Seismic considerations for new quay cranes

Michael Jordan, Yoshi Oritatsu and **Erik Soderberg**, Liftech Consultants Inc., Oakland, CA, USA

Our article in the summer 2012 edition of Port Technology International, 'Seismic protection of quay cranes', addressed the application of friction dampers in quay cranes. This is the second article of a three-part series on crane seismic issues. This article focuses on seismic design considerations for new cranes. A third article, to appear in the winter 2012 edition, will address seismic retrofit for existing cranes.

Earthquake forces and crane evolution

The size and weight of quay cranes has nearly tripled since the introduction of the first cranes in 1959. Early cranes servicing Panamax vessels weighed 500 tonnes with a 15 meter rail gauge. Modern cranes, capable of servicing post-Panamax vessels and larger vessels weigh 1,200 tonnes or more, with a 30 meter or wider rail gauge. Since cranes are now much larger, seismic forces are much larger as well.

While cranes have evolved during the last 50 years, in most cases the seismic design has not. For decades, industry specifications required that crane structures resist lateral seismic forces of 20 percent of gravity, 0.2 g. The seismic forces on smaller cranes are limited to the forces required to tip a crane and lift the legs off the rail. Consequently, they performed well during moderate and major earthquakes. For larger cranes, the seismic forces required to lift a leg are much larger. As a result, the seismic forces in the wharf are much larger as well.

For most modern cranes with a 30 meter rail gauge, it takes 0.4 g to 0.6 g of lateral inertia to cause crane leg uplift. Clearly, the 0.2 g lateral force traditionally used is no longer adequate. Cranes designed to the old criteria are likely to sustain damage, even in moderate earthquakes.

Performance-based seismic design

Ports in seismically active regions, such as Port of Los Angeles and Port of Long Beach, have established performance-based criteria for the design of wharves. Their criteria define the performance objectives for wharf structures for three earthquake levels (see Table 1). The primary goals of such performance objectives are limiting interruptions to port operations due to a moderate earthquake and preventing the collapse of structures due to a major earthquake.

While seismic performance criteria have been developed for wharves, most port authorities have no seismic requirement for cranes. In the absence of regulatory requirements, stakeholders should determine the acceptable risk of damage. For some, it may be acceptable to have serious downtime after an earthquake. For others, little or no downtime is acceptable.

Figure 2 is a concept stakeholders can use to determine the seismic performance level of their cranes. If they choose to purchase cranes with low seismic performance, the additional initial cost will be small. However, the damage cost, i.e. the crane repair cost and financial loss arising from disruption to port operations, will be large. On the other hand, if they choose to procure cranes with high seismic performance, the initial cost will be large but the damage cost will be small. By carefully examining what it costs now to obtain a certain performance level versus what the expected earthquake damage will be at that performance level, stakeholders can find an optimal performance level where the total

Early crane and modern crane.

TABLE 1: EARTHQUAKE LEVEL AND PERFORMANCE OBJECTIVES.

Earthquake level	Probability of exceedance	Performance objective
Operating Level Earthquake (OLE)	50 percent in 50 years	No significant structural damage. Minimum or no interruption to port operations.
Contingency Level Earthquake (CLE)	10 percent in 50 years	Limited structural damage. Temporary loss of port operations is acceptable.
Code Level Design Earthquake (DE)	"Design Earthquake" as defined in ASCE 7-05	Life safety and collapse prevention.

cost, initial cost plus anticipated damage cost, is minimized.

There are several design approaches available to obtain acceptable seismic performance at relatively little cost for new cranes. One approach, 'rocking frame', is to make the lower portal frame strong enough to allow a crane leg to lift off the rails, or the crane to rock, without damage (see Figure 3). A second approach, 'ductile frame', allows the lower portal frame to deform plastically but not collapse (see Figure 4). A third approach, 'seismic mitigation system', involves adding seismic isolators or energy dissipaters to reduce the seismic forces (see Figures 5 and 6). These design approaches are discussed in detail below.

Rocking frame

In regions where the design storm wind speed is low, such as the West Coast of the United States, cranes are generally never tied down to the wharf. In the absence of tie-downs, the crane legs can lift off the rails, allowing the structure to undergo a rocking motion during an earthquake. While the rocking motion appears undesirable at first glance, it interrupts the dynamic motion of the crane and reduces the seismic forces on the crane. In other words, the rocking limits the seismic force that the crane experiences in an earthquake. In the rocking frame approach, a crane structure is designed to remain elastic, i.e., no yielding, for the lateral force that causes it to rock. For modern cranes, this lateral force typically ranges from 0.4 g to 0.6 g.

Since the structure is designed to remain elastic, operations can resume relatively quickly after an earthquake. The crane may need to be reset onto the rails; however, this can be done in a matter of days. This approach may not be suitable when the vertical load or lateral capacity of the wharf is limited.

Since the rocking frame approach relies on a strong portal frame, strong structural sections are required in the portal frame. Compared to a crane designed to the earlier 0.2 g seismic design loading, the additional cost is about US$180,000 per crane, primarily due to additional material in the portal frame.

Ductile frame

Unlike the rocking frame approach, which resists the seismic force by rigidity and strength, the ductile frame approach relies on the structure's ability to deform plastically and undergo large displacements without diminished capacity. With proper detailing, crane structures can tolerate large lateral movement.

Portions of the crane legs, designated as the 'ductile yielding zone', are designed to yield before other parts of the structure (see Figure 4). By doing so, all plastic bending occurs only in the yield zone. The yield zone plates are reinforced with closely spaced stiffeners so that the leg section can develop its plastic strength without significant local buckling. In typical crane construction, tee or angle stiffeners are used. For the ductile frame approach, u-shaped stiffeners can be used to efficiently increase the local buckling strength (see Figure 4, Section A-A).

Since the ductile frame approach relies on the crane's ability to deform plastically, there will be permanent deformation. The crane frame may need realignment; bent plates may need to be restored by heat straightening, or sections may need to be cut out and replaced. Repairs and downtime will be longer than for the rocking frame approach. The ductile frame approach may only be suitable when the wharf capacity is small, and limiting the lateral loading is important.

Compared to a crane designed to the earlier 0.2 g seismic design loading, the additional cost for the ductile frame approach is about US$120,000 per crane.

Seismic mitigation systems: isolation and energy dissipation

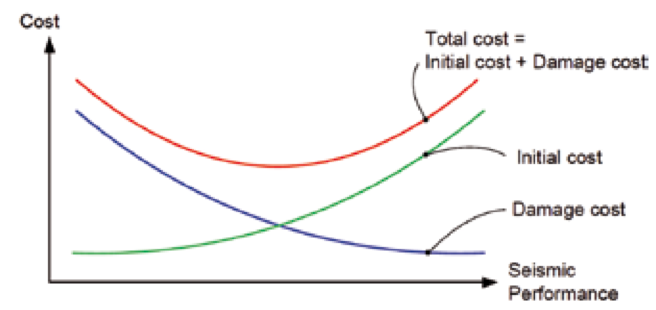

Figure 2: Initial cost and damage cost curves.

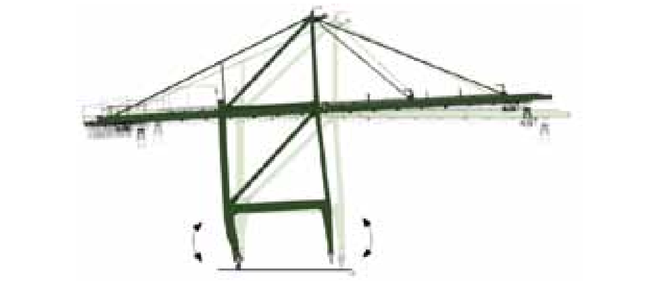

Figure 3: Rocking frame.

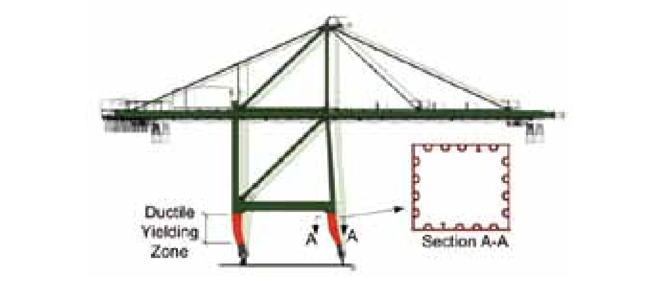

Figure 4: Ductile frame.

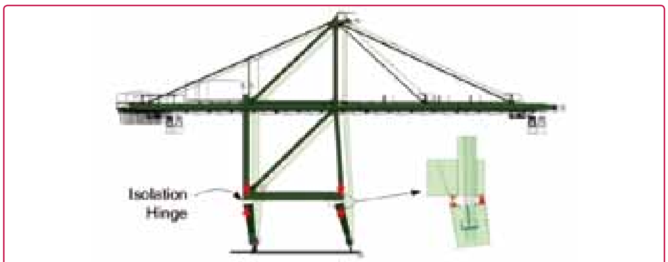

Figure 5: Isolation.

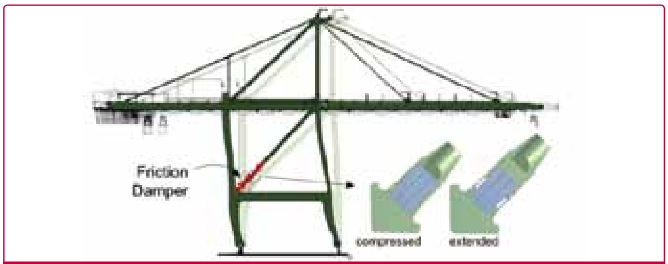

Figure 6: Friction damper.

One of the most effective ways to improve the seismic performance of a crane is to provide a seismic isolation system. The system isolates the crane so the wharf moves under the crane without developing large seismic forces. Figure 5 shows one method of isolation that uses post-tensioned steel strands as restoring springs at the leg-portal interface. The isolation joints are held closed by pre-tensioned tendons. The joints open during the earthquake when the pretension is overcome. The tendons stretch elastically with no residual deformation so they can pull the joint closed again. The cranes will remain on the rails, and there will be little to no damage, so the cranes are likely to be immediately operable after an earthquake.

An energy dissipation device can also be used to effectively reduce the internal forces in the crane. A device such as a friction damper, which was discussed in the summer 2012 article, can be installed in the lower diagonal (see Figure 6). Friction dampers convert the seismic energy into heat as the joints slide during an earthquake, limiting the internal forces in the crane. The friction dampers also isolate the crane's upper structure when the joints slide. Hydraulic cylinders may be used in place of the friction damper, but at greater cost.

A number of seismically isolated cranes have been developed and used in Japan. These cranes typically have isolation systems located at the gantry level. Some seismic isolation systems use elastomeric rubber bearings while others use ball bearings. These cranes have performed well in large earthquakes.

The cost of isolation varies considerably depending on the system used. Isolation is the most costly approach. The cost of incorporating a friction damper in the lower diagonal is minimal, estimated at US$100,000 per crane.

Summary and recommendation

Stakeholders should consider the seismic risk for their quay cranes. A number of design approaches are available to achieve acceptable seismic performance at relatively little cost. More protection will cost more initially but the damage and repair costs will be less later. The questions that stakeholders should consider when purchasing new cranes are how much does protection cost and what is it worth.

ABOUT THE AUTHORS

Michael Jordan is a Liftech structural engineer and CEO with over 50 years of experience. He is an internationally recognized expert in the container crane industry. He has been involved in the container industry evolution since participating in the structural design of the first container crane for Matson in 1958. Since then, he has designed the structures of hundreds of duty cycle cranes, prepared numerous specifications for the design of duty cycle cranes, and investigated fatigue damage problems and major failures caused by fatigue crack growth and brittle fracture.

Yoshi Oritatsu is a Liftech structural designer and registered professional engineer with five years of experience in the design, analysis, and modification of container cranes, large derrick cranes, bulk loaders, and wharf structures. His work includes the analysis of crane and wharf seismic response, including the effect of isolation and energy dissipation systems.

Erik Soderberg is a Liftech structural engineer and vice president with 18 years of experience in the design, review, and modification of a variety of structures including container cranes, wharves, buildings, heavy lift equipment, and various rigging structures. He has consulted on hundreds of cranes, participated in the design of several wharf structures, and has designed many crane transfer systems ranging from curved rails to shuttle systems. He has engineered repairs for dozens of container crane structures and for several bulk loaders. His field skills include an understanding of heat straightening techniques and the ability to develop repair procedures on site.

ABOUT THE COMPANY

Liftech Consultants Inc. is a consulting engineering firm, founded in 1964, with special expertise in the design of dockside container handling cranes and other complex structures. Our experience includes structural design for wharves and wharf structures, heavy lift structures, buildings, container yard structures, and container handling equipment. Our national and international clients include owners, engineers, operators, manufacturers, and riggers.

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Liftech Consultants Inc.
344 – 20th Street, #360, Oakland, CA 94612-3593, USA
Tel: +1 (510) 832 5606
Fax: + 1 (510) 832 2436
Email: liftech@liftech.net
Website: www.liftech.net