This is an image of Katrina, taken from the National Oceanic and Atmospheric Administration website.

Cranes in New Orleans fared well, with only some local damage to operator's cabs.

Try to remember this image later in this presentation; notice the size of the storm.

Topics

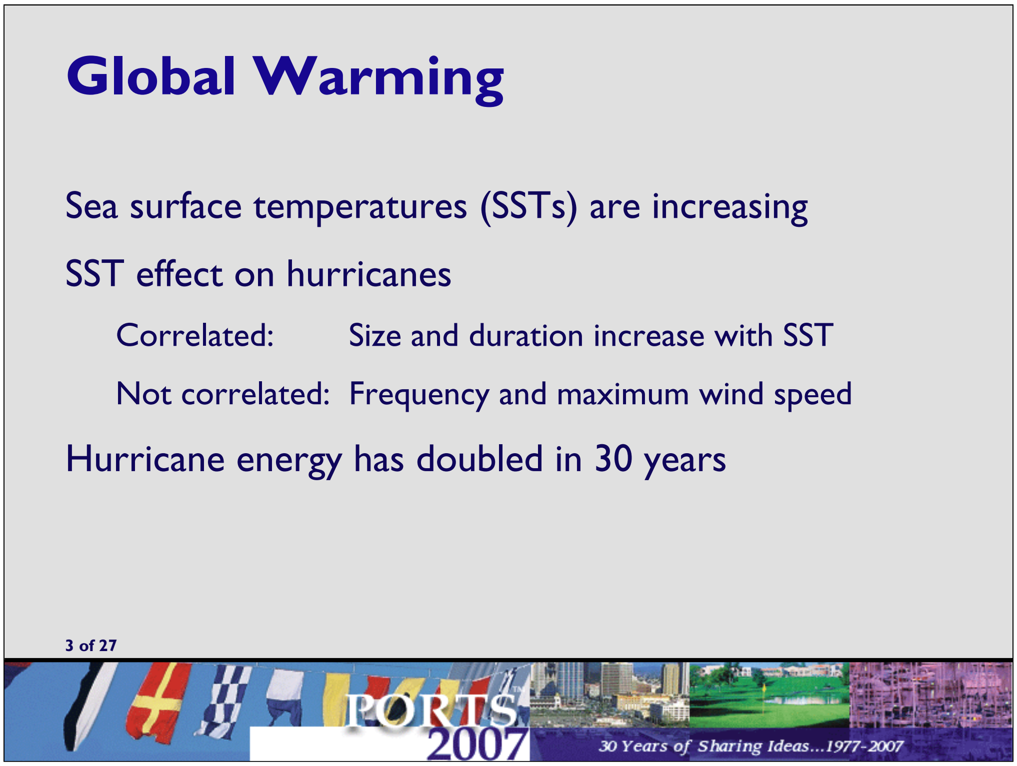
Increasing winds?

Traditional tie-down design

Ductile link tie-down design

2 of 27

We'll start by discussing hurricane winds. Are they increasing?



SSTs are increasing. This affects hurricanes.

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 (SSTs).

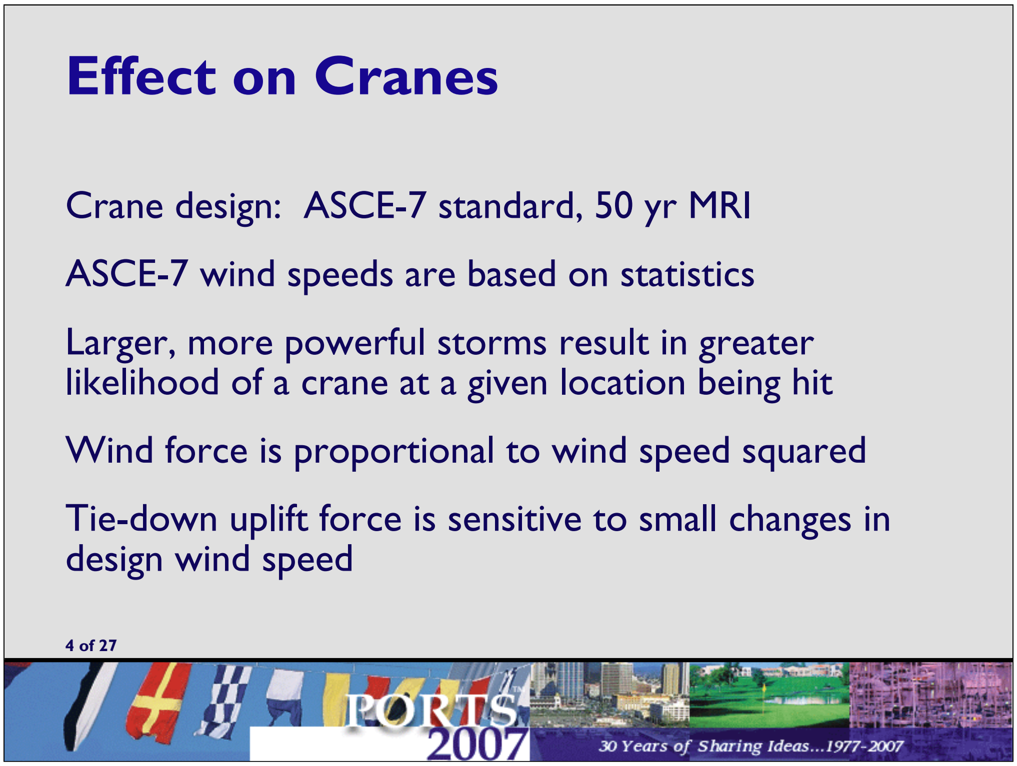
SSTs have increased approximately 0.5 C in the tropics.

Storm duration has 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 the SST.
>
> There is only a small correlation between increasing hurricane maximum wind speeds and SSTs.

In effect, the theoretical maximum wind speed may not be increasing, but the “winds” are, and that effects cranes.



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? The area hit hard by that storm was tremendous.

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

Normally, we would expect Hurricanes to “fizzle” out before hitting land, or shortly after hitting land.

If the likelihood of a hurricane hitting a location increases due to storms lasting longer (and being bigger), we would expect the ASCE-7 wind standard to gradually increase their statistical MRI wind speeds in hurricane regions. In other words, hurricanes are more likely to hit a certain location, so instead of hitting every 75 years with a certain storm, it might hit every 50 years.

The same wind speed will occur more often, decreasing the recurrence interval for the same wind speed. A current 75-year wind may become a 50-year wind.

Overturning moments are proportional to the wind speed squared.

Note: Cranes here on the West Coast typically do not have tie-downs and are not likely to be affected by changing wind effects any time soon.

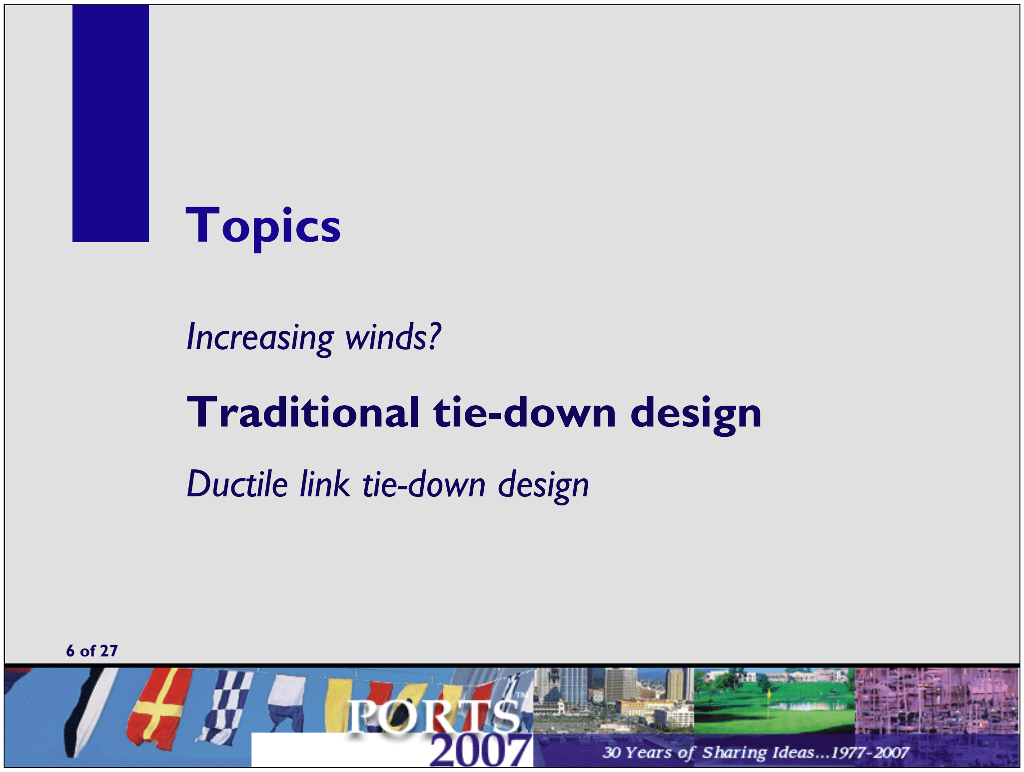
Hurricanes cause damage. The risks are real.

Typhoon Maemi struck Pusan, Korea in September of 2002.

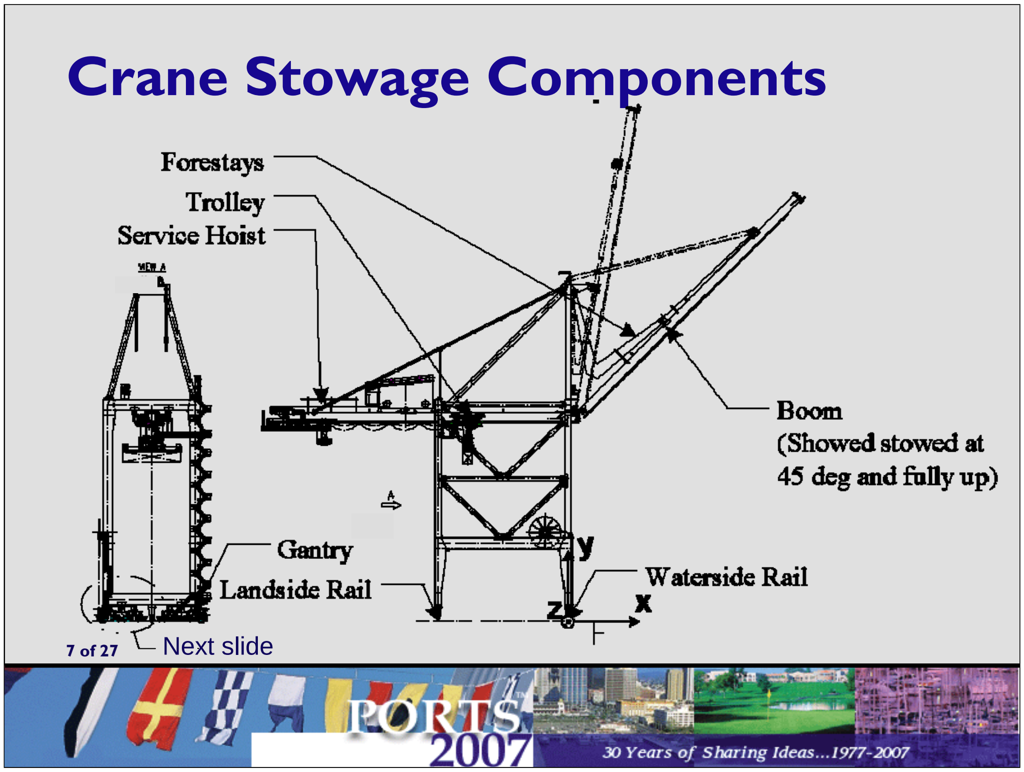
Two cranes are shown (see underside of crane boom).

Initial failure of tie-down attachment to wharf.

There can be consequential damage as well; six other cranes were also lost due to a single, initial tie-down failure and subsequent domino-effect collisions.



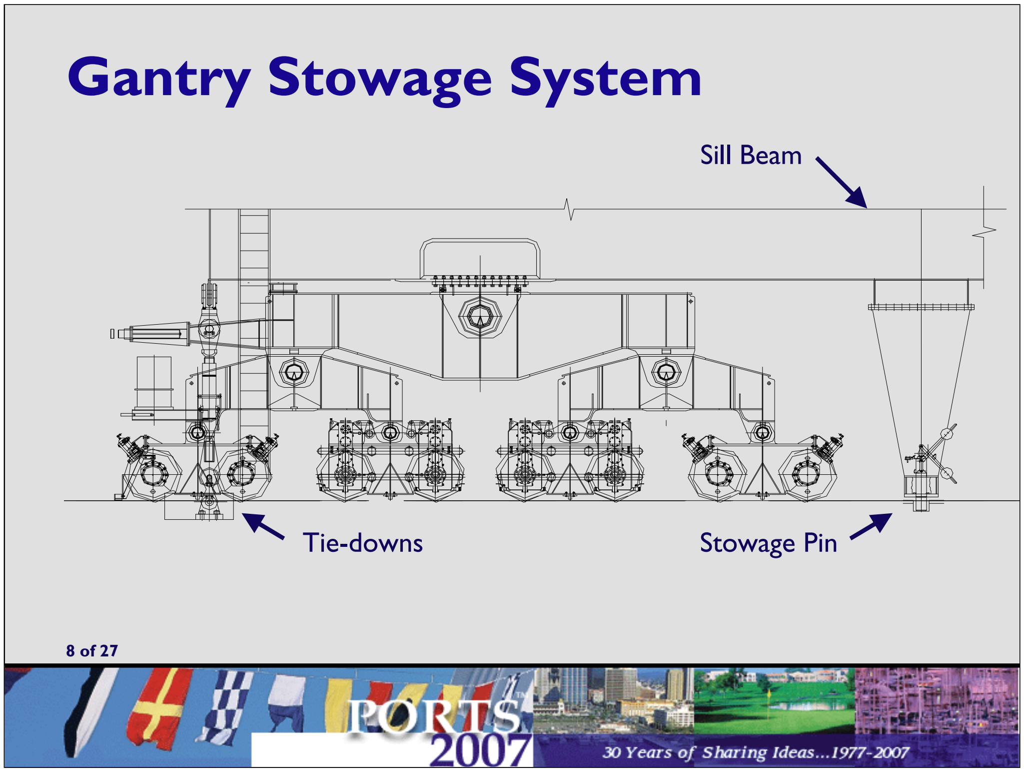
Now we will present traditional tie-down design and some associated problems.



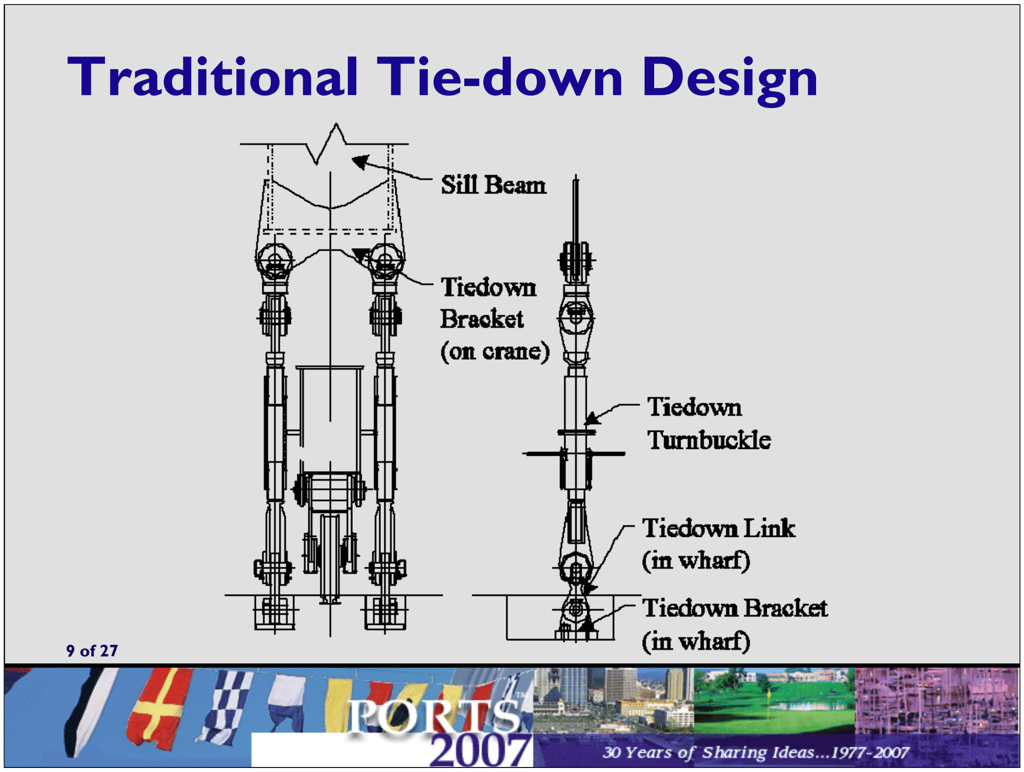
Crane stowage components are shown here.

Most failures are uplift-related, so we will focus on the tie-downs.

- Tie-downs take uplift (Y-dir)
- Stowage pins take gantry travel direction forces (Z-dir)
- Gantry wheels transmit trolley direction forces to rails (X-dir)

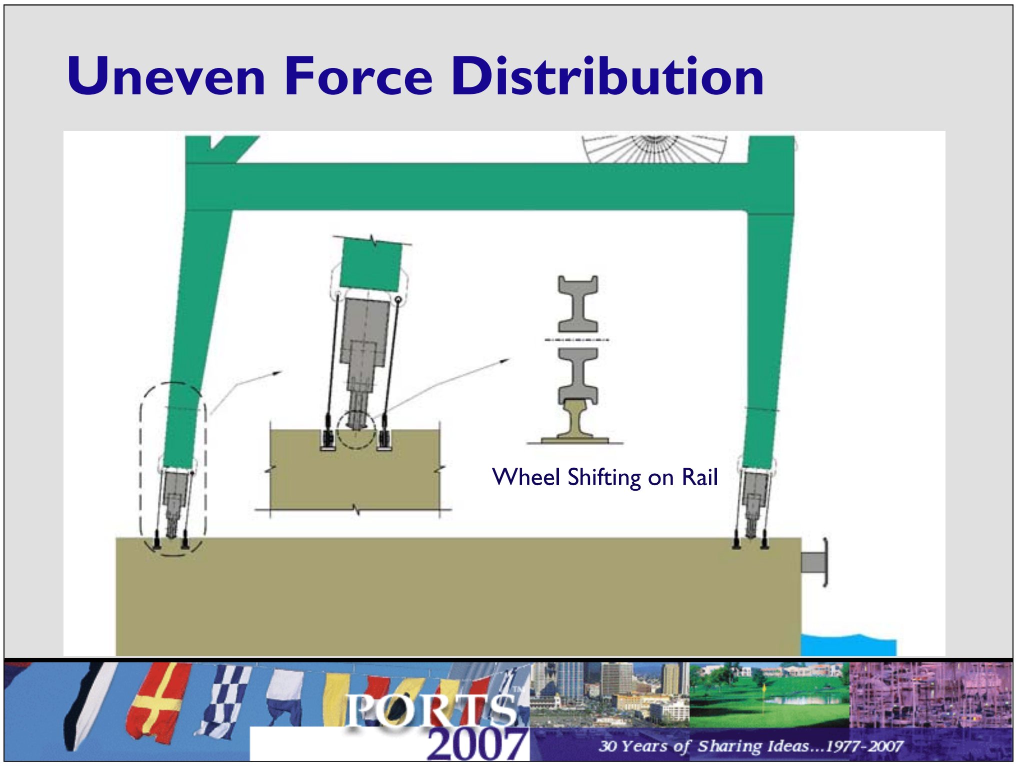


Tie-downs are most effective toward the end of the sill beam.



Ideally, we would prefer only one tie-down per corner.

For hurricane wind regions, uplift force is typically too large with today's jumbo cranes, to practically have only one tie-down per corner. The issues involved the inability to test turnbuckles, and the difficulty securing, due to size.

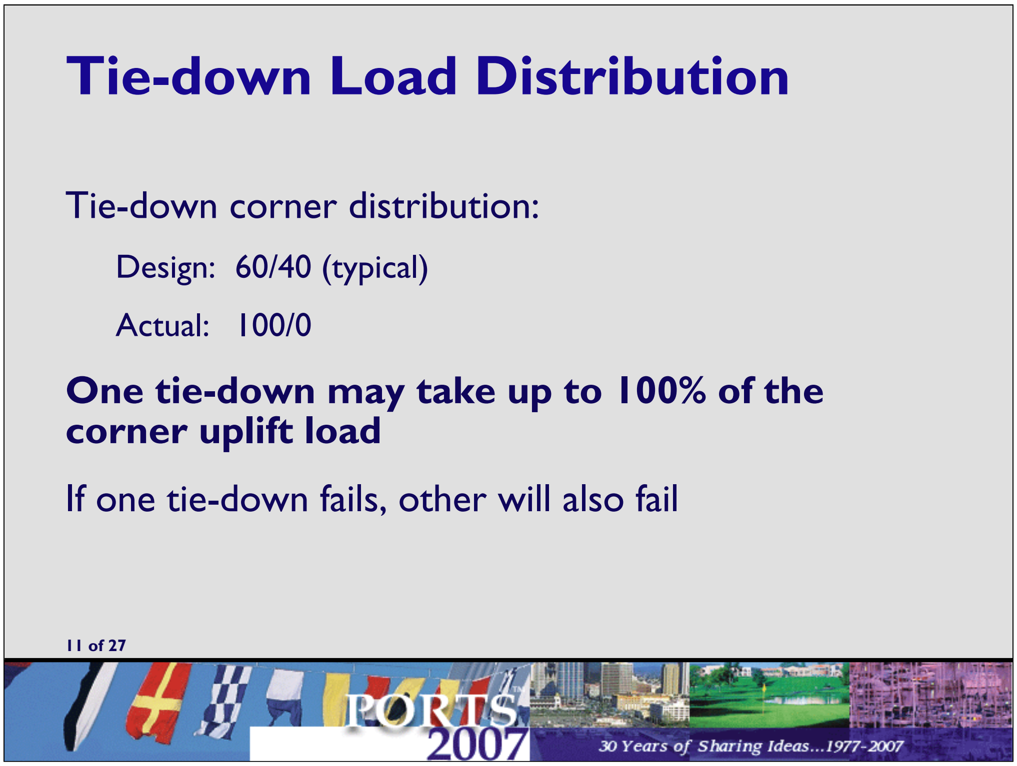


Cranes are flexible and hurricane forces cause cranes to deflect and move.

The forces in the tie-downs are not evenly distributed.

Why?

- 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



For years, designers have used a 60/40 or 70/30 load distribution per corner. We thought this was conservative.

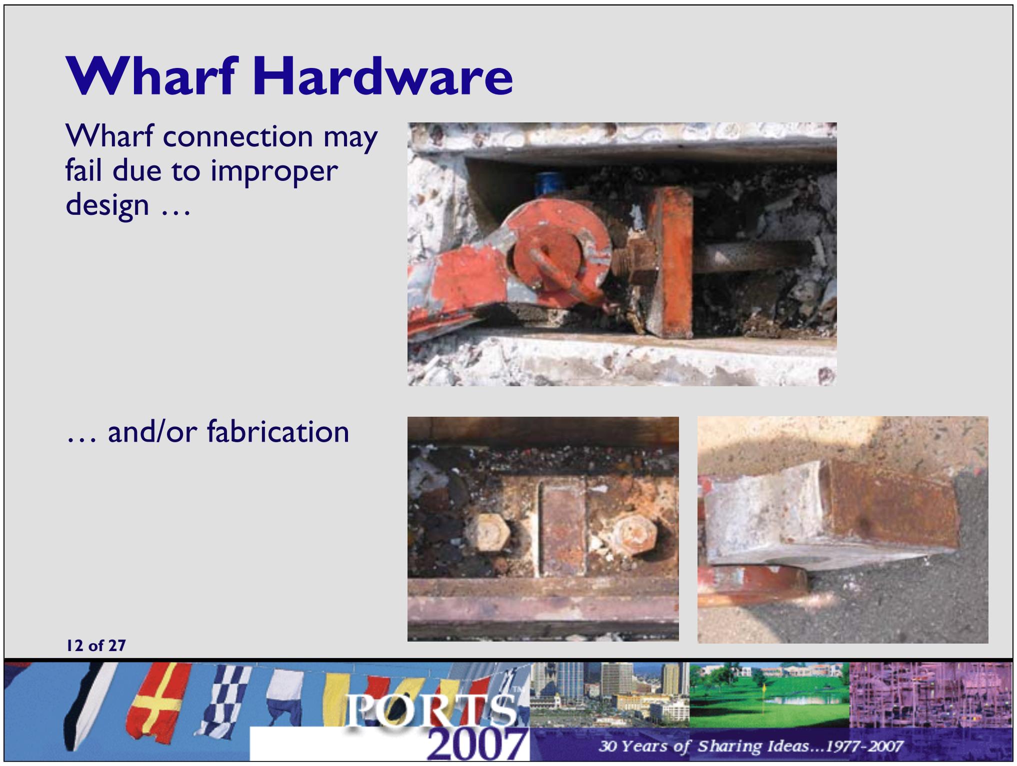
Recent analyses indicate that the actual distribution may be as much as 100/0%.

If a single tie-down was designed to 60% of the total uplift, the actual uplift would be 100/60 = 1.67 times the design uplift.

The tie-down may survive due to factors of safety—or it may not survive.

Many older cranes have seen their design wind speed. Others have not.

The tie-downs are typically not the weakest element …



Usually, the wharf hardware to crane tie-down interface is the first to fail.

Wharf connection design may not be consistent with crane design.

The tie-down wharf hardware is often designed to a lower standard, compared to the tie-down design (ASD vs. LRFD). The unequal load distribution may cause the wharf hardware to give way.

Upper image is a tie-down pullout failure with smooth anchor bolts.

Lower image is a tie-down wharf bracket failure due to improper fabrication--4 mm (3/16 in) fillet weld between base plate and 60 mm (2.5 in.) lug.

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

Onsite inspection may have prevented this terrible workmanship.

How to Design?

If possible, use one tie-down per corner

Otherwise, two equalization approaches:

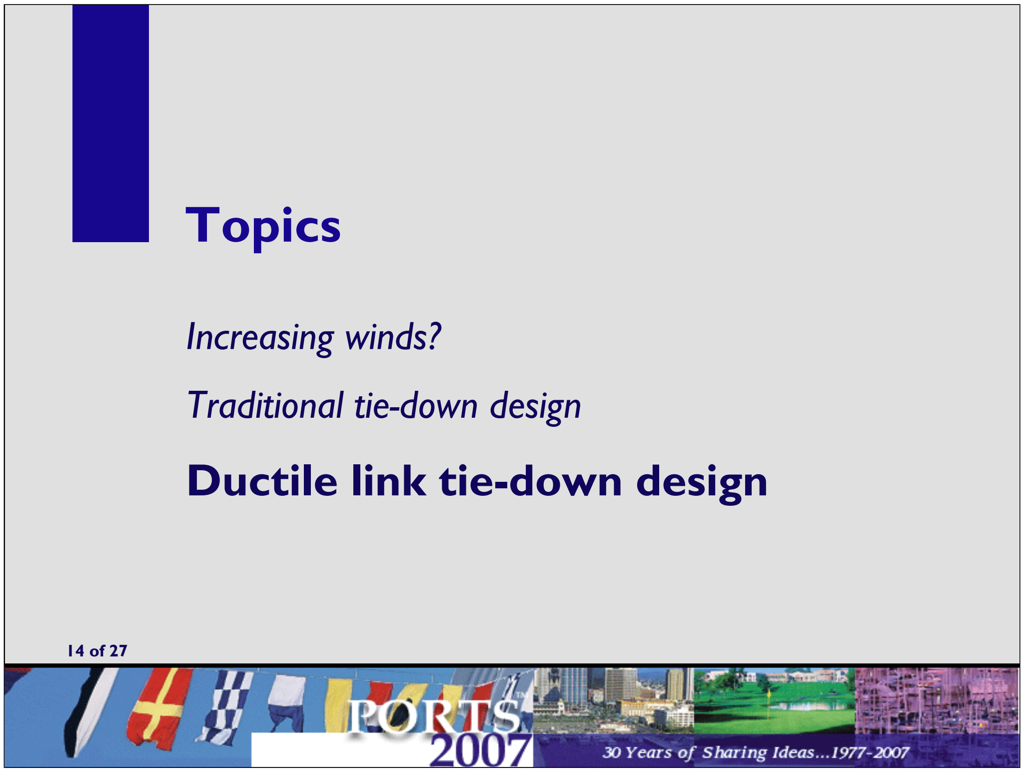
- Mechanical equalizer
- Ductile link

13 of 27

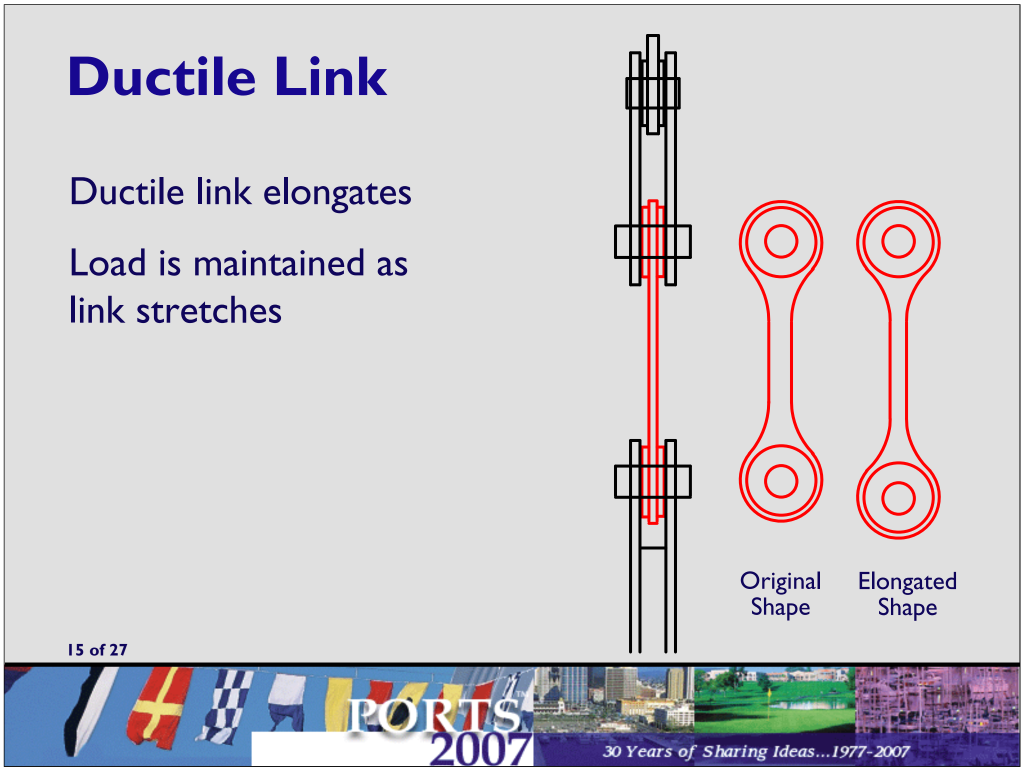
As mentioned, the best method is to use a single tie-down per corner, but this is often impractical.

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

Another choice is to use a “ductile link.”

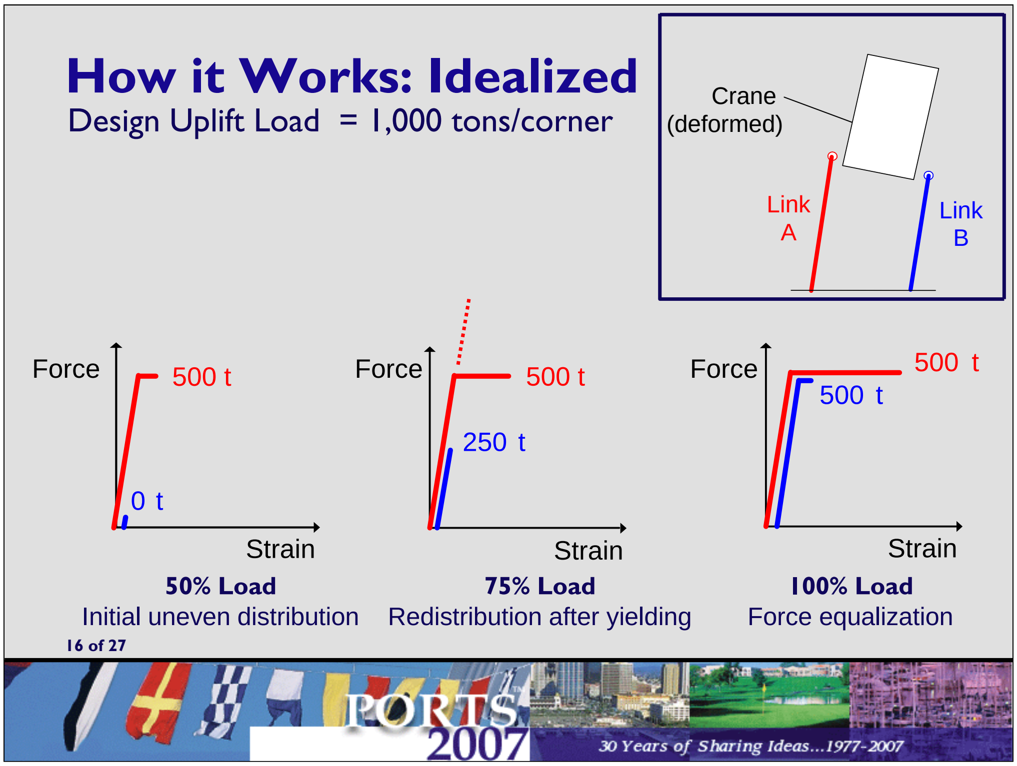


Now we’ll present equalization through ductile yielding of a structural element.



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.



How does it work?

Initially the loads in multiple tie-downs are not equal. In some cases, the entire corner upload force is carried to one tie-down. 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.

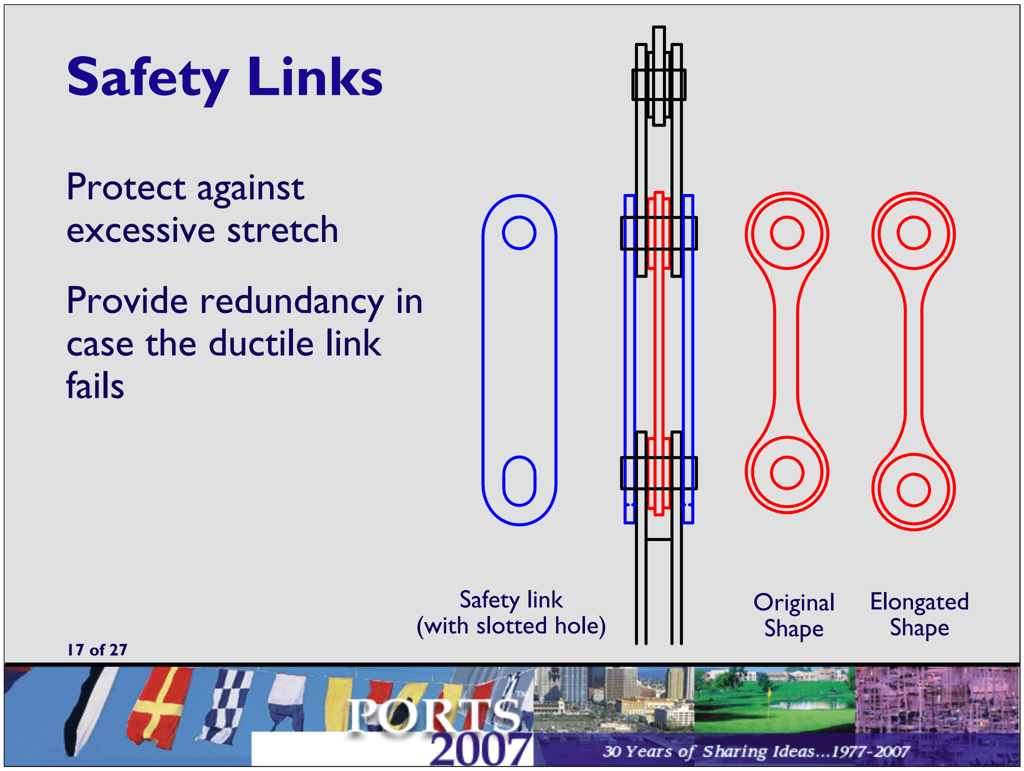
With the ductile link, the heavily loaded tie-down yields at half of the design uplift load, allowing load to transfer to the lightly loaded tie-down.

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 utilized, as intended.

(Note that the force/strain graphs are idealized.)

This protects the wharf hardware from overload.

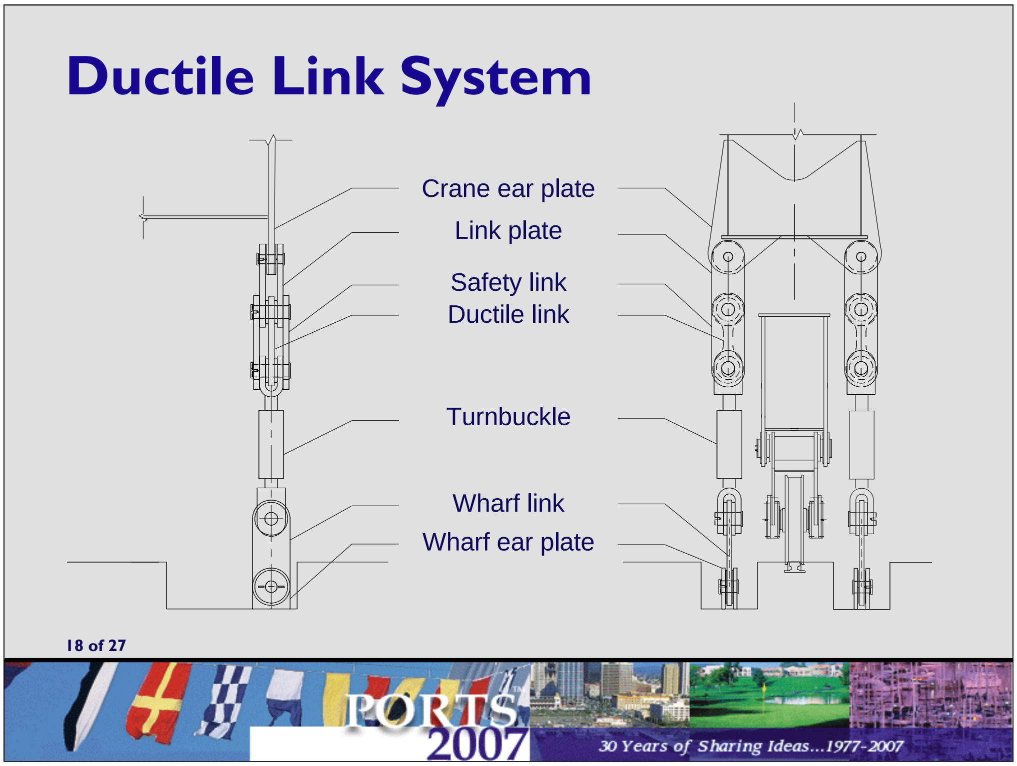


What if both links are loaded to their failure deformation? Their strength is insufficient to continue carrying the load. How can we keep failure from occurring?

It is likely that the elements in the rest of the system have some reserve strength. This strength can be utilized with the use of safety links connected in parallel with the ductile link.

The ductile link has done its job and distributed the load. Now the failure should be controlled by the remaining weakest element.

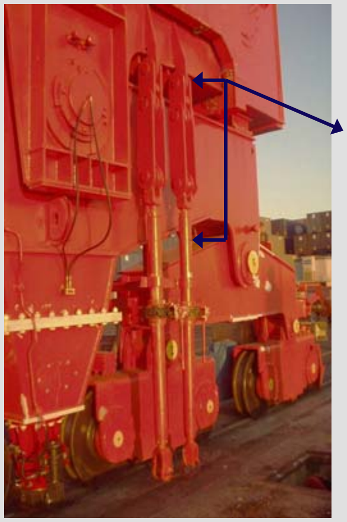
The safety link also provides some redundancy.

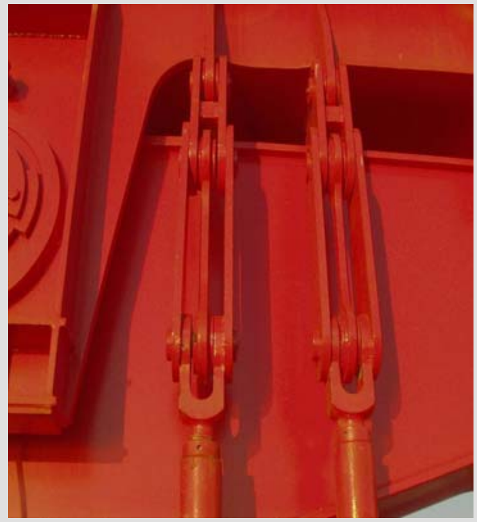


Notice how the ductile link fits in to a typical tie-down system.

The ductile link-safety link system is typically larger than a traditional tie-down. There may be some interference with the gantry.

Ductile Links Implemented





19 of 27

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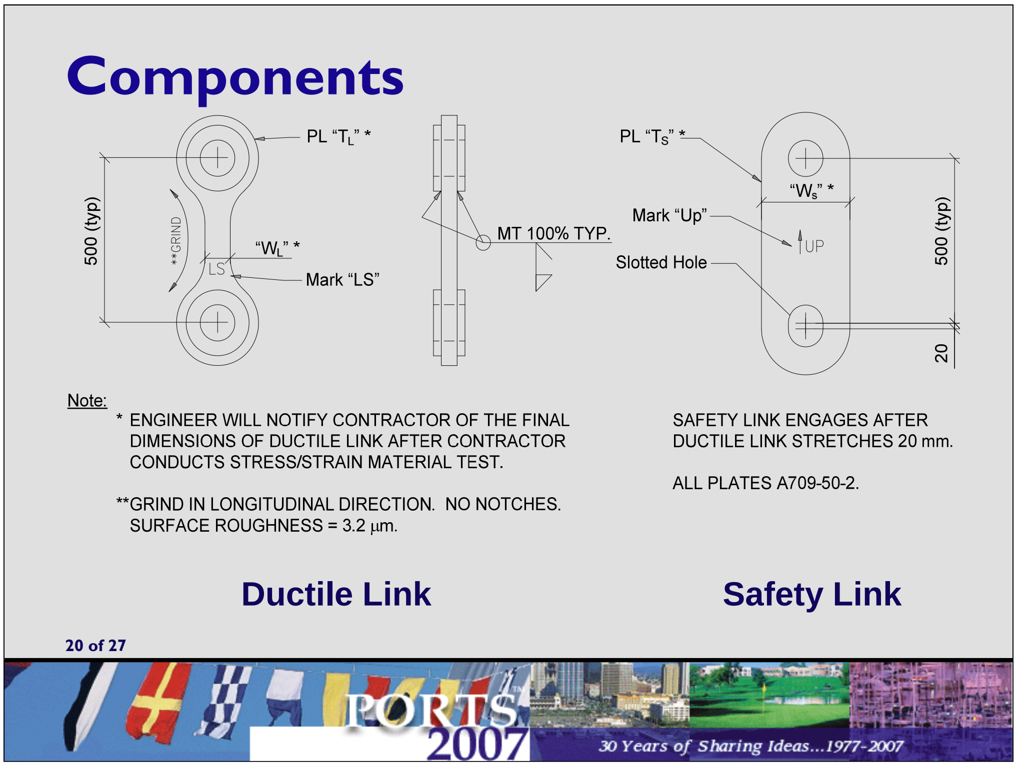
Here is a ductile link system with four tie-downs per corner.
(Implemented in New Jersey)



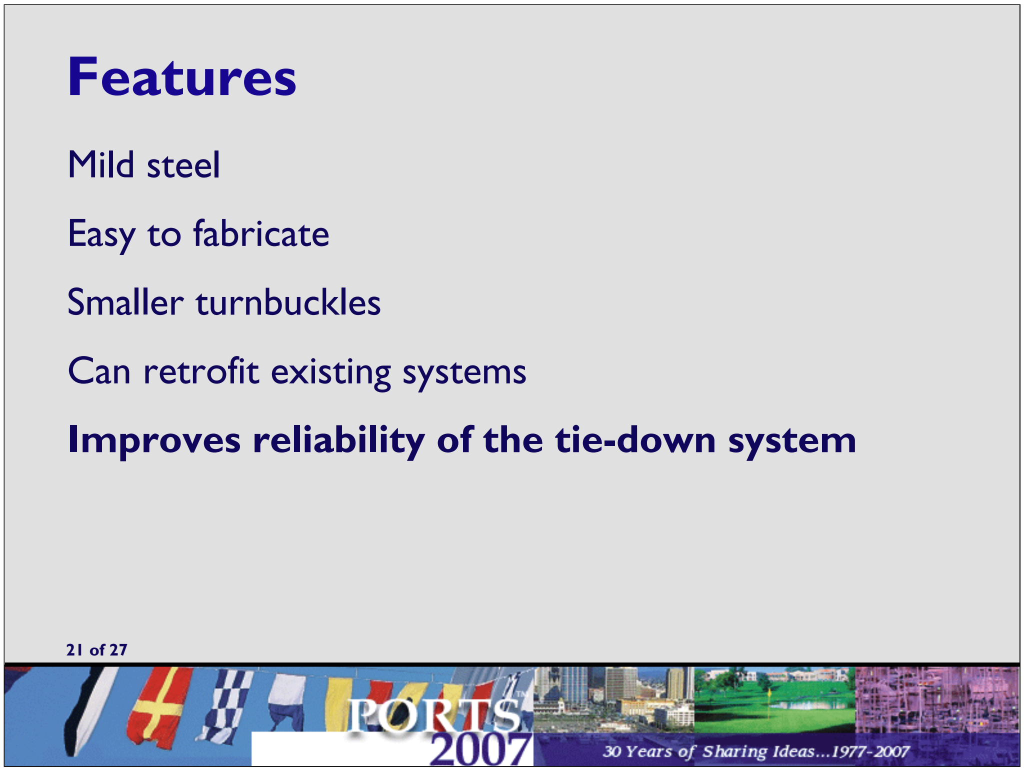
Important features:

Controlled area and material properties of the ductile link

Need material testing

Grind stretching region smooth

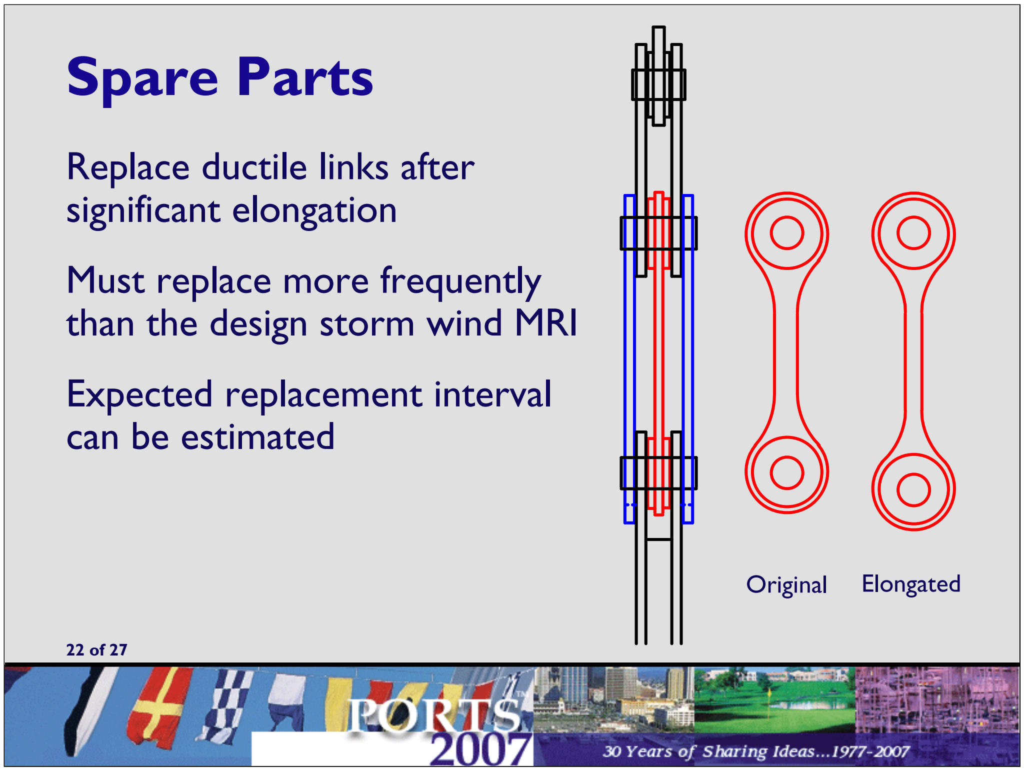
Slotted hole in safety link to allow for design stretch of ductile link (based on material testing)



Ductile links improve reliability. ←This is the main feature

Ductile links can be added to existing cranes, although it is not cheap, and sometimes it is difficult to fit.

On new cranes with multiple tie-downs, using ductile links is relatively easy and should not increase the crane price.



To ensure that adequate ductility exists and that the ductile link will equalize the loads in the next typhoon, the link should be replaced if significant stretch has occurred. This may be more frequently than design storm MRI because first link yields prior to developing full design corner uplift.

We expect a typical replacement design interval to be a decade.

Refer to the paper for a method of estimating the replacement interval.

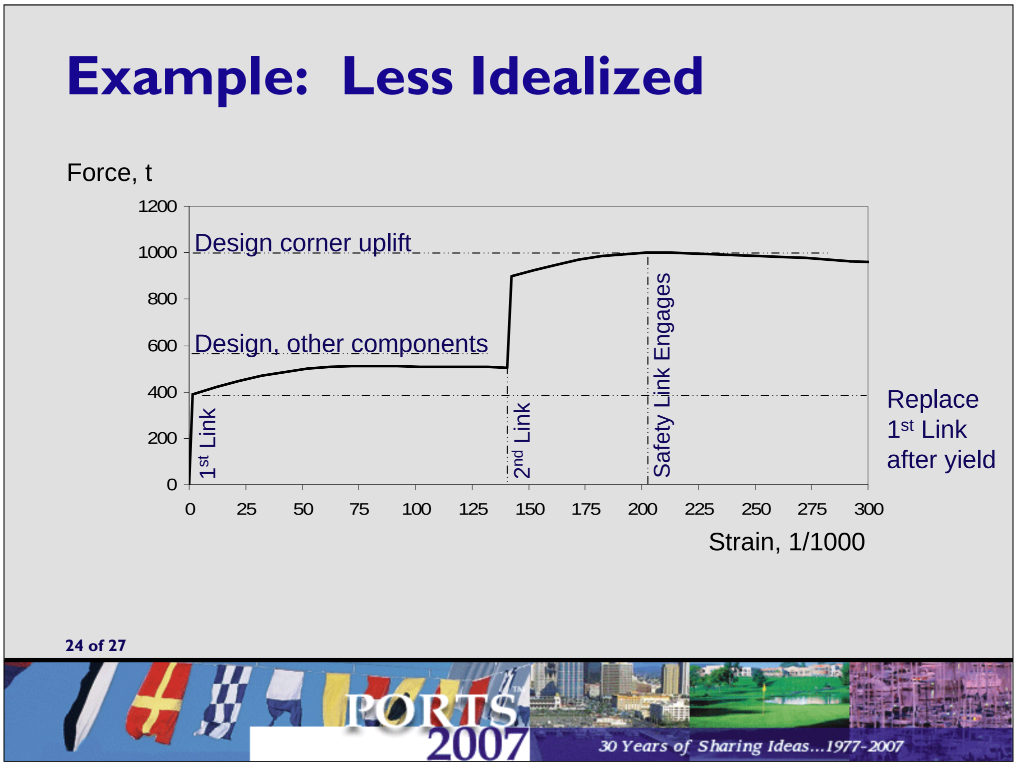
Design Process

1. Forces and displacements
2. Tie-down force at each corner
3. Design ductile link breaking strength
4. Check other members
5. Design and test ductile link
6. Design the safety links

23 of 27

The design steps provided are only guidelines and only mention a few of the design issues.

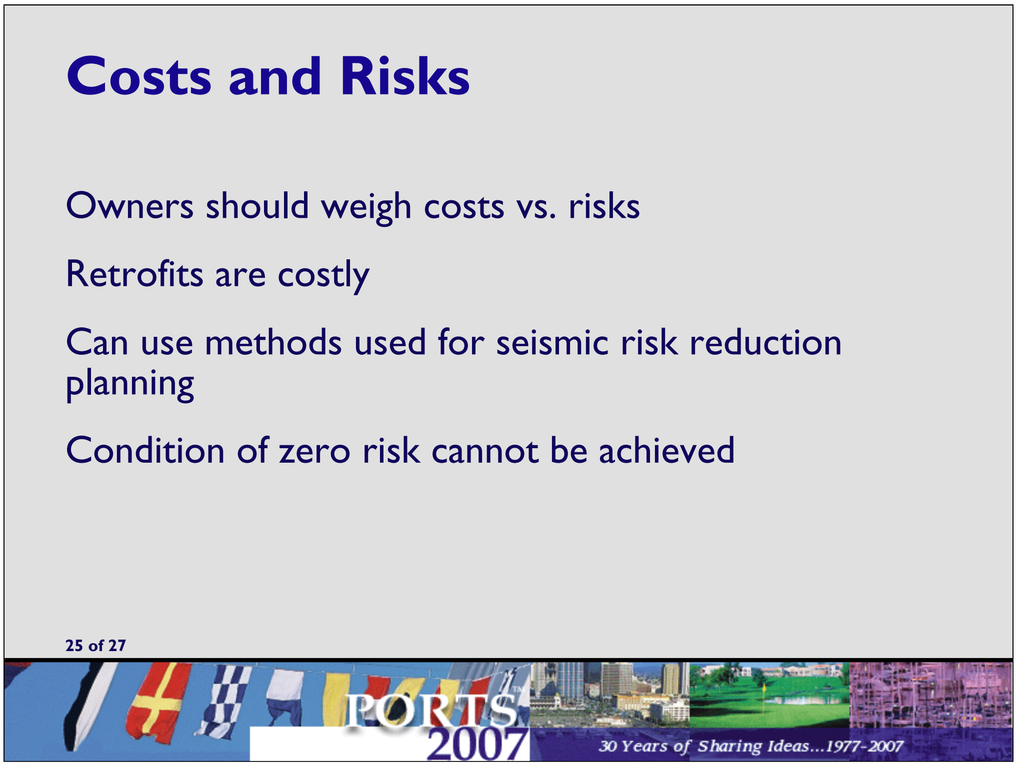
1. Calculate forces and displacements due to factored dead and storm wind loads
2. Calculate the average tie-down force at each corner
3. Design the breaking strength for the calculated average tie-down uplift force
4. Verify that the strengths of the other tie-down and wharf hardware components exceed the link breaking strength
5. Design the ductile link dimensions based on material test samples of the link material. Verify that the link is ductile enough to accommodate the required plastic deformation
6. Design the safety links to develop ~120% of the strength of the weakest element



In reality, the link force at ultimate is greater than at yield, as shown.

The design steps provided are only guidelines and only mention a few of the design issues.

1. 1st link
2. 2nd link
3. Safety link
4. Design uplift
5. Design other components in one link
6. Replacement



Retrofit cost is not cheap, but is not expensive compared to the crane costs.

(Around $50-100 K as a really rough estimate.)

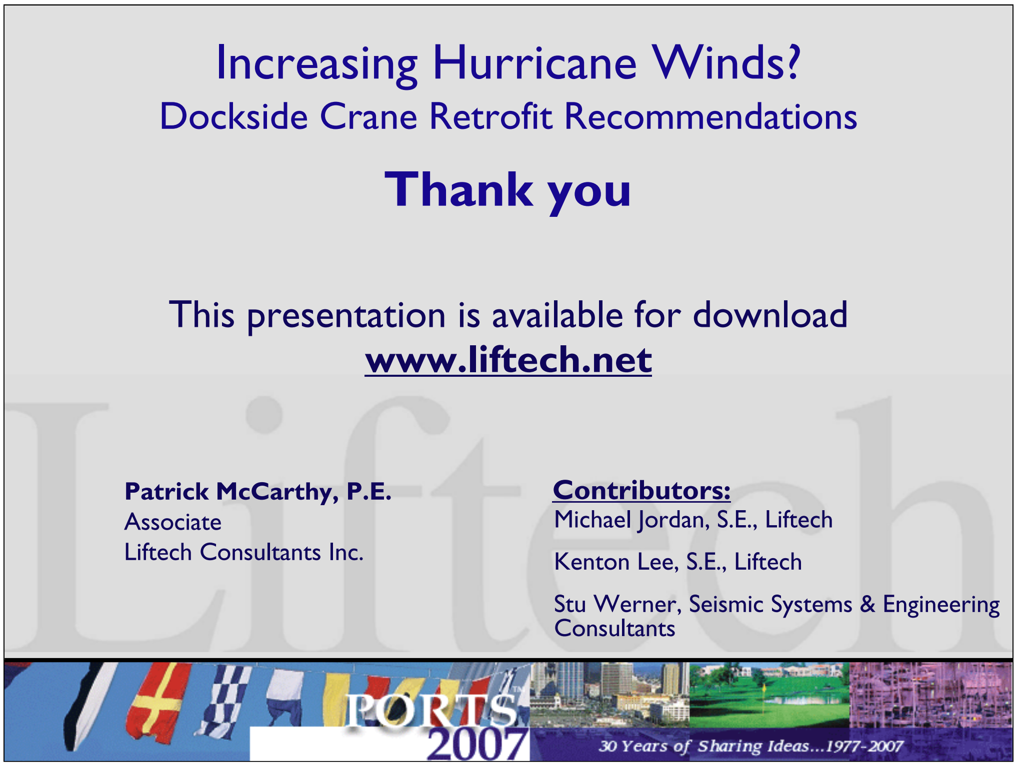
See Stu Werner's *Seismic Guidelines for Ports* (TCLEE, ASCE, March 1998) for information regarding seismic risk reduction planning at major ports.

Unacceptable crane damage risk must be weighed against costs of retrofit.

Risk of economic, life safety, political, legal, and administrative losses must be considered. These are owner-specific.

In closing, we recommend owners review their options.

Ductile links may be an attractive solution for increasing crane stowage reliability in a changing environment.



See the paper for references and more information.