Container crane boom collapse: Cause and prevention

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Background

Recently, two crane boom failures occurred while the booms were being lowered; one in Asia (Figure 1) and one in Europe (Figure 2). These failures called attention to recent boom collapse problems; however, this is not a recent problem. Over the years, a number of booms have collapsed and even more came close to collapsing.

This article presents our understanding of these failures, a discussion of loading and reliability issues, and some recommendations.

Common failure causes

There are many causes of boom failure. Three of the more common are presented below.

Hoisting – rope failure

Rope failure can be caused by the rope fouling on the drum, running off the drum, or parting. Sometimes the boom latch doesn't fully release; the drum lets loose rope out causing excess rope pileup. Eventually, the operator realises there is a problem and he stops running the drum in the lowering direction and changes to the raise direction. The rope can then run off the end of the drum or loop and 'bird nests' on the drum. Slack rope limit devices have been added to cranes to help avoid loose rope conditions.

If the rope bird nests on the drum, when the boom is lowered, the looped rope will eventually become untrapped and drop the boom until the slack is absorbed. The resulting impact can cause rope failure, and damage to the boom or its support structure.

Rope connections typically fail due to improper clamping, sharp edges, and corrosion. Corrosion is a significant risk to speltered sockets as it is difficult to keep water out of the socket and corrosion is hard to detect as it develops from inside the socket.

Most early crane booms were supported by a single reeving system, i.e., a one-rope system. If the rope failed, the boom fell. The stays sometimes caught the falling boom, sometimes they did not.

Most modern booms are supported on redundant sets of ropes. If one rope fails, the other will support the boom. Since the 'safety' factor for the boom hoist ropes is about six, half the ropes can carry the full load, including a fifty per cent load increase due to impact, while maintaining a 'safety' factor of two. If the rope is in good condition and nothing else is deficient, this is acceptable. Of course, the boom and its support structure should be designed to absorb the overload and impact when one rope fails.

Hoisting – overtopping

If boom hoisting continues after the boom has contacted the boom latch, loads greater than the design loads can develop in the ropes and the boom and apex structures. This is referred to as 'overtopping.' Sensors can detect and prevent this. Overtopping is most probable soon after erection or delivery before sensors are fully installed or adjusted properly. Overtopping may also occur if the sensors malfunction.

Although overtopping failures were not common, they occurred often enough to justify improvements in the boom hoist system.

Fatigue failure of boom support components

The forestay is connected to the boom and the apex by gusset plates. Likewise, backstays and backstruts are connected to the apex and the trolley girder by gusset plates.

When the crane operates, the stays and struts experience fluctuating tensile stresses which initiate and propagate crack growth in the series of components just mentioned. The fluctuating stresses in the gusset plates and forestay links are magnified by bending of the plates about their weak axis due to the nearly continuous lateral vibrations of the stays and struts (Diagram 1). Bending is concentrated in the flexible plate elements such as the gusset plates of diagonals and the link plates of forestays resulting in premature cracking. Cracking has also occurred in backstrut systems where multiple pipes connect to a shared gusset plate with little distance between the pipe ends.

Figure 1. Crane boom failure. Asia – October 2007.

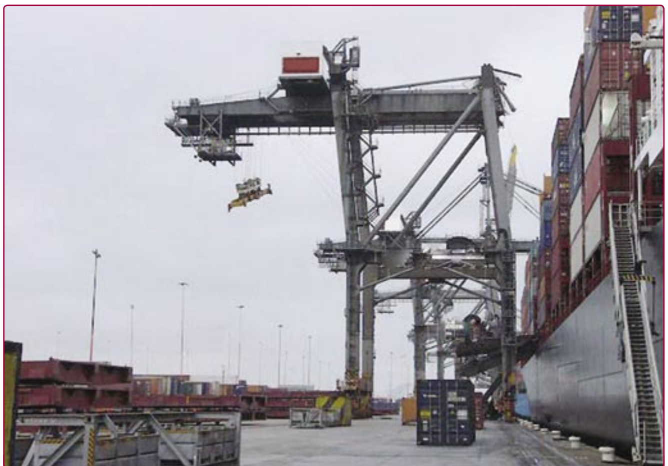

Figure 2. As in Figure 1, the failure occurred while the boom was being lowered. Europe – January 2008.

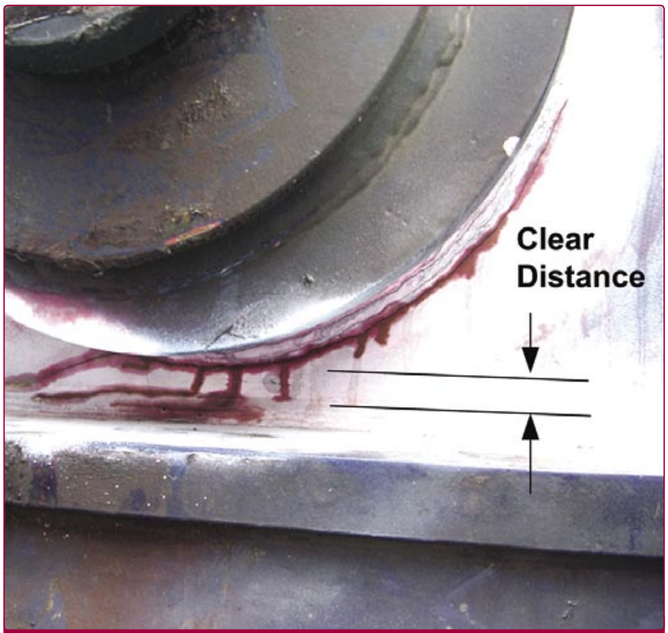

Figure 3. Fatigue crack at forestay-to-boom connection plate.

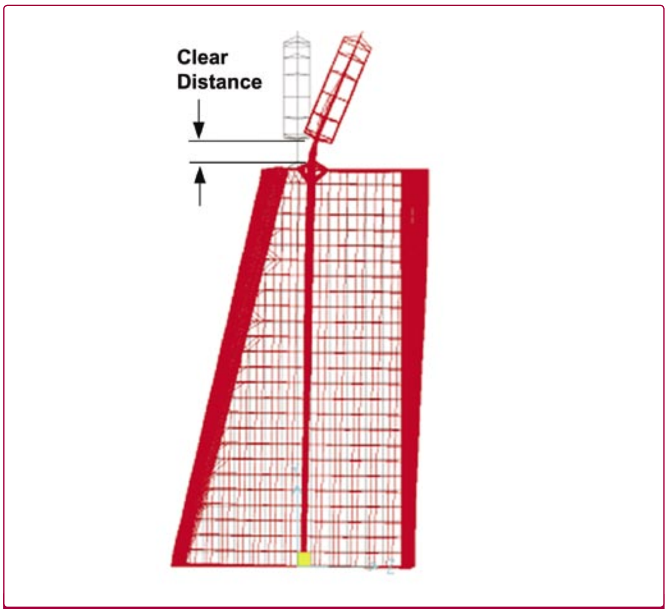

Diagram 1. Exaggerated weak axis bending of forestay-to-boom connection plate.

Although the tensile stresses can be calculated with reasonable accuracy, the weak axis bending stresses can only be estimated. The magnitude of the lateral forces depends on many variables which cannot be determined. Fortunately, the structure can be proportioned to reduce the effect of lateral vibrations. See 'Recommendations.'

Recent failures

No cause has been definitively identified in either of the failures shown in Figures 1 and 2. Some of the usual suspects have been identified though: rope failure, sudden drop due to rope bird nesting, gusset plate failure, or other connection failure. Since the failures occurred when the booms were supported by the hoist ropes, and the maximum stresses in the boom support structure occur during vessel operations, the most likely cause was boom hoist rope failure.

In the Asian boom failure, the hoist rope may have failed due to previous damage or overload. We will never know the cause.

In the European failure, the accident report issued immediately after the failure stated that as the boom was being lowered, a loud crack was heard just before the apex and boom fell. Videos of this failure indicate that the boom was almost fully lowered when the failure occurred. The cracking sound would indicate there may have been a brittle failure in a cracked plate or member. The video neither supports nor refutes this cause. Again we will never know the cause.

Figure 4. Relief hole at inner forestay-boom connection.

When a boom hoist rope fails, the remaining intact portion of rope running through the sheaves picks up speed as the falling boom picks up speed. The speed of the rope is amplified by the reeving. For example, if there are ten parts of rope and the failure occurs at the rope end, the fastest part runs through the sheaves at ten times the speed of the slowest part. If the boom falls far enough and the rope speed is great enough, as the rope end clears a sheave, it gets whipped into the nearby structure, resulting in the rope breaking into pieces. Evidence of the history of the event is lost.

Occasionally, evidence clearly indicates the cause of boom failure. In the case of near failure, evidence usually indicates what was going wrong.

Once the most likely causes of failure are known, maintenance inspections and testing or modifications can decrease the chance of catastrophic failure.

Discussion of fatigue related failures

The usual failure suspects are: hoist rope failure, overtopping, and failure due to fatigue crack growth. All of these suspects can be detected before serious failure occurs. A discussion of two of the more common fatigue failures is provided below.

Fatigue – inadequate clear distances

As discussed above, weak axis bending in gusset and link plates in the boom support system can result in significant stresses. Inadequate clear distances between welds have resulted in extensive cracking and failure at the forestay-to-boom connection plates. Refer to Figure 3 and Diagram 1. The weak axis bending stresses are linearly proportional to the plate thickness and inversely proportional to the plate clear distance squared. Doubling a plate thickness will double the weak axis stress; tripling the clear distance will reduce the stress by a factor of nine.

The distance between the weld toes should be enough to keep the weak axis fluctuating stresses below the fatigue threshold.

If this is done, the weak axis stresses are negligible and need not be considered with axial stresses. Detailed calculations are needed to determine the minimum distance. In most cases a distance of five times the plate thickness is adequate. If the clear distance is less than three thicknesses, calculations should be made to ensure the effect of lateral stay motions has been accounted for in the design. Of course, each situation is different; sometimes a clear distance of five thicknesses is more than adequate and sometimes it is not.

Fatigue – stress concentration at plate-in-a-slot connections

Large stress concentrations at plate connections may occur if the gusset plate is slotted into another plate. Serious fatigue cracking has occurred in these areas due to inadequate design, fabrication, or both. Special care is needed at locations where plates are contoured for smooth stress flow. If the contours are not smooth, the stress flow will not be smooth. Refer to Figure 5 for a crack caused by poor fabrication.

Recent cracking on two different crane designs resulted in dangerously long cracks in fracture critical members (Figure 5). Fortunately, failure did not occur because the materials are significantly tougher than specified and because inspections detected the cracking.

Figure 5. Fatigue crack at upper diagonal stress relief hole.

Recommendations

Structural maintenance

Container crane structural design criteria are based on a damage tolerant design philosophy. This criteria anticipates fatigue cracking during the life of the structure and requires structural maintenance to maintain the health of the structure. Maintenance includes the planned periodic inspection for, and repair of, fatigue cracks, corrosion, and other damage.

For the entire container crane structure, an owner should implement a structural maintenance program to maintain a desired reliability. Typical reliabilities are 99.99 per cent (1/10,000 chance of failure) for fracture critical members, and 99.90 per cent (1/1,000 chance of failure) for non-fracture critical members. The structural maintenance program should be based on fracture mechanics principles to focus the inspection where it is most worthwhile.

Boom hoisting

To reduce the more common boom hoisting risks:

1. Observe the boom entering the latch until commissioning and associated confirmation of proper limit switch operation is complete.
2. Provide sensors to detect boom hoist rope slack.
3. Locate the slack rope sensor reset at the hoist drum, so the rope condition on the drum is observed before further hoisting.
4. Do not use speltered socket connections. Speltered sockets may corrode from the inside in a marine environment and inspection is difficult.
5. Do not use rope connections with sharp edges that may damage the rope.
6. Use two independent hoist rope systems. Design the crane structure so the failure of one rope does not damage the boom.
7. Verify that notches and significant stress concentrations are not created during fabrication.
8. After a slack rope condition, inspect the rope on the drum and confirm it has not 'bird nested.'
9. Inspect limit switches and other sensors to ensure proper operation.
10. Inspect rope connections, particularly after significant loading events.
11. Do not allow cutting torches or welding near ropes without rope protection and post work rope inspection.

Fatigue – plate clear distances

Consider weak axis bending in plates due to wind and other lateral loads. The effect of tension on the bending stresses must be considered. Some guideline minimum clear distances are provided in Diagram 2 that are acceptable for most connections. Of course each situation is different; sometimes a clear distance of five thicknesses is more than adequate and sometimes it is not.

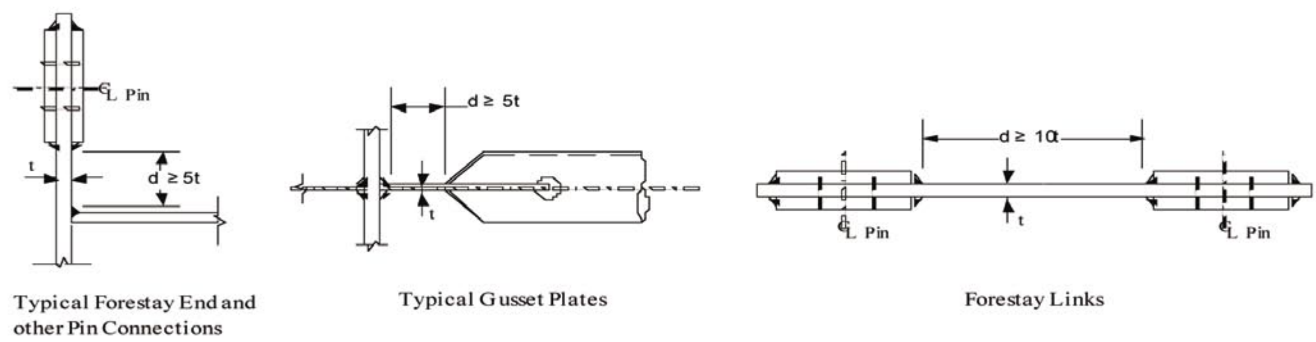

Diagram 2. Recommended minimum clear distances – Liftech Crane Specifications, 2008.

For an existing crane with plates that have clear distances less than three times the plate thickness, increase the inspection frequency as needed to maintain the required reliability, modify the structure to increase clear distances, or both.

Fatigue – plate-in-a-slot connections

The plate-in-a-slot connection detail must be carefully designed and fabricated since this connection detail has many localized discontinuities that affect its fatigue performance. Some considerations include the following:

1. Relief hole geometry and surface texture.
2. Cover plate geometry, surface texture, and weld geometry, quality, and inspection.
3. Consider the fracture critical crack length when designing the cover plate. While it is desirable to keep the cover plate weld away from the high stresses at the relief hole, it is also undesirable to cover a crack emanating from the relief hole.

If necessary, provide a relief hole cover plate with a removable plug to permit inspection using a Boroscope.

For an existing crane, an owner should increase the inspection frequency as needed to maintain the required reliability, modify the connection relief hole and cover plate, or both.

ABOUT THE AUTHOR

Erik Soderberg is a Structural Engineer and Principal of Liftech Consultants Inc. He has over 14 years of experience in all phases of container crane design, wharf design, and crane transfer system design. He has consulted on over 100 cranes, participated in the design of four wharf structures, and has designed many crane transfer systems ranging from curved rails to shuttle systems.

Mr. Soderberg is also involved in damage review and repair of steel structures. He has engineered repairs for more than two dozen container crane structures and for several bulk loaders.

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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