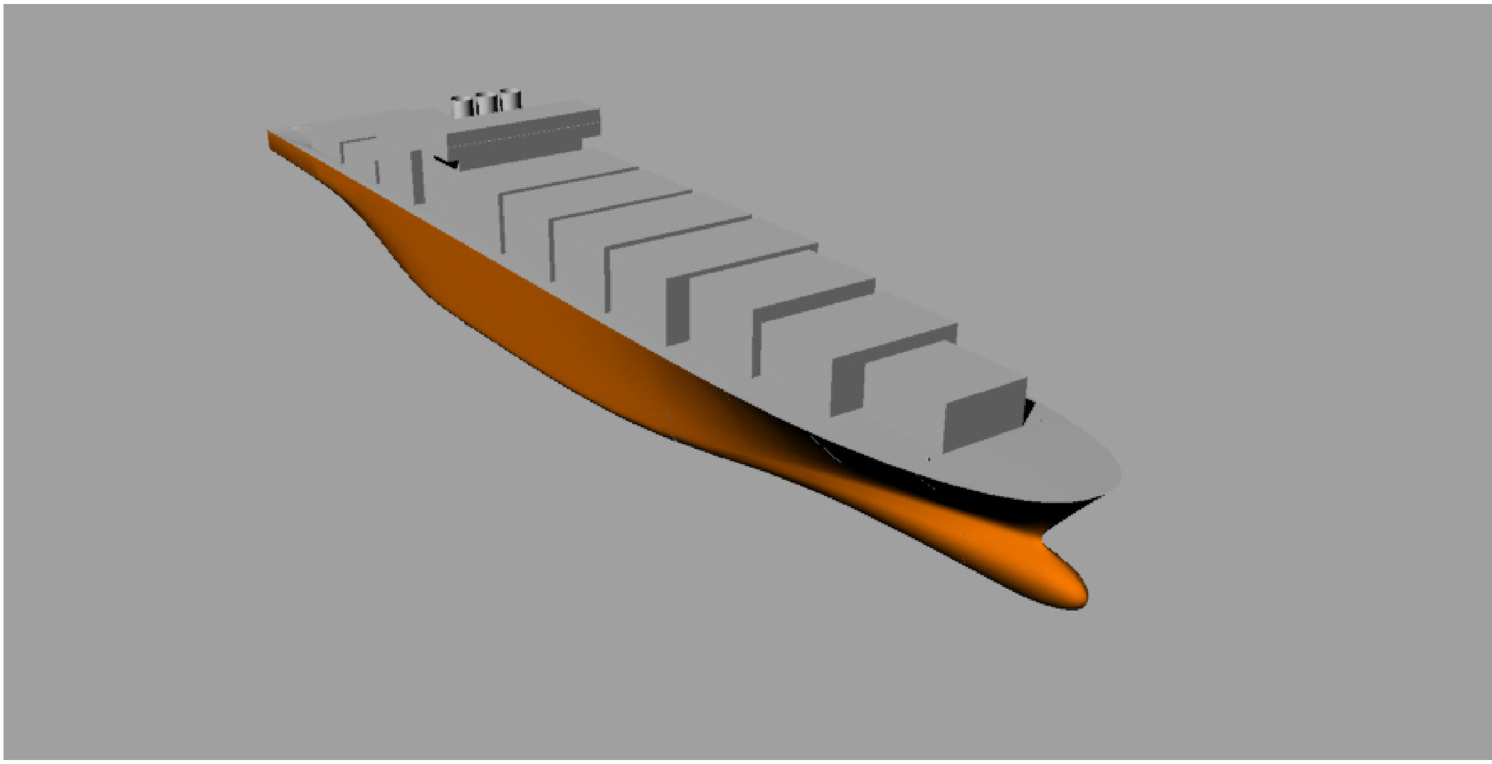
Path Dependencies and Emergent Design Failure in the NA470 Ship Design Course



Engineering Honors

Capstone Final Report

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1. Introduction

In this capstone project I sought out design failures in my NA470 ship design course and examined why they occurred, why they continued, how they plagued the design and what could have been done differently. In doing this theory centered around complex design problems namely that which concerns path dependencies and emergent design failure was applied in studying the design. My design in the course was called the *SS Steel Ducky* and will continued to be referred to as such throughout the rest of this paper.

This report begins by briefly introducing the design and the initial variables that were taken into account when creating the design, some necessary knowledge of Naval Architecture, and the ships design. Following this is a description of the design theory (Path Dependencies and Emergent Design Failure) that was studied. Lastly, Path Dependency and Emergent Design Failure theory will be applied to the design. This application will be prefaced by an overview of the relevant Naval Architecture concepts when necessary. In doing this, suggestions on how the design process itself could have been performed in a more optimal manner will be found. Furthermore, the occurrence of these theories and how there applicable to all complex design processes will be discussed.

The design failures that will be discussed in this report are as follows:

- Excessive amount of trim towards the bow.
- Low righting arm moment for the ship in intact stability.
- Righting arm for damage stability failed to pass International Maritime Organization (IMO) regulations.

2. Overview to the *SS Steel Ducky* Design

To understand this capstone project one must first understand the design of the *SS Steel Ducky* . The cover picture shows a rendering of the design.

Table 2.1 shows the important dimensions of the *SS Steel Ducky* and other important pieces of information.

Table 2.1: Summary of important information for the *SS Steel Ducky* .

Parameter	**Value**
Length Overall (LOA)	265 m
Length on Water Line (LWL)	250 m
Beam	40.5 m
Draft	11 m
Depth	20.12 m
Bloc Coefficient (C_b)	0.661
Displacement (Δ)	75502 tonnes
TEU Capacity	3500

This table gives a good introduction to the design as a whole. This ship was designed to safely carry 3500 TEU containers and crew along the 7 day path from Los Angeles, USA to Shanghai, China a 5700 nautical mile journey. The design was meant to be stable for a total of four loading conditions: 14 TEU departure, 14 TEU arrival, 12 TEU departure, and 12 TEU arrival. These indicate the weigh of each container, this container weights were evenly loaded, meaning that each container could be modeled as a standard block of either 12 tons or 14 tons uniformly distributed on the container.

The figure below is the inboard profile of the ship. The important pieces of information to note is the container placements as this will be the focus of much of the design failures that occurred.

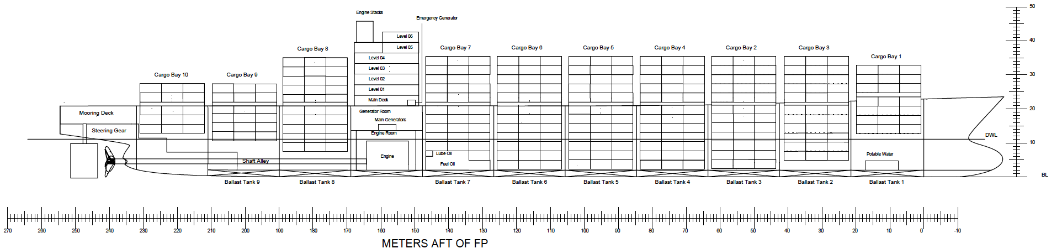

Figure 2.1: The inboard profile of the *SS Steel Ducky* .

Notice in figure 2.1 that the aft most container hull is not used and the two nearest to it have containers only stacked two rows high. In order to fit all the containers on board this was compensated for by stacking the containers in the middle most hulls five rows high above the deck. As will later be described this was part of the the design failure.

The geometry of the hull was provided in the class however the principle particulars listed above were created during the design process. This is important to note because one of the design failures arises due to the geometry of the hull. Notably, if the hull geometry were to be designed with the number of containers in mind, this would be less of a problem. In fact, many of the design failures that will be discussed may not have occurred had this been taken into account in the initial design of the geometry of the hull. This conclusion was made after discussion with Professor David Singer, the advisor for this project.

While this may have stymied the design, the design process was still incredibly valuable and the process of analyzing design failures was still valuable.

3. Background Of Design Theory

Naval Architecture is one of the most systems engineering oriented fields. Professionals who have studied the field coined the term ”wicked problem.” The following quotes give a relevant description of what this implies for design.

“Design problems are ill-defined, ill-structured, or ‘wicked’” (Cross 1982)

“Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan” (Andrews 1981).

Wicked Problems (Conklin 2006):

- The product is not understood until after the formulation of a solution.
- Design problems have no stopping rule.
- Solutions to design problems are not right or wrong.
- Every design problem is essentially novel and unique.
- Every solution to a design problem is a ‘one shot operation’.
- Design problems have no given alternative solutions.

As a consequence of the wicked problem is that as a designer makes design decisions a path is locked on. With increasing complexities of these decisions there becomes a higher chance of design failures. This occurred many times throughout the process of the design.

The emergent design failures that have been studied will be summarized graphically below.

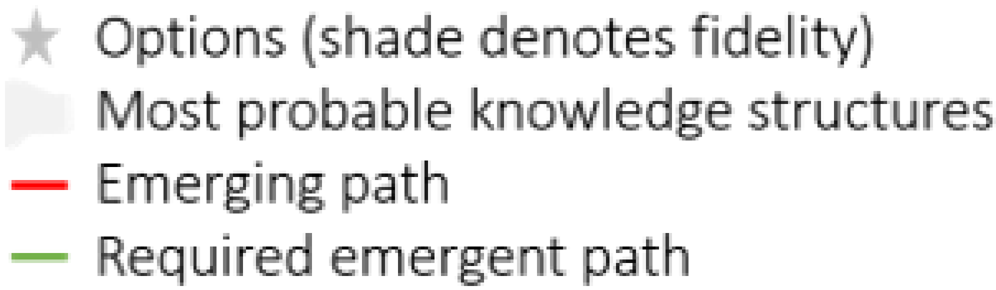

Figure 3.1: This legend is to be used in conjunction with the previous figures.

The figure above is a legend to describe the following 3 figures. The stars represent design options to explore. For example, a specific placing of containers on the ship is a star. The shaded parts are where general knowledge will most likely lead a designer. For example, a star could include stacking all 3500 containers in one compartment in the middle, however, this would not be attempted by a designer because it is not a probable solution given the knowledge already known. The emerging path is the path that is being taken that results in the design failure being described in the figure description. The green path is the required emergent path that will lead to an effective solution to the basic design problem. Once you commit to a decision you begin to explore the design space around that decision which can look like any number of shapes off paths, but often looks like a wave. This does a good job of graphically demonstrating how after committing to a design decision the designer will oscillate around the results of that decision and the knowledge structures will become smaller as a result. Design Lock-in occurs when the path takes the designer to a point of no return. This is due to the fact that a lot has been done in the design that was based on the previous act of committing to the path.

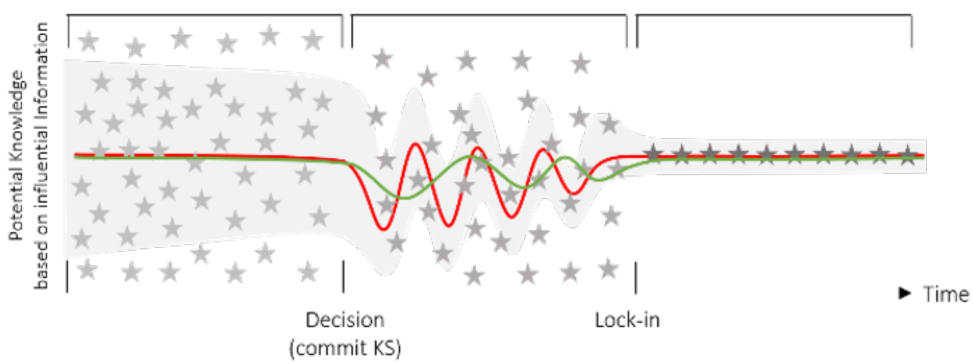

Figure 3.2: This depicts design churn.

Design churn occurs when the total number of problems being solved is not reducing as the project progresses. For example, in designing a ship, as I move my containers around I am causing more design problems in trim and upright stability. So when I make any design decision I am going far from the path that will lead to success (green path) and when I correct that problem I am over correcting. This is demonstrated by the bigger oscillations of the reed path versus the green path. As a result of this I am exploring more of the design space and using up more project time than is necessary in the process. It is important to note that this can still end up on the same path as the required emergent path, however more time is spent.

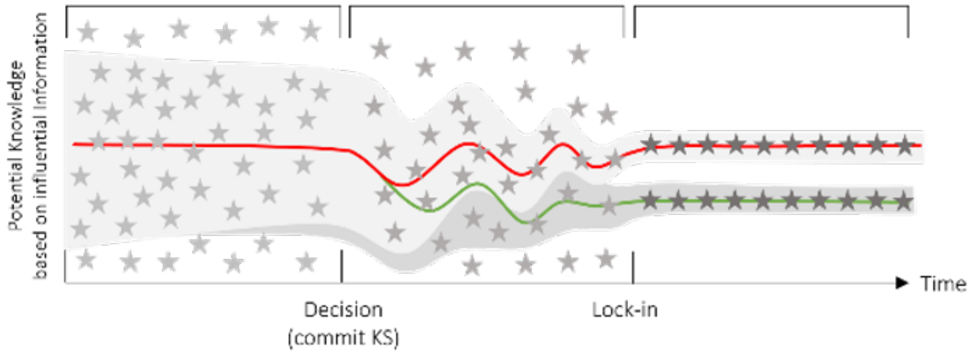

Figure 3.3: This depicts excessive rework.

Excessive reworks occurs when new information is generated by other tasks. This can be because an input of new information, the realization of an error or updates of assumptions. An example is when I realize I make an error transferring the weights or there positions from one estimation tool (Weights 2 spread sheet) to a software (*Maxsurf Stability*). Because of this error of transcribing data I will spend time iterating on the software and the calculation. As a result of this I end up going through the design space on the red line as opposed to the green line. This is a dramatic position to be in because often times the designer has to not only retrace the steps taken but also find out how to recreate the design on the proper path.

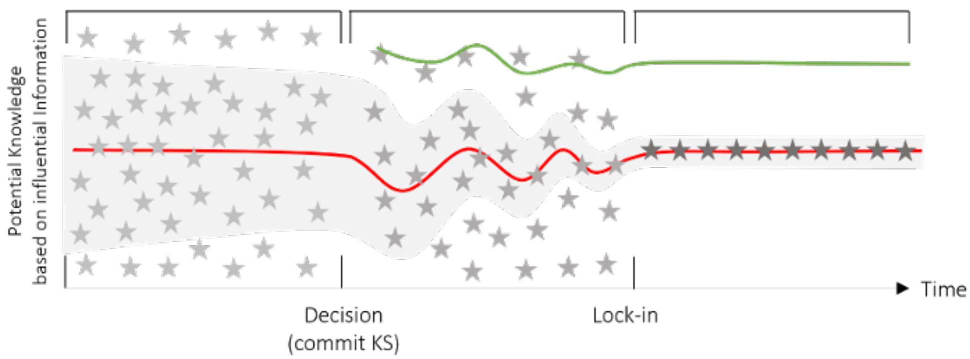

Figure 3.4: This depicts failure to integrate.

Failure to integrate is a very dramatic design failure as depicted in the graphic. This occurs when the designer is following a completely different path from the required path and as a result the knowledge structures being explored are also different than the knowledge structures that are around the required emergent path. The reason for this design failure is because the designer fails to integrate a product such as a component or system and develop the knowledge structure in that area. When this occurs and a wall is reached in the design as a result the designer must face the inability to continue with the current design activities as it has proven to be infeasible. An example in terms of Naval Architecture would be making a working with a hull form that does not provide the necessary buoyancy in the right areas to support the required weight on the ship. Due to a failure of integrating a correct hull form the designer will have to redo the hull form and redesign where the weight is placed on the ship.

4. Applying Design Theory to Design of the *SS Steel Ducky*

In this section I will discuss which design failures apply to the previously mentioned design failures. First, to summarize the design failures that were studied in this project.

- Excessive amount of trim towards the bow.
- Low righting arm moment for the ship in intact stability.
- Righting arm for damage stability failed to pass USCG (United States Coast Guard) regulations.

4.1 Excessive Rework: Excessive Trim Towards Bow

When the ship is trimming towards the bow, it is further in the water in the back of the ship. This is also denoted as positive trim. This is shown below in figure 4.1. This figure depicts the trim of the first iteration of the *SS Steel Ducky* . This indicates that there is either more weight in the bow or that there is not enough volume in the bow of the hull.

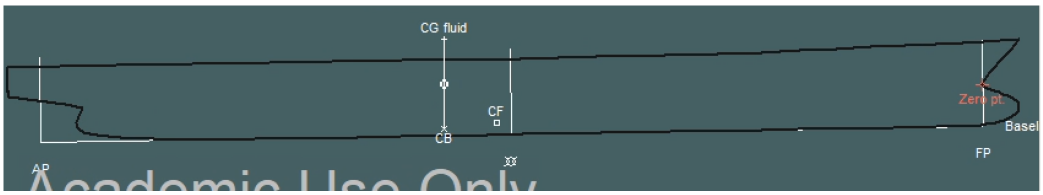

Figure 4.1: This depicts trim towards the bow or positive trim.

While this is still preferable to trim towards the stern or negative trim, the goal of this design was to have near zero trim. When I put in my weights into Maxsurf and ran the simulation I could see that the trim was positive. This lead to an excessive rework, where the new input of information was what the software indicated. As a result I began to move the containers from the aft 3 container bays to the container bays amidship. Each rework would see a different combination of the number of container rows in the aft. This ended up not working to make the trim zero. In fact in some cases specifically the 14 ton arrival load case the trim ended up being negative. The following table shows the final values of the trim and the difference in weight

Table 4.1: Load Cases Trim and Different in Weight and Displacement.

Load Case	Trim (m) + by stern	Difference in Weight and Displacement (%)
14 Ton Departure	0.15	-0.5
14 Ton Arrival	-0.57	-0.5
12 Ton Departure	0.48	-0.5
12 Ton Arrival	0.34	-0.5

When looking back, it seems like part of this problem was due to the lack of buoyancy in the bow of the ship. This partially lead to the excessive reworking. These final values are the result of excessively reworking and running out of time forcing me to settle with a configuration of containers that passed each test case as best as possible. Furthermore, it is important to note the negative trim in the 14 Ton Arrival case. This is a great demonstration of the results of an excessive rework design failure as depicted in the graphic. This is because I was not able to explore the knowledge structure around the required emergent path. As a result the design failed severely in this case and effected the rest of my design.

4.1.1 Lessons Learned: Excessive Trim

One of the most important aspects of this project is considering how this design failure could have been avoided. In this case, as with many others experience in ship design would have been key to avoiding this situation in the future. I should've been able to understand the hull lines a bit better and understand the lack of buoyancy in the aft of the ship. This would have helped educate my initial cargo hold placements. I also would have avoided spending a lot of time in the excessive reworking stage of this design. Ideally, with a more optimal placement of cargo holds I would have been able to balance the weight of the containers and the deck house in a more optimal manner to minimize the trim of the load cases. As I will discuss in the next section, this could have also been done by implementing the information gained from the floodable length curve. From a theoretical perspective, if I began making design decisions that were closer to the optimal required design path, I also would have explored the knowledge structures that would have led to an optimal design. Lastly, I could have explored more design space with the initial spreadsheet tool (Weights 2) and been more certain that my load cases and bulkhead placement would have been more optimal when I began to use the Maxsurf software. Overall, design failures of this type can be avoided by being more flexible in the earlier stages of design and spending time making sure the knowledge structures I am exploring will actually solve the problem at hand.

4.2 Description of the Righting Arm Curve

Before describing the second and third design failures it is crucial to have a basic understanding of the righting arm curve and its relevance to the design of a ship. This section aims to give the reader this necessary understanding.

Intact stability is a crucial aspect of designing any ocean going vessel. The calculations surrounding this concept allow the designer to show that when the ship is not damaged, it will be able to right itself when in the midst of waves causing it to pitch. Pitch is the ship rotating about its longitudinal access. The angle of pitch is commonly called the heel angle. The righting arm curve is the tool used to study this phenomena. The righting arm curve and the concept surrounding it is depicted graphically in the figure 4.2.

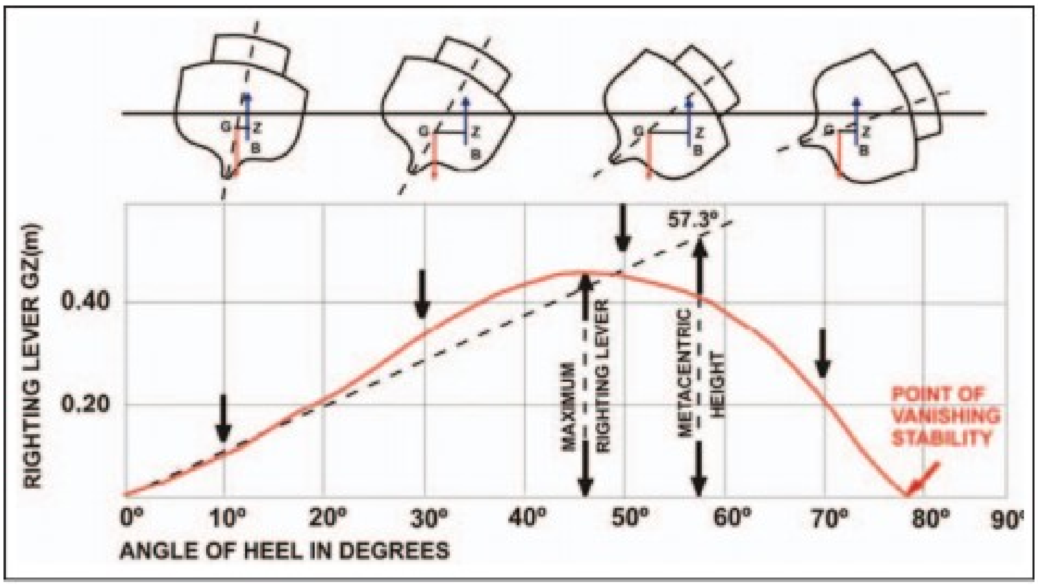

Figure 4.2: This figure describes the concept of the righting arm curve.

The righting arm moment is created because the forces of buoyancy and gravity want to be equal and opposite. When the ship experiences a heel angle typically as a result of the sea state, the center of buoyancy, where all the buoyant force acts is shifted towards the side in which more of the hull is in the water, as this side of the hull is now displacing more water. The horizontal distance between the center of buoyancy and the center of gravity is the righting arm lever, which is often denoted as GZ. The metacenter, M in the graphic above, is the point at which the buoyancy force acts when the ship experiences small angles of heel. The distance between the center of gravity and the metacenter is known as GM. These points allow for a stability triangle which can be used to solve for the value of GZ using equation 4.1 where θ is the angle of heel.

$$GZ = GMsin(\theta) \tag{4.1}$$

The righting arm moment is this distance multiplied by the force of buoyancy. The most relevant aspect of this physics to note is that **A lower the center of gravity, leads to a greater distance between the center of gravity and the metacenter height (GM), ultimately leading to a larger righting arm moment**.

In figure 4.2 the maximum point of the curve represents the maximum righting arm that can occur at the maximum angle of heel. If the ship continues to heel past this point the righting arm begins to decrease towards zero at a rapid pace eventually beginning zero and then negative which means that instead of the ship righting itself (returning to a stable position) it begins to help itself sink. The point at which the righting arm curve becomes negative is known as the point of vanishing stability.

Overall, this description means that as a designer you strive to make the maximum righting lever higher than zero and have a large range of positive stability in different angles of heel. Specifically, you want to accomplish the range of positive stability and maximum GZ that is stated in the regulatory body that you are hoping to conform to. In this case, it was the International Maritime Organization (IMO) and the United States Coast Guard (USCG). Suffice to say, this was difficult for me to accomplish.

4.3 Design Churn: Low Intact Stability

After generating the righting arm curve when the ship is intact it was clear that for all load cases the righting arm curve was not high enough. While it did pass the IMO and USCG regulations, its low value and sub optimal shape caused problems for the trickier load cases and for damage stability. Although in the case of damage stability there were other areas which caused the design to fail.

Because intact stability ended up conforming with the regulations, this design failure demonstrated design churn. Assume that the bulkhead placement is set before approaching this problem for the purposes of describing this failure. As I attempted to find an optimal placement for the containers I was continuously ending up with configurations in which they were stacked high in the center of the ship as a result I was increasing the center of gravity and causing the righting arm curve and shape to become less and less optimal. This design churn between configurations ended up looking more like the red emerging path because I was making large adjustments that caused large problems leading to large readjustments. Hence the higher amplitude of the sine wave in figure 3.2. This lead to an increase waste of time. Table **??** shows the intact stability maximum values for each required load case.

Table 4.2: Summary of the intact stability of the load cases.

Load Case	**Max GZ [m]**	**Heel at Max GZ [deg]**
14 ton Departure	1.09	31.8
14 ton Arrival	1.02	31.8
12 ton Departure	1.383	32.7
12 ton Arrival	1.28	32.7

The IMO requirements for a ship this size are Max GZ: 0.4 m and Heel at Max GZ 30 degrees (International Maritime Organization). This means that the *SS Steel Ducky* did pass these regulations however, it did not pass at a sufficient margin to ensure that the damage stability analysis would pass as the next section will show. Another important aspect to note about righting arm curves is that typically a higher righting arm moment will lead to problematic seakeeping and comfort on board. Seakeeping refers to the study of motions of a floating vessel subjected to waves and its effect on humans, the systems, and the mission. If the the righting arm curve is too high this can lead to the ship reacting strongly to waves and pitch severely. So it is important to consider this when looking at the righting arm curve and it is another dependency to consider as one is progressing through the design. In the design of the *SS Steel Ducky* I did not have this problem as the GZ curve was low.

In a further study of this design failure, I will look at the shape of the lowest performing load case in terms of the righting arm curve of the 14 Ton Arrival load case. This was the lowest performing load case because the potable water and the crew effects have been depleted which rises the center of gravity, because these are stored low in the ship. Furthermore, the increase in weight of the containers from 12 tons to 14 tons also causes a rise in the center of gravity this is shown on the next page.

Figure 4.3 shows the sub optimal shape of the righting arm curve. First, note that the trend in positive stability is not very dramatic. This indicates that as the ship heels the righting arm moment will not increase as quickly as would be the case for a ship with a more optimum design, while this is typically indicative of good seakeeping the rate of increase is low enough to the point where it would be preferable to have a more stable ship in these heel angles then a comfortable ship to be on. This will be demonstrated in the next section when damage stability is discussed.

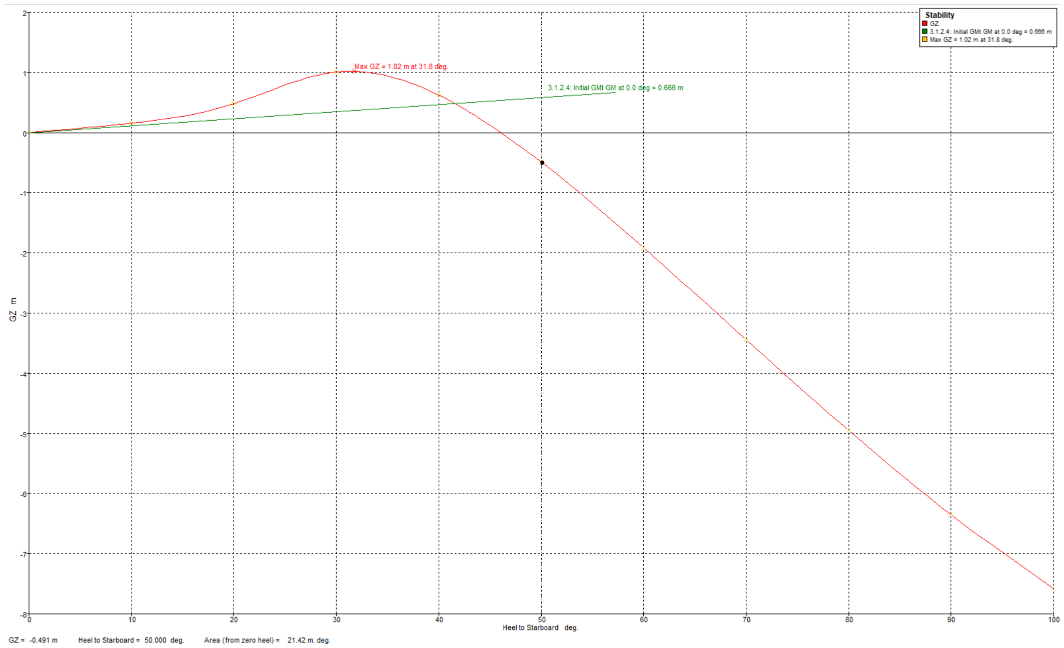

Figure 4.3: Intact Stability Righting Arm Curve for 14 Ton Arrival

Second, the majority of the heel angles that are possible will be in negative stability. As shown in the figure the point of vanishing stability is about 47 degrees. This means that if the ship heels by this amount it will sink. This may pass less strict regulations but it does not inspire confidence in the safety of the ship. This result is again due to the shape of the curve specifically the rapid decrease between the maximum GZ and the point of vanishing stability.

As I was iterating through possible container configurations, these curves continued to be sub optimal or optimal but with the caveat of a failing value of trim. This does well of demonstrating the design churn. As I iterated through the design space, problems would either arise in the trim or the intact stability curve. Ultimately, I settled on a configuration that at least saw me passing trim and intact stability for the regulations that were considered.

4.3.1 Lessons Learned: Intact Stability

To avoid design churn I should have focused on finding an extremely optimal solution to either of the problems that was being created by configuring the containers in different manners, either trim or the righting arm curve. This would have allowed me to iterate again through the configurations to make find the optimal solution to both problems in a much more timely manner. As a result, my emergent path would not have had dramatic swings through the design space and I would have been able to not spend so much time on the design churn of this aspect of the ship. Complex system engineering problems such as ships will always present these design failure paths, but with an increase of experience, the ability to have a more accurate and rich foresight into the process before going about solving these problems will make probability of being stuck in a design churn much less.

4.4 Floodable Length Explained

In order to understand the last instance of design failure it is important to have a basic understanding of the floodable length curve. To calculate the height of a point on the floodable length curve, you figure out how much of the ship in front of the point can be flooded so the ship will sink just to the margin line which is the maximum allowed height of the water plane if the ship is sinking. The margin line is 76 mm below the deck height according to IMO SOLAS (Safety of Life At Sea) regulations. So the floodable length curve represents the maximum floodable length of the ship along the ship's length. Following this calculation, to make sure that the compartment placement will not lead to sinking above the margin line in the case of a breach one can generate a figure like figure 4.4. The triangles have equivalent area in the 2D representation to the area of the fully flooded compartment.

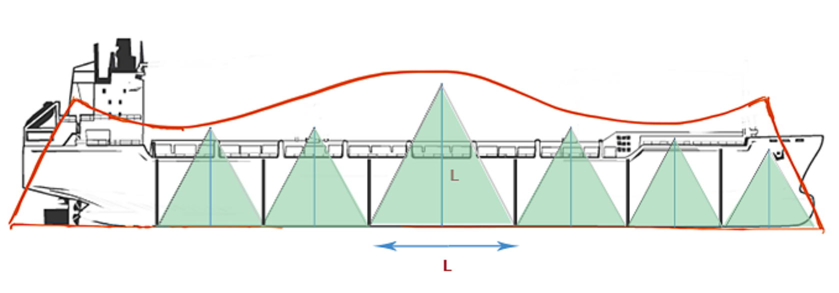

Figure 4.4: A demonstration of the single compartment floodable length curve.

As shown in the figure the floodable length curve is much higher in the middle, this is because if the center compartment is flooded it will effect the trim of the ship the least. As a result, the ship can take a lot more flooding in the center without sinking past the margin line as represented by the higher floodable length curve.

This calculation allows one to make an educated guess of how long the watertight bulkhead compartments should be in each position of the ship. Importantly, this figure only demonstrates a single compartment flooding scenario. In order to meet the standards of the IMO and USCG one must also consider parallel compartment damage cases. To complete this analysis one most also do a similar analysis with the flooding of parallel compartments up the whole length of the ship. An example of this analysis passing is showing in figure 4.5. Comparing the two figures, one can note that the compartments had to become smaller in order to still be under the floodable length curve in the parallel damage case.

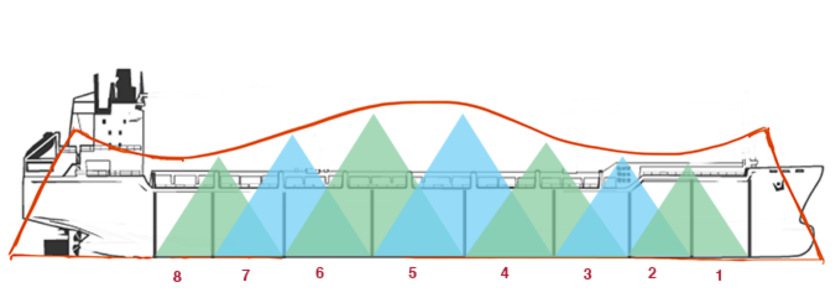

Figure 4.5: A demonstration of the double compartment floodable length curve.

Running the floodable length curve calculation before determining the positions of the bulkheads and cargo holds is an efficient way to ensure the design will perform better when studying its damage stability.

One last important piece of information is that the volume of the bulkhead that can be filled is dictated by its permeability. If the bulkhead has a high permeability it is more empty and can be filled with more water, if the bulkhead has a lower permeability less water can fill it in the case of damage.

4.5 Failure To Integrate: Damage Stability

Damage stability is intrinsically linked to the floodable length curve because both are pertinent restraints on the placement of bulkheads. In a floodable length analysis you want to make sure that the bulkheads can fill and not flood the ship. In the damage stability analysis you want to make sure you can flood two compartments and still have a stable ship in terms of trim and righting arm curve. In this section I discuss my failure to integrate the floodable length curve and how this resulted in my ship failing on many of the damage stability regulations.

Despite currently having a good working knowledge of floodable length curves, at the time of the project I greatly lacked this knowledge. As shown in figure 4.6, I not only made found the floodable length curve but I also found the triangles that denote the volume flooding for the single compartment cases and the double compartment cases.

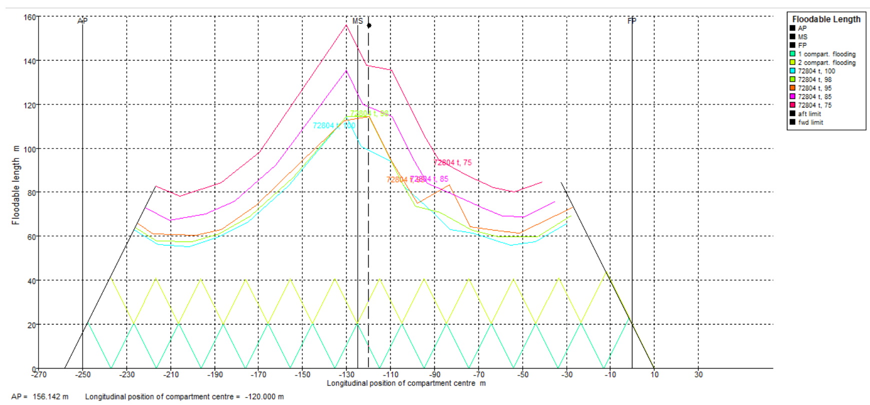

Figure 4.6: A demonstration of the double compartment floodable length curve.

This graph clearly shows that I had a lot more design space to explore in terms of how I spaced my compartments. For example, I could have made the middle compartments much larger, and made the aft and fore compartments smaller. This would mean that my damage stability analysis for the aft and fore compartments would have had a greater chance of passing. However, due to my failure to integrate this information in my design decisions I continued on the red path exploring knowledge structures that would have great consequences when damage stability was analyzed.

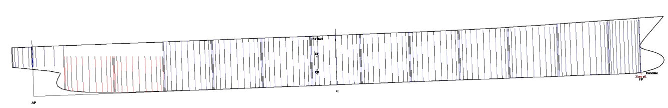

Figure 4.7: The two aft compartments that were flooded.

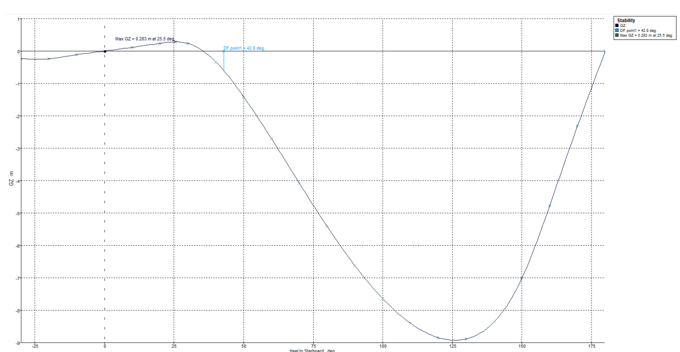

Figure 4.8: Damage stability curve when the two aft compartments are flooded the maximum GZ is 0.283 at 25.5 degrees.

The two figures above depict which compartments were damaged and the resulting righting arm curve. These each make the dubious assumption that the permeability is 75% which is not the standard for container holds which should be around 95% but as a result of not being able to pass the regulations for these damage cases I had to artificially deflate the values of the permeability.

The two figures below depict these same conditions but instead the two compartments flooded are amidship.

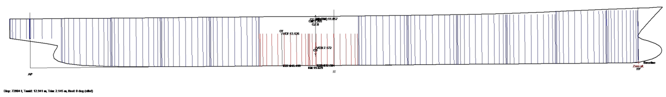

Figure 4.9: The two middle compartments that were flooded.

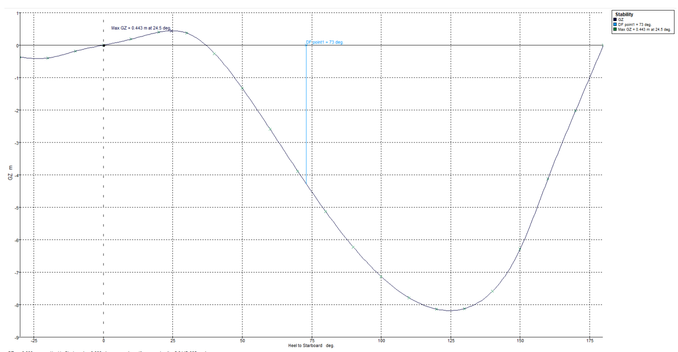

Figure 4.10: Damage stability curve when the two aft compartments are flooded the maximum GZ is 0.443 at 24.5 degrees.

Important aspects to note in both righting arm curves is that the curve begins with negative stability. This is an incredibly discouraging result as this means that if the ship is damaged and it is in rough seas the ship will begin to tip it self over with any perturbation. This means that even when it gets to a heel angle where the righting arm curve is positive it will also have to overcome the initial moment of that heel cycle. Furthermore, the maximum GZ and its heel angle for the first case is way below the IMO requirements.

When looking at this data and the floodable length curve it is clear that if I consider the floodable length curve I would have been able to create a more optimal solution. This shows that I was on the red path in the failure to integrate chart and this is due to the failure to integrate the floodable length curve.

4.5.1 Lessons Learned: Damage Stability

Failure to integrate is the most dramatic design failures because it can lead to a complete disregard for the knowledge structures surrounding the required emergent path. This is demonstrated quite well when looking at the damage stability of the *SS Steel Ducky* , as it lead to the design being completely infeasible when studying its damage stability. The solution would have of course been to use all the information that was available to me in an effective manner so I would be able to explore the knowledge structures and design options surrounding the required emergent path. In retrospect, it would have been wise to make the middle compartments longer and the compartments on the extents shorter. This would incorporate the floodable length curve and would likely ensure that the damage case righting arm curves would have had a much more optimal shape and a higher maximum GZ.

5. Conclusion

In addition to describing the design failures I encountered in my NA470 capstone design, this report also gives the reader a basic understanding of design failure theory, Naval Architecture, and the immediate application of both of these concepts in studying the design of the *SS Steel Ducky* . In doing this project, I not only gained valuable insight into the wicked problem but was also able to refurbish my knowledge of the Naval Architecture concepts I learned throughout my career as an undergraduate in NAME.

Through each design failure, excessive rework with trim, design churn with intact stability, and failure to integrate with damage stability I gained an incredible insight into how these design failure manifest and began to find out how they can be avoided in the future.

A key takeaway of this report is the interdependence of each design aspect that was discussed in this report. For example, there is a balance between the ships trim and the stability of the ship that most be appreciated to follow an optimized design path. Interdependence between design decisions is prevalent throughout the design of any complex systems engineering product. Performing an exercise such as this project allows me to gain a certain wisdom and understanding of complex system design that I would not have received from just doing the NA470 Design Course.

6. References

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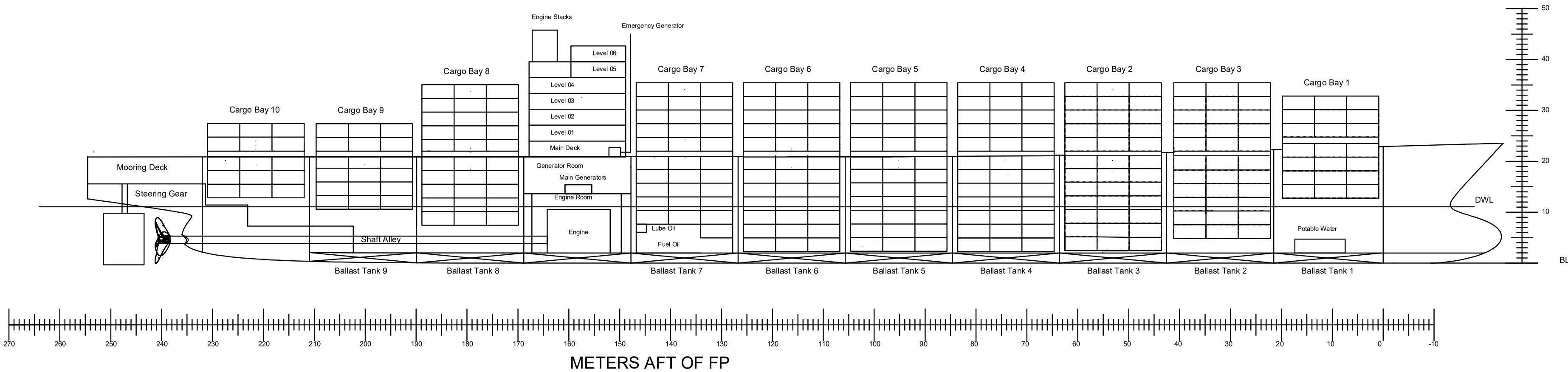

Scale 1:20

Author: Matt Georgy	
Vessel: SS Steel Ducky	
Drawing: Inboard Profile	
Type Final	Date: December, 20, 2020