Conduction of a wind tunnel experiment to investigate the ship stability weather criterion

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ABSTRACT

A wind tunnel experiment has been set up to examine several assumptions regarding the weather criterion of the intact stability code. The experimental trials are conducted in the Low-Speed Wind Tunnel of the Aeronautics Laboratory at the Universiti Teknologi Malaysia. Two models are tested. The first model is an academic model that allows comparisons to be made with analytical models. The second model is the DTMB 5415 to present a military realistic case. The models are properly weighted to present the correct hydrostatic characteristics. A water tank is installed in the wind tunnel test section; the models are free to roll around the longitudinal axis passing through the buoyancy centre owing to a frictionless rod. The experimental results are then compared with the results of the stability code using the IMO weather criterion and the military criteria. Finally, in the experimental trials, many configurations are tested to assess the effects of various geometrical parameters.

Keywords: *Second generation intact stability criteria, wind tunnel, roll angle*

1. INTRODUCTION

Intact stability is a basic requirement to minimise the capsize risk for vessels. It is a guideline for the ship designer, the ship operator and the classification society to design, build and commission the ship before it starts its service life at sea. A comprehensive background study of intact stability development was written by Kuo & Welaya (Welaya & Kuo, 1981). Their paper "A review of intact stability research and criteria", stated that the first righting arm curve was proposed by Reed in 1868, but that the application was presented by Denny in 1887. In addition, in 1935, Pierrottet tried to rationally establish the forces which tend to capsize a ship and proposed a limiting angle at which the dynamic level of the ship must be equal to or greater than the sum of energy exerted by the inclining moments. However, Pierrottet's proposal was too restrictive for the design process and it was not accepted.

Kuo and Welaya also mentioned the famous doctoral thesis written by Jaakko Rahola in 1939. Rohola's thesis evoked widespread interest throughout the world at that time because it was the first comprehensive study and proposed method to evaluate intact stability which did not require complex calculations (Rohala, 1939).

The Sub-Committee on Stability and Load Lines and on Fishing Vessels Safety 48th Session (IMO, 2005) emphasized the requirement of revising the current IS Code. The importance of the comprehensive review of the current IS Code 2008 would significantly affect the design and ultimately enhance the safety of ships (Mata-Álvarez-Santullano & Souto-Iglesias, 2014) .

Intact Stability is a crucial criterion that concerns most naval architects at the design stage. The current Intact Stability (IS) Code 2008 is in force. Except for the weather criterion, the IS Code 2008 only applies to the hydrostatics of the ship. It does not cover the seakeeping behaviour of the ship and first and foremost, it always considers a ship with a negligible trim angle. In head seas, the ship can present a significant angle of trim which may affect the righting arm. Van Santen also presented an example of a vessel capsizing due to of the small angle of trim (Van Santen, 2009).

For the enhancement and improvement of intact stability criteria, the International Maritime Organisation (IMO) introduced the new generation intact stability criteria in 2008 (Francescutto, 2007). Figure 1 presents the procedure to apply to the second generation intact stability rule. Once the basic criteria have been satisfied, each failure mode is verified to satisfaction at the most conservative level.

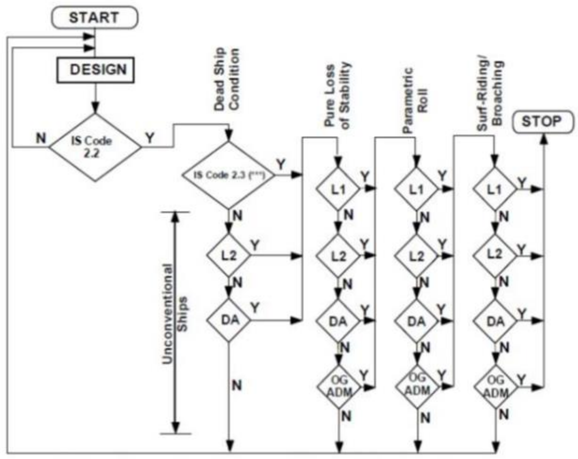


Figure 1: Structure of Second Generation Intact Stability Criteria

2. DEVELOPMENT OF SECOND GENERATION INTACT STABILITY CRITERIA

The last Sub-committee on Ship Design and Construction meeting at IMO recalled that SDC 2 had agreed, in principle, to the draft amendments of the 2008 IS Code regarding vulnerability criteria and the standards (levels 1 and 2) related to parametric roll, pure loss of stability and surf-riding /broaching (SDC 2/WP.4, annexes 1 to 3). For this purpose, SDC 2 had invited member governments and international organisations to bring the criteria to the attention of ship designers, shipyard operators, ship owners and other interested parties, and to observe and test the application of the finalised vulnerability criteria, in order to gain experience with regard to their use.

The draft amendment of the IS Code regarding vulnerability criteria and the standards (levels 1 and 2) related to dead ship condition and excessive acceleration are contained in SDC 3/INF.10 Annex 1 and 2. The level 1 check for dead ship condition is basically the same method used for current IS Code 2.3 which is weather criteria. If it failed, the design should process to level 2 check and the direct assessment. Direct assessment procedures for stability failure are intended to employ the most advanced state-of-the art technology available either by numerical analysis or experimental work for quantitative validation as stated in SDC 1/INF.8 Annex 27 (IMO, 2013).

3. THE WEATHER CRITERION

The IS Code 2008 Part A 2.3 contains the weather criterion. The ship must be able to withstand the combined effects of beam wind and rolling. The conditions are:

a. *the ship is subjected to a steady wind pressure acting perpendicular to the ship's centreline which results in a steadywind heeling lever (lw_1).*

b. *from the resultant angle of equilibrium (φ_0), the ship is assumed to present an angle of roll (φ_1) to windward due to wave action. The angle of heel under action of steady wind (φ_0) should not exceed 16˚or 80% of the angle of deck edge immersion, whichever is less.*

c. *the ship is then subjected to a gust wind pressure which results in a gust wind heeling lever (lw_2); and under these circumstances, area b shall be equal to or greater than area a, as indicated in Figure 2.*

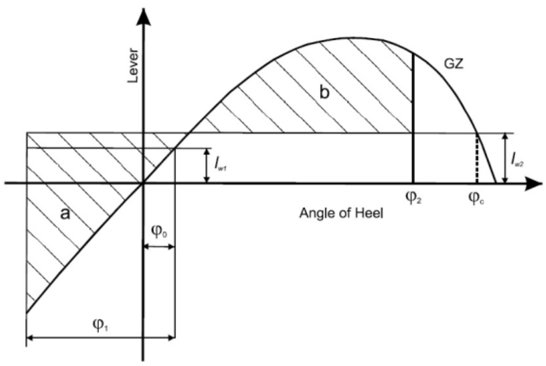


Figure 2: Severe wind and rolling

The heeling lever shall be calculated using formula:

$$l_{w1} = \frac{P*A*Z}{1000*g*\Delta} \quad (1)$$

$$l_{w2} = 1.5\, l_{w1} \quad (2)$$

where lw_1 = steady wind heeling angle, lw_2 = gust wind heeling lever, P = wind pressure of 504 Pa, A = projected lateral area (m^2), Z = vertical distance from the centre of A to the centreof the underwater lateral area or approximately to a point at one half of the mean draught (m), Δ =displacement (t) and g = gravitational acceleration). In Figure 1, a Direct Assessment (DA) can be used to verify the weather criterion for unconventional ships. The DA can be experimental. The present study shows how such an experimental DA can be conducted for two models, a civilian ship and a military ship.

In the weather criterion, two main rules are commonly used. For commercial ship, it uses the IMO weather criterion and for naval ship, it uses the Naval Rules. The IMO Weather criterion is shown in Figure 2 and the weather criterion for naval ship is shown in Figure 3. The significant different between IMO an Naval Rules are presented in the Table 1.

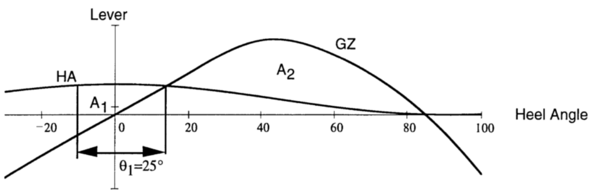


Figure 3: Weather Criteria for Naval Ships

Table 1 Comparison IMO and naval rules for weather criterion

Criterion	IMO	Naval Rules
Wind velocity	26 m/s	100 knots
Roll back angle	various*	25°
WHA	constant	$\cos^2\theta$
Ratio A2/A1	≥ 1	≥ 1.4
Gust	Yes	No

* roll back angle (phi_1) calculated based on IS Code 2008

WHA – wind heeling arm, A2 - restoring energy, A1 – capsizing energy

4. SHIP MODEL

Two models were used for the experimental work. The first model is an academic container ship geometry refered as "ASL shape" in the rest of the paper. The second model is a research ship model, the well know DTMB 5415 (Molgaard, 2000). The 5415 DTMB model is widely used for the research study in seakeeping (Begovic, Day, & Incecik, 2011; Jones & Clarke, 2010; Yoon et al., 2015). The basic geometry is presented in Table 2. The body plan and perspective view for "ASL shape" is shown in Figure 4. The body plan and perspective view for "5415 shape" is shown in Figure 5.

Table 2 Basic ship model geometry

Ship model	ASL shape	5415 shape
LOA, (m)	140	153.3
BOA, (m)	20	20.54
Draft, (m)	12	6.15
Displacement, (tonnes)	26,994	8,635
VCG, (m)	10	7.555
LCG, (m)	70.037	70.137
KM, (m)	10.206	9.493
GM, (m)	0.206	1.938

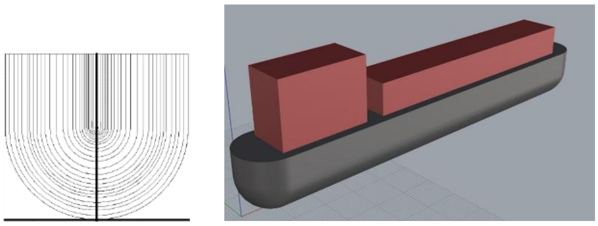


Figure 4: Body plan (left) and perspective view (right) of the ASL shape

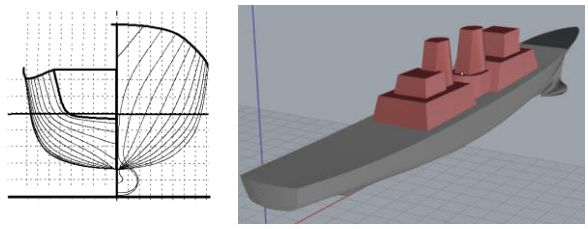


Figure 5: Body plan (left) and perspective view (right) of the 5415 shape

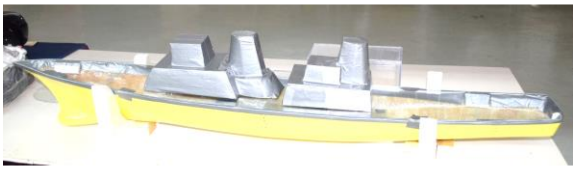
5. EXPERIMENTAL INVESTIGATION

A wind tunnel test was conducted at the low speed wind tunnel facility at Univerisiti Teknologi Malaysia. This wind tunnel has a test section of 2m (width) x 1.5m (height) x 5.8m (length). The maximum test velocity is 80m/s (160 knots). The wind tunnel has a flow uniformity of less than 0.15%, a temperature uniformity of less than 0.2˚C, a flow angularity uniformity of less than 0.15˚ and a turbulence level of less than 0.06% (Ariffin, Mansor, & Laurens, 2015).

Ship model

Two ship models were tested as described in Paragraph 4. Both models were constructed at ENSTA Bretagne, France using the Computer Numerical Control (CNC) machine. The material used was polystyrene. Both models were designed in 3D drawing and imported to CNC machine program for fabrication process. The hulls were divided into six parts for the cutting process. Then, all parts were glued and laminated with a fiberglass. The superstructure used the synthetic glass. The completed ship models are shown in Figure 6.

(a)



(b)

Figure 6: Complete build ship models (a) ASL shape (b) 5415 DTMB shape

Inlclining test

To determine the correct centre of gravity, inclining tests were performed. The inclining test is a procedure which involves moving a series of known weights, normally in transverse direction, and measuring the resulting change in the equilibrium heel angle of the ship. By using this information and applying basic naval architecture principles, the ships' vertical centre of gravity is determined from the GM. We also verified that the natural roll period is as expected. Two devices were used for the data recording, first is the Ardu Flyer device and smartphone (Djebli, Hamoudi, Imine, & Adjlout, 2016).

Wind tunnel setup

The models were allowed to heave and roll freely. It was not allowed to yaw because the model must be hold at the longitudinal axis to avoid the model bump to water tank side. The models were fixed with a rod both at bow and stern (Figure 7). It is passing through the point of longitudinal centre of buoyancy. Both rods at bow and stern were aligned using laser light to confirm the shafts positioned at same axis. The arrangement of rod used in this experiment is frictionless therefore, minimum interaction between the rod and rod stand can be obtained.

To allow the model to float in the wind tunnel, a water tank fabricated with glass of 8mm thickness was installed. Since the wind tunnel is not water tight, to avoid any leak of water during the experiment, a dummy pool was placed underneath the platform. The dummy pool is capable to cope the total volume of water if the glass water tank gets damaged. The arrangement in the test section is shown in Figure 8.

Figure 7: Rods fixed at ship models

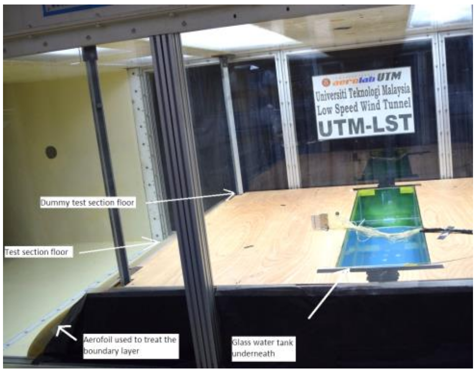


Figure 8: Arrangement in the test section.

The experiment started with the model placed in the water tank with the correct draft (Figure 9). A laser light is used to ensure the vessel is upright. The test started with measurement of the stable heel. The wind tunnel velocity was increased slowly while the heel angle was recorded using the Ardu Flyer device. The Ardu Flyer is a complete open source autopilot system designed for 3D robotics. This experiment involved three models configuration as stated below:

a. ASL shape.
b. 5415 shape.
c. ASL with bilge keel shape.

A roll back angle (φ_2*) measure was performed for all the models. The definitions of (φ_1) and (φ_2*) are shown in Figure 10. The test steps are as follow:

a. Model placed in water tank.
b. Wind applied and the wind velocity and heel angle recorded.
c. Roll back angle (φ_1) applied at the model.
d. Then model is suddenly released.
e. The maximum counter roll back angle (φ_2*) recorded.

(a)

(b)

Figure 9: Ship models ready to be tested in wind tunnel test section (a) ASL shape (b) 5415 DTMB shape

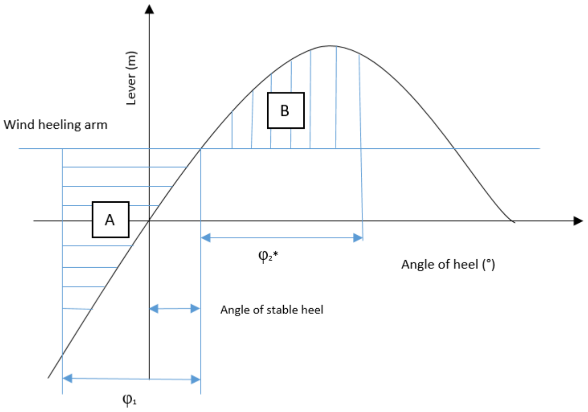


Figure 10: Definitions used in this experiment

Scaling criteria

The models used in the experiment were scale down to 1:100. It is the same scale used by (Begovic et al., 2011) for the ship motion experiment using DTMB 5415 model. For the GZ curve, the model and full scale ship has a same curve shape but values for the model are divided by 10^2. For weight calculation, values used for the model are divided by 10^6. For the wind velocity, the value used for the model is divided by 10.

Boundary layer

When the air flow over the ocean surface from any direction, a natural boundary layer is formed. This means that the wind velocity at the surface is zero and increase with higher altitude. The boundary layer thickness in the test section for this experiment is about 35mm and the velocity profile is shown in Figure 11.

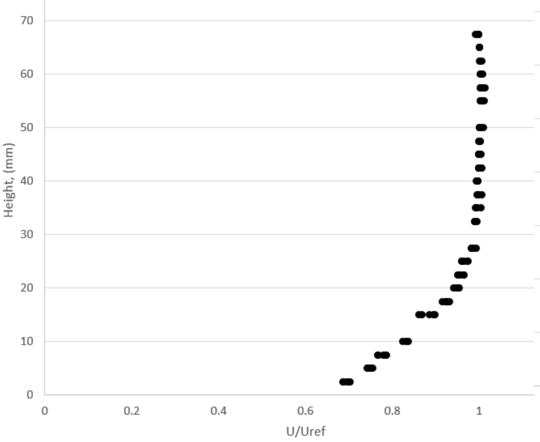


Figure 11: The velocity profile curve

To compute the weather criterion, the General Hydro Static software (GHS) was used. The GHS uses a strip method and it is widely used in the marine industry (Ariffin, Laurens, & Mansor, 2016). In GHS, there are 2 methods to specify the wind either by wind velocity or wind pressure. Specifying a wind velocity, V_{wind}, in GHS gives a standard velocity profile with V_{wind} at 10 metres from the ground (Yalla, 2001). When specifying a velocity pressure, a constant value is given. The calculation in this paper for GHS results were obtained using the wind pressure input.

6. RESULTS

Angle of stable heel (φ_0) vs wind velocity

Figure 12 shows the graph for angle of stable heel, φ_0 versus wind velocity for the two models and two methods; IMO and experimental. The 5415 curves are following a parabolic shape since as we can see in Figure 13, the GZ curve of 5415 shape follows a linear curve up to 30 degrees. Furthermore, the experimental curve is below the IMO curve which indicates that the drag coefficient C_D, of the ship silhouette is smaller than 1, the value assumed in the IMO formula (Figure 12). The ASL curves present different shapes and behaviour. At first, they do not present the parabolic shape because as we can see in Figure 13, the GZ curve is only linear up to 5 degrees. Furthermore, the experimental curve for this case is above the IMO curve (Figure 12). That is explained by the fact that the drag coefficient C_D, for the box shape of the ASL is bigger than 1. This can be confirmed by the many references that exist giving the drag coefficients of basic shapes, see for example (Scott, 2005).

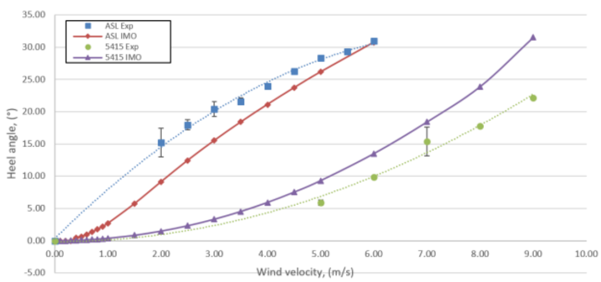


Figure 12: Graph of wind velocity and angle of stable heel for ASL shape and 5415 shape on the experimental results and GHS calculation

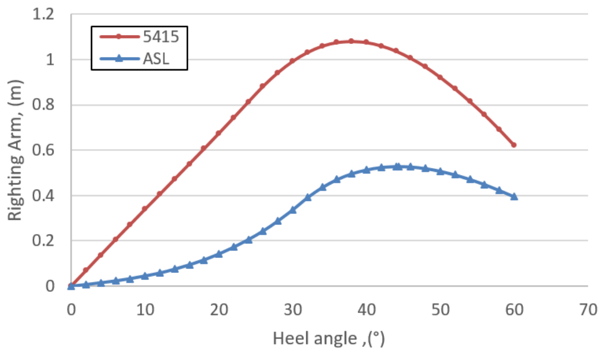


Figure 13: The GZ curves for ASL shape and 5415 shape

Roll back angle (φ_2) versus roll to windward (φ_1)*

Figure 14 shows the roll back angle (φ_2*) versus roll to windward (φ_1) for ASL shape for wind velocity range of 2 m/s to 4 m/s. Figure 15 shows the roll back angle (φ_2*) versus roll to windward (φ_1) for 5415 shape. In the absence of damping the results should be like a swing where φ_2* follows φ_1. The results suggest a far more complex behaviour where the hydrostatic force shape is playing an important role.

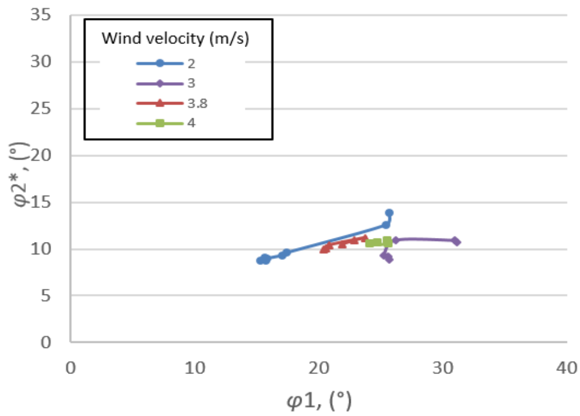


Figure 14: Roll back angle (φ2*) vs roll to windward (φ1) for ASL shape

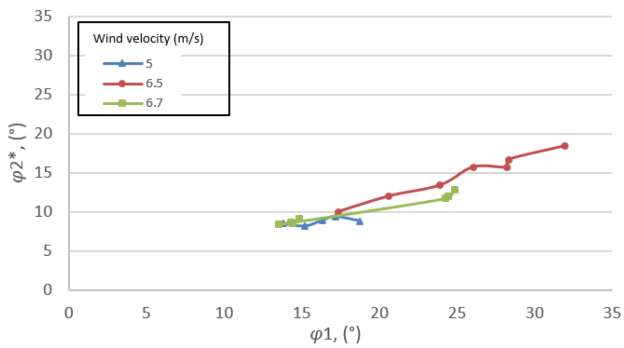


Figure 15: Roll back angle (φ2*) vs roll to windward (φ1) for 5415 shape.

Ratio φ_2 and φ_1 with bilge keel*

Figure 16 shows the ratio (φ_2^*/φ_1) for the ASL shape and the ASL with a bilge keel. Both models were tested at wind velocity 2m/s. For the bare ASL, the average ratio is 0.55 and for the ASL with bilge keel, the average ratio is 0.43. As expected, the configuration with bilge keel contributes to more roll damping than configuration without bilge keel.

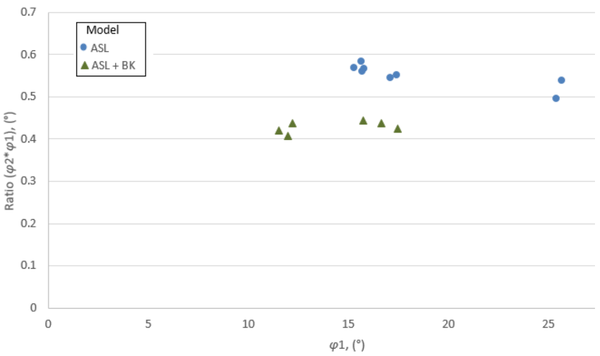


Figure 16: Roll back angle (φ2*) vs roll to windward (φ1) for ASL shape, 5415 shape and ASL with bilge keel configuration

Yaw angle effect on stable heel

Figure 17 shows the angle of stable heel for the ASL and the 5415 both with the wind direction from star board 75° and port 105°. For the ASL, the values of φ_0 are smaller for the beam wind than those obtained with the yaw angles. In other words the assumption of the beam wind in the IMO code is not necessarily conservative. This phenomenon also appears for the 5415.

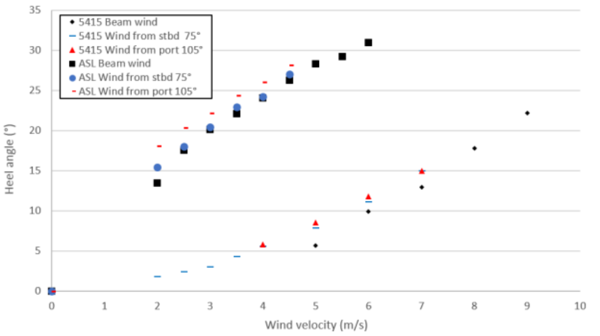


Figure 17: Angle of stable heel for wind from starboard 75° and port 105°

Effect of roll to windward (φ_1) and roll back angle (φ_2) with yaw angle*

Figure 18 shows the result for φ_1 and φ_2* for the ASL and the 5415 with beam wind and wind from starboard 75°. For the ASL, the beam wind has higher φ_2* than wind from starboard 75° and for the 5415, the beam wind has smaller φ_2* than wind from starboard 75°. The two models have a different response to the yaw angle. The behaviour is a combination of the superstructure geometry, the GZ curve and the damping.

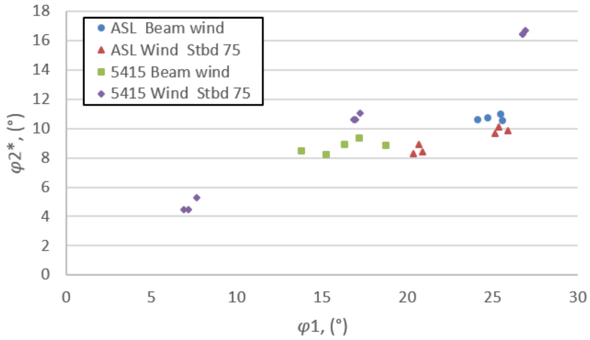


Figure 18: Roll back angle (φ2*) vs roll to windward (φ1) for 5415 shape with wind from port 105

Comparison IMO GHS and experimental result

Figure 19 shows the comparison results between IMO and experimental results. For the ASL, the counter roll back angle (φ_2*) obtained from experimental results is 24.07°, lower than IMO which is 29.638°. Therefore, IMO result is more conservative. For the 5415, the counter roll back angle (φ_2*) obtains from experimental results is 16.31°, lower than Naval Rules which is 33.82° for ratio capsizing and restoring energy 1.0 and 39.45° for ratio capsizing and restoring energy 1.4. Therefore, the IMO and Naval rules are always more conservative.

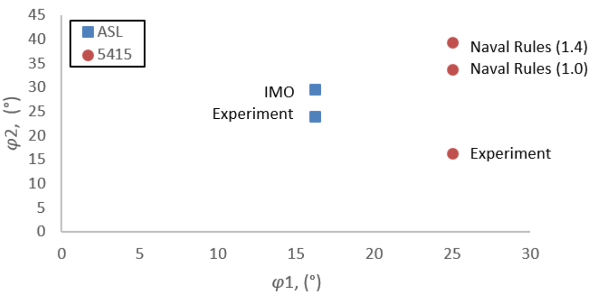


Figure 19: Comparison result for IMO rules and Naval Rules

7. CONCLUSION

In this paper the authors presented an experimental Direct Assessement (DA) of the weather criterion for two different models; a civilian ship with a simple geometry and a military ship, the well-known DTMB 5415. To conduct the experiments, the low speed wind tunnel of UTM was used. Both models were placed in a water tank in the wind tunnel. Both models were free to roll so the heel angle could be measured and compared with the IMO and Navy Rules.

Although the assumptions taken by the rules are not always conservative, the final results always show that the experimental values are lower than the values given by the rules.

8. ACKNOWLEDGEMENT

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