STS Crane Stowage Design: Key Considerations and Case Study

Anna Dix, SE[1]; Erik Soderberg, SE[2]; Tais Shiratsubaki, PE [3]

[1] Liftech Consultants Inc., 344 – 20th Street, Suite 360, Oakland, CA 94612;
Tel: 510-832-5606; email: ADix@Liftech.net

[2] Liftech Consultants Inc.; email: ESoderberg@Liftech.net

[3] Liftech Consultants Inc.; email: TShiratsubaki@Liftech.net

ABSTRACT

There has been devastating ship-to-shore crane damage, including collapse, due to failure of the stowage systems during hurricanes. The design of these systems is complex, requiring an understanding of how the wharf stowage hardware interfaces with the crane hardware, both to facilitate connecting and disconnecting the hardware, and to account for subtle but significant loading conditions that occur. This paper aims to provide a broad knowledge base for designers of such systems, as well as present a recent project case study to illustrate some design and construction challenges. Topics covered include an overview of the stowage pin and tie-down hardware components on the wharf and crane, the technical and operational design considerations, recent innovations to solve design problems, and creative solutions for the substantial effects of offsets due to construction, of operational gaps, and of crane deformations during the design hurricane. The paper also includes a case study of a recent project at Port Everglades, Florida.

INTRODUCTION

Every year, strong winds test the designs of many ship-to-shore crane stowage systems. On occasion, there is a failure because of construction errors or subtle design issues being overlooked, causing the devastating collapse of one or more cranes. As storms grow stronger and more frequent, stowage systems are tested closer to their design limits.

The design of these systems may seem simple, but there are many important considerations for wharf and crane designers to understand. The crane-wharf interface is complex, and small oversights can have major consequences.

CRANE STOWAGE SYSTEM OVERVIEW

A stowage system consists of crane and wharf hardware that resist storm wind-related loads on a crane, including lateral loads parallel and perpendicular to the gantry rail, and if wind loads are large enough, overturning moments. This paper addresses the crane-wharf interface stowage system hardware.

Lateral loads parallel to the gantry rail are resisted by the stowage pin system. Shear loads perpendicular to the rail are resisted by the crane wheel flanges against the rail. Overturning moments are resisted by the crane weight, including any ballast, and, if needed, a tie-down system. Figure 1 shows a free body diagram of the stowage system.

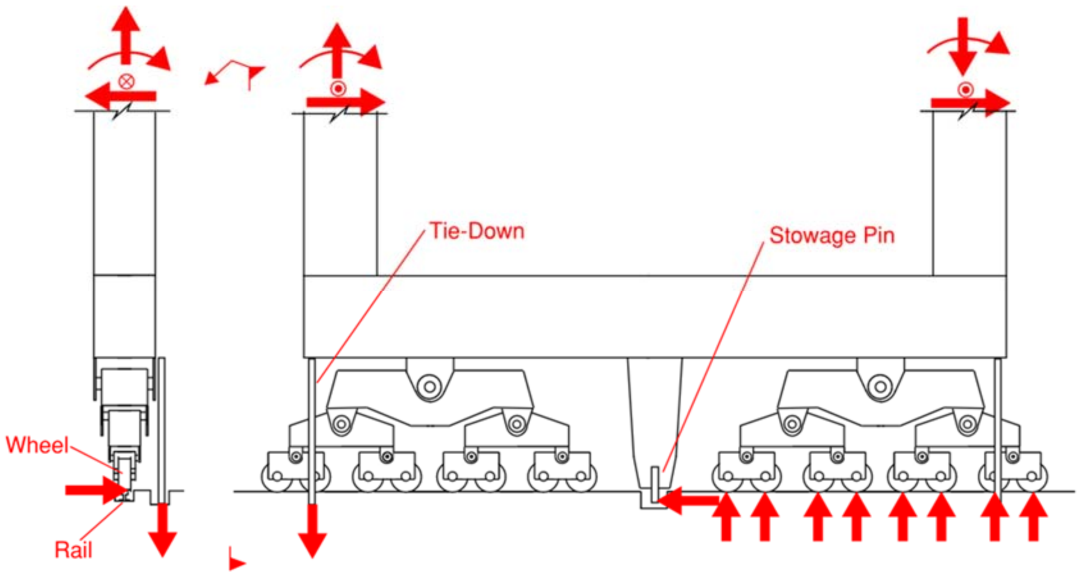


Figure 1. Free body diagram of crane-wharf stowage system.

Stowage Pin System

The stowage pin system consists of a steel pin on the crane that raises and lowers into a steel socket in the wharf. At least one stowage pin is required at each crane rail. Stowage pins may be provided on either or both sides of each crane rail and are typically located at the centerline of the crane where space is available between the wheels to prevent prying of the gantry equalizer system. Figure 2 shows photographs of a common stowage pin system.

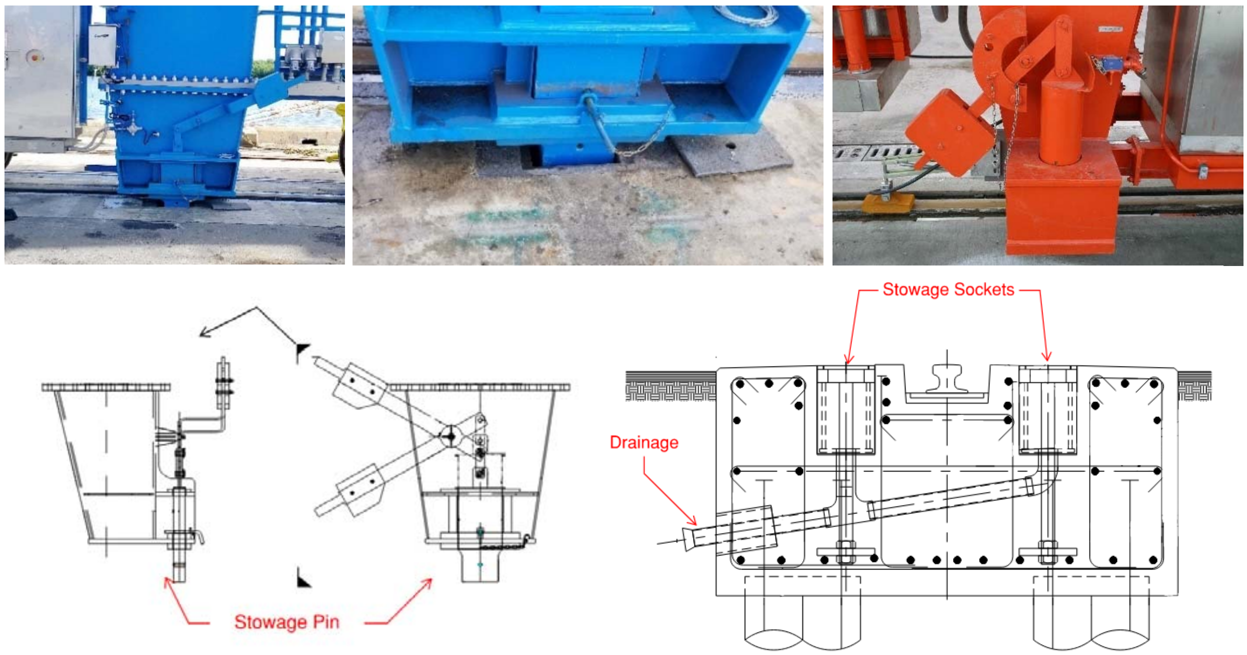


Figure 2. Typical stowage pin systems.

The pin transfers the lateral load in the direction parallel to the gantry rail in either direction by bearing against the edge of the socket opening. Crane brakes will be engaged and may also provide resistance; however, the stowage pin system is designed to resist the entire load.

Rail System

The socket opening is large enough in the direction perpendicular to the rail to accommodate the varying crane position on the rail since the wheel tread is wider than the rail head, typically about 1 ± 1/4 inch (25.4 ± 6 mm). Consequently, lateral loads in the perpendicular direction are resisted by the crane wheel flanges on the side of the rail and not by the stowage pin.

Design of the rail system ignores the friction between the wheel and rail, as the force can vary significantly depending on surface conditions and the varying vertical force at each crane corner. Figure 3 shows the crane wheel flange and rail.

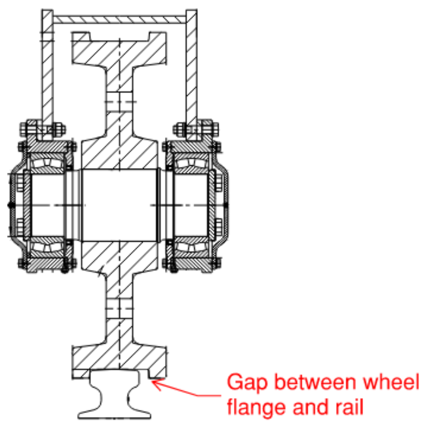


Figure 3. Wheel flange and rail.

Tie-down System

The tie-down system typically consists of an anchorage in the wharf, a wharf bracket, a link plate that rotates up out of the wharf to be pinned to the crane hardware, a removable pin, a turnbuckle, links, and an attachment to the crane. Some systems include load equalizing beams or plastically elongating links to help equalize loads between multiple tie-downs at a crane corner. The system resists vertical loads only and accommodates small relative crane movements in the longitudinal and transverse directions. Figure 4 shows some typical tie-down systems.

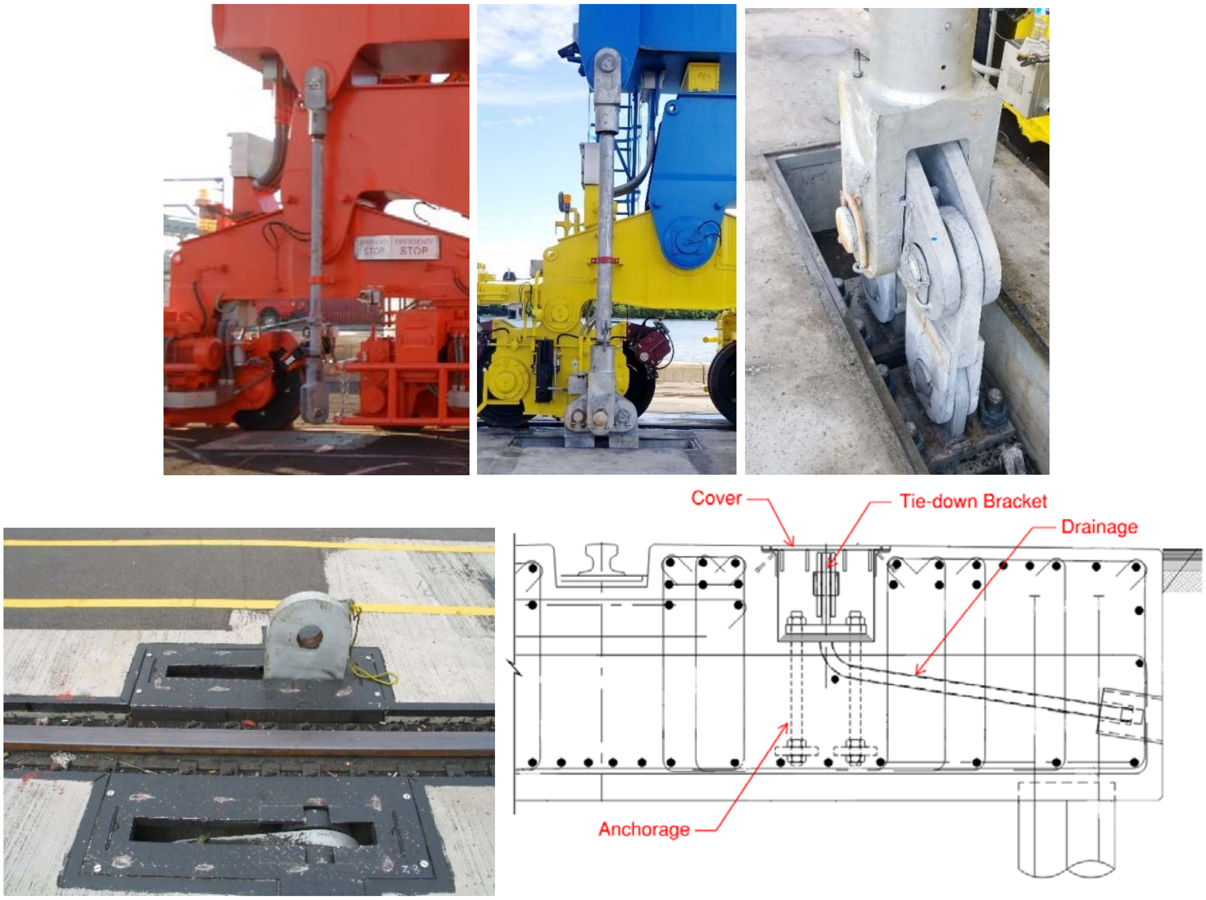


Figure 4. Tie-down system examples.

DESIGN CONSIDERATIONS FOR STOWAGE PIN SYSTEMS

Wharf and crane designers should consider three key requirements during planning and design of the stowage pin system:

Load Path Requirements

Operational Requirements

Construction Tolerances

Load Path Requirements

The basic load path of the stowage pin system is presented in Figure 5.

The lateral force on the crane structure transfers at two bearing points into the crane stowage pin. The crane pin bears laterally on the wharf socket. The pin must be sized to cantilever from the end of the crane stowage bracket to the wharf socket bearing point. The design should consider the socket and crane construction tolerances and any crane corner uplift, as these can result in a significantly larger cantilever distance and bending in the pin.

The lateral load on the socket is resisted by a large bearing force on the concrete. There is an overturning force on the socket resulting from the eccentricity between the center of pin bearing and the center of concrete bearing. This typically requires vertical anchorage of the socket into the wharf.

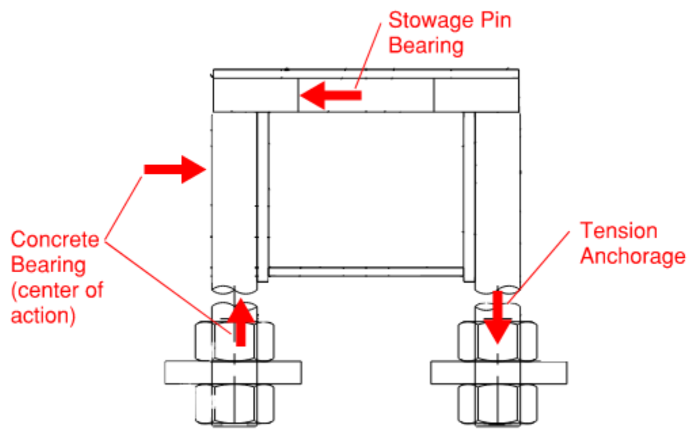


Figure 5. Stowage socket load path.

Operational Requirements

The primary operational requirement is that the crane's stowage pin be easily installed into the socket.

Transverse Fit: As mentioned above, there is a gap between the wheel flanges and rail, allowing the crane to shift on the rail landside-to-waterside. The typical gap is 0.75 in (19 mm) to 1-1/4 in (32 mm) total. Consequently, the socket opening must accommodate this amount of movement, plus construction tolerances for the pin location on the crane and socket location in the wharf.

Longitudinal Fit: The socket opening should be wide enough in the gantry travel direction to facilitate pin installation. Usually, an opening 2 in to 3 in (50 mm to 75 mm) wider than the pin is acceptable.

Vertical Fit: The crane pin must remain engaged with the wharf socket when the crane is stowed. If a crane is stowed without tie-downs and a corner may lift in the design storm condition, the pin needs to be long enough for the end to remain in the socket. As mentioned, the additional cantilever distance should be considered for the pin sizing. The crane frame should be checked for warping due to one corner lifting. Even if the pin is long enough to stay engaged, it may work its way up out of the socket during the storm as the crane moves up and down, so a secondary locking pin is provided. Depending on the wharf stowage socket design, stowage pin embedment depth may be a significant design parameter such as to prevent excessive concrete bearing pressures and spalling.

The second operational requirement is that the socket be easy to maintain. It is important to provide adequate drainage to prevent clogging and buildup of debris, e.g., dirt, sand. Drains that are 2 in (50 mm) in diameter have performed poorly. Drains that are 4 in (100 mm) in diameter have performed well.

The third operational requirement is that the socket covers should be stiff and strong enough for large tire pressures and practical for the workers to handle. Socket holes are typically small enough that easy-to-handle covers are practical.

Construction Tolerances

Construction tolerances for locating sockets should be clearly specified on the drawings. Typical American Concrete Institute (ACI) hardware tolerances were not developed for this application and are too large and unacceptable for the precision required (ACI 2019). ACI offers no tolerance guidelines for hardware location relative to other hardware, only absolute position. The recommended stowage socket location tolerances, based on the effect on design and construction, are typically 1/4 in (6 mm) in plan and elevation.

Inevitably, some sockets will be cast significantly out-of-tolerance. Socket design should allow for practical after-casting adjustments to the socket opening. Adjustments typically involve trimming the socket hole edge to make the hole larger or installing shim plates to reduce the opening.

DESIGN CONSIDERATIONS FOR TIE-DOWN SYSTEMS

Like stowage pin systems, there are three important design considerations for tie-down systems:

Tie-down Configurations

Load Requirements

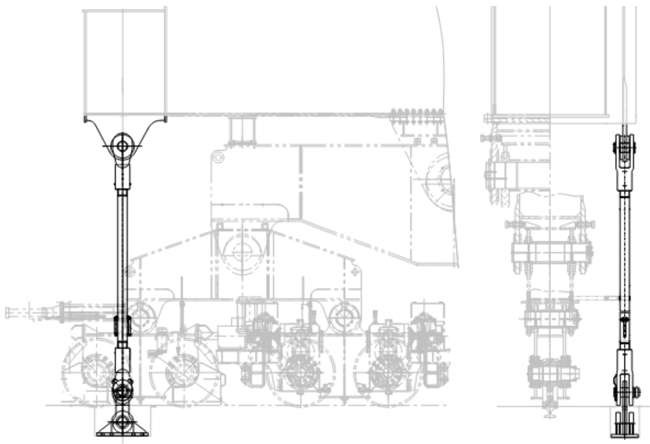
Operational Requirements

Tie-down Configurations

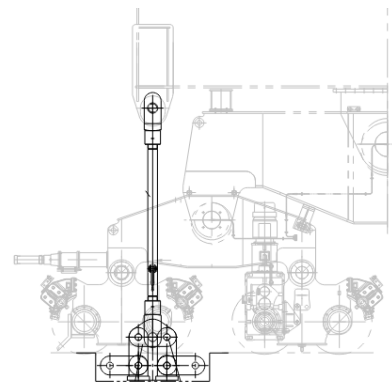
It is structurally favorable to provide one tie-down per crane corner. With multiple tie-downs at a corner, the load distribution may be uneven due to the crane deformation. However, big cranes in areas with large design winds will have large design tie-down loads. Tie-down components can be heavy and difficult for workers to handle. The owner and designers of the crane and wharf hardware need to consider the ease of use when deciding on the tie-down configuration. In some cases, it may be reasonable to use multiple tie-downs at a crane corner or to use counterweights (or another method) to assist in handling. If two tie-downs are used at a corner, it is favorable to have them on the same side of the rail to avoid uneven loading resulting from crane deflection.

The wharf hardware can be designed with a single ear plate recessed into the wharf that connects with the tie-downs, which are raised and lowered into the pit. More typically, wharf hardware is designed with link plates that swing up out of the wharf to mate with the crane tie-downs. If there is a link plate in the wharf, the path of the swing needs to be checked to ensure clearance into the crane tie-down.

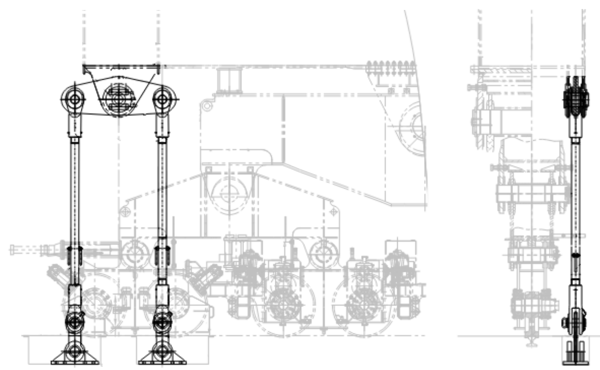
Figure 6 shows some options for tie-down configurations.



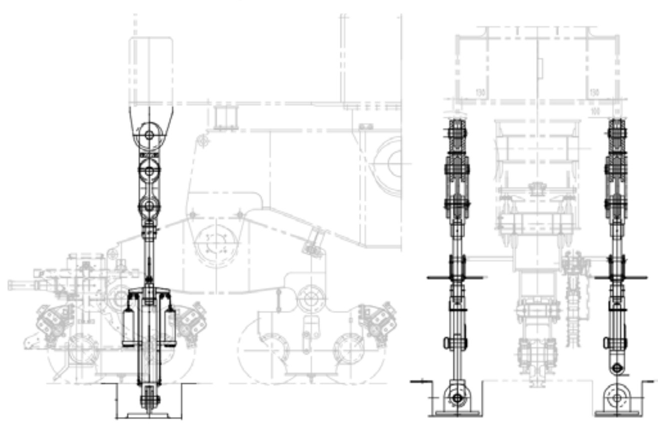
One tie-down per corner, one wharf link



One tie-down per corner, two wharf links



Two tie-downs per corner, two wharf links



Two tie-downs per corner, two wharf ear plates

Figure 6. Tie-down configurations.

Load Requirements

The load requirements to be considered include the load magnitude, load distribution, misalignments resulting in lateral loads and local bending in system components, and pile load. Some of these considerations are affected by the tie-down configuration.

Load Magnitude: A ship-to-shore container crane structure is typically designed to ASCE 7 wind, using risk category II (ASCE 2016). However, we recommend designing the tie-down system to risk category III. This provides a large increase in reliability for little additional cost. We recommend applying this philosophy locally, e.g., to the crane tie-downs and wharf hardware and anchorage, but not to the crane as a whole or the wharf piles or girders.

Load Distribution, Two Tie-downs per Corner: If two tie-downs are required at one corner, the crane tie-down design should include an equalizing system or some other system to accommodate crane deformations, and the wharf hardware should be designed for some inequality in loads. Regardless of the method, perfect load equalization is not practical. We recommend using at least 60% of the corner design uplift load for each of the two wharf connections with equalization. It would likely be much larger if there is no equalization, so we recommend equalization.

If the two tie-downs are on either side of the rail/crane gantry wheels, the tie-down system also needs to allow for the crane sill beam to rotate without overloading the tie-down on one side. It is usually not practical to use an equalizer beam to equalize the tie-down loads with this geometry, so we invented a fuse link in the tie-down that stretches when it reaches the yield limit and allows for some rotation in the sill beam without further increasing the load in the wharf hardware, until the other tie-down fully engages. With this idea, there are redundant “safety” links in the crane tie-down system in case the fuse link stretches to its breaking limit. The fuse link is replaceable if the storm wind is high enough to cause permanent elongation.

If two tie-downs are on the same side of the rail, an equalizer beam at the top or bottom of the tie-down may be a practical way to equalize the loads. From a user standpoint, this system has challenges. If the equalizer is at the top, there are two turnbuckles that need to be tightened together. If the equalizer is at the bottom, the system may be more difficult to align because of the heavy turnbuckle and links.

Misalignments: It is critical to consider misalignments, e.g., lateral loads from even slightly out-of-plumb loading in the design of the wharf and crane ear plates. Most of the tie-down load is vertical, but since the crane may shift around on the rail or in the stowage pin socket, and the crane can deform, the tie-down is not perfectly plumb. We recommend calculating or estimating the maximum angle that the tie-down will experience and using that lateral load in the design. It is usually about 2% to 3% of the vertical load in each orthogonal direction, but it may be more or less, depending on the length of the tie-down and geometry of the stowage system. We also suggest detailing the wharf and crane ear plates with a chamfer in the lowest and highest pin holes and small gaps between the plates to allow slight rotation perpendicular to the pin without binding or adding eccentricity in the tie-down links. Figure 7 shows the chamfer concept. If the ear plate has two plates, the single link plate would be chamfered instead. Centering nubs are also recommended to limit misalignment of components and local bending.

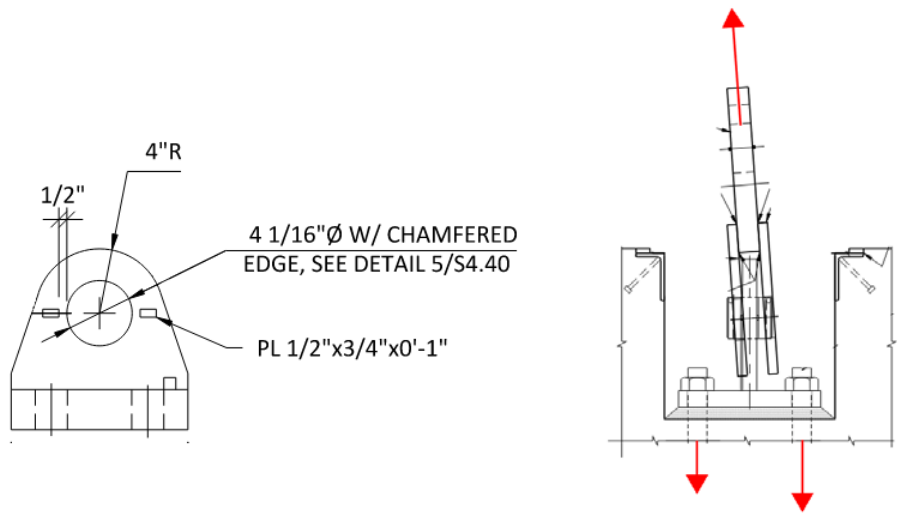


Figure 7. Ear plate chamfer concept.

Pile Load: Hurricane wind loads on cranes can be so severe, and the tie-down loads so large, that girders are pulled upward, imposing large tension forces on the girder piling and large bending moments in the girder. This potential for large tension loads in the piling should be considered in pile design, and for the load path from the tie-down hardware to the beam and pile, as applicable.

Operational Requirements

Alignment: Wharf tie-down hardware needs to be aligned with respect to the stowage pin, crane rail, and crane tie-down hardware. However, tie-downs are operationally more forgiving than the stowage pin with the alignment and fit-up between the crane and the wharf, since they are long and pinned at both ends.

Handling/Installation: Tie-down installation can be challenging, especially considering the number of cranes, number of tie-downs being installed per crane, number of trained workers, and considering time to install prior to a forecasted windstorm. Tie-down installation, for all tie-downs on one crane, should (generally) take less than 30 minutes for one or two workers to engage or disengage, but it may take longer for cranes with big tie-downs and multiple tie-downs per corner. This is a challenge when the wharf bracket is only an ear plate since the turnbuckle is typically adjusted once and then snugged with minimal turns. There are a few solutions to this. One option is similar to the counterweighted handle used on a typical stowage pin, where the tie-down can be raised and lowered into the wharf socket to install the pin, then snugged the rest of the way with the turnbuckle. A second option uses at counterweight with pulleys, similar to an old window sash. A third option, which is in development, is an electric tie-down that will lower into place and engage with the touch of a button, with one person. It disengages in a similar manner. Figure 8 shows the first two concepts.

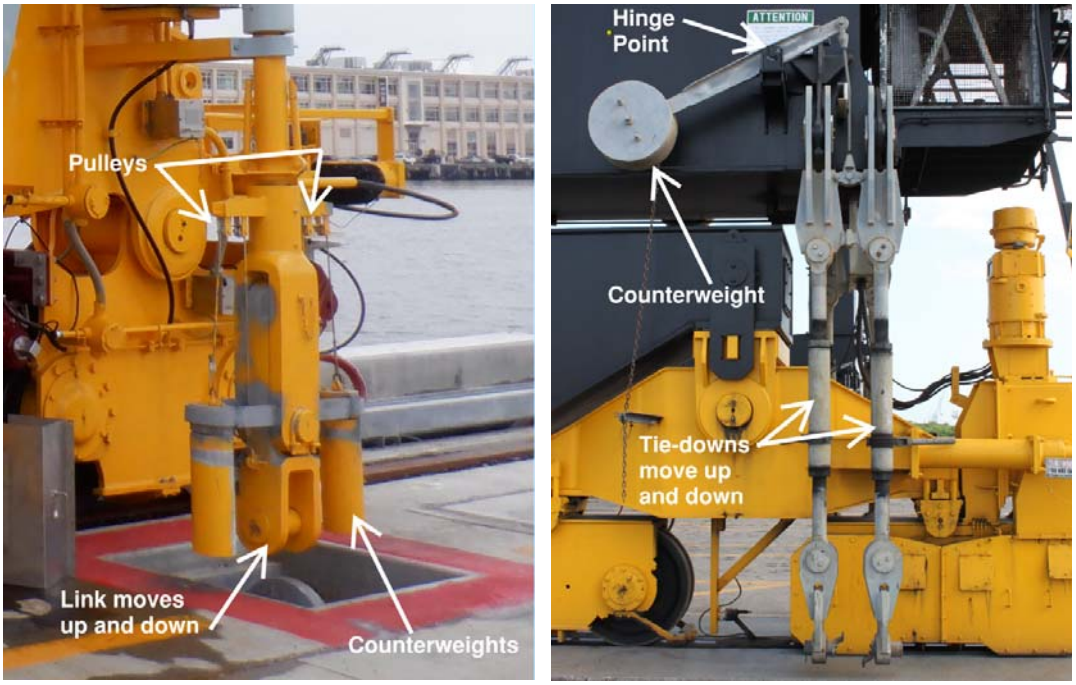


Figure 8. Quick tie-down options.

Drainage and Cover Handling: The same considerations for drainage and handling pit covers that were mentioned above in the stowage pin system section apply to the tie-down system. This is especially important for the covers since they are much larger than the covers for sockets. Determining the owner's preferred method of removal can help with the details. Tie-down covers are usually significantly heavier than stowage pin socket covers and may require handling with a forklift.

COORDINATION IN DESIGN AND FABRICATION

Coordination among parties during design, construction, and fabrication is critical to the success of the constructed stowage system.

Crane-Wharf Stowage System Fit: The wharf designer, crane designer, and crane manufacturer should coordinate the design with each other.

Stowage System Handling: The crane and wharf designers should coordinate with the owner and crane users, as mentioned in the sections above, to meet their handling performance requirements. Important considerations are how heavy the tie-downs, wharf links, and covers can be, and how the covers will be removed. One component of success is a happy end user.

Tolerances: Wharf designers should coordinate with wharf contractors to confirm the specified tolerances are practical. If not, there should be a larger allowance in the design loads to account for the added misalignment or movement of the stowage system components.

Wharf Designer and Crane Designer/Expert Coordination: Consulting with or obtaining a peer review by a ship-to-shore crane design expert can be worthwhile for a wharf designer, particularly if a crane designer/manufacturer has not been selected. For example, it is important that crane and wharf designers understand and effectively communicate the interface design loads. They need to understand if the loads are provided as service or factored loads, as combined or uncombined, for which load combinations, and for which wind category. Misunderstandings about the loads can have catastrophic consequences.

PED CASE STUDY: FABRICATION ISSUES AND SOLUTIONS

Port Everglades (PED) is in the midst of a long-term capital investment program, which includes adding six new large low profile cranes and the infrastructure to support them. Liftech designed the wharf rail girders and Moss Kiewit Joint Venture built them. Shanghai Zhenhua Heavy Industries Co., Ltd. (ZPMC) designed and manufactured the cranes and Liftech performed the design review. When the cranes were ordered, they were to be the largest low profile cranes in the world, significantly larger than the others. This project presented special design, fabrication, and construction challenges. The lessons learned are presented below.

High Strength Material Selection and Fabrication

The tie-down loads were so large that high strength materials were selected in design to keep the components manageable for handling. The high strength components included the wharf hardware, crane tie-down turnbuckles, and associated pins.

For the turnbuckles, the crane designer selected 120 ksi (830 MPa) yield strength material. This material is susceptible to hydrogen embrittlement during the galvanization process; therefore, the turnbuckles needed to undergo a special process to dissipate hydrogen during galvanizing.

For the wharf hardware, 100 ksi (690 MPa) yield strength material was specified. However, the initial galvanizer did not follow practices suitable for high strength material, e.g., slow and controlled cooling, and multiple components cracked. Figure 9 shows a crack in the 4-inch removable high-strength pin that occurred after it was galvanized.

Figure 9. Cracked high-strength pin.

The lesson learned is to use a more forgiving material to fabricate and galvanize, such as ASTM A709-HPS 70W if practical, and to ensure and specify that the fabricator and galvanizer be experienced with the specified material.

Design Loads for Wharf

Wharf design loads for the stowage hardware included a significant contingency to account for flexibility in the crane design. Changes later in the project could have been very costly, with a schedule impact, and the increase in cost to design for the contingency was a miniscule portion of the overall wharf construction project. The lesson reinforced is that a significant cushion in the stowage hardware design loads is worthwhile, particularly for a new or atypical crane design. Crane stowage systems are not a good place to save money.

Crane-Wharf Fit-up and Misalignment

During the wharf design phase, the contractor was consulted about the tolerances to confirm that they were achievable. This coordination ahead of time allowed the contractor to provide feedback to the design team so allowances or adjustability could be added to the design. This reduced the contractor's requests for deviation and reduced the cost of correcting for misalignments. However, despite understood installation tolerances and the contractor being careful during construction, a few wharf stowage pin sockets were installed out-of-tolerance. The stowage socket design consisted of an upper bearing plate with a hole, and a box below for the pin to fit into. The box below was larger than the hole, allowing the bearing plate to be modified to accommodate the misalignments. These modifications were inexpensive. The lesson reinforced is that it is important to coordinate with the contractor on achievable tolerances and for the design to accommodate misalignments.

CONCLUSION

Wharf and crane designers should understand the intricacies of stowage systems to avoid major failures and to improve project outcomes. Design considerations include following the complete load paths through the interface, anticipating crane movements and their effects on the loading condition, determining appropriate construction tolerances, designing for ease of maintenance, and incorporating end user preferences and requirements. Coordination among the crane and wharf designers, the manufacturers/contractors, and the owner can help to avoid costly changes to the structures. Ensuring communication among the crane and wharf design team and the port owner/client and wharf contractor is important to a successful and well-performing crane stowage design.

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