# DAMAGE STABILITY MODEL TESTS FOR NAVAL COMBATANTS

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**SUMMARY**

This paper addresses aspects of damage stability experiments for naval combatants. Since naval combatants are required to engage in combat and remain effective under harsh conditions, it necessary to investigate damage stability beyond the requirements typically defined for RO-RO ferries as specified in SOLAS requirements. This paper discusses test procedures conducted by NSWCCD for naval combatants.

## 1. INTRODUCTION

Naval combatants and commercial vessels face similar challenges when it comes to damage stability. They are subject to damage and flooding due to running aground, collisions, as well as structural breaches in extreme seas. However, combatants are exposed to the additional hazard of battle damage, which might occur at any point on the ship with hole sizes ranging from 2 cm to insurmountably large. The nature of warfare at sea implies that damage can be inflicted over a wide range of speeds, while maneuvering, in any seaway. Mission requirements can also require the injured warship to maneuver and transit despite damage.

U. S. Naval combatants have been subject to damage stability criteria based on calm water/wind heel relationships that were developed in the 1960's based on experience during World War II [1]. See Figure 1. Compliance with the criteria is based on the calculated equilibrium heel angle of the ship in calm water in terms of the floodable length of the ship. The specific size, shape, and location of the hole are not addressed. Flooding dynamics, as well as the dynamic behavior of the damaged ship in a seaway also are not addressed in the existing criteria.

Recent tragedies involving the flooding of commercial vessels, including the loss of the *Herald of Free Enterprise* in 1987, and the *Estonia* in 1994, have illustrated the need to account for flooding dynamics, and have encouraged the use of model tests to demonstrate compliance with IMO criteria [2]. Given the above considerations, it becomes prudent to address the role of model tests in the evaluation of naval combatants.

## 2. DAMAGE STABILITY TESTS

The loss of RO-RO ships have drawn attention to the use of model tests as a means to demonstrate suitable levels of survivability for ship designs [3]. This procedure makes the assumption that survival scenarios defined in the model experiment will guarantee an acceptable loss risk for the full-scale ship.

With respect to damage, a naval combatant is subject to a number of variables including:

1. Intact Load Condition
2. Compartmentation (Including status of damage control doors/fittings)
3. Heading
4. Speed
5. Maneuver
6. Damage Location
7. Size, Shape and Depth of Hole created by Damage
8. Wind
9. Seaway

The numerous parameters cited above could define a very large number of configurations that do not make it practical for exclusive use of model experiments to demonstrate acceptable survivability. Future evaluations of naval combatants will require the use of a combination of model experiments and numerical simulations, to properly model ship dynamics and flooding physics.

## 2.1 PHILOSOPHY

The extreme nature of warfare encourages innovative ship designs that might extend beyond the range of previous experience. This necessarily leads to advancing the state of the art in simulation tools to accommodate the new designs and the commensurate requirement to validate the amended simulation. The nature of investigating the unknown also implies that unanticipated physical behavior might occur. For these reasons, damage stability experiments should follow a philosophy such that experimental data is collected to:

1. Evaluate model performance of selected scenarios of interest
2. Allow the understanding of flooding physics in the model
3. Properly model ship dynamics
4. Collect sufficient data to validate numerical simulation tools

## 2.2 MODEL CONFIGURATION

Damage stability experiments at NSWCCD are conducted using a free running radio controlled model. The nominal size of a typical damaged model is 5 meters. This roughly defines the lower limit of length where the necessary equipment can be "stuffed" inside a model. An interesting challenge in model construction is the need to include compartmentation, running gear, instrumentation, and telemetry while limiting the overall size so as to remain within experimental capabilities for making waves. The first challenge is to define the location and extent of compartmentation to be flooded in the model. This can be defined using existing stability rules to define the most critical damage case. In the U. S. Navy, the compartmentation is selected with the worse case flooded condition as defined by DDS-079-1 [1] using the Ship Hull Characteristics Program (SHCP) [4]. The model compartmentation must be watertight to protect the propulsion motors and instrumentation in the non-flooding areas of the model, as well as to prevent undesired free-surface effects due to leakage. Permeabilities are achieved using blocks placed in the compartments representing major machinery. See Figure 2.

Instrumentation consists of data acquisition, command and control, video, and hull breaching mechanism. Six degrees of freedom ship motion responses are measured, to include roll angles up to 90 degrees in each direction of heel. The water levels in the flooded compartments are measured using a matrix of 15 custom-built capacitance probes dispersed throughout the compartments. The probes are housed in perforated aluminum tubes, which isolate each probe from the others in water and provide ventilation. Digital cameras are provided in each compartment to record the behavior of the water in each compartment during and following the flooding process. See the upper left quarter of Figure 3.

The mechanism to provide a hull breach on demand, while otherwise maintaining the integrity of the hull was challenging to design. The NSWCCD design utilizes a polycarbonate panel that slides vertically along tracks that are faired to the hull. The command switch controls a pneumatic valve that actuates a piston, which pulls cables attached to the panel. This configuration provides a fast opening of large holes to investigate transient flooding effects and a quick reset of the mechanism. See Figure 4.

## 2.3 SCALING

Froude scaling is followed in damaged stability tests due to the influence of gravity on the dynamics. The modeling of ship flooding is also best performed using orifice flow that follows Froude scaling. Since sharp-edged orifice flow theory is used in simulation programs to estimate water ingress, "knife-edges" are cut along the outer edges of the holes representing damage on the model. This provides for the separation of the water boundary and the orifice, minimizing the viscosity effects at the hole, keeping the scaling effects in the Froude realm.

Air entrapment can occur in a flooded compartment introducing scaling effects that can lead to a lower air-water interface level in the model than in the full scale ship when the damaged hole is submerged. This is because the pressure head trying to push water into the compartment is less at the hole depth for the model than it would be for the ship at full scale. This would result in less water in the flooded compartment of the model than for the ship. The air compression scalability issue is avoided by providing adequate ventilation of all flooded spaces during flooding, via the capacitance probe tubes. This is appropriate from the standpoint that upflooding and downflooding is permitted to occur between decks below the damage control deck. Ventilation topside is also considered to be plentiful too.

## 2.4 EXPERIMENT

It is useful to define the environmental variables in which a ship could become damaged. Wind, current, and waves are the obvious forces roaming the seas. Currents can be strong in some locals, but it is the waves and wind that can have the most critical effect on ship stability. Until recently, damage stability experiments have been performed with captured model arrangements, or non-powered models - in waves and in calm water. Wind and current forces have not yet been integrated with such tests.

At NSWCCD, damage stability tests are performed using radio-controlled models to investigate the effects of transient flooding and flooded equilibrium conditions. Free running radio-controlled models are employed to eliminate cables running between the model and an external platform. This is to minimize any external effect on the capsizing mechanism. Transient flooding is investigated at both zero speed and underway conditions. While at zero speed, transient flooding experiments are performed in benign, flat seas and regular waves. Underway, the transient flooding experiments are performed in calm seas, at several speeds at a constant heading and on opportunity, a maneuvering condition. Each model is also subjected to flooded equilibrium tests in large sea states, as displayed in Table 1.

Model experiments are conducted for several hole sizes corresponding to the specific interests of the investigation. It is useful to investigate hull breaches at the surface, as well as below the waterline.

At least one hole in the test matrix is sized to address the maximum dimensions allowed by the relevant stability criteria. In tests at zero speed, the model is permitted to drift in the seaway, initially at beam seas heading to examine the drifting behavior of the model in the seaway. It is important to note the heading at which the model drifts for validation in simulations because this can impact the accuracy of survivability predictions.

## 3. CONCLUSIONS

This paper discusses damage stability experiments for naval combatant ships. The requirements for warships extend beyond the scope of typical experiments as defined in SOLAS for RO-RO ships, because combatants are exposed to the hazards of warfare.

As in most investigations, answers provided by model experiments often lead to more questions. As such, it would valuable to conduct further experiments of damage stability. In particular, given that naval combatants may likely be required to continue maneuvering while in a battle condition, it would be advantageous to investigate the effects of maneuvering on the stability of a damaged model. Wind also has a significant effect on stability and is most often accompanying (driving) the large sea states. It, too, would be a beneficial ingredient in future damage stability model tests.

It would also be useful in future experiments to investigate the effects of a hull breach that occurred completely below the water surface and to compare the differences between a rectangular shape hole, which aids in simulation comparisons, and an irregular, perhaps, jagged hole.

## 4. REFERENCES

[1] Naval Ship Engineering Center, “Design Data Sheet- Stability and Buoyancy of U. S. Naval Surface Ships”, DDS 079-1, Naval Sea Systems Command, Washington DC Aug 1975.

[2] 1995 *SOLAS* Conference, “Appendix to Annex 5, Resolution 14”, *SOLAS 1997 Consolidated Edition.* 1997.

[3] J.O. de Kat, M. Kanerva, R. van 't Veer and I. Mikkonen, "Damage Survivability of a New Ro-Ro Ferry", *Proceedings of the 7th International Conference on Stability for Ships and Ocean Vehicles, STAB 2000,* Launceston, Tasmania, Feb. 2000.

[4] Naval Sea Systems Command, “Ship Hull Characteristics Program-SHCP,” *Users Manual*, CASDAC No. 231072, Dept. of the Navy, Washington DC.

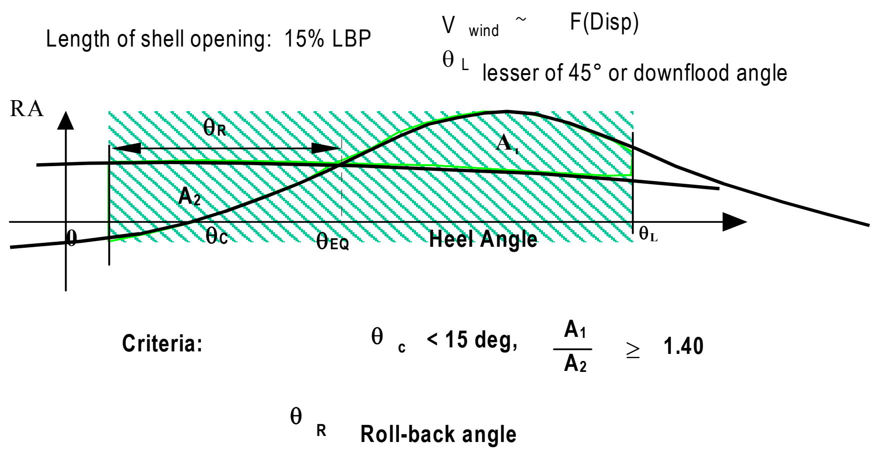


Figure 1 - U. S. Navy Damage Stability Criteria.

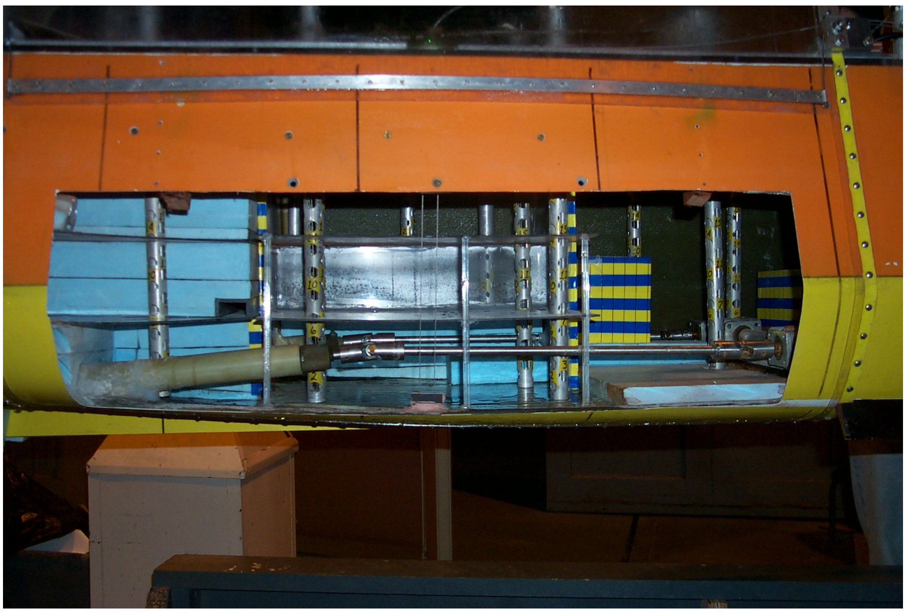

Figure 2 - Starboard view of model showing damaged section. The forward compartment is to the right, the center compartment directly ahead and the aft compartment is to the left. Blue and yellow stripes mark the elevation of compromised lateral bulkheads and blocks.

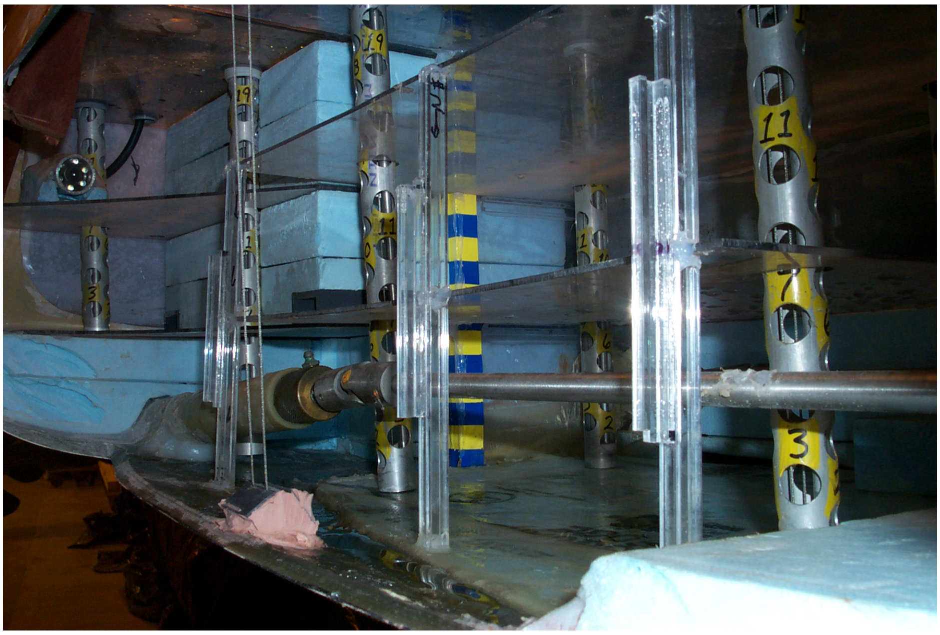

Figure 3 - Looking aft into the center and aft compartments.  A camera is located in the upper left corner.  The cross-flooding ducts, located in the aft compartment can be seen at the forward and aft ends of the foam block on the second level.

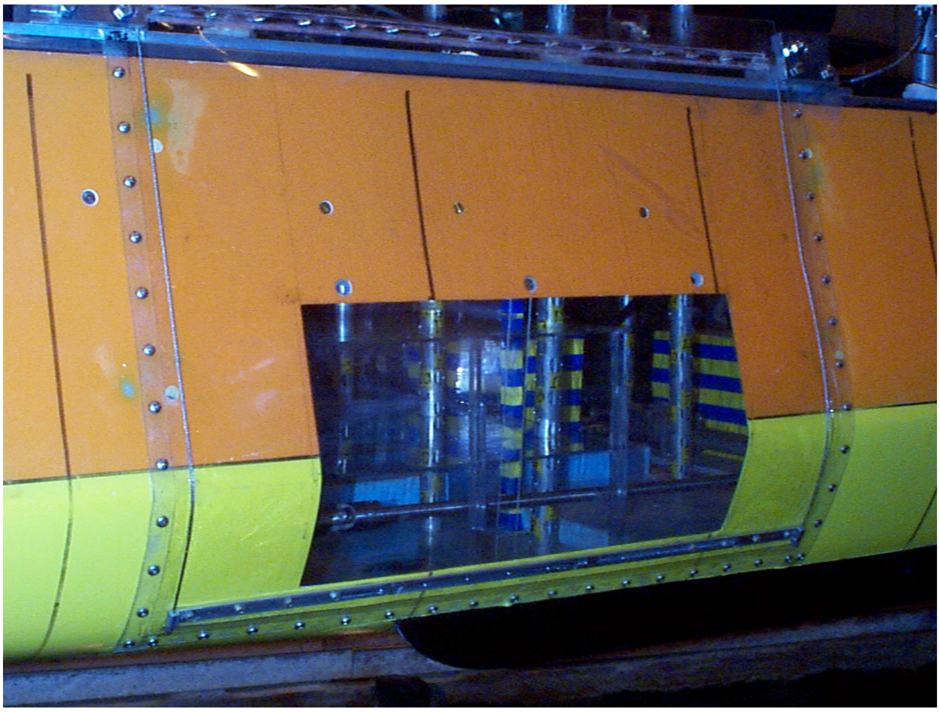

Figure 4 - View of breach mechanism panel

Table 1 – Model Test Matrix

<table>
<tr><td colspan="10">Transient Flooding</td></tr>
<tr><td colspan="3">Calm Water</td><td rowspan="8"></td><td colspan="6">Regular Waves λ / L = 1.5</td></tr>
<tr><td>Speed (Fn)</td><td>Hole A</td><td>Hole B</td><td>H/ λ</td><td>Hs (m)</td><td>To (sec)</td><td>Intact</td><td>Flooded Hole A</td><td>Flooded Hole B</td></tr>
<tr><td>0.00</td><td>X</td><td>X</td><td>1/50</td><td>4.3</td><td>11.7</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>0.10</td><td>X</td><td>X</td><td>1/20</td><td>10.6</td><td>11.7</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>0.20</td><td>X</td><td>X</td><td>1/15</td><td>14.2</td><td>11.7</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>0.30</td><td>X</td><td>X</td><td>1/10</td><td>19.5</td><td>11.7</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>High Speed Turn</td><td>X</td><td>X</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

<table>
<tr><td colspan="8">Flooded Equilibrium – Zero Speed</td></tr>
<tr><td rowspan="4">Sea State</td><td rowspan="4">Intact Hull</td><td colspan="6">Flooded</td></tr>
<tr><td colspan="2" rowspan="2">Sealed Hole</td><td colspan="4">Open Hole</td></tr>
<tr><td colspan="2">Hole A</td><td colspan="2">Hole B</td></tr>
<tr><td>Waveward</td><td>Lee</td><td>Waveward</td><td>Lee</td><td>Waveward</td><td>Lee</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td>6</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>7</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Camille</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
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