Accidents

Headblock and empty spreader traveling at high speed striking or binding in the cell guide



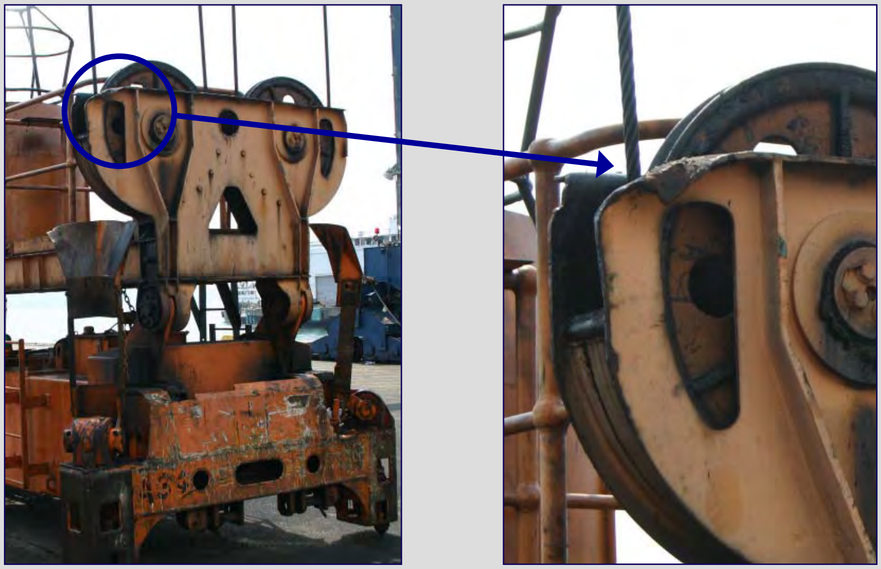
Snag accidents are common and can result in a severe loading.

Snag Damage at Boom Tip



This crane experienced a snag loading that resulted in significant damage to the waterside end tie of the boom where the hoist sheaves are located.

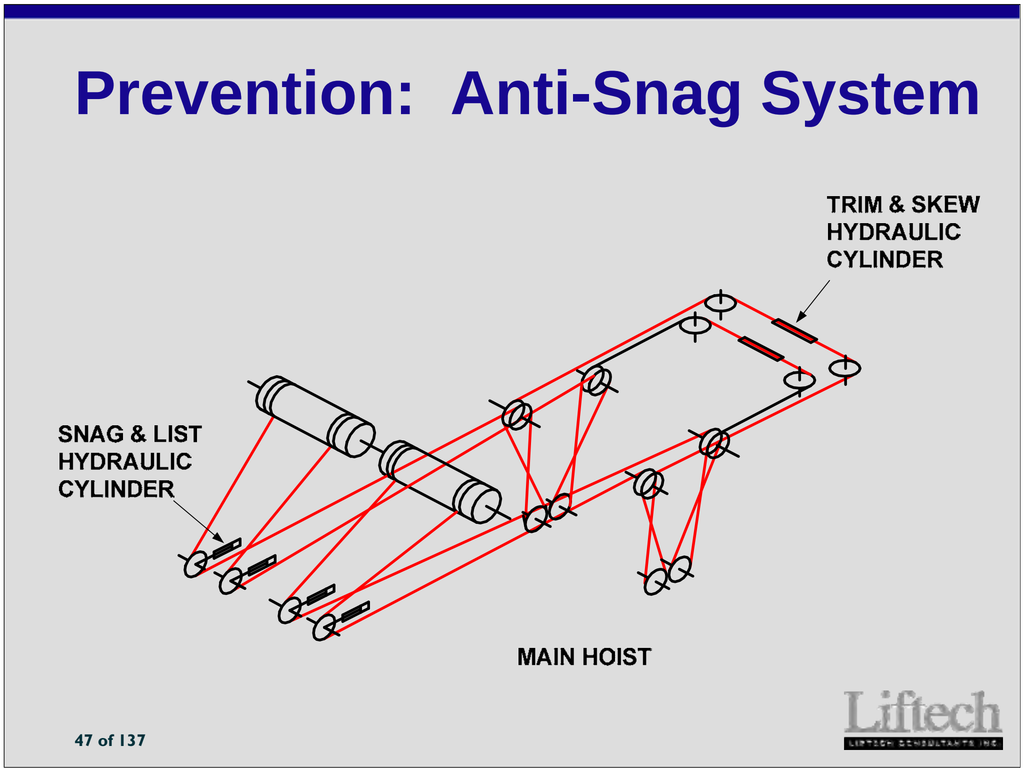
Headblock Damage



This slide shows damage to the headblock during a snag event.

Damage to the end tie is shown here. The sheave brackets did not pull from the boom structure, but pulled the boom structure up.

The damage was caused by the severe loading and significant corrosion of the end tie structure.



It is common for recent cranes to have the Anti-Snag and T/L/S systems combined at the TG end tie beam.

Hydraulic Snag Protection

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When the rope experiences a sudden large force, a pressure valve releases in the hydraulic cylinder allowing the cylinder to collapse and the arm with the sheave at its end to move toward the rope. This event absorbs the snag energy and reduces the distance between sheaves and rope tension.

Improper Load Handling

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Although snag systems help prevent overload, the load can still be handled in ways that can damage the crane structure.

In this video, an operator is attempting to free a container from the ship's deck. After several hoist attempts the crane's boom fractures. The end of the boom and the trolley with operator's cab fall onto the ship.

Summary – Lifting Failures

Design for Snag Loads

Maintain Structure

Use Snag Protection Device

Maintain Protection Devices

Inspect for Damage After Events

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The cranes shall be properly designed for snag conditions. Be sure to compute the snag energy from an empty spreader traveling at full hoist speed and striking an obstruction.

Maintain the snag device regularly and test it periodically.

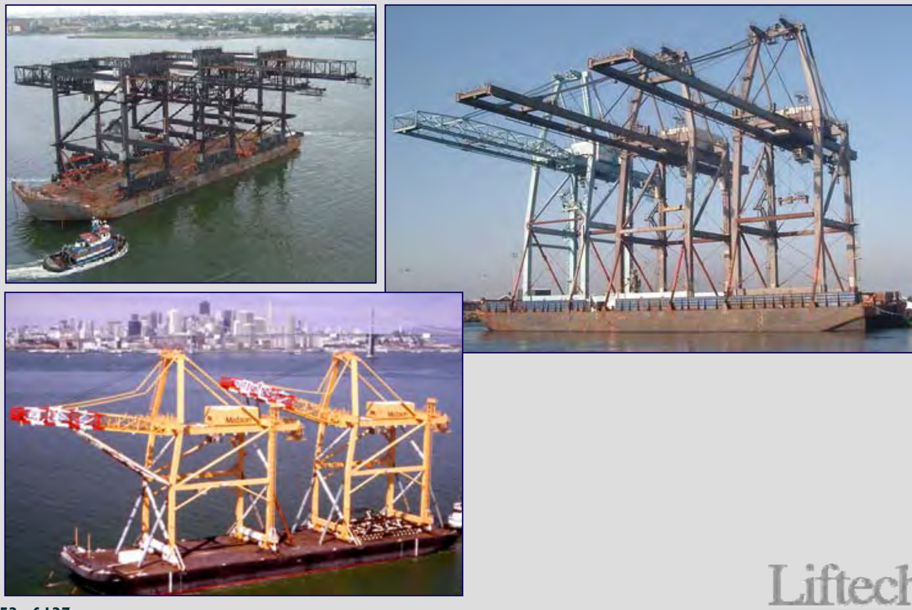
Always inspect the crane, particularly the areas in the path of the main hoist ropes after snag events.

Section Two: Transport Accidents

Transport Accidents

Voyage loss and damage are common.

Barge Transport



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Cranes are typically transported by barge or ship. Barges are typically used in the US due to the Jones Act.

The design forces for transport by barge are usually larger than for ships due to the dynamic response of the barge and because towed barges are usually slower than ships and are less likely to avoid severe weather.

This is a photo of a barge deck after two cranes fell overboard. We do not know the circumstances of the accident, but notice that the braces are not aligned with the internal structure of the barge.

Oakland to Hawaii on Barge

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This photo shows typical bracing for cranes on barges.

Transport by heavy lift vessels is more common than by barge, particularly for the delivery of new cranes.

Heavy Lift Vessel Collapsed Crane

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Damage to cranes transported by vessels also happens.

In this accident, the bracing connecting the crane to the vessel held; however, the bracing within the crane structure itself did not. It is important to perform an appropriate finite element analysis to correctly estimate the design forces within the crane structure and added bracing.

Prevention and Mitigation

Properly Estimate Voyage Forces

- Depends on vessel, cargo, sea states

Analyze Crane-and-Bracing as a System

Review:

- Crane Structure
- Crane Internal Bracing
- Sea-fastening to Deck
- Vessel Deck Structure

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Estimate voyage forces correctly considering the conditions and an appropriate criteria. Do not relax accepted design criteria regardless of how mild the weather is expected to be. Unexpected weather commonly occurs.

Adequately calculate the forces and stresses in the bracing and crane structure. This usually requires analysis using a finite element program.

Be sure to review the entire load path from the crane structure down into the structure of the vessel. **The load does not stop at the deck of the vessel!**

Voyage Design Criteria Standards

Marine operations by Veritas Marine Operations

Guidelines for marine operations, OPL

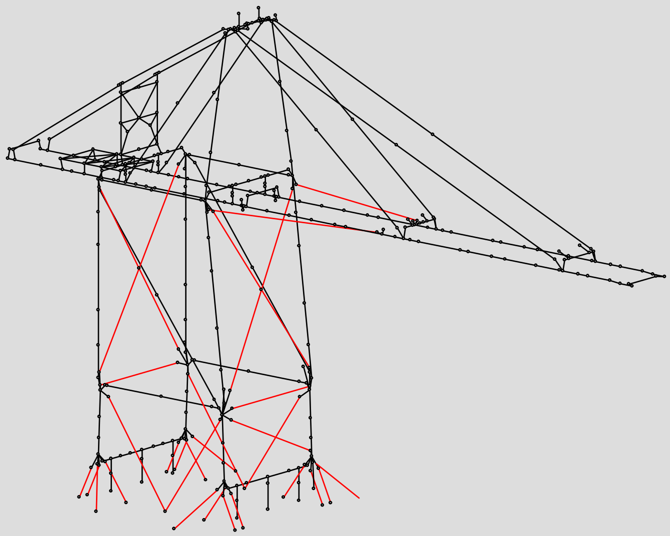
Liftech crane procurement specification

Photo from thehuffingtonpost.com

There are many standards for voyage design criteria.

Most standards have similar requirements.

Crane & Bracing Analysis



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Using the estimated maximum design voyage forces, a structural analysis is performed to calculate the following:

Brace forces and stresses

Reactions on the vessel structure

Stresses in crane structure for both strength and fatigue

The deck of the vessel is assumed to be rigid for analysis. Verify this is true and that certain braces are not resisting more load than others.

Although crane bracing and bracing connecting crane to ship are sometimes designed separately using simplified models, it is best to model all bracing with crane structure.

Installation Review Before Voyage

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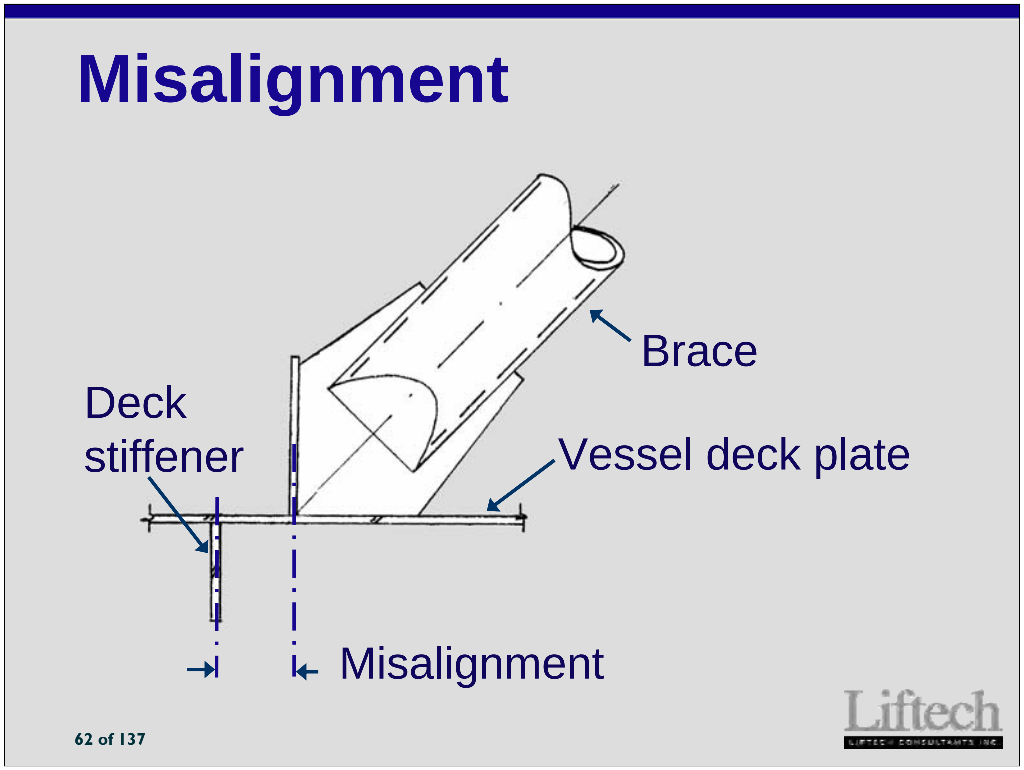
It is common to perform field reviews.

Misalignment of bracing members is common.

Because most voyages are mild does not mean there are fewer problems.

The pipe to deck connections will be discussed in the next slides.



The most common mistake is improper alignment of the braces with the vessel structure.

Misalignment will result in significant bending stresses in both the bracing and vessel structure.

Misalignment Repair

Typical alignment repair is to extend connection plates to transfer the bracing forces into the deck stiffeners below.

Offloading

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This photo is of a bogie system. Two bogies are used per corner. The bogies each have hydraulic jacks to lift the crane. The bogies roll on temporary rails. The ship's winch is used with the reeving shown to move the crane laterally.

With large bogie loads, bridge beams are commonly used to span from the ship to the wharf's waterside crane girder.

The wharf waterside of the waterside girder is typically not strong enough to support large truck loads.

Many things can go wrong.

Just prior to delivery, the ship's captain decided to begin moving the crane without installing the "hold back" lines.

The ship pitched and the crane rolled off the ship.

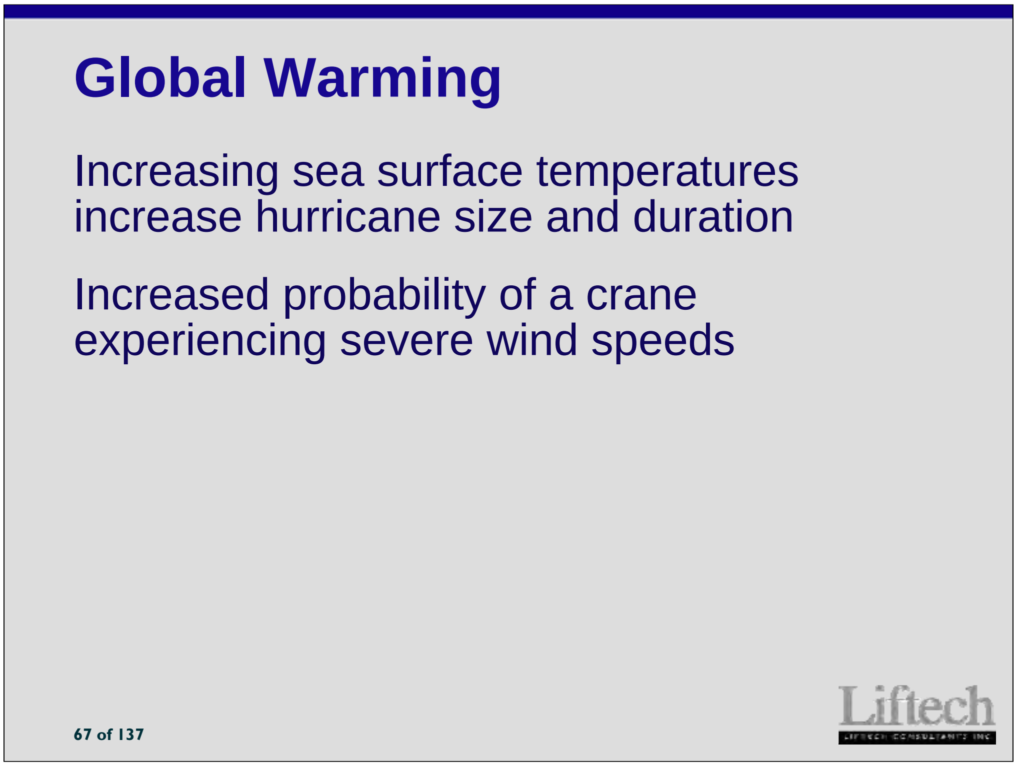
Section Three: Wind-related Failures

Typhoon Maemi, Pusan, South Korea

Hurricane Katrina. Source: www.nhc.noaa.gov

The image on the left is of damage caused by Typhoon Maemi.

The image on the right is of hurricane Katrina.



Studies by Emanuel (Nature) and Hoyos (Science Express) indicate that hurricane **intensity, size, and duration** are increasing, and are **correlated** to increasing **sea surface temperatures** (SST).

SSTs have increased approximately **0.5 C in the tropics**.

Storm **duration increased approximately 60**%.

Total North Atlantic plus Western North Pacific power dissipation index (PDI) (basically the **total energy released**) **has approximately doubled over the last 30 years**.

There is no apparent correlation between the number of hurricanes formed each year and SST.

There is only a small correlation between increasing hurricane maximum wind speeds and SST.

In effect, the theoretical maximum wind speed may not be increasing, but the probability of a severe wind occurring is increasing.

Crane designs are typically based on the ASCE-7 standard, *Minimum Design Loads for Buildings and Other Structures*, with a 50-year mean recurrence interval (MRI), 3-second gust wind speed, at 10 m elevation.

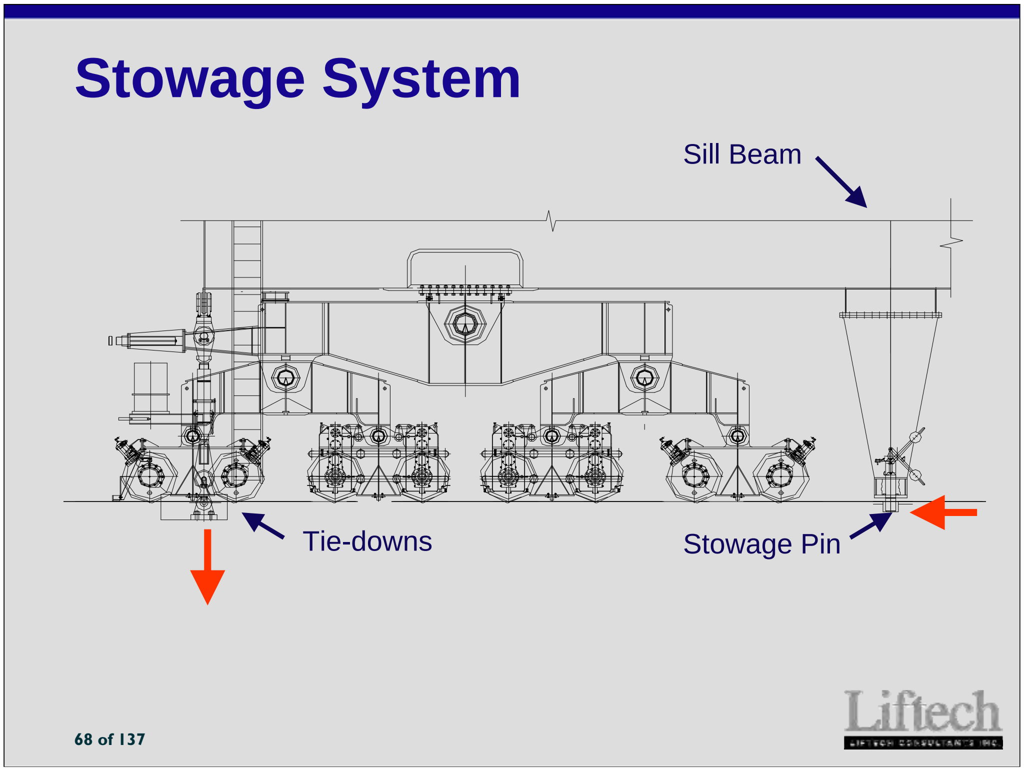
Certain-year MRI wind speeds are based on **statistics**. For instance, statistically there is a 64% chance of exceeding a 50-year MRI wind speed in 50 years, or 1/50 in any given year.

Remember the size of Katrina in the first slide? That tremendous storm caused significant damage to a large area.

You might also remember Emily, which traveled across Florida. Emily struck the west coast of Florida, went all the way through the state, and regained Category 2 status on the other side, damaging cranes on the east coast.

Normally, hurricanes are expected to “fizzle” out before hitting land, or shortly after hitting land.

In other words, hurricanes are more likely to hit a certain location, so instead of hitting every 75 years with a certain storm, they might hit every 50 years.



To explain why failures occur, I will discuss the stowage components of a crane in a high wind area.

Stowage pins resist lateral loading. Tie-downs resist the uplift due to the overturning moment.

Typical Failures

Stowage failures have not initiated in the crane structure

Tie-downs, stowage sockets, or brakes failed first

Why?

- Incorrect calculations
- Poor design
- Poor fabrication

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Failures never initiate in the crane structure.

Failures always initiate in the stowage hardware connecting the crane to the wharf.

The reasons for these failures can be equally attributed to incorrect calculations, poor design, and poor fabrication.

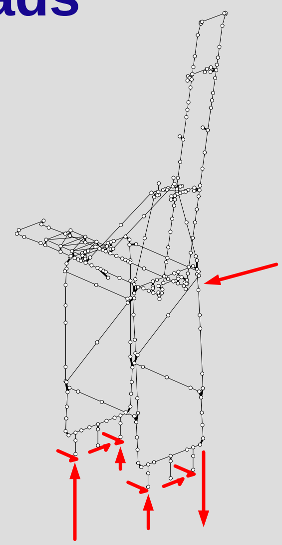
Calculating Wind Loads

Diagonal wind reactions can only be correctly calculated using a frame analysis program

A spreadsheet will not provide correct forces

Use wind tunnel results

Manufacturer’s bid document loads are often incorrect



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When calculating crane corner reactions, the warping stiffness must be considered.

In our experience, the manufacturer’s calculated loads are often incorrect.

Limit State (Factored) vs. Service Loads

Communication between the crane and wharf designers is important!

Load	Service Comb-S	Factored Load Factor	Factored Comb-F
Dead Load	-500	x 0.9 =	-450
Wind Load	+400	x 1.6 =	+640
Calculated Uplift	-100		+190
	No Uplift		Uplift

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Depending on the magnitude of the wind reaction and dead load (DL) reaction, there can be a significant difference between service and factored loads.

Design terminology follows:

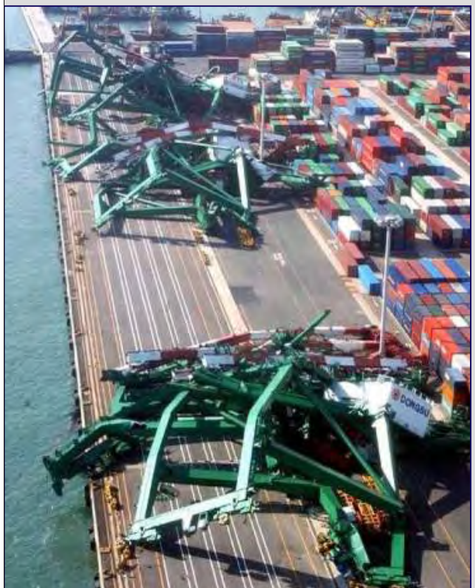
Limit State = “Factored” = “Ultimate”

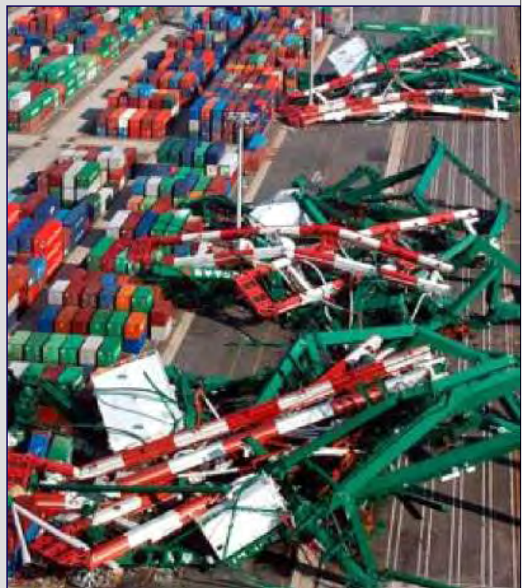
(Ultimate Limit State, as opposed to Serviceability)

Sometimes, the wharf designer asks for the DL and uplift force at the corner and designs the wharf tie-down hardware based on the unfactored uplift force. The crane designer designed the crane tie-down components for nearly 200 tons, but the wharf designer may provide a minimal design for the tie-down bracket since his calculations show that there is minimal or no uplift. Communication is key!

Crane stowage hardware design should always be based on factored loads! Allowable stress design (ASD) using service loads is acceptable provided the service loads are calculated by converting the factored loads to service loads.

Tie-down Failure





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Korea

These photographs show six collapsed cranes due to Typhoon Maemi in Pusan, South Korea. (The two photographs are taken from each end of the wharf.)

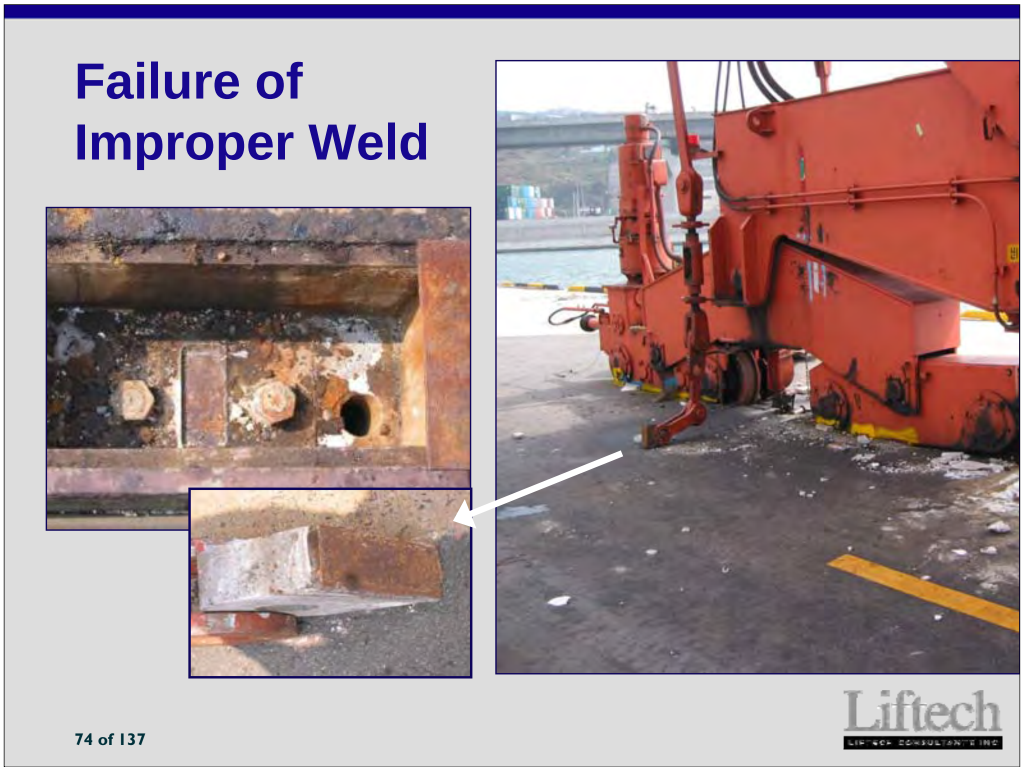
Tie-downs failed. After failing, progressive failures ensued as cranes collided with each other.

Anchorage Pull-out Failures

There were multiple types of failures during Typhoon Maemi. Tie-down anchorage was one failure type. Smooth anchors pulled out of the wharf.

Design = headed

Fabricated = no heads



Improperly made and undersized welds failed at tie-down brackets.

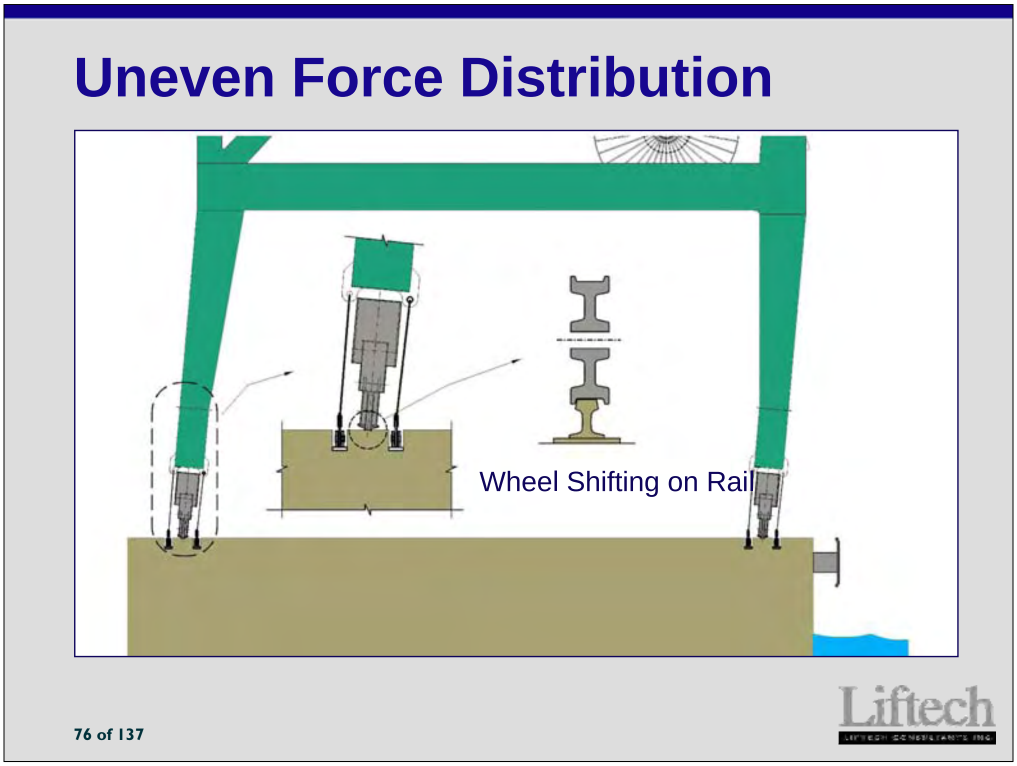
Tie-down wharf bracket failure was due to improper fabrication--**4 mm** (3/16 inch) fillet weld between **base plate** and **60 mm** (2.5 inch) lug.

The fabricator also used a **filler plate** between the lug and base plate!

The design called for a complete joint penetration weld that would have developed the strength of the ear plate. This weld would have been many times stronger than the provided weld.

Stowage Pin Socket Failure

Local concrete bearing failures occurred at stowage sockets. The design did not consider the large bearing stresses that will occur. This was exacerbated due to crane uplift and localized bearing of the stow pin on the upper end of the cast in place tube.



When calculating the design forces, the deflection of the crane must be considered, particularly when there are multiple tie-downs at a corner.

On some cranes we have studied we determined that one tie-down at a corner may experience 100% of its design load before the other corner tie-down experiences any loading.

Following are some causes of uneven tie-down loads:

- Crane structure deforms, translating and rotating
- Gantry wheels can shift
- Gap in stowage pin socket allows gantry wheels to roll (or slide) along the rail
- Links are not perfectly straight
- Wharf pins are not symmetric

How to Design?

If practical, use one tie-down per corner

If force equalization is necessary use:

- Mechanical equalizer (not recommended)
- Ductile link: equalization through ductile yielding of a structural element

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To avoid uneven tie-down loads, if practical use one tie-down per corner or locate all tie-downs on one side of the sill beam, otherwise equalize.

As mentioned, the best method is to use a single tie-down per corner, but this is often impractical due to the size and weight of the tie-down system components, e.g., the weight of the wharf link plate.

The mechanical equalizer beam system is not presented as it is heavy and difficult to implement.

Another choice is to use a ductile link.

Ductile Links Implemented

Safety links
Ductile link

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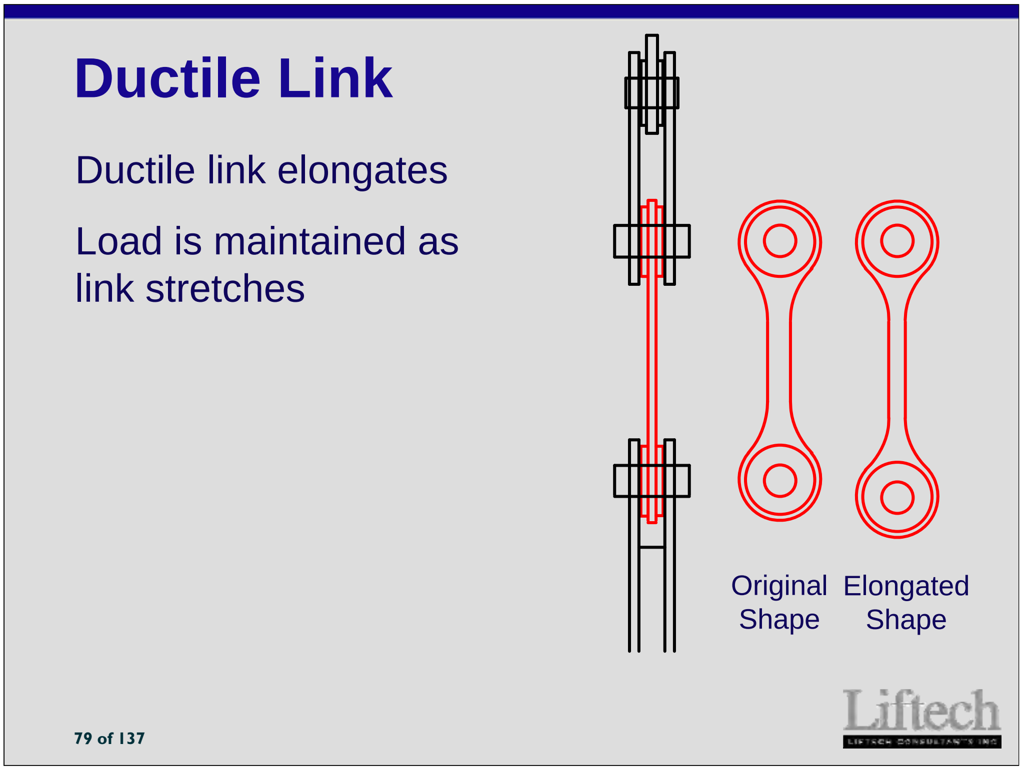
Here is a ductile link system with four tie-downs per corner.

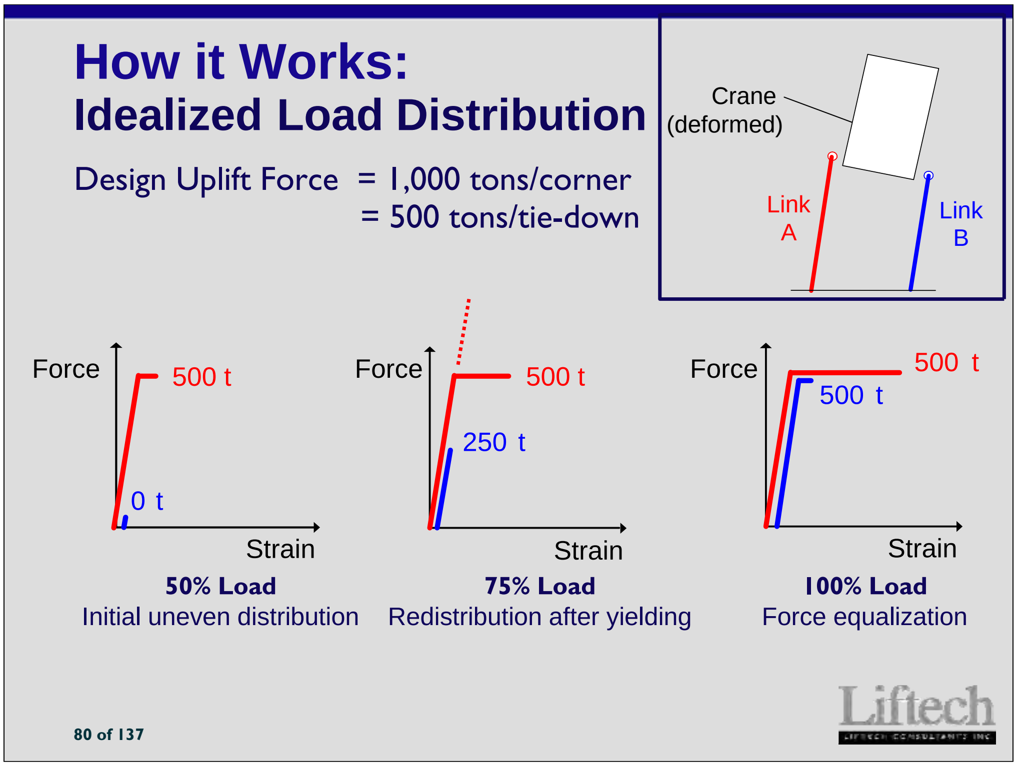


A ductile link equalizes loads between tie-downs by yielding.

A mild steel without significant strain hardening is used.

If one link in the tie-down system is capable of deforming **plastically without loss of strength** until the other link engages, the tie-down loads will eventually equalize.

Plastic elements acting as fuses have been used for decades to protect structures from severe damage during earthquakes.



The yielding equalizes the loads between tie-downs.

How does it work?

Initially the loads in multiple tie-downs are not equal. In this example, with a 1,000 ton corner load, the initial distribution is uneven. The desired distribution at the design uplift load is 50/50.

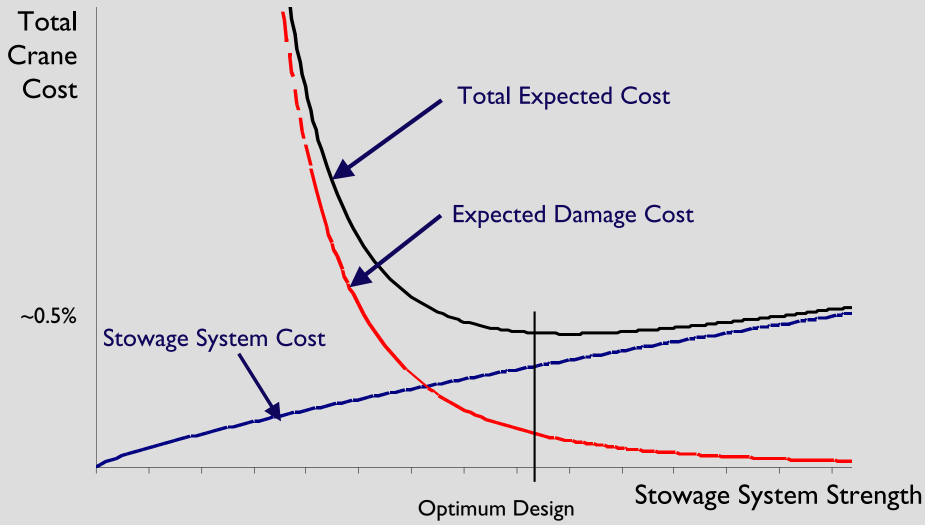
With the ductile link, the heavily loaded tie-down yields at half of the design uplift load, allowing the load to transfer to the lightly loaded tie-down.

As the uplift force increases, the ductile link stretches plastically. The load remains (relatively) constant in the heavily loaded tie-down and increases in the lightly loaded tie-down. Normally, the load might follow the dotted line shown in the middle graph.

Eventually the load is shared equally and the full strength of the multiple tie-downs is used, as intended.

This protects the wharf hardware from overload.

Stowage System Economy



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Lastly, design the stowage hardware conservatively. The additional cost is not significant to the cost of the crane. Under-designing the stowage system can result in a high cost.

Generally the stowage system is not a good place to save money.

Summary

The probability of cranes experiencing severe wind loads is increasing due to global warming.

Use accurate loads and consider crane deformations when designing stowage systems

Stowage hardware is inexpensive, design conservatively

Monitor fabrication and installation

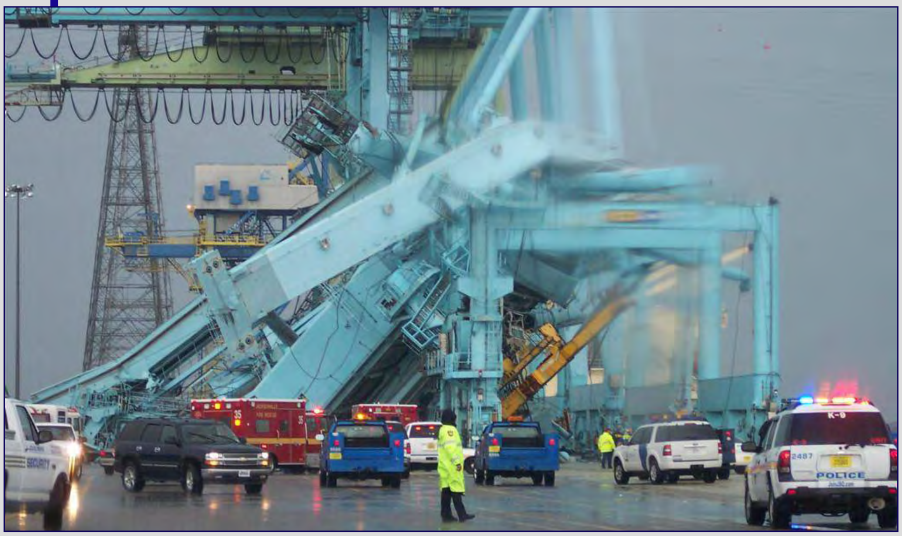
Runaway Crane

This is a video of the recent Jacksonville crane failure that occurred in August 2008.

During a storm, one crane was blown down the runway and collided with another crane, causing both to collapse.

We understand that the braking system was not at full capacity because the rail brakes on one side of the crane were disabled due to a rail clearance problem.

Braking System – Design and Operational Considerations



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This is a photo of the collapsed cranes.

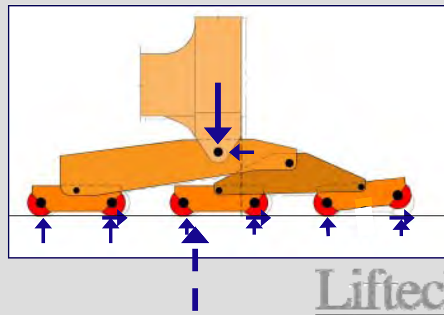
Failures similar to this due to runaway cranes occur more frequently than expected.

It is often difficult to pinpoint why braking systems fail. Some design and operational considerations are presented.

Braking System Design Considerations

Reduced Capacity Due to:

- Reduced vertical reactions from overturning
- Reduced reactions on wheels and rail brakes due to truck and equalizer prying



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When designing braking systems, be sure to consider the reduced vertical reaction due to the overturning moment on the crane, and the difference in vertical wheel reactions due to truck and equalizer rotation.

An adequate vertical reaction is needed to develop the required friction between the wheel and rail, otherwise the wheels will skid on the rail.

Braking Systems

Operational Considerations:

- Maintain brake systems
- Stow crane during brake maintenance
- Allow ample time to stow crane
- A brake system can hold a significantly greater force than it can stop

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Some operational considerations include providing ample time to stow the crane and realizing that the brake capacity of a moving wheel is less than that of a stopped wheel.

The static coefficient of friction is often significantly larger than the dynamic coefficient of friction. A moving crane also has significant inertia.

Section Four: Seismic Failures

Although there have not been many crane failures in earthquakes, this section is included because the seismic risk to large jumbo cranes is significantly greater than to the earlier, smaller cranes.

Historic Seismic Performance

Kobe - Liquefaction

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Container crane structures have performed well in earthquakes. Kobe failures occurred when rail spreading failed the crane legs.

Historically, when supports have not failed, cranes have performed well in earthquakes. The cranes lift from the rails disrupting the buildup of motion in the crane structure.

Fifty foot gage cranes have come off of their gantry rails with little damage.

In Kobe, the foundations failed causing significant damage to some cranes.

Crane Evolution

Circa 1970

Modern Jumbo

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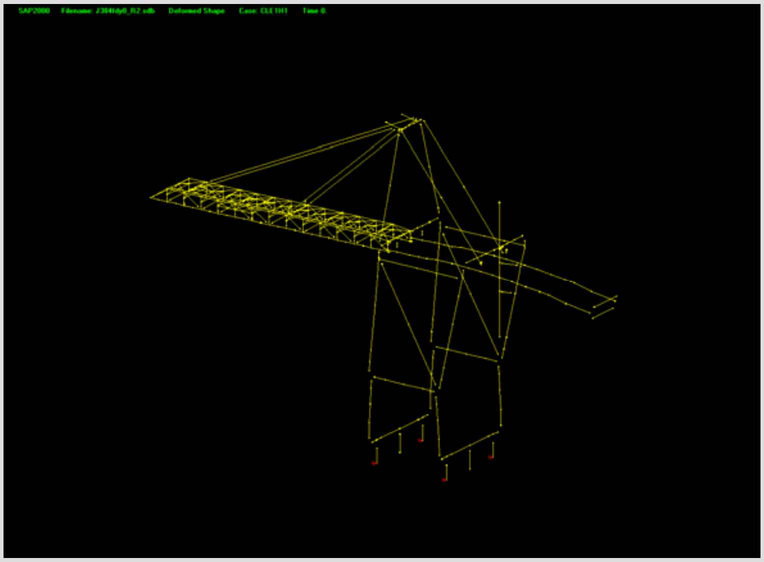
Recent studies indicate that modern jumbo cranes are significantly larger and more stable than earlier cranes.

Recent studies indicate that the seismic risk to modern jumbo cranes is greater than to earlier cranes.

What changed?

Modern cranes are larger and heavier, and more stable. The rail gage has increased to 100’ or more.

50’ Gage Crane CLE Response



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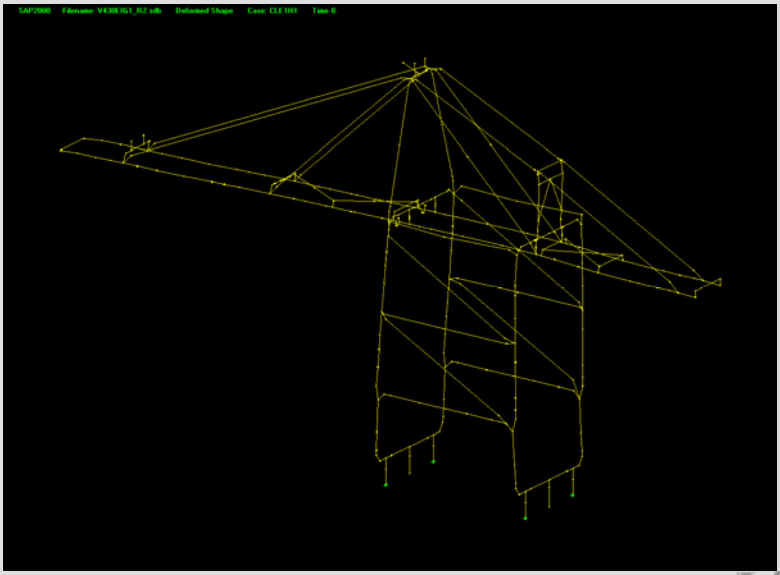
This is a time history analysis of a 50’ gage crane subjected to one of the Port of Los Angeles time histories for a contingency level earthquake (CLE) having a mean return interval of 475 years.

In the analysis, the crane is modeled on the Port of Los Angeles Berth 100, a wharf representative of many of the wharves recently constructed on the West Coast.

Only the accelerations in the trolley travel direction are applied in the model.

Due to modeling limitations, the boundary elements will stretch when the crane lifts, so focus on the sill beams.

100’ Gage Crane CLE Response



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This is a model of a recent 100’ gage crane. It is modeled on the same wharf and analyzed using the same acceleration time history.

Design for Tipping

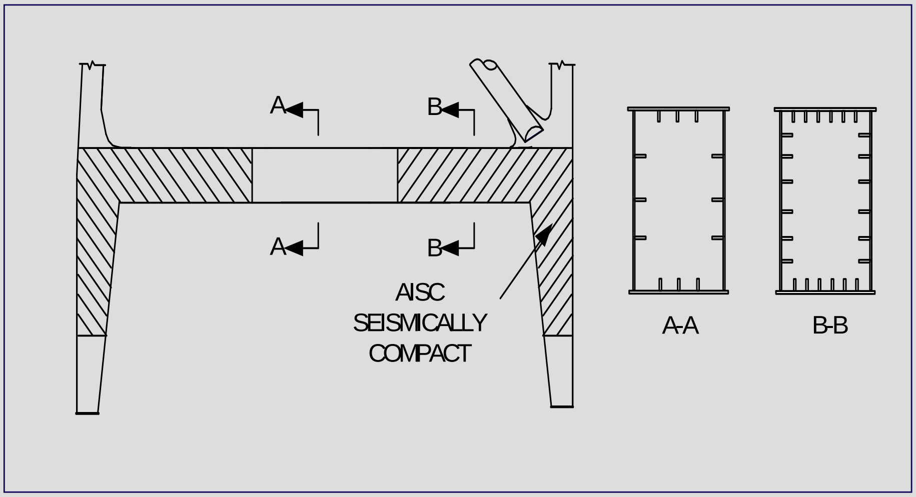
Liftech performance specifications now require one of three design approaches.

The first approach is to design the crane to tip.

Designing the crane to tip is a good option for new cranes, particularly those in typhoon wind regions where the portal frame is nearly strong enough to carry the tipped crane.

If tie-downs are in place, the crane will not tip and large forces may develop in the structure.

Design for Ductile Yielding



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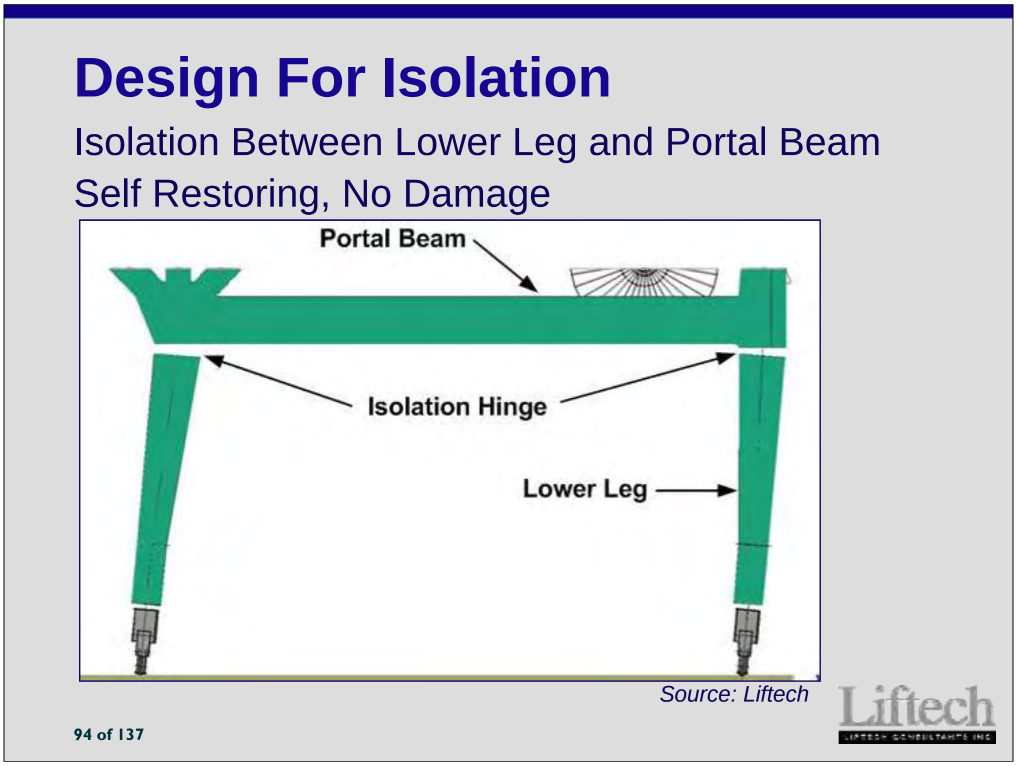
The second approach is to design the crane so that any locations that yield do so in a ductile manner to avoid collapse.

Designing for ductile yielding requires that the thin walled plate sections be made seismically compact in accordance with AISC standards. This requires significantly more stiffeners; however, the cost to the crane will be insignificant, estimated at less than 1%.

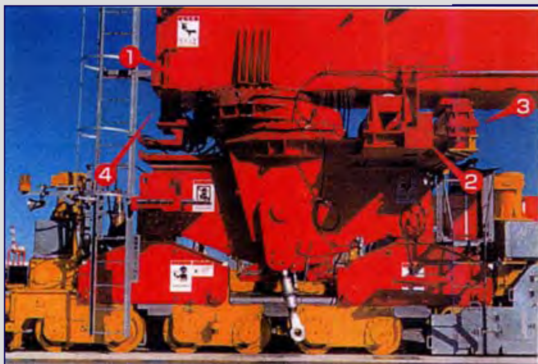


The third approach is to design to isolate the crane from the wharf movement.

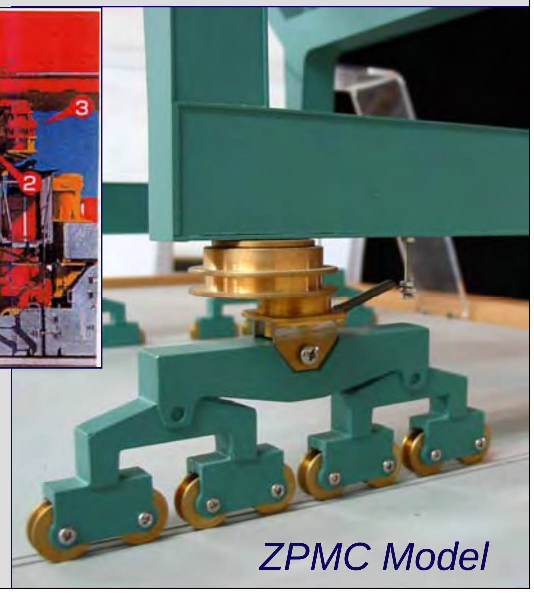
The concept shown, developed by Liftech, provides an isolation hinge between the lower legs and the portal beam.

This mechanism requires no damping, trigger, sliding, or restoring mechanisms.

Isolation Between Main Equalizer and Sill Beam



MHI Crane in Japan



ZPMC Model

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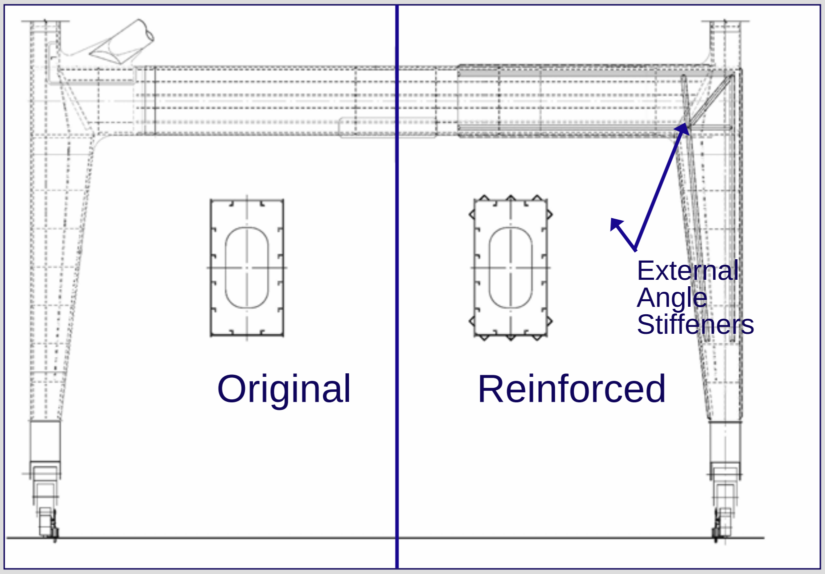
Another isolation system has been used. MHI has built a crane with the mechanism shown. This mechanism permits the gantrying system to displace with the wharf while the crane structure above the mechanism remains isolated from the movement.

The MHI mechanism requires damping, trigger, sliding, and restoring mechanisms.

Designing for isolation is the most expensive option. If done properly it will result in the least damage. It is practical to design a mechanism that will prevent damage in the CLE.

Improve Ductility: Retrofit



For existing cranes, if it is not practical to reduce the portal clearance to strengthen the crane to tip, it is still practical to add stiffeners to improve ductility.

Adding stiffeners, particularly continuous stiffeners so the thin walled sections are compact in accordance with AISC standards, will significantly improve the ductility of the portal frame box sections. This option is more practical for retrofit of an existing crane where the clearance under the portal beam must be maintained.

Notice that only the areas that are required to be ductile must meet the ductility detailing requirements.

Summary of Options

Option	Pro	Con
Design to Tip	Reduces probability of damage	For retrofit, may reduce portal clearance or be expensive
Ductile Yielding	Least costly, avoids collapse	Probability of damage is unchanged
Isolation	No damage. Limits loads on wharf; significant for large gage cranes	Expensive

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Some advantages and disadvantages of different systems are shown. The cost of options for new cranes is more similar.

If the portal clearance can be reduced, strengthening an existing crane by adding pipe braces will be practical.

If some damage can be tolerated, adding stiffeners to obtain ductility and strength is practical.

For large gaged cranes, it may be worthwhile to provide isolation to limit the crane lateral loading on the wharf.

Summary

Be aware of seismic risk

Use state-of-the-art performance criteria when purchasing new cranes

Design crane to wharf seismic criteria

Retrofit is an option and is most practical when making other modifications

In summary, be aware that the seismic risk to cranes has increased as crane sizes have increased.

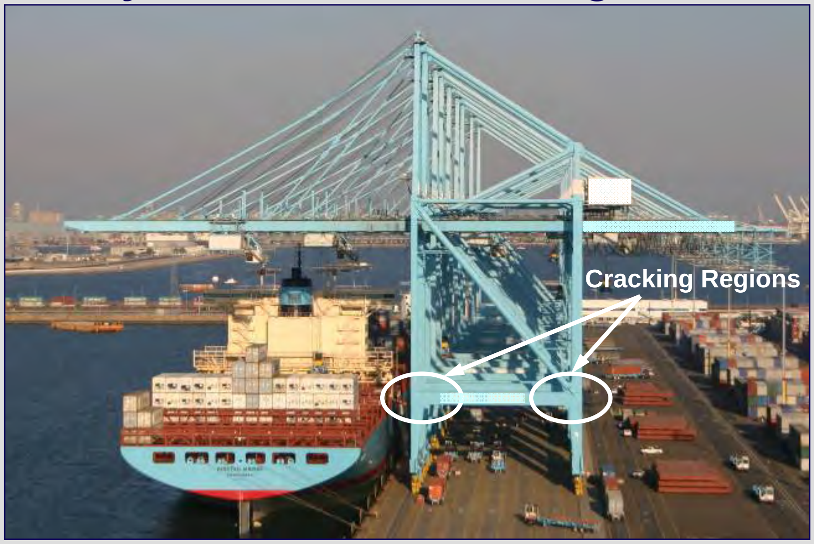
Use current seismic design criteria when purchasing new cranes.

It is practical to evaluate the seismic risk to existing cranes. Seismicities are well known. A structural engineer can evaluate expected performance of the portal frame. A crane expert is not required.

If raising an existing crane, particularly one with a 100’ rail gage or larger, consider retrofit.

In the last ten years, a new crop of fatigue problems has developed in the industry.

Portal Frame Fatigue:
Trolley Motion Induced Fatigue



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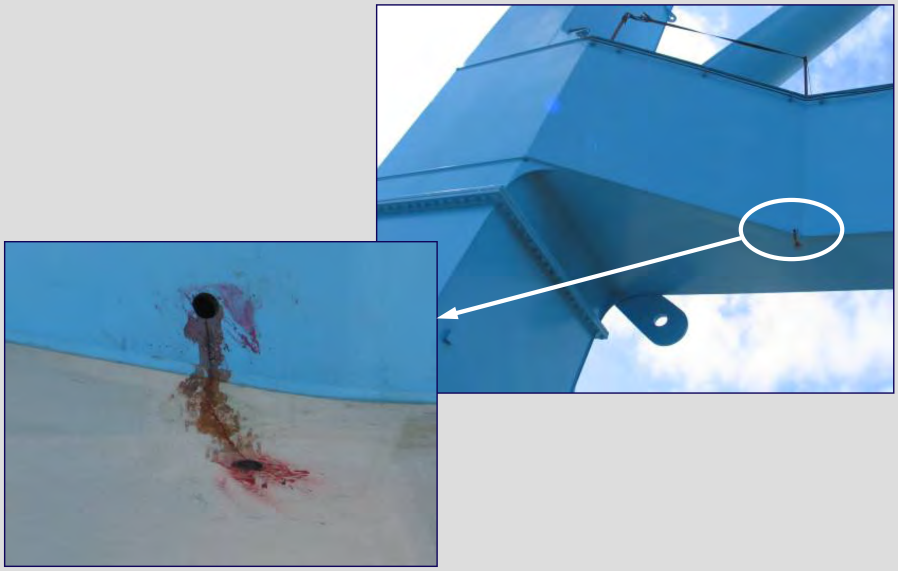
Fatigue cracking in portal frames has occurred due to crane sway in the trolley travel direction. This has occurred on a variety of cranes made by a variety of manufacturers.

Stress Concentrations



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This problem has been exacerbated by stress concentrations such as tapered portal beams.

These pictures show the crack from the outside. Notice the sharp transition of the portal beam.

Stiffener Ends

In addition to a global stress concentration due to the taper, there is a stress concentration at the stiffener ends.

The fatigue cracks initiated at the tip of the stiffener as expected.

Cracks at Stiffener Tips

These pictures show more cracking at stiffener ends.

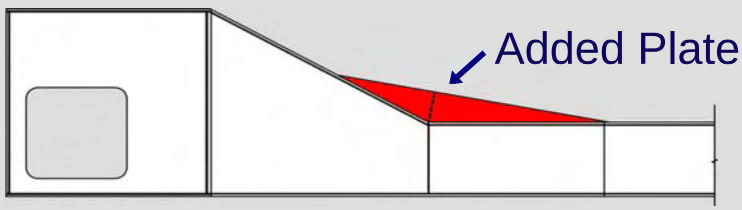
To limit stress concentrations, the Liftech crane specification requires a clear distance of three plate thicknesses with no welding at the stiffener end.

Solution

Electronic anti-sway or reduced trolley acceleration

Modify portal taper geometry

Improve stiffener end geometries



Plan

To obtain an acceptable reliability on one project, the following modifications are required:

The Solution for Stiffener Ends?

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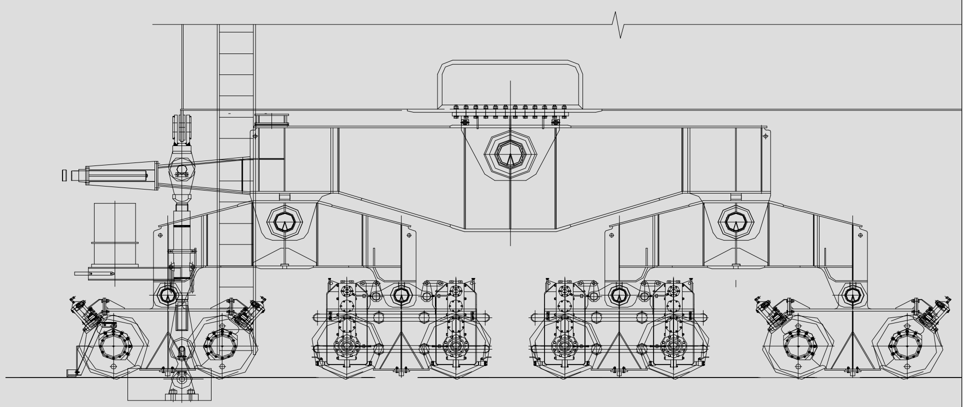
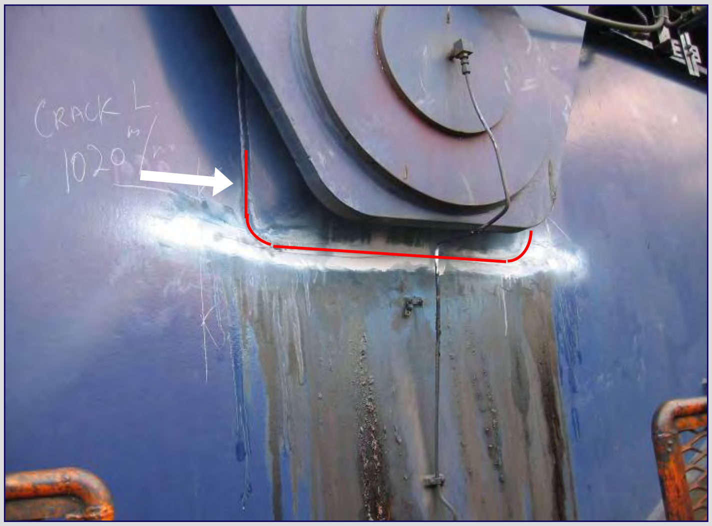
Tapering the stiffener end will reduce the stress concentration and improve performance. Connecting stiffeners to diaphragms will not.

Equalizer Cracking:
Trolley Motion Induced Fatigue



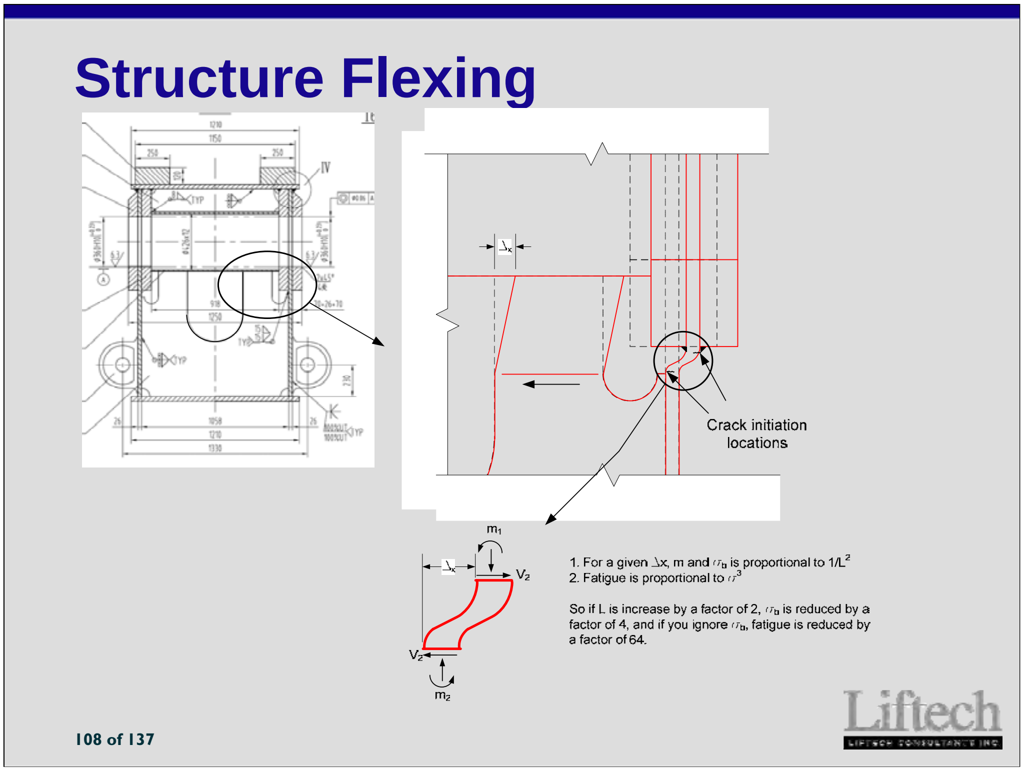
Increased crane sway in the trolley travel direction is also causing fatigue cracking in equalizer seams.

Equalizer Cracking:
Trolley Motion Induced Fatigue



Cracking has occurred at the thickened pin plate in the equalizer beam.

In this photo, a red line has been added at the crack.



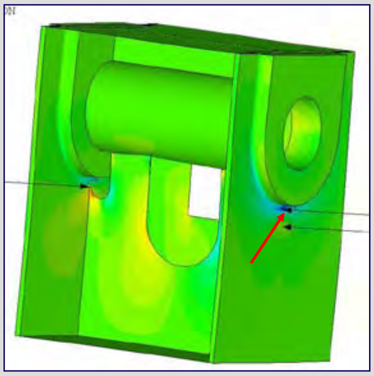
Cracking is the result of localized bending in the web due to the small clear distance between the diaphragm and boss.

The bending stress is proportional to the clear distance squared.

Fatigue damage and fatigue life are proportional to the stress range cubed, and the clear distance raised to the sixth power.

If the clear distance is doubled, the fatigue life is improved by a factor of 64!

FEA Model



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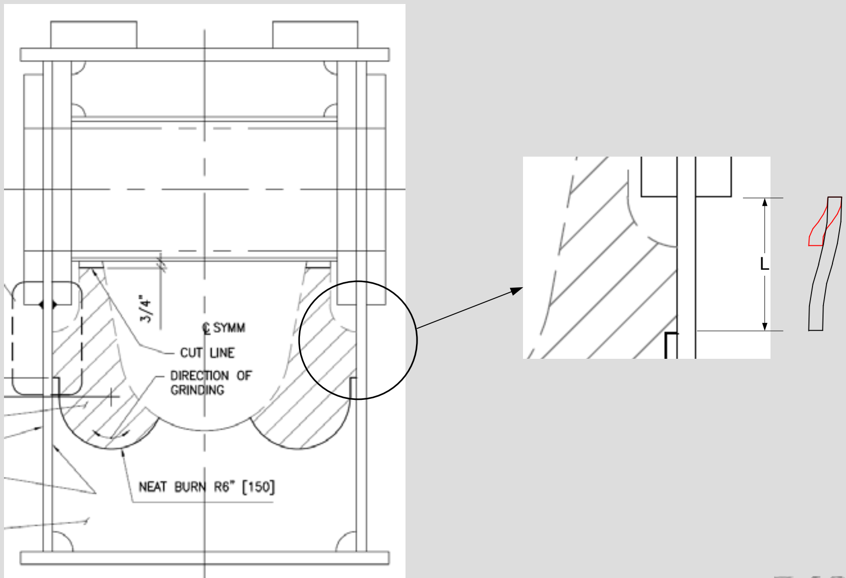
The following is a finite element analysis of one equalizer that is experiencing cracking. The analysis is consistent with expectations that significant stresses occur at the base of the thickened boss plate.

Increase Flexibility



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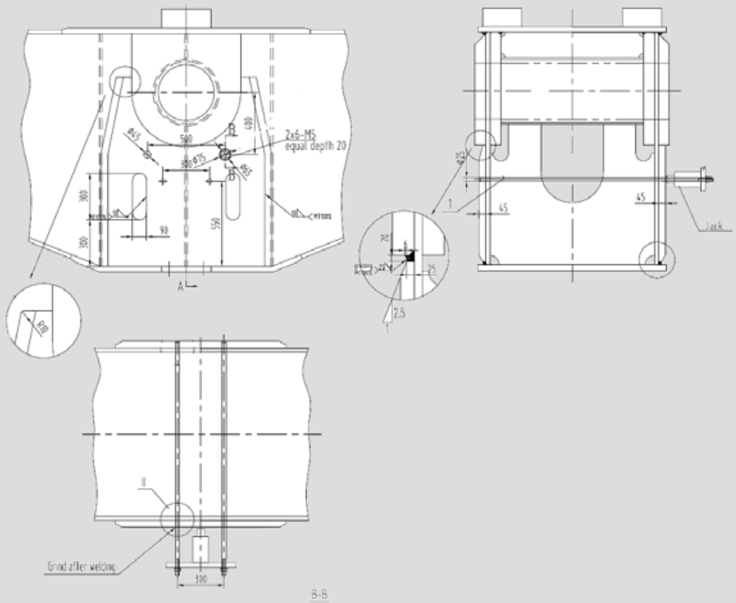
One solution is to increase the clear distance to reduce the stresses in the web.

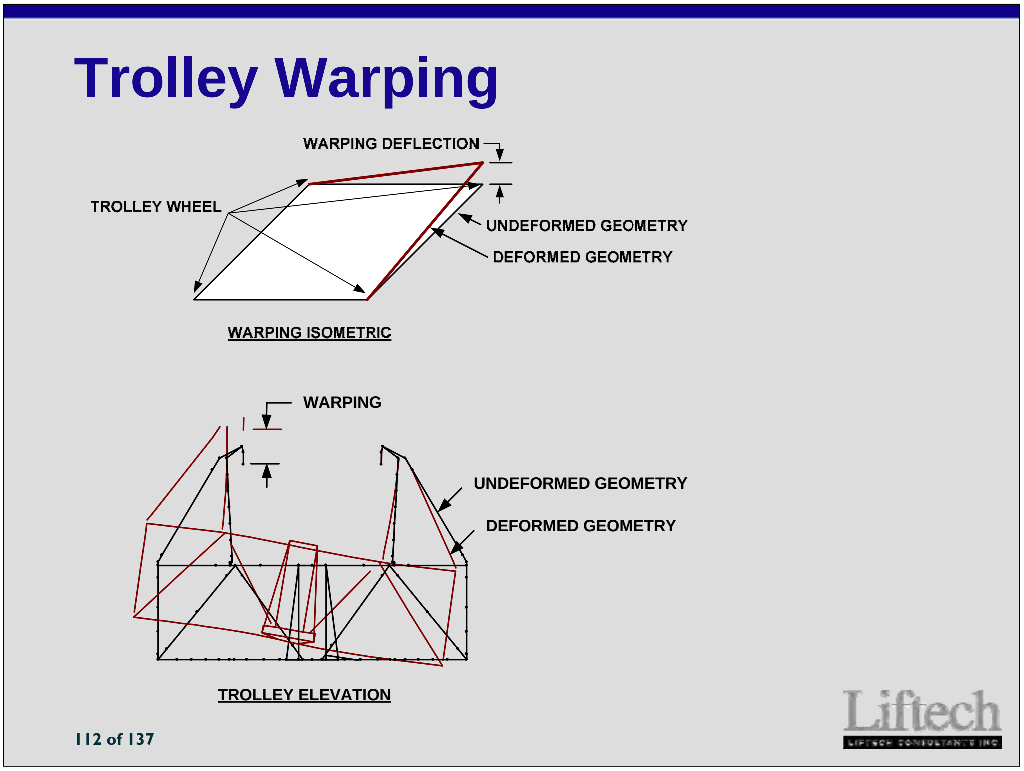
More lateral load is transferred to the adjacent diaphragms.

Strengthen



Another solution is to strengthen the web plate to reduce the stresses.

Strengthening existing equalizers typically involves adding external doubler plates as shown in this image.

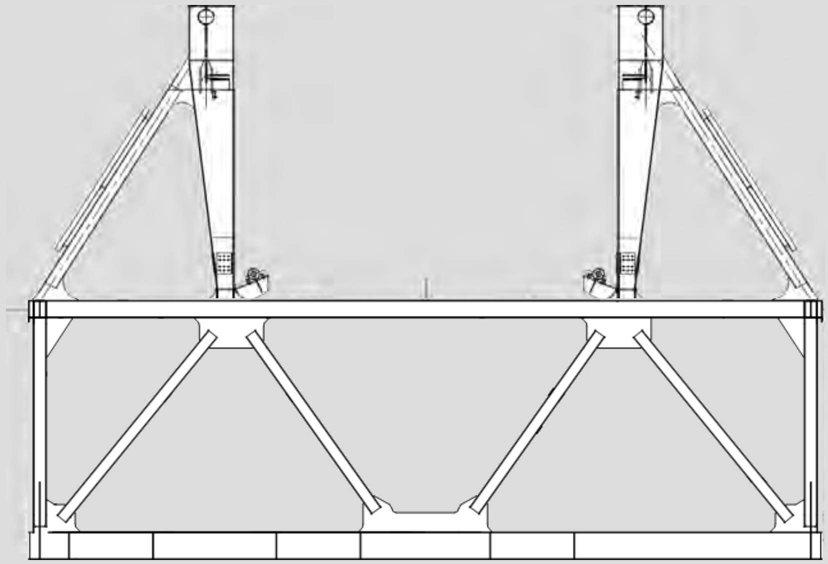


A third fatigue problem that has emerged in recent years is due to warping of the trolley structure.

Warping occurs when one of the trolley wheels displaces out of a plane through the other three wheels. All trolleys warp as they move along the trolley rail. It is not practical to install rails so that significant amounts of warping will not occur.

If the trolley structure has not been designed with sufficient flexibility to accommodate the warping, unacceptable fatigue stresses will occur in the trolley structure.

Machinery on Trolley: Rigid Frame



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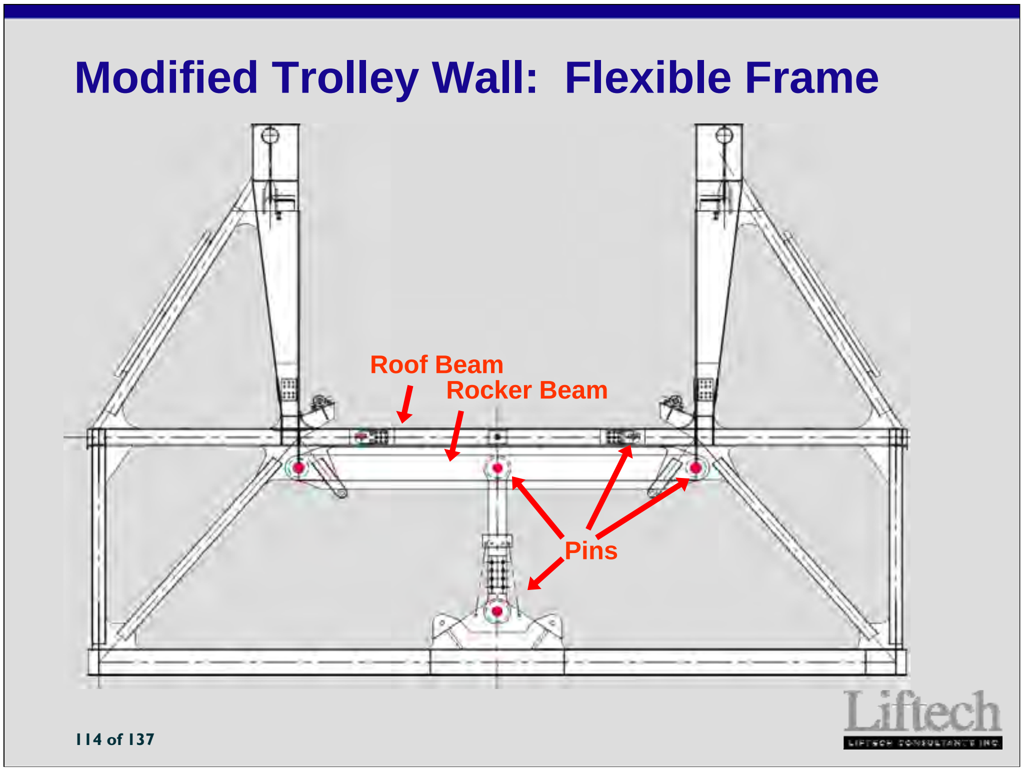
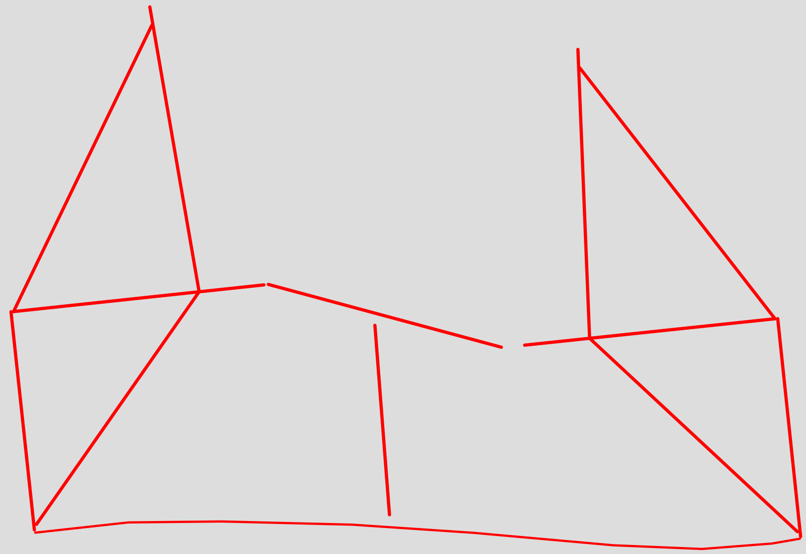
This is a section through a stiff machinery on trolley that does not easily warp that experienced premature fatigue cracking.



The stiff trolley in the previous slide was made flexible by removing diagonal braces and adding a rocker beam, tie, and six pin connections.

Response of Modified Trolley



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The modified trolley is more flexible and can deform without significant fatigue stresses. The modified trolley structure was designed for a 10 mm warping deformation for each trolley move.

Boom Support Structure

Forestay system

Backstay system

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The next discussion is about fatigue problems in forestay and backstay systems.

Forestay System Fatigue Cracking

Weak axis bending at connections

Stress concentrations

Let in plate details

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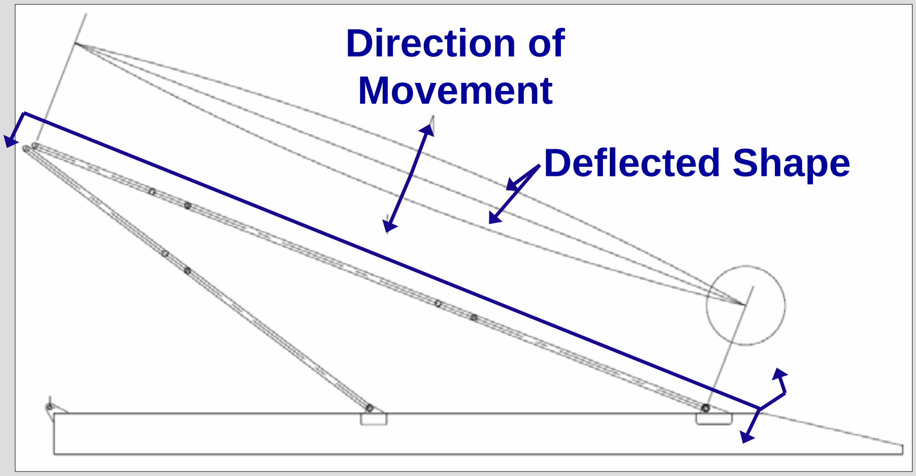
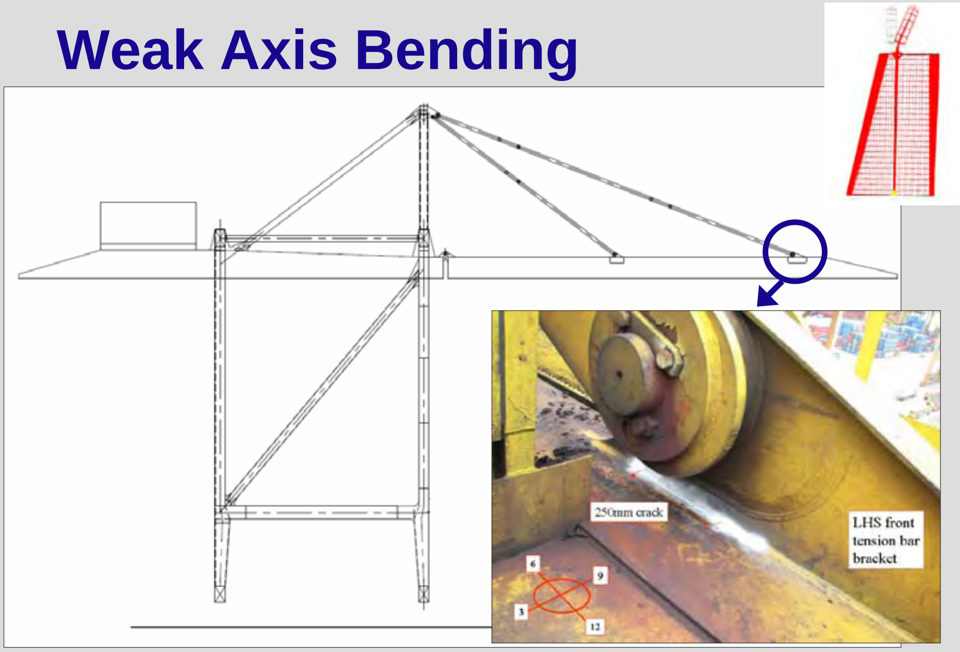
Fatigue cracking in forestay systems has occurred because the following have been overlooked.

Lateral Boom Movement



A major source of premature cracking is due to lateral deformation of the forestay.

Weak Axis Bending



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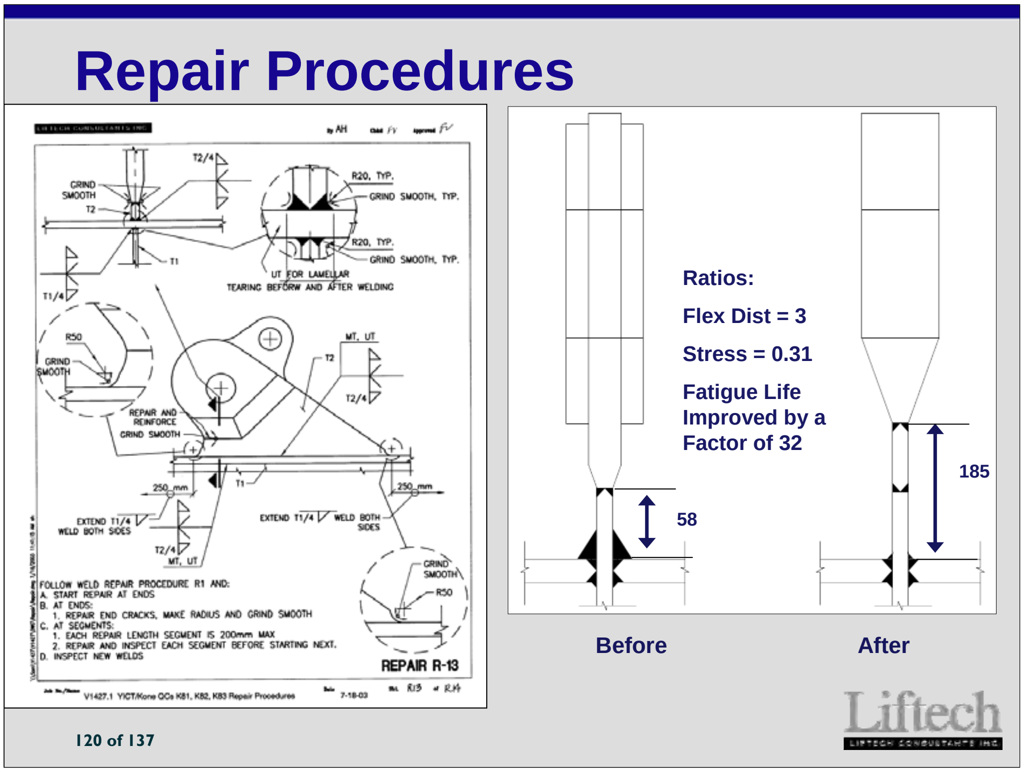
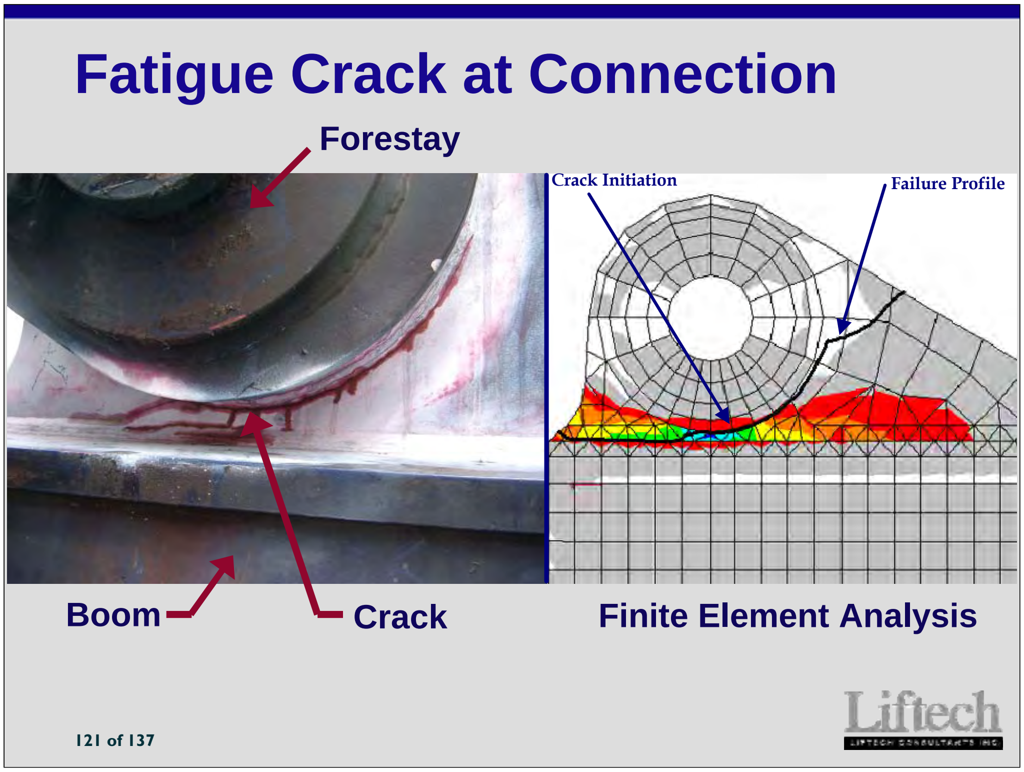
Lateral deformation of the forestay has caused lateral bending in forestay connections, and large weak axis stresses in the connection plates.



On one project the existing connection PL was removed and replaced with a more flexible plate. The plate is made more flexible by increasing its clear distance between the thickened pin plate and flange plate.

A small increase in clear distance will significantly improve the fatigue life if weak axis bending is causing significant stresses.



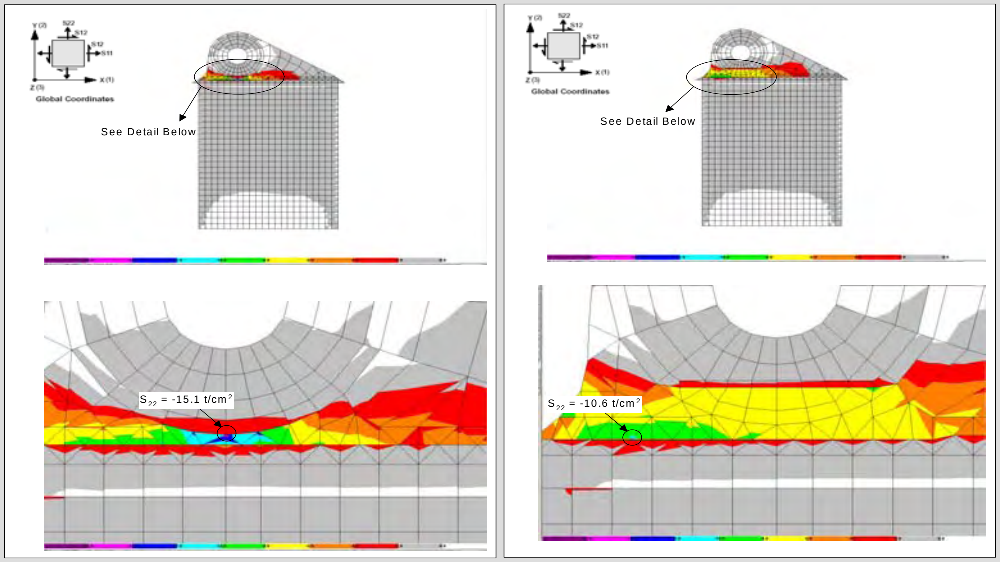
On another project, a forestay connection failed but the remaining stays held the boom. Cracks similar to that shown were discovered at all other connections.

The cracks initiated at the stress concentration at the toe of the boss weld and propagated across the plate in both directions

The photo on the left is a cracking detail that has not yet failed.

The FEM plot on the right shows the stress in the uncracked plate with the failure profile of the failed plate superimposed.

Modified Detail: Stress Analysis



Original | Modified

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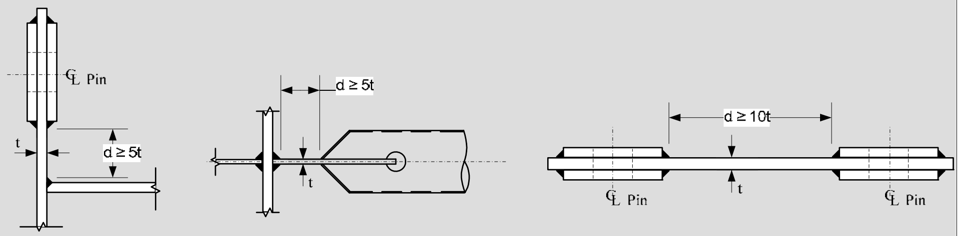
For an existing design, it was acceptable to trim the boss and to obtain adequate clear distance.

In this case, the stress is reduced by about 30%.

This results in a 66% reduction to the expected future fatigue damage due to the cubic relationship (0.7)^3.

Prevention - Provide Details to Permit Flexing



Typical Forestay End and other Pin Connections

Typical Gusset Plates

Forestay Links

Typical Minimum Clear Distances

Note: Calculations required for actual case

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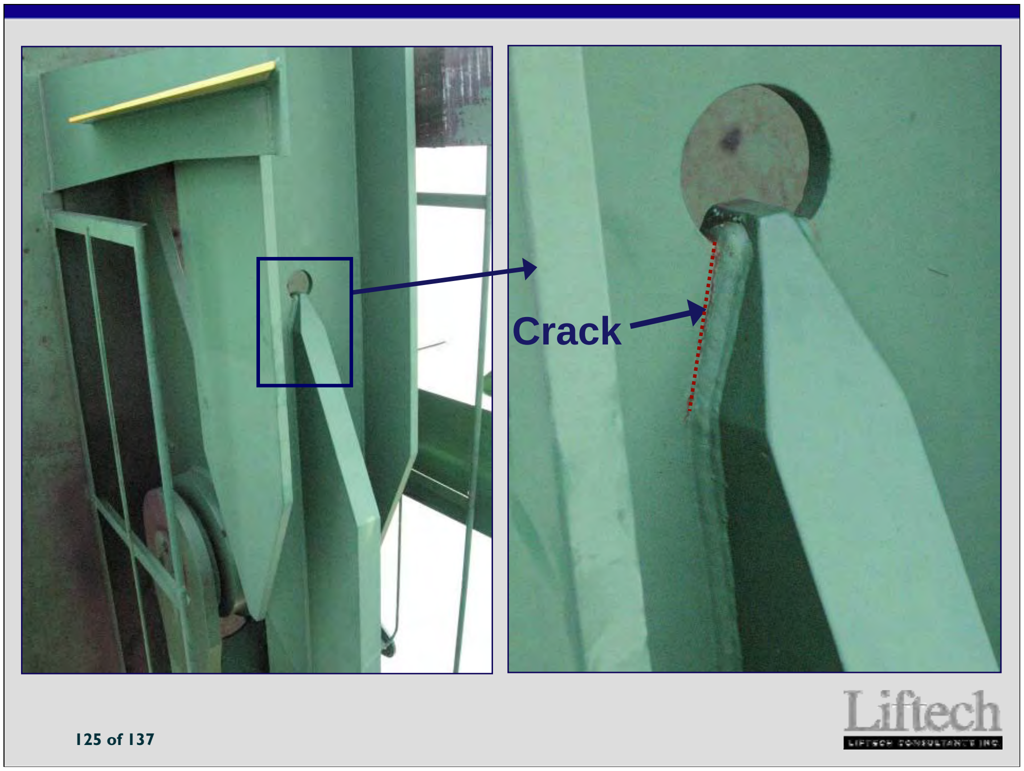
The solution to weak axis bending is to provide adequate clear distances to limit stresses. Clear distances of 5 t to 10 t are typically adequate. Calculations should be made to confirm that clear distances will provide the required performance.

Let in Plate Detail

Most forestays have a let-in plate. Cracking has occurred at some of these connections.



Cracks initiated at the plate termination due to large stress concentration. This is exacerbated by the dead load torsion on the plate when the stay is not fully tensioned, e.g., during boom raising.

Improve Relief Hole

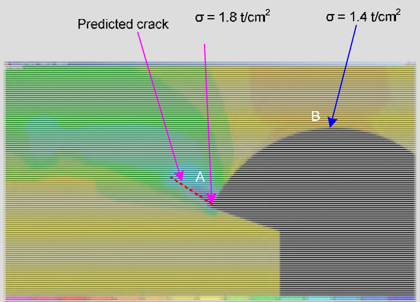
Principal Stress in Web Plate at Forestay Plate; t/cm^2

Parameter Load - 100 t Tension

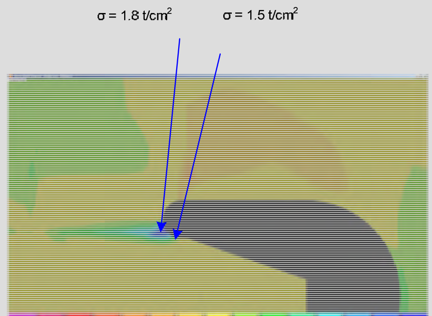
Mesh Size cm.	Original Relief Hole Region		Liftech Relief Hole Region	
	1	2	1	2
0.50	1.00	1.40	1.50	1.80
0.20	1.80	1.40	1.50	1.80
0.05	3.20	1.50	1.60	1.80

Parameter Load - 10 t Self Weight

Mesh Size cm.	Original Relief Hole Region		Liftech Relief Hole Region	
	1	2	1	2
0.50	7.00	5.00	7.00	6.60
0.20	7.40	6.20	8.30	8.00
0.05	8.00	6.60	8.50	8.60



Original Hole



Liftech Suggestion

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Modifying the geometry of the relief hole significantly reduced the stress concentration. The relief hole details including shape, surface roughness, and weld preparation are very important to these connections.

Backstay System Fatigue Cracking

Let in plate details

Weak axis bending at connections

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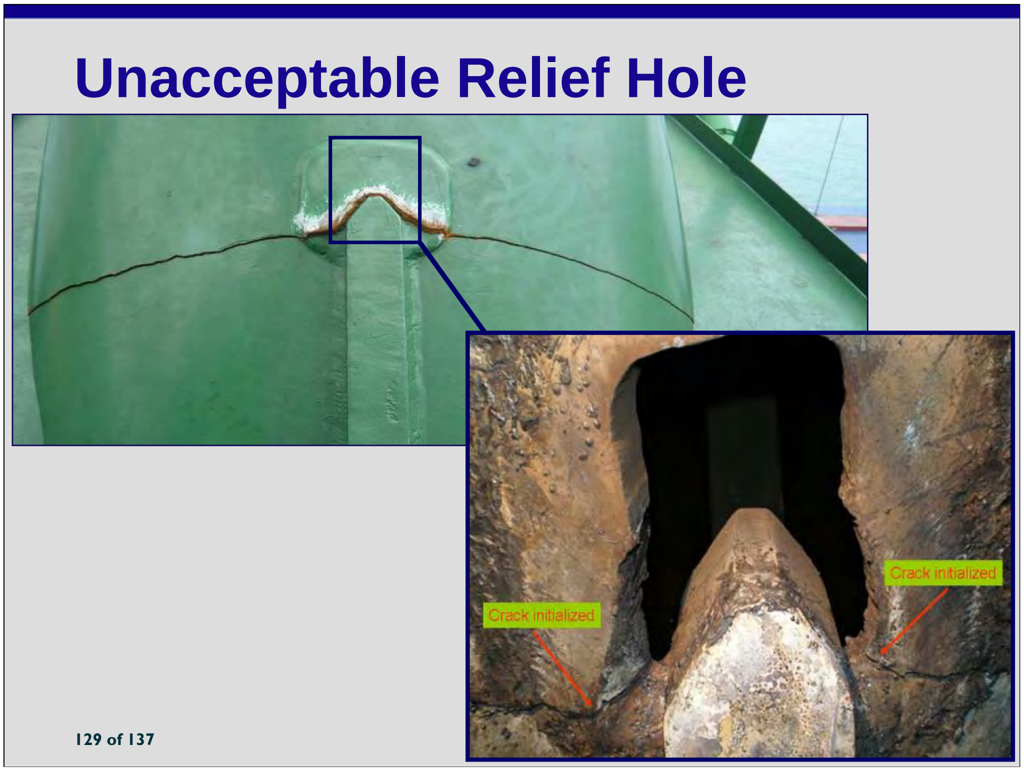
There have been more problems with backstay systems although the problems are due to similar details and phenomena.

Very large cracks have developed at relief holes of the let-in connection plate. A catastrophic failure nearly occurred but did not because materials were much tougher than required.

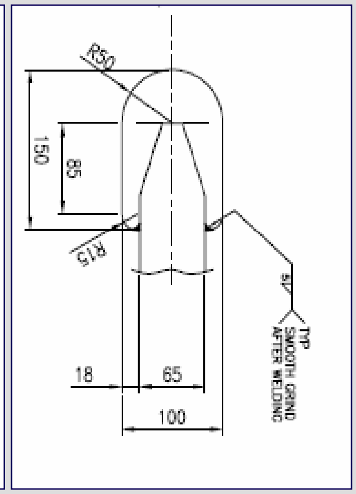


Removal of the cover plate revealed a relief hole with very poor geometry, edge roughness, and transition where it connected to the plate.

The design and fabrication of this relief hole is very poor.

This member was very close to failing under its next significant loading.

Good Relief Hole



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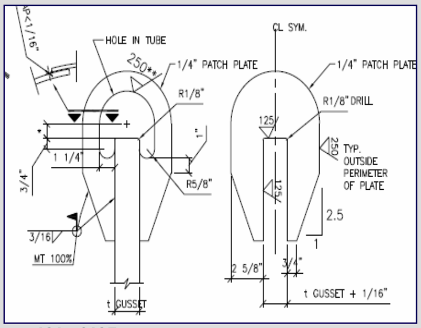
A good relief hole will have a geometry, transitions, and smooth edges to keep stress concentrations as small as practical.

Cover Plate Significantly Affects Performance



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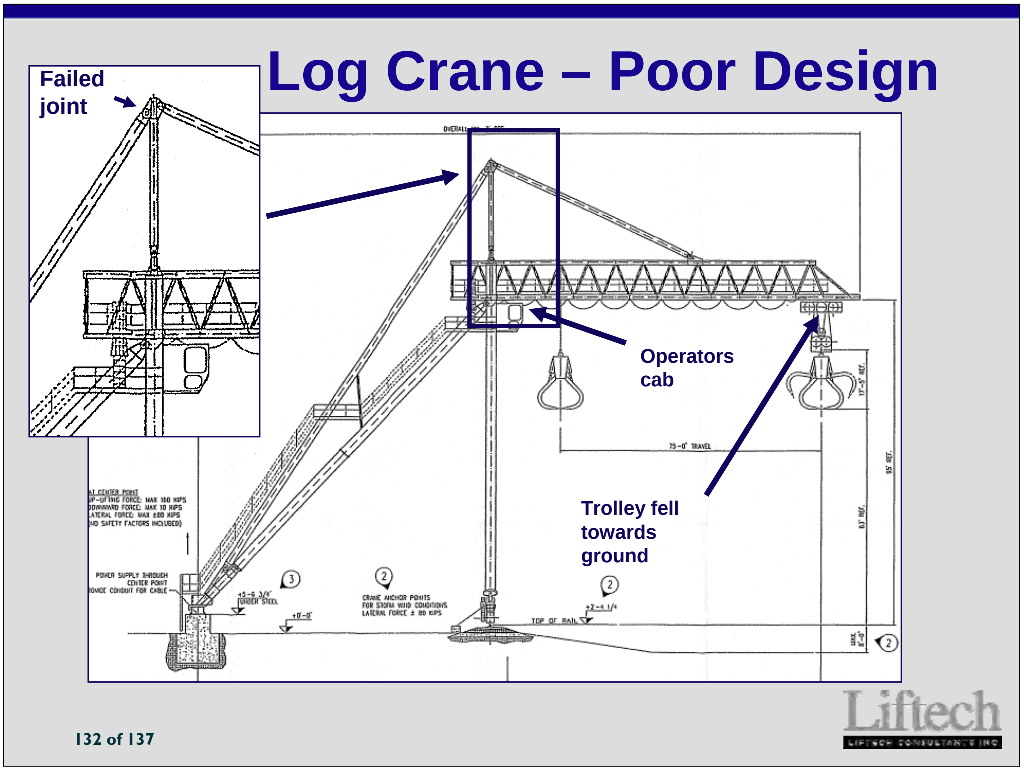
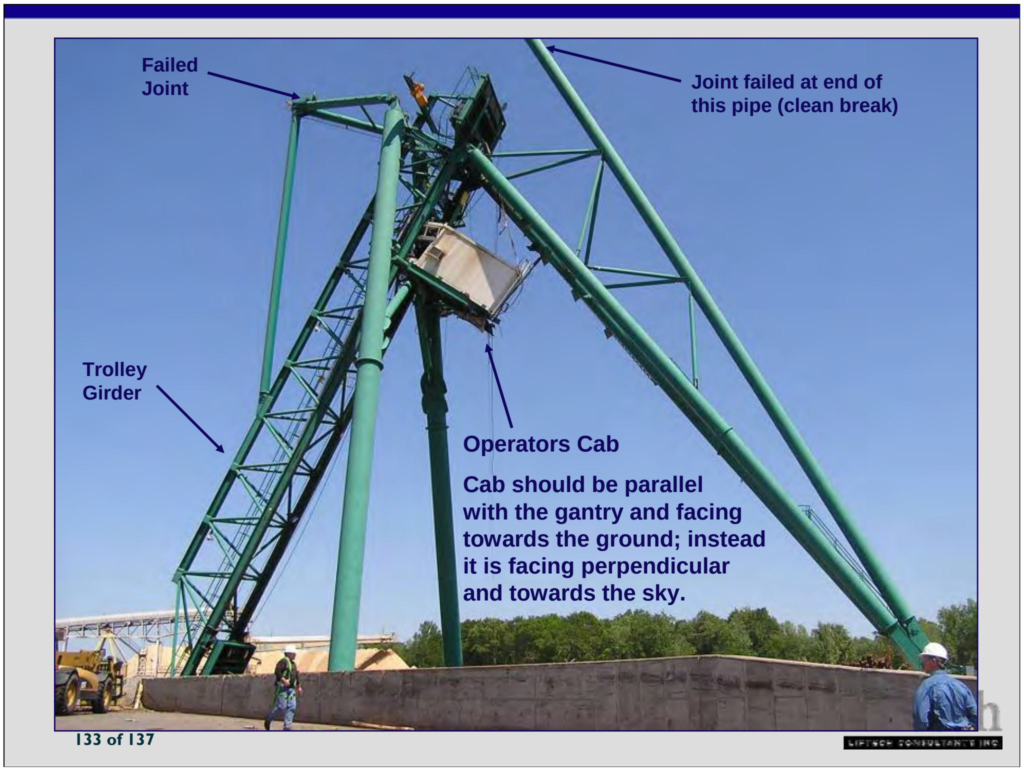
Another critical detail of the let-in plate detail that is commonly overlooked is the cover plate.

The cover plate must be fabricated without notches to limit stress concentrations.

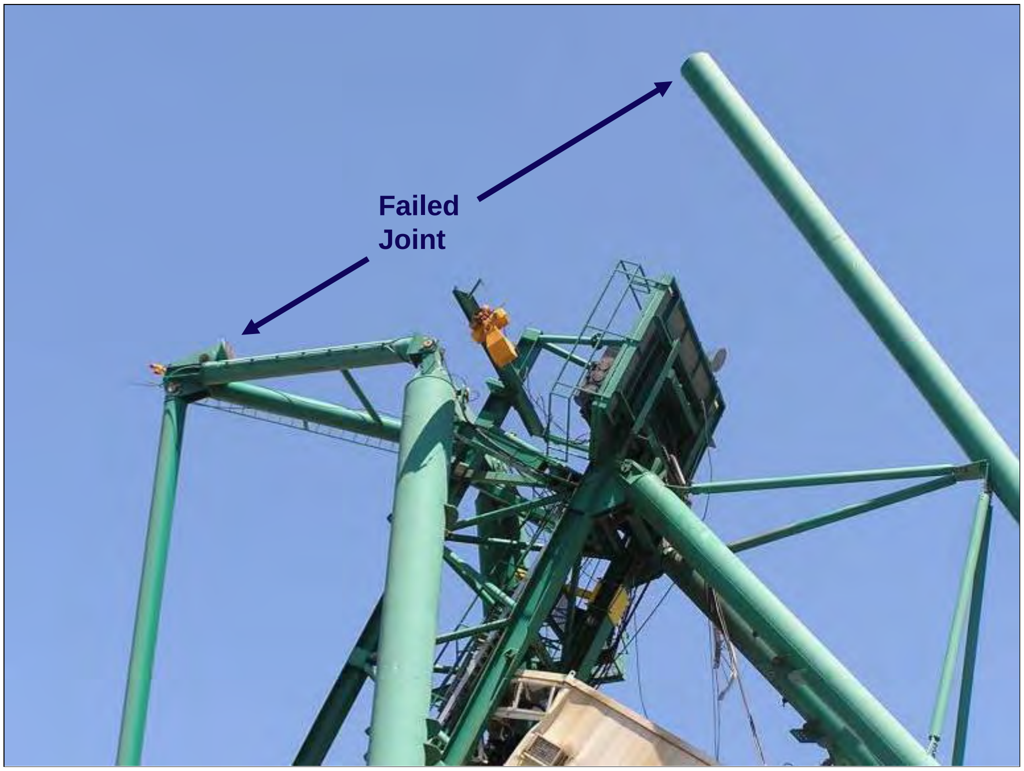
The ends and edges should be far enough away from the relief hole it covers to avoid stress concentrations. It can’t be so far away that any developing cracks may grow to unacceptable sizes before discovery.



A recent log crane failure illustrates another example of poor detailing. A pipe-pinned connection joint failed causing the crane to collapse.



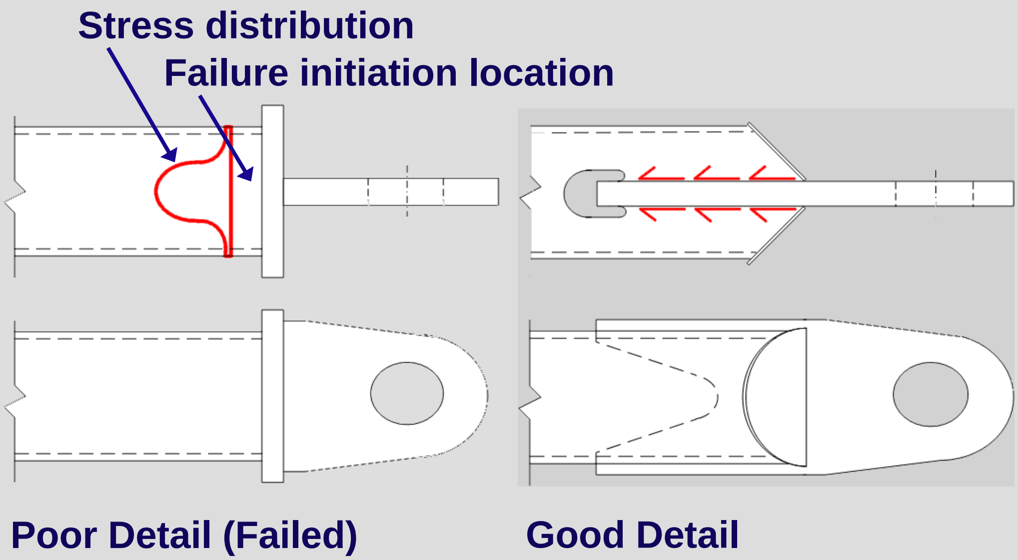
This photo shows how the failed connection caused the boom to fail.



This photo shows a close up of the connection.

What happened?

Pipe End Plate Detail



The detail used resulted in very large stress concentrations at the connection PL. This resulted in fatigue failure and subsequent fracture.

The let-in plate detail shown on the right avoids this problem.

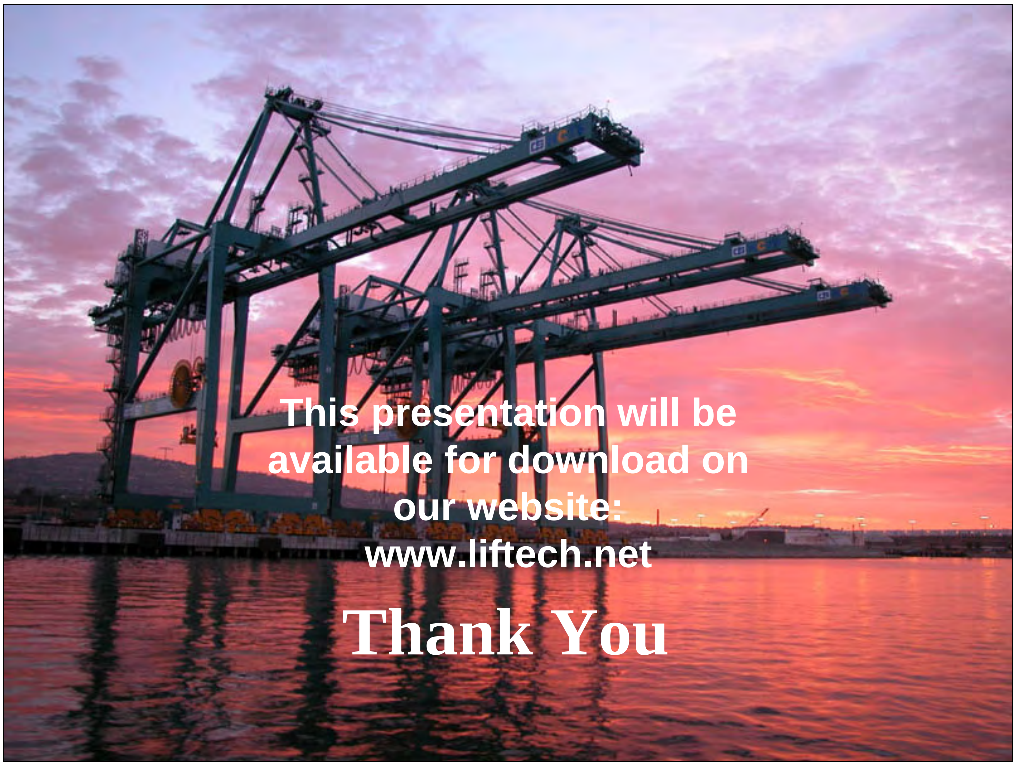
Summary

Trolley induced fatigue must be considered in design.

Use fatigue tolerant details. Avoid stress concentrations.

Monitor fabrication. Poor fabrication can drastically degrade fatigue performance.

Perform structural maintenance to maintain a healthy, reliable crane. To our knowledge, in the past year maintenance has prevented two catastrophic failures.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