Inflatable Airbag Systems to Improve Ship's Attained Subdivision Index

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This document describes and proposes different configurations of inflatable air chambers placed in different compartments of (marine floating structures like) ships to reduce permeability to sea water of these compartments, in the event of collision damage, thus improving the Attained Subdivision Index of the ship calculated as per SOLAS regulations. The document further describes some supporting systems to practically achieve this objective of installing and using such airbag systems on ships to prevent sinking of ships due to collision damage of the hull.

KEY WORDS: EMERGENCY BUOYANCY, DAMAGE STABILITY, ANTI-SINKING, SAFETY, UNSINKABLE, INFLATABLE, SOLAS

INTRODUCTION

This document introduces a system consisting of inflatable air bags placed in different compartments of (marine floating structures like) ships to reduce "permeability" to "predetermined volume" of each of these compartments, so as to improve damage stability upon water ingress due to collision damage of the hull. The application can be used as standalone "permanently" filled up air bags in void tanks etc., or a centrally controlled air bag system integrated with a pneumatic system, which is activated manually only upon collision damage. Further the integrated system can be designed to be autonomously controlled by a master computer which computes the damage stability of the vessel on a real-time basis; intelligently decides and executes decisions regarding which compartments will have what value of permeability so that the ship does not sink and will thus inflate or deflate airbags or ballast the compartments in the ship.

Prior Art

19th Century and earlier

The problems of damage stability of ships and the solutions offered to address those problems are as old as Naval Architecture itself. The use of air bags of different types are known to the industry in various forms like air bags for passenger safety in cars, in marine life rafts, hot air balloons, inflated rubber fenders, etc.

The use of inflatable air bags to increase buoyancy of sunken ships during salvaging operations and also for improving damage stability are known in the United States from the days of wooden ships.

To quote Mr. John Beninger from his 1886 patent: "….I am also aware that vessels have been provided interiorly with flexible bags permanently attached and provided with an air forcing engine for filling them and thus preventing the vessel from sinking for want of teuable space for water, and this feature I broadly disclaim."

John Beninger, 1886

It was discovered that US Patent No. 350,184 – System for preventing vessels from sinking - describes deployment, both inside and outside of a vessels hull, a system of canvas bags communicating by means of pipes with a common reservoir containing compressed gas.

Francisco L. De Villa, 1900

Further, U.S. Patent No. 644,480 - Device for preventing vessels from sinking – describes air tight cuboidal rubber compartments distributed throughout the vessel inflated by compressed air.

Thereafter, it appears, the focus shifted to welded steel hulls which provided much better safety against damage and the subject did not develop any further for a long time.

Hermann Hasse, 1976

Much later in Europe, Patent No. DE 2525202 A1 – Inflatable buoyancy tanks for boat, has compressed air bottle for tank connected via valve which operates upon capsizing – describes flexible buoyancy tanks which take up minimum stowage space when not in use, are connected to compressed air bottles via valves, and also has pressure gauge and pressure relief valves for pressure control.

Lothar Koehler, 1985

Later, Patent No. DE 3338375 A1 – Hull for yacht with devices for maintaining the buoyancy in the event of sea damage – describes foldable inflatable bags of flexible elastic material mounted in hollow spaces in the hull, connected to a propellant gas created by heating effect.

Heinz Boerner, 1987

Patent No. DE 3530618 A1 – Equipment and methods for preventing the sinking of ships – describes the use of inflatable airbags curled up in upper ceiling angle, inflated by compressed air and pressure probes to measure pressure difference.

Steven P. Van Derryt, 2008

Recently, Patent No. 7412939 B2 – Emergency Buoyancy Systems – describes a system comprising of one or more flexible inflatable bags disposed on an upper inboard bulkhead of one or more vessel compartments connected to an integral gas delivery system.

From the above information it is very clear that the idea of inflatable air bags is in existence since a long time and has developed over a period of time to suit the advancements in technology. In the next decades, we may see materials like graphene sheets or fabrics made of graphene nanotubes being used for the purpose of inflatable airbags. However, the author would not like to jump that far in this document.

DESCRIPTION

The Unsinkable Ship

Introduction

There is a huge scope to create a complete system controlled by a central master computer which autonomously calculates the damage stability of the vessel using real time signal processing, determines which compartments are to be ballasted or which air chambers are to be inflated and operates the system autonomously to execute the decisions. This will be the 21st century's "Unsinkable Ship". Pneumatically controlled inflatable air chambers will be an important component of such a system.

One can imagine how such a ship system can benefit humanity by preventing loss of human lives and property.

A Case Study to Demonstrate the Effect of Change of Permeability on the Attained Subdivision Index

The General Arrangement of a "Non Ballastable Deck Cargo Barge" is shown in (Fig. 1). A probabilistic damage stability of this barge was roughly assessed in Maxsurf software for the following two conditions to provide a simple case study:

Permeability of all spaces at 95%

In this condition, it is assumed that the permeability of all the compartments in the hull of the barge is 95%. In other words, it's a normal barge without the system installed. A detailed probabilistic calculation is attached in Appendix A.

The results show that the attained subdivision index of the vessel is 0.688. In this case, for the fully loaded departure condition, there are multiple results showing "trim limit exceeded" and "vessel has sunk".

This means the ship is very much vulnerable if it sails in fully loaded departure condition, at a permeability of 95%.

Permeability of all spaces at 35%

In this condition, it is assumed that the permeability of all the compartments in the hull of the barge is 35%. This reduction in permeability is achieved by installing the inflatable air bag system in any one of its proposed configurations. The results of a detailed probabilistic calculation for this condition are attached in Appendix B.

The results show that the attained subdivision index of the vessel has improved to 0.983, simply by reducing the permeability of the compartments by using the inflatable air bag systems. In this case, for all operating conditions, the GZ (righting lever) curves are satisfactorily completed.

The results thus demonstrate that for the conditions assumed in this case study, the damage stability of the vessel is improved through deployment of the inflatable air bag system.

Of course, this is just an approximate study of a very simple case. To develop an industry usable product, a more detailed study has to be taken up to assess the possibility of deploying the air bag systems in more complicated compartments of different types of ships.

Components of the System

The primary components which constitute the system managing the intact, damage and dynamic intact/damage stability of a vessel on a real-time basis will be as follows:

(1) Inflatable air chambers
(2) Master computer
(3) Pneumatic system
(4) Instrumentation

Outline features of these primary system components are broadly discussed in the following sections.

Inflatable Air Chambers

Industry is familiar with the air bag systems in cars which activate upon collision of the vehicle. The purpose of those bags is to reduce human injury in cases of high speed collision.

A slightly different concept is used for marine applications. When deployed on ships, the purpose of these air filled bags is to reduce permeability of compartments, or in other words, to reduce the percentage of empty volume in any compartment available for water ingress. Water ingress, which is a result of breach of integrity of the outer hull of a ship, reduces the buoyancy of any compartment, thereby having an adverse effect on the overall stability of the vessel. Usually, the permeability of empty void spaces is considered to be 95% having regard to the structural members inside the compartment.

The purpose of hollow air filled bags is to occupy as much space as possible within any compartment, and thus to prevent entry of water into the compartment. In technical terms, this means the permeability of the compartment is reduced by the amount of volume occupied by the air bag. Reduction of permeability means that in an event of damage, lesser water would enter the compartment and would therefore result in lesser reduction in buoyancy of the vessel. The effect of this on the stability of the vessel will have to be considered on a case to case basis. In most cases, this should have a positive effect on the stability of the vessel, thus preventing the vessel from sinking.

Deployment strategy

Earliest applications of such air bags envisaged deployment both inside and outside the hull. Although deploying the inflatable air bags outside the hull provides extra buoyancy, they also interfere with other factors like resistance of the ship. Conversely, when deployed inside a ship compartment there is greater control on the relative center of gravity of the air bags w.r.t. the ship. Also, when deployed inside a compartment the air bags and their instrumentation are least affected by the environmental factors. There is also no direct effect on the resistance of the ship when deployed inside a compartment. So deployment within a compartment is preferred for this study.

Broadly two types of air bags are proposed:

(1) Stand-alone inflatable air bag systems independently deployed for each void tank, and
(2) Pneumatically controlled, self-activated air bag system responding in real-time to collision damage.

Stand-alone inflatable air bag systems independently deployed for each void tank

This system, as shown in (Fig. 2) will consist of one independent air bag deployed in each void tank. Locations, quantity and volume of air bags will have to be carefully considered with due regard to damage stability calculation for the vessel. Each air bag will be attached by strings of suitable material, to the inboard side of the ship's tank. Additional supports may also be provided at deck bottom and side shell. The supports on the inboard bulkhead and deck will be regarded as the primary support members as the damage is less likely to happen from these sides. The airbag should be able to retain position even in case of partial or major damage of side shell and / or bottom. The air bags should have tension members of suitable materials inside, so as to retain shape when inflated. The material of the air bag should be water tight, wear resistant and resistant to piercing. They may even be internally subdivisioned.

The air bag has to be attached inside the tank during the first installation. Then it has to be inflated and kept inflated during its lifetime. In case the need arises for inspection or maintenance of the tank or of the air bag system, the bag should have a valve to deflate it. There should also be a relief valve to release any sudden pressure created during collision.

This system will be installed stand alone in each designated tank based on prior calculations. All control valves will be available on the most accessible deck above the tank. A portable pneumatic pump should be available on the ship to cater the need of the system.

Due to the limitation that the air bags of the system have to be kept filled all the time, this system can be used only for void tanks / unused spaces. Since any inflated air bags will not allow proper filling of the ballast tanks, this system cannot be used for ballast tanks or other spaces which require a substantial volume of the spaces to be used for another purpose.

As shown in (Fig. 3), in case of collision damage, the relief valve releases the excess pressure created by collision and allows only the required reduction in volume of the air bag, such that the air bag takes shape of the colliding object. If the object is removed soon after collision, the air bag may be re inflated to regain its original shape. This of course is a temporary solution till the vessel can be taken to salvage / repair point and will allow enough time for recue of passengers and crew.

Pneumatically controlled, self-activated air bag system responding in real time to collision damage

As shown in (Fig. 4) this system will be similar to the stand alone inflatable system, except that it will overcome the limitation of using the system in other spaces like ballast tanks and even engine room.

The internal construction of air bags will be similar to the stand alone air bags. The method of installation of air bags within the tanks will also be similar. Only difference will be that, wherever required the air bag can be installed as an un-inflated (deflated) air bag which, upon collision damage of the respective compartment will respond by getting inflated. For this purpose the system will be connected to a pneumatic system consisting of sensors and a controlling computer. In case of collision damage the sensors will identify collision damage and will sound an alarm and inform the computer. The computer will calculate the stability of the ship under damage condition and will develop a strategy to correct the stability by inflating the required air bags. Alternatively, the computer (or manual command) can simply instruct the pneumatic system to restore buoyancy of the damaged compartment only.

In engine room (which is a big unprotected compartment) multiple air bags may be deployed to reduce permeability of space below waterline. These air bags will be usually hidden in their containers and will spring into action only upon collision damage of the engine room.

Multiple airbags to tackle pressure gradient

Larger vessels will have a huge difference in pressure at deeper levels as compared to that at the surface, as seen in (Fig. 5). Due to this pressure difference, if a single air bag is used for the entire depth of the vessel, the internal pressure of the air bag may be too high at surface and insufficient to counter sea pressure at greater depth. This may result in rupture of the air bag at lower depths, due to high pressure and may also result in shape deformation at deeper levels. This problem can be tackled by providing multiple air bags at different levels, each supplied separately from the main air line. The inlet point at each air supply will have a pressure sensor with automatic cut off at predetermined internal pressure. Thus air bags of different strengths may be provided at each depth so as to reduce the overall cost of the system.

Usually, the internal pressure of the air bags has to be sufficient to counter the sea pressure at the respective depth of the vessel, highest pressure being at the deepest level.

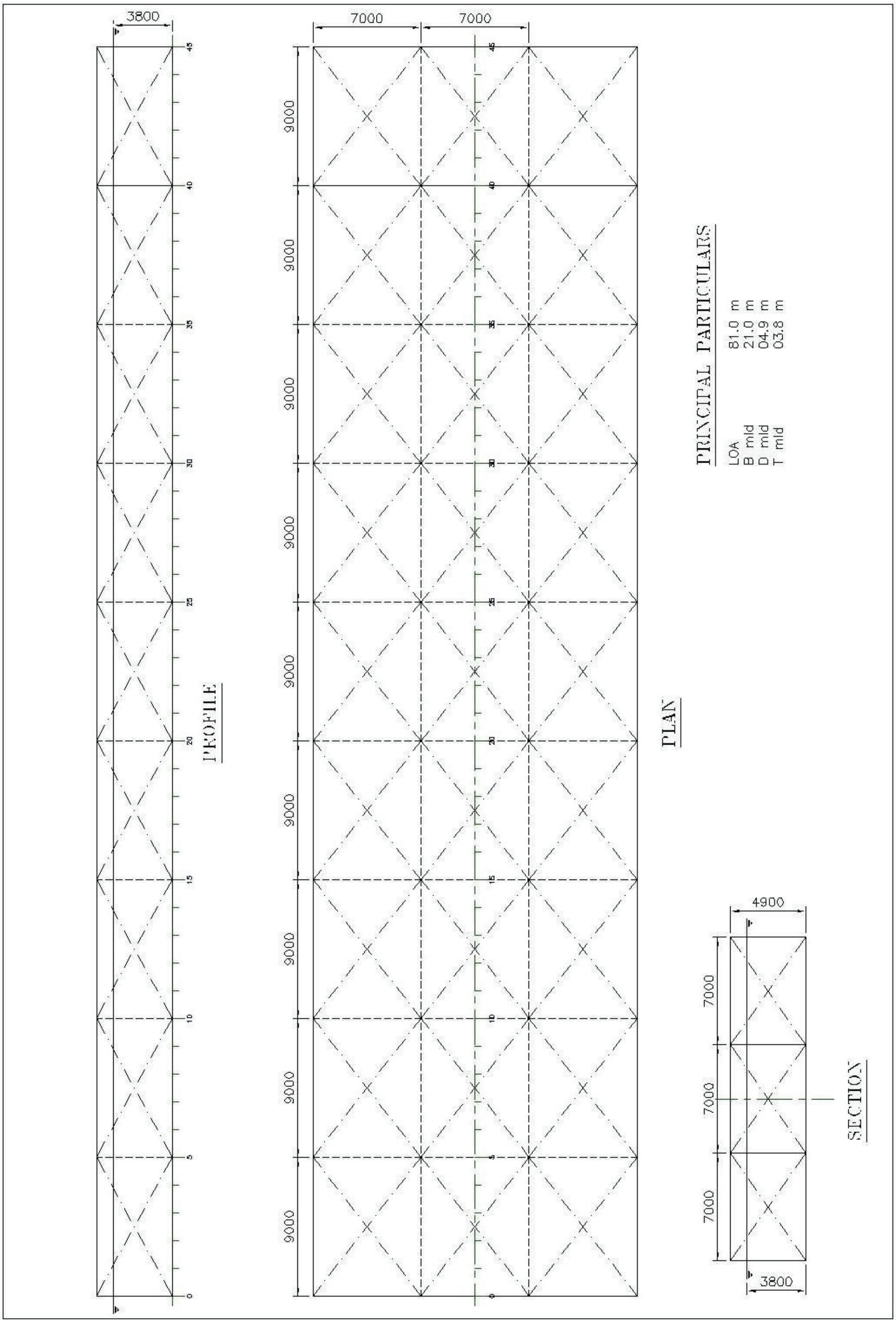

Fig. 1 Case study – general arrangement of a non ballastable deck cargo barge

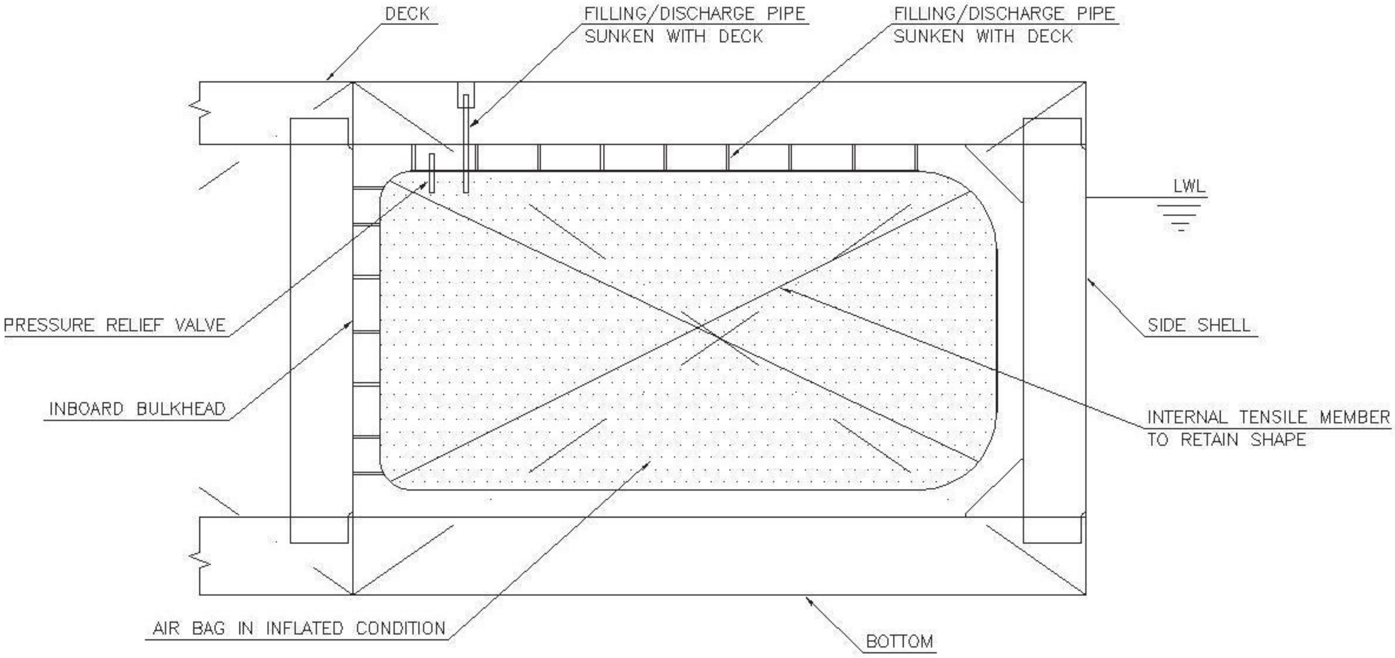

Fig. 2 Inflatable airbag system (before collision damage)

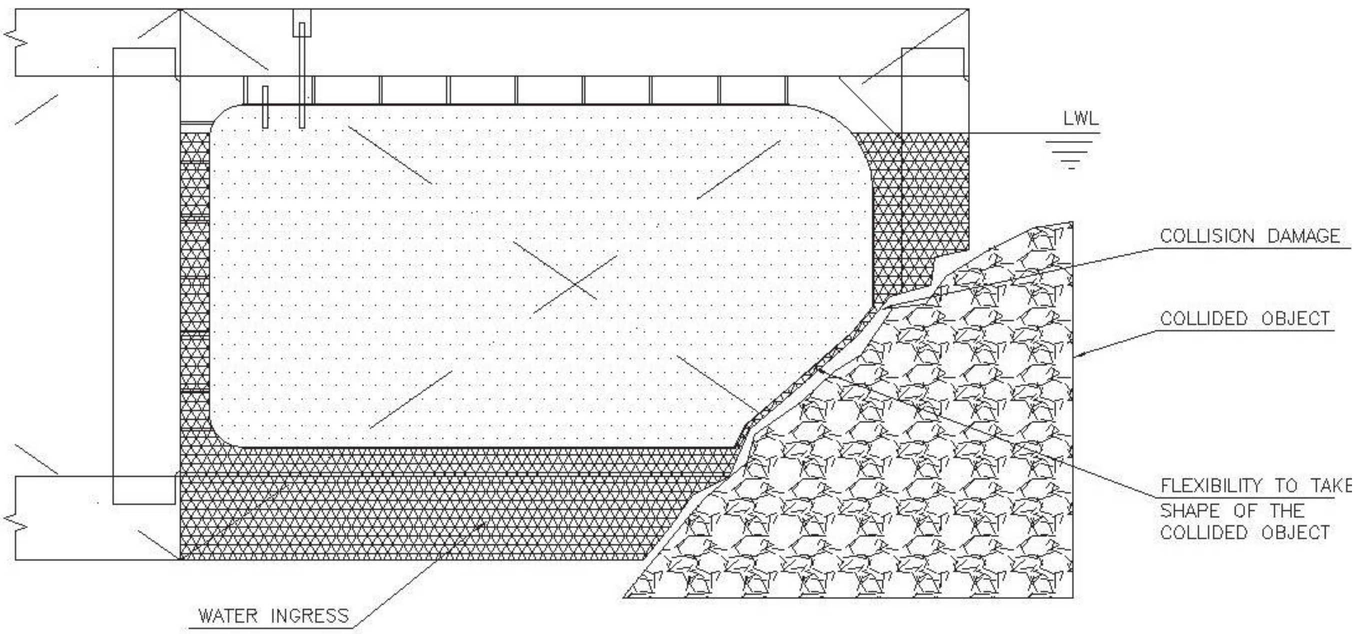

Fig. 3 Inflatable airbag system (after collision damage)

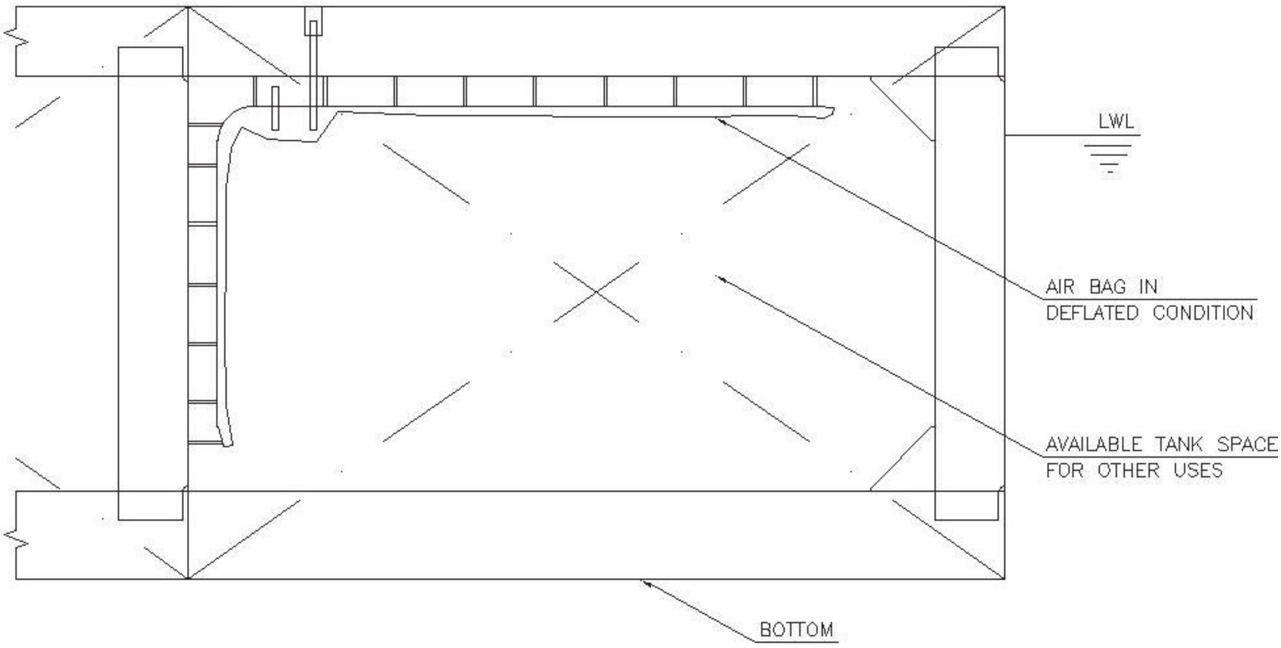

Fig. 4 Inflatable airbag system (in deflated condition)

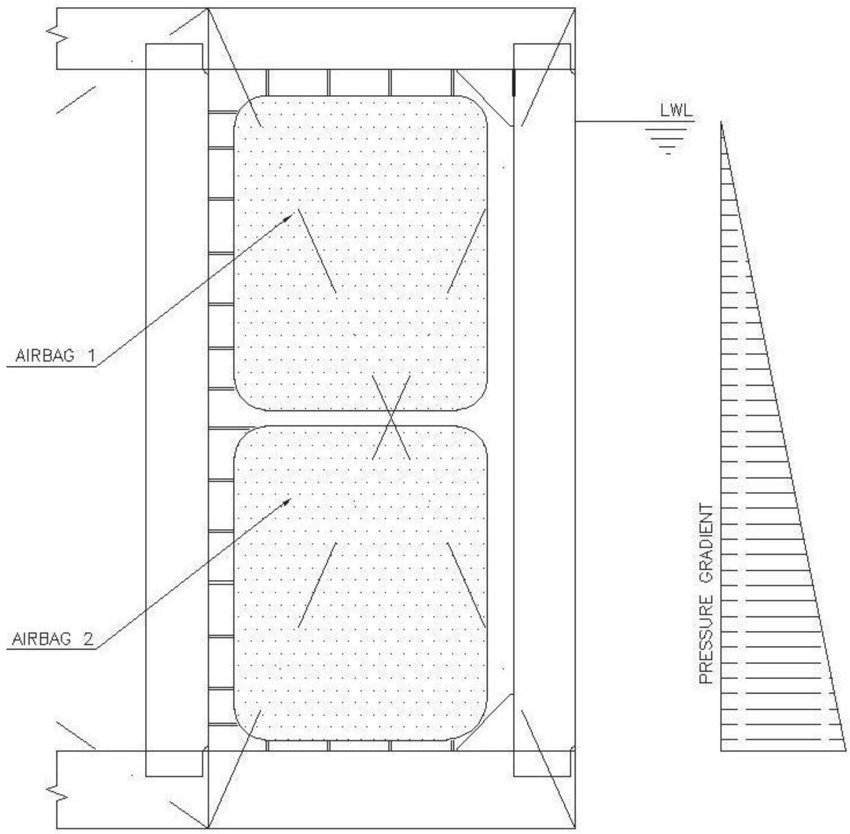

Fig. 5 Use of multiple airbags in deep tanks to counter pressure gradient

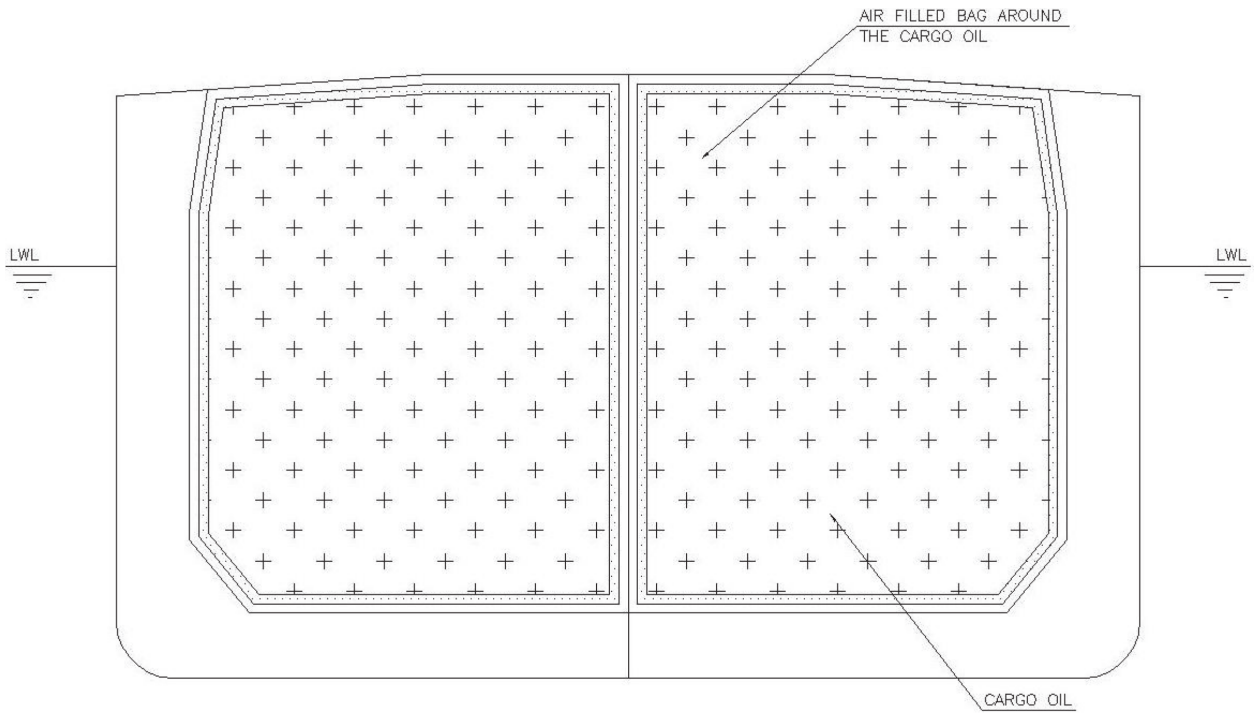

Fig. 6 Possible use of air bag protection for cargo oil to avoid spillage in the event of collision damage to hull

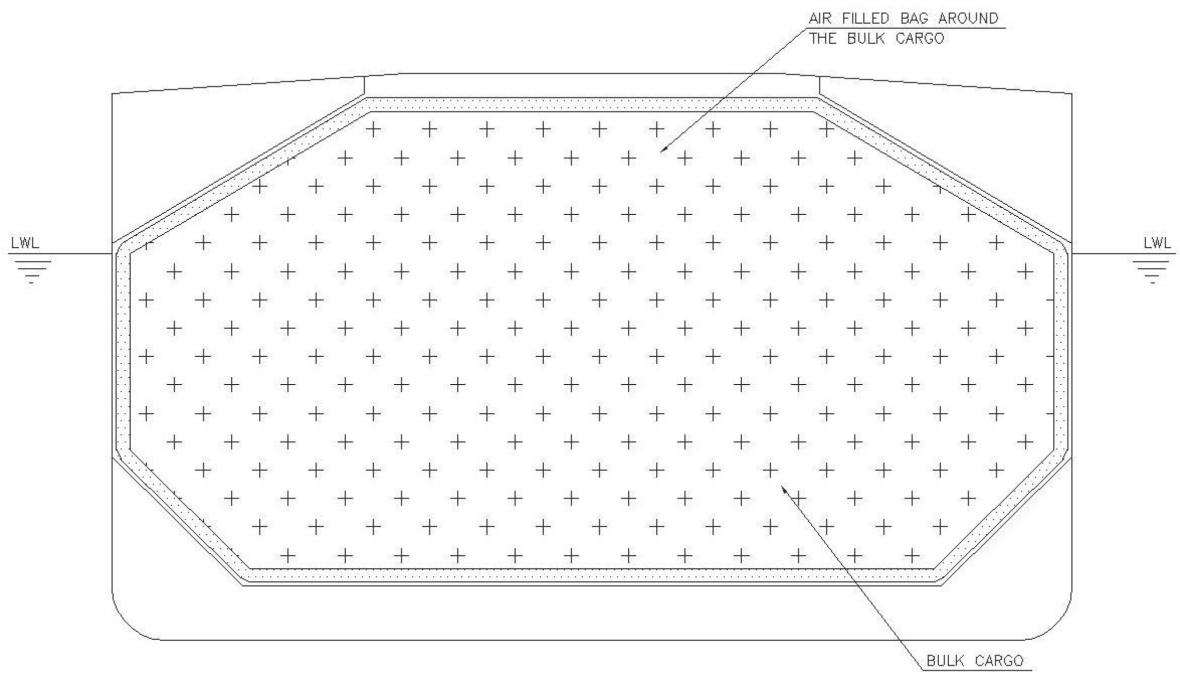

Fig. 7 Possible use of air bags to prevent bulk cargo from spilling, thus maintaining the permeability value

Maintaining permeability value of cargo holds
Generally, cargo occupies a large volume on any cargo ship. In the event of damage to the cargo hold, there is spillage of the cargo and resultant water ingress. Spillage of oil creates an environmental hazard. As far as the damage stability calculation is concerned, the spillage of cargo changes the permeability of the compartment, thereby making an accurate assessment of stability difficult.

As shown in (Fig. 6-7), the cargo spaces of oil tankers / bulk carriers may be lined with inflatable air bags to prevent spillage of cargo in the event of collision. Generally in case of low energy collisions, the double hull would protect the cargo from spilling in double hull ships. But single hull vessels like bulk carriers remain vulnerable to spillage of cargo. In case of higher energy collisions, the air bags may provide a cushioning effect by absorbing the energy of collision and releasing part of this energy by way of pressure relief valves. Thus air bags can prevent spillage of cargo, thereby maintaining the permeability value of the cargo compartment unchanged.

Master Computer

Role of master computer
A centrally located computer will be in control of the entire system, with suitable back up computer if required. This computer is expected to intelligently assess the damage situation and take remedial action to correct the stability of the vessel.

The computer will be connected to a system of sensors, which provide all the required data like draft readings, tank soundings, trim and heel values, environmental values, ship motion values, etc. which will help the computer to assess the intact, damage and dynamic stability of the vessel on a real time basis. Thus the computer will be able to decide at any given point of time, if any corrective measures like ballasting or deballasting are required to improve the stability of the vessel.

The computer will also be connected to every system in a controlling position to implement the remedial actions. Thus, the computer will be able to automatically ballast or deballast the tanks. It will be able to inflate or deflate the air bags to change the permeability value of each tank as the situation demands.

Pneumatic System & Instrumentation

Pneumatic system
This system will be used to inflate or deflate the air bags and will consist of the necessary instrumentation like pressure gauges, valves, relief valves, sensors etc. The capacity and location of the system has to be decided on a case to case basis.

USES OF THE PROPOSED SYSTEM

The system may find universal application for different ship types and designs. Once it is practically proven that the system actually improves the stability and safety of the vessel in damaged condition, the statutory authorities may provide a relaxation in freeboard for the vessel to the extent of the weight added by the system so that the vessels installing the systems do not have to pay a penalty due to added weight.

It may also reduce the initial cost of a vessel if certain dimensions can be reduced by virtue of the system. Ships may become more efficient if freeboard relaxations are possible.

In defense sector, we may be able to develop the system to adapt to actual combat situations so as to ensure that the vessels can withstand actual damage during combat.

In passenger cruise ship sector, we might be able to ensure that incidents like “Titanic” or “Costa Concordia” do not claim human lives.

CONCLUSIONS

An “Unsinkable Ship” is a concept whose time has come. With the use of proper materials and systems, and advanced computers, we should be able to create ships which can withstand major damage to the external hull. Control of permeability of compartments is a useful tool to manage the damage stability of vessels on a real-time basis. Careful control of permeability of compartments within a ship can improve the “Attained Sub-Division Index” of the ships.

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APPENDIXES

Appendix A Case study – Probabilistic damage stability results (permeability 95%)
Appendix A Case study – Probabilistic damage stability results (permeability 35%)

APPENDIX A

Probabilistic Damage Stability Analysis for 81 m Non Ballastable Deck Cargo Barge (permeability of all spaces 95%)

Description	Status	Damage (tank indices)	p factor	r factor	v factor	p.r.v.	stab range (deg)	GZ Max	Equi Angle (deg)	Angle of vanishing stab	DF angle (deg)	GZ max angle	K	s factor	A factor
Deepest subdivision draft (summer loadline) Loadcase															
Fully loaded: Z 1 (Heel to starboard)	Trim limit exceeded	1,2,3	0.082027	1	1	0.082027								0	0
Fully loaded: Z 2 (Heel to starboard)	Convergence error	4,5,6	0.052964	1	1	0.052964								0	0
Fully loaded: Z 3 (Heel to starboard)	GZ curve completed successfully	7,8,9	0.052964	1	1	0.052964	11.2	0.091	0	11.2	n/a	6.4	1	0.8541	0.045237
Fully loaded: Z 4 (Heel to starboard)	GZ curve completed successfully	10,11,12	0.052964	1	1	0.052964	12.8	0.151	0	12.8	n/a	7.3	1	0.9449	0.050046
Fully loaded: Z 5 (Heel to starboard)	GZ curve completed successfully	13,14,15	0.052964	1	1	0.052964	13.1	0.169	0	13.1	n/a	7.3	1	0.9513	0.050385
Fully loaded: Z 6 (Heel to starboard)	GZ curve completed successfully	16,17,18	0.052964	1	1	0.052964	12.8	0.151	0	12.8	n/a	7.3	1	0.9449	0.050046
Fully loaded: Z 7 (Heel to starboard)	GZ curve completed successfully	19,20,21	0.052964	1	1	0.052964	11.2	0.091	0	11.2	n/a	6.4	1	0.8541	0.045237
Fully loaded: Z 8 (Heel to starboard)	Convergence error	22,23,24	0.052964	1	1	0.052964								0	0
Fully loaded: Z 9 (Heel to starboard)	Trim limit exceeded	25,26,27	0.082038	1	1	0.082038								0	0
Fully loaded: Z 1, 2 (Heel to starboard)	Trim limit exceeded	1,2,3,4,5,6	0.053871	1	1	0.053871								0	0
Fully loaded: Z 2, 2 (Heel to starboard)	Trim limit exceeded	4,5,6,7,8,9	0.049595	1	1	0.049595								0	0
Fully loaded: Z 3, 2 (Heel to starboard)	Trim limit exceeded	7,8,9,10,11,12	0.049595	1	1	0.049595								0	0
Fully loaded: Z 4, 2 (Heel to starboard)	Trim limit exceeded	10,11,12,13,14,15	0.049595	1	1	0.049595								0	0
Fully loaded: Z 5, 2 (Heel to starboard)	Trim limit exceeded	13,14,15,16,17,18	0.049595	1	1	0.049595								0	0
Fully loaded: Z 6, 2 (Heel to starboard)	Trim limit exceeded	16,17,18,19,20,21	0.049595	1	1	0.049595								0	0
Fully loaded: Z 7, 2 (Heel to starboard)	Trim limit exceeded	19,20,21,22,23,24	0.049595	1	1	0.049595								0	0
Fully loaded: Z 8, 2 (Heel to starboard)	Trim limit exceeded	22,23,24,25,26,27	0.053872	1	1	0.053872								0	0
Fully loaded: Z 1, 3 (Heel to starboard)	Trim limit exceeded	1,2,3,4,5,6,7,8,9	0.008234	1	1	0.008234								0	0
Fully loaded: Z 2, 3 (Heel to starboard)	Trim limit exceeded	4,5,6,7,8,9,10,11,12	0.007915	1	1	0.007915								0	0
Fully loaded: Z 3, 3 (Heel to starboard)	Trim limit exceeded	7,8,9,10,11,12,13,14,15	0.007915	1	1	0.007915								0	0
Fully loaded: Z 4, 3 (Heel to starboard)	Vessel has sunk	10,11,12,13,14,15,16,17,18	0.007915	1	1	0.007915								0	0
Fully loaded: Z 5, 3 (Heel to starboard)	Trim limit exceeded	13,14,15,16,17,18,19,20,21	0.007915	1	1	0.007915								0	0
Fully loaded: Z 6, 3 (Heel to starboard)	Trim limit exceeded	16,17,18,19,20,21,22,23,24	0.007915	1	1	0.007915								0	0
Fully loaded: Z 7, 3 (Heel to starboard)	Trim limit exceeded	19,20,21,22,23,24,25,26,27	0.008234	1	1	0.008234								0	0
						0.996169									0.24095
Partial subdivision draft Loadcase															
50% Loaded: Z 1 (Heel to starboard)	GZ curve completed successfully	1,2,3	0.082027	1	1	0.082027	55.5	2.825	0	55.5	n/a	20.9	1	1	0.082027
50% Loaded: Z 2 (Heel to starboard)	GZ curve completed successfully	4,5,6	0.052964	1	1	0.052964	56.2	2.943	0	56.2	n/a	20.9	1	1	0.052964
50% Loaded: Z 3 (Heel to starboard)	GZ curve completed successfully	7,8,9	0.052964	1	1	0.052964	56.6	3.007	0	56.6	n/a	20.9	1	1	0.052964
50% Loaded: Z 4 (Heel to starboard)	GZ curve completed successfully	10,11,12	0.052964	1	1	0.052964	56.8	3.04	0	56.8	n/a	20.9	1	1	0.052964
50% Loaded: Z 5 (Heel to starboard)	GZ curve completed successfully	13,14,15	0.052964	1	1	0.052964	56.9	3.05	0	56.9	n/a	20.9	1	1	0.052964
50% Loaded: Z 6 (Heel to starboard)	GZ curve completed successfully	16,17,18	0.052964	1	1	0.052964	56.8	3.04	0	56.8	n/a	20.9	1	1	0.052964
50% Loaded: Z 7 (Heel to starboard)	GZ curve completed successfully	19,20,21	0.052964	1	1	0.052964	56.6	3.007	0	56.6	n/a	20.9	1	1	0.052964
50% Loaded: Z 8 (Heel to starboard)	GZ curve completed successfully	22,23,24	0.052964	1	1	0.052964	56.2	2.943	0	56.2	n/a	20.9	1	1	0.052964
50% Loaded: Z 9 (Heel to starboard)	GZ curve completed successfully	25,26,27	0.082038	1	1	0.082038	55.5	2.825	0	55.5	n/a	20.9	1	1	0.082038
50% Loaded: Z 1, 2 (Heel to starboard)	GZ curve completed successfully	1,2,3,4,5,6	0.053871	1	1	0.053871	41.3	1.467	0	41.3	n/a	15.5	1	1	0.053871
50% Loaded: Z 2, 2 (Heel to starboard)	GZ curve completed successfully	4,5,6,7,8,9	0.049595	1	1	0.049595	49.8	2.109	0	49.8	n/a	20	1	1	0.049595
50% Loaded: Z 3, 2 (Heel to starboard)	GZ curve completed successfully	7,8,9,10,11,12	0.049595	1	1	0.049595	52.2	2.374	0	52.2	n/a	20.9	1	1	0.049595
50% Loaded: Z 4, 2 (Heel to starboard)	GZ curve completed successfully	10,11,12,13,14,15	0.049595	1	1	0.049595	53.1	2.488	0	53.1	n/a	20.9	1	1	0.049595
50% Loaded: Z 5, 2 (Heel to starboard)	GZ curve completed successfully	13,14,15,16,17,18	0.049595	1	1	0.049595	53.1	2.488	0	53.1	n/a	20.9	1	1	0.049595
50% Loaded: Z 6, 2 (Heel to starboard)	GZ curve completed successfully	16,17,18,19,20,21	0.049595	1	1	0.049595	52.2	2.374	0	52.2	n/a	20.9	1	1	0.049595
50% Loaded: Z 7, 2 (Heel to starboard)	GZ curve completed successfully	19,20,21,22,23,24	0.049595	1	1	0.049595	49.8	2.109	0	49.8	n/a	20	1	1	0.049595
50% Loaded: Z 8, 2 (Heel to starboard)	GZ curve completed successfully	22,23,24,25,26,27	0.053872	1	1	0.053872	41.3	1.467	0	41.3	n/a	15.5	1	1	0.053872
50% Loaded: Z 1, 3 (Heel to starboard)	Trim limit exceeded	1,2,3,4,5,6,7,8,9	0.008234	1	1	0.008234								0	0
50% Loaded: Z 2, 3 (Heel to starboard)	GZ curve completed successfully	4,5,6,7,8,9,10,11,12	0.007915	1	1	0.007915	35.2	1.022	0	35.2	n/a	15.5	1	1	0.007915
50% Loaded: Z 3, 3 (Heel to starboard)	GZ curve completed successfully	7,8,9,10,11,12,13,14,15	0.007915	1	1	0.007915	45.4	1.629	0	45.4	n/a	18.2	1	1	0.007915
50% Loaded: Z 4, 3 (Heel to starboard)	GZ curve completed successfully	10,11,12,13,14,15,16,17,18	0.007915	1	1	0.007915	46.9	1.762	0	46.9	n/a	19.1	1	1	0.007915

50% Loaded: Z 5, 3 (Heel to starboard)	GZ curve completed successfully	13,14,15,16,17,18,19,20,21	0.007915	1	1	0.007915	45.4	1.629	0	45.4	n/a	18.2	1	1	0.007915
50% Loaded: Z 6, 3 (Heel to starboard)	GZ curve completed successfully	16,17,18,19,20,21,22,23,24	0.007915	1	1	0.007915	35.2	1.022	0	35.2	n/a	15.5	1	1	0.007915
50% Loaded: Z 7, 3 (Heel to starboard)	Trim limit exceeded	19,20,21,22,23,24,25,26,27	0.008234	1	1	0.008234								0	0
						0.996169									0.979702

Light service draft Loadcase															
Lightship: Z 1 (Heel to starboard)	GZ curve completed successfully	1,2,3	0.082027	1	1	0.082027	73.7	6.434	0	73.7	n/a	14.5	1	1	0.082027
Lightship: Z 2 (Heel to starboard)	GZ curve completed successfully	4,5,6	0.052964	1	1	0.052964	73.8	6.461	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 3 (Heel to starboard)	GZ curve completed successfully	7,8,9	0.052964	1	1	0.052964	73.8	6.475	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 4 (Heel to starboard)	GZ curve completed successfully	10,11,12	0.052964	1	1	0.052964	73.8	6.483	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 5 (Heel to starboard)	GZ curve completed successfully	13,14,15	0.052964	1	1	0.052964	73.8	6.485	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 6 (Heel to starboard)	GZ curve completed successfully	16,17,18	0.052964	1	1	0.052964	73.8	6.483	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 7 (Heel to starboard)	GZ curve completed successfully	19,20,21	0.052964	1	1	0.052964	73.8	6.475	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 8 (Heel to starboard)	GZ curve completed successfully	22,23,24	0.052964	1	1	0.052964	73.8	6.461	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 9 (Heel to starboard)	GZ curve completed successfully	25,26,27	0.082038	1	1	0.082038	73.7	6.434	0	73.7	n/a	14.5	1	1	0.082038
Lightship: Z 1, 2 (Heel to starboard)	GZ curve completed successfully	1,2,3,4,5,6	0.053871	1	1	0.053871	73.2	5.997	0	73.2	n/a	15.5	1	1	0.053871
Lightship: Z 2, 2 (Heel to starboard)	GZ curve completed successfully	4,5,6,7,8,9	0.049595	1	1	0.049595	73.6	6.182	0	73.6	n/a	14.5	1	1	0.049595
Lightship: Z 3, 2 (Heel to starboard)	GZ curve completed successfully	7,8,9,10,11,12	0.049595	1	1	0.049595	73.7	6.247	0	73.7	n/a	14.5	1	1	0.049595
Lightship: Z 4, 2 (Heel to starboard)	GZ curve completed successfully	10,11,12,13,14,15	0.049595	1	1	0.049595	73.7	6.272	0	73.7	n/a	14.5	1	1	0.049595
Lightship: Z 5, 2 (Heel to starboard)	GZ curve completed successfully	13,14,15,16,17,18	0.049595	1	1	0.049595	73.7	6.272	0	73.7	n/a	14.5	1	1	0.049595
Lightship: Z 6, 2 (Heel to starboard)	GZ curve completed successfully	16,17,18,19,20,21	0.049595	1	1	0.049595	73.7	6.247	0	73.7	n/a	14.5	1	1	0.049595
Lightship: Z 7, 2 (Heel to starboard)	GZ curve completed successfully	19,20,21,22,23,24	0.049595	1	1	0.049595	73.6	6.182	0	73.6	n/a	14.5	1	1	0.049595
Lightship: Z 8, 2 (Heel to starboard)	GZ curve completed successfully	22,23,24,25,26,27	0.053872	1	1	0.053872	73.2	5.997	0	73.2	n/a	15.5	1	1	0.053872
Lightship: Z 1, 3 (Heel to starboard)	GZ curve completed successfully	1,2,3,4,5,6,7,8,9	0.008234	1	1	0.008234	71.7	5.236	0	71.7	n/a	16.4	1	1	0.008234
Lightship: Z 2, 3 (Heel to starboard)	GZ curve completed successfully	4,5,6,7,8,9,10,11,12	0.007915	1	1	0.007915	73.2	5.851	0	73.2	n/a	15.5	1	1	0.007915
Lightship: Z 3, 3 (Heel to starboard)	GZ curve completed successfully	7,8,9,10,11,12,13,14,15	0.007915	1	1	0.007915	73.5	5.983	0	73.5	n/a	15.5	1	1	0.007915
Lightship: Z 4, 3 (Heel to starboard)	GZ curve completed successfully	10,11,12,13,14,15,16,17,18	0.007915	1	1	0.007915	73.6	6.016	0	73.6	n/a	14.5	1	1	0.007915
Lightship: Z 5, 3 (Heel to starboard)	GZ curve completed successfully	13,14,15,16,17,18,19,20,21	0.007915	1	1	0.007915	73.5	5.983	0	73.5	n/a	15.5	1	1	0.007915
Lightship: Z 6, 3 (Heel to starboard)	GZ curve completed successfully	16,17,18,19,20,21,22,23,24	0.007915	1	1	0.007915	73.2	5.851	0	73.2	n/a	15.5	1	1	0.007915
Lightship: Z 7, 3 (Heel to starboard)	GZ curve completed successfully	19,20,21,22,23,24,25,26,27	0.008234	1	1	0.008234	71.7	5.236	0	71.7	n/a	16.4	1	1	0.008234
						0.996169									0.996169

Attained subdivision index															**0.68749**
Required subdivision index															**0.3992**
															Pass

APPENDIX B

Probabilistic Damage Stability Analysis for 81 m Non Ballastable Deck Cargo Barge (permeability of all spaces 35%)

Description	Status	Damage (tank indices)	p factor	r factor	v factor	p.r.v.	stab range (deg)	GZ Max	Equi Angle (deg)	Angle of vanishing stab	DF angle (deg)	GZ max angle	K	s factor	A factor
Deepest subdivision draft (summer loadline) Loadcase															
Fully loaded: Z 1 (Heel to starboard)	GZ curve completed successfully	1,2,3	0.082027	1	1	0.082027	19	0.418	0	19	n/a	10	1	1	0.082027
Fully loaded: Z 2 (Heel to starboard)	GZ curve completed successfully	4,5,6	0.052964	1	1	0.052964	19.1	0.435	0	19.1	n/a	10	1	1	0.052964
Fully loaded: Z 3 (Heel to starboard)	GZ curve completed successfully	7,8,9	0.052964	1	1	0.052964	19.2	0.445	0	19.2	n/a	10	1	1	0.052964
Fully loaded: Z 4 (Heel to starboard)	GZ curve completed successfully	10,11,12	0.052964	1	1	0.052964	19.3	0.451	0	19.3	n/a	10	1	1	0.052964
Fully loaded: Z 5 (Heel to starboard)	GZ curve completed successfully	13,14,15	0.052964	1	1	0.052964	19.3	0.453	0	19.3	n/a	10	1	1	0.052964
Fully loaded: Z 6 (Heel to starboard)	GZ curve completed successfully	16,17,18	0.052964	1	1	0.052964	19.3	0.451	0	19.3	n/a	10	1	1	0.052964
Fully loaded: Z 7 (Heel to starboard)	GZ curve completed successfully	19,20,21	0.052964	1	1	0.052964	19.2	0.445	0	19.2	n/a	10	1	1	0.052964
Fully loaded: Z 8 (Heel to starboard)	GZ curve completed successfully	22,23,24	0.052964	1	1	0.052964	19.1	0.435	0	19.1	n/a	10	1	1	0.052964
Fully loaded: Z 9 (Heel to starboard)	GZ curve completed successfully	25,26,27	0.082038	1	1	0.082038	19	0.418	0	19	n/a	10	1	1	0.082038
Fully loaded: Z 1, 2 (Heel to starboard)	GZ curve completed successfully	1,2,3,4,5,6	0.053871	1	1	0.053871	13.7	0.155	0	13.7	n/a	8.2	1	0.9612	0.051781
Fully loaded: Z 2, 2 (Heel to starboard)	GZ curve completed successfully	4,5,6,7,8,9	0.049595	1	1	0.049595	15	0.228	0	15	n/a	8.2	1	0.9835	0.048777
Fully loaded: Z 3, 2 (Heel to starboard)	GZ curve completed successfully	7,8,9,10,11,12	0.049595	1	1	0.049595	15.6	0.269	0	15.6	n/a	8.2	1	0.9934	0.049268
Fully loaded: Z 4, 2 (Heel to starboard)	GZ curve completed successfully	10,11,12,13,14,15	0.049595	1	1	0.049595	15.8	0.287	0	15.8	n/a	9.1	1	0.9973	0.049461
Fully loaded: Z 5, 2 (Heel to starboard)	GZ curve completed successfully	13,14,15,16,17,18	0.049595	1	1	0.049595	15.8	0.287	0	15.8	n/a	9.1	1	0.9973	0.049461
Fully loaded: Z 6, 2 (Heel to starboard)	GZ curve completed successfully	16,17,18,19,20,21	0.049595	1	1	0.049595	15.6	0.269	0	15.6	n/a	8.2	1	0.9934	0.049268
Fully loaded: Z 7, 2 (Heel to starboard)	GZ curve completed successfully	19,20,21,22,23,24	0.049595	1	1	0.049595	15	0.228	0	15	n/a	8.2	1	0.9835	0.048777
Fully loaded: Z 8, 2 (Heel to starboard)	GZ curve completed successfully	22,23,24,25,26,27	0.053872	1	1	0.053872	13.7	0.155	0	13.7	n/a	8.2	1	0.9612	0.051782
Fully loaded: Z 1, 3 (Heel to starboard)	Trim limit exceeded	1,2,3,4,5,6,7,8,9	0.008234	1	1	0.008234								0	0
Fully loaded: Z 2, 3 (Heel to starboard)	GZ curve completed successfully	4,5,6,7,8,9,10,11,12	0.007915	1	1	0.007915	7.8	0.026	0	7.8	n/a	4.5	1	0.5693	0.004506
Fully loaded: Z 3, 3 (Heel to starboard)	GZ curve completed successfully	7,8,9,10,11,12,13,14,15	0.007915	1	1	0.007915	11.2	0.098	0	11.2	n/a	6.4	1	0.8705	0.00689
Fully loaded: Z 4, 3 (Heel to starboard)	GZ curve completed successfully	10,11,12,13,14,15,16,17,18	0.007915	1	1	0.007915	11.8	0.12	0	11.8	n/a	6.4	1	0.927	0.007337
Fully loaded: Z 5, 3 (Heel to starboard)	GZ curve completed successfully	13,14,15,16,17,18,19,20,21	0.007915	1	1	0.007915	11.2	0.098	0	11.2	n/a	6.4	1	0.8705	0.00689
Fully loaded: Z 6, 3 (Heel to starboard)	GZ curve completed successfully	16,17,18,19,20,21,22,23,24	0.007915	1	1	0.007915	7.8	0.026	0	7.8	n/a	4.5	1	0.5693	0.004506
Fully loaded: Z 7, 3 (Heel to starboard)	Trim limit exceeded	19,20,21,22,23,24,25,26,27	0.008234	1	1	0.008234								0	0
						0.996169									0.963516

Description	Status	Damage (tank indices)	p factor	r factor	v factor	p.r.v.	stab range (deg)	GZ Max	Equi Angle (deg)	Angle of vanishing stab	DF angle (deg)	GZ max angle	K	s factor	A factor
Partial subdivision draft Loadcase															
50% Loaded: Z 1 (Heel to starboard)	GZ curve completed successfully	1,2,3	0.082027	1	1	0.082027	58.5	3.301	0	58.5	n/a	21.8	1	1	0.082027
50% Loaded: Z 2 (Heel to starboard)	GZ curve completed successfully	4,5,6	0.052964	1	1	0.052964	58.5	3.31	0	58.5	n/a	21.8	1	1	0.052964
50% Loaded: Z 3 (Heel to starboard)	GZ curve completed successfully	7,8,9	0.052964	1	1	0.052964	58.5	3.317	0	58.5	n/a	21.8	1	1	0.052964
50% Loaded: Z 4 (Heel to starboard)	GZ curve completed successfully	10,11,12	0.052964	1	1	0.052964	58.6	3.321	0	58.6	n/a	21.8	1	1	0.052964
50% Loaded: Z 5 (Heel to starboard)	GZ curve completed successfully	13,14,15	0.052964	1	1	0.052964	58.6	3.322	0	58.6	n/a	21.8	1	1	0.052964
50% Loaded: Z 6 (Heel to starboard)	GZ curve completed successfully	16,17,18	0.052964	1	1	0.052964	58.6	3.321	0	58.6	n/a	21.8	1	1	0.052964
50% Loaded: Z 7 (Heel to starboard)	GZ curve completed successfully	19,20,21	0.052964	1	1	0.052964	58.5	3.317	0	58.5	n/a	21.8	1	1	0.052964
50% Loaded: Z 8 (Heel to starboard)	GZ curve completed successfully	22,23,24	0.052964	1	1	0.052964	58.5	3.31	0	58.5	n/a	21.8	1	1	0.052964
50% Loaded: Z 9 (Heel to starboard)	GZ curve completed successfully	25,26,27	0.082038	1	1	0.082038	58.5	3.301	0	58.5	n/a	21.8	1	1	0.082038
50% Loaded: Z 1, 2 (Heel to starboard)	GZ curve completed successfully	1,2,3,4,5,6	0.053871	1	1	0.053871	57.2	3.095	0	57.2	n/a	20.9	1	1	0.053871
50% Loaded: Z 2, 2 (Heel to starboard)	GZ curve completed successfully	4,5,6,7,8,9	0.049595	1	1	0.049595	57.4	3.135	0	57.4	n/a	20.9	1	1	0.049595
50% Loaded: Z 3, 2 (Heel to starboard)	GZ curve completed successfully	7,8,9,10,11,12	0.049595	1	1	0.049595	57.6	3.157	0	57.6	n/a	20.9	1	1	0.049595
50% Loaded: Z 4, 2 (Heel to starboard)	GZ curve completed successfully	10,11,12,13,14,15	0.049595	1	1	0.049595	57.6	3.168	0	57.6	n/a	20.9	1	1	0.049595
50% Loaded: Z 5, 2 (Heel to starboard)	GZ curve completed successfully	13,14,15,16,17,18	0.049595	1	1	0.049595	57.6	3.168	0	57.6	n/a	20.9	1	1	0.049595
50% Loaded: Z 6, 2 (Heel to starboard)	GZ curve completed successfully	16,17,18,19,20,21	0.049595	1	1	0.049595	57.6	3.157	0	57.6	n/a	20.9	1	1	0.049595
50% Loaded: Z 7, 2 (Heel to starboard)	GZ curve completed successfully	19,20,21,22,23,24	0.049595	1	1	0.049595	57.4	3.135	0	57.4	n/a	20.9	1	1	0.049595
50% Loaded: Z 8, 2 (Heel to starboard)	GZ curve completed successfully	22,23,24,25,26,27	0.053872	1	1	0.053872	57.2	3.095	0	57.2	n/a	20.9	1	1	0.053872
50% Loaded: Z 1, 3 (Heel to starboard)	GZ curve completed successfully	1,2,3,4,5,6,7,8,9	0.008234	1	1	0.008234	55.7	2.86	0	55.7	n/a	20.9	1	1	0.008234
50% Loaded: Z 2, 3 (Heel to starboard)	GZ curve completed successfully	4,5,6,7,8,9,10,11,12	0.007915	1	1	0.007915	56.2	2.945	0	56.2	n/a	20.9	1	1	0.007915

50% Loaded: Z 3, 3 (Heel to starboard)	GZ curve completed successfully	7,8,9,10,11,12,13,14,15	0.007915	1	1	0.007915	56.5	2.987	0	56.5	n/a	20.9	1	1	0.007915
50% Loaded: Z 4, 3 (Heel to starboard)	GZ curve completed successfully	10,11,12,13,14,15,16,17,18	0.007915	1	1	0.007915	56.6	3	0	56.6	n/a	20.9	1	1	0.007915
50% Loaded: Z 5, 3 (Heel to starboard)	GZ curve completed successfully	13,14,15,16,17,18,19,20,21	0.007915	1	1	0.007915	56.5	2.987	0	56.5	n/a	20.9	1	1	0.007915
50% Loaded: Z 6, 3 (Heel to starboard)	GZ curve completed successfully	16,17,18,19,20,21,22,23,24	0.007915	1	1	0.007915	56.2	2.945	0	56.2	n/a	20.9	1	1	0.007915
50% Loaded: Z 7, 3 (Heel to starboard)	GZ curve completed successfully	19,20,21,22,23,24,25,26,27	0.008234	1	1	0.008234	55.7	2.86	0	55.7	n/a	20.9	1	1	0.008234
						0.996169									0.996169

Light service draft Loadcase															
Lightship: Z 1 (Heel to starboard)	GZ curve completed successfully	1,2,3	0.082027	1	1	0.082027	73.8	6.595	0	73.8	n/a	14.5	1	1	0.082027
Lightship: Z 2 (Heel to starboard)	GZ curve completed successfully	4,5,6	0.052964	1	1	0.052964	73.8	6.598	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 3 (Heel to starboard)	GZ curve completed successfully	7,8,9	0.052964	1	1	0.052964	73.8	6.599	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 4 (Heel to starboard)	GZ curve completed successfully	10,11,12	0.052964	1	1	0.052964	73.8	6.6	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 5 (Heel to starboard)	GZ curve completed successfully	13,14,15	0.052964	1	1	0.052964	73.8	6.6	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 6 (Heel to starboard)	GZ curve completed successfully	16,17,18	0.052964	1	1	0.052964	73.8	6.6	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 7 (Heel to starboard)	GZ curve completed successfully	19,20,21	0.052964	1	1	0.052964	73.8	6.599	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 8 (Heel to starboard)	GZ curve completed successfully	22,23,24	0.052964	1	1	0.052964	73.8	6.598	0	73.8	n/a	14.5	1	1	0.052964
Lightship: Z 9 (Heel to starboard)	GZ curve completed successfully	25,26,27	0.082038	1	1	0.082038	73.8	6.595	0	73.8	n/a	14.5	1	1	0.082038
Lightship: Z 1, 2 (Heel to starboard)	GZ curve completed successfully	1,2,3,4,5,6	0.053871	1	1	0.053871	73.8	6.517	0	73.8	n/a	14.5	1	1	0.053871
Lightship: Z 2, 2 (Heel to starboard)	GZ curve completed successfully	4,5,6,7,8,9	0.049595	1	1	0.049595	73.8	6.527	0	73.8	n/a	14.5	1	1	0.049595
Lightship: Z 3, 2 (Heel to starboard)	GZ curve completed successfully	7,8,9,10,11,12	0.049595	1	1	0.049595	73.8	6.532	0	73.8	n/a	14.5	1	1	0.049595
Lightship: Z 4, 2 (Heel to starboard)	GZ curve completed successfully	10,11,12,13,14,15	0.049595	1	1	0.049595	73.8	6.535	0	73.8	n/a	14.5	1	1	0.049595
Lightship: Z 5, 2 (Heel to starboard)	GZ curve completed successfully	13,14,15,16,17,18	0.049595	1	1	0.049595	73.8	6.535	0	73.8	n/a	14.5	1	1	0.049595
Lightship: Z 6, 2 (Heel to starboard)	GZ curve completed successfully	16,17,18,19,20,21	0.049595	1	1	0.049595	73.8	6.532	0	73.8	n/a	14.5	1	1	0.049595
Lightship: Z 7, 2 (Heel to starboard)	GZ curve completed successfully	19,20,21,22,23,24	0.049595	1	1	0.049595	73.8	6.527	0	73.8	n/a	14.5	1	1	0.049595
Lightship: Z 8, 2 (Heel to starboard)	GZ curve completed successfully	22,23,24,25,26,27	0.053872	1	1	0.053872	73.8	6.517	0	73.8	n/a	14.5	1	1	0.053872
Lightship: Z 1, 3 (Heel to starboard)	GZ curve completed successfully	1,2,3,4,5,6,7,8,9	0.008234	1	1	0.008234	73.8	6.433	0	73.8	n/a	14.5	1	1	0.008234
Lightship: Z 2, 3 (Heel to starboard)	GZ curve completed successfully	4,5,6,7,8,9,10,11,12	0.007915	1	1	0.007915	73.8	6.452	0	73.8	n/a	14.5	1	1	0.007915
Lightship: Z 3, 3 (Heel to starboard)	GZ curve completed successfully	7,8,9,10,11,12,13,14,15	0.007915	1	1	0.007915	73.8	6.462	0	73.8	n/a	14.5	1	1	0.007915
Lightship: Z 4, 3 (Heel to starboard)	GZ curve completed successfully	10,11,12,13,14,15,16,17,18	0.007915	1	1	0.007915	73.8	6.465	0	73.8	n/a	14.5	1	1	0.007915
Lightship: Z 5, 3 (Heel to starboard)	GZ curve completed successfully	13,14,15,16,17,18,19,20,21	0.007915	1	1	0.007915	73.8	6.462	0	73.8	n/a	14.5	1	1	0.007915
Lightship: Z 6, 3 (Heel to starboard)	GZ curve completed successfully	16,17,18,19,20,21,22,23,24	0.007915	1	1	0.007915	73.8	6.452	0	73.8	n/a	14.5	1	1	0.007915
Lightship: Z 7, 3 (Heel to starboard)	GZ curve completed successfully	19,20,21,22,23,24,25,26,27	0.008234	1	1	0.008234	73.8	6.433	0	73.8	n/a	14.5	1	1	0.008234
						0.996169									0.996169

Attained subdivision index															**0.98311**
Required subdivision index															**0.3992**
															Pass