

COMPARATIVE DAMAGE STABILITY AND SURVIVABILITY PERFORMANCE ANALYSIS OF CONVENTIONAL AND PODDED ROPAX VESSELS

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Abstract

The development of azimuthing propulsion systems brought great flexibility to internal design of vessels. Combination of diesel electric engines and the pod system gives designer an opportunity to decide where to locate the engine room(s), and as no shaft is needed those engine room spaces can be anywhere along the vessels length. This provides opportunity to improve the damage stability of the vessels. Therefore, damage stability and survivability performance calculations have been carried out for both conventional and podded designs using a combination of IMO instruments, European regional rules and performance-based safety assessment. This paper presents the results of a research that contains comparative analysis of damage stability and survivability performance measures for Conventional and Podded ROPAX vessels with identical dimensions.

1. INTRODUCTION

The Ro-Ro concept has proven to be the most commercially successful to date as it provides the capability to carry a wide variety of cargo in the same ship, thus being able to offer a competitive frequency with minimum port infrastructure or special shore-based equipment. Short sea routes are dominated by Ro-Ro ships with lorries, trailers, train wagons, containers, trade cars and passengers being transferred from the “outer” regions (UK, Ireland, Scandinavia and Finland) to the “main” land (continental Europe). Also in the Southern Europe corridors, the Ro-Ro freight service is progressively increasing in volume. The case for a long-distance Ro-Ro service to provide a European maritime highway has also been made several times before. This is particularly relevant and important in respect of fast sea transportation where again Ro-Ro ferries play a prominent role. The main concern with the Ro-Ro ship, whether justified

or unjustified, relates to safety. With safety becoming of paramount importance, it is of vital importance that a rational approach to safety is demonstrated, validated and adopted. This is the only way to ensure both the survival and a meaningful evolution of Ro-Ro ships in the future. These safety instruments are “intact stability criteria”, “damage stability criteria of SOLAS’90”, “stockholm water on deck calculations (known as SOLAS’90 + 50)”, “probabilistic subdivision and damage stability resolution A.265”, numerical simulations and model experiments of damaged ship in waves

All these regulatory developments, which have much higher standards, force changes in Ropax design such as increased height of freeboard deck, and use of side casings, while passenger cabins and spaces below main deck are not acceptable anymore. Those spaces, which were used for storage of onboard shopping goods, are not viable for these type of activities, especially in Eu waters due to the restrictions

on tax free sales of goods. On the other hand increasing demand for cargo space and trying to improve the passenger comfort and earning capacity of ropax vessels force designers and operators to improve the designs by using the technological advances such as azimuthing propulsion systems (Pod propulsion) as well as looking at alternative subdivision arrangements such as extended lower holds [1]. The volume below the main ro-ro deck is large and leaving it as void is waste of valuable space.

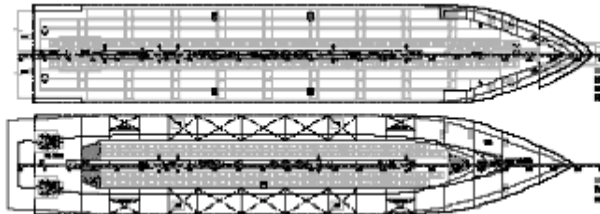


Figure 1: Podded Ropax Vessel

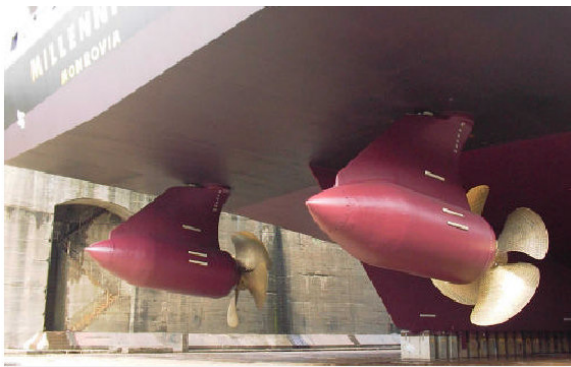


Figure 2: A typical Pod propulsion system [16]

The claimed advantages of Pod propulsion can be listed as below [2]

- Increased Cargo Capacity or Reduced Vessel Size
- Increased Propulsion System Efficiency
- Increased Propulsion System Redundancy and Power Availability
- Increased Propulsion System Reliability (Fewer Components)
- Reduced Total Installed Power Generation
- Reduced Total Fuel Consumption & Exhaust Emissions
- Reduced Maintenance and repair
- Reduced Noise & Vibration Levels
- Reduced Vessel Turning Circle
- Improved Manoeuvrability and Stopping Capability for all operational speeds
- Improved Harbour Manoeuvrability

In this paper, the stability and survivability of a new Ropax design equipped with technological advances and new internal arrangements (especially long inner hold) are examined for two propulsion alternatives by using various stability and survivability standards [3]:

- Conventional propulsion system (Diesel Mechanical)
- Podded propulsion system (Diesel electric-podded)

2. DAMAGE STABILITY RULES AND APPROACHES

The maritime industry, which is acutely aware of recent shipping casualties involving Ropax vessels, which have resulted in severe loss of life, have been facing new standards for Ro-Ro ship configuration, construction aimed at improving the safety of these vessels [4,5,6,7]. However, the application may not be straight forward as designers and operators face the regulatory regime that provide equivalent available options, approaches and optimum choice to ensuring compliance and to ascertaining the level of safety attained with regard to any such choice;

- (i) deterministic (SOLAS'90) vs probabilistic (A.265 (VIII))
- (ii) prescriptive (SOLAS'90 + WOD) vs performance based (physical model experiments)
- (iii) method to tackle damages, which are not covered by the standards but potentially realistic and dangerous

Details of these regulations can be found in [4, 5,6,7 8, 9]. Item III is mainly concerned with inner hold and large scale flooding. One of the major concerns with the inner hold is the residual stability of vessel if the inner hold is flooded. International rules clearly indicate that provided the longitudinal bulkheads are beyond B/5 from the side shell of the vessel, they are assumed to be intact during a collision, provided that the margin line is not immersed when this inner hold is flooded. Currently there are no international rules to require minimum stability if damages penetrate beyond the B/5 line (some national administrations require minimum standards).

SSRC developed an Unique rational approach to ferry safety with the capability of attending to the needs of the shipping industry cost-effectively and led to the establishment of what is termed a “Total Stability Assessment” (TSA) procedure [8]. The procedure comprises assessment of a vessel’s survivability utilising all the currently available instruments, namely: A.265 (VIII) + amendments (probabilistic procedure), SOLAS ’90, Stockholm Agreement (prescriptive criteria) and “ Safety Equivalence” tests by means of physical model experiments and numerical simulations (performance-based criteria). Furthermore, TSA allows the investigation of any damages beyond the perspective of regulations effectively to overcome any deficiencies that can be overlooked when the current standards are applied. This is the right way to ensuring both the survival and a meaningful evolution of Ro-Ro ships in the future.

3. PARAMETRIC INVESTIGATION

Both the Conventional and Podded ROPAX vessels have the same main characteristics and the only difference between them is the internal arrangements due to the different propulsion systems. The main characteristics of both vessels can be found in Table 1, while general arrangements can be seen in Figures 3 and 4.

When the two internal arrangements are concerned, the only difference is observed with the subdivision arrangement below the main deck. The machinery arrangement of the conventional vessel is located just aft of midship in three adjacent compartments. The machinery arrangement with the Podded ROPAX vessel is more flexible as shafts for the propulsion system is not required anymore. The machinery is located in separate compartments at forward and aft of amidship. As the machinery is diesel electric type they do not have to be connected mechanically as is the case with conventional types.

Traditionally the most vulnerable area of the conventional vessels is the machinery compartments due to relatively high permeability and longer compartment length to fit the machinery systems. As a result, when

larger volume is flooded, it causes a reduction in the stability due to the loss of freeboard and waterplane area (free surface effect).

Table1: Main characteristics of Conventional and Podded ROPAX vessels

MAIN DIMENSIONS		
	Conventional	Podded
Length Overall(L_{oa})	194.4 m	194.4 m
Length between perpendiculars (L_{pp})	172.2 m	172.2 m
Breadth moulded (B)	28.4 m	28.4 m
Depth to bulkhead deck	9.7 m	9.7 m
Depth to upper deck	15.0 m	15.0 m
Draught design (T)	6.6 m	6.6 m
Light weight	16400 ton	16400 ton
Deadweight	3800 ton	3800 ton
Max number of persons on board	2660	2660
CARGO CAPACITIES		
Trailers (Main deck)	Abt. 850 m	Abt. 850 m
Cars	Abt. 1033 m	Abt. 1033 m

These two designs have very high intact and damaged freeboard due to the much higher car deck compared to old style vessels. The major influence on these designs is the SOLAS’90 standards and Stockholm Water on Deck Agreement Regulations.

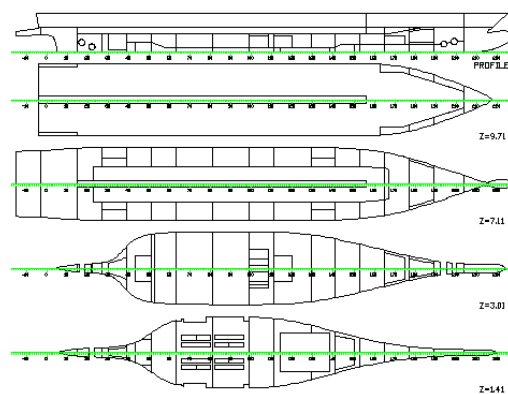


Figure 3: General Arrangement (Conventional Ropax)

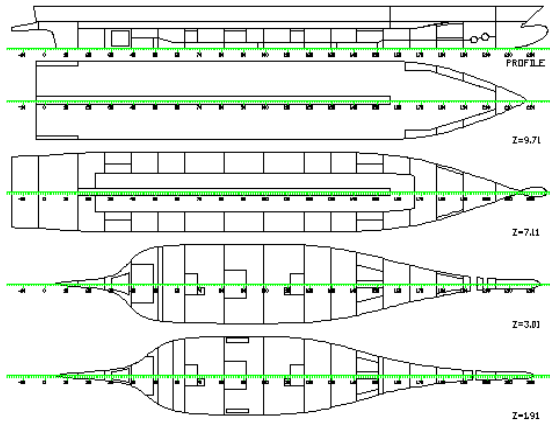


Figure 4: General Arrangement (Conventional Ropax)

Both vessels have a long inner hold to carry extra cars. This is the trend in recent designs to utilise the space below main deck (car deck) as it is not popular to locate passenger facilities below car deck due to safety and comfort reasons. Due to the height of the lower hold, only private cars can be stored. However, the height of the lower hold can be increased to accommodate trailers. In this parametric study inner hold damages will be an essential part of the investigation. A parametric study is carried out for:

- Stability compliance according to SOLAS'90 damage stability standards
- Stability compliance according to Regional Stockholm Water on Deck Agreement
- Probabilistic method according to IMO Resolution A.265
- Survivability assessment of damaged vessel in beam seas by using numerical simulations.

4. STABILITY ASSESSMENT OF ROPAX VESSELS

According to the SOLAS'90 standards this is a two compartment standard vessel and therefore all the possible combinations of two

compartment damages along the length of the vessel should be investigated. For the calculations, the following loading conditions (see Tables 2 and 3) are taken into account. All results are presented in the form of KG limiting curves.

Table 2: Loading conditions for Conventional ROPAX vessel

Code	Disp (ton)	draft(m)	KG/(GM)(m)
LC1	20200	6.58	13.81/(3.18)
LC2	20106	6.57	13.74/(3.15)
LC3	18679	6.24	13.80/(2.84)
LC4	18336	6.16	13.89/(2.76)
LC5	16000	5.55	14.90/(2.39)

Table 3: Loading conditions for Podded ROPAX vessel

Code	Disp(ton)	draft(m)	KG(GM)(m)
LC1	20200	6.60	13.82(3.15)
LC2	20006	6.56	13.79(3.12)
LC3	19170	6.37	13.62(3.15)
LC4	18756	6.27	13.79(2.91)
LC5	16000	5.58	14.90(2.39)

4.1 Damage Condition

Solas'90 Calculations

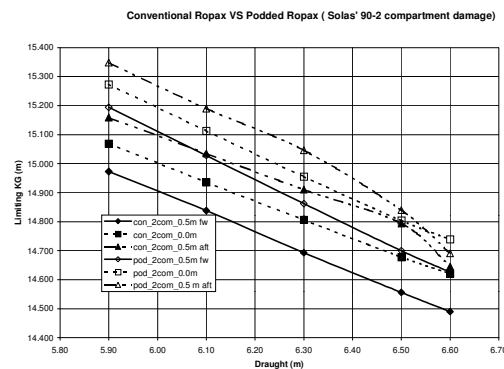


Figure 5: Conventional vs Podded (2 comp Damage)

Two compartment damages are investigated according to SOLAS'90 damage stability standards for various trim conditions (Figure 5). As expected KG limiting curve decreases with the increasing draught. However, the margin between the limiting KG and the loading KG (actual KG) is around 0.5m – 0.7m

and is sufficient to provide extra safety and some degree of flexibility for future modifications on both ships. Podded vessel, compared to conventional vessel has marginally better KG limiting curve (between 0.1m-0.25 m).

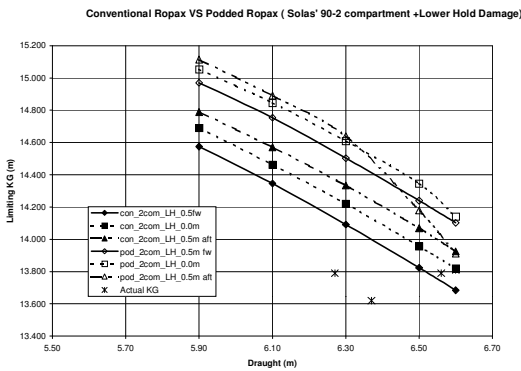


Figure 6: Conventional vs. Podded (2 comp+ Inner Hold Damage)

Although, flooding of the lower hold is not currently covered by mandatory SOLAS'90 damage stability standards as the longitudinal bulkhead is within B/5 line, operators demand that for such damages, which are highly possible, a relevant assessment should be carried out to make sure that ship has minimum level of stability standards. As Figure 6 clearly indicates, both vessels have very good reserve stability despite inner hold being flooded. Both vessels comply with all SOLAS'90 standards except 0.5 forward trim at deepest draught, at which conventional Ropax marginally fails. This demonstrates clearly how the stability and safety standards of modern Ropax designs improved. Again, when both vessels are compared Podded Ropax has better stability standards with as much as 0.4 m margin in GM/KG compared to conventional Ropax.

When '3 compartment damage' cases are investigated the margin is suddenly lost [Figure 7]. For the deepest draught, limiting KG falls below the actual KG for some trim conditions for both vessels (especially for conventional Ropax). In comparison, however, podded ropax vessel has significantly better damaged stability compared to conventional vessel, especially for forward damage. This is due to the flexibility that podded vessel had regarding the tank arrangements.

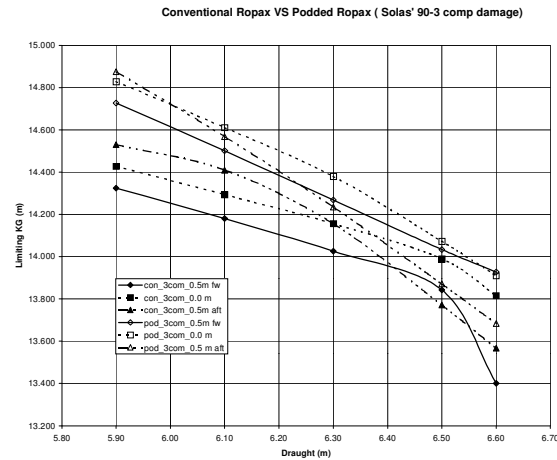


Figure 7: Conventional vs. Podded (3 comp Damage)

Calculations According to Stockholm Water on Deck Standards

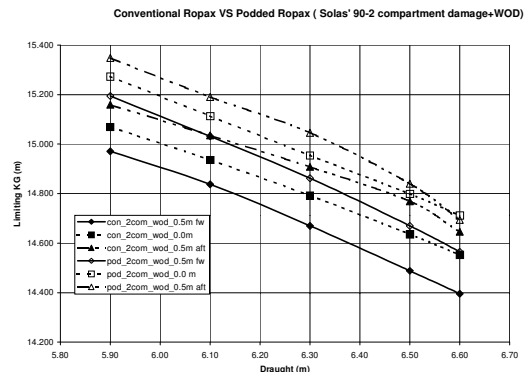


Figure 8: Conventional vs. Podded (2 comp+ Water on Deck)

All the water on deck calculations are carried out for the significant wave height of 4.0 m, which is the maximum wave height considered within Stockholm water on deck standards.

The height of freeboard at the damage opening plays a very important role for the compliance of the ship with the Stockholm standards as it determines the amount of water on the car deck in terms of water height. As the Figure 8 demonstrate, due to the high damaged freeboard both vessels easily comply with the stockholm water on deck calculations with as much as 0.6 m margin in GM/KG. The worst

damage is identified as the damage to compartments 9 and 10 for conventional Ropax vessel for all the damage cases (2 comp, lower hold and water on deck 3 compartment damages). For podded ropax vessel compartments 10 and 11 appears to be the worst damage for 2 compartment SOLAS 90 damage and water on deck case (due to large heeling tanks), but compartments 6, 7 and 8, which are machinery rooms become the worst region when the inner hold is flooded.

When the Stockholm water on deck calculations are carried out for 3 compartment damages it is clearly seen from Figure 9 that ships fails to comply with SOLAS'90 standards by significant margin especially the conventional Ropax. This comparison also clearly indicates the advantages of podded vessel. Again, Podded Ropax in this case demonstrates higher standards compared to the conventional Ropax.

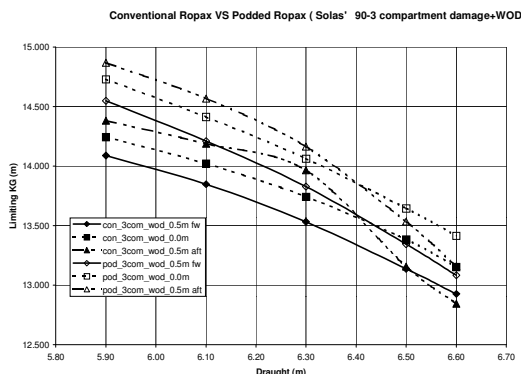


Figure 9: Conventional vs. Podded (3 comp+ Water on Deck)

For most of the conditions the 'Maximum righting lever after passenger crowding' is the limiting requirement due to the large passenger number on these vessels. This criterion requires a residual GZ-lever of 0.04m in damaged condition after the passenger crowding is taken into account. The heeling moment lever from passenger crowding is equivalent of 0.11m and hence, the total GZ requirement for this condition is 0.15m.

Overall, it can be clearly stated that, although almost in all cases Podded Ropax vessel possesses better stability characteristics due to the flexibility it provides for internal

arrangement, the real advantages of pod propulsion become very clear when the large scale flooding such as inner hold flooding or 3 compartment damages are considered. This is due to the different compartment arrangement at the forward part of the conventional ROPAX.

4.2. Probabilistic Damage Stability Assessment

IMO Resolution A.265 has been used to calculate the probabilistic damage survivability for both ROPAX vessels. The basis of the resolution is that the required subdivision index R needs to be exceeded by the attained subdivision Index A in order to comply with the resolution. In addition IMO A.265 requires compliance with certain deterministic requirements. The attained subdivision index is based on the formulation:

$$A = \sum w \cdot a \cdot p \cdot s$$

where;

“w” represents a weighting factor determined by the draught, “a” represents the probability of (centre of) damage location of a compartment, or group of compartments, “p” represents the probability of a compartment or group of compartments being damaged, “s” represents the probability of survival of the specific damage.

Three intermediate draughts (D_1 , D_2 , D_3) between the subdivision draught (D_s) and the lightest service draught (D_0) are used for the calculations. The required subdivision index R is calculated according to:

$$R = 1 - 1000 / (4 \cdot L_s + N + 1500)$$

For both the deterministic and probabilistic study three different trim conditions are used for each intermediate draught. The most unfavourable trim condition for each damage case is used to calculate the Attained Subdivision Index.

Conventional ROPAX

The probabilistic calculations for the Conventional ROPAX vessel is based on three different intact draught conditions and three intact trim conditions for each draught. The draughts are $D_1=6.31\text{m}$, $D_2=6.45\text{m}$ and $D_3=6.53\text{m}$. Trim conditions for each draught are 0.5m forward trim, even keel and 0.5m aft trim. A metacentric height of three metres has been used for all the intact conditions.

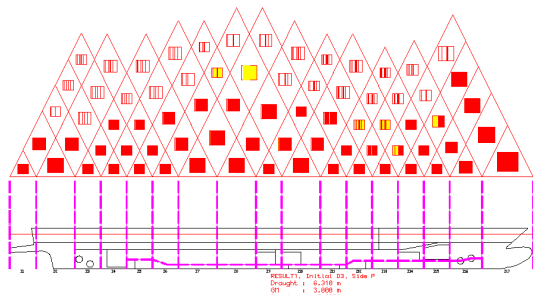


Figure 10: Survivability plot for Conventional ROPAX vessel

In order to make overall compliance with IMO A.265 a set of deterministic requirements (Regulation 5), based on two compartment damages need to be met. The regulation specifies a minimum allowed intact metacentric height for each intermediate draught, based on the worst trim condition. The GM requirements for each draught are $D_1=2.224\text{m}$, $D_2=2.527\text{m}$ and $D_3=2.568\text{m}$.

The basis of the probabilistic calculations is that the attained subdivision index A needs to be higher than the required subdivision index R. The required subdivision index is dependent only on the subdivision length and the passenger number.

R for the conventional ROPAX: 0.797
A for the conventional ROPAX: 0.884

The probabilistic calculations demonstrate that the conventional ROPAX vessel is assumed to survive all one compartment damages and most of the two compartment damages. Some two compartment damages are considered critical when the damage extent penetrates beyond the longitudinal bulkhead of the long lower hold. These are the engine room damages and the forward damages in zones 9-14 (compartment 8-13 between the frame numbers 99 and 177).

This is in good agreement with the SOLAS'90 calculations. For three compartment damages the most critical ones are the aft damages in zones 1-3, which the vessel is assumed not to survive and forward damages in zones 11-16 (compartment 10-15 between the frame numbers 129 and 204).

Podded ROPAX

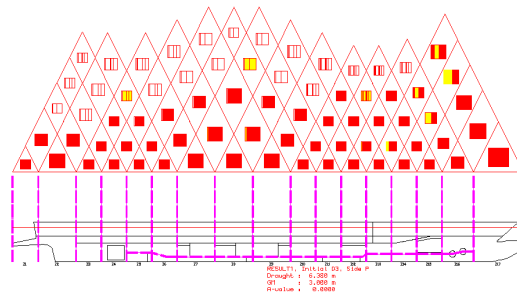


Figure 11: Survivability plot for Podded ROPAX vessel

The three draughts conditions D_1 , D_2 and D_3 are taken, according to the regulations, as intermediate draughts between the subdivision draught D_S and the lightest service draught D_0 . The draughts are $D_1=6.38\text{m}$, $D_2=6.49\text{m}$ and $D_3=6.54\text{m}$. Trim conditions for each draught are 0.5m forward trim, even keel and 0.5m aft trim. A metacentric height of three metres has been used for all the intact conditions. The GM requirements according to regulation 5 for each draught are $D_1=2.364\text{m}$, $D_2=2.524\text{m}$ and $D_3=2.510\text{m}$. These values are marginally lower than the equivalent values for the conventional ROPAX vessel.

R for the Podded ROPAX: 0.797
A for the Podded ROPAX: 0.982

The probabilistic calculations demonstrate that the Podded ROPAX vessel is assumed to survive all one compartment damages and most of the two compartment damages. Some two compartment damages are considered critical when the damage extent penetrates beyond the longitudinal bulkhead of the long lower hold. These are the engine room damages and the forward damages in zones 12-14 (compartment 11-13 between the frame numbers 141 and 177). This is in good agreement with the SOLAS'90 calculations. For three

compartment damages the most critical ones are the aft damages in zones 1-3, which the vessel is assumed not to survive.

Comparison of Probabilistic Standards Between Podded and Conventional Ropax Vessels

The conventional and the Podded ROPAX vessel have the same level of survivability for one-compartment damages. For two or more adjacent compartment damages the Podded ROPAX vessel demonstrates a higher level of survivability than the conventional vessel. This is reflected in the higher attained subdivision index and is in good agreement with SOLAS'90 static stability calculations. The most pronounced difference in survivability between the two vessels is for forward damages in zones 11-14 (compartment 10-13 between the frame numbers 129 and 177), where the survivability level of the conventional ROPAX is considerable lower than the Podded ROPAX version. The major difference between the two vessels in this region is the tank arrangement. The larger tanks in the conventional vessel cause more severe non-symmetrical damages.

5. SURVIVABILITY ASESMENT

In order to avoid a repeat of the *Estonia* disaster, following considerable deliberations and debate, a new requirement for damage stability has been agreed among North West European Nations to account for the risk of accumulation of water on the Ro-Ro deck. This new requirement, known as the *Stockholm Agreement* [6,7], ameliorates the original proposals by demanding that a vessel satisfies SOLAS '90 requirements (allowing only for minor relaxation) with, in addition, water on deck by considering a constant height rather than a constant amount of water as was originally intended. However, in view of the uncertainties in the current state of knowledge concerning the ability of a vessel to survive damage in a given sea state, an alternative route has also been allowed which provides a non-prescriptive way of ensuring compliance, through the "Equivalence" route, by performing model experiments in accordance with the Model Test Method of SOLAS '95 Resolution 14, [5]. Based on the same

principal, SSRC developed numerical equivalence route, which was applied over 80 vessels to achieve survivability and cost effectiveness [8].

5.1 Numerical Simulations

The conventional and the Podded ROPAX vessels have both been modelled with different side damages and run in various sea-states in beam seas. Random sea states are created using standard Jonswap spectra with a gamma value of 3. During the experiments the significant wave heights are changed until the boundary where the ship survives systematically is found. All the numerical simulations are carried out for the design KGs corresponding to GM of 3.0m.

Tables 4 and 5 clearly demonstrate that based on the numerical simulations to find the limiting significant wave height, both vessel performs well for standard damage cases and for the majority of the non-standard damages. Both vessels can survive large waves even for three compartment damages or two compartment+ inner hold damages. This is again the clear indication of how by good design very high survivability standards can be achieved.

Table 4: Summary of numerical simulation calculations for Conventional ROPAX

Conv. Damage Case	Compartments			Limit Hs
	two	three	Inner Hold	
DD06	√			5.00
DD06L	√		√	3.75
DD09	√			4.75
DD09L	√		√	3.00
TD0405		√		4.50
TD0405L		√	√	1.25
TD0506		√		4.00
TD0506L		√	√	1.50
TD0910		√		3.25
TD0910L		√	√	0

When two vessels are compared, the advantages of Podded Ropax become clear

when large scale flooding is taking place. The Podded vessel, in general can survive much higher sea-states compared to the conventional vessel. It should be mentioned that model tests, as part of the project, was carried out to validate the numerical results.

Table 5 : Summary of numerical simulation calculations for Conventional ROPAX

Podded	Compartments		Inner Hold	Limit Hs
	two	three		
DD06	√			5.00
DD06L	√		√	3.75
DD07	√			4.50
DD07L	√		√	4.00
DD10	√			5.25
DD10L	√		√	4.00
TD0102		√		5.00
TD0102L		√	√	0
TD0607		√		3.75
TD0607L		√	√	2.25
TD1112		√		5.00
TD1112L		√	√	2.00

6. COMPARISON BETWEEN DIFFERENT STABILITY STANDARDS

6.1 Deterministic Standards Vs Probabilistic Standards

For the design GM of 3m the conventional ROPAX vessel complies with the A.265 by a large margin. Further calculations demonstrate that the GM can be reduced to a minimum of 1.7m to comply with the required subdivision index. This gives GM of 1.3 m margin. However, the deterministic part of A.265, regulation 5, limits the GM to 2.224-2.568m, depending on the loading condition. According to Solas'90 standards, limiting KG calculations provide only 0.8 m GM margin.

For design GM of 3m, the Podded ROPAX vessel complies with the A.265 by a large margin. Further calculations demonstrate that the GM can be reduced to a minimum of 1.2m to comply with the required subdivision index.

This gives GM of 1.8 m margin. However, the deterministic part of A.265, regulation 5 limits the GM to 2.364-2.510m, depending on the loading condition. According to Solas'90 standards, limiting KG calculations podded vessel has only 0.9 m of GM margin. This demonstrates that without the deterministic part of A265 standards, SOLAS'90 and A265 do not provide equivalent standards, as SOLAS'90 require much higher standards.

6.2 Stockholm Water On Deck Calculations Vs. Numerical Simulations/Model Tests

It should be emphasised that this vessel, was designed according to Stockholm water on deck calculations by taking the advantage of influence of freeboard on the height of water on Ro-Ro deck. This is reflected in the results as both ships, for two compartment standard water on deck calculations, comply with 4 m wave height by big GM margin (0.6-0.8) m. Similarly numerical simulations indicate that for the design GM ship survives above 5 m significant wave height for the same damage. Stockholm water on deck calculations and Numerical simulations provide similar results for conventional Ropax for both 2 and 3 compartment damages.

For Podded Ropax, however, numerical simulations indicate that a different damage location is more dangerous than the one that indicated by the water on deck calculations (DD07 rather than DD10).

However, big difference between the Stockholm Water on deck calculations and numerical simulations can be observed for Podded Ropax, when 3 compartment damages are considered. Numerical simulations indicate good survivability standards for all three compartment damages (Table 5) while Ropax vessel fails to comply with *Stockholm 4.0 m standards* by big margin as limiting KG is required to decrease by 0.6 m below the actual loading condition. For the Limiting Damage case according to Stockholm water on deck standards (DD1112) Numerical simulations demonstrate survival above 5.0 m significant wave height.

This clearly demonstrates the fundamental



differences between Stockholm water on Deck Calculations and equivalent survivability tests in waves for new vessels as well. This was already proven for the existing Ropax vessels[8].

7. CONCLUSIONS

Following the detailed studies of two same vessels with different internal arrangements and propulsion systems provided following concluding remarks that can be used towards achieving better designs and equivalent standards.

- Modern Ropax designs can achieve very high stability and survivability standards without economical penalties.
- The results indicate that the Podded Ropax vessel illustrates better stability and survivability performance characteristics than the Conventional Ropax vessel. This clearly demonstrates that designs can be improved by proper optimisation of internal arrangements and use of technological developments such as podded propulsion systems
- The study also indicates that equivalent stability standards yield to different limiting stability parameters. This clearly indicates that this can be eliminated by performance-based assessment.

8. ACKNOWLEDGMENT

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