Seismic Guidelines for Container Cranes

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ABSTRACT

Historically, seismic forces have not been a concern for early container cranes, which were lighter and less stable than today's larger jumbo cranes. During an earthquake, the earlier cranes would lift from the rails before significant inertia forces could develop in the crane structure.

Current large cranes, with 100-foot or greater rail gages, are much heavier, which results in significantly larger seismic forces in the crane structure. Liftech has performed time-history analyses of A-frame and low profile jumbo cranes. Our studies indicate that many jumbo cranes will be extensively damaged in moderate earthquakes, and that many jumbo cranes will be severely damaged, or will collapse, in a major earthquake.

Container crane seismic design criteria are changing to address the seismic risk to jumbo cranes. Several upcoming design standards, one from the American Society of Civil Engineers, and others from ports, will specify seismic performance requirements for new cranes.

This paper presents the following:

1. Expected seismic performance of cranes built to early design criteria
2. Recent design standards and their crane seismic performance requirements
3. New crane seismic design criteria, their effect on the crane design and costs
4. Options for retrofitting existing cranes

EARLY SEISMIC DESIGN REQUIREMENTS

Most local building codes are suited to building design and are not suitable for container crane structures that can move around and lift from the wharf. Container cranes historically have been designed to meet project performance specifications provided by consultants, manufacturer specifications, or both.

Early on, the industry studied the seismic loading issue and determined that seismic loading was not a significant design load. Early cranes were small and could tip before damage occurred. Typical seismic design service loads of 0.2 g in the trolley and gantry travel directions applied non-concurrently were specified to ensure reasonable lateral strength. In hurricane regions, wind loads typically controlled the lateral design.

CRANE EVOLUTION

Container cranes have changed significantly since early designs. Early cranes capable of servicing Panamax vessels weighed 600-800 t, had lift heights of approximately 25 m above the wharf, outreaches of around 35 m, and wheel gages of 15.24 m.

Modern jumbo cranes weigh 1300-1800 t, have lifting heights of 35 m to 42 m above the wharf, and have outreaches of over 60 m. Now that the Dual Hoist Tandem 40 cranes are becoming popular, the demand for reasonable wheel loads and increased traffic lane widths are resulting in increased rail gages, 35 m to 42 m. These cranes weigh about 2000 t. These larger cranes have stiffer portal frames to control crane motions during operations.

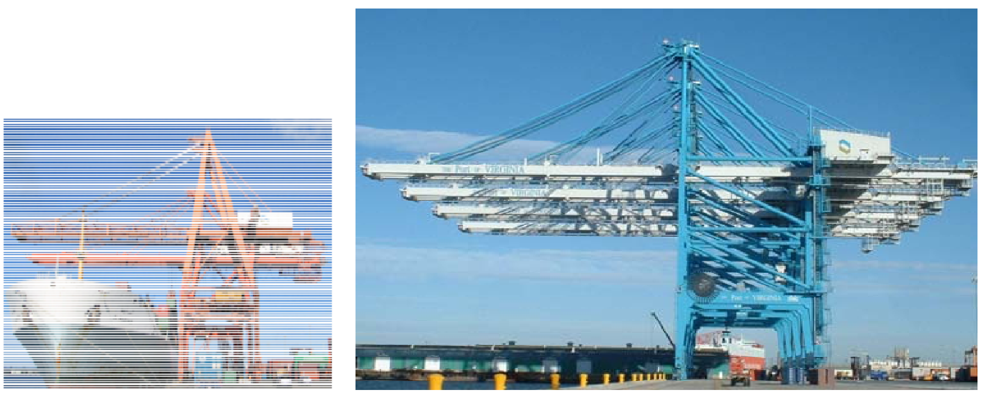

Figure 1. Size Comparison of Early and Modern Jumbo Cranes.

HISTORIC SEISMIC PERFORMANCE OF CONTAINER CRANES

To date, cranes have performed well in earthquakes when their supports have not failed. No modern jumbo cranes have experienced a large earthquake.

As expected, early cranes have tipped and lifted from their rails without significant damage. Some cranes that tipped did not land on their rails. Often, even though the wheels were off the rails, the portal frame was still elastic. Restoring the wheels to the rail was not difficult because after lifting the frame with jacks, the portal frame pulled the wheels back over the rail.

When crane supports failed, such as in the Kobe 1995 earthquake, significant damage did occur. In Kobe, where the crane rails spread, the crane legs spread until plastic hinging developed in the portal frame. Refer to Figure 2. One crane collapsed due to excessive spreading.

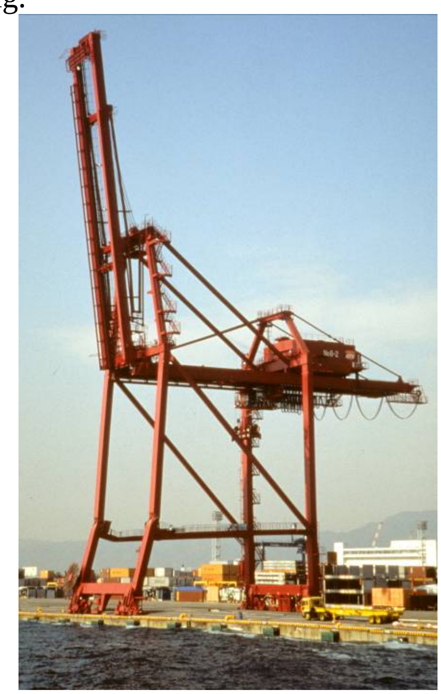

Figure 2. Crane Damage from Rail Spreading, Kobe 1995 Earthquake.

EXPECTED PERFORMANCE OF MODERN JUMBO CRANES DESIGNED TO EARLY SEISMIC CRITERIA

Several years ago, studies revealed that the early seismic design criteria are no longer suitable for modern jumbo cranes. The jumbo cranes are more massive, have greater portal clearances, and are more stable, resulting in much larger lateral loads. The strength of the portal frame has not kept up with the increased lateral seismic loading demand. If modern jumbo cranes are designed to early criteria, they cannot tip elastically and permanent damage will occur. For these cranes, Liftech studies predict the following performance:

1. In a design operating level earthquake (OLE) of 72 year mean return interval (MRI), the portal frame would suffer significant damage consisting of localized plate buckling at the leg to portal connection and possibly other areas of the portal frame.
2. In a large 475 year MRI earthquake, the portal frame would be significantly damaged resulting in possible crane collapse. Performance in this level earthquake is highly dependent on the ability of the plastic hinges to maintain adequate strength over the many cycles of loading.
3. Damage to the portal frame occurs due to lateral displacement in the trolley travel direction.

Studies predict that lateral displacement in the gantry travel direction is not a significant concern. Since the crane's period of vibration in this direction of about three seconds is much longer than the wharf structure's period, the crane response is limited and does not result in significant stresses. The crane is also less stable in this direction and will tip from the rail before large lateral loads will develop.

Performance will vary between crane designs. Cranes designed for hurricane winds and that are less stable will perform better than cranes designed for light winds, those with large rail gages, or both.

The studies were a wakeup call for the industry.

RECENT AND UPCOMING DESIGN STANDARDS

The industry has become aware of the seismic performance issues of modern jumbo cranes. Seismic requirements have been revised in the Liftech procurement specification, and used by several owners to procure new cranes. In addition to requirements by manufacturer and owner procurement specifications, recent port standards and an upcoming national design standard include minimum design requirements for cranes and similar structures on wharves.

An upcoming American Society of Civil Engineers (ASCE) standard for the seismic design of new piers and wharves will require that the ancillary structures to the pier or wharf, such as cranes, be designed so they will not collapse in the new ASCE Maximum Considered Earthquake (MCE), a 2475 year MRI design earthquake. The standards of many West Coast ports have similar and in some cases, more stringent requirements.

The Port of Los Angeles's design standard not only requires that a new crane not collapse in an MCE level earthquake, but suffer only minor damage in the 72 year MRI OLE. Minor damage in the OLE may be the controlling requirement for some cranes.

Refer to Table 1 for a summary of adopted or impending design standard requirements.

Table 1. Container Crane Performance Requirements.

Standard	Expected Adoption Date	Required Crane Seismic Performance	
		Minor Damage in 72 Year MRI Earthquake	No Collapse in Largest Design Earthquake
ASCE Seismic Design Standard for New Piers and Wharves	2010		X
Port of Los Angeles	2007	X	X
Port of Long Beach	2009		See note 2
Port of Oakland	2008		X
Port of Tacoma	2009	X	

Notes:
1. Based on conversations with Port personnel and published materials.
2. Port of Long Beach currently does not have a standard that specifically addresses crane performance but requires that the crane be designed to not collapse based on the requirements of the California Building Code.

NEW SEISMIC DESIGN CRITERIA

One new design criteria gaining acceptance in the industry, the Liftech seismic design criteria, has been used on recent crane projects. These criteria specify design requirements for a 72 year MRI and a 475 year MRI earthquake.

Operating Level Earthquake – 72 year MRI. The Liftech design criteria require elastic design stresses in the crane structure. Any damage that occurs should be easily repaired.

Contingency Level Earthquake – 475 year MRI. The Liftech design criteria require two phenomena be considered: (1) Tipping – design the crane to tip with stresses less than 90% of yield, (2) Special Moment Frame – design the portal frame to yield plastically. Where stresses exceed 80% of yield, the member shall meet the AISC seismic detailing requirements.

The performance criteria require that collapse be prevented and life safety be maintained. Three different design approaches that meet the intent of the performance criteria follow: (1) that the crane be designed to tip, (2) that the structure be ductile, and (3) that the crane structure be seismically isolated from the wharf.

Designing the structure to tip elastically results in crane performance similar to that of early cranes. If the crane structure remains elastic, it may tip and land off of the rails, but only minor damage is expected. The maximum lateral force that can develop is that which tips the crane. This approach may impose large lateral loads on the wharf structure, particularly cranes with large wheel gages.

Designing the structure to be ductile is similar to the approach most common in building design. The seismic energy is absorbed through ductile yielding. This approach requires more closely spaced stiffeners in the thin walled box members. Continuous stiffeners through diaphragms will improve the ductility at plastic hinges. A drawback for this approach is that inelastic yielding will occur in the portal frame.

Designing the structure to be isolated from the wharf requires an isolation joint to allow the wharf to move beneath the crane, limiting the forces in both structures. This approach is also used in building design, particularly in retrofit situations.

IMPLICATIONS FOR NEW CRANES

The good news is cranes designed to the new seismic criteria do not cost significantly more than those designed to the earlier criteria.

Design to Tip. On Liftech projects to date, manufacturers have opted to design and provide cranes based on the tipping design approach. This approach results in stronger portal frames, i.e., stronger lower legs and portal beams. On a recent project with the cranes designed for hurricane winds, the additional cost to strengthen the portal so the crane could tip elastically was estimated at $150,000 per crane. On another recent project not in a hurricane wind region, the additional cost was estimated at $180,000 per crane. These costs were reported for cranes built near the peak of steel costs in 2008, and for cranes with wheel gages of 30.48 m or less. Reportedly, the additional crane weight was 5%. Other design approaches are more suitable for cranes with wheel gages in excess of 30.48 m.

Design for Ductile Yielding. No cranes have been designed using the ductile yielding approach. This approach is less clear to manufacturers and will require more study and understanding before it is adopted. As discussed above, it will require more stiffeners in the portal frame, and possibly continuous stiffeners. The additional material costs will not be significant. Eventually, we expect that this approach will become more prevalent.

Design for Isolation. Japanese manufacturers developed an isolation mechanism that is located between the sill beam and main equalizer pin. Refer to Figure 3. Japanese and Chinese manufacturers have built cranes using this type of isolation mechanism.

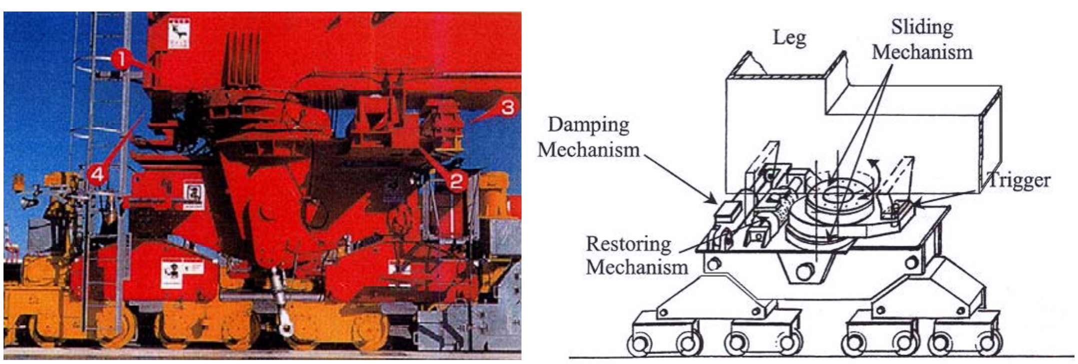

Figure 3. Sill-Equalizer Seismic Isolation Mechanism.

Liftech has proposed another isolation mechanism that is located between the leg and portal beam. Refer to Figure 4. No cranes have been built with this type of mechanism, but a similar concept is currently being used in some new building designs. This mechanism has advantages over the sill-equalizer mechanism – it does not require a tripping fuse, is self-restoring, can accommodate larger displacements, and is expected to be less costly.

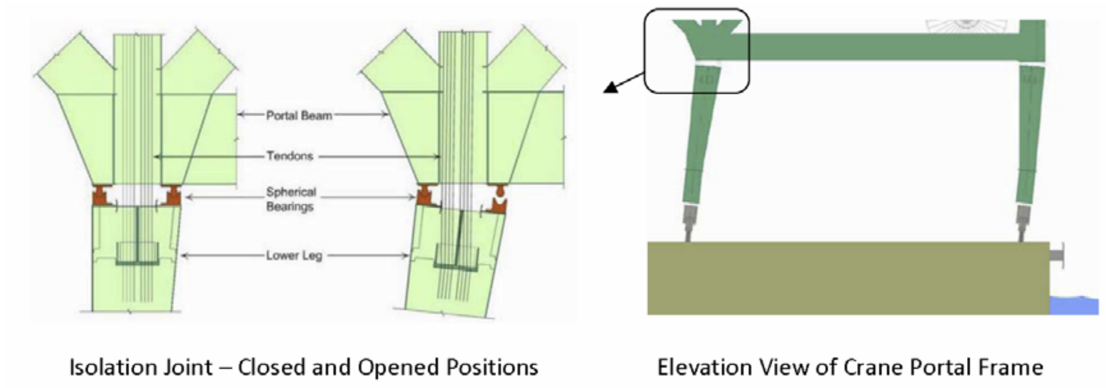

Figure 4. Portal-Leg Seismic Isolation Mechanism.

Seismic isolation mechanisms will be more costly than other options, but the probability of damage is lower, and the forces imposed on the wharf structure less. If the mechanism is self-restoring, the crane will be operable immediately after an earthquake. This approach may be the most suitable for large gage cranes.

IMPLICATIONS FOR EXISTING CRANES

The Need for Retrofit. There are many modern jumbo cranes on the West Coast that were designed and built to the early design criteria, which may not perform well in the design earthquakes.

Most building codes do not require improvement of an existing structure to current codes unless it is being altered, and the alteration increases the seismic loading or reduces strength of the structure by 10% or more. Refer to the 2007 California Building Code. This is reasonable, as the cost to modify an existing structure is typically much greater than for new construction. We believe a similar logic is appropriate for cranes, provided that the crane is not likely to collapse. The industry has not addressed this issue.

No studies have been made to determine if the risk of earthquake damage justifies modifying the structures of existing cranes to limit damage, including collapse. If ports do not have a significant percentage of cranes that will remain operational after the more probable earthquakes, improving the performance of some cranes is worthwhile. If collapse is probable, it is worth improving the performance of a crane.

Modification approaches to existing cranes parallel those for new cranes. Some compromises and considerations apply as discussed below.

RETROFIT OPTIONS

Modify to Tip. Modifying an existing crane to tip is most worthwhile if the portal clearance can be reduced and braces installed. A modification concept for a recent 30.48 m gage jumbo crane is provided in Figure 5. This modification is estimated to take one month and cost $300,000, not including the cost of lost operation, to install four 0.75 m diameter pipe braces from the lower end of each leg to the center of the portal beam. This modification is not an option where straddle carrier or RTG operations occur or will occur.

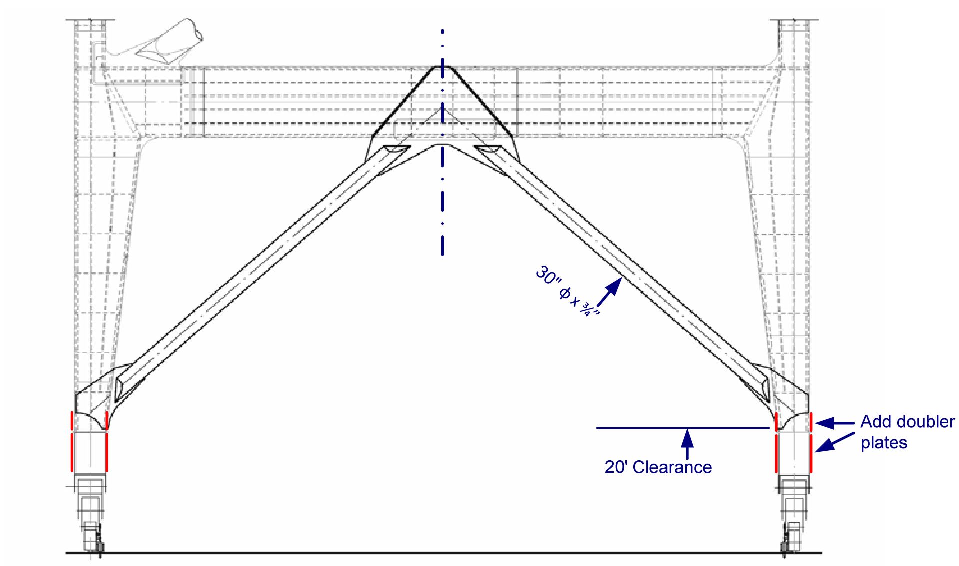

Figure 5. Added Portal Frame Bracing.

Modify for Ductile Yielding. Modifying an existing crane so that it will yield in a ductile manner is most easily done by adding external stiffeners. A modification concept for a recent 30.48 m gage jumbo crane is provided in Figure 6. This modification is estimated to take two months and cost about $500,000, not including the cost of lost operation. This modification is most suitable when portal clearance is required and strengthening with portal frame bracing is not practical.

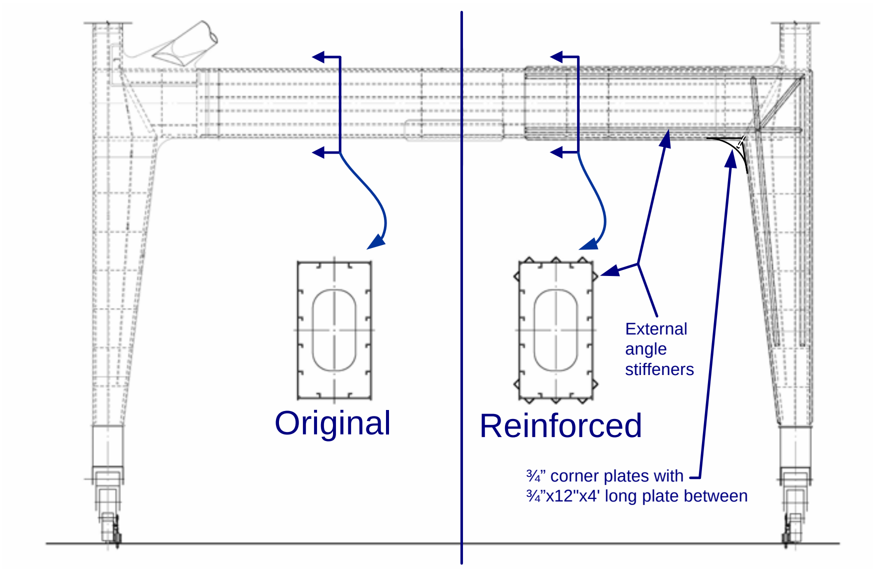

Figure 6. Added External Stiffeners for Seismic Ductility.

Modify for Isolation. Modifying an existing crane to have an isolation mechanism is the most expensive option. The Liftech portal-leg mechanism should be considered particularly if a crane is also being raised for additional lift height.

Summary. A summary of some of the advantages and disadvantages of modifications to improve the seismic performance of existing cranes is provided in Table 2.

Table 2. Advantages and Disadvantages of Seismic Retrofit Options.

Option	Advantages	Disadvantages	Comment
Modify structure to tip elastically	Structure can tolerate larger lateral load without damage	Imposes the largest lateral load on wharf	Less costly if the clearance under portal can be decreased
Improve ductility by adding stiffeners	Maintains portal clearance	Plastic yielding will require repairs	Can also strengthen the portal frame to tip without damage
Add isolation mechanism	No significant damage, limits lateral loads on crane and wharf, resilience	May be expensive	Less expensive if added with crane raise modification

CONCLUSION

In conclusion:

1. Early cranes performed well in earthquakes as they were light and could tip easily. Design specifications included modest requirements for the seismic loads.
2. Modern jumbo cranes are significantly larger than early cranes. Increases in portal strength have not kept up with the seismic demand resulting from the increase in mass, greater stability, and larger portal clearance.
3. Early container cranes have performed well in earthquakes when their supports have not failed.
4. Recent studies revealed that modern jumbo cranes designed in accordance with early design specifications will perform unacceptably in earthquakes.
5. The industry is adopting more stringent seismic performance requirements. Some seismic design specifications have already been revised. Recent or soon to be adopted port and ASCE standards will include crane seismic performance requirements. Typical requirements are that the crane remains operational after a 72 year MRI earthquake, and does not collapse in a large earthquake of 475 year or greater MRI.
6. For new cranes, the cost to achieve acceptable seismic performance is a small percentage of the total crane cost. The cost to design and build recent cranes to tip elastically was between $150,000 and $180,000 more than if designed and built to the earlier design specification.
7. The industry has not addressed what to do with existing cranes that may not perform well in earthquakes.
8. Retrofitting existing cranes to obtain acceptable performance can be costly. The least costly option is to add pipe braces to the portal frame. The cost for this option is estimated at $300,000. Adding stiffeners for ductility or to strengthen the crane to tip is estimated at $500,000. Installing isolation mechanisms is expected to cost over $500,000, but will be least costly if installed during a crane raise modification.

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