Balance Crane – A New Type of STS Crane in Development

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ABSTRACT

Liftech conceived a new crane concept, the *Balance Crane* (BC) for unloading containers from large vessels, and developed the design in collaboration with crane manufacturer ZPMC, Shanghai, China. The BC has reduced wheel loads and tie-down loads compared to a standard ship-to-shore (STS) container crane but functions similarly. The boom is continuous from the landside legs to the boom tip. The landside girder is connected to the boom with a parallel linkage. To clear the vessel bridge, the boom and upper works rotate as a unit about waterside. The machinery house and shortened trolley girder landside of the landside leg remain horizontal while translating in a downward arc. The end results are a stowed crane with a lower center of gravity and reduced overturning moment due to stowed wind loads. In the operating position, there will be reduced trolley rail hinge maintenance due to fewer trolley cycles crossing the hinge relocated to the landside. The paper discusses selected BC design features and presents analyses and study results.

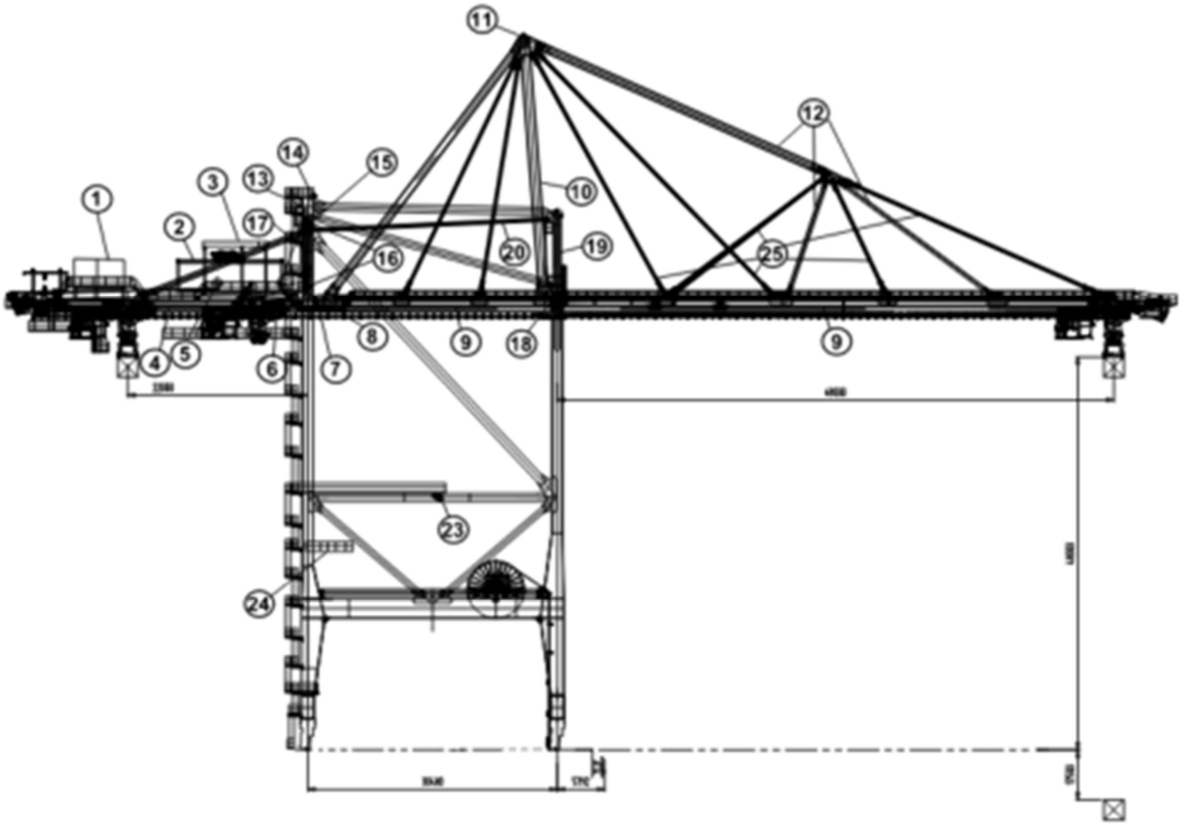
INTRODUCTION

STS container cranes have increased in height and outreach to accommodate ever-increasing ship sizes, while the crane footprint has not changed. Consequently, vertical loads on the wharf due to crane lateral loads have increased significantly, resulting in large wheel loads and tie-down loads on the wharf, which are especially problematic in high wind regions and when a terminal wants to place larger cranes on an older wharf with limited crane girder capacity.

STS cranes are the workhorses of the industry and require a significant maintenance effort. For crane operators, maintaining the rail joint between the crane trolley girder and boom is a source of significant labor and cost.

Liftech conceived a new crane concept to address these issues—the *Balance Crane* (BC)—and developed the design in collaboration with ZPMC, Shanghai, China, see Figures 1–4 (ZPMC 2021).

The paper will discuss selected BC design features and present analyses and study results.



① Electrical house
② Service crane
③ Roof for machinery platform
④ Trolley girder
⑤ Machinery platform
⑥ Trolley
⑦ Trolley girder - boom hinge
⑧ Girder lateral support beam and access
⑨ Boom
⑩ Pylon
⑪ Apex
⑫ Forestay pipe
⑬ Landside cross beam
⑭ Boom latch
⑮ Trolley girder landside pin support
⑯ Boom hoist sheaves
⑰ Trolley girder support link
⑱ Waterside boom support pin
⑲ Waterside cross beam
⑳ Parallel linkage
㉑ Waterside cross beam upper strut
㉒ Waterside cross beam lower strut
㉓ Stowed girder lateral support & access point
㉔ Trolley access, stowed position
㉕ Cablestays

Figure 1. Operating position, main features, side view.
(Image courtesy of ZPMC. Used with permission.)

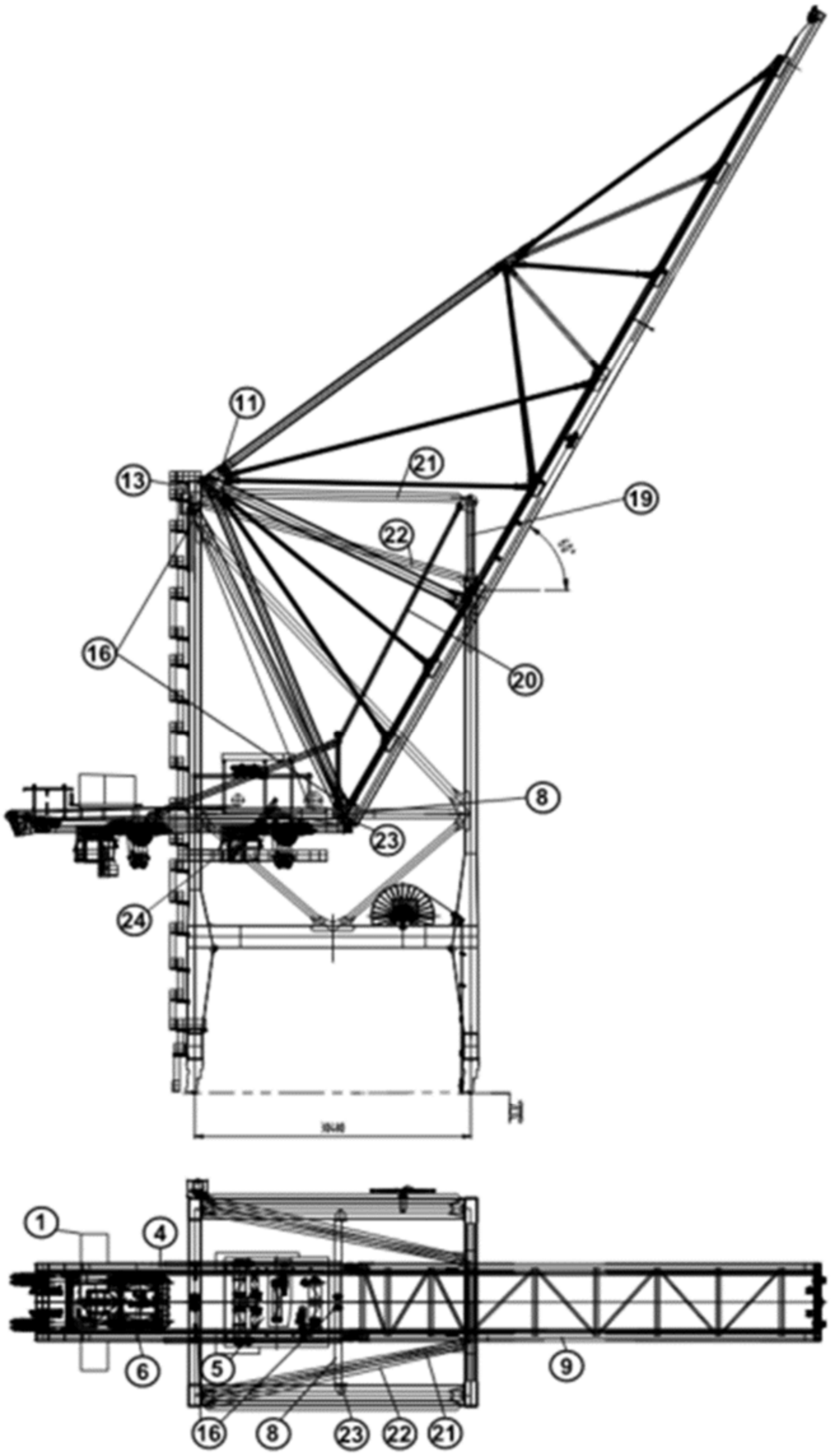
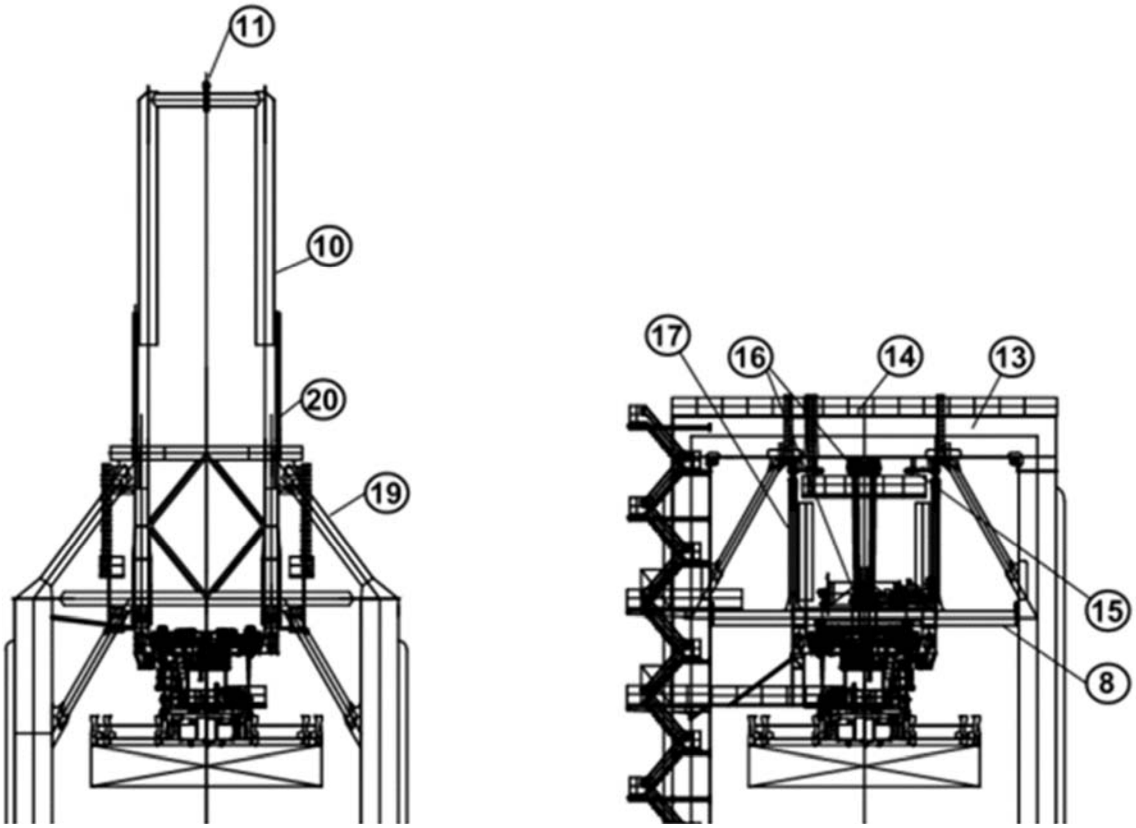


Figure 2. Stowed position, side view and top view.
(Image courtesy of ZPMC. Used with permission.)



Waterside **Landside**

Figure 3. Operating position, front view of upper waterside and landside frames. (Image courtesy of ZPMC. Used with permission.)

Figure 4. Isometric view. (Image courtesy of ZPMC. Used with permission.)

DESCRIPTION

The BC mechanical design is the same as a standard rope-towed trolley crane, except the boom hoist has fewer parts of ropes. Although the structural design may look the same as a standard STS crane when in operating position, it is different because the boom is continuous from waterside boom tip to the landside cross beam, and there is a parallel linkage supporting the trolley girder at the landside. When the boom is raised, the landside part of the boom and the trolley girder are lowered as the boom rotates about boom pins at the waterside cross beam. The parallel linkage keeps the trolley girder, machinery platform, electrical room, and trolley parallel to the ground as the boom is raised or lowered.

In the following discussion, the numbers (1–25) refer to the numbering in Figures 1–3, above.

The boom hinge (7), normally at the waterside support, is now at the landside support, so the boom and trolley rails are continuous from the boom tip to the landside support cross beam (13). The pylons (10) to the apex (11) connect to the boom (9) directly instead of to the waterside support cross beam (19)—which is the case on a standard STS crane—and rotate with the boom. Instead of four folding stays, 14 fixed cable stays (25) and pipe diagonals (12) support the boom. The support members do not change position relative to the boom when it is raised. The boom support is discussed in detail later.

The boom-girder assembly is supported vertically by pins at the landside (15) and waterside (18) cross beams. The waterside pins (18) allow the boom to rotate, for raising and lowering. The landside pins (15) can be retracted to allow the girder at landside to lower to the stowed position. A mechanical assembly provides adequate tolerances to allow the pin to be automatically inserted when returning to operating mode.

When the boom is rotated, a “parallel-linkage” (20) holds the trolley girder parallel to the ground. The parallel linkage and the boom support design result in large forces at the top and bottom of the waterside cross beam (19). To resist the large forces, the waterside cross beam (19) is a deep truss structure. The lateral loads at the top and bottom are supported by pipe struts (21, 22) carrying the loads to the landside cross beam (13) and down to the portal.

In the operating position, lateral loads on the landside portion of the boom and trolley girder are resisted by a lateral support beam (8) that pushes against the landside legs. In the stowed position, this beam (8) pushes laterally against the upper portal beams.

The strut (8) has a mechanism to engage and disengage against the leg or portal beam prior to the boom-girder being raised or lowered.

In the stowed position, the apex of the pylons (11) is connected to the landside cross beam (13, 14). This connection takes trolley direction loads from the stowed boom-girder.

The pylons are supported by a standard pipe upper diagonal, extending down to the landside end of the boom. In addition, two landside cable stays (25) support the trolley girder between landside and waterside.

The machinery platform (5) layout is the same as on a standard rope-towed crane. However, the platform does not have walls or a floor opening for the service crane. The service crane (2) operates parallel to the trolley direction and can lower components to the ground in the space landside of the main hoist drum. The same service crane can also service the trolley (6). There is a fixed roof (3) above the machinery platform to provide protection from sun and rain.

The closed, air-conditioned electrical house (1) is located between the machinery platform (5) and the trolley girder landside end tie, which is also the location of the trim, list, and skew system and other hardware. In addition to the drives and control rooms, the electrical house has a room housing transformers and switchgear.

WHEEL LOADS, STABILITY, AND STIFFNESS

Wheel Loads and Stability

The following characteristics of the design contribute to reducing wheel loads:

1. The boom and girder weight are reduced due to the increased number of supports.
2. The long, continuous boom rotating about waterside means the machinery platform, electrical house, and trolley rotate down with the girder, toward the waterside at the portal beam level when the boom is raised. This movement centers the total dead load of the crane.
3. The stowed position of the trolley girder is lower, so the wind load and its overturning effect are reduced. Wind load is reduced because wind pressures typically have a gradient profile, increasing with height. The girder, machinery platform, and electrical house are lowered 30 m, resulting in a 10% reduction in the design storm wind force on these components.
4. Since the boom and girder are not as deep with the added stay supports, the wind area (and force) in the gantry direction is reduced.
4. The machinery platform and electrical house have reduced wind area, mainly because the main machinery platform does not have walls. If walls were provided, the wind load would be higher, but still smaller than for an STS crane, as the house is smaller and more optimally oriented when stowed.
5. The electrical house is located farther to landside, limiting operating wheel loads at waterside.
6. High-strength pipes with reduced wind drag and no internal stiffeners or diaphragms are used as structural members where practical. The round pipe stays and cable stays combined with the pipe diagonals experience less wind force than standard I-beam forestay sections due to lower drag coefficient.
8. Stairs on the pylon are not required since the apex of the pylons can be maintained from the landside cross beam.

See Table 1 for a crane loads summary from a study comparing loads from an STS crane ZPMC supplied to The Bahamas in 2018, to a comparably sized BC, for the same design criteria. Loads are unfactored (ASD level), except for the storm wind uplift loads, which are factored (LRFD level). Both STS and BC have 30.5 m rail gage, 48 m lift height, 68 m outreach, and 61 t rated load. This design is for a straddle carrier terminal—the 16 m high clearance under the portal beam has some negative effect on the structure and weight. Allowing a lower portal beam results in a lighter, more efficient crane structure with smaller wheel loads.

As shown in Table 1, the result is that the BC landside wheel loads are about 10% higher for operations, but nearly 20% lower for the storm wind case compared to the standard STS crane. Similarly, the BC waterside wheel loads are reduced about 10% for operations and 6% for the storm wind case. At both the landside and waterside, the storm wind loading governs over the operating case, for an overall reduction of governing wharf design loads of 6% to 19%.

Table 1: Wheel Loads and Stability Comparison.

	Landside	**Waterside**	**Notes**
Operating Wheel Loads, tonne/wheel			"*STS*" – reference ZPMC crane, Freeport Container Port Bahamas. "*BC*" – designed for the same criteria as the STS reference crane. % Change = (BC-STS)/STS %. Wheel loads are service (ASD) level; eight wheels per corner. Storm uplift is factored (LRFD) level, at the main equalizer pins using 0.9 D + 1.0 W. Dead load is without trolley and lift system weights.
STS	60	88	
BC	66	79	
% Change	+10	-10	
Storm Wheel Loads, tonne/wheel			
STS	134	145	
BC	109	137	
% Change	-19	-6	
Storm Uplift + Dead Load, tonne/corner			
STS	752	1046	
BC	560	832	
% Change	-26	-20	
Crane Dead Load, tonne			
STS	1445		
BC	1414		
% Change	-2		

Both landside and waterside tie-down loads are reduced by 20% or more from a comparably sized STS crane.

The basic design wind speed (factored, LRFD level) in this case is 72 m/s at 10 m height with an ASCE-7 gradient wind profile above 10 m. The total wind load is approximately 600 t in each direction, gantry travel and trolley travel. Note that The Bahamas is a severe hurricane region. We chose this high-wind location to (1) optimize this crane for storm wind and (2) illustrate the benefits of this design for severe wind regions. For less severe wind regions, the wheel load reduction for storm wind will be less.

Crane Stiffness

Crane stiffness in the trolley travel direction and boom tip vertical deflections are comparable to standard STS cranes, while lateral deflection in the gantry travel direction at the outreach is reduced.

DESIGN FOR MAINTENANCE

While the function and layout of all the mechanical equipment is nearly the same as on a typical STS crane, the design has new features intended to reduce maintenance effort.

Differences from a typical STS crane design include:

1. Trolley girder-to-boom hinge rail joint (7) is moved from waterside to landside, where there will be fewer load cycles from trolley movement, reducing wear and related maintenance at the rail joint.
2. The low stowed position (23) of the electrical room, machinery, and trolley means that maintenance access will be faster and easier, and service crane hoisting times are

reduced. Access to the machinery platform and electrical room will be over the girder stowage beam (8) at the upper portal.

3. Access to the trolley will be from the elevator stop on the leg below the portal beam directly to the cabin (24). The trolley will also be directly accessible from the upper landside leg, when in operating position.
4. Only 12 parts of boom hoist rope are required, each part much shorter than on a standard STS crane. As a result, less than half as much boom hoist rope is required, and the boom hoist drum is smaller and easier to handle. On the BC, only ten boom hoist sheaves (16) are required, whereas on a standard ZPMC STS crane 24 boom hoist sheaves are used.
5. The machinery platform (5) has the same layout as the STS crane, but it has no walls. It has a large service crane (2) and a roof (3).
6. The service crane (2) runs parallel to the trolley rail. The crane can lower loads to the ground between the main hoist drums and the electrical house and can service the trolley directly.
7. The electrical house (1) is fully enclosed, separate, and landside of the machinery platform (5). It includes the transformers and switchgear. From the control room inside the electrical room, one can look onto the machinery house platform.
8. In boom up position, the apex beam (11) latches to the landside cross beam (13) at (14). Inspection of stays, wind speed indicator, lightning rod, and lights is possible from the landside cross beam (13). There is no boom hoist equipment at the apex. The boom hoist sheaves (16) are located under the landside cross beam and at the girder lateral support beam (8).
9. The cable stays (12) have no links requiring inspection, so access platforms are not required for this purpose at the waterside cross beam (19). However, the forestay pipe connections and their connections to the cable stays over the boom will be provided with access ladders to allow structural inspection.
10. The pin insertion mechanism (15) supporting the trolley girder and boom at the landside cross beam (13) will be a new item requiring inspection and maintenance.

BOOM SUPPORT

The BC uses a combination of pipe and cable stays to support the boom. The cable stays will likely be fully locked coil cables for stiffness and corrosion resistance. Fully locked coil cables are common and time-tested in cable-stayed bridges. The final configuration of the boom support is designed to minimize sag of the cable stays and increase the overall stiffness of the boom. The design was developed based on detailed wind load and vibration modelling. The use of 14 support locations as opposed to 4 support locations on an STS crane allows the weight of the boom to be reduced. A team of cable-stay bridge specialists at Tongji University in Shanghai, China, conducted vibration analyses of the stays and boom for various stay configurations (Tongji 2021).

The original boom support configuration was inspired by fan-type, cable-stayed bridges and was aesthetically pleasing. See Figure 5 for the original stay configuration. The stays are shown in green.

Although the original stay configuration is similar to that used in many cable-stayed bridges, it was found that it would be problematic for the BC. The primary reason is that cables cannot be properly prestressed, since the boom is light, slender, and cantilevered, which is a very different condition than on a cable-stayed bridge. The boom must be raised, the dead load of the boom is less, and wind blowing in the trolley travel direction toward the land would cause the cables to sag excessively (catenary effect) and overstress the boom. Container cranes must travel on rails and are subjected to lateral inertial motion. Also, the moving load is a large percentage of the total load supported by the stays. The studies took these factors into consideration and found excessive sag and vibration to be the major problems.

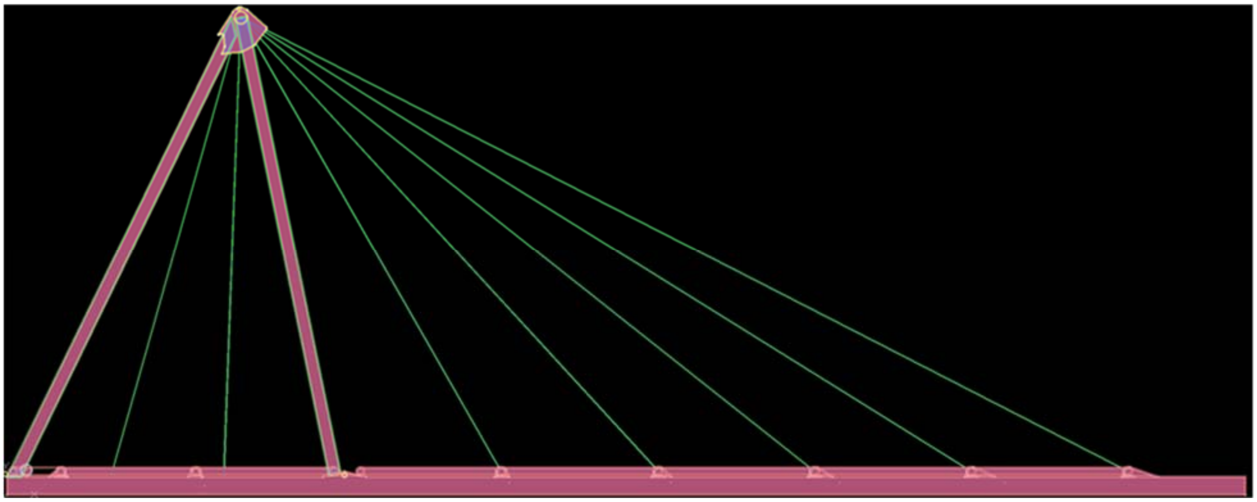


Figure 5. Original configuration of the cable stays.

In addition, the cables were found to have low stiffness and, therefore, low efficiency for supporting the boom.

The final stay configuration is shown in Figure 6. The stays are shown in green and the pipe struts in red.

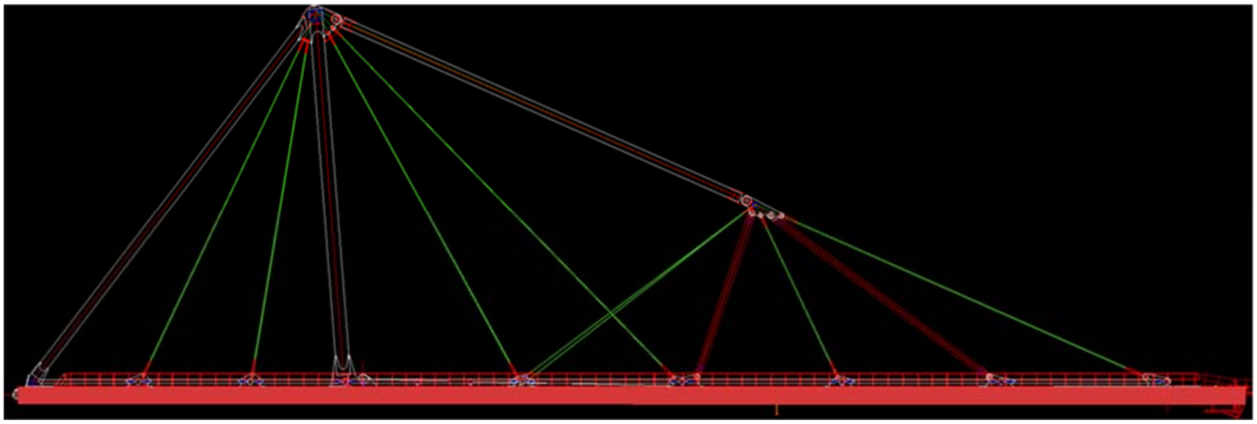


Figure 6. Final configuration of the cable stays.

Pipe struts were added at strategic locations to eliminate or shorten the longer and flater outer cables. The pipe struts and the opposing stays allowed the remaining shorter or steeper cables to be pretensioned. The pretensioning reduces cable sag and increases the stiffness of the cables. Although the final boom support configuration is heavier than the original configuration, the wheel loads and uplift loads only increase marginally. This is because the boom can be lighter as the stays are stiffer and more efficient at supporting the boom.

SUMMARY

STS container cranes have increased in height and outreach to accommodate ever-increasing ship sizes, while the crane footprint has not changed. Consequently, vertical loads on the wharf due to crane lateral loads have increased significantly, resulting in large wheel loads and tie-down loads on the wharf. The high wheel loads are especially problematic in high wind regions and when a terminal wants to place larger cranes on an older wharf with limited crane girder capacity.

For crane operators, maintaining the rail joint between the crane trolley girder and the boom is a source of significant labor and cost.

Liftech conceived a new crane concept to address these issues—the Balance Crane (BC)—and developed the design in collaboration with ZPMC, Shanghai, China. For operations, the BC functions similar to a standard STS crane. For stowage, an elongated crane boom and upper works rotates as a unit about hinges near the top of the waterside legs, providing clearance for the vessel, while the machinery house and shortened trolley girder landside of the landside leg remain horizontal while translating in a downward arc. The end results are a stowed crane with a lower center of gravity and reduced overturning moment due to stowed wind loads, and reduced trolley rail hinge maintenance due to fewer trolley cycles crossing the hinge relocated near the landside leg.

In the development process, Liftech and ZPMC examined a recent rope-towed trolley STS crane that is intended for a hurricane region, redesigned it for the BC concept but using the same design criteria, and compared the crane weight, wheel loads, and stability of the two cranes. The crane trolley travel direction stiffness and boom tip vertical deflections are comparable to standard STS cranes, while lateral deflection in the gantry travel direction at the outreach is reduced.

The rope-towed trolley BC design is based on complete stress and fatigue analyses of the primary structure. The BC analysis methodology and design criteria are similar to those Liftech performed for hundreds of STS cranes operating worldwide. The BC uses a combination of pipe and cable stays to support the boom. A team of cable-stay bridge specialists at Tongji University in Shanghai, China, conducted vibration analyses of the stays and boom for various stay configurations. ZPMC made concept design drawings of the prototype.

The BC has the following benefits:

1. Significantly reduced waterside rail operating wheel loads, stowed wind wheel loads at both landside and waterside, and tie-down loads.
2. Reduced maintenance effort at the boom hinge.
3. The crane will operate the same as an STS crane, but the boom hoist time is reduced.

At the time of writing this paper, ZPMC is searching for a port that is interested in procuring the BC.

REFERENCES

Tongji University. (2021). Report BDMP-2020-23, “Analysis of Vibration of Balance Crane Stays.”

ZPMC (Shanghai Zhenhua Heavy Industries Co., Ltd.). (2021). Figures of prototype cranes.