DOCKSIDE SHIP-TO-SHORE CRANES
SEISMIC RISK AND RECOMMENDED DESIGN CRITERIA

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Quality Assurance Review
for Liftech Consultants Inc.

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OVERVIEW

DOCKSIDE SHIP-TO-SHORE CRANE SEISMIC DESIGN CRITERIA

The importance of a port to the economy and vitality of the community served by the port is recognized by experts and discussed in other publications and presentations. A port may never fully recover if its services are interrupted for more than a few months (Yin 2007). For example, the Port of Kobe never fully recovered from the 1995 earthquake.

Reasonable criteria for the seismic design and performance of wharves have already been established by several West Coast ports. The Ports of Los Angeles and Long Beach updated performance standards for seismic response to defined ground motions (Arulmoli 2007). Currently, prescribed ground motions are available from the Port of Los Angeles and Port of Long Beach web sites.

The Los Angeles "Code for Seismic Design, Upgrade and Repair of Container Wharves" (POLA Code) May 18, 2004, addresses issues related to wharves but does not address issues related to the equipment needed to meet the wharves' performance criteria. Liftech's suggested interim criteria are presented below.

JUMBO CRANES ARE AT GREATER RISK

The forces that can develop in smaller cranes (i.e. cranes servicing 13- to 16-container-wide ships) during a seismic event are 0.20 to 0.30g. Inertia forces greater than this will lift at least one leg of the crane and limit the internal moments and forces. Because of this limiting phenomenon, Liftech specifications prior to 2006 required a seismic service inertia loading of only 0.20g.

Smaller cranes have performed well in earthquakes; plates have buckled and legs have lifted causing crane derailment. Some cranes have even collapsed. The crane collapses in the 1995 Kobe earthquake, although dramatic, were not due to excessive inertia forces but rather to lateral spreading of the crane supports caused by liquefaction.

The vulnerability of jumbo cranes (i.e. cranes servicing 17- to 22-container-wide ships) to serious damage during earthquakes was only recently recognized after conducting finite element time history analyses. These analyses indicate that the seismic risk of damage to jumbo cranes is much greater than the risk to smaller cranes.

The Port of Los Angeles design code specifies two levels of design earthquake, the operating level earthquake (OLE) and the contingency level earthquake (CLE). These earthquakes have mean return intervals of 75 and 500 years, respectively. The OLE, or larger earthquake, has a 50% chance of occurring in 50 years. The CLE, or larger earthquake, has a 10% chance of occurring in 50 years. Jumbo cranes may not be operable after an OLE and may be severely damaged and may collapse in the CLE.

An additional event, the maximum credible earthquake (MCE), is expected to be specified in the California Building Code. The MCE is defined as an earthquake having an MRI of 2500 years, with a 2% chance of being exceeded in 50 years. The ASCE 7-05 specification will probably be the basis for the seismic design requirements in the next California Building Code. ASCE 7-05 requires that structures meet life safety requirements when subjected to 2/3 of the ground motion predicted for the MCE.

LIFTECH'S OPINION

A port's design standard should include provisions that apply to both the wharf and the essential equipment on the wharf since performance criteria will not be met if the wharf is operational but essential equipment is not.

The criteria for the ship-to-shore container cranes are typically specified in the crane purchase specifications. The crane criteria should meet the intent of the criteria for the wharf. In keeping with our recommendation, the seismic portion of the Liftech ship-to-shore crane specification was revised in 2006 to bring the crane design criteria more in line with the wharf criteria. Each purchaser, however, prepares its own specification, typically with no provision for seismic design. Currently, port authorities typically require little or no provision for the seismic design for cranes.

Although pre-2006 versions of Liftech's crane specifications have been widely used throughout the industry, and even though we expect that our new specification with seismic design criteria, or similar specifications, will eventually become the industry standard, we recommend that port codes include seismic requirements for ship-to-shore cranes.

Reports of the first cranes designed to meet the current Liftech crane specification indicate that cranes can be designed to meet the wharf criteria with a modest, less than 5%, increase in their initial purchase price.

An excerpt from the Liftech copyrighted specification is provided in Appendix A.

RECOMMENDATIONS

Envision port facilities as a system. For the system to function, all the essential components need to function. The performance criteria applicable to one essential structure should be applied to all essential structures, regardless of ownership.

These concerns should be discussed by the port community, so a consistent and reasonable approach to seismic criteria can be established. The issues, listed on page 3, should be explained to the stakeholders so laymen will understand the acceptable risks approach and properly address concerns.

Some of the issues to be addressed are:

Seismic criteria for new cranes

What damage is acceptable in an OLE?

At what magnitude of earthquake is collapse acceptable?

Seismic criteria for existing cranes

Is significant damage acceptable in an OLE?

At what magnitude of earthquake is collapse acceptable?

Should different criteria be used for different cranes? Should a stakeholder strengthen select cranes?

Seismic criteria for upgrading cranes

If the wharf is upgraded, what consideration should be given to upgrading the cranes?

If only the cranes are upgraded, what should the criteria be?

In the meantime, we recommend designing new cranes to the same seismic criteria as required of new wharves. For example, if a wharf is designed to remain operational with only elastic strains, the crane should also be designed to this criterion. Use of criteria similar to those provided in Appendix A will meet this recommendation in many cases.

RECENT ANALYSES, FINDINGS, AND FURTHER INVESTIGATIONS

The following section describes the recent analyses,findings, and discusses some of the issues that may be helpful in understanding the performance of cranes during expected West Coast seismic events.

RECENT ANALYSES

The analyses data and parameters of recent analyses are:

1. Finite element analyses of 50'-gage and 100'-gage cranes modeled on the Port of Los Angeles Berth 100 wharf were performed. Pre-2006 POLA OLE and CLE design ground motion time histories were used. The design ground motions were applied in two orthogonal directions.

2. Cranes characteristics

Crane Type	**Smaller**	**Jumbo**
Gage	15.24 m	30.48 m
Manufacturer	ZPMC	ZPMC
Date commissioned	2005	2003
Weight	1050 t	1500 t
Tie-downs	Yes but not engaged in analyses	
Lifted load	40 LT	60 LT
Outreach	48 m	65 m
Lift height above rail	30 m	42.2 m
Clearance under portal	≈13.5 m	≈16.5 m
Seismically compact sections?	No	No
Location[1]	Portsmouth, Virginia	Yantian, China
Designed for hurricane wind?[A]	Yes	Yes

[A] The cranes selected for this study were located in high wind regions. These cranes were selected for convenience, since dynamic math models were already developed. See the discussion below.

The cranes were designed to resist hurricane loads and therefore have stronger O-frames (i.e. the landside and waterside frames that the containers pass through) and may have slightly stronger portal frames (i.e. the gantry frames that the wharf equipment passes through) than the typical west coast jumbo crane. This difference is insignificant and will not affect the conclusions and recommendations in this report.

3. The finite element model for the time history analysis included linear elastic elements for the structural members of the wharf and crane, and nonlinear elements for the boundary elements. A viscous damping of 5% was used for both the linearly elastic crane and wharf structures. Measurements of the elastic crane response to dynamic loads indicate that the elastic damping is 1%; so the elastic forces are probably underestimated. Considering the magnitude of the calculated stresses, some nonlinear behavior is expected. Nonlinear behavior is expected to make the effects of the seismic motion more severe because the P-delta moments would increase significantly.

4. The modeled POLA Berth 100 wharf is a cast-in-place deck supported on vertical 24" octagonal prestressed piles. The lateral ground resistance is modeled using bi-linear springs.

5. The yield stress of the crane leg material is 3.5 t/cm^2. Legs are stiffened box members with local buckling strength of 2.85 t/cm^2. The members do not meet the AISC compact member requirements and are expected to buckle during OLE and possibly fail during the CLE. Further analyses would determine the behavior with more certainty.

FINDINGS

1. Response and performance of the analyzed cranes during an earthquake (EQ):

EQ Size	Response / Performance	Smaller 50' Gage Crane	Jumbo 100' Gage Crane
OLE	Leg lift and derailment?	Maybe	Yes
	Structural performance of lower leg at portal beam	Elastic, little or no localized plate buckling; repairs unlikely.	Localized plate buckling, repairs likely.
	Collapse?	Unlikely	Possible
CLE	Leg lift and derailment?	Yes	Yes
	Structural performance of lower leg at portal beam	Localized plate buckling; repairs likely.	Severe localized plate buckling and damage.
	Collapse?	Possible	Probable

2. The forces in a crane are the result of a combination of various dynamic responses and modes. For the ground motions considered, significant accelerations in the trolley travel direction occurred for both earthquake directions considered. Damage from seismic events is most probable due to displacements in the trolley travel direction. In the gantry travel direction, modern cranes have periods of 3 seconds or more.

3. For operational reasons, the crane structure has a natural period of 1.5 seconds or less in the trolley travel direction. Periods much larger than this result in unacceptable crane sway during operations. This smaller period of vibration results in larger inertia forces during earthquakes. Isolation components could be added to reduce forces during an earthquake without affecting the operating conditions.

4. Tipping of the crane so that its weight is carried through only two of the four equalizer pins is expected to occur during CLE ground motions. The portal frames of most jumbo cranes are not strong enough to carry the weight of the crane and the tipping shear. Therefore, if jumbo cranes are subjected to the design CLE, most cranes will probably collapse.

FURTHER INVESTIGATIONS

Additional analyses are necessary to better predict the crane behavior and should include the following:

1. Ground motion:
   Perform time history analyses for ground motions in various directions, e.g. in 15 degree increments. Multiple ground motions should be considered.

2. Nonlinear elements:
   Develop the moment curvature relationships for the legs and portal tie. Improve the modeling of the effects of wheels lifting off the rails and the crane skidding down the rails.

3. Portal performance:
   We have made limited calculations on a few portal frames. It may be prudent to investigate the response for a range of portal structures, or it may be most effective to look at each case individually.

4. Entire crane structure:
   Make calculations to evaluate the damage in the rest of the crane structure, e.g. boom, stays, machinery house.

REFERENCES

Arulmoli, Arul K. et al. 2007. "Port of Los Angeles and Long Beach Port-Wide Ground Motion Study," presented at ASCE Ports 2007.

Soderberg, Erik G. 2007. "Seismic Response of Jumbo Cranes and Design Recommendations to Limit Damage and Prevent Collapse," presented at ASCE Ports 2007.
http://www.liftech.net/LiftechPublications/EGSjumbocranes.pdf and
http://www.liftech.net/LiftechPublications/1EGSjumbocranes.pdf

Yin, Peter et al. 2007. "Seismic Engineering Program at the Port of Los Angeles," presented at ASCE Ports 2007.

APPENDIX A

LIFTECH CONTAINER CRANE SEISMIC DESIGN CRITERIA – 2006

APPENDIX A

EXTRACT FROM
LIFTECH CONSULTANTS INC
CRANE SPECIFICATION

SEISMIC DESIGN

Caveat

This extract from the Liftech Consultants' crane specification is included to provide guidance regarding the type of provisions that are needed to bring the crane seismic design criteria in line with the typical west coast wharf seismic design criteria. The specification is a living document in its infancy and is subject to changes as knowledge increases. The specification is being used currently for one project.

Seismic Considerations

The cranes supplied under this contract will be placed on a wharf designed to criteria similar to that described below.

The provisions of this specification are intended to provide a crane design criteria such that the crane seismic performance will meet the intent of the wharf seismic performance criteria. The crane criteria are based on a study of a typical jumbo crane on a typical wharf in the Long Beach-Los Angeles region. The typical wharf consists of a concrete deck supported on vertical prestressed concrete piles. The wharf deck and piles form a moment frame.

Wharf Performance Criteria

EQO Operating Level Earthquake, also referred to as OLE in other documents, forces and deformations, including permanent embankment deformations, shall not result in significant structural damage. Repairs shall not interrupt wharf operations. All damage shall be located where visually observable and accessible for repairs.

EQC Contingency Level Earthquake, also referred to as CLE in other documents, forces and deformations, including permanent embankment deformations, may result in controlled inelastic structural behavior and limited permanent deformations. All damage shall be repairable and shall be located where it is visually observable and accessible for repairs. Collapse of the wharf must be prevented, life safety must be maintained. There may be a temporary loss of operations, restorable within an acceptable period of time.

Crane Response

Recent studies indicate that the typical jumbo crane designed in accordance with traditional criteria will be expected to perform well in a moderate earthquake with a 50% probability of being exceeded in 50 years (the Operating Level Earthquake EQO) but may collapse in a major earthquake with a 10% probability of being exceeded in 50 years (the Contingency Level Earthquake EQC).

Other General Crane Issues

Two crane seismic criteria are presented:

A forced based criterion for the EQO

A displacement based criterion for the EQC

The criteria shall be applied to the loaded crane, consisting of the crane dead load and the trolley, lift system, and half of the rated load. The crane configuration shall be with the boom horizontal, raised 45 degrees, and fully raised. All boom configurations shall be analyzed.

The crane rail on the wharf may be damaged during the EQO. This is acceptable. The crane design shall be based on the rail remaining intact, even though the rail may be damaged.

The EQC may cause some of the wheels to leave the crane rail and come to rest on the wharf away from the rail. The crane designer does not need to consider the performance of the wharf. For the purposes of design, the wharf shall be considered capable of supporting the crane if the wheels leave the rail and come to rest off the rail and the allowable wheel loads to the wharf, in all directions, shall be considered to be unlimited[1]. The gantry wheel brakes may be incapable of preventing movement in the gantry travel direction loading. For the purposes of design, the gantry-travel direction loads shall not be reduced based on the gantry braking capacity.

The orthogonal X Y Z coordinates are used as follows:

The X coordinate is the direction of trolley travel

The Y coordinate is vertical

The Z coordinate is in the direction of gantry travel

Definitions

The following notation is used in the seismic sections of this specification.

Symbol	Definition	Notes
F_y	Specified steel yield stress.	
F_{ym}	Measured steel yield stress.	F_{ym} shall be determined by coupon tests. Three coupons shall be tested for each plate used on ductile members. The analysis shall be based on F_{ym} or 1.15 F_{ym}, whichever is more severe.

[1] The peak wheel load due to seismic response is of extremely short duration, 0.2 sec or less. For typical concrete wharves, the effects of inertia plus the high rate of loading is such that the wharf is not damaged. Notice that the wharf is usually not designed to resist stability or collision loads, even though these occur. Liftech knows of no case where a wharf has been damaged due to cranes tipping onto one rail or being knocked down by collisions. Calculations taking into account the rate of loading and high short term strength of concrete explain this phenomenon.

Symbol	Definition	Notes
g	Acceleration of 386 in/s2 (980 cm/s2)	
DL	Dead load weight of the crane Including all permanently attached machinery and equipment	All boom positions and both crane heights shall be considered.
DLX DLZ	1 **g** acceleration of the dead load in the X direction. 1 **g** acceleration of the dead load in the Z direction.	Both positive and negative directions shall be considered. Accelerations shall be applied uniformly over the height of the crane without consideration of mode shapes.
TL	Trolley load weight	The trolley shall be in the most adverse position.
LS	Lift system weight	
LL	Lifted load weight	
TLX TLZ	1 **g** acceleration of the trolley load in the X direction. 1 **g** acceleration of the trolley load in the Z direction.	Both positive and negative directions shall be considered.

EQO Criteria

EQO shall be the lesser of EQC or both of the following combinations (not concurrently):

Combination	
EQO 1	DL + TL + LS + 0.5 LL + 0.30 (DLX + TLX) + 0.05 (DLZ + TLZ)
EQO 2	DL + TL + LS + 0.5 LL + 0.10 (DLX + TLX) + 0.15 (DLZ + TLZ)

Note: For the boom raised configurations, the trolley shall be in the stowed position with no load under the lift system.

The analysis shall be based on elastic behavior, as described in the structural section.

Boundary conditions: The wheels shall be modeled so tensile forces and forces parallel and perpendicular to the gantry rail may be developed, even though this may be physically impossible. If the main equalizer pin lifts more than 0.75 in (20 mm), the X restraint shall be released. This will produce a slightly conservative but reasonable design.

The calculated stresses shall not exceed those given in the structural section. P-delta effects shall be included. Plate buckling shall be checked as specified in the structural section.

All walkways, platforms, the elevator, electrical conduit, and other components shall be designed so they are not damaged during the EQO.

EQC Criteria

Two phenomena shall be considered:

Phenomena	Description
Tipping	The crane tips about the landside rail, the waterside rail, or the main equalizer pins.
Special Moment Frame, SMF	The legs yield plastically, in effect isolating some of the mass of the crane.

Tipping

Tipping occurs about the Z axis when the lateral seismic forces in the X direction cause both landside legs or both waterside legs to lift. Similarly, tipping occurs about the X axis when the lateral seismic forces in the Z direction cause both left-hand ("left" facing the water) or both right-hand legs to lift. The lateral forces required to tip the crane shall be applied uniformly over the height of the crane without consideration of mode shapes.

The calculated stresses shall not exceed 0.90 times the specified material yield stress. P-delta effects shall be included. Plate buckling shall be checked as specified in the structural section.

If the structure is capable of tipping both ways about the Z axis or both ways about the X axis, Special Moment Frame (SMF) behavior does not need to be considered about the axis in which tipping occurs.

Special Moment Frame—SMF

For X axis loads, the structure shall be analyzed using collapse mechanism analysis (also called "pushover analysis"), including P-delta effects and nonlinear yielding.

The structure shall be capable of displacing 30 inches (0.76 m) in the +X and -X directions, 60 inches (1.52 m) total, at the portal beam without causing the strain in the steel components to exceed six times the yield strain.

The crane will tip about the X axis before yielding. There is, therefore, no need of a SMF to resist Z forces. As noted above, the tipping analysis will be sufficient. However, the forces due to the loads required to cause tipping about the Z axis, factored by 0.30, shall be combined with the SMF X axis forces.

The design and analysis shall comply with the recommendations in the references. Seismically compact sections shall be used where the calculated stresses exceed 0.80 F_y. The slenderness ratios in AISC 341 shall apply. For sections and conditions not covered by AISC 341, criteria comparable to that of AISC 341 shall be used. The Generalized Force-Deformation curve shown in FEMA 356 Figure 5-1 shall be used.

Where calculations indicate that ductile yielding is not required, the members shall be designed in accordance with the structural sections using an allowable stress of 0.90 times F_y.

All joints that connect yielding members, i.e. members in the SMF that are designed to yield, shall be designed for 1.3 times the full plastic strength of the yielding member, based on 1.15 times F_{ym}.

Submittals with the Bid

The bidder shall submit concept designs and calculations to show compliance with all the seismic criteria. The Engineer may request additional information after the proposals are received.

References

American Institute of Steel Construction, Chicago 2002. *ANSI/AISC 341-02, Seismic Provisions for Structural Steel Buildings.*

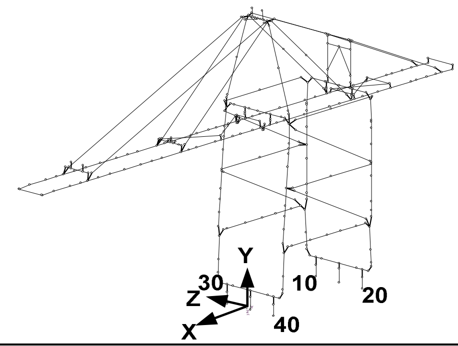
FEMA and the ASCE, Reston, Virginia 2000. *FEMA 356/November 2000, Prestandard and Commentary for the Seismic Rehabilitation of Buildings.*

Priestley, M.J.N., Seible, F., Calvi, G.M. 1996. *Seismic Design and Retrofit of Bridges*, John Wiley & Sons, Inc., New York

APPENDIX B

SELECTED ANALYSIS RESULTS

Date:	4/16/2007	**APPENDIX B**
Grid:	r:\projects\calculations\generic_calculations\time_history\ports2007\[reaction summary_3_mj.xls]summary	**Forces, Displacements, Stresses**
By:	AD	Units: t, cm



ANALYSIS RESULTS

			OLE 3								CLE 1							
			50' Gage				100' Gage				50' Gage				100' Gage			
		EQ Direction	0º		90º		0º		90º		0º		90º		0º		90º	
	Force or		F or D	at Time	F or D	at Time	F or D	at Time	F or D	at Time	F or D	at Time	F or D	at Time	F or D	at Time	F or D	at Time
	Displacement		t,cm	s	t,cm	s	t,cm	s	t,cm	s	t,cm	s	t,cm	s	t,cm	s	t,cm	s
Joint 10	FX	Min	-32.9	9.81	-22.70	20.19	-174.4	9.81	-176.5	10.02	-50.7	9.56	-80.8	10.01	-209.3	7.31	-268.0	8.41
		Max	25.4	11.69	25.53	19.79	183.9	10.20	171.7	6.08	48.3	7.65	74.3	8.02	266.3	8.93	346.5	8.07
	FY	Min	0.0	9.97	27.36	20.27	0.0	9.94	0.0	10.13	0.0	9.68	0.0	8.79	-0.1	9.49	-0.1	8.59
		Max	711.1	10.50	612.00	12.09	829.6	10.22	725.8	10.42	1139.0	10.39	970.3	9.35	1312.0	7.82	1017.0	9.13
	FZ	Min	-45.1	10.01	-2.21	15.47	-30.3	10.02	-66.1	8.21	-358.1	9.71	-389.7	8.78	-127.8	7.54	-243.8	8.68
		Max	265.7	10.51	227.40	12.09	648.0	10.29	652.4	7.85	447.9	10.40	383.7	9.44	983.8	8.84	1028.0	9.14
	DY	Max	0.21	9.97	-0.03	20.27	2.30	9.94	2.07	10.13	3.10	9.68	2.44	8.79	9.38	9.49	8.38	8.59
Joint 20	FX	Min	-37.5	9.83	-19.09	20.19	-160.8	9.83	-148.9	5.71	-73.7	9.65	-56.2	9.99	-228.0	6.59	-280.1	8.41
		Max	28.6	10.23	26.63	16.16	198.8	10.20	167.7	6.09	74.5	7.71	81.5	8.05	370.8	7.71	207.0	8.00
	FY	Min	0.0	10.02	0.00	19.17	0.0	9.95	0.0	10.11	0.0	9.90	0.0	8.77	-0.1	8.40	0.0	8.76
		Max	475.5	12.99	547.10	10.97	754.7	10.22	718.7	6.16	1069.0	9.08	1221.0	8.23	1087.0	7.07	1421.0	8.16
	FZ	Min	-179.4	11.50	-206.50	10.98	667.7	10.27	-642.3	7.85	-402.1	9.10	-499.8	8.28	-986.6	7.90	-1074.0	9.13
		Max	75.3	10.02	21.89	16.73	41.6	10.03	77.2	8.21	282.1	9.85	420.0	8.77	122.7	9.32	218.3	8.70
	DY	Max	0.54	10.02	0.17	19.17	1.87	9.95	3.84	10.11	2.03	9.90	2.69	8.77	8.73	8.40	6.34	8.76
Joint 30	FX	Min	-39.2	9.80	-28.70	20.19	-189.4	9.81	-192.5	10.02	-57.1	9.55	-87.6	10.01	-221.0	7.30	-282.1	8.41
		Max	20.2	11.69	18.98	19.79	164.0	10.18	149.3	6.09	44.5	7.64	69.3	8.02	249.5	8.95	323.8	8.05
	FY	Min	0.0	10.37	0.00	11.02	25.2	10.28	0.0	7.87	0.0	9.04	0.0	8.21	0.0	8.96	0.0	8.15
		Max	621.4	9.97	545.90	16.67	873.4	9.83	1099.0	10.02	771.4	9.87	910.7	10.15	1275.0	8.23	1241.0	9.55
	FZ	Min	-95.7	10.37	-102.30	11.03	7.6	10.29	-34.7	7.87	-493.1	9.08	-638.7	8.23	-1316.0	8.96	-1397.0	8.15
		Max	230.8	9.99	201.50	16.69	510.6	9.84	687.8	10.02	316.3	9.90	350.2	10.16	843.0	8.23	777.7	9.55
	DY	Max	0.32	10.37	0.84	11.02	0.00	10.28	-0.03	7.87	3.23	9.04	4.72	8.21	1.35	8.96	1.36	8.15
Joint 40	FX	Min	-43.2	9.83	-25.09	17.94	-173.2	9.83	-158.3	5.71	-79.4	9.65	-60.0	7.74	-238.7	6.59	-286.0	8.41
		Max	23.4	10.23	20.59	16.17	179.0	10.19	148.8	6.09	71.5	7.71	75.2	8.05	347.0	7.71	188.5	8.01
	FY	Min	0.0	10.39	0.00	12.15	0.0	10.29	21.8	6.16	0.0	10.33	0.0	9.37	0.0	7.82	0.0	9.23
		Max	572.5	11.16	482.00	15.46	925.6	9.84	936.0	15.27	910.5	6.71	789.5	8.63	1414.0	9.31	1179.0	7.90
	FZ	Min	-204.6	9.92	-183.40	15.48	-574.6	9.84	-582.8	15.26	-371.7	9.68	-289.7	8.64	-898.0	9.31	-794.4	7.90
		Max	129.0	10.41	109.90	12.15	191.6	10.30	-5.8	7.85	439.6	10.39	562.4	9.37	1470.0	7.82	1152.0	9.23
	DY	Max	0.99	10.39	0.79	12.15	0.19	10.29	0.00	6.16	3.15	10.33	3.85	9.37	1.45	7.82	1.19	9.23

Notes:
1. 0º = H1 X, H2 Z   90º = H1 Z, H2 X; OLE3 and CLE1 are POLA pre-2007 design time history
2. 50' Gage = J1384.04 PMT Crane Procurement,   100' Gage = V1430 YICT Phase III Crane Procurement
3. POLA Pier 100 Wharf

CALCULATED STRESSES IN LEG JUST BELOW PORTAL BEAM

Dist rail to Portal, cm		1350	1350	1650	1650	1350	1350	1650	1650
Dist to inflection O-frame, cm		722	722	1126	1126	722	722	1126	1126
Controlling Leg Loading									
Legs Lift from Rail?		**No**	**No**	**No**	**No**	**Yes**	**Yes**	**Yes**	**Yes**
Joint		**40**	**30**	**30**	**30**	**40**	**30**	**40**	**30**
FY	t	573	546	873	1099	911	911	1414	1241
FX	t	-43	-29	-189	-193	-153	-168	569	549
FZ=0.3xFY	t	172	164	262	330	273	273	424	372
MZ	t-cm	58253	38745	312510	317625	206699	227286	938264	905488
MX	t-cm	124004	118242	295035	371242	197214	197258	477649	419210
Leg Properties									
A	cm^2	1170	1170	1672	1672	1170	1170	1672	1672
SZ	cm^3	84627	84627	114278	114278	84627	84627	114278	114278
SX	cm^3	72297	72297	134914	134914	72297	72297	134914	134914
Stresses (If Elastic)									
fa	t/cm^2	0.49	0.47	0.52	0.66	0.78	0.78	0.85	0.74
fbZ	t/cm^2	0.69	0.46	2.73	2.78	2.44	2.69	8.21	7.92
fa+fbZ	t/cm^2	**1.18**	**0.92**	**3.26**	**3.44**	**3.22**	**3.46**	**9.06**	**8.67**
fbX	t/cm^2	1.72	1.64	2.19	2.75	2.73	2.73	3.54	3.11
fa+fbZ+fbX	t/cm^2	**2.89**	**2.56**	**5.44**	**6.19**	**5.95**	**6.19**	**12.60**	**11.77**

Notes:
1. When leg lifts from rail, add FX from lifted legs to FX on non-lifted legs.
2. FZ for controlling FX loading estimated at 0.3 x FY.