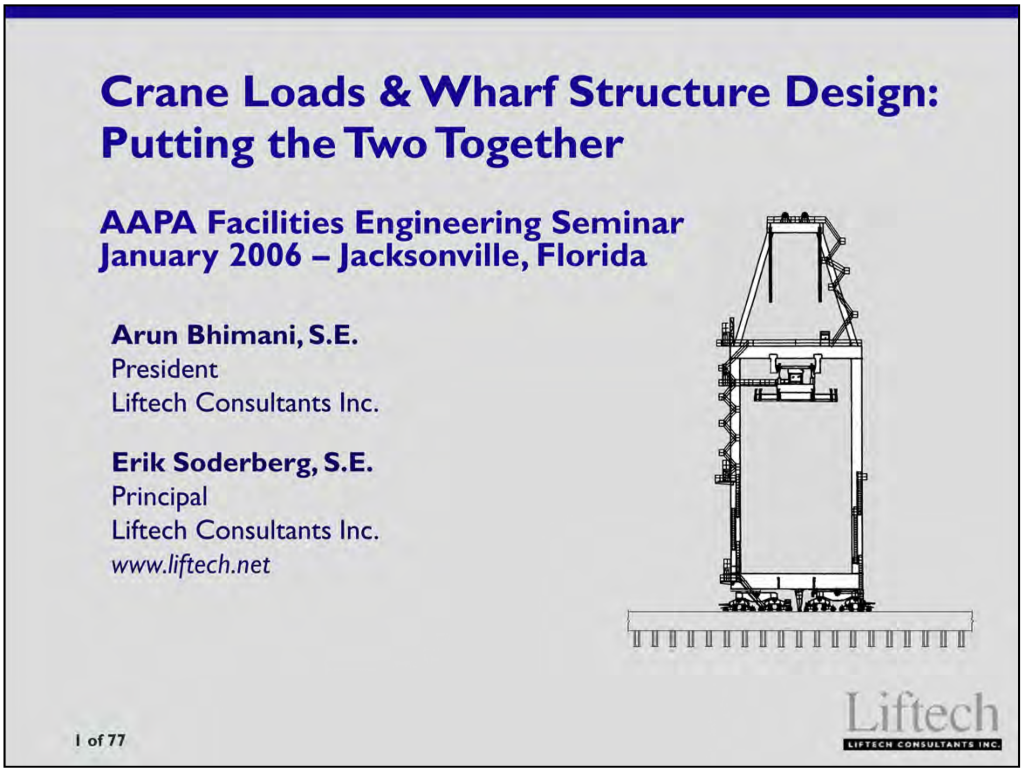
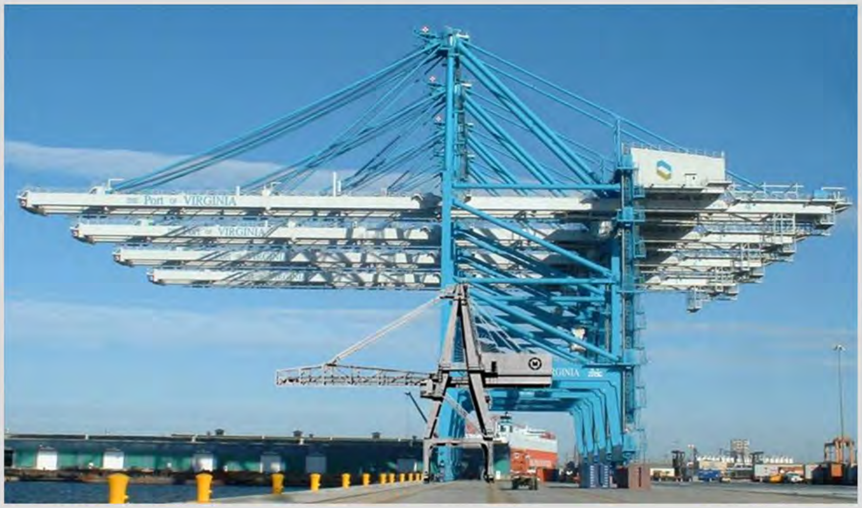


This presentation discusses historical problems with crane loads and wharf structure design, and offers recommendations to reduce these problems.

Crane Size Growth:
First Container Crane and Jumbo Crane



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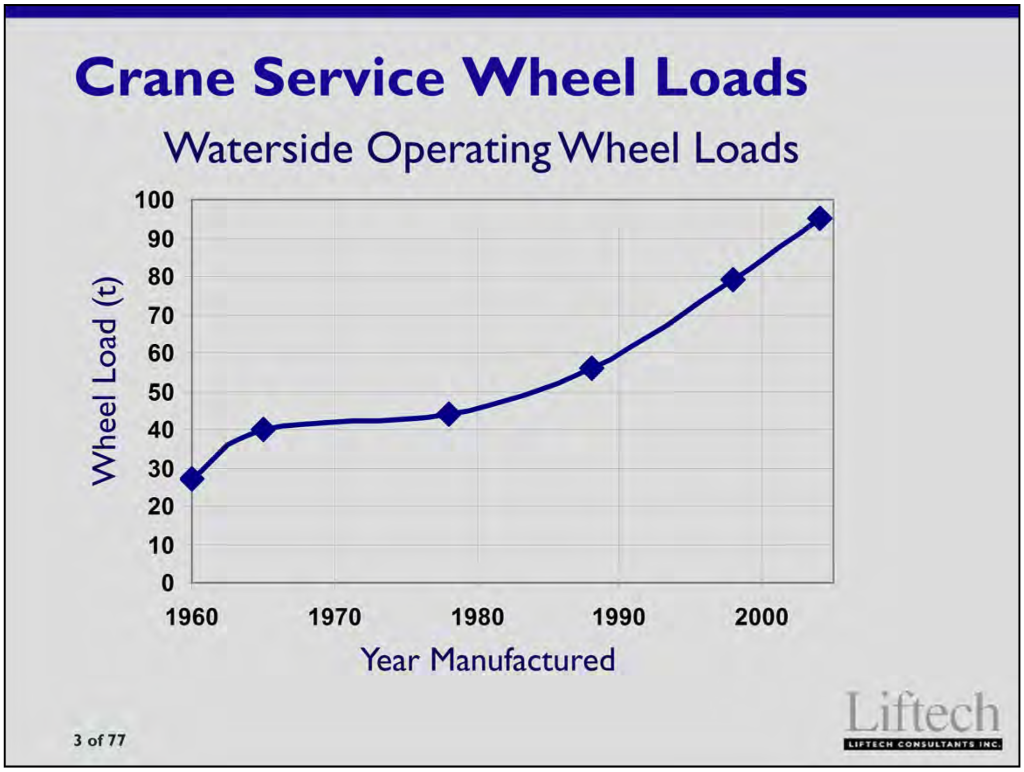
This image shows the first Matson crane scaled and superimposed in front of the existing Virginia Suezmax cranes.



As the weight and height have increased, so have the wheel loads.

Crane Loads

Crane loads increasing

Consequences of misapplication more severe

Codes becoming more complex

Chance of engineering errors increasing

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There is an increasing risk of engineering errors because the loads are more significant, and the design codes are becoming more complex.

Presentation Outline

The Problem – Overview

Wharf Designer's Perspective

Crane Designer's Perspective

Putting the Two Together

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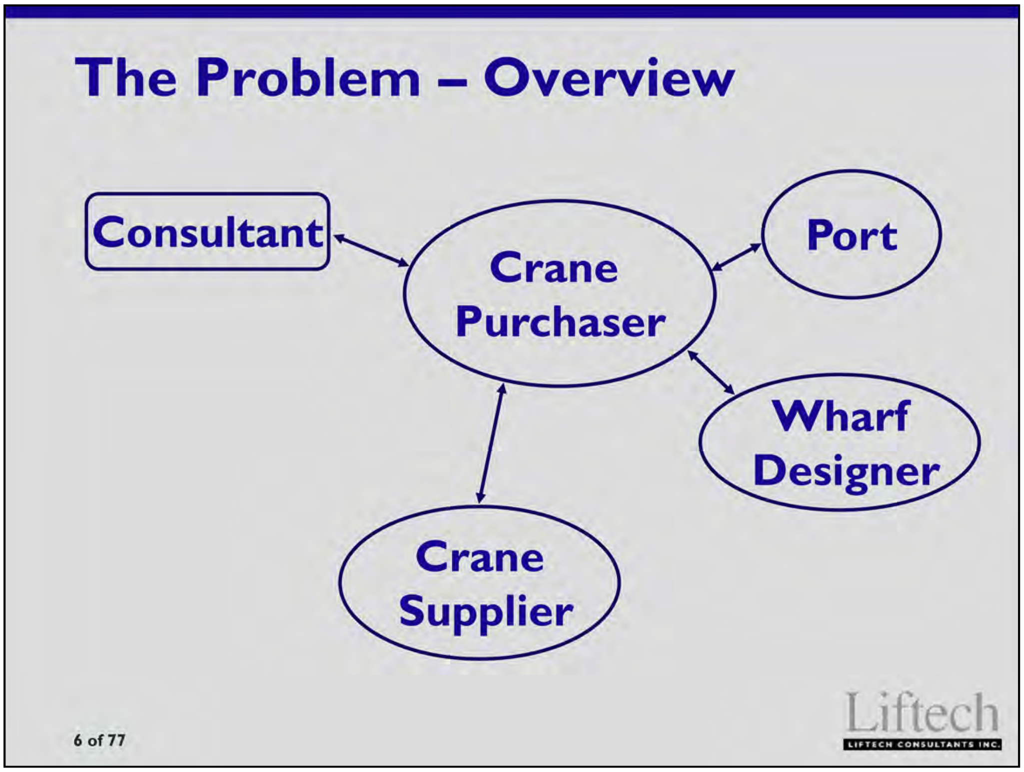
Today's presentation will address these topics.



Historically, communication between engineers goes through the crane purchaser. This results in confusion and misunderstandings.

Crane Purchaser Difficulties

Purchaser specified

"Allowable wheel load: 200 kips/wheel"

Suppliers submit

Supplier A	180 k/wheel
Supplier B	200 k/wheel
Supplier C	220 k/wheel

Which suppliers are compliant?

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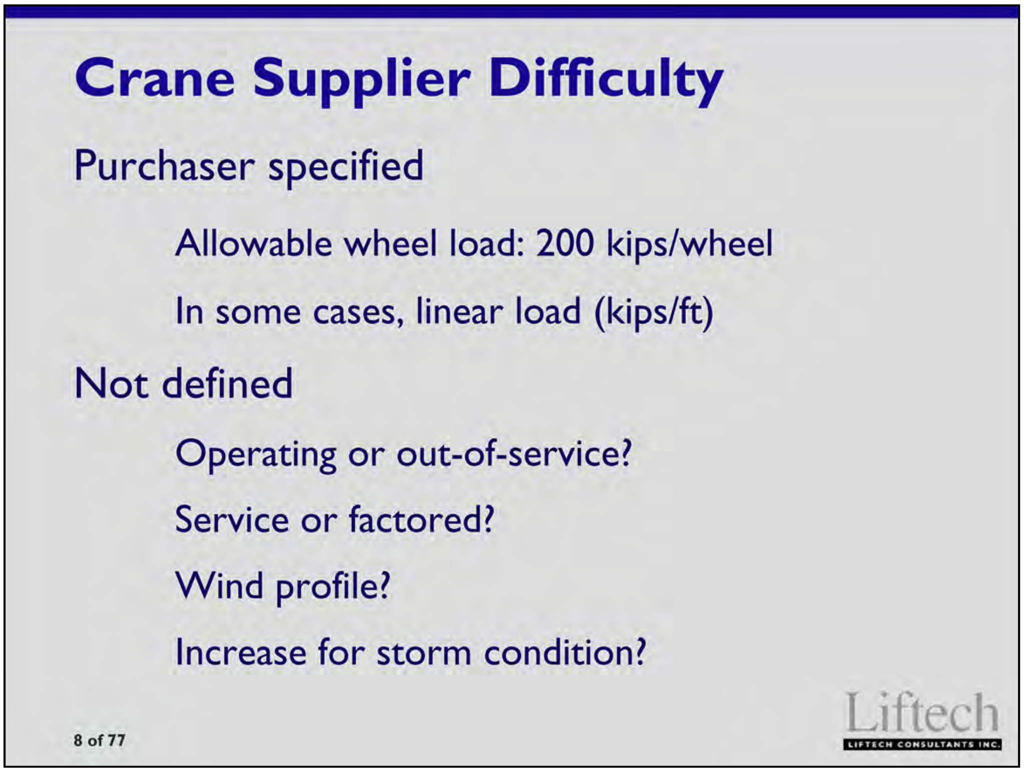
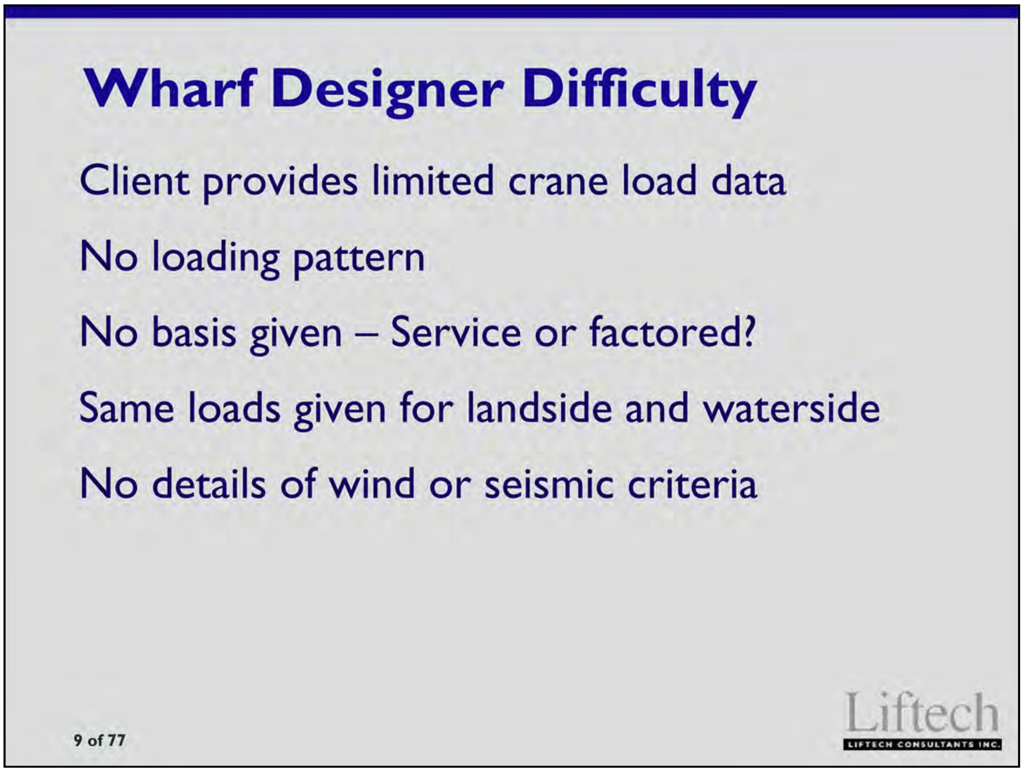
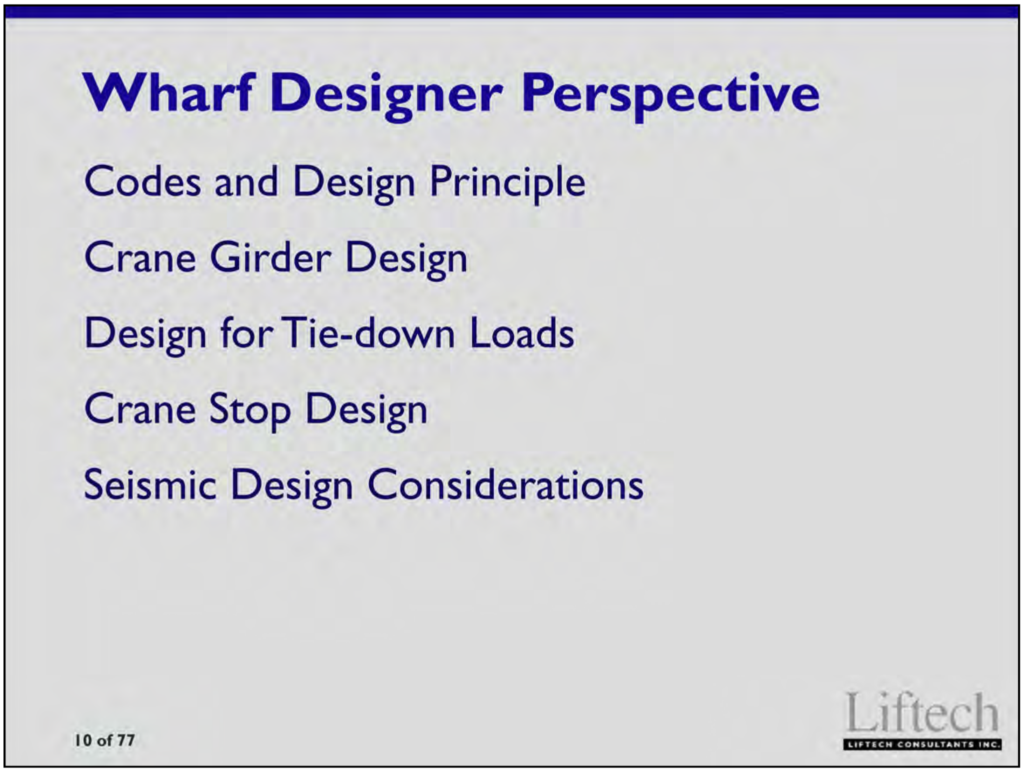
A crane purchaser must understand many engineering terms to properly evaluate loads provided by suppliers.



Crane suppliers also have problems when inadequate information is provided by the crane purchaser. When providing allowable wharf loads, the type of loading, whether the loading is service or factored, and the design criteria should be understood.



A common problem for the wharf designer is limited loading data.



To understand the wharf designer's perspective, aspects and wharf design considerations will be presented.

Codes and Design Principle

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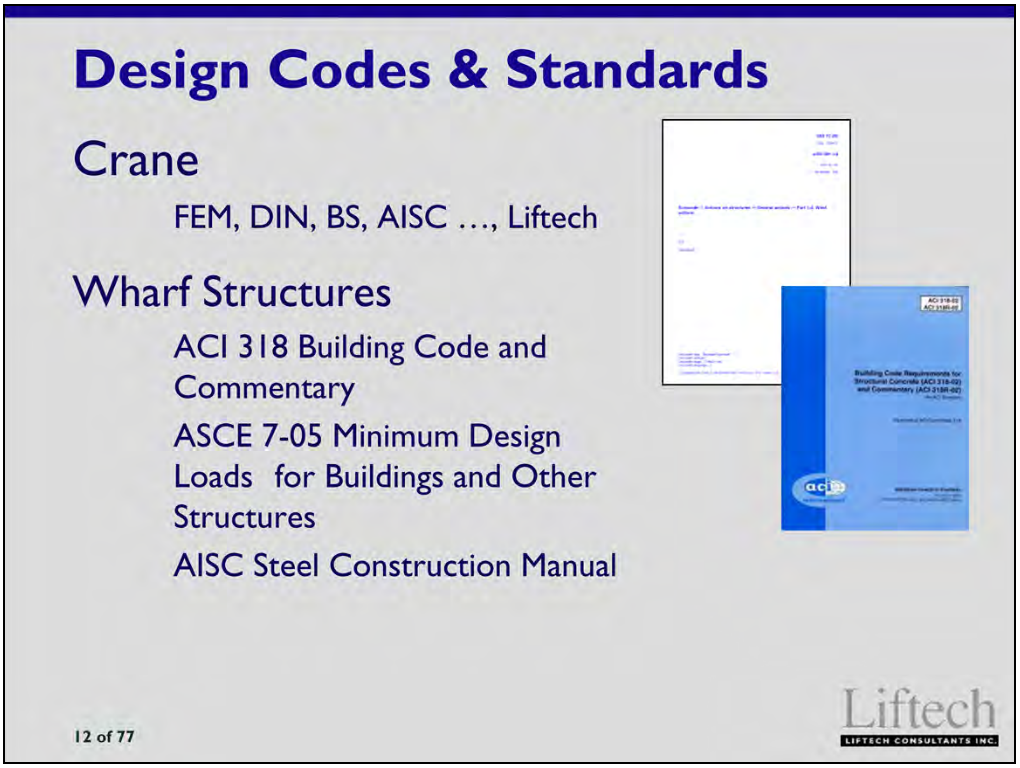

The design codes used for crane structures include a variety of worldwide codes. Typically, several of these codes are used in a crane specification.

For wharf structures in the United States, the ACI code is used for the design while ASCE is used for the loading. AISC is used for designing steel piling and wharf hardware such as crane stops, tie-down brackets, and stowage sockets.

The codes used by the crane designer and wharf designer are often inconsistent.

Design Principle – Wharf Structure Design

Load Resistance Factored Design (LRFD)

Required Strength $\leq$ Design Strength

Required Strength = $\sum$ Service Loads * Load Factors

Design Strength = Material Strength * Strength Reduction Factor Φ

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The LRFD design principle is used to design the wharf structure. The required strength is based on the factored service load, while the design strength is based on a reduced nominal strength.

The load factor depends on the accuracy and possible variance of the loading.

The reduction factor depends on the possible variance of a material strength. The reduction factor is never greater than 1.

Refer to structural engineering texts for a more detailed explanation.

Load Factors & Φ Factors

ACI 318	Load Factors			Concrete Φ Factors		
	D	L	W	Ten	Comp	Shear
to 2001	1.4	1.7	1.3	0.90	0.75/.70	0.85
from 2002	1.2	1.6	1.6*	0.90	0.70/.65	0.75

* 1.3 if directionality factor is not included

Load factors and strength reduction factors have recently changed.

Be sure to use the appropriate load factor for wind.

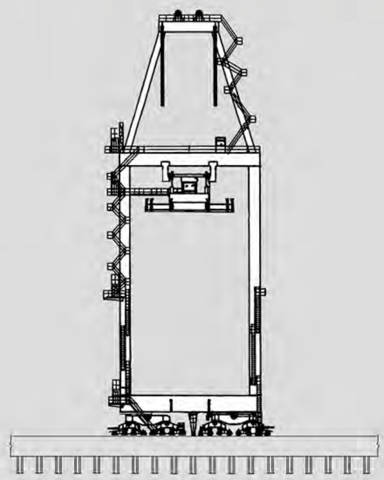
If a directionality factor is applied when calculating the basic wind loading, use 1.6.

If a directionality factor is *not* applied, use 1.3. Directionality factors were often not applied prior to 2002.

Notice that the tensile phi factor has not changed. The newer code permits higher loads on existing wharves if the capacity of the existing wharf is controlled by its flexural strength.

Geotechnical engineers typically design the foundation using an allowable stress approach. Usually a soil capacity twice the maximum service load is designed for. This factor will vary depending on the condition.

Crane Girder Design



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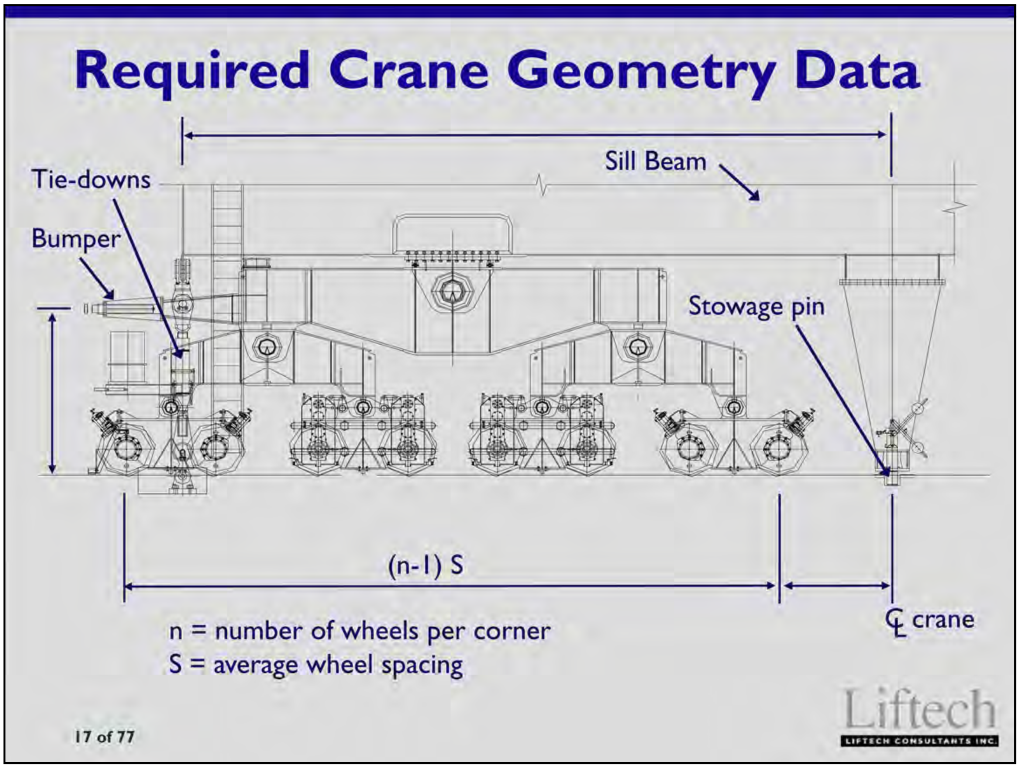
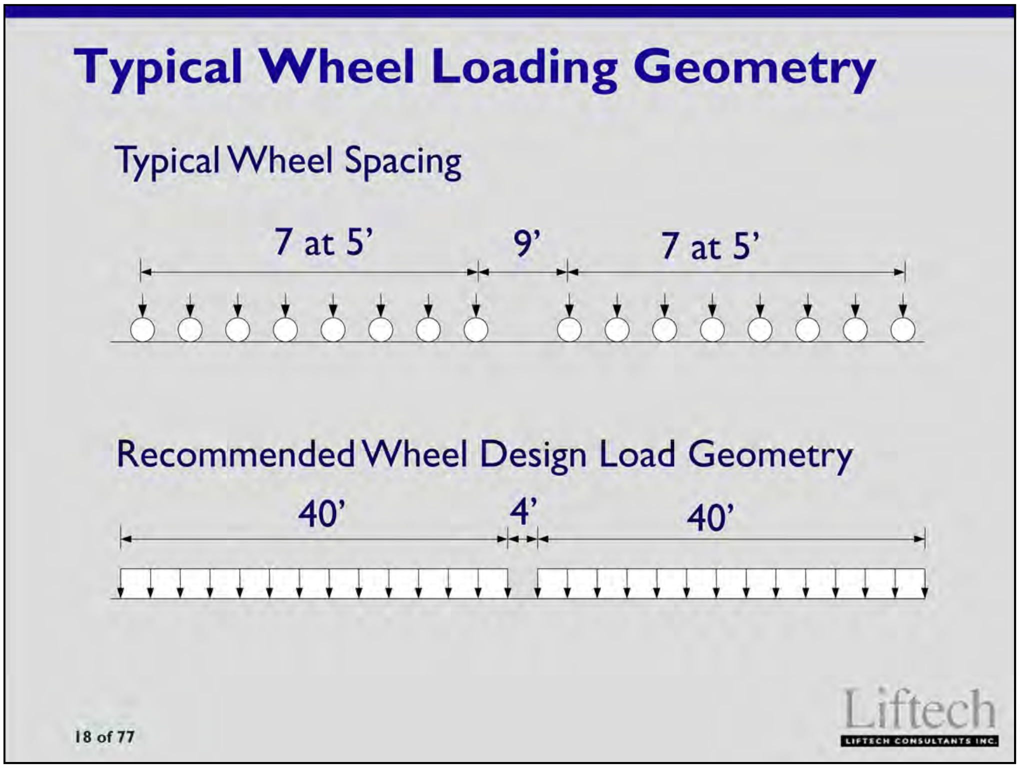


The wharf designer should have an understanding of the crane geometry. At a minimum, the wharf designer should understand these parameters.



Wheels should be, and typically are, spaced as far apart as possible to distribute the loading into the wharf. The spacing is controlled by the out-to-out bumper distance of the crane (88'6"), and the need for a checker's cab, stowage bracket, or both, at the center of the crane.

Eight wheels have historically resulted in acceptable wheel and rail stresses. The wheels and rails used have gotten larger over time to keep pace with the increasing wheel loads.

Dead Loads and Live Loads

Wharf Loads

D – Wharf structure self weight

L – Wharf live load, includes containers and yard equipment (does not control)

Crane Loads (ASCE 7-05)

D – Weight of crane excluding lifted load

L – Lifted load or rated capacity

Both the wharf structure and crane weight are considered dead loads because both are accurately estimated. After assembly, it is common to weigh the crane to within a 3% accuracy.

Containers and yard equipment are typically considered live loads due to the possible variations in reactions. The container and yard equipment loads are insignificant girder loads.

ACI Load Factors – Crane Loading

ACI 318	Load Factors		
Year	D	L	Composite
to 2001	1.4	1.7	1.45
from 2002	1.2	1.6	1.30

Some designers treat crane dead load as live load and use the 1.6 factor. This results in 23% overdesign; 1.6 / 1.3 = 1.23.

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This table provides the typical composite load factor for the container cranes loading.

If a load factor of 1.6 is used for the crane weight, the factored load increases 23%.

Example Combination Table: Service Wheel Loads

Mode		Operating				Stowed
		WOP1	WOP2	WOP3	WOP4	WS1
Dead Load	DL	1.0	1.0	1.0	1.0	1.0
Trolley Load	TL	1.0	1.0	1.0	1.0	1.0
Lift System	LS	1.0	1.0		1.0	1.0
Lifted Load	LL	1.0	1.0		1.0	
Impact	IMP		0.5			
Gantry Lateral	LATG	1.0				
Op. Wind Load	WLO		1.0	1.0		
Stall Torque Load	STL			1.0		
Collision Load	COLL				1.0	
Storm Wind Load	WLS					1.0
Earthquake Load	EQ					
Allowable Wheel Loads (tons/wheel)	LS	50 x S				70 x S
	WS	65 x S				90 x S

S = Average spacing, in meters, between the wheels at each corner.

Example:

*S = 1.5 m, Allowable LS Operating = 50 t/m * 1.5 m = 75 t/wheel*

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Typical wheel load combinations

Example Combination Table: Factored Wheel Loads

Mode		Operating				Stowed
		WOP1	WOP2	WOP3	WOP4	WS1
Dead Load	DL	1.2	1.2	1.0	1.0	1.2
Trolley Load	TL	1.2	1.2	1.0	1.0	1.2
Lift System	LS	1.2	1.2		1.0	1.2
Lifted Load	LL	1.6	1.6		1.0	
Impact	IMP		0.8			
Gantry Lateral	LATG	0.8				
Stall Torque Load	STL			1.0		
Collision Load	COLL				1.0	
Storm Wind Load	WLS					1.6
Earthquake Load	EQ					
Allowable Wheel	LS	60 x S				80 x S
Loads (tons/wheel)	WS	75 x S				100 x S

S = Average spacing, in meters, between the wheels at each corner.

Example:

*S = 1.5 m, Allowable WS Storm = 100 t/m * 1.5 m = 150 t/wheel*

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Typical load factors

Design for Tie-down Loads

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Historically, the most significant design and performance problems occur with the tie-down system. This loading is not well understood by wharf designers and crane manufacturers. Additionally, manufacturers do not understand what parameters are important for the wharf designer.

Multiple Tie-downs at a Corner

Uneven tie-down forces

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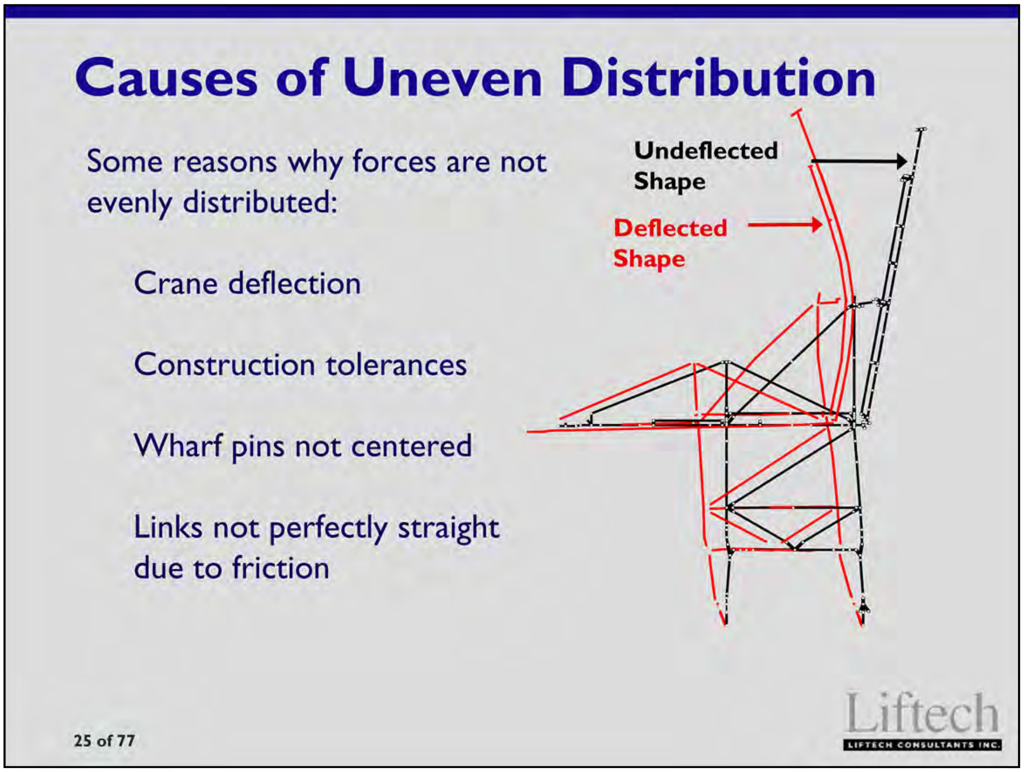
If there are multiple tie-downs at a crane corner, the crane movement, combined with other factors, will cause one tie-down to carry significantly more than its share of the load. If the tie-down system is not ductile, it may fail before the load can be shared by the other tie-downs. This will result in a progressive failure of the tie-downs and crane collapse.

Equalizers, including equalizer beams and fuse links, are sometimes added to the tie-down system.

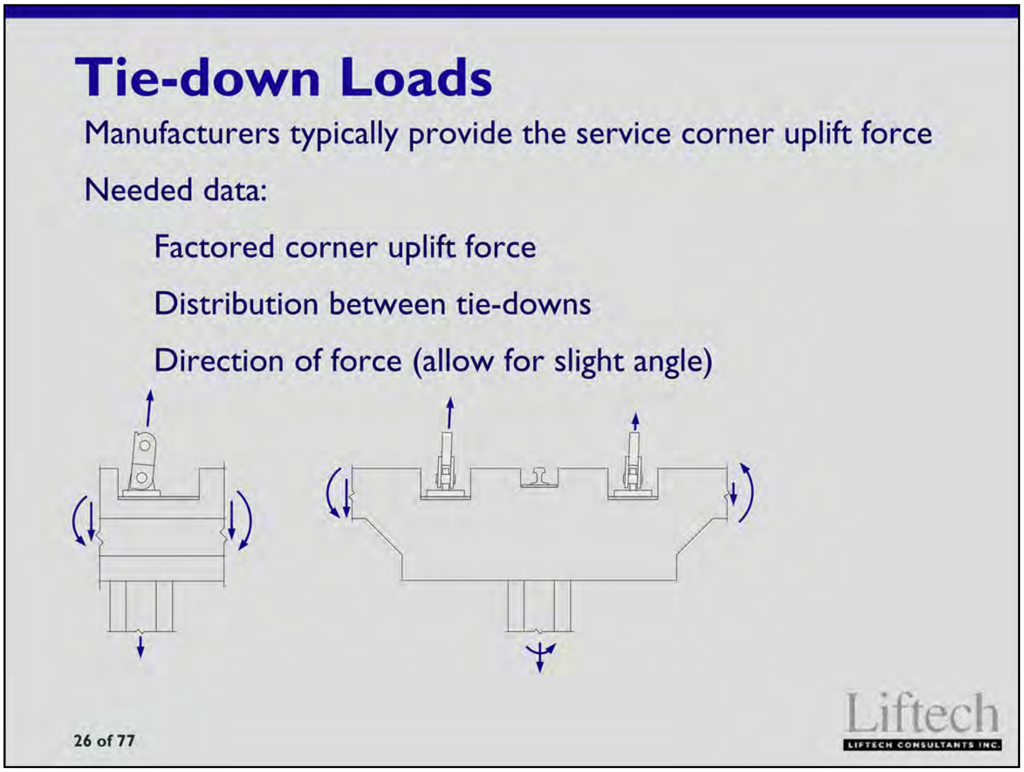
Due to the potential uneven tie-down load distribution, it is advantageous to provide one large tie-down at a corner instead of multiple, smaller tie-downs. One tie-down is often not practical with large forces because connecting the tie-downs to the wharf hardware becomes difficult due to the weight of the tie-down components.



Several factors cause unequal loading in multiple tie-downs at a corner.

If the tie-downs are not vertical, or if the tie-downs are asymmetric about the rail, loads will vary.

The initial tension in the tie-downs may vary, or the tension may not be sufficient to make the tie-down linkage perfectly straight.



The design data provided generally differs from the data that is needed.

A wharf designer should obtain the factored uplift load per crane corner. The load distribution between multiple tie-downs is significant. In some cases, 100% of the corner load can be resisted by one of two tie-downs due to crane deformations, construction tolerances, etc.

The direction of the uplift force is also significant for the hardware design. Slight eccentricities will significantly change the bolt loading and the distribution between tie-down hardware ear plates. It is generally beneficial to design the tie-down link plate so that it can rotate about the weak axis, and chamfer the pin hole of the ear plate to minimize the loading eccentricity.

Crane Stop Design

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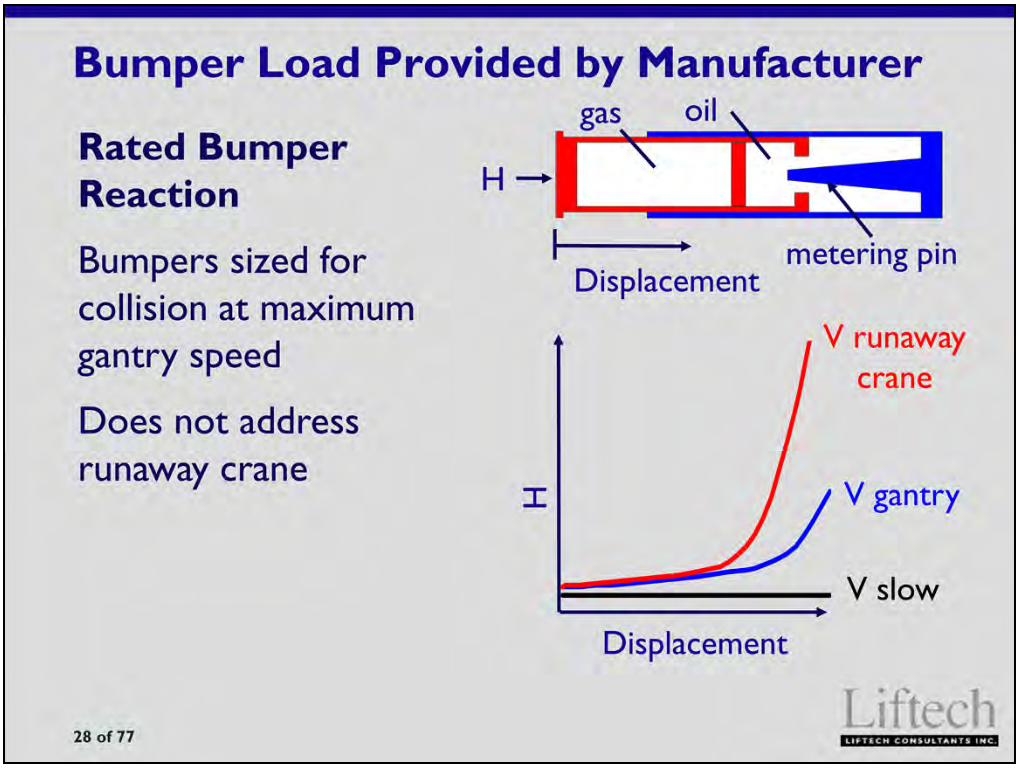
It is important for the designer to understand the basis of the crane stop load that is provided by the crane manufacturer.



The crane manufacturer typically provides the rated bumper reaction.

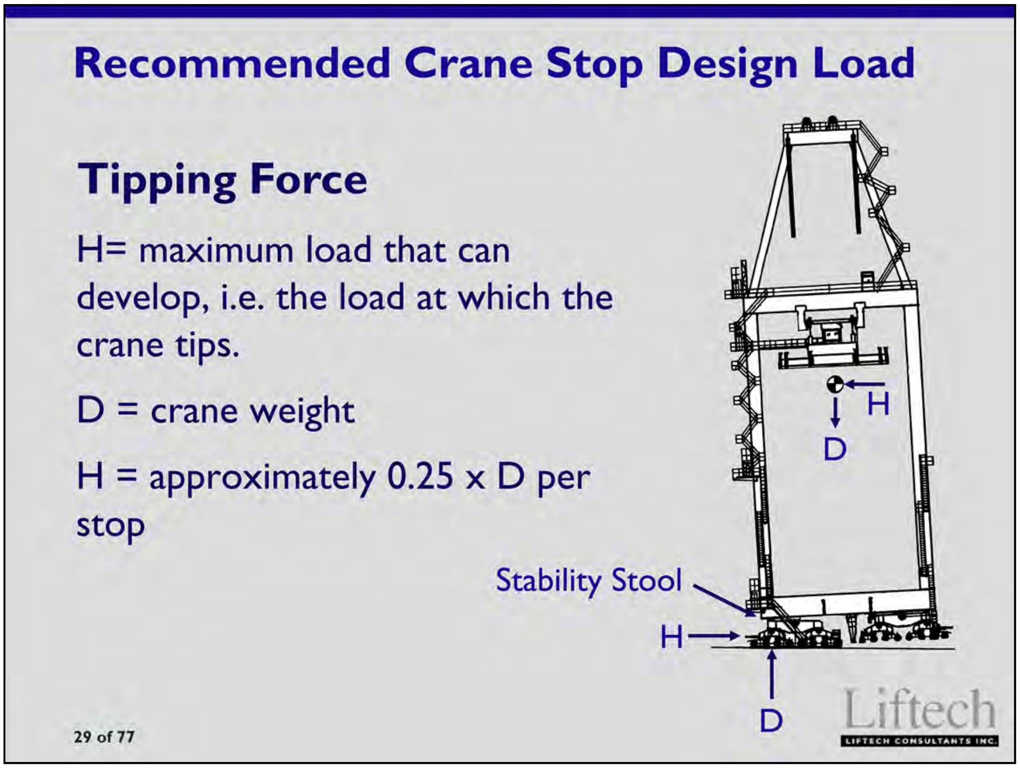
The rated bumper reaction is the maximum reaction that occurs when the crane gantries into the crane stop at maximum gantry speed.

The bumper reaction depends on the crane speed.

As the bumper compresses, the gas spring compresses, and the oil flows through a metered orifice, which is sized for a particular speed.

If the crane is very slow, the oil will flow through the orifice slowly with little reaction.

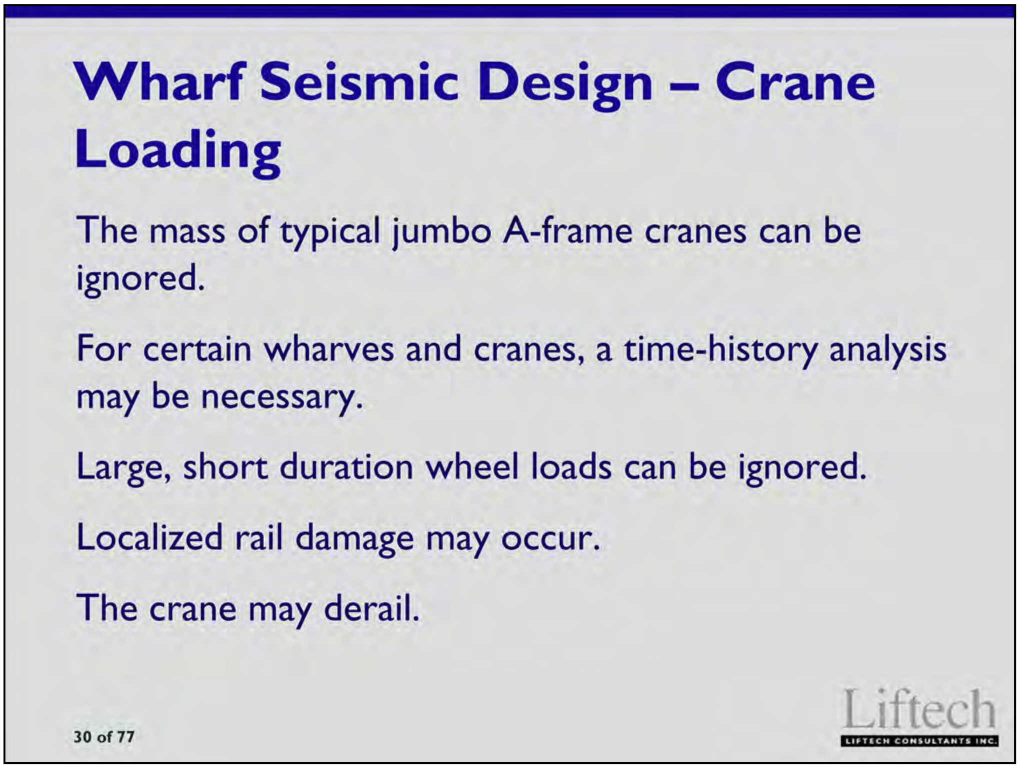
If the crane speed is high, a significant reaction can develop.



For a runaway crane, the crane stop force will likely exceed the rated bumper force. Localized damage to the crane bumper and support may occur.

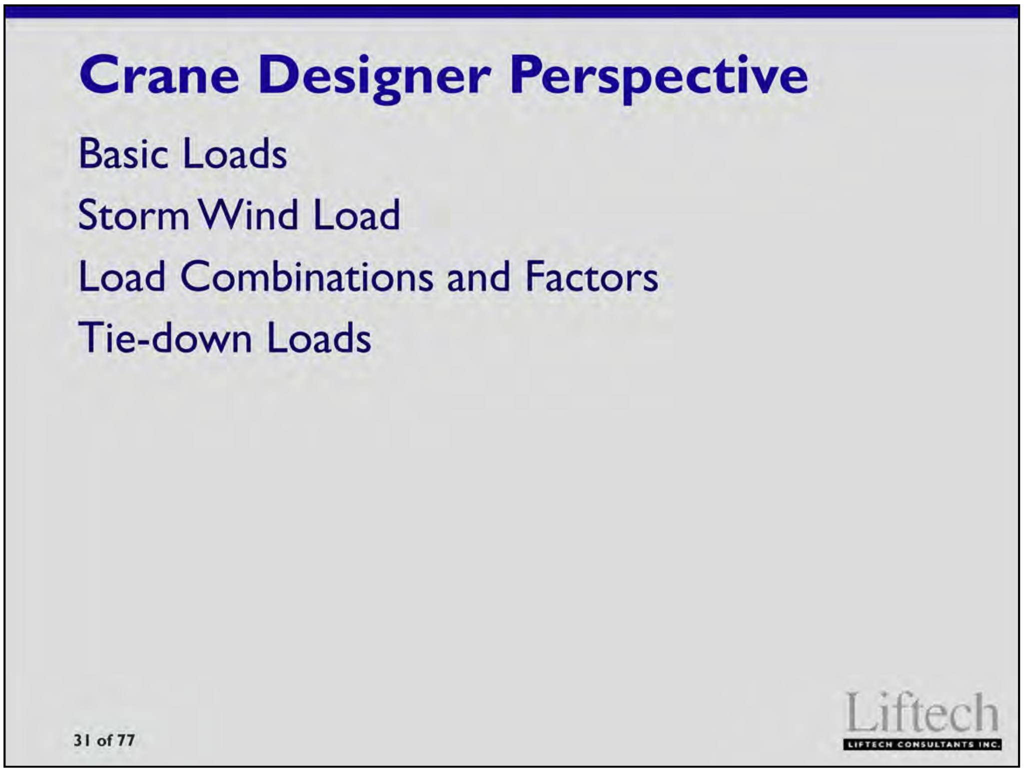
The maximum bumper on the force that can develop, is the force required to tip the crane about its stability stool.

The tipping force is recommended as a design force because the additional crane stop cost for this loading is marginal. The crane girder is usually strong enough to resist this loading.



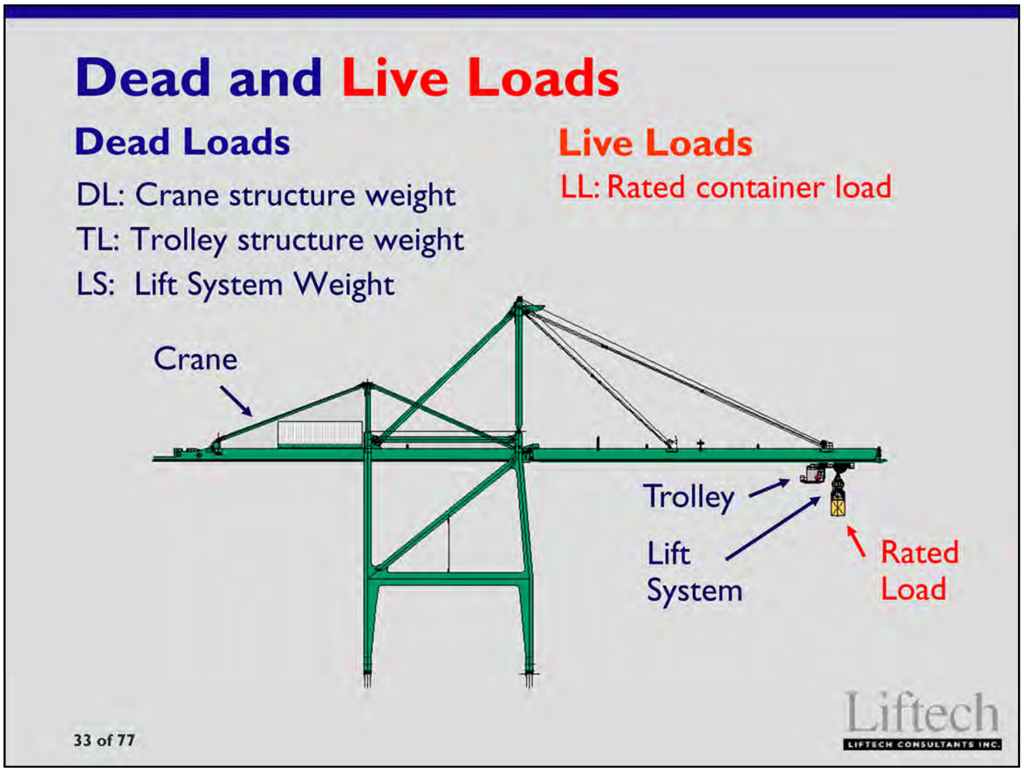
During earthquakes, the crane loading on the wharf has not been a problem. Localized damage occurs at the crane rail, and the crane may need to be jacked back onto the rail. Damage repair and setting the crane back onto the rail do not require significant cost or time.

Designing the crane for seismic loads is a more significant design issue and is outside the scope of this presentation.



To understand the crane designer's perspective, aspects and crane design considerations will be presented.

Basic Loads



Everything but the rated load is considered a dead load.

Inertial Loads

IMP: Vertical impact due to hoist acceleration

LATT: Lateral due to trolley acceleration

LATG: Lateral due to gantry acceleration

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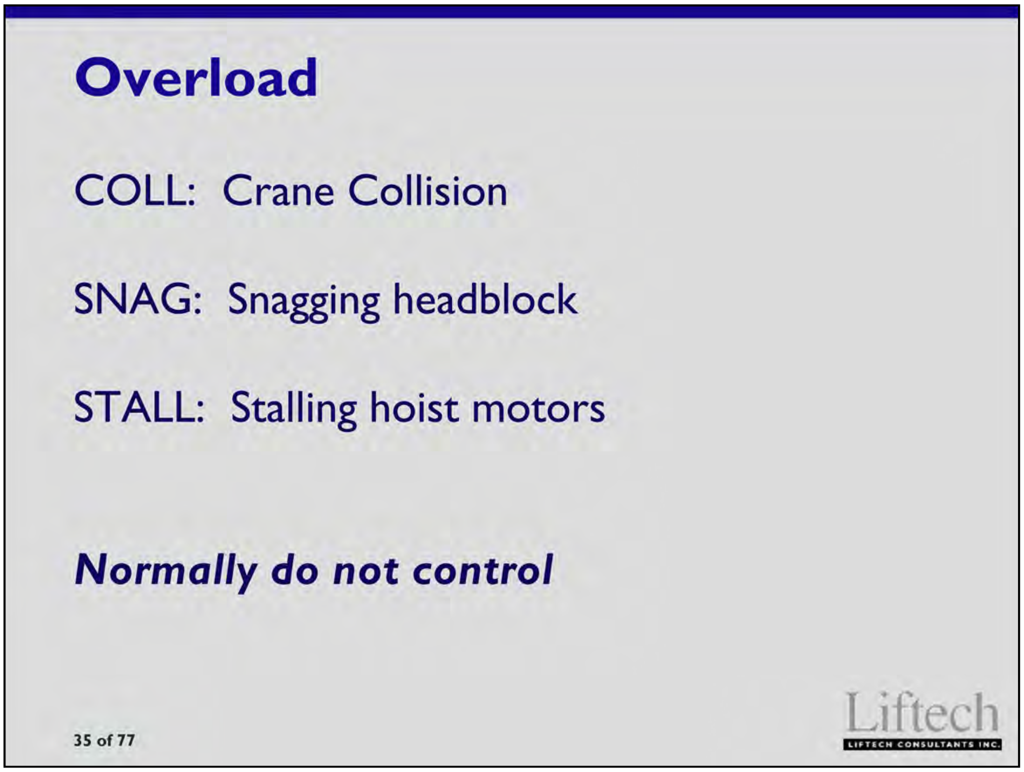
Inertia loads include hoisting accelerations, trolley accelerations, and crane accelerations.



Overloads include the crane colliding with other cranes, the headblock snagging on the ship, and the hoist motors stalling.

Environmental Loads

WLO: Wind load operating (In-Service)

WLS* : Wind load storm (Out-of-Service)

EQ: Earthquake load

Often a major source of discrepancies

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Environmental loads include wind and earthquake loadings.

WLS can also be Wind Load Stowed.

Wind Load, Storm

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Most problems occur with the wind loading.

WLS: Out-of-Service Wind

Wind Force = $\sum A \times C_f \times q_z$

- A = Area of crane element
- C_f = Shape coefficient (including shielding) } From wind tunnel testing
- q_z = Dynamic pressure, function of:
  - Mean recurrence interval (MRI)
  - Gust duration
  - V_{ref}^2, where V_{ref} is a location-specific, code-specified reference wind speed
  - Exposure (surface roughness)

  } Need to clearly specify

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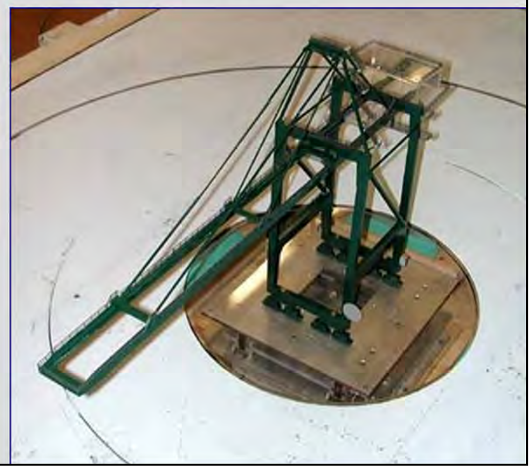
The typical wind force equation is shown. Each of the variables will be discussed.

Shape Coefficient, C_f

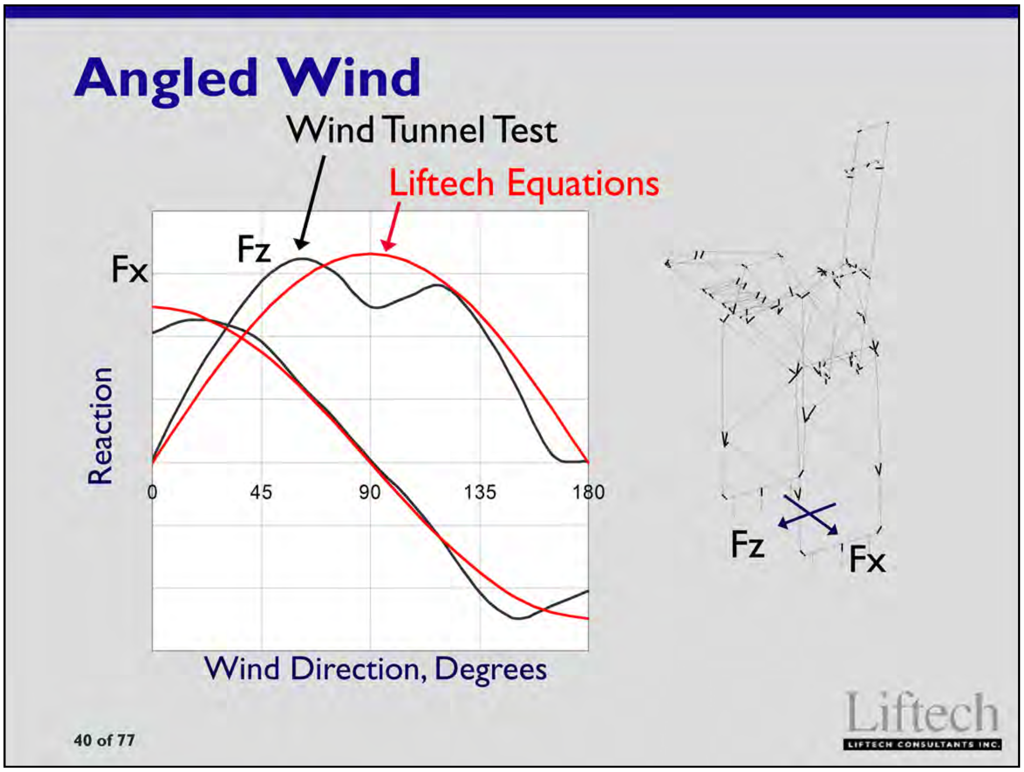
Empirical values: FEM, BSI, etc.

Wind tunnel tests are more accurate

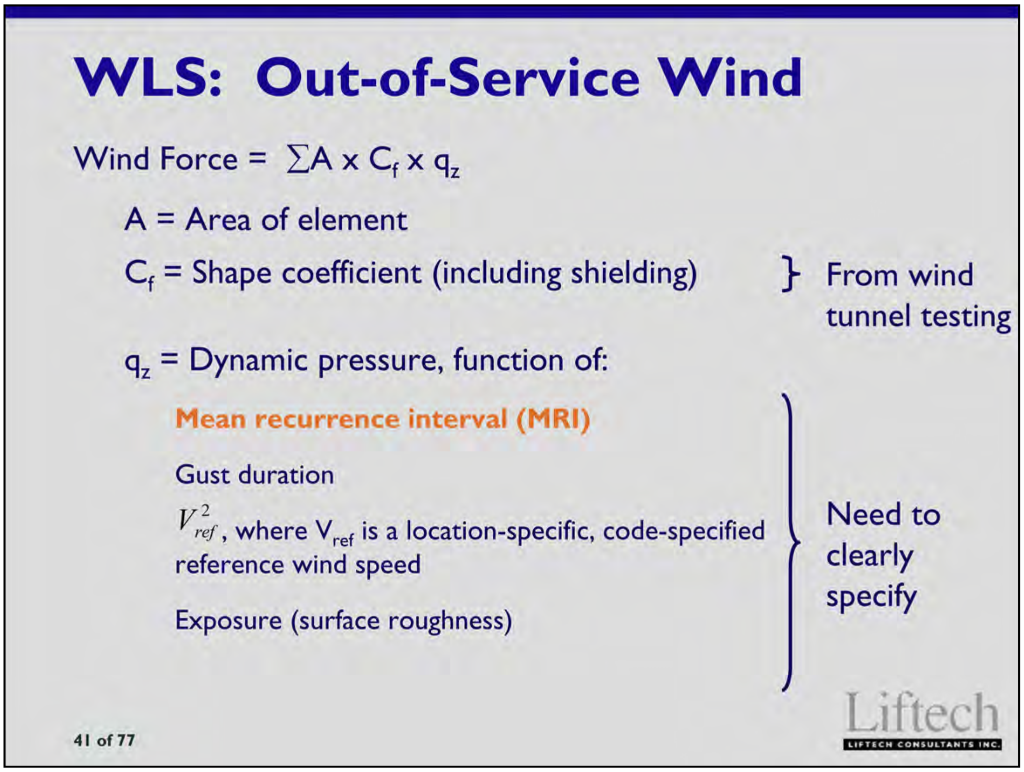
- Boundary layer
- Angled wind effects
- Shielding effects



Shape factors for various member shapes have been estimated from many wind tunnel tests. The wind tunnel test shape factors typically differ from the empirical values provided in codes.



Wind tunnel tests take into account the wind direction.



Mean recurrence interval

Mean Recurrence Interval

Probability of Speed Being Exceeded

	Years in Operation				
MRI	1	10	25	50	100
10 yrs	.10	.64	.93	.99	.99997
25 yrs	.04	.34	.64	.87	.98
50 yrs	.02	.18	.40	.64	.87
100 yrs	.01	.10	.22	.39	.64

Example:
Chance of 50-yr wind being exceeded in 25 years: 40%

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The probability of exceeding the design wind should be understood. For example, a 50-year MRI design wind has a 40% chance of being exceeded in 25 years, and a 64% chance of being exceeded in 50 years.

Notice that a particular MRI always has a 64% chance of being exceeded over a time equal to the MRI.

WLS: Out-of-Service Wind

Wind Force = $\sum A \times C_f \times q_z$

A = Area of crane element

C_f = Shape coefficient (including shielding) } From wind tunnel testing

q_z = Dynamic pressure, function of:

- Mean recurrence interval (MRI)
- Gust duration
- V_{ref}^2, where V_{ref} is a location-specific, code-specified reference wind speed
- Exposure (surface roughness)

} Need to clearly specify

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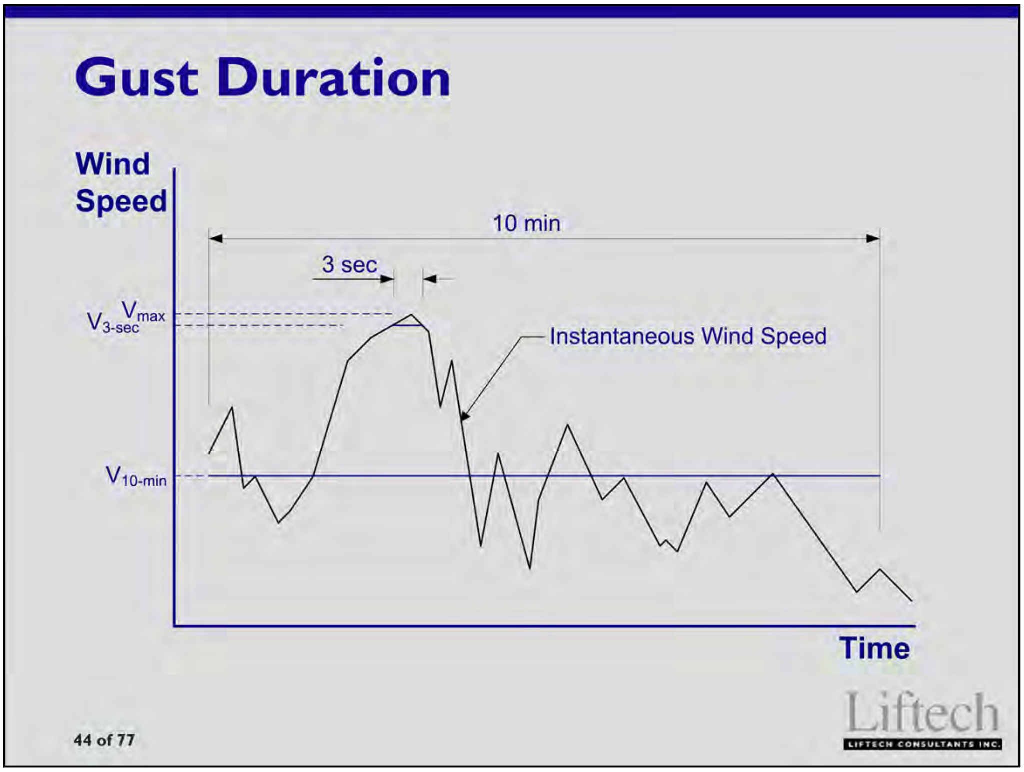
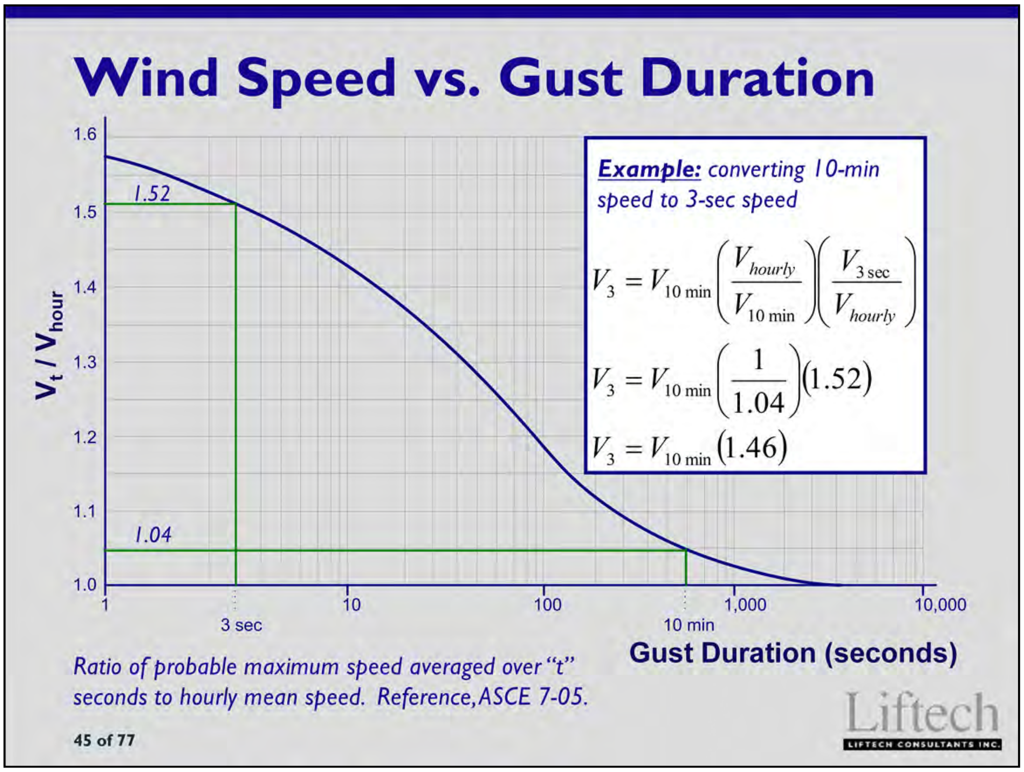
Gust duration



The gust duration is the time over which a wind speed is averaged.

The design gust duration is very significant to the design wind speed.



A 3-second gust wind speed is significantly larger than a 10-minute gust wind speed.

Based on wind measurements, a 3-second gust wind speed is typically 46% larger than a 10-minute gust wind speed.

Code Gust Durations

Code definitions of basic wind speed

Code	Gust Duration	MRI
EN 1991-1-4	10 min	50 yrs
FEM 1.004	10 min	50 yrs
ASCE 7-02	3 sec	50 yrs
HK 2004	3 sec	50 yrs

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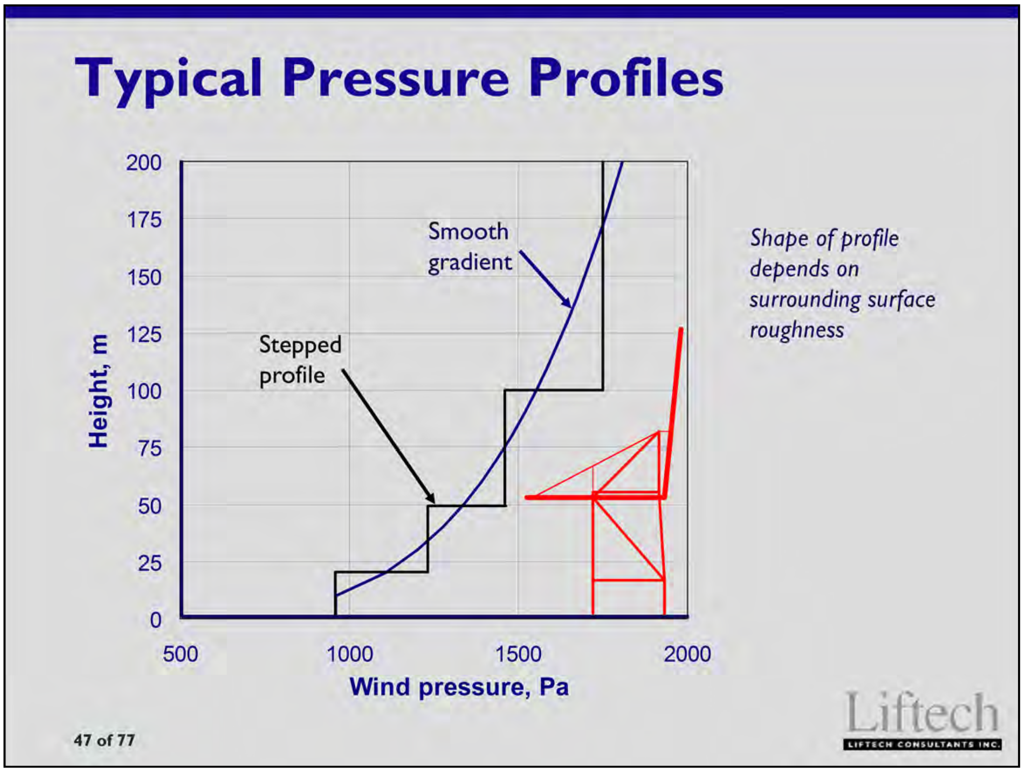
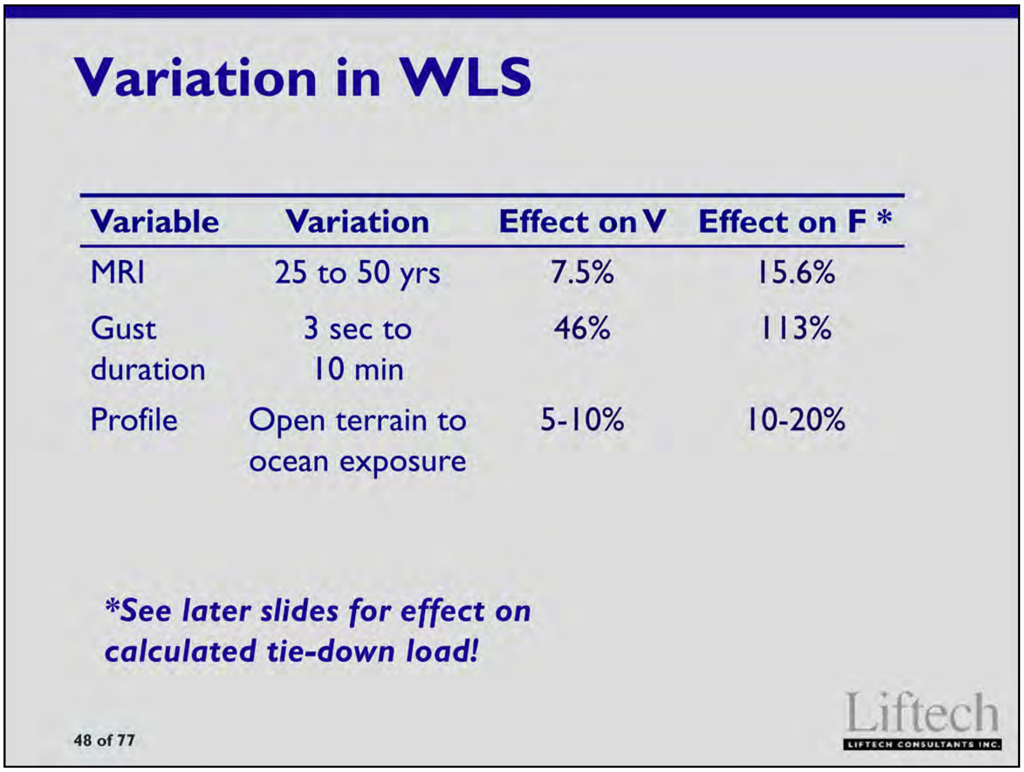
The gust duration used to define the design or basic wind speed may differ significantly between codes.

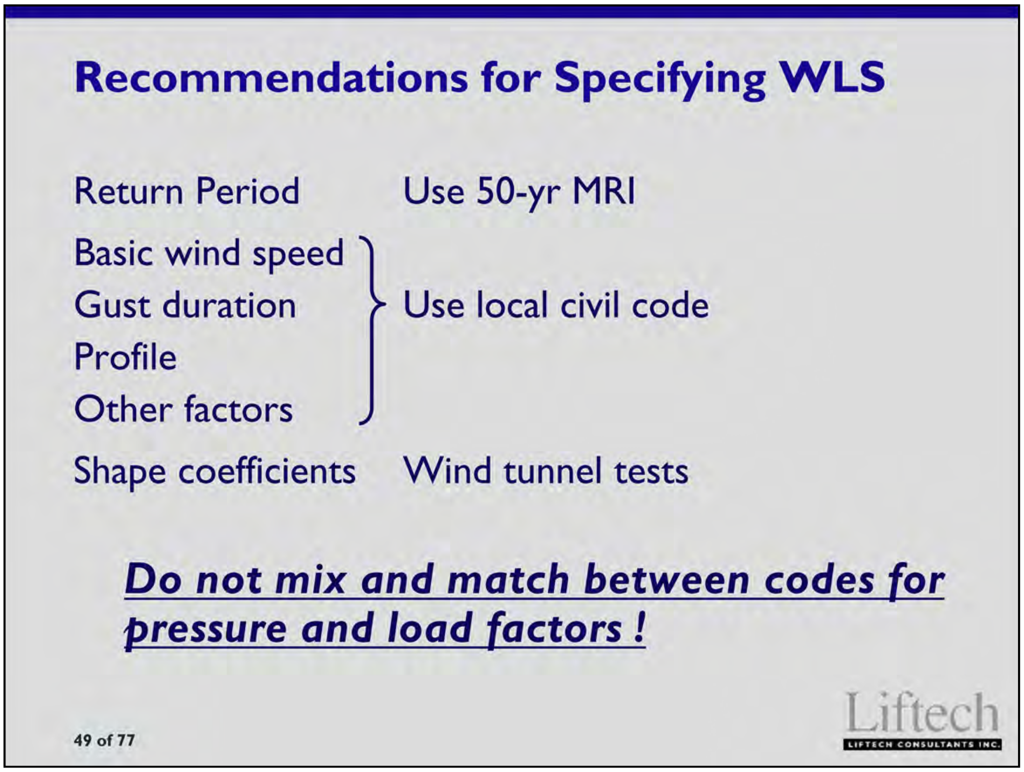


The wind speed and resulting wind pressure profile depends on the surface "roughness" of the area windward of the crane.

Design profiles are typically defined using a stepped or smooth gradient.



The effect of these variables on the wind speed, V, and on the wind force, F, is shown. The wind force is proportional to the wind speed squared.



Since personnel are not on the crane or wharf during storms, there is no risk to life safety. When there is no risk to life safety, most codes permit a design MRI of 25 years.

We recommend a design MRI of 50 years because the cranes are valuable structures, have long design lives, and the cost to design for a 50-year MRI is marginal.

We recommend using local codes to determine design wind speeds and wind profiles, and using load factors that are consistent with the local code.

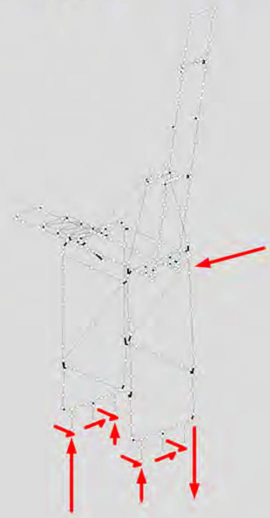
We recommend using shape coefficients based on wind tunnel tests.

Corner Reactions – Angled Wind

Do not use spreadsheet !

Use frame analysis program

Frame stiffness is significant to reactions



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The frame stiffness is significant to the wind reactions.

Load Combinations

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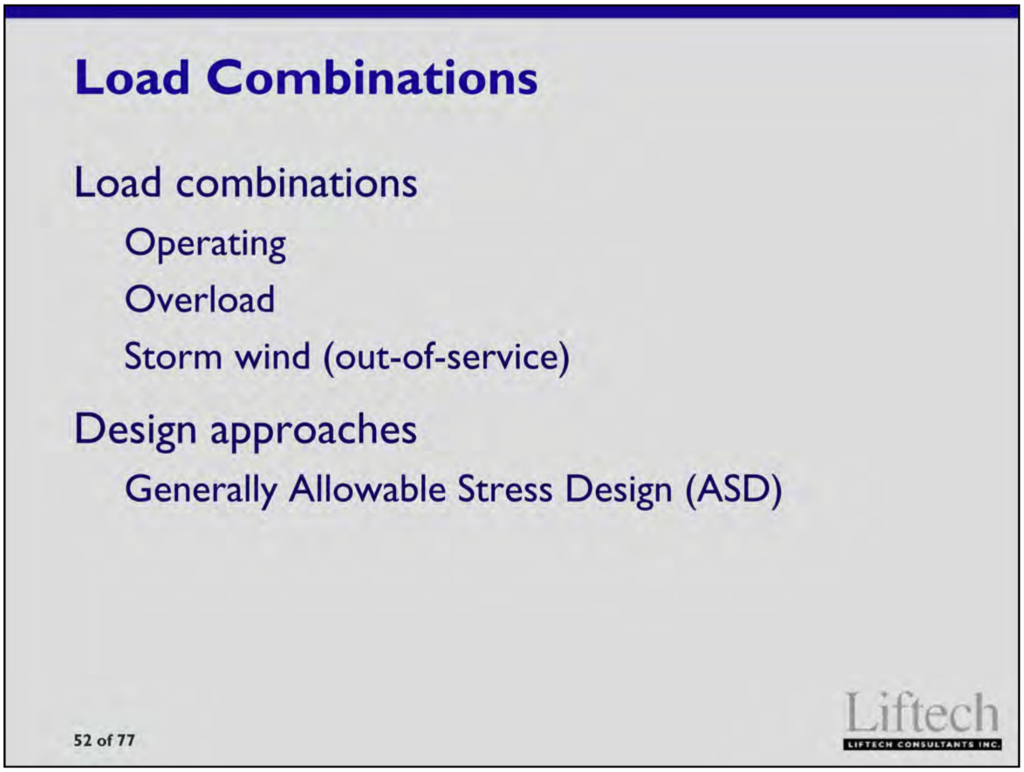

The strength load combinations considered when designing a crane include operating conditions, overload events, and storm wind (out-of-service) conditions.

The allowable stress design method is commonly used.

Operating Condition Loads

DL:	Crane weight*
LL:	Rated container load
IMP & LAT:	Inertial loads
WLO:	Wind load, in service

****Excluding Rated Load***

Operating loads similar to those required by the wharf designer are considered.

Out-of-Service & Overload

DL: Crane weight*

WLS: Wind load storm (out-of-service)

Overload Conditions (in and out-of-service)

**Including trolley and lift system*

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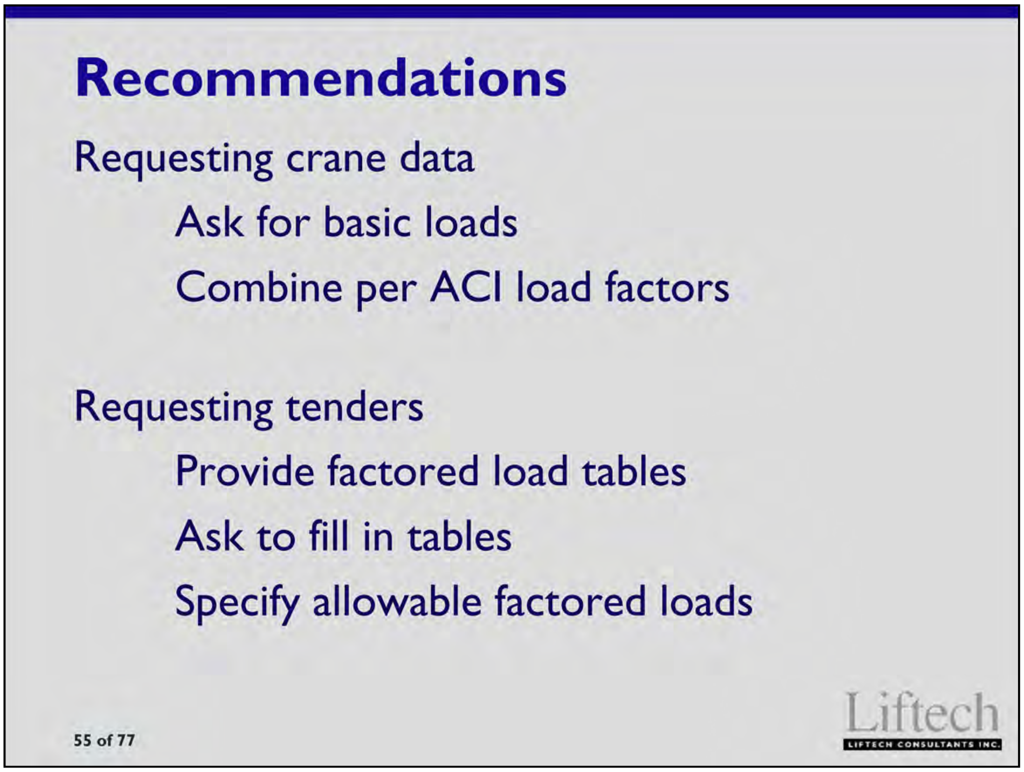
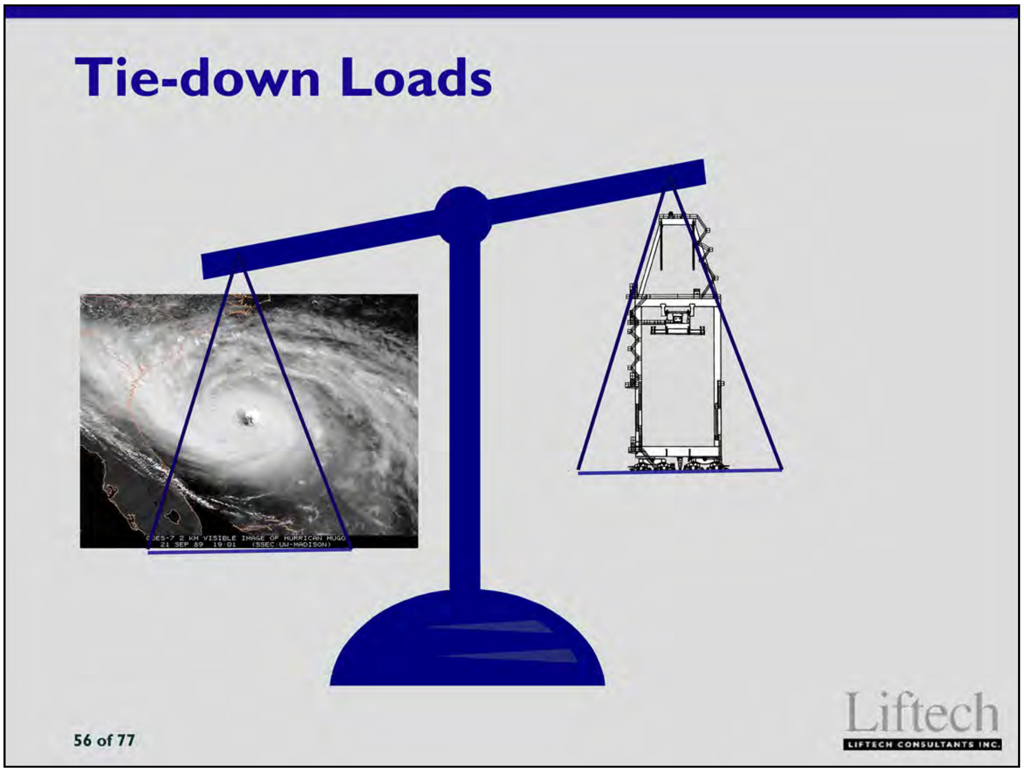


We recommend obtaining the basic loads from the crane manufacturer and combining these loads in accordance with ACI.

When requesting tenders, provide factored load tables, and ask the manufacturer to fill in the table. Also specify the allowable factored loads so the manufacturer is aware of any design constraint.



As mentioned previously, tie-down loads are the greatest source of problems.

Tie-Down Failures

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Tie-down failures occur more often than one would expect.

The failures are often due to a lack of understanding, a lack of QA during fabrication or installation, or all of these.

Little additional effort is required to prevent such failures.

Crane Tie-downs

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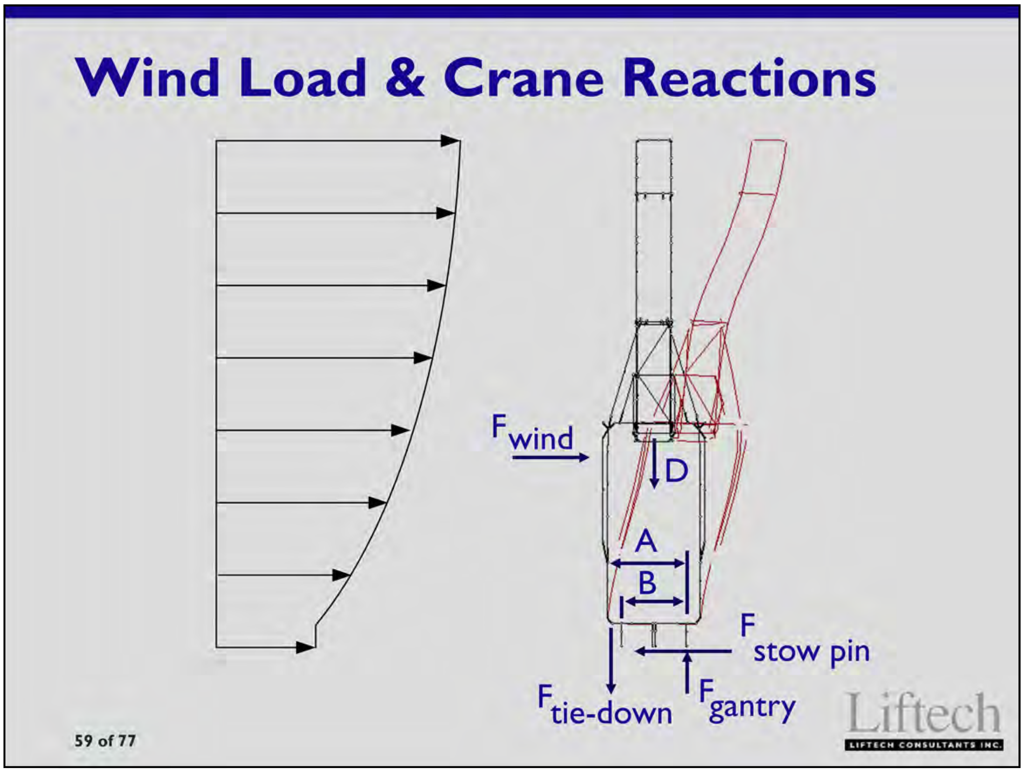
VPA cranes, like the one shown on the left, have two tie-downs per corner.

PED low-profile cranes, like the one shown on the right, have up to four tie-downs per corner.

Notice the assist lever to lift the wharf link plates.

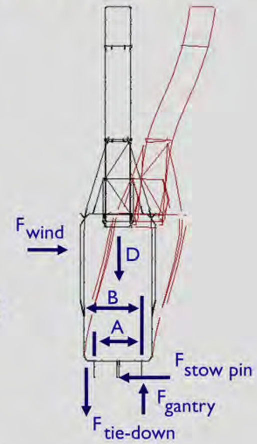


Tie-downs are positioned as close as possible to the end of the sill beam to improve leveraging.

Error in Calculated Tie-down Force

Ratio of moments:

$$\gamma = \frac{F_{wind} h}{D \frac{B}{2}} = \frac{Overturning\ Moment}{Righting\ Moment}$$



Error in calculated tie-down force:

if "e" = error in wind force,

$$\frac{F_{Tiedown,Actual}}{F_{Tiedown,Calculated}} = \frac{\frac{1}{A}\left[(1+e)F_{Wind} h - D\frac{B}{2}\right]}{\frac{1}{A}\left[F_{Wind} h - D\frac{B}{2}\right]} = \frac{(1+e)\gamma - 1}{\gamma - 1}$$

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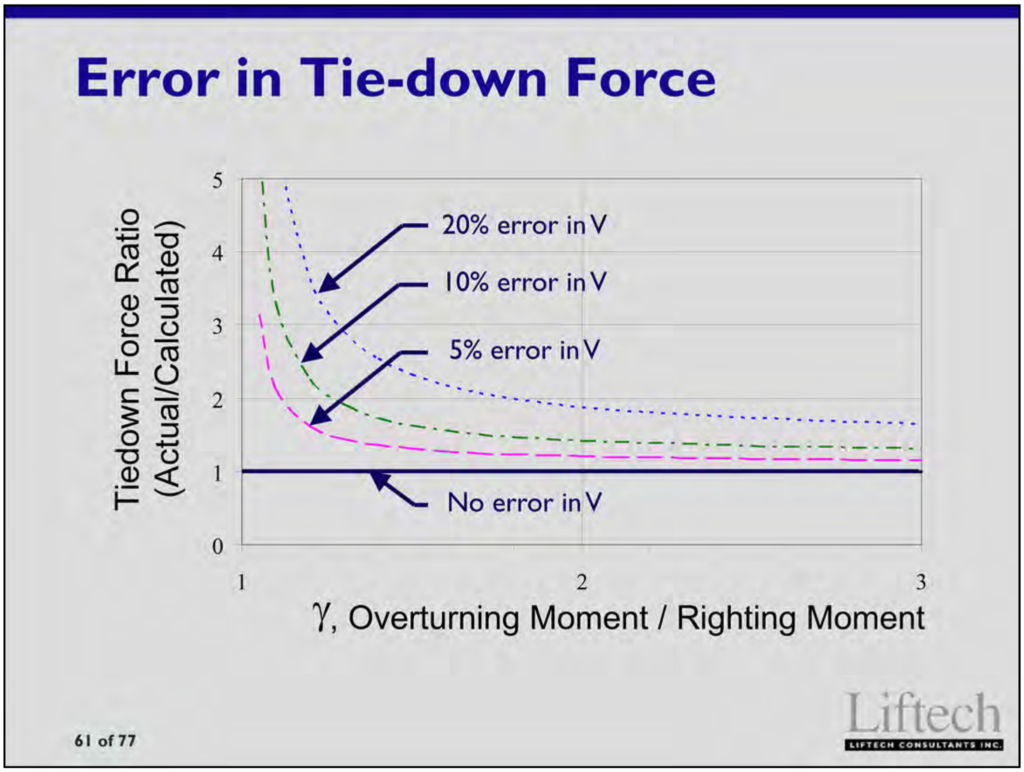
gamma = ratio of overturning to righting moments

e = error in wind force due to shape factors, wind speed, etc.



As the ratio of moments increases (bigger uplift), the error in the calculated tie-down force approaches the error in the wind force.

Be cautious if the overturning moment is nearly equal, or equal, to the righting moment.

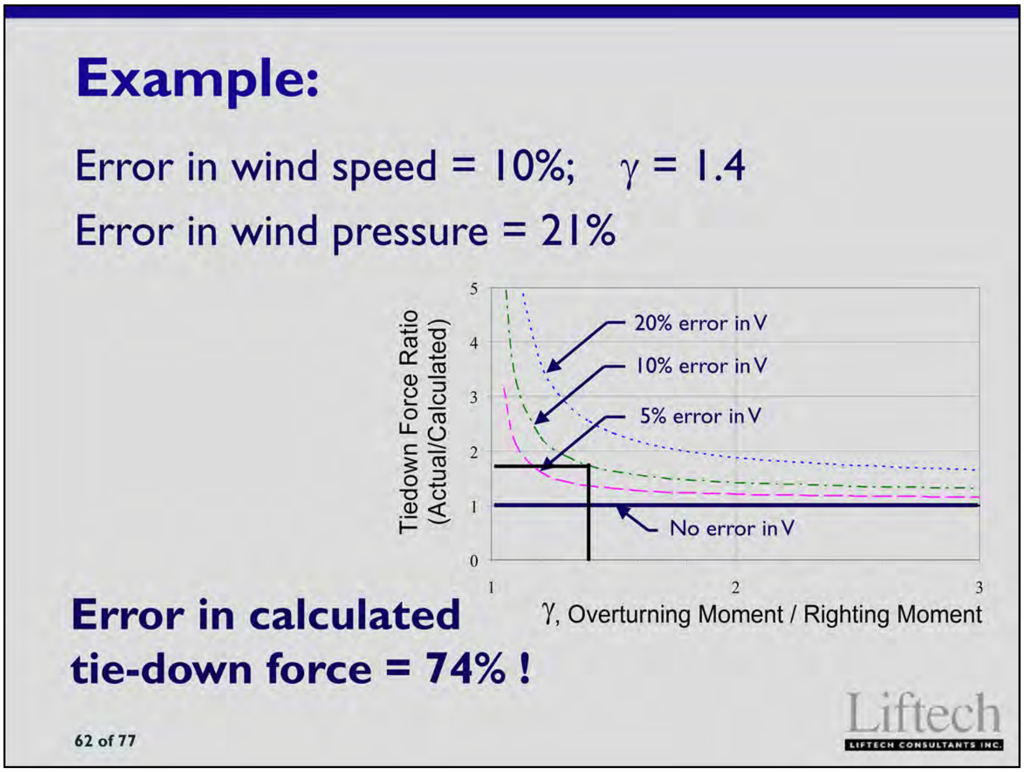
This may be an issue for the landside tie-down on older cranes in hurricane zones

Typical values of gamma:

LS: 1.0 to 2.5

WS: 2.0 to 5.0

Avoid minimalistic design! We recommend to design the LS for at least 50% of WS. The cost of installing a larger than required tie-down is marginal.



If, for example, the overturning moment is 40% greater than righting moment

A 10% error in wind speed produces a 21% error in pressure (force) and consequently, a 74% error in calculated tie-down force!

Check your cranes for possible minimal design on the landside.

Stability Load Factors

Load	Factor		
	BSI	ACI	FEM
Dead Load	1.0	0.9	1.0
TL + LS	1.0	0.9	1.0
Wind Load, 50-year MRI	1.2	1.3*	1.2

* *1.6 with ASCE 7-02 "directionality factor"*

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Use 1.0 DL factor if crane is weighed.

If wind directionality factor isn't applied (ASCE 7-02), use 1.3 factor here.

Uplift: Factored vs. Service

Load	Service	Factored Load Factor	
Dead Load	-500	x 0.9 =	-450
Wind Load	+450	x 1.3 =	+585
Calculated Uplift	-50 "No Uplift"		+135 "Uplift"

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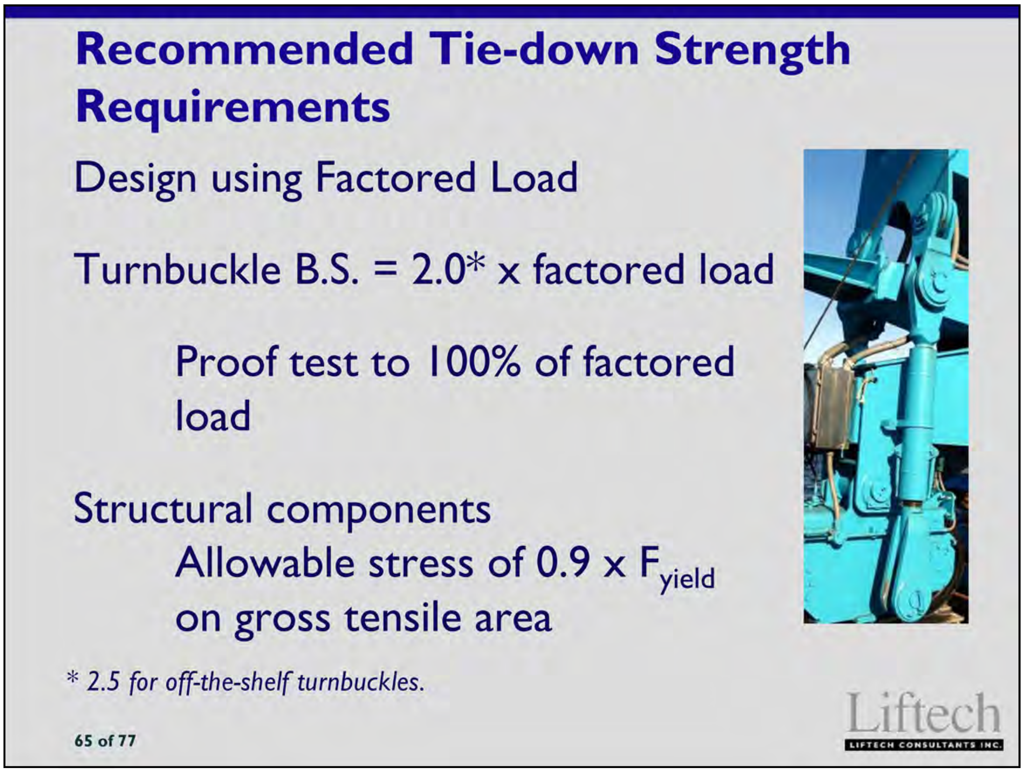
Sometimes, the quay designer asks for the DL and uplift force at the corner, and designs the tie-down based on the resulting service uplift force.

The crane designer has designed the tie-down for nearly 150 tons, but the quay designer may provide a minimal design for the tie-down bracket, since his calculations show that there is no (or minimal) uplift.

It is important to design based on the factored load. An ASD approach can still be used by factoring the calculated load down to a service load.



These requirements partially compensate for possible uneven load distribution between tie-downs, if there is more than one per corner. In addition, since the turnbuckle is a mechanical, high-strength, threaded component, it may fail in a brittle manner, unlike the main crane structural components. From our experience, the crane structure is not the "weak link." We recommend that the quay attachment be designed to the same loading and safety factor as the crane tie-down components.

When multiple tie-downs are required at a corner, we recommend equalizing the uplift force using a ductile fuse link to limit the tie-down loading. For more information, refer to the "Ductile Links in Quay Crane Tie-down Systems" presentation at http://www.liftech.net/lpublications_wharves.html

The turnbuckle should show no permanent deformation, and the screw should turn freely after the test. Ideally, the entire load path, including the wharf hardware, would be proof tested. This is typically not practical.

Design structural components local to the tie-downs, to an allowable stress of (0.9*Fy for gross tensile area), using the factored tie-down force.

Be sure to consider eccentricities due to crane deformations and the gaps between tie-down components. These are particularly significant to the wharf bracket, the anchor bolts, and the load distribution to the various ear plates.

Putting the Two Together

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Problem Overview

Crane supplier and wharf designer work with incomplete and inconsistent data.

Crane supplier generally uses Service Load approach.

Wharf designer generally uses Factored Load approach.

Neither knows what basis the other uses.

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Solution

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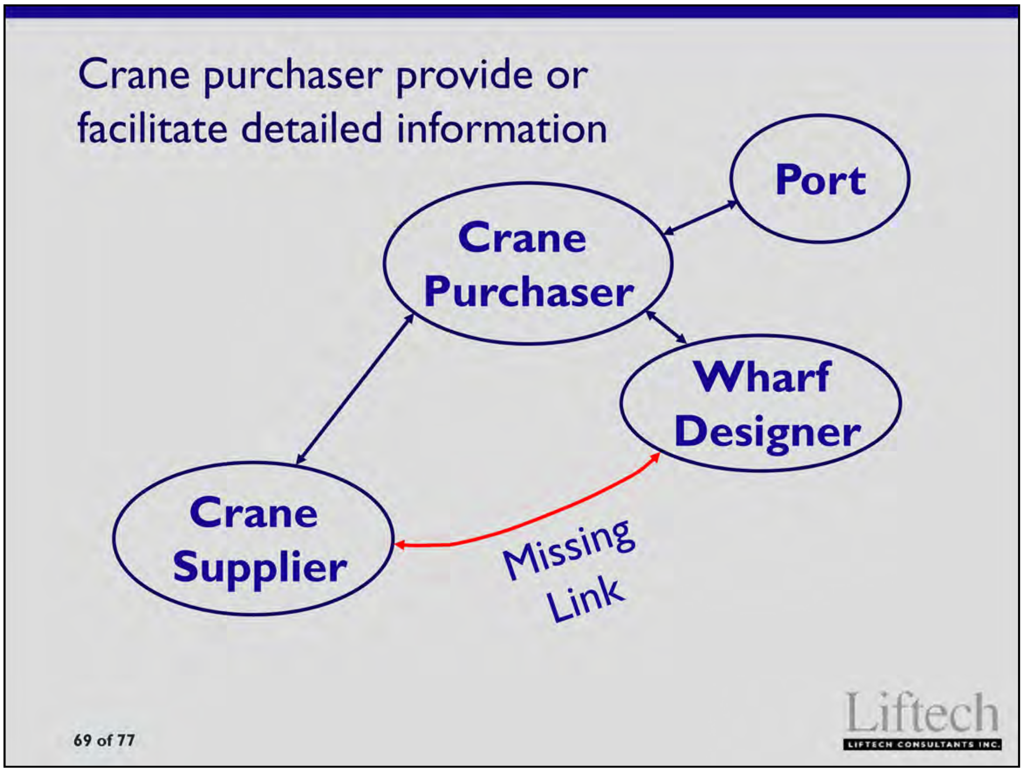

Improve communication among the designers.

Obtain From Wharf Designer

Assumed wheel arrangement

Service or factored

Load factors

Load combinations for operating, overload, and out-of-service conditions

Complete wind criteria

Allowable wheel loads, kips/ft*

** Crane supplier tends to provide kips/wheel*

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Provide the following to the crane designer so the crane design is consistent with the wharf design.

Example Combination Table: Service Wheel Loads

Mode		Operating				Stowed
		WOP1	WOP2	WOP3	WOP4	WS1
Dead Load	DL	1.0	1.0	1.0	1.0	1.0
Trolley Load	TL	1.0	1.0	1.0	1.0	1.0
Lift System	LS	1.0	1.0		1.0	1.0
Lifted Load	LL	1.0	1.0		1.0	
Impact	IMP		0.5			
Gantry Lateral	LATG	1.0				
Op. Wind Load	WLO		1.0	1.0		
Stall Torque Load	STL			1.0		
Collision Load	COLL				1.0	
Storm Wind Load	WLS					1.0
Earthquake Load	EQ					
Allowable Wheel Loads (tons/wheel)	LS	50 x S				70 x S
	WS	65 x S				90 x S

S = Average spacing, in meters, between the wheels at each corner.

Example:

*S = 1.5 m, Allowable LS Operating = 50 t/m * 1.5 m = 75 t/wheel*

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Establish and provide the design service load combinations.

Example Combination Table: Factored Wheel Loads

Mode		Operating				Stowed
		WOP1	WOP2	WOP3	WOP4	WS1
Dead Load	DL	1.2	1.2	1.0	1.0	1.2
Trolley Load	TL	1.2	1.2	1.0	1.0	1.2
Lift System	LS	1.2	1.2		1.0	1.2
Lifted Load	LL	1.6	1.6		1.0	
Impact	IMP		0.8			
Gantry Lateral	LATG	0.8				
Stall Torque Load	STL			1.0		
Collision Load	COLL				1.0	
Storm Wind Load	WLS					1.6
Earthquake Load	EQ					
Allowable Wheel	LS	60 x S				80 x S
Loads (tons/wheel)	WS	75 x S				100 x S

S = Average spacing, in meters, between the wheels at each corner.

Example:

*S = 1.5 m, Allowable WS Storm = 100 t/m * 1.5 m = 150 t/wheel*

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Establish and provide the design factored load combinations.

Ask Crane Supplier For

Wheel arrangement

Wheel loads for individual loads

Combined wheel loads for operating, overload, and out-of-service conditions

Complete wind criteria used and basis for shape factors

Individual and corner factored loads for tie-downs including direction of loading

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Obtain this data from the crane supplier.

Example Design Basic Load Table

Wharf Designer needs from Crane Supplier

		Wheel Load			
		Seaside		Landside	
		LHS	RHS	LHS	RHS
Dead load	boom down				
	boom up				
TL + LS	outreach				
	backreach				
	parked				
LL	outreach				
	backreach				
IMP	outreach				
	backreach				
LATT					
LATG	outreach				
	backreach				
OWLx					
OWLz					
OWL< (Angled Max)					
Stall					
COLL	boom down				
	boom up				
EQx					
EQz					
SWLx					
SWLz					
SWL< (Angled Max)					

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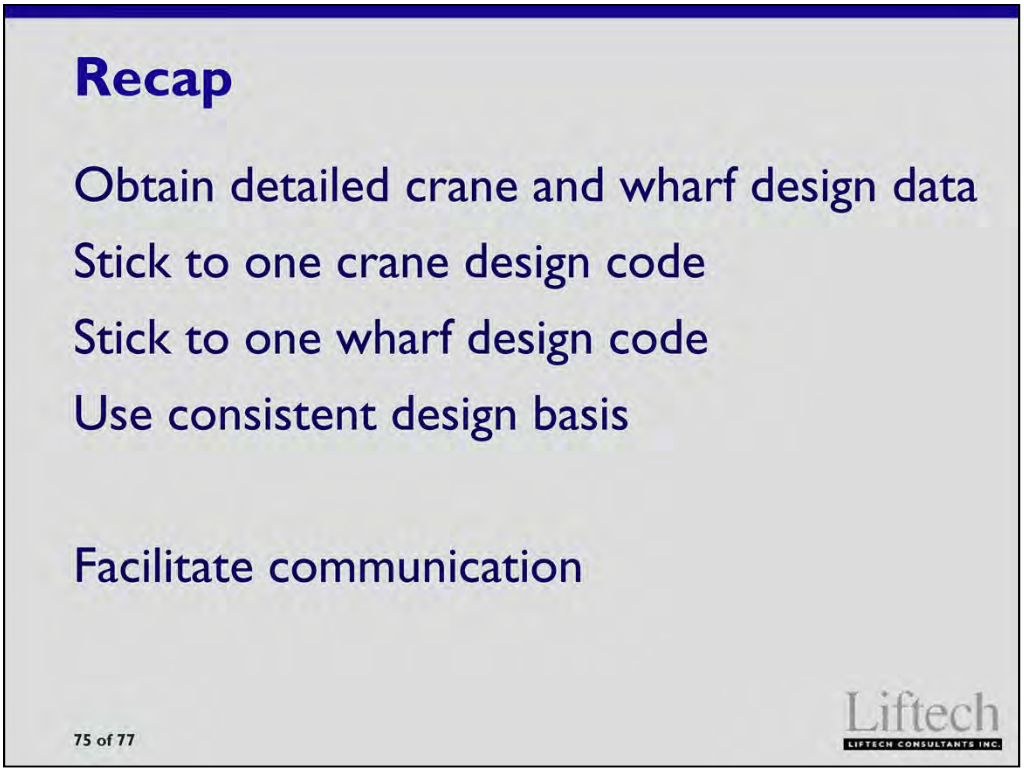
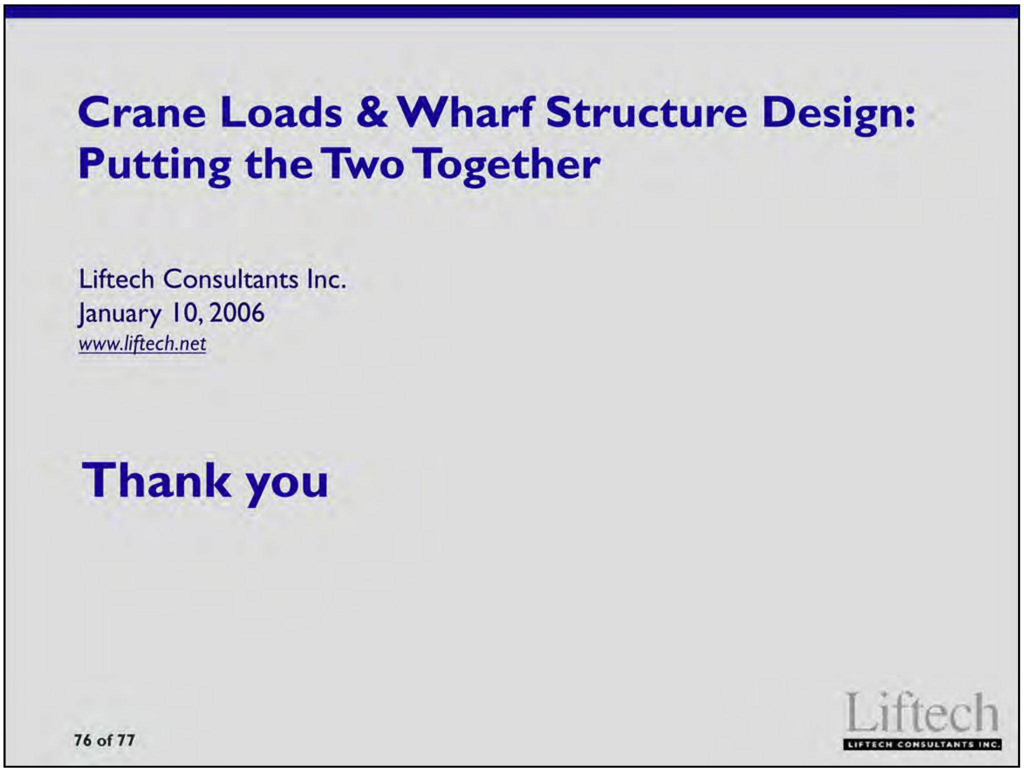
Provide the crane supplier a table containing the desired basic loads for the supplier to fill out and return.



Use consistent design data for the crane and wharf.

Facilitate communication between the crane and wharf designers.



Feel free to contact us with questions.

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