Increasing Hurricane Winds?
Dockside Crane Retrofit Recommendations

Patrick McCarthy,[1] Michael Jordan,[2] Kenton Lee,[3] and Stu Werner[4]

[1] Patrick McCarthy, PE, Associate, Liftech Consultants Inc., 344-20th Street, Suite 360, Oakland, CA 94612: Tel 510-832-5606, Fax 510-832-2436; pmccarthy@liftech.net

[2] Michael Jordan, SE, CEO, Liftech Consultants Inc.; mjordan@liftech.net

[3] Kenton Lee, SE, Principal, Liftech Consultants Inc.; klee@liftech.net

[4] Stu Werner, Principal, Seismic Systems & Engineering Consultants, 8601 Skyline Blvd., Oakland, CA 94611: Tel 510-531-7489, Fax 510-531-7293; sdwerner@ix.netcom.com

Introduction

General

Recent hurricanes have struck the US East and Gulf Coasts with historic fury. Studies indicate that the intensity, size, and duration of tropical cyclones (hurricanes and typhoons) are increasing dramatically 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. Dockside cranes are typically designed to resist hurricane wind pressure based on 50-year mean recurrence interval (MRI), 3-second gust wind speeds, at 10 m above ground. Refer 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 cranes, unlike buildings, have very little redundancy in their structural design for resisting wind loads. In hurricane-prone regions, the cranes are held by one or more tie-downs at each corner. 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 new 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.

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 tie-down uplift forces at one corner are not evenly distributed between the multiple tie-downs. 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, 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 loading.

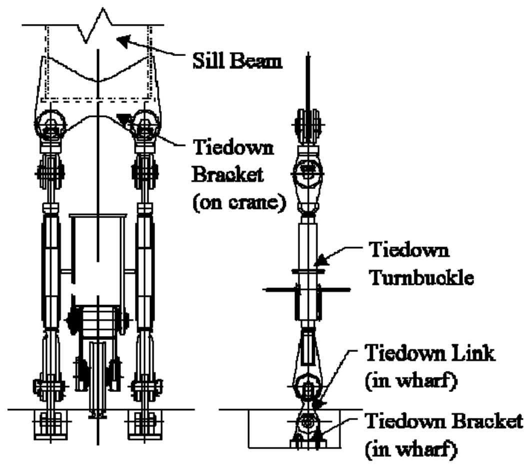

Figure 1. Traditional dockside crane tie-down system

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.

Recent studies by 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. Kerry 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 likelihood of a storm with that gust wind speed hitting a given location in any given year. If the likelihood of a hurricane hitting a location 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, 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 shape factors used to calculate the total wind force on the crane, structural analysis, material properties, and as-built fabrication are all as designed. This equates to a 10% chance of exceedance in 50 years. The crane owner should decide what level of risk is acceptable.

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 their design wind speeds.

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

Most wharf hardware is designed with the assumption that the tie-downs are perfectly vertical and the uplift forces are equally distributed among multiple tie-downs at one 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 gantry 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.

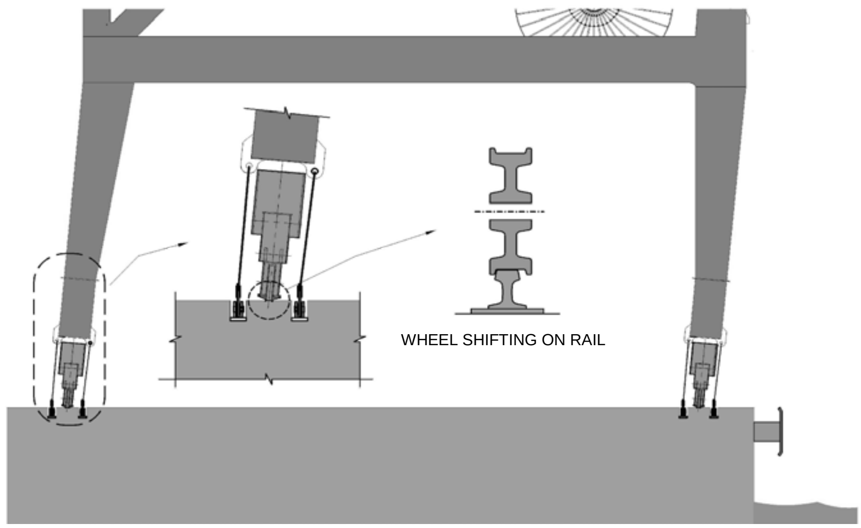

Figure 3. Crane deflection and movement during a hurricane

It is impossible to tighten the multiple turnbuckles such that the tensions are equal. A difference of a few millimeters 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.

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 in that corner. During the hurricane, the tie-down pretensions are unequal, and the crane displaces and deflects, causing one tie-down to carry more than its share of the load. The tie-down fails, usually at the wharf hardware. Consequently, the second tie-down must now carry the full load in that corner. Since the second tie-down is also designed to carry only part of the load in that corner, it too fails. Both tie-downs fail well before the intended total corner load is reached. A tie-down equalization method will reduce the probability of such a scenario.

“Ductile Link” Tie-Down System

When there are multiple tie-downs at a crane corner, the load to each tie-down should 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 full 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.

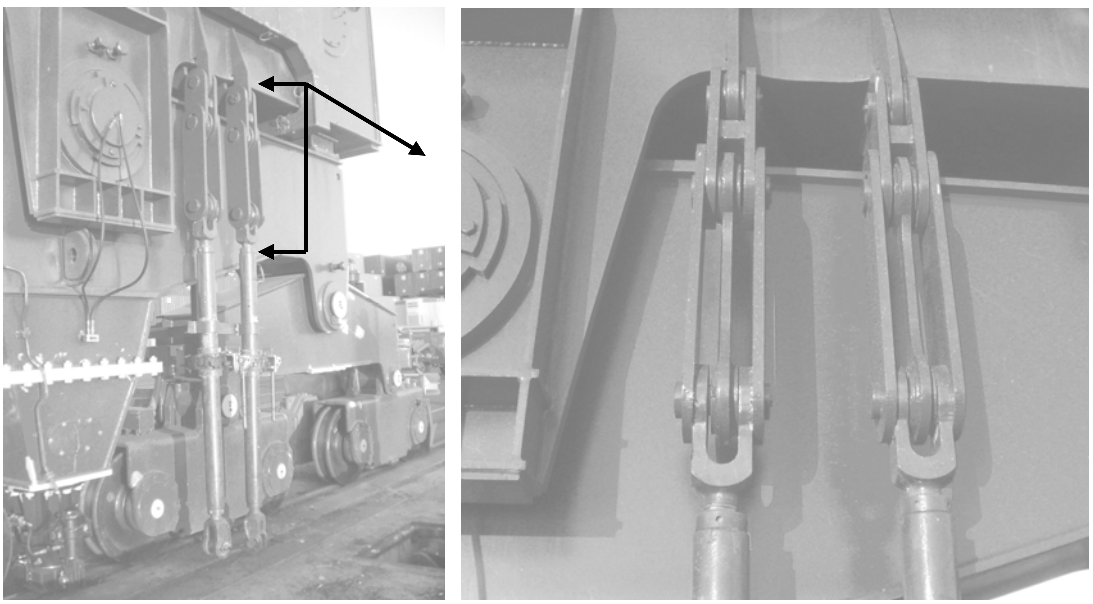

Figure 4. Ductile link system in the tie-downs of a new crane

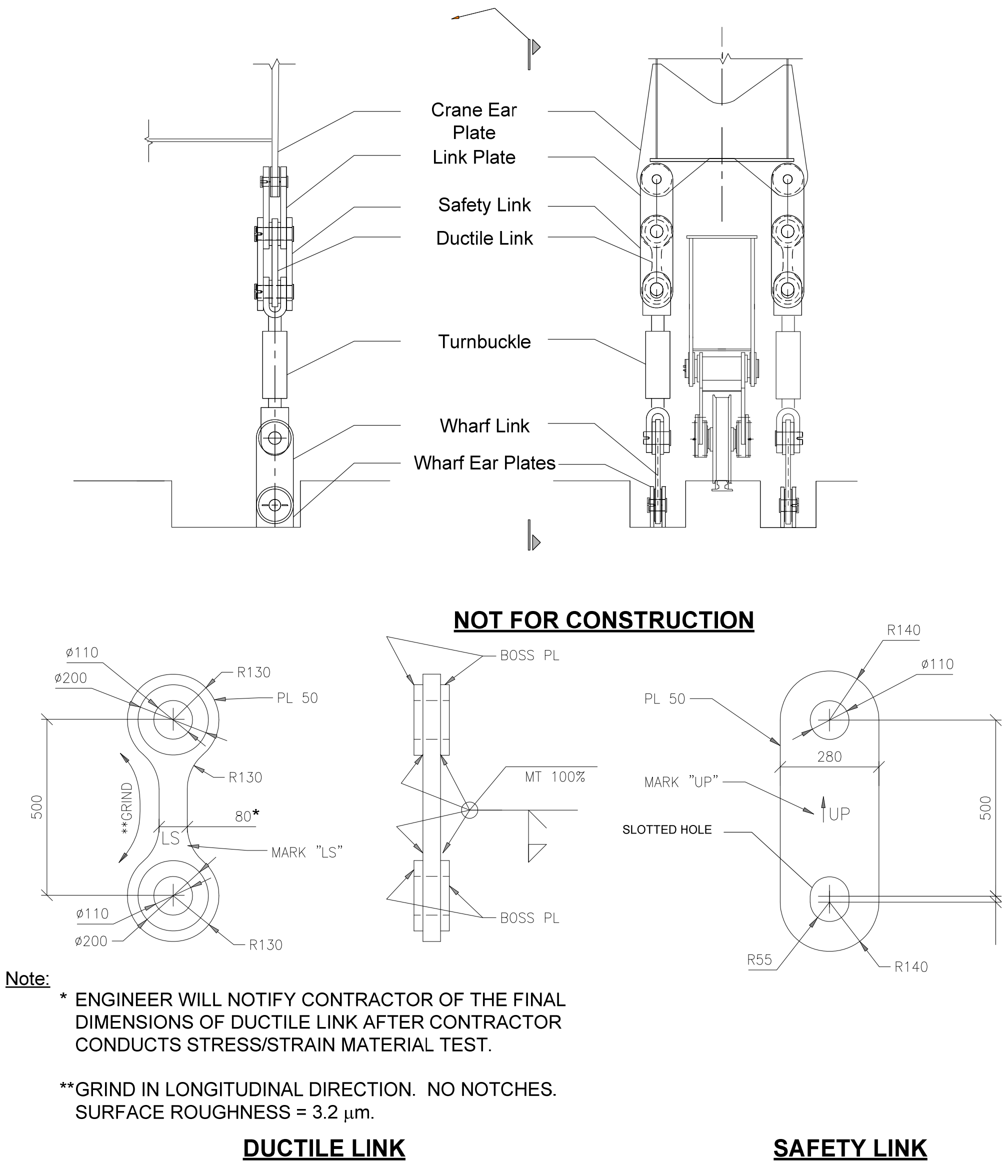

Figure 5. Ductile link system

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), 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 more 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.

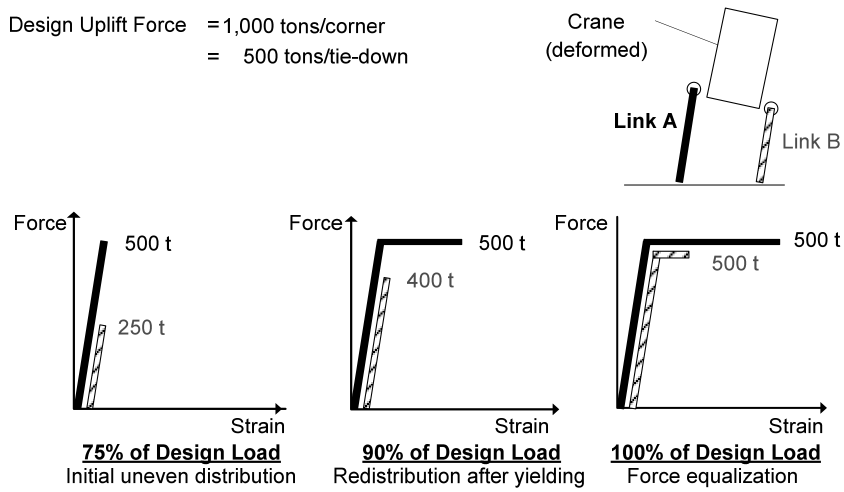

Figure 6. Ductile link example—How ductile links work (idealized)

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 selected. 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 is insufficient. By the nature of their design, they will no longer have capacity to continue resisting the total uplift force without stretching to failure. Safety links connected parallel to the ductile link provide reserve strength. 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 force that initially yields the link and 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. Refer to equation [6] below. If the weakest component in the tie-down system is designed to resist more than half the uplift force, these intervals will be longer. The basis for the link replacement MRI is provided below.

Define the factored uplift force as:

$$U = F_W W - F_D D, \quad [1]$$

where W is the corner wind uplift force, D is the corner dead load, and F_W and F_D are the wind and dead load factors. Further, define ρ as the ratio of the uplift force required to cause initial yield of the first tie-down to that of the factored design uplift, as:

$$\rho U = F_W W' - F_D D, \quad [2]$$

where W’ is the reduced corner wind uplift force at initial yield. To simplify, define the ratio of the corner factored wind uplift and dead load forces as:

$$\gamma = \frac{W}{D}. \quad [3]$$

Combining [1] through [3] and noting that the ratio of the design factored corner wind uplift force to that at yield equals the ratio of the squared of the wind speeds (i.e. $\frac{W}{W'} = \left(\frac{V}{V'}\right)^2$), we find:

$$\frac{V'}{V} = \sqrt{\rho + \frac{F_D}{\gamma F_W}(1-\rho)}. \quad [4]$$

Wind codes often define MRIs for wind speeds other than 50-year design wind speeds. The ASCE–7 standard provides a table for correlation. The Hong Kong code (*Code of Practice on Wind Effects in Hong Kong 2004)* defines equation [5], which leads to values very close to those shown in ASCE–7, but is easier to use:

$$\frac{V'}{V_{50}} = \left(\frac{5+\ln(MRI)}{5+\ln 50}\right)$$, where V_{50} is the 50-year MRI wind speed. [5]

Equating [4] and [5] and solving for the MRI leads to the following:

$$MRI = \exp\left[(5+\ln 50)\left(\sqrt{\frac{F_W}{1.05}}\right)\left(\sqrt{\rho + \frac{F_D}{\gamma F_W}(1-\rho)}\right) - 5\right]. \quad [6]$$

We have added the $\sqrt{\frac{F_W}{1.05}}$ term to equation [6] to account for the fact that the design wind load was factored, whereas the 50-yr MRI wind speed is not. The wind load factor represents uncertainty in determining the wind load on the structure for a known wind speed and also the variability in the wind speed itself. According to the ASCE–7 standard commentary, the variability in the wind speed can reasonably expected to account for the entire load factor, less about 5%. For instance, if the wind load factor is 1.6, the wind speed variability accounts for approximately 1.6/1.05 = 1.52 of this factor. Factoring the wind speed effectively increases the MRI.

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 conditions 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 (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.

Cost vs. Risk

If Dr. Emanuel is correct in predicting more 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-damageinduced repair costs and business interruption losses when each retrofit level is in place. Life safety, environmental, political, legal, and administrative 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.

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 may be 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 are 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.

The proposed ductile link tie-down system equalizes the uneven loading between 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.

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