Streamlining Shipyard Rigging Analysis

Final Technical Report
Milestone 17

National Steel and Shipbuilding Company
Initial Design & Naval Architecture

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Forward

This final report summarizes much of the information that was learned after two years of instrumentation, analysis, and review of several shipyard lifts. Along with the six block report deliverables, the primary desire is to provide relevant information to assist the engineering of shipyard lifts by reducing some of the uncertainty in shipyard rigging, along with an estimation of the accuracy of various analysis methods. These technical references are necessary as shipyard lifts are getting larger and more heavily outfitted, and present increasing challenges to traditional methods of review. A significant portion of this research reviewed the application of the Finite Element Method to shipyard lifts. However, it is not considered necessary to undertake these advanced methodologies to gain benefit from the assessments compiled. These reports are in parts fairly technical in nature, and are intended for review by engineers who already a have solid understanding of structural analysis and shipyard rigging.

It is also important to understand that this research was very much a learning process and the block reports compiled on later dates should be considered more accurate, as discoveries were made during the course of this research, and understanding gained, that was subsequently incorporated into following reports thereby increased the quality, and technical accuracy.

The dynamics of lifted structure and operational variability documented are no doubt directly related to the process that GD NASSCO has developed through years of experience. As a result, aspects of the operations are specific to this particular shipyard. Lifts conducted under significantly different circumstances such as with the application of goliath or crawler cranes may experience a different set of dynamics or operational variables when compared to what was observed and recorded during this research. Similarly, operations conducted are always highly dependent on the equipment and personnel involved, their experience, and how they function as a team. Different organizations each with unique processes may experience a divergent range of variability, and quite possibly effects not encountered in this research. Despite this, it is believed that much of what is presented is universally applicable and other shipyards will find it useful and adaptable to their processes.

It should be noted that any reference will not cover all information needed, or all sets circumstance, and thorough Engineering review should be undertaken whenever the well being of personnel or property is at risk. Similarly, however technical the information which can be taught, and is available for reference, there is no substitute for experience. Proper analysis of the forces within ships structure during various lifting arrangements requires significant experience and detailed knowledge to approximate the result. Although the goal was to create detailed references to aid the design of shipyard lifts, it does not eliminate for need for sound Engineering judgment accompanied with analytical thought. For the final design review of any rigging operation, the ultimate responsibility rests with the user.

Lucas Gray P.E.

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1. STREAMLINING SHIPYARD RIGGING ANALYSIS

As U.S. shipyards continue to progress toward world class standards in order to reduce the cost of ship construction to their customers, build strategies continue to be modified in a manner that results in work content moving to earlier stages of construction, facilitating erected units that are more complete. The desire to minimize work in the final stages of construction requires the design to be divided into increasingly larger, heavier, and more complex erectable units that must be individually supported and lifted during assembly, outfitting and erection sequences. Larger lifts also enable more pre-outfitting and the completion of greater quantities of production effort in controlled environments. This complicates rigging engineering as a larger percentage of weight is non-structural, more difficult to estimate, and more variable. The process of lifting, moving, and supporting these products requires complex and diverse rigging activities, with significant impacts on staffing, safety, and construction schedules. Similarly, the margin for error is disappearing as the steady shift of work to earlier stages of construction and accompanying schedule compression, leaves less tolerance in the production timeline for rework due to assemblies that have been distorted in the lifting process. The lack of documented analysis techniques and references results in considerable variation in methods used, bracketed between the two extremes of rule-of-thumb and detailed Finite Element Analysis (FEA). Also, modern analytical means can be time consuming, making it difficult for rigging engineering staff to keep pace. Errors in analysis can result in costly oversights resulting in serious injury, loss of life, and significant construction delays including damage to equipment, rework, and required repair to critical assets. This research project was undertaken in order to advance the state of the art with the investigation of the accuracy of different analysis techniques complete with comparison to data collected on typical shipyard lifts.

1.1. Project Goals

This research project had several goals related to the improvement of shipyard rigging engineering and the analysis of lifted structure. In summary these were:

- Determine the relative accuracy of various analysis methods
- Research and improve upon existing analysis methodologies
- Record the deviation between predicted and measured stresses during block lifts
- Document the dynamics and variation of actual stresses during block lifts
- Create references for shipyard rigging engineers

The most accurate structural analysis for a lift may be done with a highly detailed Finite Element model which has all of the mass of the block modeled. However, determining the weight and location of everything on a typical ship block is significantly more complex than a completed vessel, as significant uncertainty surrounds what will be on a block during a lift, caused by temporary construction equipment and general uncertainty. As most rigging analysis and planning is typically done months before a lift, complete certainty may never be possible. This research project benefited significantly from the ability to continue conducting analysis after a lift took place, with the goal of creating the most accurate analysis. This most accurate highly detailed FE model was then compared to simplified models that took several times less effort to create. This allowed the direct comparison of how much accuracy could be maintained with significant approximation to just the core structure of the block, as well as weight and Center Of Gravity (COG) simplifications. Finally, hand calculations with assumed sections were completed such that much more basic, traditional method of structural analysis could be compared to advanced methods. The goal of this was to allow direct comparisons of simplified methods, with more thorough and complex methods, and possible error margins associated. This allows a generalized relationship between effort and accuracy to be created.

Strain gauges and accelerometers were attached to multiple blocks during shipyard rigging operations with the goal of measuring the actual lift strains and thus inferring stresses caused. This allowed both the direct comparisons of predicted stresses from lifting events to the actual stresses, and the creation of data with regards to the dynamics of the load and internal stresses caused. As there are many unknowns in rigging operations, this also provided significant benefit as it assisted in uncovering additional load cases and their respected ranges, important dynamics, and stress variations caused by how the operation was conducted. Recently, the American Society of Mechanical Engineering (ASME) altered their guidance for lifting devices and equipment to specify design factors based on an assumed dynamic load spectrum and similar probabilistic possibility of overload. Although there is no requirement for this methodology or guidance best documented in ASME BTH-1-2008 to be applied to internal stresses of the load, understanding the variation within the load that occurs is significantly beneficial. The application of these types of statistical methods to the structural analysis of lifted ship structure would require one to know the general accuracy of both structural analysis performed, and the variation of loading expected. Similarly, data on load ranges helps to validate resistance based analysis approaches being more commonly used. The documentation of actual loading ranges within lifted structure is possibly a first, and therefore provides valuable data in support of future and ongoing efforts such as Shiplift software.

Initial surveys of rigging analysis methodologies revealed that different organizations apply various forms of analysis. Many shipyards have experienced rigging departments that have learned the lifted behavior of typical ship structure though experience, and only require rough assumed sectional calculations to compare proposed lifts to past successful practice. Similarly, shipyards have standard parts, requirements, and processes that have endured through mature learning curves with many decades of success. Significantly more evolved build strategies with heavier lifts and a smaller percentage of structure is creating the needs for new analysis methodologies. Of three shipyards known to use FEA for the analysis of lifted structure, very different methods are in use. These different methods have different strengths and weaknesses and one of the goals of this research was to investigate their relative accuracies, costs, complexity, and the difference between them. The understanding of the accuracy of current lifting and handling analysis methods is an important first step in improving analysis efficiency while maintaining high levels of safety. This investigation also allows methods to be improved and the limits of acceptable use to be better defined. Finally, documenting methods for shipyard rigging analysis is a key element in fulfilling an overall need for improved standards, methods, and tools for rigging engineering in support of high-efficiency, safe ship construction.

Finally this research project also included a short parallel effort into the behavior of integrated lifting lugs. Very little published data exists on thin plate lifting components which are subject to a type of buckling failure known as dishing. As there is significant opportunity for real cost saving through the direct integration of these lifting strategies into ship bulkheads, creating additional data on their behavior was beneficial. Destructive test were conducted to confirm the failure mode and ultimate strength of several geometric designs and loading angles. A full report summarizing this effort can be found in Deliverable 2.

1.2. Executive Summary

With any analysis, assumption need to be made that will typically reduce the accuracy of any estimation. This is especially true for operations subject to considerable dynamics and variability which rigging if often noted for. First, a documentation of the actual dynamics and stresses within lifted structure was desired, and this was accomplished through the application of accelerometers and strain gauges to shipyard lifts. These instruments showed that during a rigging operation the stresses within a lifted structure varied significantly from the relatively steady stresses recorded when it hung motionless. For most structure lifted using sound rigging practices the highest stresses occur near the attachment points of the slings to the load. These attachment points are commonly composed of padeye or lifting lugs, for which there is considerable variation for the design of within the industry. However, most padeye designs are especially prone to significant stress increases with the application of even small side loads, so determining this typically range during a lift is highly beneficial. The most common cause of side load results from an error in the estimation of the Center of Gravity (COG), but proper rigging practice will eliminate this declivity though sling adjustments as the structure is first lifted. Two crane lifts are common practice at shipyards at it was found that dynamics during this type of operation are significantly larger than single crane lifts. In a two crane lift it was found that once the structure is lifted angles slings and therefore side loads will develop from the relative motion of the two cranes. Figure 1 shows a summary of the results from the lifts reviewed where the dynamics of twisting and swinging of the load were generally found to cause about one degree of side load. More operational effects such as the positional tolerances of the different hooks, or the cranes themselves were found to create much larger side loads, with generally up to 5 degrees observed.

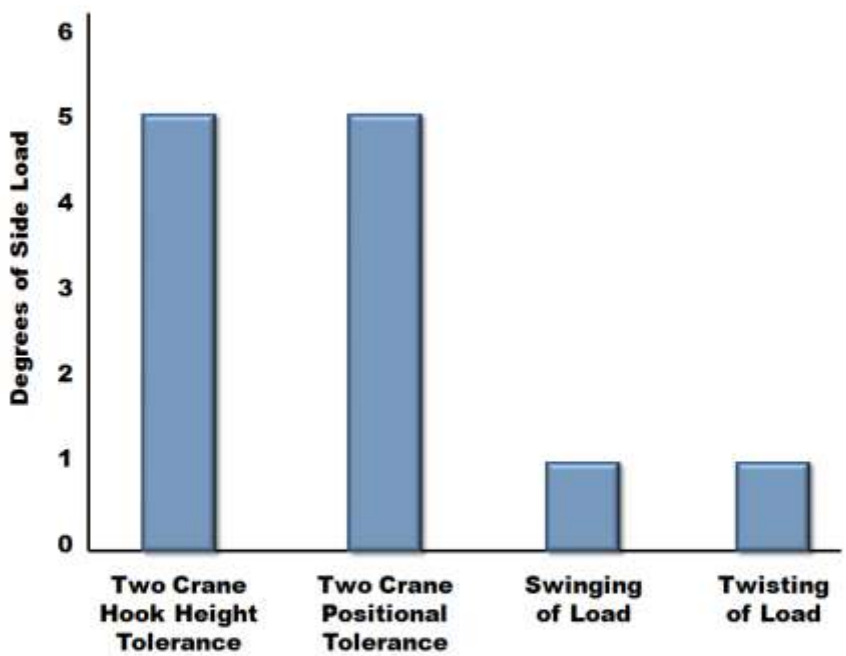


Figure 1: Angular Changes Caused by Dynamics and Operational Variables

Additionally there are other factors which will cause the stresses in various parts of the structure to be higher than one might estimate after the standard set of assumptions. Figure 2 shows some of the known and recorded causes and approximate magnitudes. During this research the bouncing of the load caused by crane movement, with accelerations up to 5% of gravity were observed, and undoubtedly caused an equivalent, but relatively minor increase in stresses during all rigging operations reviewed. Another common cause for increased sling loads are errors in the weight estimate. Despite having the opportunity of significant post lift review, the project team had significant difficulty accounting for the weight of large lifted objects better than within 2% of actual. Estimating the exact weight and COG of an erected ship unit months before a lift is more complex and weight errors of up to 15% are rare but do occur. If the structure is heavier, the sling loads will be greater, and the internal stresses equivalently larger. Errors estimating the COG will also cause a shift in the individual sling tensions and internal stresses. Although this greatly depends of the geometry of the rigging arrangement utilized and the magnitude of the error, it is believed that these effects can frequently cause slings to see 10% more load than estimated. One well known problem is that large lifts often have multiple slings arranged in a statically indeterminate arrangement, where actual sling tensions depend on many different tolerances and factors. Although not specifically studied in this project, many common rigging arrangements in a worse case scenario could see sling tensions twice the optimistic plan. Finally, the interaction between the load and the ground, as a structure is first lifted produced shocking large increases in stress. Some relatively low stress areas of the structures lifted saw stresses orders of magnitude higher as a result of ground interaction, than what was experienced during the rest of the operation. All structures reviewed had some stress increases as a result of ground interactions, and were typically less than a 50% increase. However, one structure saw global stresses and bending moments twice what was projected during the lift. Although this may have been a peculiarity specific to this one structure and its blocking arrangement, it is possible that such incidences occur regularly. The results of this research clearly show that rigging operations are dynamic, and that there can be significant uncertainty surrounding the loads and internal forces of lifted objects.

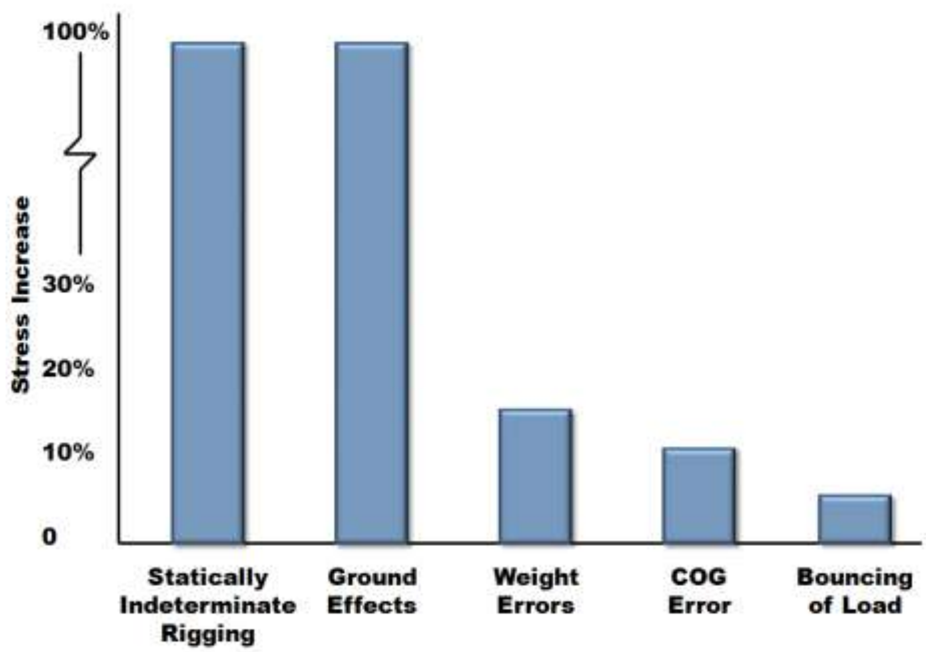


Figure 2: Stress Increases Caused by Dynamics and Operational Variables

Finally given known loading conditions, an understanding what the relative accuracy of various methods of rigging analysis is desired. Part of this effort researched the best boundary conditions to apply to FEA efforts, in order to match the actual behavior of lifted structure. Using the most detailed FEA created as a baseline, the comparisons in Figure 3 were made. Simplification of the FEA was undertaken to determine how much detail could be eliminated and still retain reasonable accuracy. It was found that FE models simplified to just a core structure projected behavior and stresses within typically 30% of the highly detailed model, and were created in a fraction of the time. From these efforts the simplification guidelines were developed and refined and an 80/20 rule generally applies. It is believed that structural models that are 80% as accurate could be produced through simplification, while only requiring 20% of the effort. This suggests that for rigging analysis one does not need to model all of the mass of a lifted structure to obtain reasonable stress predictions. Similarly, classical methods of analysis were reviewed where free body diagrams are used to estimate the sling tensions, load paths assumed, resulting forces and moments calculated, and structurally effective sections assumed. Although for simple structures, with assumptions made by experienced personnel, stresses could be projected within 30% of the detailed FEA, much higher errors were possible. Conservative assumptions or overly generous effective sections routinely resulted in estimates in error by a factor of five when compared to the detailed FEA. On very large and complex structure the errors resulting compound, and experienced personnel had trouble projecting stresses within this range. As a simplified FE model might only take slightly more time than classical methods this shows there is a strong case for the application these methods to the rigging analysis of complex structure. Furthermore, given the naturally large variability of rigging, high design factors appear to be inevitable to ensure safe operations. As a result, there appears to be marginal benefit for utilizing highly detailed but more accurate FE models to represent lifted structure.

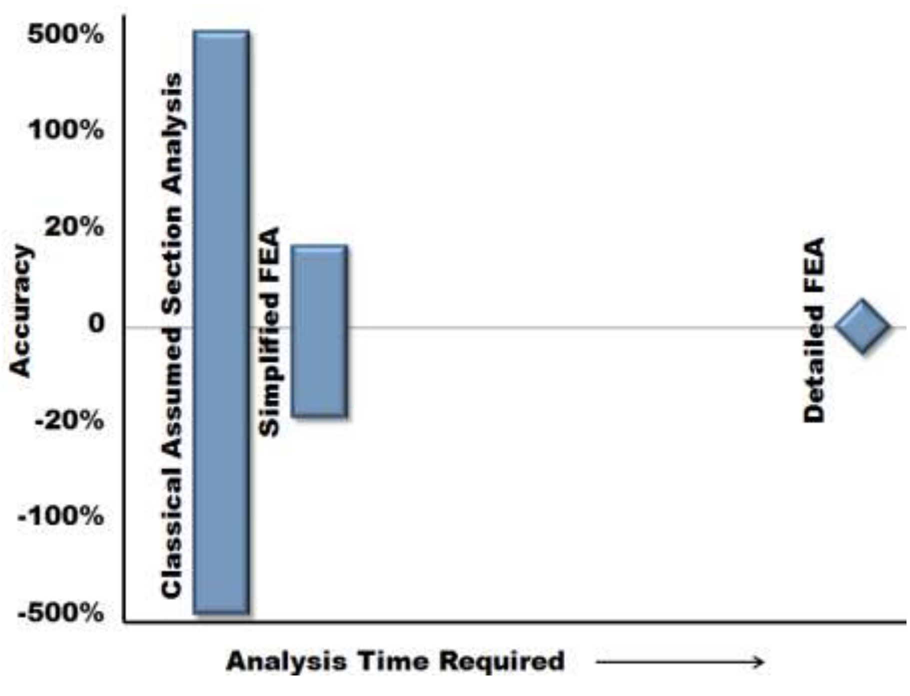


Figure 3: Relative Accuracy of Analysis Methods

1.3. Lifted Ship Structure

Fully defining the rigging process for all types of structure, using every method of material handling is an effort much larger than the scope this project. The scantlings of every type of ship and even various parts of a ship are different, and any review conducted must be aware of this. In addition to the size and spacing of structural members there can be considerable variation in the amount of structure on a block or any section of a ship under construction. One way to categorize this is the number of continuous bulkheads or vertical planes of structure that a block has. For rigging applications the increasing size of members both adds to strength and weight, so the simplification of them to planes of structure is directly relevant. Approximately two hundred small blocks were reviewed for a general cargo ship which created the bell curve distribution with a fat tail shown in Figure 4. These blocks had a range of weight from 44 to 212 short tons with the heavier blocks generally having more planes of structure. This distribution shows that over half of all small blocks have two or three bulkheads on them. Only a tenth of the blocks had just one vertical plane of structure which was typically a part of the shell plating. For the vessel reviewed, just over 15% of the blocks were inner-bottom blocks, blocks forward of the collision bulkhead, or blocks near highly shaped areas such as above the propellers. These types of blocks generally have a significant number of planes of structure as the design of them is typically driven by classification society requirements with higher loading conditions. This explains the fat tail, which may be a common feature to modular block ship construction. To create documentation and references that were as relevant as possible, blocks were chosen for analysis that provided an appropriate sampling of the spectrum seen. Finally NASSCO's crane capacity pushes large erected blocks to typically be composed of 2 to 6 small blocks, which is similar to other large tier yards. With grand blocking the numbers of planes of structure will typically increase, although not all planes of structure are continuous across multiple tiers of blocks.

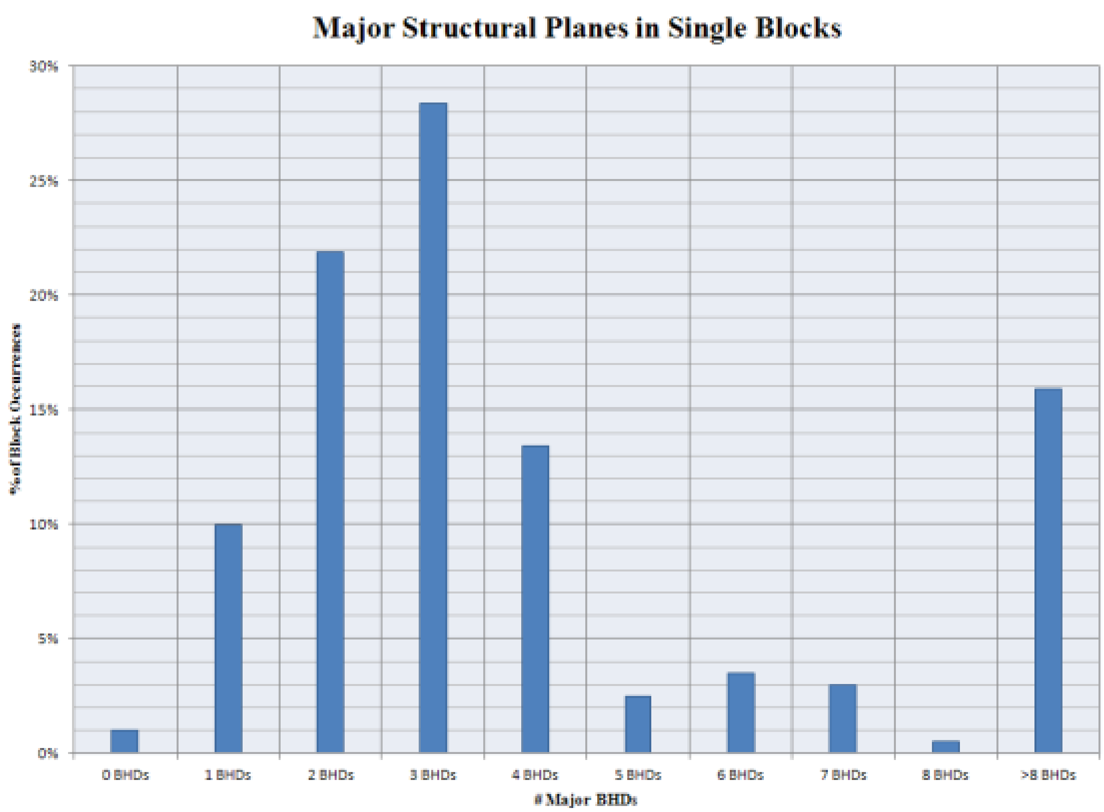


Figure 4: Major Structural Planes in Single Blocks

One critical aspect of rigging engineering is the connection philosophy and local structure around the lifting padeyes. However, the review of this subject is highly dependent on the design of these attachment parts, and there is considerable variation in the industry of these parts. As a result the focus of this research is targeted towards global analysis and the lifted behavior for typical ship blocks. This provides industry references for the global behavior and lifted stresses, and should assist rigging engineers when a more detailed review is warranted.

The global rigidity and strength of lifted steel structure is closely related, where generally more flexible structure is not as strong. Figure 5 shows the general progression from left to right with regards to the structural rigidity of ship structure or blocks. During construction, all ship structure starts relatively flexible, such as unstiffened plates, and subsequent operations add more structure and stiffness. As stiffeners, frames, and bulkheads are added the blocks become larger and more rigid. Some of the most rigid structure on ships is the double bottom or inner bottom which is designed to balance large water pressure loading while creating a foundation for the ships self weight. Similarly, many large blocks are composed of several stacked smaller blocks which adds rigidity as they are assembled and connected. The primary concern for rigging engineers on rigid blocks is typically stresses near the attachment locations.

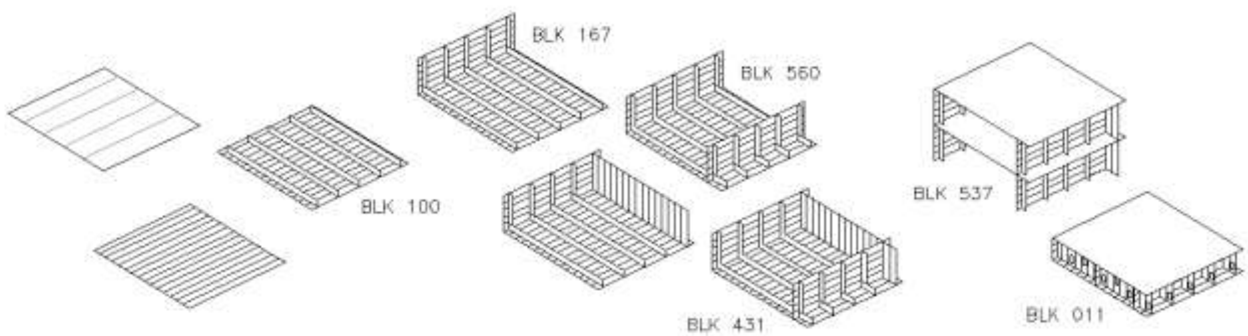


Figure 5: Typical Sub-assembly and Block Types

The addition of outfitting to blocks under construction typically increased the non-structural deadweight loading and also represents a general investment in the block. As a result, the study of the lifting of blocks that are more heavily outfitted is therefore more pertinent. Similarly the material cost consequences of improper handling of a single plate are significantly lower than larger more outfitted structure. In order to maximize the benefits of this research, blocks were sampled for extensive analysis and instrumented lifts that encompassed a range of typical block structures, that a typical shipyard might desire review of.

1.4. Sampled Blocks

During this research six different types of blocks were lifted each of which had a comprehensive report created, which are intended to act as references for shipyard rigging engineers. These structures were:

- Deck and shell block (Deliverable 1)
- Inner-bottom block (Deliverable 3)
- Small house block (Deliverable 4)
- Frame stiffened panel (Deliverable 5)
- Double decked grand block (Deliverable 6)
- Hangar grand block (Deliverable 7)

1.4.1. Deck and Shell Block 167

During the first phase of this research an initial desire was to determine the accuracy and consistency of the data that could be produced during the project, and assess its value. In this first phase only a deck and shell block was lifted, which was square in shape 53 ft wide, 52 ft long, and 13 ft high with a weight between 82 and 96 short tons. This block only had one plane of structure that was intended to be rigid, which was the shell plating. On the opposite side of the block there was a sheet metal elevator door which was installed still inside of its protective shipping frame, and was only temporarily connected to the block with a one sided skip weld. It is believed that this frame did in fact act as a rigid plane, although it did not run the full length of the block. One of the three strain gauged lifts of block 167 attempted to confirm this behavior. Unfortunately, a failure of these instruments occurred and confirmation its structural behavior did not occur. During this full extent of this research project, 156 individual strain gauge channel recordings were attempted with only 7 failures, 5 of which occurred during this first assessment phase.

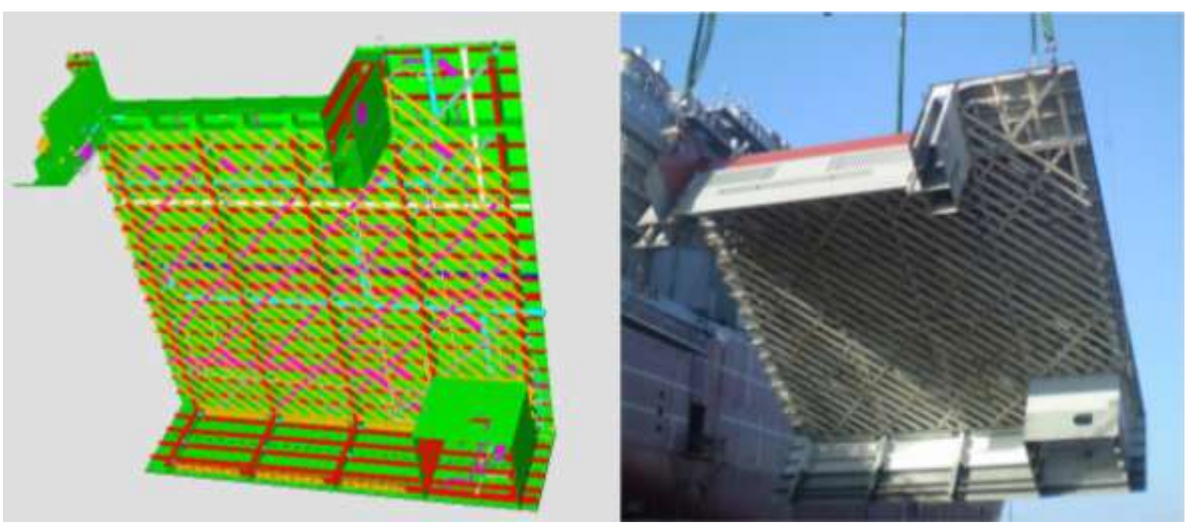


Figure 6: Deck and Shell Block During June 17, 2010 Turn

Instrumented lifts of block 167 took place on three separate occasions which allowed a direct comparison of data from separate but similar lifts of identical blocks from sister ships, such that an estimation of typical variation could be made. These variations could be from different rigging equipment used, crane operators, ambient conditions, construction assembly variations, or initial supports heights and locations which can cause initial internal stresses in the structure. Two of the lifts were when the block had a weight of 82 shorts tons, of which about 93% was structural steel. These two operations were conducted almost exactly six months apart by different cranes with different spreader bars and slightly different rigging arrangements. Before these lifts, the block was supported with different methods and materials with the first lift having precisely sized steel supports providing a completely level foundation. The lift of the sister ship block occurred from wood supports that did not provide a precisely level condition, and imparted more initial bending stresses in the deck of the block. As a result many of the strain gauges measured different stresses during these lifts. Determining and accounting for the initial stresses in block was a difficulty throughout the project and often influenced where gauges were installed. One methodology for blocks that were turned was a comparison between their initial lifted and final lifted state. This allowed the relative change between ships position and build position to be compared, which are two more defined load cases. It is believed that this methodology significantly reduced the errors induced by the initial state of a block and its many supports with highly unknown loading.

Importantly instruments that were on the shell of this block and that were not susceptible to initial support conditions and did produce data that was very similar on all lifts. Data from this shell bulkhead was used to estimate the relative angle that the slings made to the block and suggested that during both crane movements through the shipyard the slings were oriented through an angle that ranged through about 6 degrees. Although the mean of these ranges were not the same it did suggest that a certain repeatability from the data that was recorded. During the rest of the project, other data sets recorded by strain gauges also indicated that this amount of variation is likely to occur.

Figure 7: June 7, and Dec 8, 2010 Deck and Shell Block Lifts

During the first lift of the deck and shell block a notable twist was observed in the structure as it cleared the ground. In the report detailing the analysis conducted and results obtained, it was mistakenly thought that this was in part because of the sling length utilized, which is now known to not be a significant contributor in this case. This wracking was subsequently not observed during the lift and turn of this block which was conducted after a significant amount of diagonal metal outfitting was added. On the final lift of this block from the sister ship, with different sling length rigging arrangement used, a wracking of the block was observed again. This showed that the wracking was a consistent function of the blocks structure, weight distribution, and was less dependent on its lifted arrangement. At the time this resulted in some confusion as to the exact cause of the wracking, a debate which did not fully make it into the report at the time. The lifted deflection of blocks can be important since as they become more heavily outfitted, the clearances during erection are often less, and therefore the tolerances of global deflection must be smaller. For many lifts wracking is not a concern, but for large highly complete unit erections, having a better understanding of this phenomenon is highly beneficial as it will help minimize rework, and increasing safety. The desire for the direct measurement of this prompted the procurement of accelerometers which were used on all subsequent lifts, to measure the stable orientation of various parts of the lifted structure.

The accelerometers obtained also helped measure and confirm the dynamics that were occurring as well. On during both lifted movements of block 167 oscillations were seen in the recorded strain gauge data that matched the natural frequency of a pendulum under the crane sheave. On subsequent block lifts motions of lifted structure matching these periods were confirmed.

1.4.2. Innerbottom Block 011

The most rigid block analyzed in this research was an inner-bottom which is part of the double-bottom structure of the ship. This block was almost square 61 ft wide, 51 ft long, and 7 ft high with an estimated weight of approximately 212 short tons, which was almost entirely structural steel weight. Counting the bilge radius which had a large bilge keel as a structural plane, there were a total of twelve such planes connecting the bottom shell to the tank top. One of the main reasons for the blocks rigidity is the bottom shell plate and the tank top were connected by so many structural planes, which transfer internal shear and therefore allow the resistance of bending forces in the unit. Because this block is essentially the foundation of the ship, it is designed to be strong and rigid, as it supports the vertical weight of the entire ship and is heavily loaded by water pressure on the underside. As a result the global lifted stresses in this block were very low, with the highest stresses directly under the attachment of the padeyes.

The rigging operation conducted was a single-crane lift, and only vertical dynamics were recorded during the lift. This is evidence that most of the dynamics seen during the other lifts was mainly a result of being multiple crane operations.

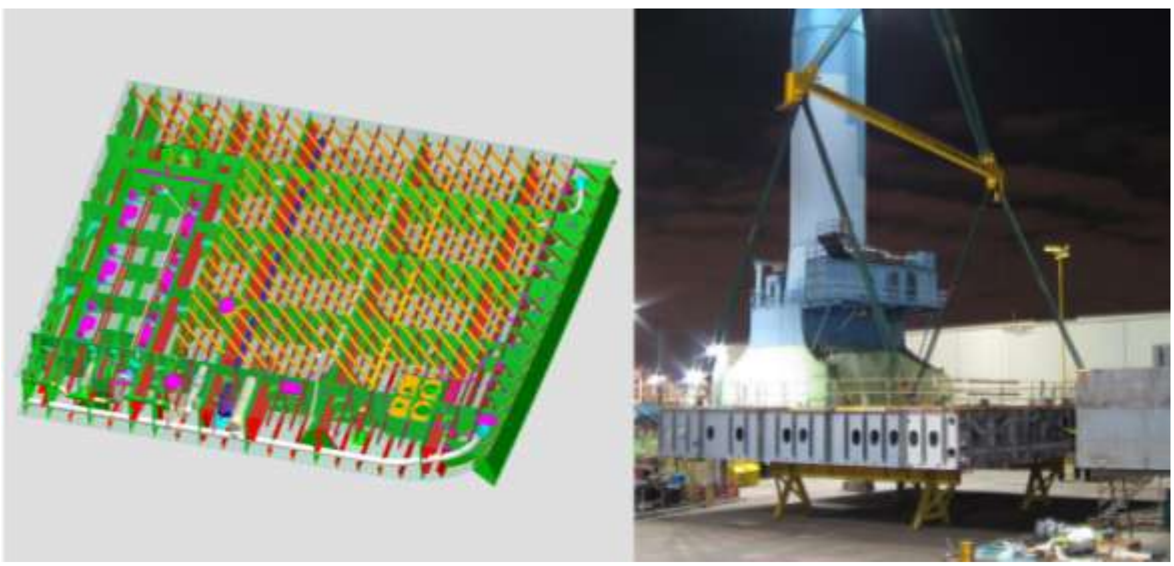


Figure 8: Innerbottom Block

1.4.3. Small House Block 431

One of the blocks reviewed was a small house block, which allowed the investigation of the lift and turn of a relatively flexible block with minimally sized structure. The block was roughly rectangular in size 77 ft long, 38 ft wide, and 10 ft high and weighed approximately 44 short tons, 82% of which was structural steel. This unit is a good representation of a block designed to ABS rules for an accommodation-type structure high above the water that was designed for relatively light loading conditions. This resulted in the block having relatively small plate thicknesses and light overall scantlings with vertically stiffened bulkheads. Almost all bulkheads on the block are the minimum thickness according to ABS rules for superstructure at a significant tier. This block had two main bulkheads running its length that acted as the main structural members, one of which was weakened by several door cutouts. Also, as these bulkheads were vertically stiffened, they required temporary bracing along their length to reduce the chance of buckling and ensure that they were effective load carrying members. Transversely, there were two bulkheads at one end that effectively strengthened only that end.

This was the first block in this research project for which the use of accelerometers assisted in confirming that wracking or twisting of the lifted structure was taking place. Imparting the measured wrack into the detailed FEA suggested that some of the sling loads were up to 2.4 short tons or 35% different than the idealized free body diagram predicted. However since stresses built into the block could have also effected the lifted deflections, there is no way of knowing exactly what the individual sling tensions were. Calculating the torsional stiffness of a block by traditional methods is quite complex and subject to significant error. Similarly, experimentation with the detailed FEA at the time was unable to uncover a method to project lifted deflections due to wracking. Continued analysis since this block's report was issued has uncovered such analysis methods, but they are not generally workable even on small blocks as they require a very high percentage of the mass to be modeled.

Finally, during the turn of this block two stain gauges measured a several second duration stress spike of significant magnitude, after which the recorded data reverted to the average trend. A likely explanation for this are weld related shrinkage stresses relieving themselves through general yielding of the bulkhead near the gauges, or possibly a localized elastic buckling of the bulkhead. Inspections of the block after the lift showed no apparent cause or deformations visible, and there were no reports of alignment problems later. No additional theories have offered themselves since this blocks lift report was originally issued and exactly what happened will probably never be known. This anomaly can only stand as evidence that there is a considerable amount of uncertainties and unknowns in shipyard rigging operations.

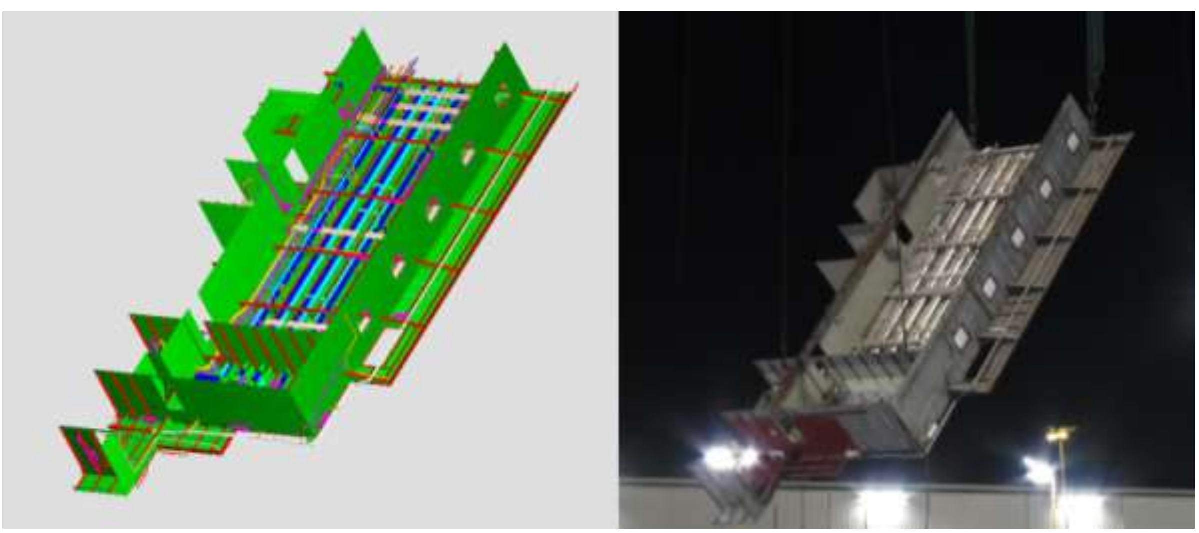


Figure 9: Small House Block

1.4.4. Frame Stiffened Panel BLK 100

One lift reviewed in this research project was of a heavily outfitted frame stiffened panel, which allowed the investigation of the lift and turn of a relatively flexible block with no bulkheads. Since flexibility is largely a function of moment of inertia, blocks or panels that do not have any bulkheads are particularly flexible. This block was rectangular in size 66 ft wide, 20 ft long, and 8 ft high, and had an estimated lift weight of 44 short tons. About 34% of the weight was from outfitting which consisted of wire ways, ventilation ducting, and a significant amount of piping including a 30” diameter pipe approximately 60 feet long. Due to its size this pipe is not run through the neutral axis of the frames, but below them, and therefore was of special interest as in this position it is more likely to be subject to the global bending stresses from the lift.

During this lift it was found that the large pipe did contribute to the global strength of the block but did not act as a fully effective member. There are a number of factors that limited its effectively such as rigidity of the pipe hangers, their spacing, and clamping force applied during installation, which is generally only snug until final positioning. These factors most probably will result in installed piping merely matching the deflection of the lifted structure, which was also observed on the deck and shell block. One other interesting result from this lift was the considerable unforeseen stresses that resulted from the interaction with the ground when it was first lifted. This phenomenon was observed on other lifts but perhaps due to the locations of the padeyes relative to the blocks overall size, significantly larger stresses were observed.

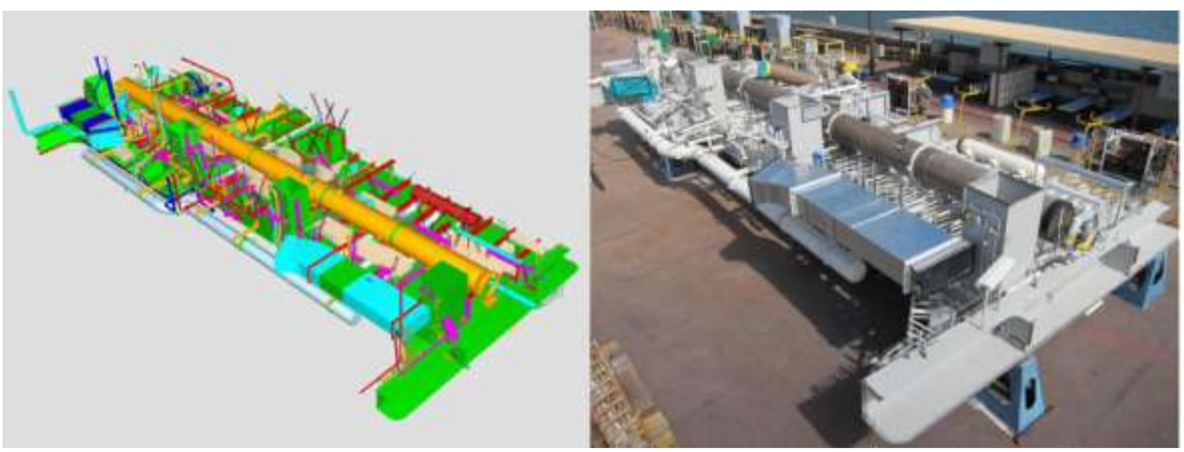


Figure 10: Frame Stiffened Panel

1.4.5. Double Decked Grand Block 537

The heaviest block lifted during this research was a large double deck grand block, which allowed the investigation of the lift and erection of a structure of significant size. This block was rectangular in size 106 ft wide, 52 ft long, and 32 ft high, with an estimated lift weight of 531 short tons, 72% of which was structural steel. This block was essentially composed of four smaller blocks similar to the deck and shell block also reviewed, but with more minor bulkheads. In addition to having two decks, this block had a transverse watertight bulkhead on both levels which provided significant stiffness to the block. There was also shell plating on both sides of the block which acted as rigid planes of structure. Aside from these three major planes of structure there were twelve steel bulkheads of various sizes. Most of these were relatively short in length and of slightly smaller scantlings, and did not contribute any significant resistance to global bending. Only two of these smaller bulkheads ran the length of the block on the lower level, and five tied short segments of the two decks together. From a global perspective, the block has enough structure that it could be treated as a rigid object. As a result most of the deflections and stresses caused during the lift were local to the members connecting the padeye locations to the main structural planes.

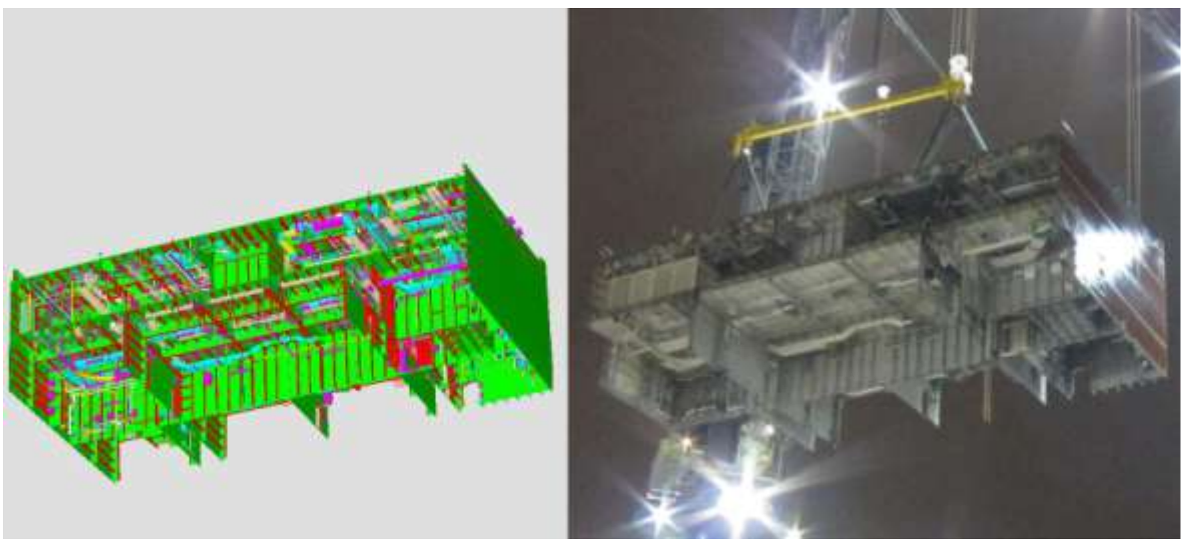


Figure 11: Double Decked Grand Block

1.4.6. Hangar Grand Block 560

The final block that was lifted during this research was part of the house superstructure and consisted of a helicopter hangar, which allowed the review of the lift and erection of a relatively flexible non-homogeneous block of significant size. This structure was roughly trapezoidal in shape being 106 ft wide, 59 ft long, and 47 ft high, with an estimated lift weight of 354 short tons. Most of this block had only one deck which was over the hangar, and this large lightly stiffened area significantly defined the lifted behavior of the block, and did not promote global rigidity. The structure of this block was built to relatively minimal scantlings with mainly vertically stiffened bulkheads common to ship superstructure. On both sided of the hangar there were longitudinal bulkheads, the port side having one, and the starboard side having two, all of which were 23 ft high. Although these longitudinal bulkheads have cargo doors cutouts, they still act as significantly rigid planes. The starboard side also has an additional deck joining the two longitudinal bulkheads which created a relativity rigid section on that side of the block. The aft side of the block had a transverse bulkhead but this had many large cutouts and even with many temporary braces did not act as a robust structural plane.

It was learned over the course of this research that large single decked structures do not lend themselves to behaving as rigid objects which further complicates rigging analysis if there is significant variation in the distribution of mass and lifted deflection is critical. Block 560 had a non-uniform mass distribution and was therefore targeted for an instrumented lift and detailed analysis. Wracking of this structure was recorded when it was lifted. The wracking of a lifted object will alter the loads in the slings and although methods of analysis to project these deflections are known, projections are difficult as they require accurate FE modeling of all the structure, and importantly all of the mass of the lifted block. Similar to the small house block lifted, the best efforts available were unable to replicate the angular wracking measured by the accelerometers. However, in this case it is believed that the wracking did not alter the sling loads sufficiently to cause much error in the FEA projected stresses. Finally, this structure also had lifted stresses of significant magnitude in the overhead of the hangar, and in the temporary strongbacks across the hangar door at the aft end. Traditional assumed section analysis methods required multiple layers of convoluted assumptions to project these stresses and were found to be accompanied by considerable error. Simplified FEA did a much better, and efficient job of projecting the lifted stresses, and therefore provides a strong case for the use of simplified methods when confronted with large complex lifts.

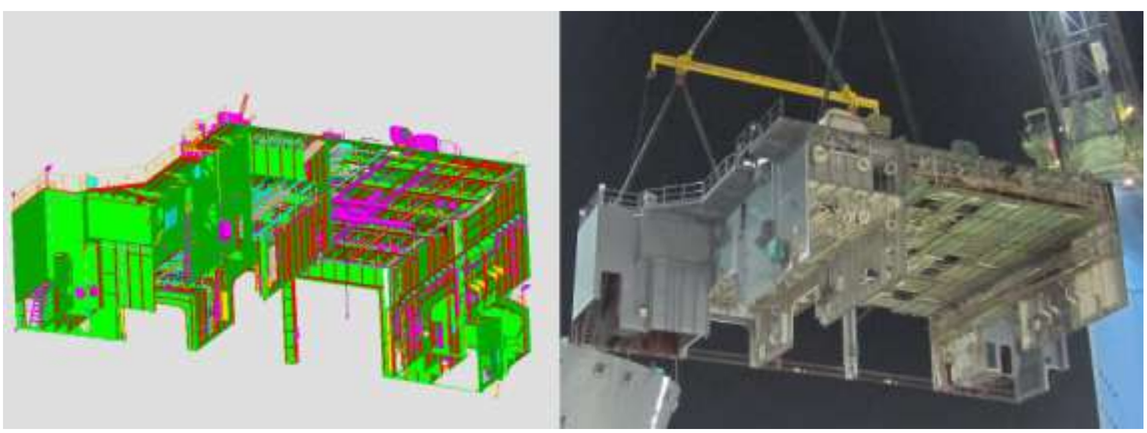


Figure 12: Hanger Grand Block

1.5. Review of Rigging Analysis

Historically riggers at shipyards have typically depended on rules of thumb, experience of previous practice, and high factors of safety to ensure the safe conduct of rigging operations. In the days when a 40 ton lift was considered large, and analysis was conducted by slide rule, this approach was usually acceptable. Rarely would moving an assembly require the application of analytical tools by engineers. Also, since the heaviest lifts were often large cast machinery, little review was required of the internal forces within these objects. When analysis was conducted it was relatively basic free body diagrams, used to determine sling forces and review local attachment loading conditions, which would be compared to previous practice. As assembly sizes and weights have increased and their modes of movement become larger and more varied, complex rigging analysis is becoming more necessary, while the increasing scale of lifts reduces the effectiveness and accuracy of traditional methods. Modern analytical means however powerful, can be time consuming, making it difficult for rigging engineering staff to keep pace. This research reviewed a spectrum of analysis methods for lifted structure, from the most basic free body diagrams and assumed sections, to highly detailed Finite Element Analysis (FEA).

The fundamental basis of this research was that it takes much longer to do a complicated, highly detailed analysis than a simple rudimentary one, and a very thorough analysis may only be slightly more accurate than a simplified one. Compounding the difficulties encountered when undertaking an analysis is that rigging can be highly variable, with many different loading conditions possible, many of which significantly affect lifted stresses. Given the typical variability of rigging operations, even highly detailed analysis can be subject to considerable error. The natural variability of rigging encourages the use of high design factors, which in turn partially reduces the need for highly accurate analysis, with exact loading conditions and well defined ranges. At the extreme, a perfect FE model of a large structure with all details and mass included is practically impossible, as this may take an unacceptable amount of time to create. Similarly, reviewing all possible loading conditions was not even possible in this generously funded research. This illustrates that for all analysis, assumptions about structure and loading need to be made, and these assumptions will reduce the precision and accuracy of any analysis. In rigging analysis there are two main sources of inaccuracy stemming from the assumptions required, the approximations with regards to the structure being lifted, and the uncertainty regarding the loading conditions. To conduct efficient rigging engineering the uncertainty created by simplifications of the analysis should be directly balanced against the expected variability of the rigging operation. The relatively error of various levels of analysis detail is discussed in the following sections.

1.5.1. Classic Assumed Section Analysis

The vast majority of shipyard lifts rely primarily on classical methods of structural analysis, combined with the significant experience of qualified personnel and comparison to past practice. Before any structural analysis begins the weight and Center of Gravity (COG) of an object must be established, along with a proposed rigging arrangement. After this first step a free body diagram can quickly be used to calculate the loads on the cranes and estimate the loads in individual slings. This is the most efficient method of determining if the cranes are big enough, have the reach required, and can lift from a suitable attachment plane. Classical methods then take these projected padeye loads and use them to review the strength of various members of the lifted structure. If the structure is inherently simple, relatively accurate lifted stresses can be predicted, but as more assumptions are required the possible error increases exponentially.

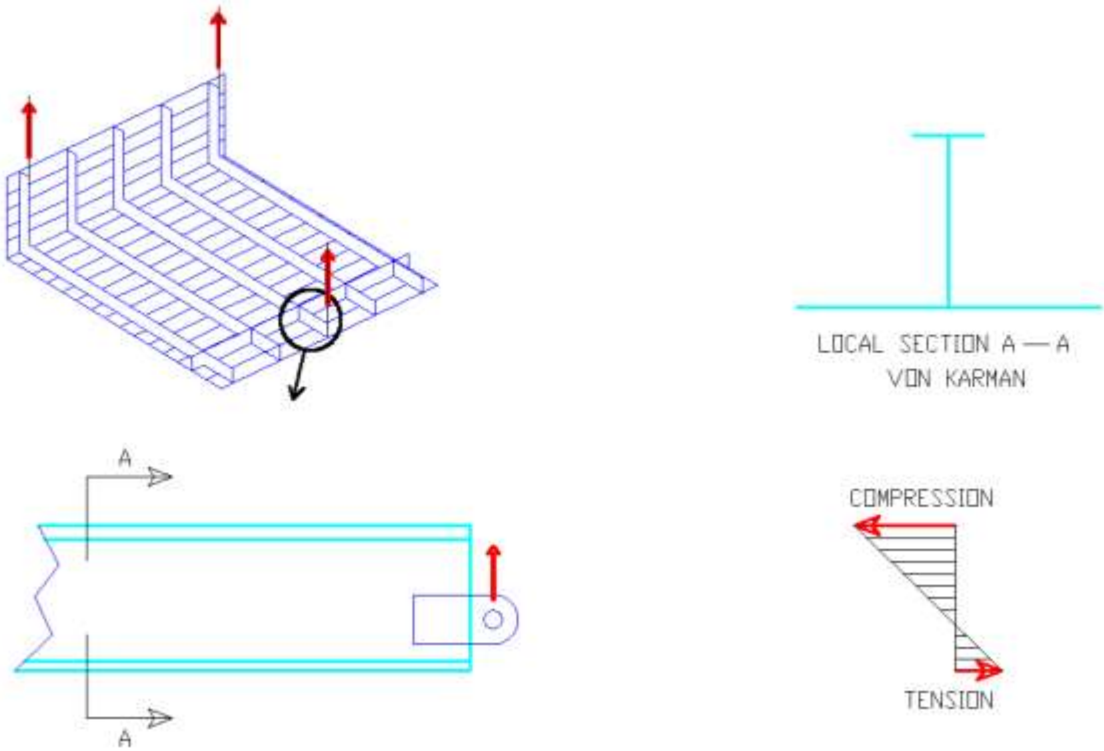


Figure 13: Local Classical Analysis

Classical analysis starts with the tensile, or compression forces, and moments that result from the lifted loads being calculated for the section of interest or concern. Depending on the scope of the analysis, gravity loads may need to be included as well. Considerable assumptions are undertaken during the selection of an applicable section. Saint Venants principle requires that for valid projections to be made, the section must be far enough away from the load that the stresses will be evenly distributed through it. This results in difficulties regarding the chosen section on large plate based structures, as the assumption that the entire structure is bending uniformly with linear elastic behavior is typically too optimistic. This is directly contrast with the conservative assumption that just one minimum sized beam of the structure is resisting the load. Importantly, these two assumptions should bracket any estimate of stress, with predictions either too high, or too low. If the review is being conducted of an area very close to a padeye, the assumption that just a small section based on Von Karman plate buckling is effective, and should produce the more accurate estimate. This is best shown in Figure 13. For the global bending analysis of a structure that is much longer than it is wide, the assumption that the entire section is resisting the bending forces, with the inclusion of gravity loads, is more likely to produce the more accurate estimate at a section removed some distance from the lift points. This is similar to Figure 14. In this research, it was sometimes found that the full section assumption produced stress estimates five times less than the detailed FEA projected. This directly mirrors the estimates produced by a conservative section assumption, which produced estimates sometimes five times larger. It is unknown if this range is common to most ship structure or just a coincidence. This does however show the considerable range of estimates that are possible using classical analysis methods and a correct assumption of effective section and load path is highly variable.

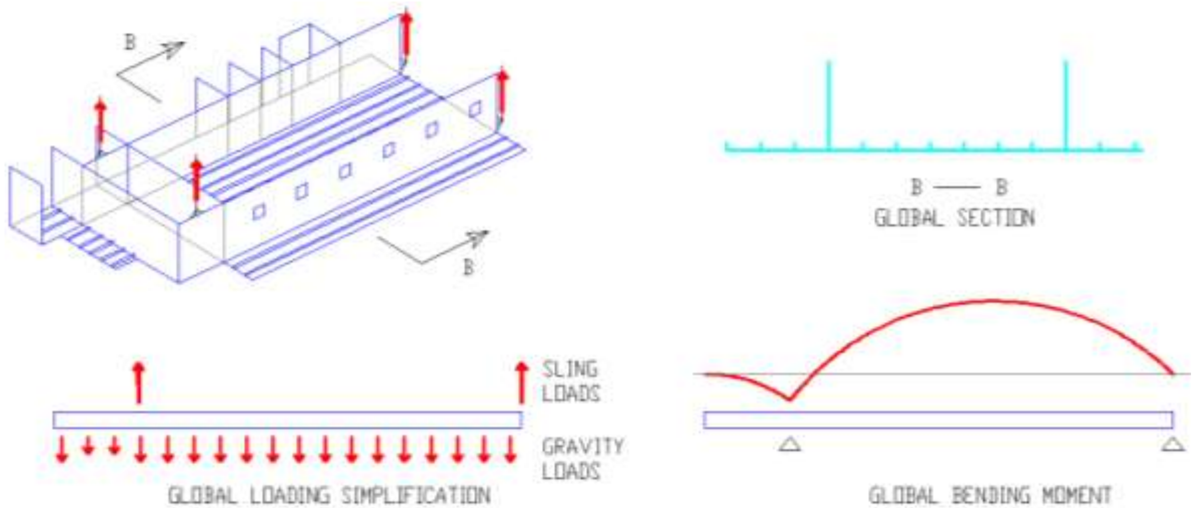


Figure 14: Global Classical Analysis

To assist in narrowing the considerable range of strength estimates possible, a fanning method for choosing an effective section was reviewed. This method increases the width of the assumed section the further away from the padeye, or point of load application. A 30 degree arc to each side of the primary member is swept through the structure and the inclusive members are assumed to be effective at resisting the bending moment. This section will roughly balance the increasing moment with the sections moment of inertia, before self weight is accounted for. This method is shown in Figure 15, where the bending moment of interest is near the padeye located on the central of five frames. In this example, the further from the padeye location the higher the global bending moment will be, generally up to very near the transverse COG location. This moment would increase linearly with distance, but when the self weight of the structure is accounted for results in a lower total moment. A section's moment of inertia will on average increase linearly with distance from the padeye due to the fanning of increasing section size, but can vary significantly due to the stepping of structure included. This can be seen in the figure where the section though (C) will have a much larger moment of inertia than at (B). This leads to some variation when using this method. Also, this method requires the assumption that the structure being reviewed is sufficiently constructed, with both frames and longitudinals providing stiffness to the structure. Structure running in both directions facilitates the transfer of deflections and therefore moment to adjacent frames. The relative stiffness between the primary members to the secondary members will also significantly affect this assumption. The larger the secondary members are the better the moment transfer between frames is. In this research, and where applicable, this method produced results that were much closer to what the detailed FEA predicted.

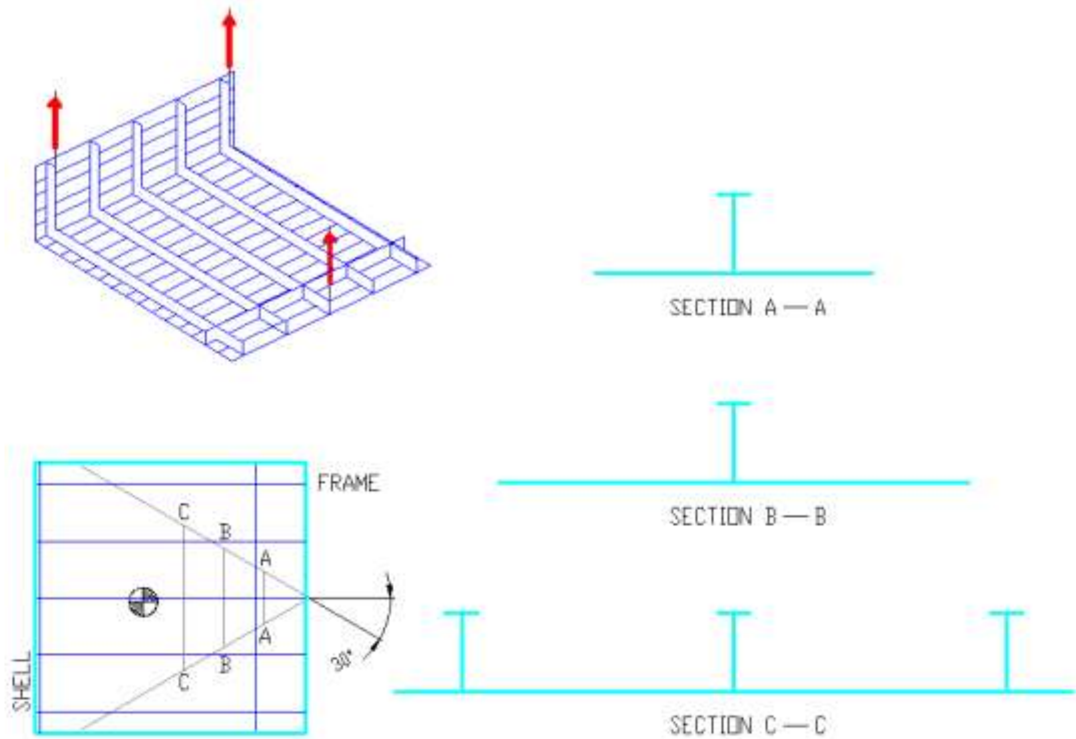


Figure 15: Fanning of Section Effectively

1.5.2. FE Detail for Lifted Structure Analysis

Finite Element Analysis FEA is an immensely powerful and valuable tool that provides detailed insight into the behavior of structures unavailable just decades ago. To have a high degree of confidence in the analysis of very complex structures, FEA is almost a requirement. Unfortunately, FEA can be expensive, as aside from just the direct cost of the software, specialized highly trained individuals are required, which currently limits its use to mainly larger tier shipyards. For shipyard rigging engineers this expense typically limits its use to isolated blocks which present exceptional challenges due to uniqueness or complex geometry. Furthermore, it is difficult to compare the results predicted by FEA to previously lift analyses, when little analysis is available for reference. Finally, it is difficult to apply this relatively new technology to shipyard lifts as the dynamics and operational ranges of loading conditions possible, often critical, is not well defined. One of the primary goals of this research was to create better references and definition of the operational bounds to aid the application of FEA to shipyard rigging.

One of the major drivers of cost when applied FEA to shipyard lifts can be the creation of the structural model. The larger and more detailed the model, the longer it takes to both create and run or manipulate. Erected ship blocks are often of significant size with a considerable amount of equipment and miscellanies items onboard. Weight is one of the most important things in rigging, and up to 40% of the blocks weight could be non-structural steel, outfitting, or equipment, which can present a significant challenge. Not all of the final mass of the block is included during the lift, and temporary items related to production also exist. As a result, the vessels final weight report is only of partial help. To create a highly detailed and accurate structural model, the exact locations and weights of all items included during the lift need to be tracked down and documented. As a result, creating an exact model of what will be lifted takes tremendous effort, and there will always be uncertainly with regards to temporary parts, stashed items, or missing equipment. This is further complicated as rigging engineering must be done significantly in advance of the operation, when the installation schedules for many items are still highly variable.

Although in theory the accuracy of the structural FE model will increase as detail is added, the law of diminishing return applies as eventually minimal benefit can be expected. Furthermore this increase of accuracy will only be for the loading condition assumed, which will be different than the operation that takes place, and may vary significantly during the operation. It has been shown that the dynamics and operational variables that can occur create considerable variation in the stress within lifted structure, especially near the lifting attachment points. This suggests that a high design factors may be required to account for the uncertainty of the rigging operation. Balancing the uncertainties will result in the most efficient analysis being less than highly accurate. A primary goal was to research the relationship between the effort or modeling detail required, and the apparent accuracy of rigging analysis resulting. This should allow the optimal level of detail to be selected for which to analyze a rigging operation.

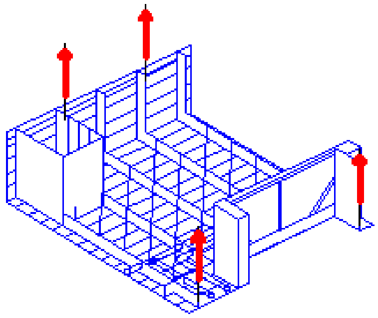
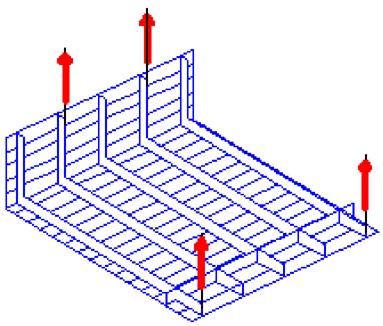
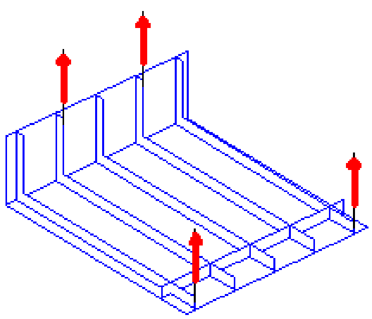
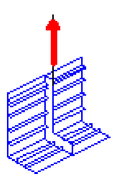
To streamline rigging analysis such that minimally beneficial work is reduced, various detailed levels of FE structural models were created, analyzed, and the relative results compared. Although time and resource constraints, along with block variability did not allow for exact consistency in modeling methods, in general levels of uniformity were strived for to assist in making broad conclusions. These levels of structural detail investigated can be referenced in Table 1. The detailed model was an attempt to model as much of the block as possible with the time and resources allocated. This attempted to include as much of this mass as possible with approximately 70% to 90% of the total mass of the blocks reviewed being represented. Generally 90% or greater of the structural steel on the block was included, with only small items such as local headers, lugs, and small chocks omitted. Partially compensating this is that almost all small holes were ignored, unless they were near one of the installed strain gauges or might affect how the loads from the pick points got distributed. As a result this was the most comprehensive structural analyses on the lifts conducted, and was used as a baseline from which to compare the other analysis. The detailed model has all structure modeled as plate elements as it was desired to easily extract localized stresses to compare to the strain gauge data recorded. As a result some time savings could be expected if some of these members were simplified to beam elements. When built from scratch the detailed model generally took at least five times as long to create as the simple model.

The ultra simple model only included the largest continuous primary members of a lifted block such as deck plating and frames or bulkheads. To further simplify the modeling the deck plating was reduced to the smallest thickness plate. Unfortunately this resulted in very little of the mass of the block being accounted for, and to make up for the missing mass, the gravity loading was artificially increased. The omission of longitudinals, combined with the minimum plate thickness used, and a gravitational acceleration being sometimes more than twice normal, generally resulted in significantly abnormally stresses in the areas of unsupported plate. This creates difficulties extracting useful information from such a reduced structural model. This research showed that this extreme simplification results in errors that are unacceptably high.

Much of this research was targeted towards defining an acceptable simple model. It was found that an acceptable simplified model generally did not take significantly more time than the ultra simplified model, and only took a fraction of the time as the detailed model. A simple model primarily just consisted of structurally significant bulkheads, frames, and longitudinals. The addition of longitudinal stiffeners greatly reduces the problems encountered by the ultra simple model. Generally outfitting can be completely ignored and the simple model only included structure that was considered significant to the global behavior of the block. Depending on the amount of outfitting, local foundations, and minor bulkheads, the percentage of the blocks weight modeled varied significantly from about 40% to 85%. As one would expect, the more mass of the block that the simple model had, the greater similarity the resulting estimates were to the detailed model. The simple models that had less than half the mass of the block modeled still had a reasonable correlation to the detailed model, however modeling more than half the weight of the block was much better. Along these lines, the more distributed the non-modeled mass was, the less critical its inclusions appeared to be. A simple model does not just have omission of mass, but will also have extra. In simple models only very large cutouts, such as hangar doors, were included if they were located in positions that obviously would significantly affect results. Not including holes in plates increases the mass of the model. It is believed that the omission of most holes directly compensated for much of the small headers, brackets, chocks, and stiffeners that are also ignored. Various approximations are also used to assist the creation of a simple model. The locations of planes of structure or stiffeners are averaged to create an even uniform spacing which is easier to create and work with. Similarly temporary rigging strongbacks or other stiffeners might be shifted location in the model such that they became placed were a modeled surface edge already existed. Much of this simplification attempts to generalize the structure, and as a result the structure will generally behave the same. For the blocks reviewed in this research, it was found that there was a consistent difference between the stress predictions of different FE models that were significant factors of effort apart. Although a simplified model can be used to produce good estimates of lifted stress, the lifted deflections and especially wracking cannot be accurately predicted as they require a significant percentage of the mass to be represented to accurately estimate this behavior.

Finally for most structures lifted the highest stresses are often near the pick points and there is sometimes a desire to just review this area. For most structures lifted during this research models of just small sections near padeyes on the block were reviewed. The results were difficult to interpret as some section models closely matched the global model, and others showed significant error. The primary problem relies in determining how large of an area to review, and setting appropriate boundary conditions to reflect the global response and load paths within the structure. Unfortunately, this project was unable to determine or develop guidelines to assist this analysis methodology.

Table 1: FEA Level of Detail

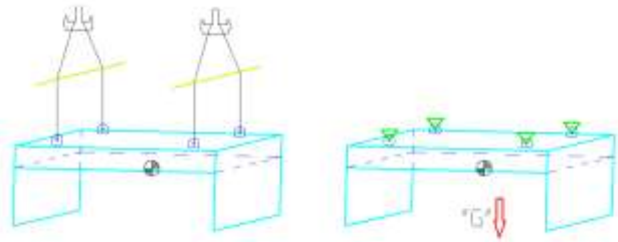
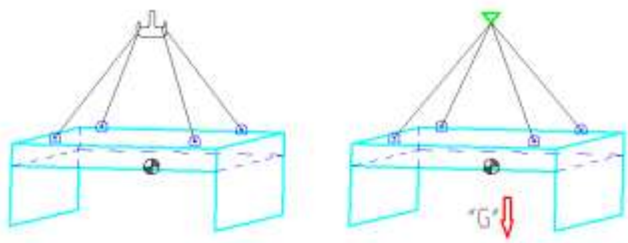
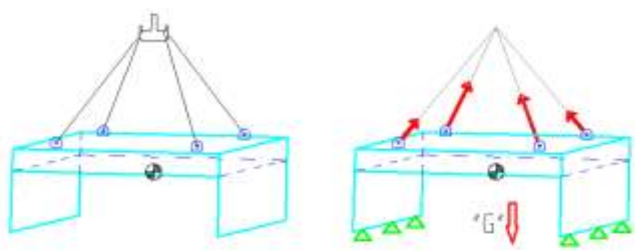
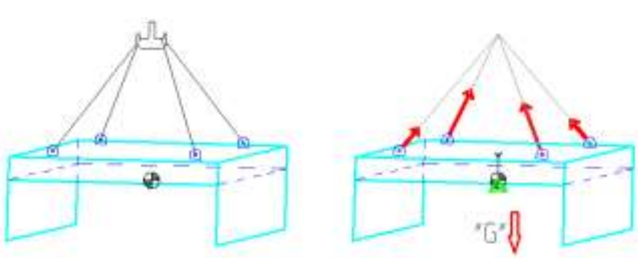
Detail		Description
Detailed		• All structure included as plate elements • Pipes near areas of interest included • Local foundations included • Large or heavy equipment included as mass nodes • Non-ship structural metal outfitting included • All plate thicknesses modeled
Simple		• Only significant or continuous structure included • Various plates simplified to minimum thickness • Longitudinals simplified to uniform spacing • Longitudinals simplified to minimum size
Ultra Simple		• Only primary continuous structure included • Various plates simplified to minimum thickness
Section		• Significant detail in area of interest • All structure included as plate elements • All holes and cut outs modeled

1.5.3. FEA Boundary and Loading Conditions for Lifted Structure

Selecting how a structural model is loaded and restrained is one of the most important steps when performing a Finite Element Analysis (FEA). The main consideration with regards to boundary conditions is that they are chosen in such a way that they accurately represent the supporting forces or restraint at various locations of the structural model, and allow appropriate deflections and translations to occur. This is especially difficult for rigging since all boundary connections cannot be chosen as pin connections that are free to translate or rotate, which will results in no solution being found. When conducting FEA, at least one rigid connection must be included. Also slings and rigging geometry are especially challenging components to model since their real world behavior is non-linear, since they are free to adjust themselves into lower energy states. This means that only an approximate method of representing them can be used in a linear FEA program, which inevitable leads to some inaccuracy. When selecting appropriate boundary conditions the geometry and rigidity of each individual structure being analyzed needs to be considered. During this research several different boundary conditions were investigated and an overview of some of the final refined methods can be referenced in Table 2. The methods shown for restraining a global model are Pins, Slings, Grounded, and Balanced boundary conditions. Some global methods such as the Pins or Slings boundary conditions suspend the modeled structure from fixed points and allow an acceleration to impart the load onto the blocks padeyes and structure. Other methods such as the Grounded or Balanced method use the predictions of classical free body diagrams to impart rigging forces onto the model. Depending on the structure being reviewed the different methods of restraining a FE model can produce noticeably different results. Finally, if stress predictions are only desired for the immediate area around a lifting point, the method of only creating small sectional models was also reviewed. However, these smaller models cannot predict global stresses, and determining how large a region should be reviewed increases the overall uncertainty.

Stable rigging is the balance of the sling forces applied to the structure, opposed by the objects self weight. This self weight is best applied to a FE model with a material density and an acceleration. If the FE model being analyzed does not have all of the mass or volume of the structure included, using the standard acceleration of gravity will not create a total weight of the structure equal to the anticipated vertical load. To overcome this gravity can be increased. This effectively takes the non-modeled mass of the structure and uniformly distributes it over the entire volume of the structure. In this research it appeared that reliable results were obtained when accelerations up to 150% higher than the nominal value were used. One drawback to this loading method is that the resulting COG of the FE model will be different than the more accurate fully weight engineered position. This can cause error in the loads that result at the padeyes. Fortunately, the effects of the FE models resulting COG error are believed to be relatively minor, although this may vary significantly depending on what is omitted from the model. In comparison, this research has shown that the dynamics and operational variables that occur during a lift can cause stresses to be orders of magnitude larger than might be caused by a slight weight or COG error. However the best way to minimize the error in a models COG is to model all of the steel bulkheads, decks, or large plates on the block since they often account for the vast majority of the weight. For structures that have large concentrated machinery or outfitting loads, point masses can also be included and will help increase the accuracy of the model. Similarly, a pressure load can be applied over area of the model to account for a larger percentage of the lifted structures weight.

<u>Table 2: Global FEA Boundary Conditions</u>

Boundary Condition		Description
Pins		• All padeye are pinned, preventing vertical translation • One padeye is fixed against all motion • Gravitational acceleration is applied • Gravity is increased to account for missing mass
Slings		• Slings are modeled as beam elements to the attachment location on the spreader bar or hook. • Slings fixed at the ends and therefore capable of transferring some moment • Attached to padeye holes using rigid elements • Gravitational acceleration is applied • Gravity is increased to account for missing mass
Grounded		• Calculated sling tensions from free body diagram applied to padeye • Model minimally fixed to ground preventing translation • Gravitational acceleration is applied • Gravity is increased to account for missing mass
Balanced		• A node created at the models Center Of Gravity (COG) is rigidly fixed • A beam is used to connect to the closest block structure • Calculated sling tensions from free body diagram applied to padeye • Gravitational acceleration is applied • Gravity is increased to account for missing mass

1.5.4. FEA Pin Boundary Method

Pining a lifted structure at the padeyes is one of the simplest boundary conditions for securing a structural model, but important considerations limit the applicability. First, this method can only produce reasonable results if the slings are mainly vertical, as only vertical forces will be imparted to the structure being analyzed. Also, this method works best if there are very few padeyes that the rigging loads are being transmitted to, and can sometimes produce terrible results if there are many padeyes that are close together, or on the same structural plane.

When undertaking this method a specific methodology needs to be followed. If the model is rigidly pined at all the sling connections points, it will impart stresses that do not really exist in the model. This is because it is not allowed to deflect or freely move due to the applied forces. However, a certain amount of fixity does need to be built into the FE model to ensure its algorithms will find a solution, and one acceptable method is to rigidly fix one location and allow the others to slide freely. This can result in stresses near the padeye that is rigidly fixed to be in slight error.

Another shortcoming of this method is that the pined padeyes of a global model are now held in-plane, and not allowed to develop global deflections due to bending. This is especially problematic for rigging arrangements with more than a minimum number of padeye locations. This also causes the actual sling loads to be different from what really occurs, especially when they are grouped on the same bulkhead or structural plane. These resulting loading errors on individual pined padeyes could be expected to be as large as a factor of two greater or only a small fraction what the rigging loads will be. Even significantly larger differences in predicted stress will result if all padeyes are pinned in all directions.

1.5.5. FEA Sling Boundary Method

Appling somewhat arbitrary slings to the model of a lifted structure at the padeyes is a fairly simple boundary conditions that generally produces better results than the pined method. Importantly this method is more likely to impart forces on each padeye that are of similar direction to the actual rigging loads. However, this method will not predict accurate tensions and especially elongations for the slings themselves but does allow the structure to respond more accurately. Generally the stresses that result in the model from this method are fairly accurate but the translations are not. This method seems to be acceptable no matter how many padeyes that there are on the structure, but the more padeyes that there are the larger the error will be in any specific one. This is mainly because the magnitudes of the sling tensions often distribute themselves proportionally to the mass distribution of the structure. Similarly beam slings only allow a very limited amount of flexibility in lifted structures. This also prevents any global wracking of the block from taking place. These factors create error in the analysis and in this research the largest error in loading seen on any specific padeye was 33% of the actual rigging load.

Slings are especially challenging rigging components to model since they are tension only members that are free to rotate about the connection points. If the slings are modeled exactly as they are, the FEA would be unable to find a solution since there would not be enough constraint on the model. The Sling boundary method of constraining the model has the slings modeled as beam elements with specially defined properties to create a rough approximation of the stiffness of the sling used. By modeling the slings as fixed beams some of these challenges are overcome, but depending on how the model is set up they can still lead to misleading predictions. Also, for a solution of the model to be found, the slings must be allowed to transmit a certain amount of moment through their length and into the block. To do this the slings are rigidly fixed on top and to the block model which is typically done with rigid elements. In this research it appeared that this moment transmitted by the slings generally had minimal effects which were typically small and localized to the area around the padeyes.

1.5.6. FEA Grounded Boundary Method

The Grounded boundary method simulates what the stresses will be in the structure moments before it is lifted from the ground. In theory these stresses should be very similar to the lifted stresses. This method assumes that the structure is still in contact with the ground, which is accomplished by restraining some support points under the structure. The frictional forces providing horizontal resistance just before the structure is lifted are likely to be minimal. Therefore the boundary conditions should be selected to provide vertical support only, with the required exceptions to allow a solution to the FEA algorithms. These support point reactions are countered by the sling forces applied to the pick points, which should be calculated from free body diagrams. The vertical component of the sling forces should be equal to the structures self weight, and will result in the average vertical force at all supports being zero. Any specific location where ground support is provided will ideally have minimal vertical force. However locations too close to, or directly below pick points may provide a direct load path to ground. This will result in the ground holding the block down in some areas while still supporting it in others. Therefore careful review of the forces at the various ground supports is required when using this method. The best results can be obtained by iteratively removing supports where they are found to be significantly loaded and holding the structure down.

Unfortunately, this method has the drawback of not modeling the global response of the structure very well, which limits its best use to more rigid blocks, where deflections and wracking are not a concern. This is due to the structure being restrained from vertical translation which does not allow global bending stresses to develop. Similarly this method works better on structures that are multiple tiers in height, and in ships position.

Importantly this boundary method allows user input of the sling forces and angles, to help estimate the effects from various possible loading conditions and scenarios. A grounded model is not sensitive to having all forces balance, since the ground can be allowed to provide significant support to the model. This allows considerable variation in the applied forces, and even the creation of highly improbable arrangements to test various effects of loading on lifted structure. This greatly assists in determining localized deflections and stresses in the areas around a padeye. However, many of the possible loading conditions require additional review and consideration since it is likely for the ground to impose forces on the structure that cannot actually exist. This method might be most appropriate if the global bending stresses and lifted deflections in a large multiple tiered structure are not a concern, and review of only localized areas is desired.

1.5.7. FEA Balance Boundary Method

The Balance boundary condition might be the best method researched for estimating the global bending stresses, deflections, and the complex wracking of lifted structures with linear FEA. Unfortunately, it can be tedious to input the exactly balanced loading conditions into the analysis, which are needed to accurately estimate deflections. Excessive FE model size and the complexity required on full scale lifts cause difficulties during the integrative alterations required to get the deflections to closely match observations and measurements. Similarly the FEA needs to have a very high percentage of the mass and structure modeled to accurately predict global behavior, which in turn drives up model size. As a result complete success with this method was not obtained for full scale large shipyard lifts. However, during this research, simplified scale models were built to test methodologies, and the Balanced method predicted the deflections and wracking that were measured. Regardless of errors in the full scale deflections, it is believed that this method produces the most accurate predictions for global bending stress.

Primarily the Balanced boundary method attempts to overcome the deficiencies of the Grounded method by allowing the block to globally flex. This is accomplished by only restraining the model at a single point, which for balance to be achieved, is located at the blocks Center Of Gravity (COG). This false boundary point must be completely fixed. Also since this point will never be exactly on the structure, it needs to be attached to the structure though additional invented structural connections. Two different methods of doing this were undertaken, either short fixed beams, or small rigid elements, both of which appeared to work equally. Ideally the gravitational loads on the structure will completely balance out the rigging and sling forces such that at the boundary point, and in the connection beam, no additional stresses are induced. In this regard the structure is now balanced on a false boundary point through which minimal forces and moments are exchanged. Importantly, this method leaves the majority of the global block model completely free to deflect or twist in any direction that the forces induce it to, and it is possible to predict the deflections that take place during the lift.

This method does unfortunately have several sources of error. First, the FE model and the actual structures estimated COG will not exactly match, since it is almost impossible to model 100% of the mass accurately on very large complex structures. As a result, the sling and rigging forces to make the model balance are not the same as what the actual slings forces will be, and the research conducted suggested that errors of 10% may exist. This subsequently requires a separate free body diagram to be made for the FE model, and the precisely calculated tensions and directions applied to the padeyes. These tensions may then have to be adjusted slightly until the forces and moments at the false boundary points are minimized. Although complex, one of the benefits of this method is that the padeye forces can be altered to better account for various possible loading conditions and scenarios. The ability to alter the angle of the slings and tensile forces allows significant freedom during the analysis to scope out the bounds of how altering the loading conditions and inputs affects the global stresses and deflections. Getting the model to balance with minimal deflection often required an integrative approach that can be time consuming for large models and somewhat tedious. Since it is difficult to achieve an exact balance, there will inevitably be some support forces at the false boundary point that will impart stresses into the block which will show up as elevated stress near the COG and fictitious attachment. As long as these forces and moments are minimal, the stresses estimated in the vast majority of the global structure should be more accurate that the other boundary methods reviewed. Although significant error in deflection may be expected, the global bending stresses in the structure are considered more accurate than the other methods.

2. UNPREDICTABILITY IN SHIPYARD RIGGING

> "Working with suspended loads is not a fully predictable exercise, because load behavior relies on a number of factors, including the actions and interactions between the crane or derrick operator, crew members, and the wind; the reactions of the slings, hoist ropes, and other crane components, and of the load itself."
>
> –Shapiro, Cranes and Derricks

There can be considerable uncertainty within rigging engineering and determining a realistic approximation of what is likely to occur can be a challenge. Any approximation developed must be based on the experience of those planning and conducting the operation and will vary accordingly. This process typically starts with an estimation of the weight and center of gravity of the load, but an actual design must account for loads that are more variable than these basic numbers might suggest. There are many factors which can cause the actual forces to be different, ranging from errors in weight estimation, or caused by the sequence of the operation, the choreography of the cranes and their interaction with each other. Shipyards have considerably more variation than a typical lift in the construction industry, as the lifts are generally larger and more likely to involve multiple cranes. Multiple cranes will tug at each other and the load causing significantly more variability than a single crane lift. The dynamics of the operation will also affect the angle of the slings, the load on the cranes, and even the load radius of the crane. Similarly, movements are caused by accelerations, which imply variable inertial forces which alter the magnitudes of the loads involved. Other factors affecting the actual loads stem from the environment where wind loads on structures or pools of rain water can have significant effects, but are less frequent and in theory could be eliminated through ideal procedures. For complex operations, projecting exact numbers is exceedingly difficult an understanding of the complexities and effects that may occur is a requirement. The following sections overview some of the challenges shipyards rigging engineers face when planning lifts.

2.1. Operational Variables

An engineer designing a lift will ideally have an experienced team, ample budget, sufficient time to compile complete documentation on the operation planned, and a large window of time in which the operation can take place. Given these things it could be possible to have a thorough review of everything about an operation before it takes place, plan and orchestrate it such that these variables and uncertainties are eliminated or minimized. Similarly if the operation itself has no time constraints and can take place at a very slow methodical and controlled pace under ideal conditions, many operational variables that increase stresses and loads can be greatly reduced or eliminated. However this is never the case. The deviation from this ideal creates error that increases risk and the following sections review many of their common causes for shipyard lifts.

2.1.1. Weight and Center of Gravity

The most important thing in planning a rigging operation is determining the weight and center of gravity of the object that is to be lifted. In shipbuilding this process starts during the initial block breakdown, where an initial lift weight estimate for each modular unit is fundamental. From a rigging engineering perspective, this process is complicated by various factors that often strive to push the envelope of capabilities. To make shipbuilding as efficient as possible, and reduce the cost of ship construction, build strategies are modified to results for as much work content as possible being completed as early as possible. One of the primary effects this has is to result in a larger percentage of the lift weight being non-structural steel. This effort takes place not only from contract to contract, but even within a class of ships, as cost down initiatives inevitably increase the weight and complexity of the erected units. These efforts not only make blocks heavier with more dead load, but increase the number of components on them, making it more difficult to accurately calculate their center of gravity. This goal of erecting blocks as complete as possible is further complicated with the desire to maximize the utility of shipyard cranes, such that erected units are as heavy as possible. This creates a weight distribution of erected units similar to what is show in Figure 16. These goals inevitably result in a large amount of shipyard erections planned with equipment being used near capacity. This effectively reduces average margins, and necessitates more detailed analysis and review.

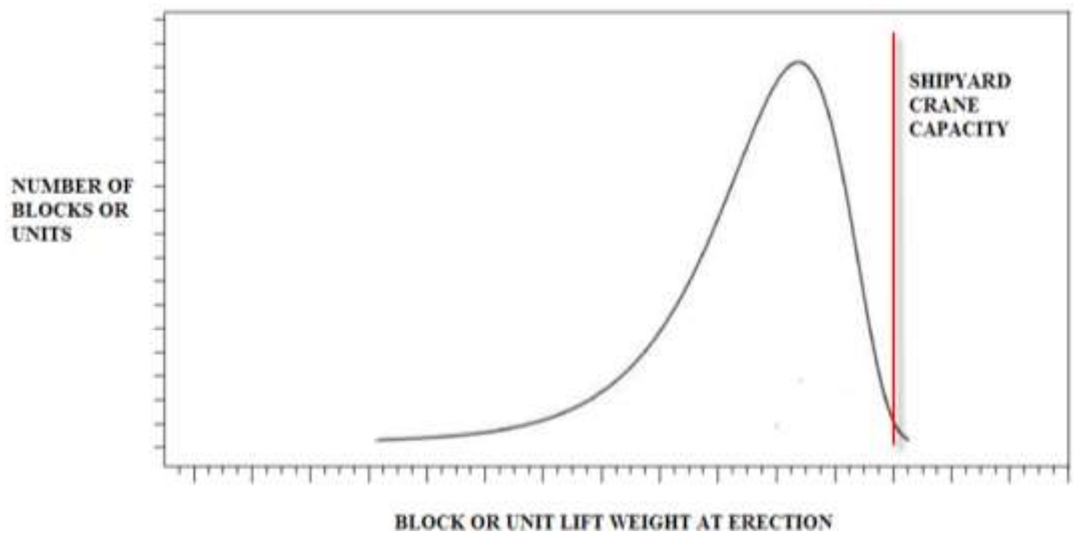


Figure 16: Block Weight Probability Density Function

Shipyards have always had the size of erected panels or assemblies limited by the capacity of their cranes. As a result, even in the recent past, an erected block's steel weight was often a limiting factor preventing significant outfitting from being installed in earlier stages of construction. This limitation is certainly true for large pieces of machinery, which historically would have only been installed late in the construction process. A modern cost effective shipbuilding yard with high capacity cranes has the ability to lift both relatively large units, and those that have a significant amount of outfit installed. As a result, the fraction and lifted weight of non-structural steel is steadily increasing, but, it is typically less than 50% of the total.

Table 3 shows approximate ranges for different SWBS groups on a completed steel auxiliary vessel, for various block types. From this it can be seen that superstructure blocks, which usually have the thinnest steel and least amount of structural steel, will typically have the largest fraction weight that is not SWBS group 100.

Table 3: Completed Block Weight SWBS Distribution

Percentage of Ship Block Weight Per SWBS Group

	Steel	Electrical & Electronics	Outfit & Furnishings	Machinery& Propulsion
SWBS	100	300 & 400	600	200 & 500
Block Type				
Tank	80-99%	0-2%	0-5%	1-10%
General Cargo	50-75%	0-2%	1-20%	5-30%
House Accommodations	40-80%	1-10%	1-40%	5-55%
Machinery	50-90%	0-20%	1-20%	5-35%

Modern 3D production oriented ship CAD packages greatly assist estimating the steel weight of a block. As the software knows the size of any plate, density, and thickness; and estimating the weight and Center Of Gravity (COG) of any structure becomes relatively straight forward. A steel weight estimate that is directly extracted from a production model will typically have a relatively high degree of accuracy. This accuracy is thought to be much less than 2% once certain corrections are made. One production model weight exclusion is mill tolerances, which usually result in plate thickness being slightly different than the median or specified. Also, the production model does not usually account for the weight of weld, which is sometimes taken as just over 1% of the total steel weight of the structure. There will also be some variance between the model and the block under construction as penetrations, holes, and cutouts may not match the model at a given point in time. Examples are that the cutouts for doors may be tabbed in to keep the rigidity of the panel, and other holes may be mark only, so that steel is there when the ship model indicates it is not. On the other hand, some holes may have been left out of the production model due to uncertainty, but cut in the assembly. Overall the steel plate attributes in a production model are generally correct, with enough interested parties helping to ensure their accuracy. There is however the chance that last-minute material substitutions can affect these estimates, typically increasing the weight slightly. It is believed a 3D production model steel weight estimate is the most accurate method of calculating steel weight since it in part it minimizes the human element, which is often a source of error. Finally there can typically be confidence that the structural steel of a block shown in the CAD model, will be present at the time of the lift, as its omission will generally be noticed and corrected.

The ship related non-structural steel weight of a block is always more difficult to accurately estimate. This non-structural weight is comprised of different components: installed ship related outfit, free ride equipment and structure, and temporary construction related equipment or tools that are not part of the final ship.

The outfit weight of a vessel has an active shipyard effort to account for, and project it, a process which starts long before the keel of a ship is laid. This effort will typically keep variation in predicted outfit weight for the final vessel to a margin of less than 10%. The margin related to an estimated outfit weight at any specific time during construction will be considerably more variable. First the lift weight and center of gravity of outfitting items is subject to the same completed ship related errors in its estimation. Figure 17 shows some of the common 3D ship production model outfit or equipment weight errors. First, there can be errors in the listed weight of the item, or the location of its center of gravity. Although, venders are usually required to provide this information, there is the possibility it is not correct, or errors have been made transcribing it into the computer model. The ship model outfitting may have the wrong weight, the wrong units of measure may have been used, the wrong location or offset to the COG may have been entered, or the reference location or insertion point used in the model may have been substituted. For the global ship model the summation of such errors can be relatively minor or offsetting, but for a small section of the ship these errors will have a greater effect.

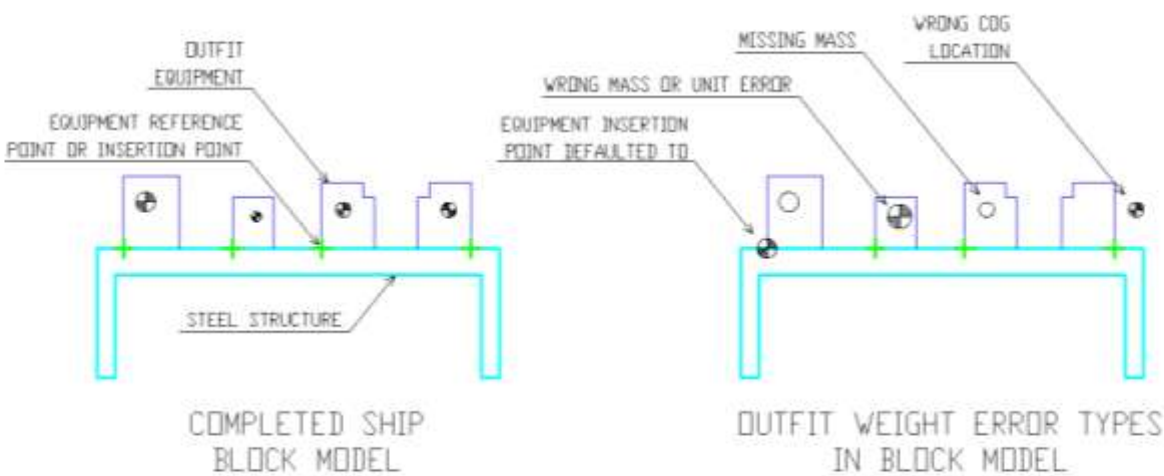


Figure 17: Common 3D Production Model Equipment Weight Errors

The problem of estimating non-structural steel components of a ship block during a lift, are significantly more complex that a completed ship block. One of the largest problems in estimating the weight of a structure months before its planed lift is attempting to estimate what is going to be on the block at the time. Shipping delays or fabrication problems may mean that items scheduled to be on the block may not in fact be there. Missing items effectively have a weight estimate error of 100%. Conversely, it may be just as common to run ahead of schedule on vessels that follow the first of class, and have the opportunity to add items to a block that are not yet scheduled to be there. Again, this can cause a significant change to a weight estimate. Both of these occurrences lead to a relative estimated weight and center of gravity error greater than that of the original complete ship block estimate. Finally, ship components may be placed on the block at the time of the lift, but may not be in their final location. This can cause a slight error in center of gravity. More importantly these items may not be listed as installed at the time of the lift, since their installation has not been completed. This may lead to the assumption that the item is not on the block, when it is, just in a different location.

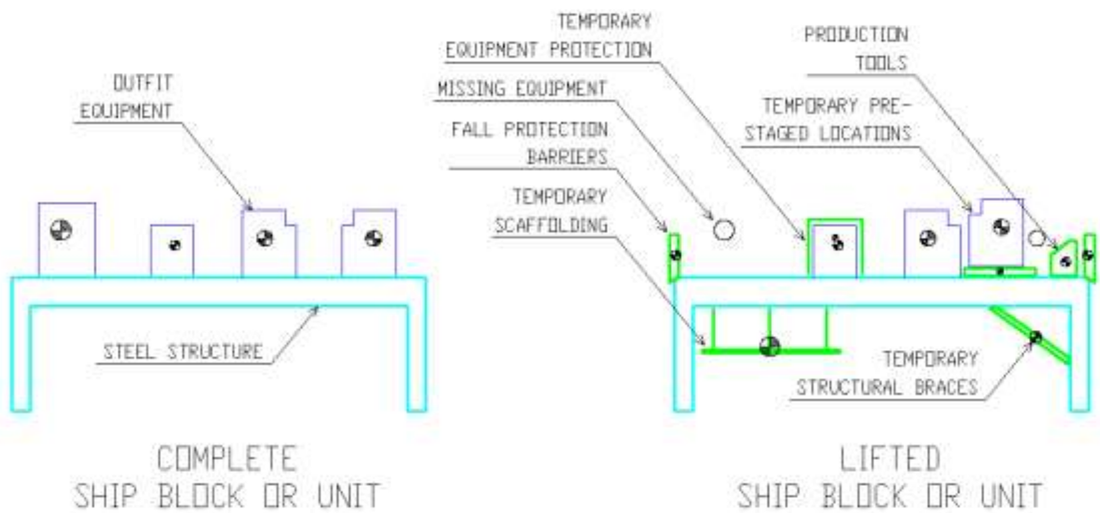


Figure 18: Complexity of Ship Unit Non-Structural steel Components During a Lift

In addition to the variable outfit weight, another important non-structural steel weight is the temporary non-ship parts on block at the time of the lift. Figure 18 shows some of the many temporary parts that may be on block during a lift, that will not show up in a computer ship model. Some of these temporary parts are directly related to the lifting arrangement to ensure a safe lift of the structure which includes:

- Padeyes for lifting
- Temporary backup structure under padeyes
- Vertical or diagonal braces to tie structure together
- Horizontal strongbacks to prevent buckling of vertically stiffened structure
- Spreader bars and slings used in rigging arrangement

Some of the temporary weight or parts are not related to the final completed ship, but are usually found on vessels under construction or sections thereof. Many of these parts are directly related to the assembly and integration of the block's components, facilitating future work in difficult to access areas, or are directly associated with the requirements of shipyard workers. These may include:

- Fall protection barriers,
- Temporary scaffolding, and ladders
- Deck and material protection or packaging
- Erection related staging clips or shipfitting equipment
- Gang Boxes, welding machines, or other tools
- Blank pipe flanges and remnant pressure testing fluids
- Uncleared production related remnants or rainwater
- Trash bins or chutes and associated gear
- Temporary power distribution junction boxes, lighting, and associated electrical cables
- Temporary ventilation equipment and ducting
- Temporary sanitation modules or other shipyard worker comfort facilities
- Portable office trailers

Finally there may be free ride parts, which are parts that will be part of the final ship, and may or may not be associated with the weight estimate of the lifted block, but can generally be considered to be in the wrong location. These parts can include:

- Pipe make up spools, or monorail connections
- Reels of uninstalled or partially installed electrical cable
- Stacks of uninstalled non-structural bulkheads, and doors
- Staged deck underlayment and tile or covering
- Small structural steel components such as brackets, intercostals, collars
- General outfitting

Any temporary part weight estimate is usually not more than an educated guess with a high degree of uncertainty, especially when an engineer must guess the weight of the structure long before its construction. Fortunately the temporary parts often represent a small fraction of the overall block weight, and these parts are usually distributed over a large area of the block, so there is only a small effect on the overall mass statistics. It should be noted, that the placement of individual heavy items can have a disproportionately large effect due to a shift in the block center of gravity. Although highly variable and relatively block specific, the temporary construction related parts are typically not in excess of 5% of the total estimated lifted weight.

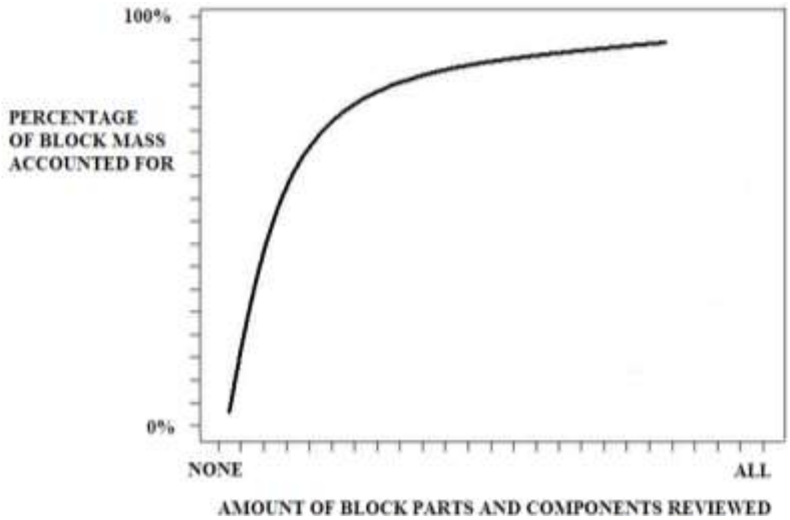


Figure 19: Few Parts Often Account for the Majority of the Blocks Weight

Typically a relatively small percentage of the parts for a block will account for the majority of the weight, as shown in Figure 19. This is similar to an 80/20 rule, where 20% of the parts on the block account for 80% of its weight. To reduce the uncertainty of a blocks mass statistics, a review of just the largest weight items will provide significant benefit. This research had the luxury of a post lift detailed review and correction which lead to a more accurate weight estimate than might typically be expected. Even with significant review there was still uncertainty with regards to the exact mass statistics of various structures. Based on the review of blocks, it is very reasonable that pre-lift weight estimates within 5% of the probable mass can be expected. Although weight review is essential, significant review is unlikely to result in an estimate with accuracy greater than 2%, especially for large highly outfitted shipyard lifts. It should be remembered that the reality of rigging engineering is that weight estimates are required to be done months before a lift takes place. The challenges posed by new construction programs where the design and planning may be fluid in nature, leads to even more error. Current practice and historical documentation suggest that occasionally weight estimates of lifted structure can be in error by 15%. The operational uncertainty of what the mass will be is larger if a significant number of revisions are occurring to the vessel, and to its build strategy. Finally it is believed that the pre-lift center of gravity of a block can be projected to less than 2% of a corresponding directional length, similar to what is shown in Figure 20. However no historical or current documentation exists for typical errors in COG estimates for ship blocks.

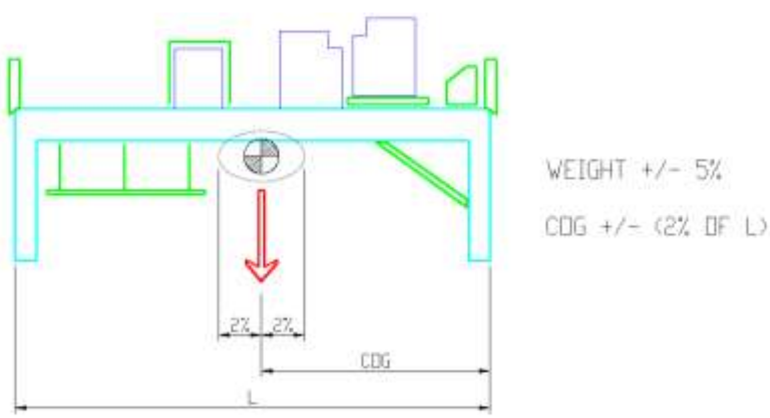


Figure 20: Typical Error in Estimated Block Mass Statistics

2.1.2. Multiple Crane Lifts

With the desire to maximize the weight and size of shipyard lifts many are conducted with more than one crane. Multiple cranes lifts have significantly more operational uncertainty than single crane lifts as the variables in equipment, and possible tolerances in position are much greater. As a result industry experts have noted that a single crane lift at full capacity, is usually better than a multiple crane lift at less than full capacity. This is mostly due to the considerable variation in loading that will result when two cranes interact with each other. Figure 21 shows some of the positional tolerances of the cranes such as their boom radius, and hook height, all of which can change as the operation progresses. Pick and carry operations are especially subject to these effects due to the increased variation in the crane positions which will vary over the course of the movement. Also the hook height can be a very large factor as it affects the declivity of the load. During this research the dynamic oscillation of stresses and direct measurement through accelerometers indicated that in general, two crane lifts were more subject to load variation than single crane lifts, especially when the cranes were required to travel with the load. The following sections will detail the effects of these operational factors.

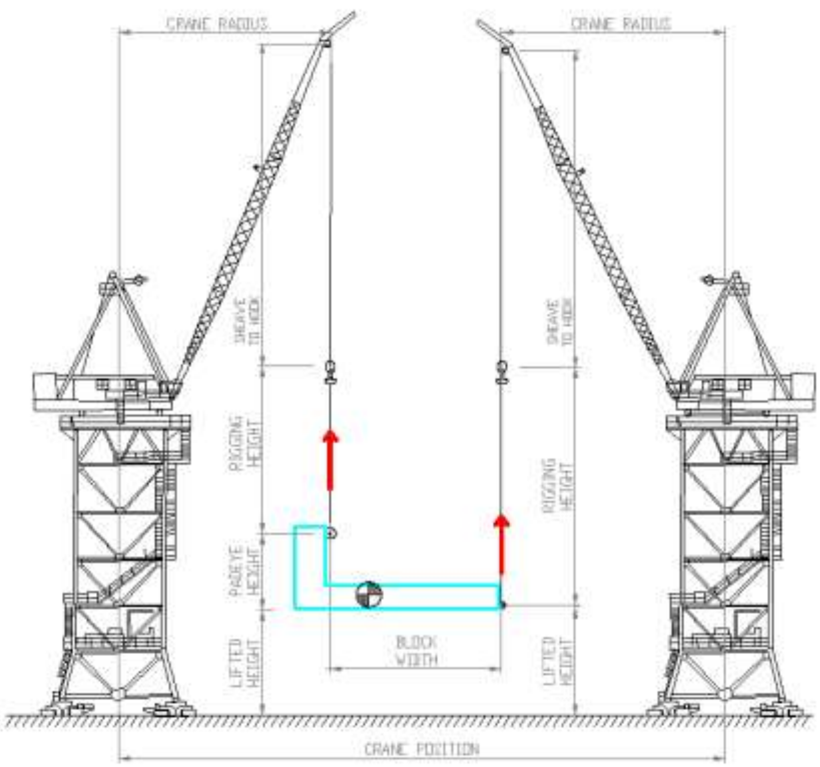


Figure 21: Two Cranes Positional Variables

2.1.3. Hook Height

In a multiple crane lift the hook height will have influence on how much load is carried by a given crane, and on the various slings of that crane. Figure 22 shows the basic principle of the relative hook height in a two crane lift, where load transfers from one crane to another as the lifted block comes out of level, or develops declivity. On critical lifts using the cranes full capacity, such adjustment can cause overloading. Also, unless the distance from the cranes sheave and the load is relatively high, as the block rotates the slings will come out of plumb. In this figure this effect is barely noticeable. Although the intent of a lift plan may be to lift the block off the ground completely level, the winch speed of even identical cranes will be different. As a result when the block is lifted it may deviate from level unless the operation is carefully controlled. This problem is even more likely to occur when using cranes that are of different models from each other. One widely used crane and derrick reference suggests that monitoring by eye will typically keep the load to be level within 5 degrees, and this is more or less what was observed in this research. Based on the shape of many erected ship blocks this conceivably could add 6% on average to the load seen by a crane. Finally, the angle that the block develops will not only increase the sling tensions, but may cause localized side loading at the pick points, which can significantly increase the stresses at these locations. Procedures can be developed to minimize this operational variable; however some lifts such as the erection of a block on an inclined launch ways will almost inevitable require declivity of the lifted structure.

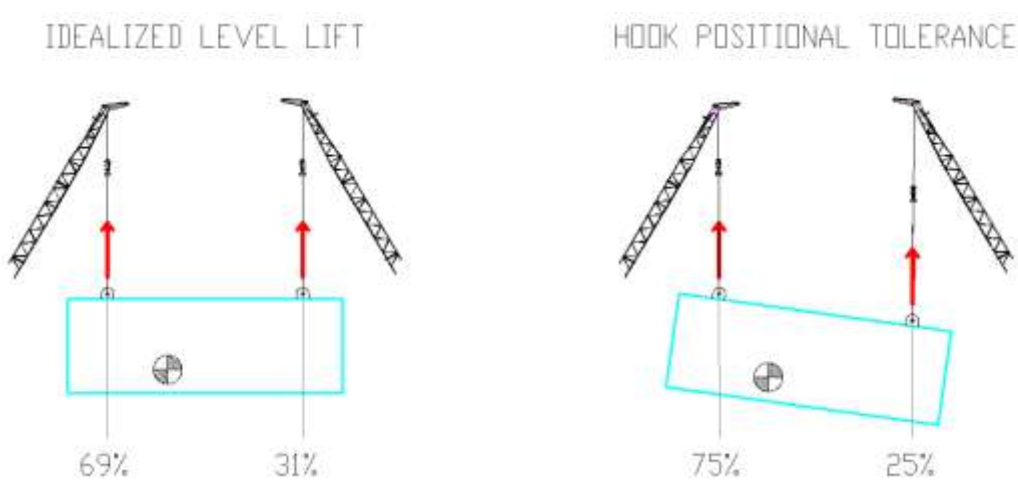


Figure 22: Crane Hook Height Effects

2.1.4. Two Crane Lift Positional Tolerance

The notion that a lift will be conducted with perfectly vertical slings is just an idea, and there are a number of factors working against this. Two cranes lifts are significantly more likely to have variable sling angles and some of these factors are:

- Raising the load
- Booming in or out
- Swinging the load
- Cranes traveling at different speed
- Crane traveling on non parallel direction
- Travel path is not level

First there will always be some positional error when the cranes are first hooked up, and for large lifts the mass of the rigging gear can make final precise adjustments difficult. Any initial sling angle will increase as the load is raised, as the load will get closer to the crane sheave and the relative positional error will become a larger proportional component of the distance between the pick point and the crane sheave. This is one reason that it is often recommended that the load be carried at as low a height as possible, although the compressed layout of many shipyards places restrictions on this. During this research data was recorded in areas that would be significantly affected by the relative angle between the sling and the block, and the stresses showed the highest variation during final the erection. This is when the distance between the block and the crane sheave was the least. Also during a pick and carry operation, crane speeds will undoubtedly be slightly different, and therefore lead to offsets in their relative position. Similarly the travel paths of two cranes may not be perfectly parallel, notable so when the travel path is not straight. This will typically require careful control of the cranes relative distance through adjustments of travel speed, boom angle, and swinging the load. Slight errors in any of these variables will lead to slings that are not completely vertical. Similarly when the crane swings or booms the load the relative distance between the two crane sheaves will change. Finally the ground on which mobile cranes travel is never perfectly level as slight settling of the cranes tracks under the large loads often imposed is possible. A slight out of level at a cranes base will typically be magnified by an order of magnitude at the boom tip. For mobile cranes set on rails that meet their associated ANSI standard, this will not typically be an issue, but for mobile cranes on rough terrain can be quite problematic. The effects of this type of positional offset that leads to non vertical slings are:

- Change in effective boom radius of the cranes
- Possibility of side loading of the crane boom.
- Change in relative percentage of load shared by the cranes
- The resultant summation of crane loads will be higher than weight of object
- Possibility of localized side loadings on padeyes and structure underneath

These effects have several important considerations for many shipyard crane operations. First a few degrees of sling angle will increase the effective load radius of the crane. This effect is typically insignificant for most shipyard lifts, but can be a problem for cranes operating near their overturning limit. It is also possible that in certain lift configurations the tolerance of the cranes positions could create side loading of the crane booms, for which many cranes have less reserve strength. Slings coming out of vertical will also cause a slight increase their tension. However the additional tension caused by a few degrees out of plumb is small, and may only be noticeable when these angles are much larger than normal operations would create. Also, changes in tension will be slightly affected by the COG location, where load can be transferred from one crane to another. Figure 23 shows the percentage of weight that will result after a positional offset of two cranes. It can also be seen that if the COG lies close to a plane defined by the pick points, no shift of the loads weight will result, and only angles will develop. However the further the COG is away from this plane, the more likely there will be a slight load transfer from crane to crane. Also a slight block angle will develop if the ratio of load share between the cranes is large, or if the distance from the pick point to the crane sheave is significantly different. The most important thing to note is that the crane with the lighter load will develop the largest angle in its slings. If the positional offset is caused by movement of the more heavily loaded crane, its operator may be unaware of the adverse effects being caused to the lightly loaded crane. This stresses the need for good communication between personnel. One significant concerns related to side loads are localized to the area around the pick points which are not always designed or checked for these loading conditions. A few degrees of side load can have a significant effect on the stresses that develop in the padeye and in the structure directly under the pick points.

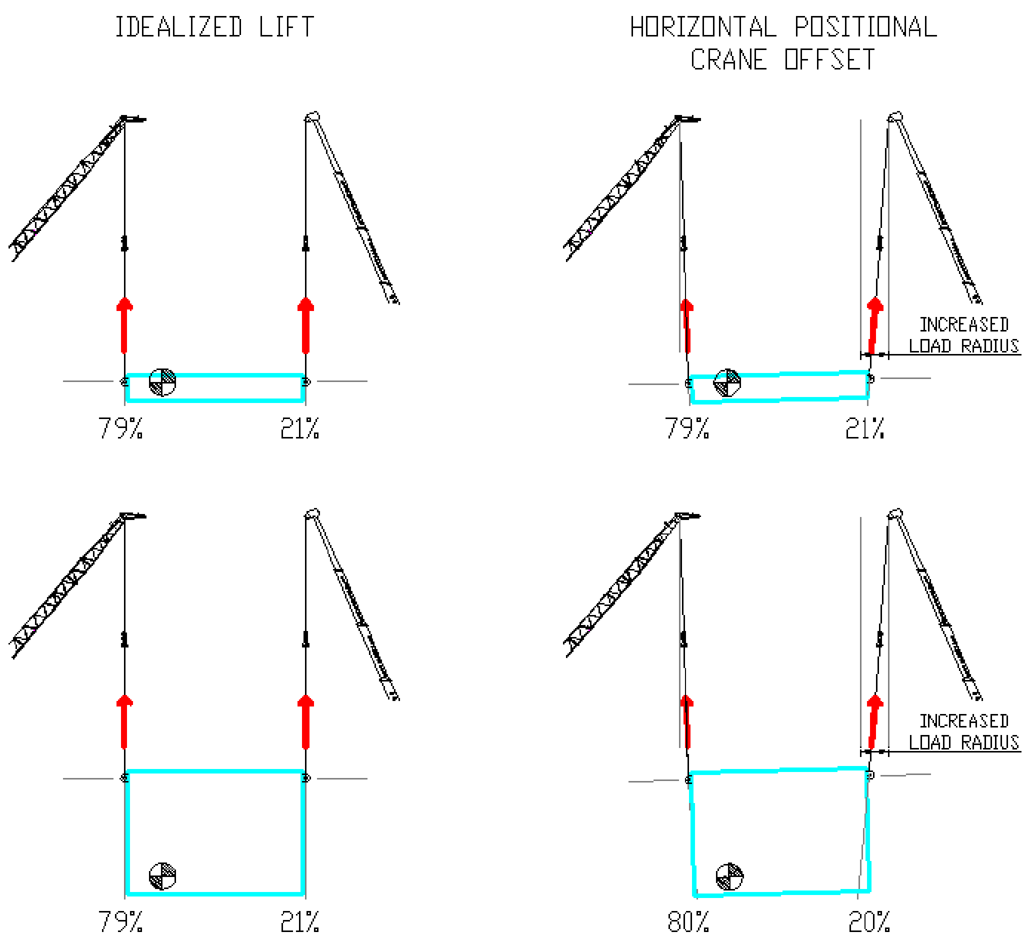


Figure 23: Crane Positional Effects on Crane Load

2.1.5. Turning of Units

Most build strategies for ship structure starts with the structure upside-down to facilitate more ergonomic work in what will become the overhead. This requires the structure to at some point be turned upright, which for large plate based steel structure is usually accomplished with cranes. The turn of a structure starts with the level lift of the structure and typically transport to a pre-designated turning area that is clear of obstructions and has plenty of working space. The turn itself is usually conducted in one of two ways. First, one crane can lifts its side of the block until it carries all the weight of the block and it has rotated through roughly ninety degrees. Another method is for one crane to lower its side of the block until it no longer carries any of the weight of the block. Either method results in a change of both cranes relative hook heights and Figure 24 shows the first half of this turning process for a typical deck and shell block. Typically during this process the cranes will swing theirs booms or move closer to attempt to keep the slings as vertical as possible. This figure assumes that the operation is conducted such that this is accomplished perfectly.

Several important things happen during this turning process. One set of padeyes sees its load dramatically increase and the angle of the load sweep through roughly ninety degrees. The other padeye on the shell will see its load drop to zero and it also sweeps through roughly ninety degrees. With the assumption that the sling remain vertical these sling tensions can be readily be calculated. The variation of the tensions place considerably stresses in the structure surrounding the padeyes, which are typically reviewed to determine if temporary structure to shore up the shell is required. Figure 25 and Figure 26 show the typical range of stresses that develop in the shell of this block, and it can be seen that the largest stresses occur after the block has rotated through a significant angle.

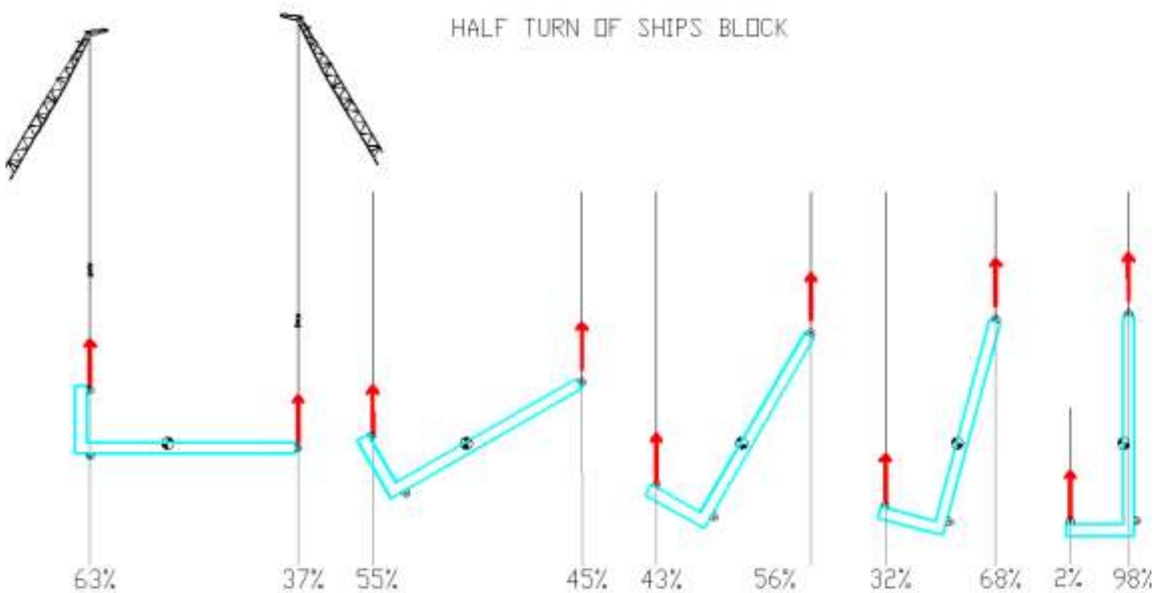


Figure 24: Loads During Turn of Blocks

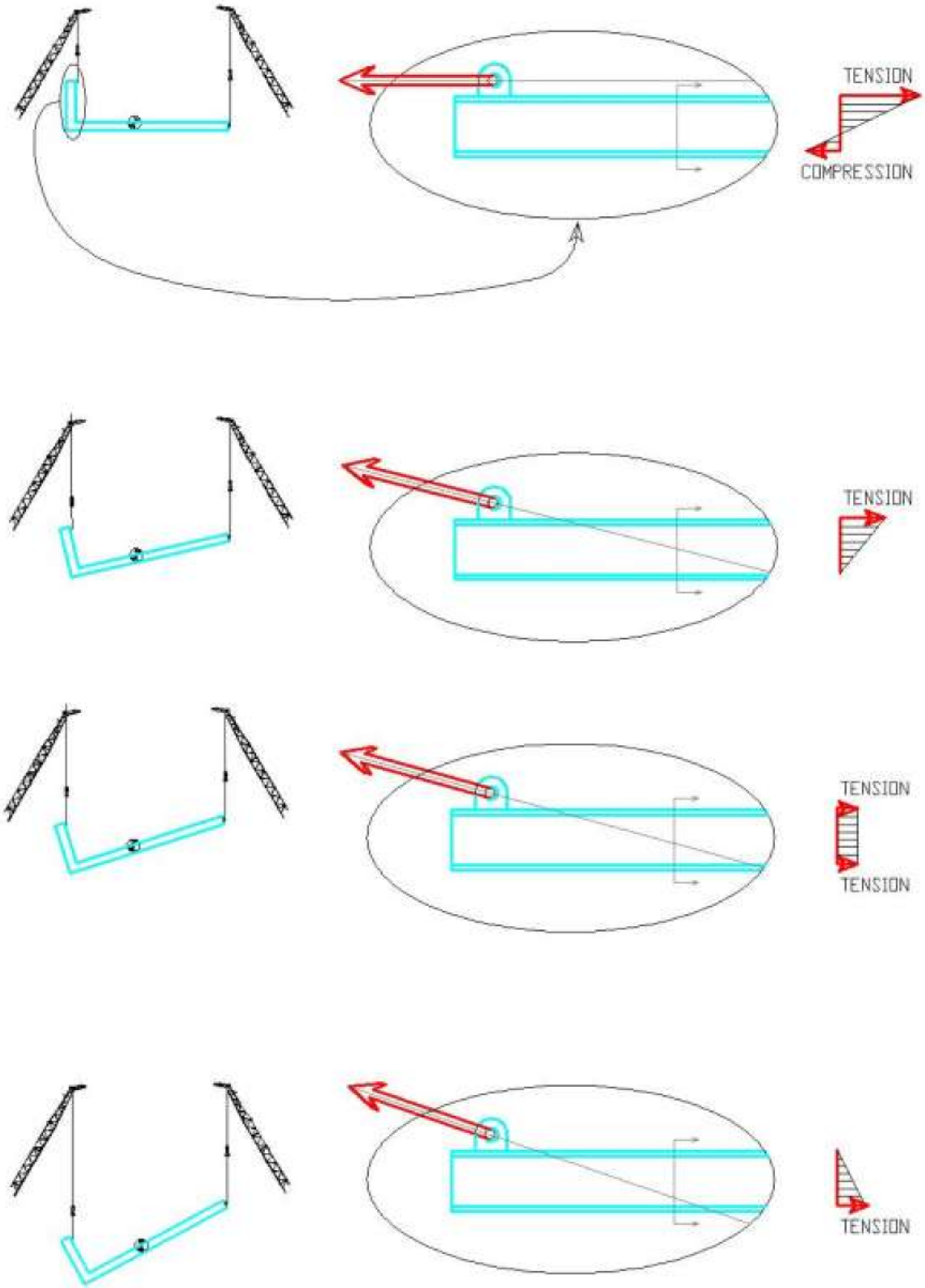


Figure 25: Stresses in BHD During Turn of Block

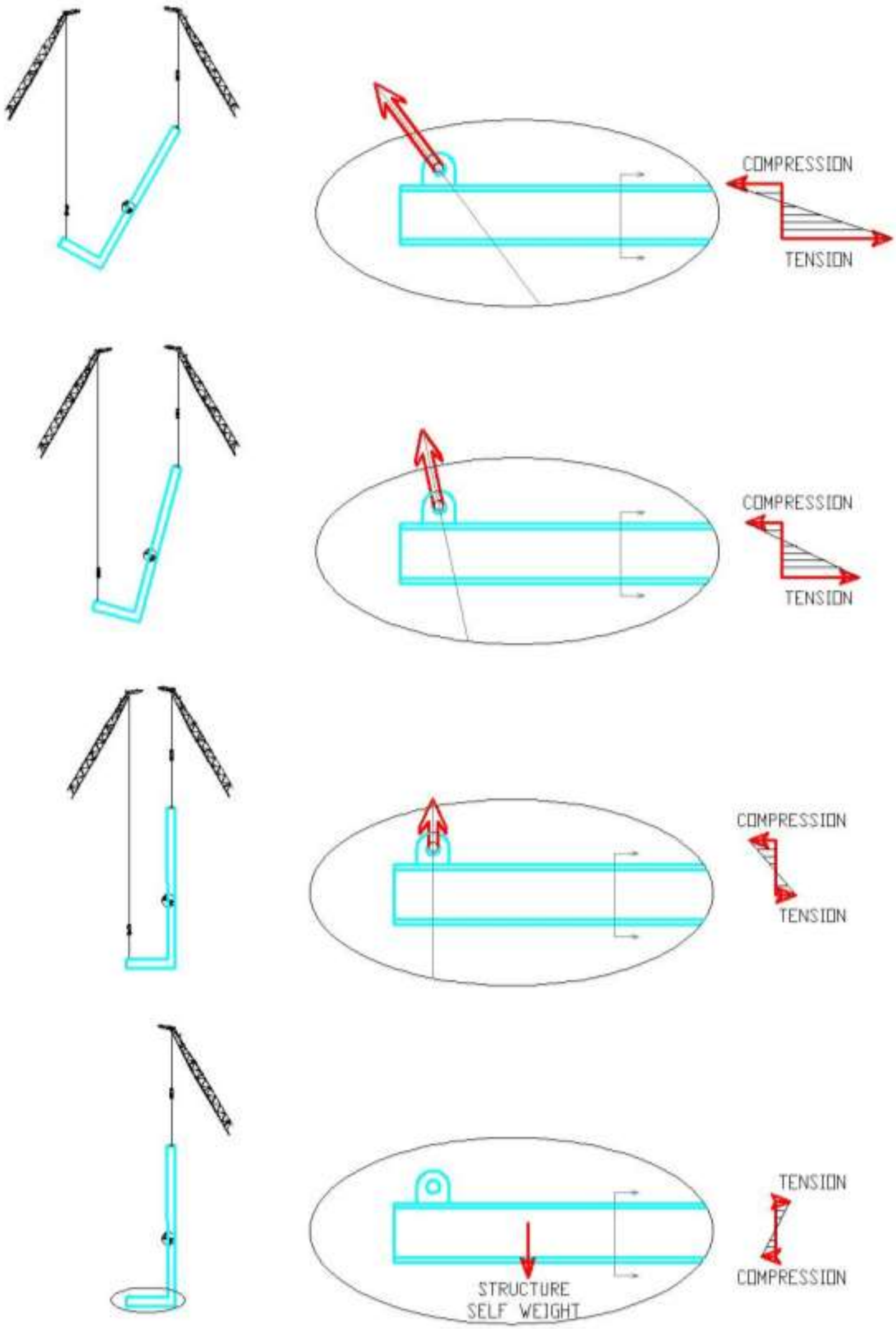


Figure 26: Stresses in BHD During Turn of Block (cont)

The weight held by the pick points on the shell bulkhead can be determined by the following formula.

$$\text{Fb} = \text{Weight} - \text{Weight}\left(\frac{(\,b\cos(\theta) + c\sin(\theta))}{(b\cos(\theta) + c\sin(\theta) + a\cos(\theta))}\right)$$

The application of this formula to a typical shipyard block is shown in Figure 27. In this figure one can see that if the pick points on the shell are located only slightly above the center of gravity, they will retain significant load through most of the turn. If the pick points on the shell bullhead are significantly above the center of gravity the load in the slings will be reduced much sooner. However, the greater distance from the center of gravity will typically cause larger moments, and stresses in the structure. This is shown in Figure 28 where notional bending moments are presented. Here it can be seen that the largest bending stresses for this shape block occurs somewhere between 55 and 75 degrees. Sparing the desire for significant review, often an approximation of 60 degrees is chosen for a spot calculation. Given that there is uncertainty with regards to the exact sling angles below the crane, COG and weight of the block, the total associated operational uncertainty could easily be in the double digit percentage range.

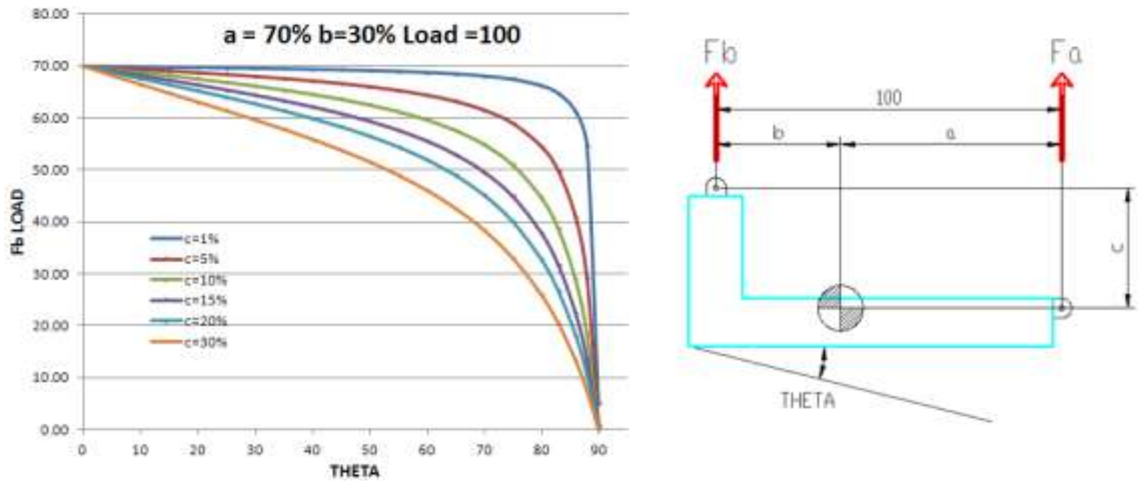


Figure 27: Turning Load on Shell Bulkhead

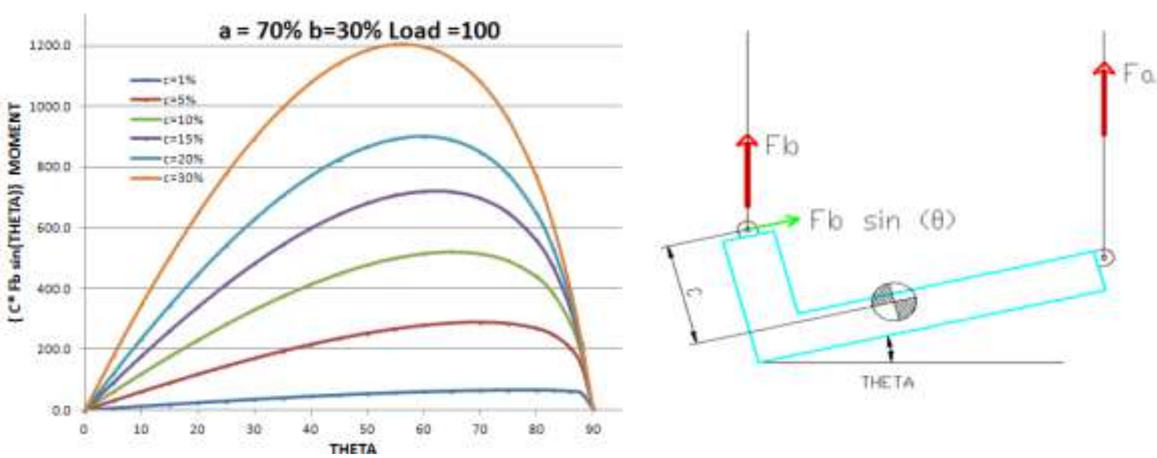


Figure 28: Turning Moment in Shell Bulkhead

Although not specifically reviewed during this research, the turn of a unit is also known to cause the tensions in slings to change in complex statically indeterminate arrangements. This operational variable is directly related to the efficiency of the equipment at equalizing the sling tensions, and the design of the rigging arrangement. The primarily cause for this variation is that the axis of more than three pin connections will inevitably not be collinear. As a result the relative distance from the pick points to the spreader beam will change during the turn. These orientation effects are the most pronounced for ship structure such as main decks and inner-bottoms that may have significant amount of shape to them. Figure 29 shows a depiction of a highly cambered deck being flipped, subject to these effects. In this exaggerated case with a block with significant shape, it can be seen that after the block has been rotated from upside-down to ships position significant load is transferred between the slings. Even if the sling lengths are initially set such that they all equally sharing the load, the act of turning will alters the relative sling tensions. It is possible with poor rigging design and poor equipment selection for an initially balanced arrangement with all slings equally sharing the load, could result in only two slings carrying the entire load after the turn. Furthermore, not only will padeyes see an increase of overall load, but a change of the angle at which the tension is applied. This can result in a greater amount of side load, which will significantly increase the local stresses. Complete analysis is close to impossible as during the turn, the many different orientations of the block will have a non-linear variation of the tensions and their angles. Although most vessels will not have such extreme camber as shown in the figure, one must still be aware of these operational effects. Ideally all attachment points will occupy the exact same axis, so that the centers of all pin connections that experience rotation during the turn are collinear. Finally this effect will be minimized if the aspect ratio of the equalizer is high because this geometric configuration allows the most forgiveness in this application due to the larger rotation sweep possible and subsequent equalization range. However, poor design can lead to sling tensions increasing by 100% and the sling angle possibly changing by several degrees.

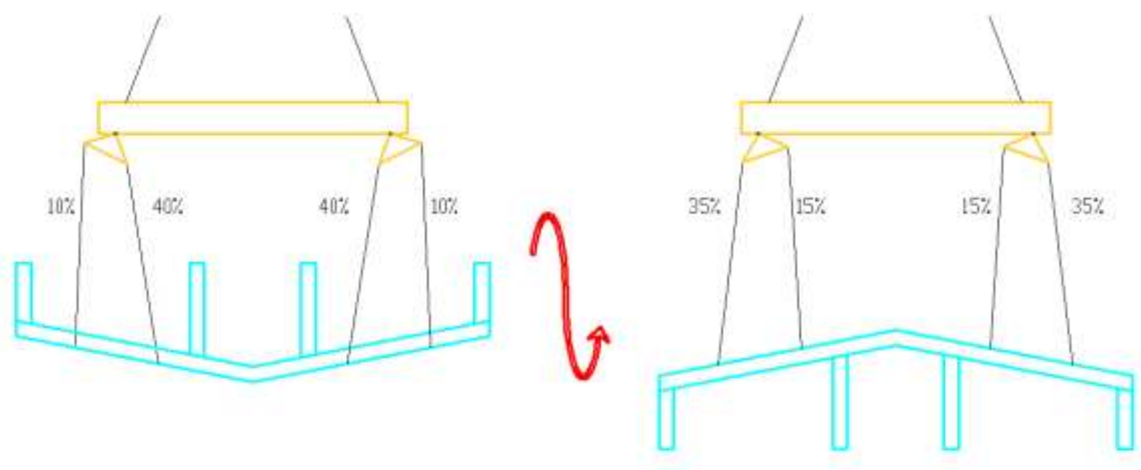


Figure 29: Operational Effects of Turning on Sling Tensions

2.1.6. Statically Indeterminate Factors

One of the largest and most variable operational factors associated with many lifts are the sling tensions. In the simplest possible scenario, when a single sling is used to pick up an object with a known mass but unknown Center Of Gravity (COG), one will still know exactly what the sling tension will be. Things get increasingly complex with the addition of more slings. In the case of two or three slings one can calculate what the tensions will be if one knows both the weight and COG. As more slings are added the complexity of the problem become even more variable. Calculating accurate tension in the four slings lift as shown in Figure 30 is significantly difficult. An exact tension depends on not only on the mass and COG of the object to be lifted, but also on several other factors such as:

- Exact length of slings
- Elasticity of slings
- Angle of slings
- Attachment location of slings
- Flexibility of lifted structure
- Mass distribution of lifted structure

On the left of the figure, (A) shows an idealized possible solution if all slings are balanced around the COG of a rigid structure, where ideally all carry equal load. If the slings are not elastic such has chain slings, a one link difference in length for any one sling will significantly alter how the load is carried, as shown in (B), where two slings carry no load. As can be seen from the right of this figure (C), an error in the sling tension calculation can be further compounded if the estimate of the COG is in error. Finally, lifting large plate based ship structure often requires many slings to avoid over loading local structure around the padeyes. The more slings that are needed for a given lift, the larger the number of variables there will be that affect the tensions, and the more complex determining what any one sling tension will be. This operational variable is can however be reduced on critical lifts through the use of various equalizing devices or spreader beams, but a lift designer must be well aware of the amount of variance still possible.

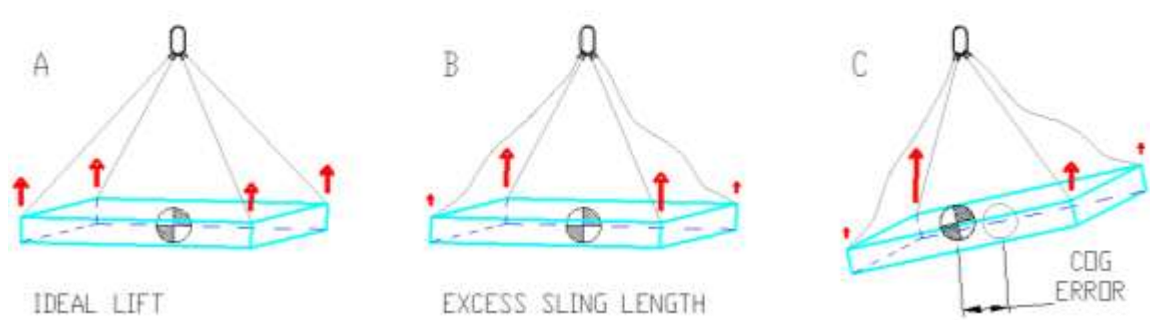


Figure 30: Single Crane Four Rigid Sling Lift

On large multiple sling lifts as shown in Figure 31, additional uncertainties are created by the rigidity and mass distribution of the block, which can also play a part in effecting sling loads and lifted behavior. If the block if flexible, and has heavy and opposite corners, it will not behave like a rigid body when lifted. This will result in a wracking or twisting of the structure as it is lifted, which will both alter the stresses in the structure as well as the loads in the slings. Accurate estimation of the torsional rigidity of a block is significantly complicated and may require a highly detailed Finite Element (FE) model, if an accurate estimate of lifted deflections and sling tensions is desired. Even then it is very difficult to set the FE model's boundary conditions to estimate wracking in large complicated models. Fortunately most lifted ship structure is rigid enough that racking will only slightly alter the sling loads.

This figure also shows a rigging arrangement which is statically indeterminate regardless of any block wracking. Four slings in the same plane under a spreader bar can have highly variable sling tensions. In such circumstances a device to assist the equalizing of the slings is essential, but will probably not exactly balance the tensions. It can also be shown that the geometric design of equalizers, and the length and elasticity of the slings used, can have significant effects of the division of load, and result in variable sling tensions.

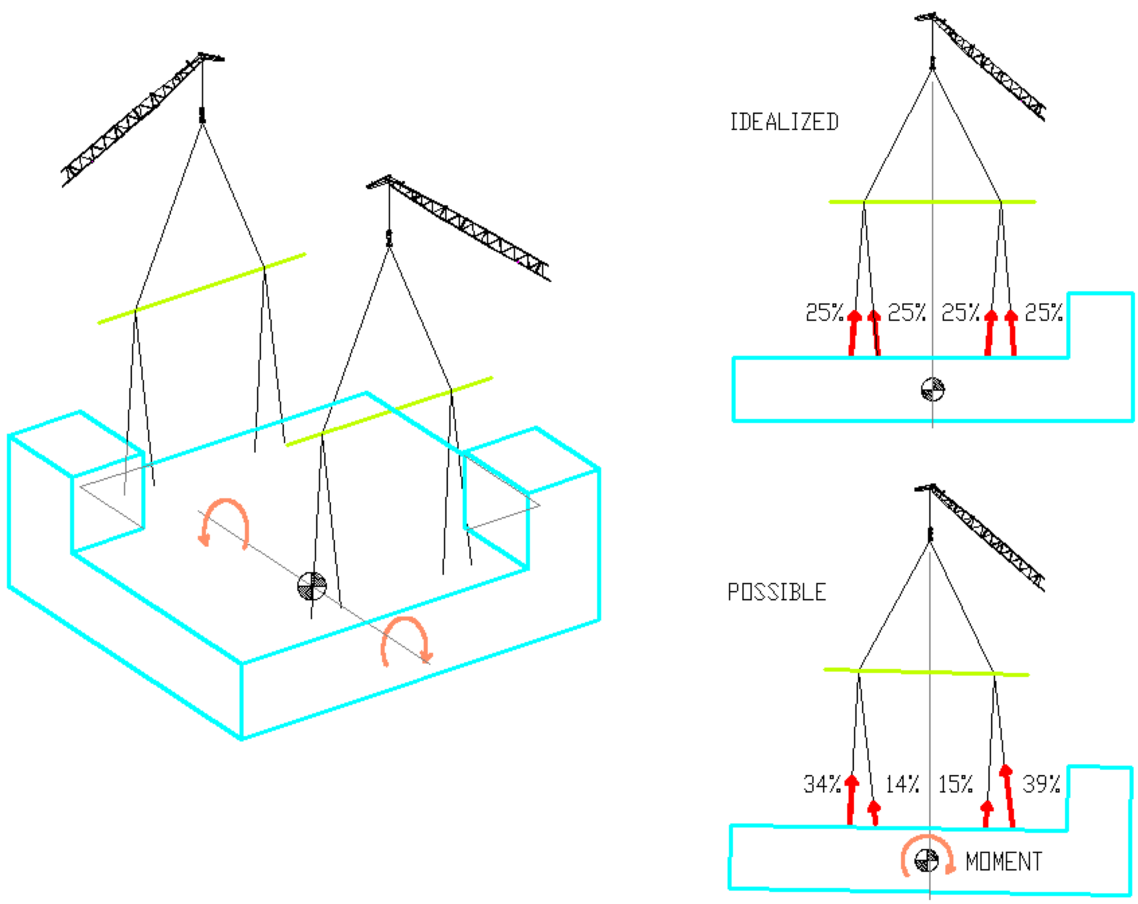


Figure 31: Two Crane Multiple Sling Non-Rigid Block Lift

2.1.7. Shackle Loads

One operational variable is the exact position of the shackle in the padeye as shown in Figure 32. Ideally the padeye used in a rigging operation will have a width that is greater than 80% the opening of the shackle. In addition to providing ample bearing area, this will ensure that the line of action of a straight pull is transmitted down the center of the padeye. However this requires the padeye and shackle to be matched beforehand. To make organizing and planning a rigging operation easier, padeyes are sometimes made thinner, such that a larger range of possible shackles can be used. Unfortunately this means that that the slings line of action may not be perfectly centered in line with the padeye, or bulkhead underneath. This will create an initial moment on the padeye and structure even when the block is lifted perfectly level, with crane slings that are perfectly vertical.

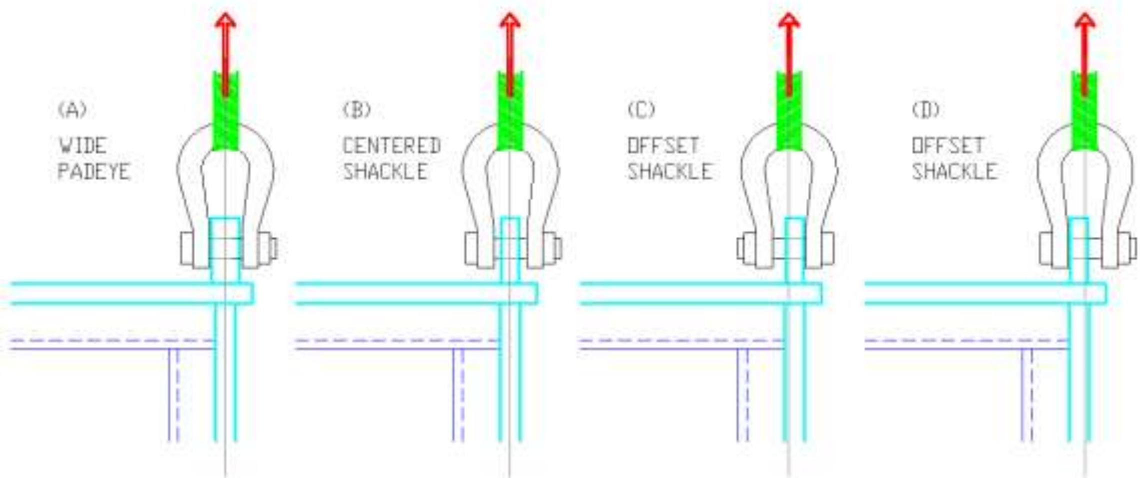


Figure 32: Operation Variable of Offset Shackle

2.1.8. Ground Interactions

Some of the uncertainty regarding a rigging operation is resolved when the object is lifted from the ground, however this specific process itself can have considerable additional uncertainly. From an operational perspective, a crane may not be perfectly centered about the COG before the lift, as a result of an estimating error or initial crane positional tolerance. An example of the results from both a COG estimating error and initial positional tolerance of the crane can be seen in Figure 33. When the load is lifted, the rigging and it will start to rotate into equilibrium and may be held by friction from translating, which can impose side loads on vertical bulkheads. After clearing the frictional interface with the ground interface it will accelerate horizontally to place the COG under the hook, and may also inevitably overshoot. The direction it will swing can be highly uncertain making an initial lift particularly hazardous due to the possible initiation of dynamics.

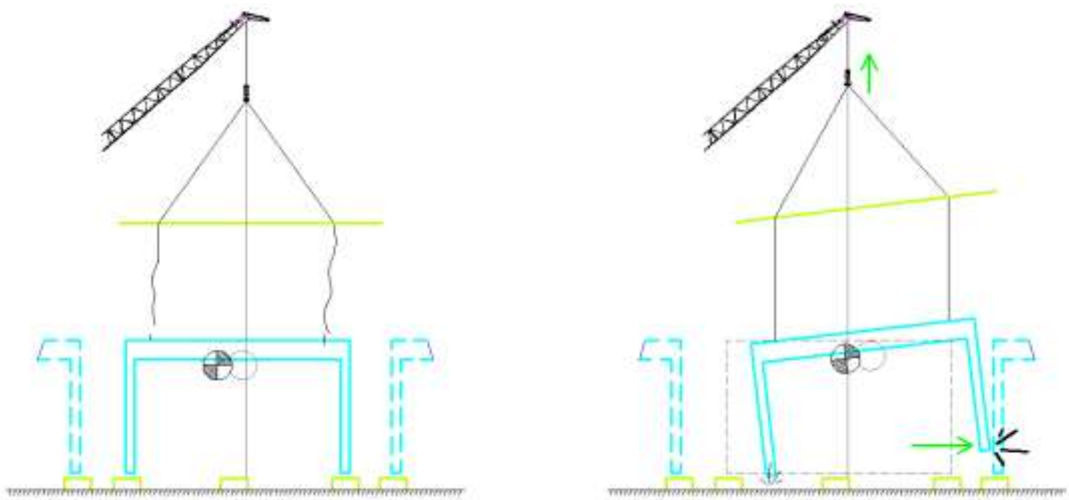


Figure 33: Compounded COG and Positional Crane Errors

The initial acceleration of the load is not the only uncertainty surrounding the first lift of an object. The ground interference will change the sling tensions as well as impose forces from dragging or being caught on the ground. This is partly explained by the ground interface forces, which will alter the loads seen in the padeyes as shown in Figure 34. Here the right lifting padeye sees 20% more load as it is lifted from the ground, than in the lifted position. This figure has a relatively large COG error at 5%, but the suggested increase in some loads in three dimensional space may not be. These same effects will also occur during the initial wracking of a lift of a flexible block with a non-homogeneous mass distribution.

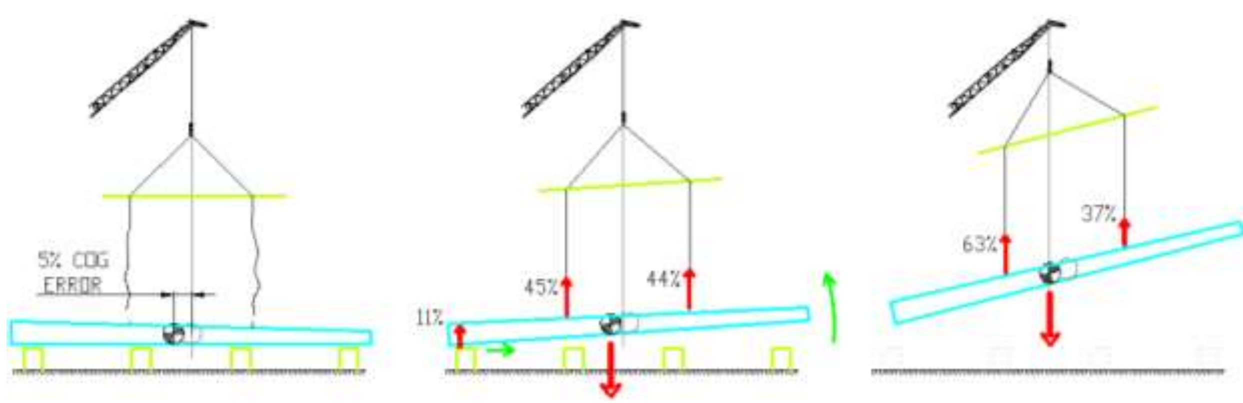


Figure 34: Ground Interaction is an Operation Variable

During this research bending moments recorded in structure near padeyes, vertical bulkheads, and even global bending stresses saw significant increases in measured strain as the block was lifted from the ground. Of the six different types of shipyard blocks lifted, every one showed some elevated stresses during the initial lift as shown in Table 4. On many blocks the recorded elevated stresses occurred in just a few of the many gauges on the block. However, other lifts such as the two crane lift of block 100 showed these effects in almost every gauge indicating a truly global phenomenon. This one lift measured considerable stresses roughly double what the recorded steady state lift value was, with additional stress magnitudes of up to 8,000 psi. This spike in stresses lasted roughly 20 seconds which was roughly the observed amount of time that the last corner of the block was on a support. Finally the wide spread nature and duration of the elevated stress period clearly indicates that these occurrences are not errors in the data, but genuine events which corresponding exactly to the field observations.

Strain gauges near padeyes were especially prone to experience ground related effects, however, these increases were typically on the smaller side, rarely causing more than a 50% increase in stress. The lift of block 560 saw the largest unexpected increase in stress which was roughly five times the steady state recorded value. This reading was on the flange of a major stiffener on a vertical bulkhead 23 feet high. It is believed that as the lift started, the block translated sideways, and dragged a corner on the ground, creating a significant moment during this short 12 second time period. This gauge recorded bending stresses that were 18,000 psi larger than the steady state lifted value at this location. It should be noted that the strain gauges were often not located at the position of highest stress, which was done to avoid areas of large strain gradient and assist a pure reading. This suggests that actual stresses elsewhere were probably even higher.

Table 4: Selected Stress Increases During Block Lift off Ground

Block #	Block Type or Description	Estimated Weight (ST)	Crane #	Observed Location of Largest Stress Increase	Stress Increase Above Projected	Magnitude Stress Anomaly (psi)	Duration of Increase (sec)
167	Deck and Shell Block	82	12, 14	Local Bending by Padeye	40%	2,000	60
		96	15, 16	Local and Global Bending	4%	500	60
		82	15, 16	Local Bending by Padeye	63%	1,400	5
11	Innerbottom Block	212	15	Under Padeye	10%	500	8
431	Small House Block	44	15, 16	Global Bending in Frame	12%	500	7
100	Framed Stiffened Panel	44	16	Local Bending by Padeye	45%	5,500	40
		44	15, 16	Global and Local Bending	100%	8,000	20
		44	15	Local Bending by Padeye	12%	3,000	5
537	Double Deck Grand Block	531	15, 16	Deck Bending Under Padeye	35%	1,000	60
560	Hanger Superstructure Grand Block	354	15, 16	Bending in Bulkhead Frame	500%	18,000	12

Significantly the two lifts of block 167 from sister ships, were initially supported on contact surfaces of different materials, lifted by different cranes, nearly half a year apart, and both lifts had similar magnitude measured stress increases in almost identical locations. This is strong evidence that this is to some degree a repeatable phenomenon that may be possible to project and design for. However, these ground interactions would be highly dependent on operational factors that would be very difficult to control, and attempting to project the extent of their effects may be so dependent on block specifics that no universal guidance can be provided. The complexities of large scale material handling is a very strong incentives to adopt design factors appropriately sized to minimize the chance of unforeseen events causing damage to property, equipment, or personnel.

Although not covered in this research, often material is rolled on the ground by a single crane similar to what is shown in Figure 35. This can have significant operational factors which may lead to increasing the loads seen and the effective crane radius. This can be especially true when loads go “over the top” during which the tension in the slings may temporarily go slack. Also when handling loads on the ground it is also possible that they may be stuck, such as through mud suction, or embedment, and may take considerable extra force to pull them free. When they do come free they may rebound from the elasticity of the slings and may start to bounce and swing. Although no numbers or guidance can be provided to the amount of operations stress these types of occurrences may cause, provisions should be in place if required.

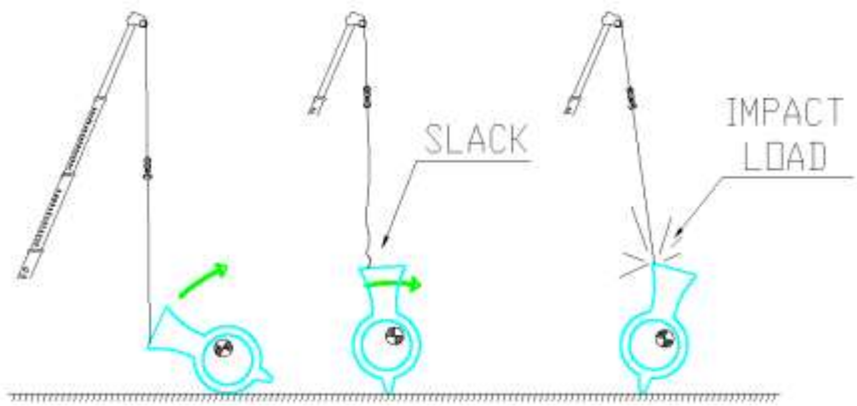


Figure 35: Rolling Operations can be Subject to Impact Loads

2.2. Dynamic Variables

When lifting and especially transporting a lifted object there will always be motion, and therefore accelerations and dynamics of that object. Although the number and types of cranes, experience of the operators, and speed of the operation will have a significant influence on the amount of the dynamics that occur, it is probably impossible to completely minimize or eliminate relative motions during the operation. It is likely that dynamic variables will always be present and it is merely their magnitude that is in question. The single crane lifts in this research had minimal dynamic motion observed and in the data recorded. It is believed that this is because they were conducted by very large mobile cranes. The cranes utilized had a mass that was 5 to 25 times that of the block that they were lifting, and were set on foundations of steel rails, which no doubt greatly assisted in creating a stable platform to promote smooth motions with minimal jerk. Conversely it is known that off road mobile cranes with large rubber tires are much more likely to have load dynamics as any irregularities over the transit path are magnified many times over at the boom tip. The two crane lifts for which data was recorded showed dynamics that were orders of magnitude larger than the single crane lifts. These motions were observed despite the fact that no lift was conducted when wind speeds were in excess of 8 mph, and most lifts were conducted at night with no measureable wind at all. Almost universally three types of motion were recorded during the transport of ship blocks with multiple cranes:

- Bouncing
- Swinging
- Twisting

The bouncing of a load was the most universally present, but the smallest acceleration in magnitude. Swinging in pendulum fashion as well as twisting about a vertical axis passing through the COG produced accelerations much larger in magnitude. These dynamics were typically instigated when:

- Cranes start moving
- Cranes came to curve in the tracks and altered direction of travel
- Cranes boomed the load in or out
- Cranes swung the load to the side

2.2.1. Bouncing of Load

0.25 – 4 [Second Periods Observed During Shipyard Lifts]:

The bouncing of the load was a relatively high-frequency oscillation generally with small magnitude. On the blocks reviewed during this research these oscillations have observed having affects up to 5% of the weight of the load, though typically were only half of that. In general the magnitude appeared to be mass dependant with larger loads generally bouncing a greater amount. Every lift and every block displayed vertical motions with several frequencies present, which varied slightly. The heaviest lifts showed largest periods of just over three second frequencies, and the lighter lifts of just over two seconds. The difference in mass held by the cranes between the recorded lifts was over a factor of ten, and since the natural frequency for a mass below a spring is a function of weight, this frequency should be different by a factor of the square root of the block mass. Because the periods of oscillation recorded does not vary by a factor of two, this oscillation appears to be largely independent of block weight, and more relevant to the system weight of both the crane and the load. Figure 36 shows a simplified representation of the complex multi degree of freedom system that affects the vertical motions of the block. Some of the primary functions of the vertical motion are believed to be main hoist wire rope the load is suspended by, the rotation of the boom and the boom hoist rope, and the stiffness of the entire crane.

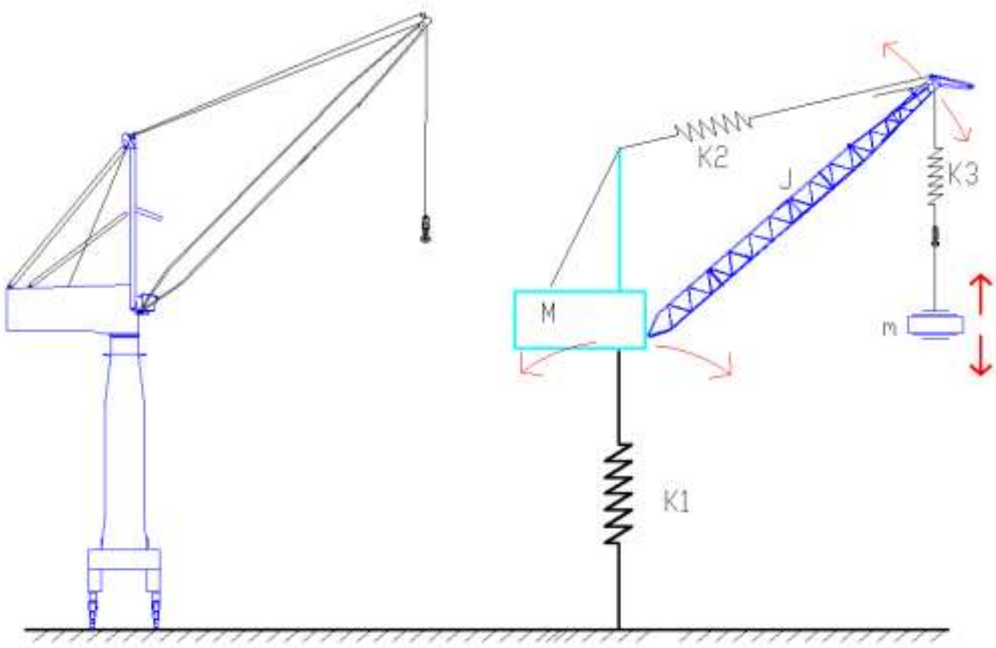


Figure 36: Theoretical Model of Vertical Motion Due to Crane Oscillation

The different components of the crane and load system will each have their own natural frequencies. One of the clearest plots of these various components of the vertical accelerations is shown in Figure 37 from the lift of block 431. In this plot the roughly quarter second and just under three second periods are clearly visible in the data. This two crane lift and turn of a 44 ton block had the accelerometers placed close to the attachment of the slings with gauge 4 and 5 being under heavily loaded crane attached to the block. If one counts the weight of the rigging gear, this crane was loaded only to about 12% of capacity, with the quoted weight of the crane being over 40 times this amount. The single crane lift of block 011, which was of a much more rigid 212 ton structure, had similar vertical dynamics magnitudes, with the periods of oscillation being only slightly different. This is strong evidence that the vertical motions experienced during the different lifts reviewed was not very block dependant, suggesting that most of this imposed motion is crane induced. Also although both cranes are the same make and model, the vertical accelerations they caused were slightly different. This can be explained by the fact the elasticity of wire rope changes over its life, becoming less elastic with age, and would thus stiffen the system. As the different cranes are on alternating maintenance schedules, a different stiffness should be expected. This can account for why in the figure the vertical accelerations recorded by gauge 2 and 3 are slightly different than 4 and 5. One can thus expect that the vertical dynamics that may take place during a lift will be highly crane dependant and the 5% factor suggested may only apply to very large mobile cranes with steel rail foundations.

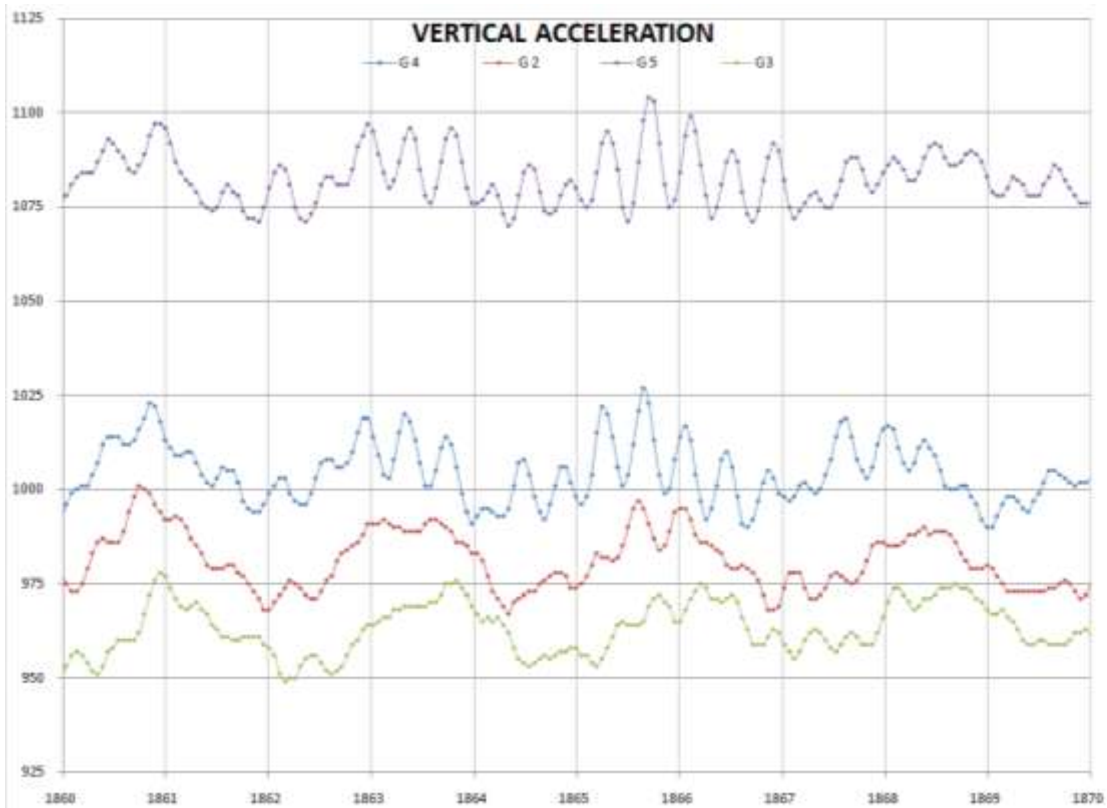


Figure 37: Typical Vertical Accelerations (Milli Gravity vs. Seconds)

2.2.2. Swinging of Load

11 -16 [Second Periods Observed During Shipyard Lifts]:

During the very first lift of this research, oscillations in the recorded stresses were observed occurring at a periods that corresponded to a simple pendulum with a length equal to the vertical distance between the lifted structure and the crane sheave. At some locations these dynamics resulted in recorded stress increases by over 50% of the steady state lift value, although only of a magnitude of 1,500 psi. At the time the cause of these oscillations was not obvious. Small accelerometers were obtained for the following lifts to help confirm the lifted motions as it appeared that they could have significant relevance with regards to the amount of uncertainty when analyzing lifted structure. Fluctuations in the stresses that correspond to a period predicted by the simple algebraic expression of a pendulum was subsequently found in most lifts, and frequently were also apparent in various strain gauges. The periods of oscillation for a simple pendulum of various lengths can be seen in Table 5 which is valid for small angles and produced by the equation:

$$T = 2\pi\sqrt{L/g}$$

Table 5: Periods of a Pendulum

Pendulum [feet]	T[Seconds]
100	11.1
120	12.1
130	12.6
140	13.1
150	13.6
160	14.0
170	14.4
180	14.8
190	15.3
200	15.7

There are two primary directions of swinging for the typical two crane rigging arrangement utilized through most of this research seen in Figure 38. If the block swings in the plainer direction of the rigging as shown on the left of this figure, the block will develop an angle as it swings. If the block swings out of the plane of the rigging as shown on the right, and both rigging arrangements are close to the same height, the block will mainly translate horizontally. Importantly in this second case the slings will develop an angle relative to the block which can greatly affect the stresses near the attachment points. The scale of critical shipyard crane lifts is typically large, so the speeds that the lifted structure will travel at, and the angle that it will be sweep through is usually small. As a result swinging in the plane of the rigging is less of a concern. However since swinging normal to the plane of the rigging will change the angle that the slings make with the block, this can be more important. This in part depends on the orientation of the attachment points, which can be side loaded by this direction of swinging.

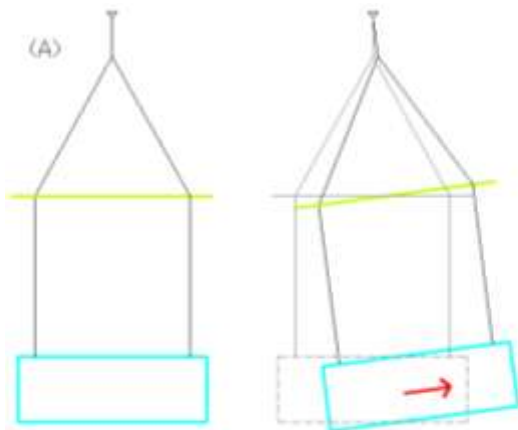


Figure 38: Types of Pendulum Motion

Dutermining the extent of motions that occoured on various lifts is complex as the two primary direction of swigning are only parts of a very complex multi-degree of freedom pendulum system. Most of the time the motion that develops is difficult to decipher as various modes shapes of occilation influence each other, come in and out of promenance and result in both regular and chaotic motion. As a result, the typical plots of accelerations recorded cannot be accuratly modeled with simple algabraic formula, and assuptions must be made to create an estimates as to the angular extent of motion caused by the accelerations recorded. These simplified approximations sugest that during the largest of dynamic events recorded in this research, lifted shipyard blocks rarely appeared to swing though an angle much greater than one degree.

2.2.3. Twisting of Load

5- 30 [Second Periods Observed During Shipyard Lifts]:

The twisting of a two crane lift about a vertical axis was one of the most dominate dynamics observed during this research. This oscillation is initiated when a crane starts moving, swings the load, or changes direction of travel. When a crane undertakes one of these actions it will cause a change in its position relative to the other crane, and importantly to the blocks COG. This will impart a force and a torque to the block, which instigates both a twisting and swinging motion. For unknown reasons, of these two motions the twisting appeared to be the more dominate mode of oscillation. This dynamic had highly variable periods ranging from roughly only 5 seconds on small light weight blocks, to about 30 seconds on the heavy and relatively large blocks. This range is proportional to a lifted blocks size, mass, and its mass moment of inertia. The larger and heavier a block is, the slower it is likely to twist when lifted, and the longer the period will be. Where the rigging attaches to the block also has affects as two cranes attaching to close to the COG of the block will result in a longer twist period since they impart less torque to oppose this motion. Similarly twisting is also proportional to lift variables such as the height of the crane sheave, where a greater distance between the sheave and the block will result in a longer twisting period.

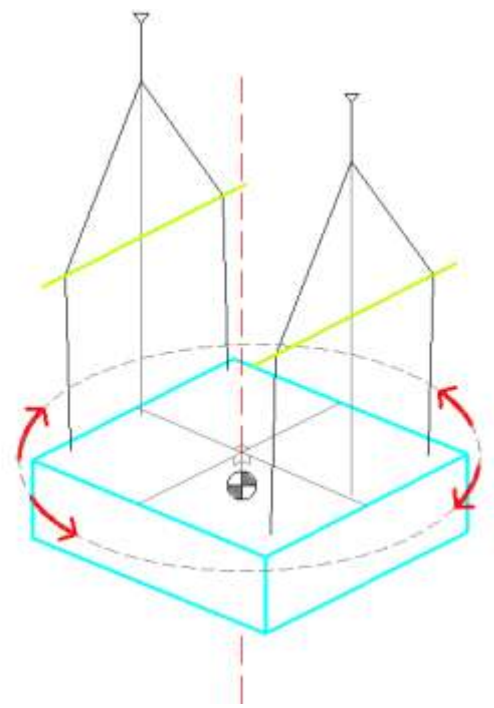


Figure 39: Torsional Motion of Block

The twisting of the block is of interest as this motion will alter the angles that the slings attach to the block. The dynamics that typically took place during this research were quite complex and rarely was a pure swinging or twisting occurring. Any analysis is further complicated because the declivity of the block can change as a result of the motion of the block. As a result calculating twisting angles reliably could not be done. It is however believed that the effects of twisting are no larger than the postulated motions for block swinging, causing sling angles of roughly one degree.