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Wind Damage to Dockside Cranes: Recent Failures and Recommendations

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INTRODUCTION

General

Wind-related damage is a threat to most dockside container cranes. Typically, damage is localized and easily repaired, but occasionally cranes collapse. Recent crane collapses have been caused by hurricane winds, usually when tie-downs fail, and by lesser winds under operating conditions.

Recent hurricane seasons have struck the US East and Gulf Coasts with historic fury. Studies indicate that the size and duration of tropical cyclones (hurricanes and typhoons) are increasing and may be correlated, at least in part, to increasing ocean surface temperatures (Emanuel 2005 and 2006, Hoyos 2006). This appears to be a global phenomenon and many scientists predict the trend is not likely to abate any time soon. Today's structural crane designs for hurricane winds are based on 50-year return interval wind speeds according to the ASCE 7 standard (*Minimum Design Loads for Buildings and Other Structures).* These design wind speeds are statistical, based on historic wind speed data. Does this historic data reflect current trends?

Dockside container crane structures, unlike buildings, have very little redundancy for resisting wind loads. In hurricane regions, the cranes are held by one or more tie-downs at each crane corner. Research indicates that tie-down uplift forces at one corner are not evenly distributed between multiple tie-downs. Slight increases in wind speed have amplified effects on corner tie-down uplift forces (McCarthy, Vazifdar 2004). If a single tie-down fails, the crane will likely collapse.

This paper presents recent trends in hurricane wind loads, a novel design "ductile link" tie-down system, and an acceptable risk method for guiding the selection of an appropriate level of retrofit for an existing crane structure.

This paper also discusses winds during crane operations, and provides recommendations for braking and stowage systems.

Traditional tie-down systems

Ideally, only one tie-down should be used per corner, but cranes in hurricane regions typically require more than one. See Figure 1. Recent research indicates that the tie-down uplift force at a corner is not evenly distributed between multiple tie-downs, especially if they are on both sides of the sill beam. Indeed, for a corner with two tie-downs, a single tie-down could be loaded with 100% of the total corner uplift force, depending on the tie-down geometry and preload, and crane deformations. Existing and new tie-down systems may not be properly designed for uneven load distribution, and may fail prior to achieving the intended uplift capacity.

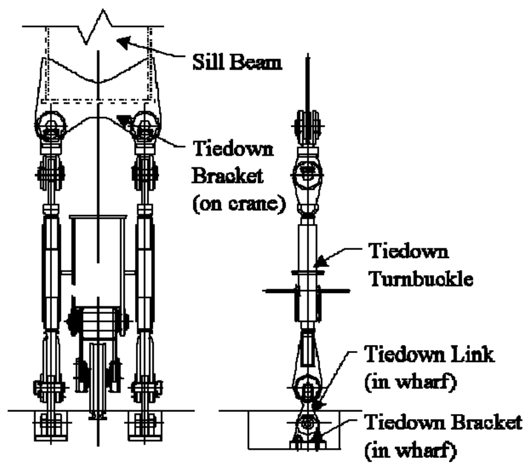

Figure 1. Traditional dockside crane tie-down system

Recent Performance

Tie-down failures result in serious consequences—cranes collapse. If, after a tie-down failure, the crane stowage pins disengage, the crane may get blown down the gantry rails and destroy adjacent cranes. Such domino-effect failures occurred in 2003 during Typhoon Maemi after a single tie-down failure resulted in the subsequent collapse of five adjacent cranes. See Figure 2. Conversely, cranes in the United States have fared relatively well, with only minor damage to some cranes in Florida during Hurricane Wilma and in New Orleans during Hurricane Katrina.

HURRICANES AND GLOBAL WARMING

There is some disagreement between scientists regarding the cause of global warming. You could say this has become an increasingly hot subject. Whatever the cause though, there is overwhelming agreement that sea surface temperatures are rising, adding energy to tropical storms.

Recent studies by Dr. Kerry Emanuel at MIT indicate that, although there is no apparent change in hurricane formation frequency or significant change in maximum cyclone wind speed, the intensity and duration of tropical cyclones have increased dramatically. Dr. Emanuel introduced an index of potential hurricanes destructiveness based on the total energy dissipated over the life of a hurricane. This “power dissipation index” (PDI), is “highly correlated with tropical sea surface temperature” (Emanuel 2006). Dr. Emanuel finds that over the past 30 years, hurricane PDI has more than doubled in the North Atlantic and North Pacific oceans, with the annual duration of storms increasing by approximately 60%.

Other studies by Carlos Hoyos et al., at the Georgia Institute of Technology show that the “increasing numbers of Category 4 and 5 hurricanes for the period

1970–2004 is [also] directly linked to the trend in sea-surface temperature" (Hoyos 2006).

The crane design 50-year MRI wind speed represents a two percent probability of a crane at a given location experiencing a storm with that gust wind speed or greater in any given year. If that probability increases due to increased storm duration or size, we would expect the ASCE–7 wind standard's 50-yr MRI wind speeds for hurricane regions to increase. This has not happened yet. Currently, we do not have a rational recommendation for increasing the design wind speed above what is recommended by the ASCE–7 standard. Crane owners may, however, find it prudent to consult wind experts or arbitrarily increase the storm wind speed by 10% for the tie-down system design. Statistically, there is a 64% chance that a structure will see a 50-year MRI wind speed in 50 years, a 45% chance in 30 years, and an 18% chance in 10 years, based on historic records. Safety factors currently used in the design of crane tie-downs essentially increase the effective MRI to approximately 475 years. Of course, this assumes that the shape factors used to calculate the total wind force on the crane and the structural analysis are accurate, and that the material properties and fabrication are as designed. A 475 year MRI equates to a 10% chance of exceedance in 50 years. The crane owner should decide what level of risk is acceptable.

Figure 2. Dockside crane collapses in Korea caused by Typhoon Maemi, 2003

TIE-DOWN DESIGN

Why do cranes collapse? We have not heard of a single hurricane-related crane collapse worldwide in which the crane structure failed first; the tie-down system has always been the weak link. Poor workmanship and faulty design are two primary causes. In many cases, investigated failures would have likely occurred at wind speeds well below design wind speeds.

Most wharf hardware is designed with the assumptions that the tie-downs are perfectly vertical and that the uplift forces are equally distributed among multiple tie-downs at a crane corner. Some designers assume an uneven distribution, such as

60/40 between tie-downs on either side of the gantry rail. These assumptions, however, are often unconservative since cranes rotate, shift, and deflect during hurricanes.

During a hurricane, the crane is held in the gantry travel direction by stowage pins. The wharf stowage pin sockets, which are offset from, but near the rail, are larger than the stowage pins extending down from the crane, allowing the crane to have limited movement in the crane travel direction. The crane wheels may also shift perpendicular to the rails since there are gaps between the outer edges of the rail and the inner edges of the wheel flanges. Figure 3 shows the deflected crane at a corner with two tie-downs. To further complicate the problem, wharf designers and crane designers seldom use a consistent design methodology.

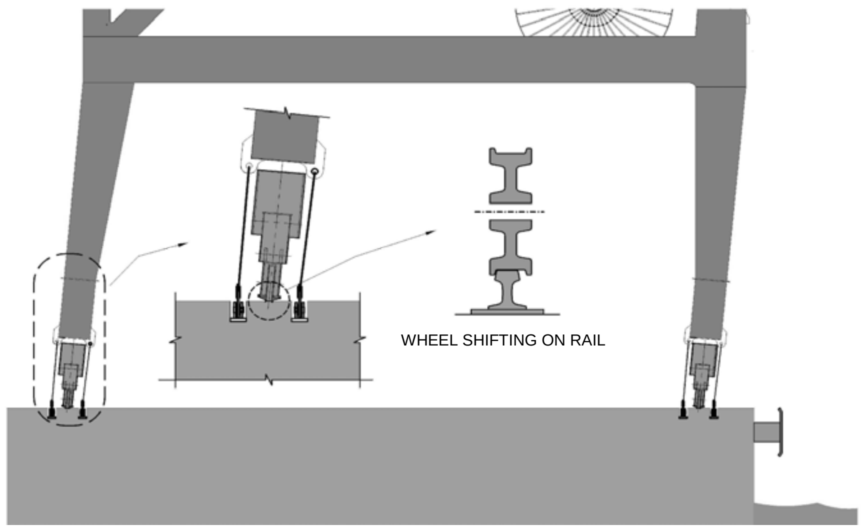

Figure 3. Crane deflection and movement during a hurricane

It is impossible to tighten the multiple turnbuckles such that the tensions are equal. A difference of a few millimeters (caused by loose installation, for instance) may significantly change the distribution of load between the tie-downs.

As mentioned, our analyses indicate that one tie-down may take up to 100% of the uplift load due to the above factors.

Consider the following scenario. Two tie-downs are at one corner, and the wharf is designed with the assumption that each tie-down carries half, or even 60%, of the load at that corner. During the hurricane, the initial tie-down tensions are unequal, and the crane displaces and deflects, causing one tie-down to carry far more than its share of the load. That tie-down fails at the wharf hardware. Consequently, the second tie-down must now carry the entire corner load. Since the second tie-down is also designed to carry only part of the corner load, it too fails. Both tie-downs fail well before the intended corner design load is reached. A tie-down equalization method will reduce the probability of such a scenario.

"DUCTILE LINK" TIE-DOWN SYSTEM

When multiple tie-downs are needed at a crane corner, the load to each tie-down may need to be equalized. There are many ways to equalize the load. One method of equalizing, and limiting, tie-down loads between multiple tie-downs at one corner is to use ductile tie-down links. The ductile link is capable of deforming plastically without losing strength until the other tie-down(s) at the same corner share the load, thereby developing the design capacity of the tie-down *system*. The ductile link is simply a way of equalizing the load at a corner, protecting the wharf hardware and other tie-down links from premature failure. Figure 4 shows a ductile link system used in a recently-delivered crane. Figure 5 is a sketch of an integrated ductile link tie-down assembly, which consists of a ductile link and two safety links.

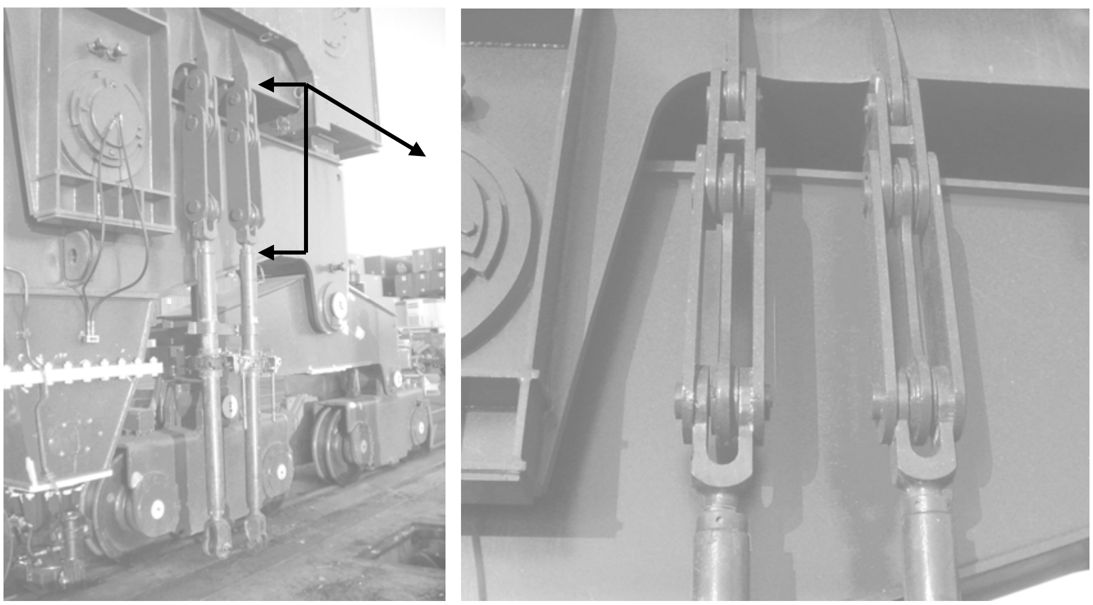

Figure 4. Ductile link system in the tie-downs of a new crane

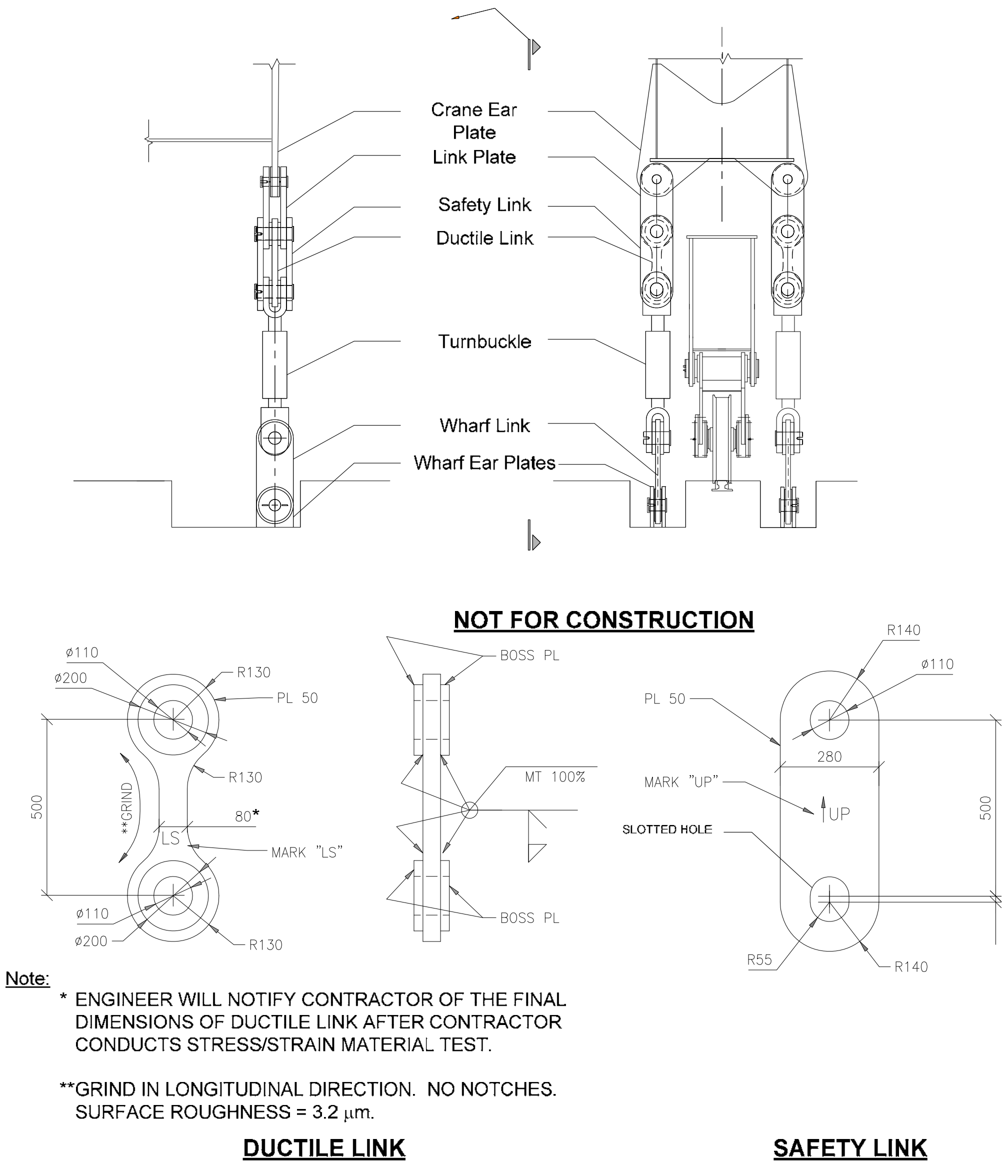

Figure 5. Ductile link system

How it Works—Simplified Example

Initially, the loads in multiple tie-downs are not equal. Figure 6 illustrates a simplified example in which the initial distribution between two tie-downs is 2:1. The desired distribution is 1:1.

With the ductile link, the more heavily loaded tie-down yields at the design tie-down load (about half of the total design corner load), and additional uplift force is resisted by the more lightly loaded tie-down. As the total uplift force increases, the yielded ductile link stretches plastically without resisting additional load. Eventually, the more lightly loaded tie-down yields and the total uplift force is resisted equally by both tie-downs, and the full strength of the multiple tie-down system is utilized—without overloading the wharf hardware.

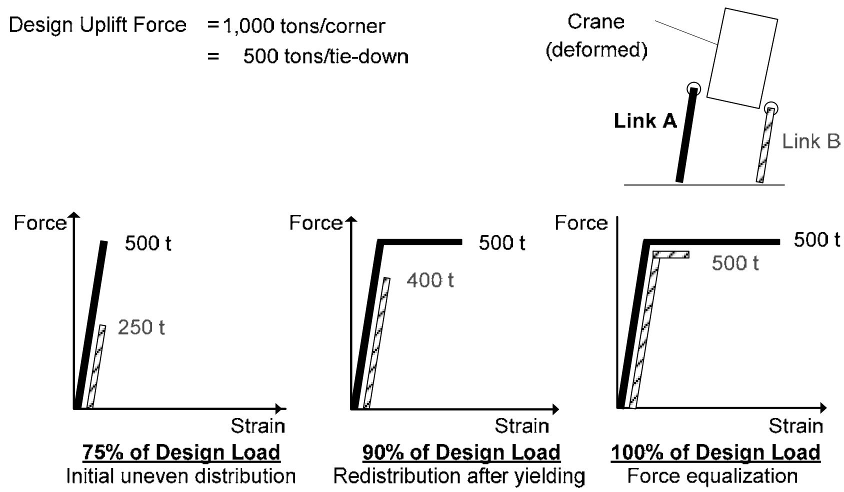

Figure 6. Ductile link example—How ductile links work (idealized)

Ductile Link Components

Ductile Links

The ductile link should be designed to minimize stress concentrations and allow for the required strain. It must stretch enough to equalize the loads in the tie-downs. The material properties must be controlled and the material must be tested. After stress-strain tests are performed, the ductile link length and cross-sectional dimensions can be determined. Note that the above example is simplified. In reality, after yielding, the ductile link material will strain harden and resist additional load as it stretches. We recommend designing the ductile link such that the ultimate stress is achieved at half of the design corner uplift force. Wharf hardware should be designed for higher loads.

Safety Links

If both ductile links are loaded to their full yield deformation, their combined strength may be insufficient, especially for loads greater than anticipated. By the nature of their design, the ductile links may not have capacity to resist the full design or greater uplift force without stretching to failure. Safety links connected parallel to the ductile link provide reserve strength at each tie-down. The safety links have slotted holes to allow the ductile link to stretch a prescribed amount before the safety links engage. If the uplift force increases beyond the design uplift force, the weakest link or wharf hardware component will eventually fail, but not until the ductile links have accomplished their purpose of equalizing the tie-down loads and allowing the tie-down system to resist its full design capacity.

Spare Parts

It is important to note that once a ductile link deforms plastically, it will require replacement. Therefore, spare ductile links will be needed. Since the ductile link will yield at forces less than the design uplift, they will need replacement more frequently than the design storm wind MRI. The expected replacement interval can be estimated based on the design storm wind MRI and uplift force, the corner dead load, the specified load factors, and the ratio of the force that initially yields the link to the force at which the safety link engages.

For most dockside cranes, the waterside links will need to be replaced more often than those on the landside. We estimate the ductile link replacement intervals to typically be 10–20 years for the waterside and 20–100 years for the landside. If the weakest component in the tie-down system is designed to resist more than half the uplift force, these intervals will be longer.

Retrofitting existing cranes

The ductile link system is ideal for new cranes that have multiple tie-downs at the corner, but may also be practical for retrofitting existing cranes. When retrofitting existing cranes, the tie-down system and wharf hardware should be analyzed to determine capacity and identify weaknesses. For a retrofit, the ductile link system can be designed for either of the following approaches depending on the strength of the tie-down components:

a. Yield at the design uplift load—This can be achieved if all link and wharf hardware components in the existing tie-down system can resist this load, or are easily modified to do so. This approach is preferred.

b. Yield at less than the design uplift load—This approach may be an economic solution to significantly improve the tie-down system performance by utilizing all the available strength of the weakest existing component if upgrading to the design uplift load is impractical.

New Cranes

If practical, use a single tie-down per crane corner. High strength ductile steel should be considered to minimize the weight of the handled components. If impractical, equalize the tie-downs.

COST VS. RISK

If Dr. Emanuel is correct in predicting more intense, longer duration, and larger storms, upgrading some cranes may be justified. Unfortunately, retrofits are costly, necessitating the modification or replacement of several, if not all, of the existing tie-down and wharf hardware components. Stakeholders must decide if, and to what extent, retrofitting is justified.

This decision can be guided by applying an acceptable risk method as described in Chapter 3 of Werner (1998). The method has been successfully used for seismic risk reduction planning at major seaports and airports. As applied to hurricanes and cranes, the basic premise of this method is that: (a) any such decision will have costs and risks associated with it, and (b) a condition of zero risk to a crane from hurricanes can never be achieved. That is, no matter what level of crane retrofit is carried out, there will always be some residual risk of unacceptable damage to the crane. Residual risk is termed "acceptable" when the owner determines the additional cost to further reduce the risk is prohibitive.

Various types of risks can be considered in this method. For example, acceptable economic risks can be assessed by comparing construction costs for different levels of crane retrofit against the potential for excessive hurricane-damage-induced repair costs and business interruption losses when each retrofit level is in place. Life safety, environmental, political, legal, administrative, and other intangible risks can also be considered. These risks will depend on the frequency of occurrence of various hurricane levels at the crane's location. Risks will also be owner-specific depending on economic, legal, and other constraints under which each owner must invariably operate.

NON-HURRICANE WINDS

Significant damage and failures have occurred in less than hurricane winds. Damage during these winds typically occur when cranes are not stowed and braking systems fail or correct high-wind procedures are not followed, resulting in runaway cranes.

Braking Systems

The following discussion presents typical minimum specified braking system capacities and operating parameters. Braking capacities for a particular crane design may vary from those discussed below. Understanding the braking component and system capacities, the wind characteristics at the crane site, and the time required to stow a crane is necessary in deciding when to begin stowing a crane.

During normal crane operations, only the gantry motor is used for stopping a moving crane. The gantry motors are usually designed to move or stop a crane moving at the rated speed with at least the specified operating wind load (WLO), which usually corresponds to a 25-m/s wind speed.

Gantry motor (disc or caliper) brakes are also required and are usually designed for at least 150% of the WLO, which usually corresponds to about a 30 m/s wind speed. During an emergency in which control power is lost, the gantry motors will not work, but the gantry motor brakes will set shortly after power is lost.

Gantry wheel or rail brakes should also be specified and be designed to hold the stopped crane without the gantry motor. To reduce operational and wear problems, the wheel (or rail) brakes are programmed to remain unengaged for some time after the crane comes to a stop. The wheel (or rail) brakes together with the motor brakes are designed to resist at least 200% of the WLO, which usually corresponds to a 35 m/s wind speed.

Gantry wheel and rail brakes should set during an emergency stop. If the crane is moving, some damage to the wheel (or rail) brake, and wheel (or rail) may occur. We recommend using wheel brakes instead of rail clamp or rail head brakes because there is less likelihood of damage, and because rail head brakes reduce the vertical reaction and friction available to the wheels for braking.

Cranes should have anemometers mounted to the highest fixed part of the crane structure, usually at the crane apex beam. Clearly audible alarms should sound at the wharf level and in the operator's cab at pre-defined wind speeds. The *operating wind warning alarm* is usually set at a wind speed of 16–18 m/s; the *high-wind alarm* is usually set at 20–25 m/s. The wind speeds at which the alarms are set depend on the location, typical wind conditions, and other requirements.

Gantry motor brakes and wheel (or rail) brakes usually engage at the *operating wind warning alarm*.

Design Considerations Affecting Braking System Performance

Two phenomena that can significantly affect that performance of a crane's braking system are the effect of a "light" crane corner due to the wind's overturning moment and the effect of "prying" in the gantry equalizer beam system.

The overall braking system design should consider the effects of a light crane corner, which occurs at the crane corners with the least vertical dead load reaction and with the angled wind applied in the most severe direction to cause uplift. If the vertical reaction at a crane corner is insufficient, the friction between the rail and wheel may not develop the required braking capacity.

The design should also consider prying effects in the gantry system, especially at the light corner. A prying effect is the reduction in vertical reaction between gantrying system components due to lateral forces. Refer to Figure 7.

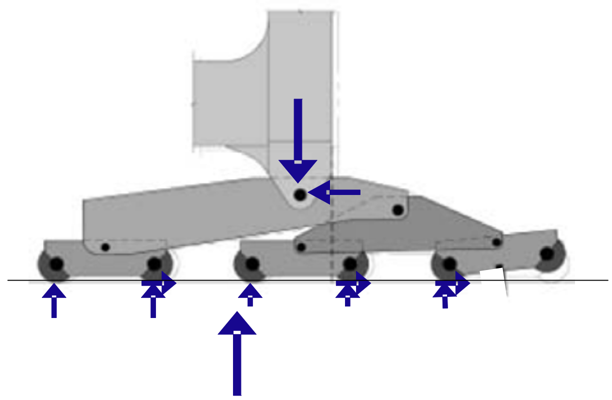

Figure 7 Gantrying System Prying Free Body Diagram

Braking and Stowage Procedures in High Winds

For hurricanes, usually the storm is predicted well in advance and sufficient time is allocated for stowing cranes. During operations, however, this is not always the case. If a crane is stopped, but not stowed, and an *operating wind warning alarm* or *high-wind alarm* sounds, what is the correct operational procedure?

Acceptable braking and stowage procedures for high winds will vary depending on the crane design and the nature of the winds that occur at a given location. The procedure should be determined by the crane manufacturer and owner working together during the design phase.

Typically, when the *operating wind warning alarm* sounds, the gantry brakes and wheel (or rail) brakes set and only open when gantry motion is requested. They will set again once the gantry stops or if there is an emergency stop. The intent is to allow the crane to stop operations and gantry to a stowage position to insert the stowage pins and, if applicable, attach the tie-downs.

At the *high-wind alarm*, gantry motion is stopped, all of the brakes are set, and a bypass is usually required to attempt to move the crane. The reason for this is that once the crane is moving, it is more difficult to stop due to inertia, differences in dynamic and static friction, and because the wind could increase to beyond that which the brakes are designed. Crane operators should be educated so they understand the high wind braking and stowage procedures and the bases and limitations thereof. Weather forecasting services should be used to help predict and prepare for high-wind conditions. Operating instructions for high winds should be posted in the operator's cab of each crane.

Brake Maintenance Procedures

Brake maintenance is common. If practical, engage the stowage pins when working on braking systems; if not, provide chocks, lashing, or other restraint as necessary. If cranes must operate with less than full braking capacity, which we do not recommend, the operator should understand the impact on the stowage procedures. One suggestion is to adjust the wind alarms such that the crane operates in lesser winds. The risk of a runaway crane increases if the brake system is compromised.

Anemometers should also be checked regularly for proper operation and be periodically calibrated. Audible alarms should also be periodically tested and maintained.

CONCLUSIONS

Growing scientific evidence suggests that global warming exists, ocean surface temperatures are rising, and in particular, the occurrence, size, and intensity of hurricanes are increasing. A greater number of dockside container cranes will experience their design wind loads or larger.

During a hurricane, multiple tie-downs at a crane corner are not equally loaded. Existing tie-down systems may be insufficient for these conditions. Upgrading the tie-down system is the best way to improve dockside crane hurricane resistance and reliability. Consider a single tie-down per crane corner for new cranes if practical.

The proposed ductile link tie-down system can be used to equalize the uneven corner uplift loading between multiple tie-downs and can be incorporated into all new, and many existing, tie-down systems. The ductile link is a cost-effective and practical approach to improving the reliability of dockside container crane tie-down systems in hurricane-prone regions. Stakeholders should carefully determine the acceptable damage risks before upgrading existing tie-down systems.

Crane designers and owners should evaluate operational braking capacities, including the effects of a light crane corner and the effects of prying, and should implement rational crane operating and high-wind stowage procedures. Crane operators should understand operating and stowage procedures.

Gantry brake maintenance procedures should ensure the braking and wind speed measuring and alarm systems are not compromised during operations. If a crane must be operated with a compromised braking system, the operator should be aware of adjustments to the operating and stowage procedures.

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