ANALYSIS OF A WWII T2-TANKER USING A VIRTUAL 3D MODEL AND CONTEMPORARY CRITERIA

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SUMMARY

The S.S. Ohio that saved the Maltese from capitulation during WWII made it to Malta barely afloat on the 15th of August 1942. Historical literature provides three main hypotheses as to why the tanker did not sink under heavy attack, namely: the use of water pumps partially restored buoyancy, the cargo density and a strong fully welded hull. A stability, floodable length and residual strength analysis was conducted to confirm or disprove the hypotheses. The results indicated that the vessel was stable, the water pumps partially restored buoyancy and was sinking despite her welded structure and cargo on-board. A challenge was to draw a comparison between the results and applicable criteria. At the time, criteria only governed the ship's scantlings and did not focus on stability, floodable length and residual strength. The research provided engineering evidence on how the S.S. Ohio survived, whilst contemporary criteria were identified to assess the tanker's characteristics.

NOMENCLATURE

ABS	American Bureau of Shipping
AP	Aft Perpendicular
AVS	Angle of Vanishing Stability (^{o})
B	Moulded beam (m)
C_1	LR section modulus coefficient
C_2	0.01 as per ABS rules
C_B	Block coefficient
CoG	Centre of Gravity
D	Depth (m)
f_1	Ship service factor
f_p	Nominal permissible bending stress (N/m^2)
GM	Metacentric Height (m)
GZ	Righting Lever (m)
I	Moment of inertia (m^4)
k_L	Tank dimensionless coefficient
L_{BP}	Length between perpendiculars (m)
LCB	Longitudinal Centre of Buoyancy (m)
LCG	Longitudinal Centre of Gravity (m)
L_{OA}	Length Overall (m)
LR	Lloyd's Register
MARPOL	International Convention for the Prevention of Pollution from Ships
$\overline{M_S}$	Permissible still water bending moment (Nm)
M_w	Wave induced bending moment (Nm)
RINA	Registro Italiano Navale SpA
SOLAS	International Convention for the Safety of Life At Sea
TCG	Transverse Centre of Gravity (m)
USCG	United States Coast Guard
VCG/KG	Vertical Centre of Gravity (m)
WPA	Waterplane Area (m^2)
Z	Ship section modulus with respect to either keel or freeboard deck (m^3)
Δ_{LIGHT}	Lightship displacement (t)

1. INTRODUCTION

The 15th of August 1942, a date enshrined in Maltese history, is fondly remembered by the population as the day Malta was saved from capitulation during WWII. On that day, the T2-tanker S.S. Ohio was towed into Grand Harbour, Valletta, Malta carrying vital oil replenishments without which the islands would have surrendered to the Axis Powers (Pearson, 2004). However, those witnessing the arrival of the tanker were astonished how, despite the heavy damage inflicted en-route to Malta, she remained afloat.

This historic event provided a research opportunity to analyse the tanker's damage and understand the factors that kept her afloat. A major challenge was to draw a comparison between the results obtained and applicable standards. At the time of construction of the S.S. Ohio, any rules and criteria governed only the ship's scantlings without providing any specific requirements on stability, floodable length and residual strength.

Thus the main aim of this work is to:

- Provide an engineering explanation on how the S.S. Ohio survived her ordeal
- Compare the stability, floodable length and residual strength characteristics of the WWII tanker with contemporary standards and analyse the results obtained.

2. HISTORICAL BACKGROUND

2.1 THE S.S. OHIO

The S.S. Ohio (Figure 1) was an American T2-tanker, built by the Sun Shipbuilding and Drydock and owned by the Texas Company (later transformed into Chevron Corporation). Her keel was laid on the 7th of September 1939 and seven months later, on the 20th of April 1940, the

S.S. Ohio was launched (Pearson, 2004), (The Texas Company, 1940(a)). Initially, the tanker was registered under the American flag, but on the 29th of June 1942, the ship was bareboat registered under the British flag to take part of the convoy mission, code- named Operation Pedestal (Bogart, 1994), (UK Ministry of War Transport, 1942).

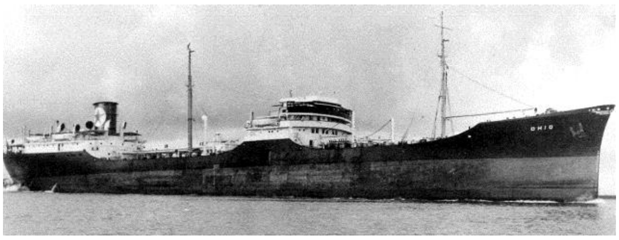


Figure 1: S.S. Ohio (Bogart, 1994)

The overall length (L_{OA}) of the S.S. Ohio was 156.7m, whilst the length between perpendiculars (L_{BP}) was equal to 147.8m. Her moulded depth (D) and moulded beam (B) were equal to 11.0m and 20.7m respectively (The Texas Company. 1940(a)), (Lloyd's Register, 1940), (Lloyd's Register, 1939). The tanker had a total deadweight of 14377t, whilst her lightship displacement (Δ_{LIGHT}) was equal to 5253t (The Texas Company, 1940(a)), Lloyd's Register, 1940), (Lloyd's Register, 1939). Her ship side was riveted, whilst her internal structure, bottom shell and deck plating were welded. The tanker was divided by two longitudinal bulkheads and a series of transverse bulkheads, forming 18 watertight compartments with a total cargo capacity of 1705m^3 (The Texas Company. 1940(a)), (Lloyd's Register, 1940), (Lloyd's Register, 1939).

The S.S. Ohio was classed by Lloyd's Register (LR) and American Bureau of Shipping (ABS) and assigned the following class notation:

✠ *100A1, Carry Petroleum in Bulk, LMC* (Lloyd's Register, 1940)

Such a class notation meant (Lloyd's Register, Marine, 2014(a)):

- ✠ : the tanker was constructed under the survey of a classification society
- *100*: the tanker was considered suitable for sea going service
- *A*: the tanker was maintained in a good and efficient manner
- *1*: the tanker had good and efficient anchoring and mooring equipment
- *Carry Petroleum in Bulk*: ships intended to transport petroleum products
- *LMC*: propulsion and auxiliary machinery were constructed, installed and tested under class survey

The S.S. Ohio's main machinery consisted of two Westinghouse Steam Turbines and Babcock and Wilcox steam boilers, which generated a total of 9000shp at 90rpm, which propelled the ship at 17 knots (The Texas Company, 1940(b)).

2.2 OPERATION PEDESTAL

The S.S. Ohio was acquired under the British Flag to form part of Operation Pedestal, the last convoy mission undertaken by the allies to supply the besieged islands of Malta in August 1942. Had it not been for Operation Pedestal, Malta would have surrendered to the Axis Powers in September 1942 (Pearson, 2004), (Lucas, 1993), (Holland, 2003).

The T2-tanker was joined by 13 other merchant ships and naval escort and approached the Strait of Gibraltar under the cover of darkness on the 10th of August 1942 (Pearson, 2004), (Lucas, 1993), (Holland, 2003). The 13 merchant ships were carrying a variety of cargo replenishments required by the islands, but as the sole oil tanker, only the S.S. Ohio was capable of delivering the required oil supplies to keep the country fighting against the enemy (Pearson, 2004), (Lucas, 1993), (Holland, 2003). So important was the S.S. Ohio that if all the other merchant ships reached Malta, except for the S.S. Ohio, the convoy mission would have been considered a failure (Pearson, 2004), (Lucas, 1993), (Holland, 2003). Knowing how important the tanker was to the Maltese islands, the Axis Powers attacked her relentlessly. So large was the damage inflicted that she was left dead in the water with her freeboard at 0.76m (Figure 2) and only reached Grand Harbour under tow by the escorting destroyers (Pearson, 2004), (Lucas, 1993), (Holland, 2003).

Figure 2: S.S. Freeboard of the S.S. Ohio at 0.76m (Cook, 1942)

As the years passed by, several hypotheses were put forward as to how the S.S. Ohio survived mainly being:

- Auxiliary water pumps supplied by the escorting destroyers decreased the flooding rate and partially restored the tanker's buoyancy (Shankland & Hunter, 1983). Historical literature says that additional water pumps from the escorting destroyers decreased the flooding rate and bought ample time for the tanker to reach Malta and discharge her cargo before she sunk (Caruana, 1992)

- The oil cargo being less dense than water prevented the ship from reaching Davy Jones' Locker (Caruana, 1992)
- The strong fully welded hull was able to withstand such an ordeal that the welded structure prevented the ship from collapsing (Shankland & Hunter, 1983)

However, tangible engineering evidence providing a clear understanding on how the S.S. Ohio survived her ordeal, whilst proving or disproving the hypotheses does not exist. Thus the main scope of this work is to establish such facts, whilst comparing the attained results to contemporary rules and criteria.

3. METHODOLOGY

The following methodology was adopted for the research.

- First a historical literature review of both primary and secondary sources was undertaken to determine the chain of events surrounding the ordeal of the S.S. Ohio. Such accounts shed light on the inflicted damage as the tanker proceeded onwards to Malta.
- An information gathering process followed to determine the main characteristics and dimensions of the S.S. Ohio. Several sources were consulted including but not limited to the company which owned the tanker, the ship's classification societies and the flag registers.
- The main characteristics and principal dimensions were then utilised to create a 3D virtual model of the S.S. Ohio using *Bentley Maxsurf 20.04 V8i Suite Software* which includes *Maxsurf Modeller Advanced* and *Maxsurf Stability Enterprise* (Bentley Systems, 2014).
- Using design formulae, the lightship Centre of Gravity (CoG) was located.
- Stability, floodable length and residual strength analyses were carried out using manual calculations, results of which were verified using *Maxsurf Stability Enterprise*.
- Afterwards, contemporary rules and criteria were analysed to determine applicability as if the S.S. Ohio was built recently.
- Finally the results were compared to the 'applicable' rules and criteria to assess the stability, floodable length and residual strength results.

Through the adopted methodology and results obtained, valuable insight was shed on how the S.S. Ohio remained afloat.

4. VIRTUAL MODEL CREATION

A virtual 3D model of the S.S. Ohio was essential for the research, especially when a physical model suitable for testing was not available. The foundation of the tanker's 3D model is the table of offsets. Unfortunately no such table was available for the S.S. Ohio. Instead a table of offsets of a similar ship was utilised (Bailey, 1976) and Bailey's method implemented to modify the offsets table and recreate that of the S.S. Ohio (Bentley Systems, 2014). Afterwards the modified table was inputted in *Maxsurf Modeller Advanced* to create the virtual model of the tanker's hull. Using a general arrangement plan (Lloyd's Register, 1939), the tanks and compartments were modelled (Figure 3) and the margin line placed 76mm beneath the freeboard deck of the 3D hull.

The virtual model was then ready for analysis after it was loaded with crew weight, defensive armament to protect the ship against air attacks, required ammunition and full complement of cargo as per quantities listed below (Pearson, 2004):

- Fuel oil – 8334.6t
- Diesel oil – 1733.0t
- Kerosene – 1924.4t
- Bunker fuel – 1320.9t
- Lubricating oil – 15.3t.

5. CENTRE OF GRAVITY LOCATION

A vessel's lightship CoG is the fulcrum of the stability, floodable length and residual strength calculations. Unfortunately reliable information or direct calculations indicating the location of the CoG of the S.S. Ohio in the lightship condition were not available. As a result, design methods and formulae implemented during the rudimentary stages of ship design were adopted to locate the lightship CoG of the S.S. Ohio, which was then inputted in the virtual model. The CoG is divided into three components being:

- Vertical Centre of Gravity (VCG)
- Longitudinal Centre of Gravity (LCG)
- Transverse Centre of Gravity (TCG)

5.1 THE VERTICAL CENTRE OF GRAVITY

The design formulae put forward by Schneekluth and Bertram (Schneekkluth & Bertram, 1998), Ganesan (Ganesan, 1999) and Benford (Benford, 1967) were utilised to reverse engineer the VCG of the S.S. Ohio. The theory put forward by Schneekluth and Bertram (Schneekluth and Bertram, 1998), Ganesan (Ganesan, 1999) and Benford (Benford, 1967) divided the lightship weight and VCG into three components being:

- Steel structure
- Hull equipment and outfit
- Machinery

The VCG and the weight of each component were located using the design formulae, results of which were included in the Principle of Moments method used to locate the lightship VCG. The latter was located at 7.7m above the baseline.

5.2 THE LONGITUDINAL CENTRE OF GRAVITY

The lightship LCG of the S.S. Ohio was evaluated at 70.8m from the AP. Knowing that for equilibrium the LCG and the LCB lie on the same vertical plane and that the LCB position is the centroid of the underwater volume along the ship's longitudinal centreline, Approximate Integration Methods were utilised to locate LCB in the fully loaded condition. Afterwards, considering the loaded and lightship mass displacement of the S.S. Ohio, the LCB (the LCG in the loaded condition), the mass displacement and LCG of the individual cargo on-board were identified; the lightship LCG was calculated using the Principle of Moments.

5.3 THE TRANSVERSE CENTRE OF GRAVITY

The S.S. Ohio was symmetrical about the ship's centreline (Bogart, 1994), (US Maritime Administration, 2006), therefore the TCG lay on the ship's centreline.

6. DAMAGE SUSTAINED

During Operation Pedestal heavy damage was inflicted on the S.S. Ohio. Yet for the scope of the research only the damage scenarios which caused flooding were analysed. Any other damage was not included in the research.

6.1 FIRST DAMAGE SCENARIO – 12th OF AUGUST 1942, 19.56HRS

On the evening of the 12th of August 1942, at 19.56hrs, the Italian submarine, Axum fired a 21 inch torpedo and hit the S.S. Ohio in her port side midship pumproom, blowing a 24 foot (7.32m) wide by a 27 foot (8.23m) hole (Pearson, 2004), (Bogart, 1994), (Caruana, 1992) (Figure 3). The force of the explosion damaged the pump room bulkhead whilst two centre tanks and four wing tanks were also damaged (Pearson, 2004), (Bogart, 1994), (Caruana, 1992). Fortunately no further damage was reported for the remainder of the day.

6.2 SECOND DAMAGE SCENARIO – 13th OF AUGUST 1942, 08.10HRS

The following morning, August 13th 1942, at 08.10hrs, the S.S. Ohio was near missed by a 500lbs bomb at the ship's bow (Figure 3). According to the damage report by Captain Mason and Chief Engineer Wyld the near miss flooded the forepeak tank (Pearson, 2004), (Bogart, 1994), (Caruana, 1992), (Smith, 1970), (Wyld, 1942), (Barton, 1942), (Mason, 1942).

6.3 THIRD DAMAGE SCENARIO – 13th OF AUGUST 1942, 18.30HRS

Major damage was reported when in the evening of the same day at 18.30hrs, the S.S. Ohio was hit in the engine room (Figure 3). A 500lbs bomb pierced the boat deck forward of the ship's funnel, destroyed the engineer's accommodation on the upper deck and exploded in the boiler room (Pearson, 2004), (Bogart, 1994), (Admiralty, 1942-46), (Wyld, 1942), (Mason, 1942), (Jerome, 1942). The boilers were destroyed, the boiler room aft bulkhead was blasted and the rest of the engine room was flooded (Bogart, 1994).

6.4 FOURTH DAMAGE SCENARIO – 14th OF AUGUST 1942, 10.50HRS

Further damage was inflicted on the 14th of August 1942. At 10.50hrs, an air attack formed over the S.S. Ohio (Pearson, 2004). A 1000lbs bomb exploded in the vicinity of the vessel's stern (Figure 3), misaligning the ship's propeller and blowing off her rudder. In addition, the aft peak tank and steering gear room were flooded (Pearson, 2004), (Caruana, 1992), (Smith, 1970), (Jerome, 1942).

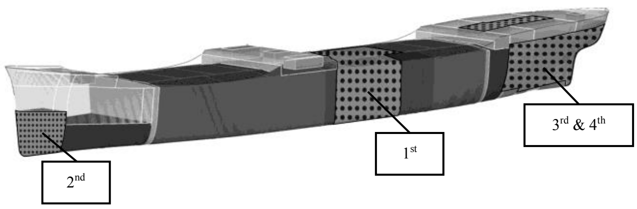


Figure 3: S.S. Ohio 3D virtual model using *Maxsurf Modeller Advanced* (Bentley Systems, 2014) and showing damaged scenarios (dotted compartments)

7. STABILITY ASSESSMENT

7.1 INTACT STABILITY

A stability analysis was undertaken to examine the intact stability of the S.S. Ohio. Consumable items such as bunker fuel, whose quantities varied during the voyage, were accounted for in the intact stability assessment. Using manual calculations, an equilibrium condition and a Righting Lever (GZ) Curve (Graph 1) were established at the instant prior to the first damage scenario. The results were verified using *Maxsurf Stability Enterprise* and compared to the 2008 Intact Stability Code (IMO, 2011) and the stability requirements set in MARPOL Annex I, Regulation 27 (IMO, 2011) (Table 1). Whilst noting that the S.S. Ohio was built well before the stability criteria entered into force, thus not applicable, the same were used as a means to obtain a clearer picture of the tanker's stability in light of today's requirements.

The analysis presented here indicated that the S.S. Ohio exhibited adequate stability when loaded. Furthermore the intact stability assessment showed that the S.S. Ohio satisfied and exceeded the stability criteria set by today's codes and conventions. Therefore one can state that the stability characteristics of the tanker when built in 1940 have been proved to even surpass today's criteria.

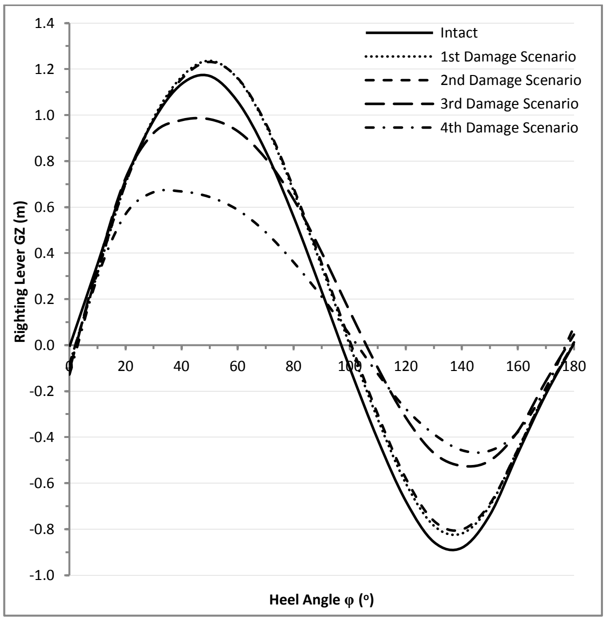
Table 1: 2008 Intact Stability Code (IMO, 2009) and MARPOL Annex I, Regulation 27 (IMO, 2011) intact stability criteria as on the 12th of August 1942

2008 Intact Stability Code	**Results**	**Criterion Met?**
The area under the righting lever curve shall not be less than 3.151mdeg up to a 30° angle of heel	37.6mdeg	Yes
The area under the righting lever curve shall not be less than 5.157mdeg up to a 40° angle of heel	55.2mdeg	Yes
Additionally , the area under the righting lever curve between the angles of heel of 30° and 40° shall not be less than 1.719mdeg	17.6mdeg	Yes
The righting lever shall be at least 0.2m at an angle of heel equal to or greater than 30°	1.8m	Yes
The maximum righting lever shall occur at an angle of heel not less than 25°	26.4°	Yes
The initial metacentric height shall not be less than 0.15m	5.9m	Yes
MARPOL Annex I, Regulation 27	**Results**	**Criterion Met?**
At sea the area under the righting lever curve shall not be less than 3.151mdeg up to a 30° angle of heel	16.2mdeg	Yes
At sea the area under the righting lever curve shall not be less than 5.157mdeg up to a 40° angle of heel	27.1mdeg	Yes
At sea the area under the righting lever curve between the angles of heel of 30° and 40° shall not be less than 1.719mdeg	10.9mdeg	Yes
At sea the righting lever shall be at least 0.2m at an angle of heel equal to or greater than 30°	1.2m	Yes
At sea the maximum righting arm shall occur at an angle of heel preferably exceeding 30° but not less than 25°	47.3°	Yes
In port, the initial metacentric height *GM*, corrected for the free surface measured at 0°, shall not be less than 0.15m	2.0m	Yes

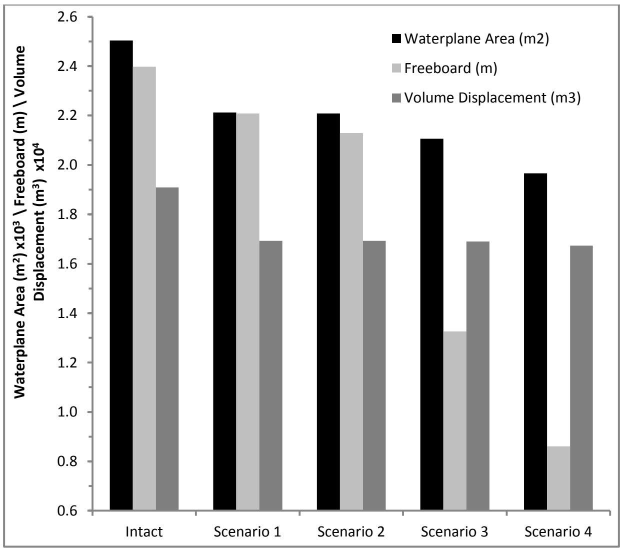
7.2 DAMAGE STABILITY

The Lost Buoyancy Method was utilised to establish the equilibrium condition of each damage scenario. Using *Maxsurf Stability Enterprise*, the GZ curve of each damaged condition was plotted (Graph 1).

The GZ curves plotted for the first and second damage scenarios indicated that the stability of the S.S. Ohio was improved when compared with the intact condition. The maximum GZ of the first and second damage scenarios was equal to 1.3m, whilst that for the intact condition was equal to 1.2m. In addition, the Angle of Vanishing Stability (AVS) for both the first and second damage scenarios was equal to 100° whilst the AVS of the intact condition was equal to 98°. Thus a larger maximum GZ and AVS in the first two damage scenarios resulted in a larger area under the graph when compared with the intact condition, meaning that the S.S. Ohio could absorb higher heeling forces before she capsized. According to Patterson and Ridley (Ridley & Patterson, 2014), such a scenario occurs when there's either a reduction in displacement or an increase in freeboard. However, as shown in Graph 2, the S.S. Ohio experienced both a reduction in displacement, due to cargo loss from damaged tanks and a freeboard reduction, due to buoyancy loss from damaged compartments. Despite of this anomaly, stability was improved when the S.S. Ohio was damaged because for the first two damage scenarios, the reduction in displacement had a far more superior effect than the freeboard loss. Such a scenario was consolidated further, as despite the enhancement in the ship's stability when damaged, the Water Plane Area (WPA) decreased for each damage scenario (Graph 2). Such a scenario should have impaired the ship's stability, yet as shown in Graph 1, the ship's initial stability was also increased.



Graph 1: GZ curves for both intact and damage scenarios



Graph 2: Column chart of waterplane area, volume displacement and freeboard variation between each intact and damage scenario

On the contrary, for the third and fourth damage scenarios, a reduction in stability was observed when compared to both the intact condition and the preceding damage cases. The maximum GZ for third and fourth damage scenarios was equal to 1.0m and 0.7m respectively, smaller than that obtained in the intact and first two damage scenarios. As a result, the area under the GZ curves of the last two damage scenarios was smaller than the intact and first two damage scenarios.

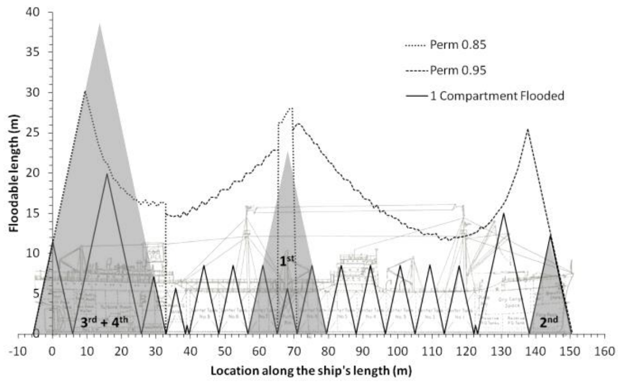
As shown in Graph 2, a reduction in both displacement and freeboard was also observed for the third and fourth damage scenarios. However the freeboard reduction was considerable when compared to the previous scenarios, whilst the displacement in each scenario remained almost constant. Hence the decline in stability for the last two damage scenarios was attributed to the freeboard reduction being more significant than the displacement loss. Even though a reduction in WPA was observed, the initial stability for the third and fourth damage scenarios was better than the intact condition.

The GZ curves of the S.S. Ohio also indicated that at neither instant of damage was the tanker at risk of capsizing, as the angle of final equilibrium of each damaged condition was less than 3^o. Despite the reduction in stability, the S.S. Ohio was never exposed to a capsizing risk. In fact, the late Allan Shaw, the last living crew member who was on-board the S.S. Ohio, confirmed that any list due to damage went unnoticed (Shaw, 2014).

8. FLOODABLE LENGTH CALCULATIONS

A ship is divided into several watertight divisions to ensure that when a compartment is breached, flooding will remain contained within the compromised subdivision. The adequate subdivision lengths are determined from the floodable length calculations. For the S.S. Ohio the calculations were based on the method put forward by Shirokauer in (Shirokauer, 1928) as cited by Nickum in (Nickum, 1988), results of which were verified using *Maxsurf Stability Enterprise*.

The floodable length calculations indicate the maximum length which could be flooded without immersing the margin line below the waterline and assuming the ship as lost (Nickum, 1988). The maximum length which could be flooded without immersing the margin line is determined from the floodable length curve, as shown in Graph 3.



Graph 3: Floodable length curve of the S.S. Ohio with the flooded length of each damage scenario

Thus the length of each watertight compartment should be smaller than the allowable floodable length as indicated by the height of the apex of each triangle (Nickum, 1988). Graph 3 indicates that a single flooded compartment of the S.S. Ohio would not immerse her margin line below the waterline (Bogart, 1994), (Lloyd's Register, 1939) as per SOLAS 1948, Chapter II, Part B, Regulation 7 which states:

"Sufficient intact stability shall be provided in all service conditions so as to ensure the ship to withstand the final stage of flooding of one main compartment which is required to be within the floodable length" (International Community, 1948)

One shall note that such a requirement was first introduced in SOLAS 1948. Therefore it could be stated that the S.S. Ohio was a one compartment ship and satisfied criteria implemented well after her date of build. Furthermore SOLAS 1974 as amended, Chapter II-1, Regulation 4.3 states:

"Ships shall be as efficiently subdivided as is possible having regard to the nature of the service for which they are intended" (IMO, 2014(a))

Graph 3 indicated that the S.S. Ohio was divided into 18 watertight compartments, efficiently subdividing as much as possible her length, as per today's requirements.

On the other hand, if two adjacent compartments were breached and flooded, at certain instances along the tanker's length, the flooded length would be greater than the allowable floodable length. At such instances of damage the S.S. Ohio would be assumed lost. Yet despite being a one compartment ship, when the S.S. Ohio was torpedoed (first damage scenario), three compartments at her midship were flooded but was not assumed lost. The floodable length of the breached compartments within the midship region did not exceed the allowable floodable length and the margin line was not immersed beneath the waterline as shown in Graph 3. In reality, the damaged compartments were not fully breached because the starboard longitudinal bulkhead of the damaged region held despite the torpedo explosion (Wyld, 1942), (Mason, 1942), (Shaw, 2014), (Gray, 1942). Thus an unaccounted reserve of buoyancy was still present in the damaged compartments. In fact, after the torpedo damage, she continued with her voyage under her own steam (Pearson, 2004), (Caruana, 1992), (Smith, 1970). The floodable length calculations showed that despite the considerable structural damage, the torpedo was not the blow which crippled the tanker. Similarly, in the second damage scenario, the margin line was not immersed beneath the waterline because the flooded length was still smaller than the allowable floodable length.

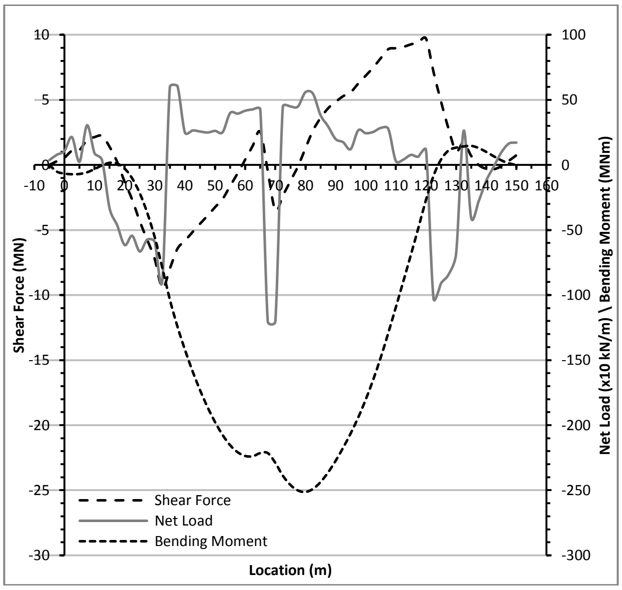
It was not the case for the third damage scenario. The S.S. Ohio received a direct hit aft, which flooded her engine room. According to the floodable length curve, the length of the flooded compartment within this region was larger than the allowable floodable length with the margin line possibly immersed beneath the waterline. The flooded length was increased further in the fourth damage scenario, as shown in Graph 3. Compartments adjacent to the engine room were also flooded because of a near miss aft, which could have immersed the margin line further beneath the waterline. At this stage the S.S. Ohio was assumed lost and on the brink of sinking. The direct hit in the engine room and the near miss aft were the blows which could have crippled the tanker. History says that the S.S. Ohio was only saved due to the auxiliary water pumps brought onboard from the escorting destroyers to decrease the flooding rate (Shankland & Hunter, 1983), (Caruana, 1992). The floodable length calculations show that had it not been for these auxiliary pumps, the S.S. Ohio may have sunk before she reached harbour and discharge her valuable cargo (Shankland & Hunter, 1983), (Caruana, 1992).

9. RESIDUAL STRENGTH ASSESSMENT

9.1 INTACT CONDITION

A residual strength assessment of the S.S. Ohio was undertaken to understand her strength characteristics in her fully loaded and intact condition. The induced shear forces and bending moments were analysed using Simple Beam Theory, results of which are presented in Graph 4. The latter was verified using *Maxsurf Stability Enterprise*.

The results indicated that in still water, fully loaded and intact, the vessel was sagging. Thus the S.S. Ohio experienced the largest bending moment when sailing through sagging waves.



Graph 4: Still water net load, shear force and bending moment diagrams of the S.S. Ohio in the intact condition

Using the bending moment obtained from Graph 4 and the ship's midship section (Lloyd's Register, 1939), the moment of inertia and the section modulus of the tanker's midship were calculated and found equal to $38.7m^4$ and $6.3m^3$ respectively. Class criteria were used to analyse the strength characteristics because in 1940, the year the T2-tanker was constructed, international regulations and class rules governed only the required scantlings, without providing any specific residual strength requirements (International Community, 1929), (ABS, 1938), (Lloyd's Register, 1938). Therefore contemporary regulations and criteria were used for guidance purposes only to analyse the S.S. Ohio's residual strength. In fact SOLAS Chapter II-1, Part A-1, Regulation 3-1 states:

"...ships shall be designed, constructed and maintained in compliance with the structural, mechanical and electrical requirements of a classification society..." (IMO, 2014(b))

As such the residual strength criteria set forth by LR and ABS for single hull oil tankers were applied to the S.S. Ohio, as shown in Table 2 (Lloyd's Register, 2014(b)), (ABS, 2015).

Table 2: Residual Strength Criteria according to LR and ABS

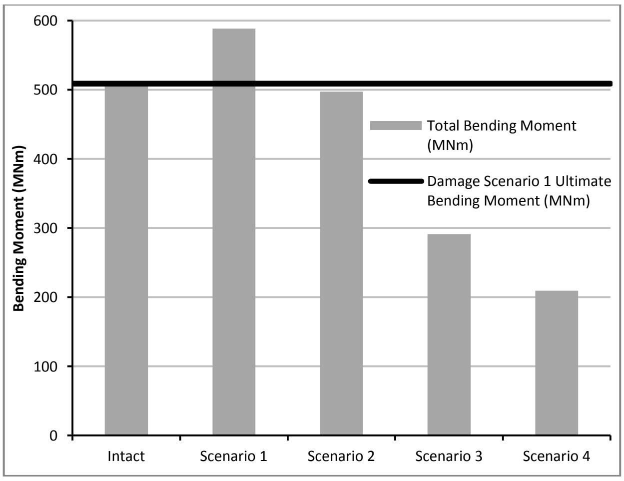
LR Residual Strength Criteria		
Criterion	*Rules and Regulations for the Classification of Ships Part 3, Chapter 4, Section 5.4.1: Minimum Hull Section Modulus:* The hull midship section modulus about the transverse neutral axis, at the deck or the keel, is to be not less than $Z_{min} = f_1 k_L C_1 L^2 B(C_B + 0.7) \times 10^{-6}$	
Results	**Required Z_{min} = 5.6m^3** Z_{keel} of S.S. Ohio: 6.3m^3	
Criterion met?	Yes	
Criterion	*Rules and Regulations for the Classification of Ships Part 3, Chapter 4, Section 5.8.1:* The hull midship section moment of inertia about the transverse neutral axis is to be not less than the following using the maximum total bending moment, sagging or hogging, $I_{min} = \frac{3L\lvert\bar{M}_s + M_w\rvert}{k_L f_p} \times 10^{-5}$	
Results	**Required *I* = 21.4m^4** *I* of the S.S. Ohio: 38.7m^4	
Criterion met?	Yes	
ABS Residual Strength Criteria		
Criterion	*Part 3, Chapter 2, Section 1, Regulation 3.7.1: Hull Girder Section Modulus3.7.1a: The required hull girder section modulus for 0.4L amidships is to be the greater of the values obtained from the equation $Z = \frac{M_t}{f_p}$ or 3.7.1.b: Minimum Section Modulus. The minimum hull girder section modulus amidships is not to be less than obtained from the equation $Z = C_1 C_2 L^2 B(C_B + 0.7)$*	
Results	3.7.1a: *Z* = 4.73m^3 3.7.1b: *Z* = 5.63m^3 **Required Z: 5.63m^3** Z_{keel} of S.S. Ohio: 6.28m^3	
Criterion met?	Yes	
Criterion	*Part 3, Chapter 2, Section 1, Regulation 3.7.2: Hull Girder Moment of Inertia. The hull girder moment of inertia amidships, is to be not less than $I = \frac{LZ}{33.3}$*	
Results	**Required *I* = 24.99m^4** *I* of the S.S. Ohio: 38.68m^4	
Criterion met?	Yes	

The class criteria served as a mean to assess the S.S. Ohio's strength in light of today's requirements. Table 2 indicates that the S.S. Ohio was capable of meeting requirements applicable to ships built well after her time. Furthermore compliance with class criteria showed that the S.S. Ohio was built to high residual strength standards.

9.2 DAMAGE CONDITION

Using *Maxsurf Stability Enterprise* the still and wave induced shear forces and bending moments were compiled for each damage scenario. The method put forward by Paik, Thayamballi and Hong Yang in (Paik, Thayamballi and Hong Yang, 1998), was adopted to analyse the vessel's strength when damaged. The method determined the ultimate bending moment a damaged ship in either hogging or sagging condition could withstand before the hull collapsed (Paik, Thayamballi and Hong Yang, 1998).

The results showed that the S.S. Ohio experienced the largest bending moment when the tanker was torpedoed (Graph 5). From the analysis, the maximum bending moment imparted to the S.S. Ohio in her first damage scenario was equal to 588.4MNm, higher than that obtained in the intact condition and 16% higher than the ultimate bending moment of 509.2MNm, as predicted by Paik et al's method for the first damage scenario (Graph 5). As such it was concluded that when the S.S. Ohio was torpedoed (first damage scenario) she was at the greatest risk of hull collapse, even though her internal structure was welded.



Graph 5: Bending moment for the intact and damage conditions

As further damage was inflicted elsewhere along the ship's length, the maximum bending moment decreased as shown in Graph 5. Such a scenario was also observed in separate studies carried out by Teixeira and Guedes Soares (Teixeira, Guedes Soares, 2009) and Horte, Skjong, Friis-Hansen, Teixeira and Viejo de Franciso (Horte, Skjong, Friis-Hansen, Teixeira and Viejo de

Franciso, 2007). A plausible explanation to such a scenario is that the remaining buoyant sections in her aft and forward regions were also flooded, sinking the ship deeper into the water, whilst decreasing the tanker's bending moment. The damage itself, served as a life saver, since despite the S.S. Ohio sinking further, the ship's sagged condition decreased.

However even though the maximum bending moment amidship was decreasing with each damage scenario, this does not imply that the tanker's strength was improved. On the contrary, with every damage scenario, cross-sectional area was being lost from the ship's length, thus reducing the moment of inertia and the ability to withstand bending. Furthermore, between the first and third damage scenarios, almost 24 hours had elapsed when the total bending moment was considerably reduced. As a result, the S.S. Ohio was at a high risk of collapse for an elongated period of time, amplifying the risk of breaking in half. Such a risk could have been mitigated by the low speed of the tanker due to the damage sustained and thanks to the calm weather conditions the S.S. Ohio encountered (Pearson, 2004), (Bogart, 1994), (Met Office, 1942). Synoptic charts for the 12th, 13th and 14th of August 1942, show high pressure areas forming over the Mediterranean Sea, with low wind speeds and low wave heights reminiscent to calm weather conditions. In fact from the synoptic charts, the average wave height for the 12th, 13th and 14th of August 1942 was equal to 1.28m (Met Office, 1942). Thus it was concluded that if heavy weather was encountered after the tanker was torpedoed, a different fate would have served the Maltese islands. However, the reduction in the ship's sagged condition and bending moments probably reduced the stresses acting on the remaining intact plating, minimising the risk of breaking in half. In fact, as history says, the S.S. Ohio entered Grand Harbour as a single ship (Pearson, 2004), (Bogart, 1994), (Shankland & Hunter, 1983), (Caruana, 1992), (Wyld, 1942), (Mason, 1942), (Gray, 1942).

10. CONCLUSION

The stability, floodable length and residual strength analyses provided an engineering perspective on how the S.S. Ohio survived her ordeal. Further insight on the tanker's stability, floodable length and residual strength characteristics was obtained after the results were compared to contemporary criteria. Finally the hypothesis put forward in historical literature were verified or disproved.

The stability analysis indicated that for the first two damage scenarios, stability was improved but was not the case for the remaining scenarios. Despite the stability reduction when severely damaged, the S.S. Ohio was not subjected to a capsizing risk and only suffered parallel immersion when damaged. Furthermore, the analysis indicated that the S.S. Ohio satisfied the intact stability criteria applicable to modern tankers.

The floodable length calculations confirmed that the auxiliary water pumps supplied by the escorting destroyers partially restored the tanker's buoyancy. The S.S. Ohio could be assumed lost when the engine room was flooded. Had it not been for the auxiliary water pumps, the tanker would have been lost and never reached Grand Harbour. Nonetheless, the calculations disproved the hypothesis that the S.S. Ohio kept afloat because of the cargo on-board being less dense than water. The results indicated that even though the majority of the cargo tanks remained intact, the flooded engine room could have rendered the tanker as lost. The calculations also showed that the tanker was efficiently subdivided as per today's requirements.

The hypothesis that a strong fully welded hull was able to withstand the sustained damage was disproved. Literature provided by Chevron Corporation (The Texas Company 1940(a)) showed that the S.S. Ohio was a combination of riveted and welded construction. However despite being of welded and riveted construction, the intact residual strength results met contemporary LR and ABS strength criteria applicable to single hull oil tankers. The damage residual strength assessment showed that when the S.S. Ohio was torpedoed (First Damage Scenario), the maximum bending moment was greater than the ultimate bending moment. At this instant, the S.S. Ohio was exposed to the greatest risk of collapse. However, as further damage was inflicted along the tanker's length, the bending moment decreased. Reason being, as the remaining buoyant sections were flooded, the sagged condition decreased, resulting in lower bending moments. Thus it was concluded that despite the initial risk of hull collapse, the damage itself prevented the ship from breaking in half.

The results presented here served as a means to fill the vacuum in the area of knowledge and determine how the S.S. Ohio survived her onslaught. In addition, the research shed light on stability, floodable length and residual strength of the S.S. Ohio. The information provided will answer some of the longstanding questions on how the S.S. Ohio saved Malta.

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12. REFERENCES

22. ADMIRALTY, "Ohio War Loss Cards," Guildhall Library, London, UK, 1942-1946.

36. AMERICAN BUREAU OF SHIPPING, *1938 ABS Rules for Building and Classing Steel Vessels*. 1938.

41. AMERICAN BUREAU OF SHIPPING, "Part 3 - Hull Construction and Equipment," in *Rules for Building and Classing Steel Vessels*, ABS, 2015, pp. 32-63.

15. BAILEY, D., *The NPL High Speed Round Bilge Displacement Hull Series: Resistance, Propulsion, Manoeuvring and Seakeeping Data*. Royal Institution of Naval Architects, 1976.

24. BARTON, D. E, "Operation Pedestal - M/011281/42," London National Archives - ADM1/15526, United Kingdom, 1942, August 20.

20. BENFORD, H. "The Practical Application of Economics to Merchant Ship Design," *Journal of Marine Technology,* 1967, January.

14. BENTLEY SYSTEMS MAXSURF 20.04 V8I SUITE SOFTWARE, (2014, January 6) "Maxsurf - Naval Architecture Software for all Types of Vessels", https://www.bentley.com/~/asset/14/2708.ashx [Accessed 2014, February 10]

3. BOGART, C. H. "Operation Pedestal," *Steamboat Bill,* vol. LI, No.3, pp. 173-185, 1994.

13. CARUANA, J., "Ohio Ordeal," *The Sunday Times,* 1992.

11. COOK, H. E. "Operation Pedestal and the Siege of Malta, August 1942," *Imperial War Museum,* vol. IWM GM 1480.

19. GANESAN, V. "A Model for Multidisciplinary Optimization of Containerships," Virginia Polytechnic Institute and State University, July, 1999.

39. GRAY, D. H. "Report by Chief Officer D. H. Gray," Shell Historical Archives, The Hague (SLA), SC 88/5 file 1. 1942.

10. HOLLAND, J. *Fortress Malta*. UK: Orion Books Ltd., 2003.

44. HORTE, T. SKJONG, R. FRIIS-HANSEN, P. TEIXEIRA, A.P. and VIEJO DE FRANCISO, F. "Probabilistic Methods Applied to Structural Design and Rule Development," *Developments in Classification and International Regulations,* 2007.

33. INTERNATIONAL COMMUNITY, "SOLAS Chapter II: Construction, Part B: Subdivision and Stability, Regulation 7 - Stability of Ships in Damaged Condition," in *SOLAS Convention*, Consolidated Edition, London, UK: International Maritime Organization, 1948, June 10.

35. INTERNATIONAL COMMUNITY, "SOLAS Annex I - Construction," in *International Convention for the Safety of Life at Sea* 1929, May 31.

27. INTERNATIONAL MARITIME ORGANIZATION (IMO), *International Code on Intact Stability, 2008, Chapter 2 – General Criteria*. London, UK: International Maritime Organization, 2009.

28. INTERNATIONAL MARITIME ORGANIZATION (IMO), "MARPOL Annex I: Regulations for the Prevention of Pollution by Oil, Regulation 27 - Intact Stability," in *MARPOL Convention*, Consolidated Edition ed. London, UK: International Maritime Organization, 2011.

34. INTERNATIONAL MARITIME ORGANIZATION (IMO), "SOLAS Chapter II-1: Construction - Structure, Subdivision and Stability, Machinery and Electrical Installations, Regulation 4 -General," in *SOLAS Convention*, Consolidated Edition, London, UK: International Maritime Organization, 2014a.

38. INTERNATIONAL MARITIME ORGANIZATION (IMO), "SOLAS Chapter II-1: Construction - Structure, Subdivision and Stability, Machinery and Electrical Installations, Part A-1 - Structure of Ships, Regulation 3-1 - Structural, Mechanical and Electrical Requirements for Ships," in *International Convention for the Safety of Life at Sea (SOLAS), 1974, as amended*, Consolidated Edition, London, UK: International Maritime Organization, 2014b.

26. JEROME, H. J. A. S. "Report on Operation "Statue" from the evening of Wednesday, 12th to 0800 of Saturday, 15th of August," London National Archives - ADM1/15526, United Kingdom, 1942, August 26.
37. LLOYD'S REGISTER, *Lloyd's Register of Shipping - Rules and Regulations 1938-1939*. UK: LR, 1938.
17. LLOYD'S REGISTER, *S.S. Ohio Scantlings and General Arrangement Plan*. Royal Museums Greenwich, London, UK. 1939.
7. LLOYD'S REGISTER, "S.S. OHIO - CLASS SURVEY REPORT," TECH. Rep. 7881, 1940, July 31.
8. LLOYD'S REGISTER MARINE, "Classification," in *Classification and Statutory Surveys*, London, UK: LR Marine Training Services, 2014a, pp. 1-12.
40. LLOYD'S REGISTER, "Part 4 - Ship Structures (Ship Types), Chapter 9 - Double Hull Oil Tankers, Section 3 - Longitudinal Strength," in *Rules and Regulations for the Classification of Ships*, LR, 2014b, January.
9. LUCAS, L. *Malta - The Thorn in Rommel's Side*. UK: Penguin Group, 1993.
25. MASON, D. W. "Report by Captain Dudley. W. Mason," Shell Historical Archives, The Hague (SLA), SC 88/5 file 1. 1942.
45. MET OFFICE NATIONAL METEOROLOGICAL ARCHIVE, *Climatological Return for Valletta for August 1942 and Northern Atlantic Charts which Cover the Mediterranean for 1st to 15th of August 1942*. Exeter, United Kingdom.
32. NICKUM, G. C. "Subdivision and Damage Stability," in *Stability and Strength*, 1st ed., E. V. Lewis, Ed. USA: The Society of Naval Architects and Marine Engineers, 1988, pp. 111-194.
42. PAIK, J. K. THAYAMBALLI, A. K. and HONG YANG, S. "Residual Strength Assessment of Ships After Collision and Grounding," *Mar. Technol. SNAME News,* vol. 35, pp. 38, Jan 1998.
1. PEARSON, M. *The Ohio and Malta: The Legendary Tanker that Refused to Die*. England: Pen and Sword Books, 2004.
29. RIDLEY, J. and PATTERSON, C. "Large Angle Stability - Just How Far Can She Roll?" in *Reeds Vol 13: Ship Stability, Powering and Resistance*, Bloomsbury Publishing, 2014.
18. SCHNEEKLUTH, H. and BERTRAM, V. "Chapter 5: Computation of Weights and Centres of Mass," in *Ship Design for Efficiency and Economy*, 2nd ed. Oxford, UK: Butterworth-Heinemann, 1998, pp. 149.
12. SHANKLAND, P. and HUNTER, A. *Malta Convoy*. UK: Fontana Press, 1983.
30. SHAW, A. "S.S. Ohio Related Queries - Personal Communication with Allan Shaw via E-mail," 2014, January 4.
31. SHIROKAUER, F. *A Simplified Method for Exact Arithmetical Determination of Bulkhead Curves*. 1928.
21. SMITH, P. *Pedestal - the Convoy that Saved Malta*. England: Crecy Publishing Limited, 1970.
43. TEIXEIRA, A. P. and GUEDES SOARES, C. "Reliability Assessment of Intact and Damaged Ship Structures," in *Advanced Ship Design for Pollution Prevention,* Split, Croatia, 2009, pp. 79-96.
2. THE TEXAS COMPANY, "1939-1940 S.S. Ohio Sun Shipbuilding Construction Reports," Chevron Corporation, California, USA, 1940a.
5. THE TEXAS COMPANY, "Trial Trip of a Texaco Tanker," *The Texaco Star,* vol. 27, pp. 14-17, 1940b.
4. UK MINISTRY OF WAR TRANSPORT, "Transcript of Register for Transmission to Registrar General of Shipping and Seamen," 1942, June 29.
6. UNITED STATES COAST GUARD, "Ohio Registration Card - ON: 239732," 1942, June 2.
16. US MARITIME ADMINISTRATION, "Historic American Engineering Record – USS Saugatuck T2-SE-A1," *HAER,* vol. HAER No. VA-128, 2006.
23. WYLD, J., "Report by Chief Engineer Mr. J. Wyld," Shell Historical Archives, The Hague (SLA), SC 88/5 file 1. 1942.