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**Investigations into the Stability of an Intact
and Damaged Jack-Up during a Wet Tow
Part 1: The Model Test Programme**

by

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ABSTRACT

This paper describes a model test investigation into the stability of a large jack-up during a wet tow in severe North Sea wind and waves. It describes the purpose of the tests, and the test programme itself, but does not include results or conclusions, which will be presented in a follow-up paper. The aim of the tests was to establish the limiting value of KG at which capsizing occurred, to compare the area ratio, stability range and intercept angle in this condition with values predicted by a conventional stability analysis, and thus assess whether the stability criteria provide a satisfactory measure of the unit's ability to resist capsizing. Tests were performed on the model in the intact condition, after major waterline damage in corner and side compartments, and after internal flooding.

1. BACKGROUND

In 1994 BMT Fluid Mechanics undertook a review [1, 2] for the Health and Safety Executive (HSE) to investigate losses of jack-ups during wet tows, and the availability of relevant model test data. This review showed that most past casualties have been associated with long exposure to a severe storm, damage to items on deck such as vent pipes, hatch covers and deckhouses, and gradual flooding of several compartments. The review found little systematic model test data available, however, to shed light on the seakeeping behaviour and stability of either damaged or intact jack-ups.

The present model test programme was undertaken to investigate the physical processes involved in the capsizing of both an intact and damaged jack-up, and to address the lack of available data on seakeeping behaviour during a wet tow. The purpose of these tests was to find out whether existing stability criteria are adequate, but not to come up with alternative new criteria. The two key objectives were stated to be:

- to provide an informed view on the robustness and reliability of damage stability survivability standards contained in the HSE's Fourth Edition Guidance [3];
- to investigate the margin of stability provided by the existing Guidance, and to provide a better understanding of the factors associated with loss of stability and capsizing of damaged jack-ups during wet tows in severe sea conditions.

The tests were performed in the Offshore Wave Basin at the Danish Hydraulic Institute (DHI), Hørsholm, Denmark. The stability analysis, model tests, data analysis and subsequent interpretation were undertaken by a 'BMT User Group', consisting of BMT itself, Marine Structure Consultants (MSC) bv, and the University of Glasgow. The project received financial support from the European Union programme for the Training and Mobility of Researchers - Access to Large Scale Facilities - and was also supported by the UK Health and Safety Executive.

2. GENERAL APPROACH

2.1. Intact and Damaged Stability Criteria

The Health and Safety Executive Guidance Notes [3] specifies certain stability criteria that a jack-up unit should satisfy whilst undergoing a wet tow. The Guidance Notes are no longer mandatory, but the HSE wish to ensure that the Guidance continues to represent good industry practice. Previous investigations [1, 2] had suggested that existing damaged stability criteria might be deficient in some respects.

In common with other regulatory authorities, the HSE specifies stability criteria which should be satisfied while the structure remains intact and watertight, and less stringent criteria which have to be satisfied after damage or flooding. The requirements relating to damage are further subdivided into criteria for peripheral damage around the waterline, primarily associated with collision damage, and criteria relating to flooding of a single internal compartment. The criteria are quasi-static in character, and are based on characteristics of the steady wind heeling moment and static righting moment curves, expressed as functions of the heel angle about a ‘most critical’ axis.

Figure 1 shows typical heeling and righting moment arm curves, together with parameters considered during a conventional intact stability analysis. The HSE’s intact stability criteria for a jack-up unit may be summarised as follows:

- a) The ratio of areas, AR , under the heeling and righting moment curves has to satisfy the criterion:

$$AR = \frac{A + B}{B + C} \geq 1.4$$

where the areas A , B and C are integrated up to an angle q_R , which is either the second intercept angle, q_2 , or minimum downflooding angle, q_D , whichever is the smaller.

- b) The second intercept angle, q_2 , must be not less than 30° in the severe storm condition, and not less than 20° (neglecting wind heel) during a location move.
- c) The static heel angle, q_1 , must be no greater than 15° .
- d) The metacentric height, GM , must be not less than 0.5m.
- e) The righting arm parameter, GZ , must satisfy the relationship: $GZ \geq 0.5 GM_0 \sin q$ over the range $0 \leq q \leq$ (the minimum of q_D or q_M or 15°), where q_M is the angle of maximum righting lever, and GM_0 is the minimum permissible value of GM specified above.

After the unit has suffered a specified level of damage to a peripheral compartment, or flooding of any one internal compartment, it has to satisfy the following damaged stability criteria:

- a) The ratio of areas under the heeling and righting moment curves has to satisfy the criterion:

$$AR = \frac{A + B}{B + C} \geq 1.0$$

where the areas A , B and C are now integrated from the static angle of heel after damage (without wind) up to an angle q_R , which is either the second intercept angle, q_2 , or minimum

downflooding angle, q_D , whichever is the smaller. The downflooding angle for the damaged condition has to allow for 4m clearance above the wave surface.

- b) The static heel angle after damage, but without wind, q_1 , must be no greater than 15° .

The damaged criteria are therefore based on a minimum value of the area ratio and a maximum static heel angle only, whereas the intact criteria also specify a minimum value of the second intercept angle, and minimum values of GM and GZ .

2.2. Model Testing Philosophy

Tests were performed first on the intact model, and then after damage to a peripheral compartment, or after flooding of a large internal compartment. The underlying approach adopted during these tests was as follows:

- i) The height of the centre of gravity above the keel level, KG , was first set to the maximum limiting value, calculated according to standard HSE intact stability criteria, with a 30-degree second intercept angle.
- ii) The internal compartmentation was designed so that subsequent damage to a single large side or corner compartment, or flooding of the main internal compartment, would bring the model close to the limiting stability condition, $AR = 1.0$, specified by the damaged stability criteria.

The model's internal compartments were much larger than those of the original jack-up, and the level of damage and flooding represented on the model would represent extremely severe multiple-compartment damage and loss of buoyancy on the actual unit. The compartmentation of the model was chosen to provide near-capsize conditions, and near limiting conditions for compliance with the stability criteria. The fact that the model sometimes capsized should not, therefore, be surprising. The test programme was designed to find out exactly when and how this occurred.

The model was designed to avoid downflooding in both the intact and damaged conditions. The stability range, SR , was therefore simply the difference between the second and first intercept angles: $SR = q_2 - q_1$. Hydrostatics calculations showed that requirements based on the maximum value of the static heel angle, and minimum values of the metacentric height, GM , and righting arm, GZ , were easily satisfied. These parameters were therefore considered no further.

The stability parameters of primary interest in this investigation were therefore the area ratio, AR , the stability range, SR , and the second intercept angle, q_2 . These parameters are illustrated in Figure 2 for a unit in the damaged condition. The cases of interest were considered likely to lie between two righting moment curves: the first corresponding to $AR = 1.0$, and the second to $SR = 0.0$. $AR = 1.0$ is the minimum value specified by the HSE in the damaged condition. If the damaged criteria are valid, the model should be stable in this condition. The model will be statically unstable, however, at $SR = 0.0$. The stability boundary should therefore lie somewhere between these two conditions. This range of righting moment curves is illustrated in Figure 3.

The test programme therefore sought to answer the following questions:

- Is the model dynamically stable when AR is equal to 1.0 ?
- If so, how far can AR be reduced towards the $SR = 0.0$ condition before the model capsizes ?
- If the model is dynamically unstable when $AR = 1.0$, how far should AR be increased in order to make it stable ?

The tests were therefore based on the following principles:

- a) The model was set up initially with KG equal to the maximum permissible under HSE's requirements for the intact condition. The intact model was then tested in wind and waves.
- b) The model was then damaged, either by opening a compartment or setting the tank contents and weight, to obtain the predicted area ratio $AR = 1.0$. The damaged model was then tested in wind and waves.
- c) If the model remained upright for the entire test duration, its centre of gravity was raised, thereby reducing AR . The model was again tested in wind and waves. If the model was still found to be stable, this process was repeated until it capsized.
- d) If the model capsized in the $AR = 1.0$ condition, however, the centre of gravity was lowered, increasing AR , and the test in wind and waves was repeated. If the model was still unstable, this process was repeated until it remained upright.

These tests do not necessarily define a precise stability boundary, but were considered to be sufficient to show whether there are significant deficiencies in the existing stability criteria based on a minimum value of the area ratio, $AR = 1$, and whether the actual stability boundary lay close to, or well away from, this point.

3. THE MODEL TEST PROGRAMME

A test matrix was agreed, based on the procedure described in the previous Section, and on initial stability calculations carried out by MSC. The investigation was based on the following initial intact model conditions:

- **Intact condition I1**, based on a 30-degree minimum value of the second intercept angle, as specified by the HSE for a tow in severe storm conditions;
- **Intact condition I2**, based on a lower, 20-degree minimum value of the second intercept angle.

Four damage conditions were selected initially, as illustrated in Figure 4. The first three damage conditions, A1, B1 and C1, represented peripheral damage to outer compartments:

- **Condition A1** represented damage to a large side compartment;
- **Condition B1** represented damage to corner compartments surrounding a leg well;
- **Condition C1** represented asymmetric damage to both side and corner compartments.

Flooding of any one of these compartments, after the model had been set up in the intact I1 condition, resulted in a damaged area ratio $AR = 1.0$. In order to comply with the stability criteria, these compartments were allowed to free flood, by removing plugs from the top and bottom of each compartment.

Condition D1 represented flooding of an internal compartment with no direct access to the sea. In this condition the large central compartment was filled to $\frac{2}{3}$ of its capacity before the test, and the amount of water in that compartment remained constant throughout the test. **Condition D3** represented the central compartment pressed full.

Some of the tests in the damaged condition were repeated with a different topsides orientation. These additional damage cases were described as conditions A2 and D2.

3.1. Environmental Conditions

It was agreed that the tests should be based on steady wind speeds defined in the HSE's Guidance Notes [3]: 70 knots for a location move in the intact condition, and 50 knots in the damaged condition.

Representative North Sea wave conditions then had to be selected, which were compatible with these mean wind speeds. A 50-knot hourly mean wind speed has a return period of about one year in the central North Sea area, and a sea state with 9m significant wave height has a similar return period. The main programme of damaged model tests therefore took place in a 50-knot steady wind and 9m significant sea state, which were assumed to occur simultaneously.

The intact unit was tested in a more severe sea state associated with a 70-knot mean wind speed. A 70-knot hourly mean wind speed has a return period longer than 100 years in the central North Sea, and would be a very extreme event in that area. There is some doubt, however, whether the wind speeds specified in the stability criteria are intended to represent hourly mean values or gust speeds. A 12m sea state has a return period of less than 100 years in the central North Sea, but seemed to be a reasonable upper limit for testing. The *West Gamma* was reported to have been lost in 12m sea conditions [1], although there is some doubt about the reliability and interpretation of this value.

These wind and wave conditions would represent a very extreme event during a location move in the central North Sea area, and would only occur if there had been a major failure in weather forecasting, and if the unit were unable to reach shelter before the storm developed to its full extent. They would not represent particularly unusual storm conditions, however, for an open ocean tow (e.g. West of Shetland).

The above 70-knot and 50-knot wind speeds were assumed to remain steady for the entire duration of the test. It was not considered practical to model wind gusting. Any dynamic behaviour of the model therefore came from its response to waves only.

The following environmental conditions were therefore represented in the model tests:

a) *with the model intact:*

steady wind speed 70 knots, wave height $H_s = 12\text{m}$,
steady wind speed 50 knots, wave height $H_s = 9\text{m}$ (one test only).

b) *with the model damaged:*

steady wind speed 50 knots, wave height $H_s = 9\text{m}$.

A small number of tests on the A1-damaged model were performed in a range of sea states. These tests were intended to represent a developing sea state during a storm, with the wind speed remaining at 50 knots throughout. The centre of gravity was set at its original location for the intact I1 condition, the model was then damaged, and the significant wave height was increased in steps of 1m until capsizing occurred.

The wind and waves were assumed to be co-linear throughout. The majority of the sea states were modelled as long-crested (uni-directional) waves, although a few short-crested (multi-directional) wave conditions were also run for comparison.

The wind and wave directions were chosen to be consistent with the most critical axes determined from the stability analysis. It was not clear whether capsizing would be more likely with the damaged compartment on the windward or leeward side of the unit. Traditional static arguments suggested that damage on the leeward side should be more critical. Earlier model tests in the intact condition, however, suggested that the model might show a tendency to heel to windward, because of the effects of green water on deck. Tests were therefore performed with the damaged compartment on both the windward and leeward sides.

3.1.1. Wave Modelling

The tests were all performed in irregular random waves for a period of 3 hours full-scale (23 minutes model scale), unless the model capsized, whereupon the test was halted. This test duration was considered sufficient to provide a good definition of the spectra, response amplitude operators and motion statistics. There was no other obvious reason, however, for selecting this particular test duration, because it was not obvious which conditions were likely to cause a capsize, or how long it would be necessary to have to wait in order to find them. It nonetheless became apparent during the tests that the model tended to capsize in one of about three groups of high waves.

All sea states were represented using a mean JONSWAP wave spectrum, described by the formula:

$$S(f) = \mathbf{a} H_s^2 T_p \left(\frac{f}{f_p}\right)^{-5} \exp\left[-1.25\left(\frac{f}{f_p}\right)^{-4}\right] \mathbf{g}^e$$

where f is the wave frequency, H_s is the significant wave height, T_p is the peak spectral period, $f_p = 1/T_p$, \mathbf{g} is the JONSWAP peakedness parameter. The constant \mathbf{a} was calculated numerically so as to provide the correct value of H_s , and the peakedness parameter was set equal to the mean JONSWAP value, $\mathbf{g} = 3.3$. The other parameters are:

$$\mathbf{e} = \exp\left\{-0.5 \left[\frac{f - f_p}{\mathbf{s} f_p}\right]^2\right\}$$

and:

$$\mathbf{s} = 0.07 \text{ for } f \leq f_p$$

$$\mathbf{s} = 0.09 \text{ for } f > f_p$$

The associated wave periods were chosen to make the significant wave steepness, $S = 2\mathbf{p}H_s / gT_z^2$, approximately equal to 1/15. This value of S represents a fairly steep storm wave condition, and capsize was considered to be more likely in steep and breaking waves. Particulars of the wave spectra represented in these tests are summarised in Table 1.

Short-crested versions of these sea states were represented using a $\cos^{2s} \mathbf{f} / 2$ spreading function, where \mathbf{f} is the wave direction, and s is the peakedness of the spreading function. A peakedness value $s = 15$ was used, based on representative measurements in the North Sea.

3.1.2. Wind Modelling

After considering alternatives (e.g. the use of wind fans, or weights on lines), it was agreed that the most reliable method was to simulate the effect of the wind moment by shifting the centre of gravity of the model horizontally. This approach avoided difficulties with lines wrapping around the model during a capsize, and minimised the force to be resisted by mooring lines. The main advantage of this method over wind fans was that the applied wind moment was known precisely. It was acknowledged that the model would respond dynamically in a slightly different way about its new centre of gravity, but this effect was considered to be minimal.

3.2. The Model and Instrumentation

The experiments were based on a 1:60 scale model of a large jack-up unit. The model design was based on that of an actual unit, but the topsides and details of the spud cans and leg wells were simplified in

order to make the hydrostatics analysis and model construction easier. The leg wells and peripheral compartments were also free flooding, but no effort was made to model the flooding/drainage rate. The model was constructed from PVC. Froude's scaling laws were used and the weight of the model was corrected for the difference in density between salt and fresh water. The main particulars of the full-scale unit are given in Table 2, and Figure 5 shows the model being prepared for testing.

It was crucial that the mass properties of the model should be known precisely, especially its weight and centre of gravity position. The weights of individual components (e.g. legs, hull and accommodation) were therefore checked when the model was finished and these agreed well with predicted values. The target displacement mass of the complete model was 112.9 kg. When the model was assembled, with all the associated equipment, tracking system markers, lead weight fixings, tape, cable ties, etc., the model was about 1 kg above the target mass. The model was weighed on several occasions during the test programme, and it was found that the model gained a further 0.8 kg in mass after capsizing, but then remained stable. This additional weight was considered to be due to water, either on the model's surface or trapped in crevices. The hydrostatics analysis was therefore repeated at the end of the test programme, based on the total dry model mass, 114 kg, which had been measured immediately before tests started.

Mooring lines were considered to be an unfortunate necessity, to keep the model in position, at the correct heading angle, and in view of the motion tracking system. The model was moored with a soft elastic system such that the natural periods in surge, sway and yaw were kept well above the wave response periods. The attachment points on the model were located at its lateral extremities, in order to minimise interference with its heeling response and capsize, and to minimise the chances of the mooring lines wrapping themselves around the model during a capsize.

Wave elevations ahead of the model and to one side were measured using conductivity wave gauges. The responses of the model were measured using an optical, non-contacting system, consisting of a number of infra-red sensitive cameras which tracked target markers on the model. Eight reflective balls were mounted on the models via light wooden support rods, so that at least three targets could be viewed by the cameras.

3.3. The Test Facility

The tests were performed in the Offshore Wave Basin at the Danish Hydraulic Institute. The dimensions of this basin are 30m by 20m. The basin aspect ratio is unusual in that the basin is wider than it is long. The basin is also fitted with small side absorbers which are intended to help reduce cross-basin waves. The water depth during these tests was 3m at model scale, representing 180m at full scale. Sixty hydraulic wave generator are located along the 30m side of the basin. On the opposite side is a wave absorber, or beach. There was no current.

3.4. Initial Tests

The wave spectra were calibrated initially in the absence of the model. An additional wave height gauge was mounted at the position in the tank where the model was later to be installed. The waves were then run, and measurements from the gauge at the model position were saved, to be used during subsequent analysis.

The model was then installed in the tank. Measurements were made of its static heel angle and *GM*, both with and without wind, in selected intact and damaged condition, for later comparison with results from the hydrostatics analysis, and with measurements of initial heel angles obtained from the tracking system.

Free decay tests were also performed in order to measure the model's natural periods and damping in intact conditions I1 and I2. Results from these free decay tests were analysed using a conventional log-

decrement analysis based on peak-to-trough and trough-to-peak ranges, and are summarised in Table 3. Measurements in waves were also analysed using a ‘synthetic decrement’ analysis technique, which first obtained an average decay history before applying a conventional log-decrement analysis.

3.5. Tests in Waves

Over 50 valid and complete tests were run, covering a range of intact and damaged conditions, *KG* values, wave height and heading conditions. They included the following cases:

- 16 tests in the intact condition, including one test in 9m waves,
- 10 tests in damaged condition A1, including two tests in short-crested waves, and four tests at different wave heights,
- 6 tests in damaged condition B1,
- 7 tests in damaged condition C1,
- 4 tests in damaged condition D2,
- 8 tests in damaged condition D3.

The A1 series tests included a repeat test, a test in a different realisation of the same sea state, and a test without applying the wind heeling moment.

Three sets of tests were performed in the D condition, with the central compartment flooded. The central compartment was filled to $\frac{2}{3}$ of its capacity in the D1 condition, with the topside forward, and in the D2 condition, with the topside to starboard. After several runs of the D1 condition, it was realised that the accommodation block was providing additional buoyancy, which had not been included in the hydrostatics analysis, and which prevented the model from capsizing as predicted. The D1 condition was therefore removed from the list of valid runs, and replaced by condition D2. Tests were also performed in a third condition, D3, which represented a repeat of the D2 condition but with the central compartment pressed full.

Figure 6 shows the model in the A1 damage condition, at 180 degrees heading, both in calm water and in the $H_s = 9\text{m}$, $T_p = 12\text{s}$, sea state.

4. CONCLUDING COMMENTS

This paper describes a series of systematic hydrodynamic model tests to investigate the stability of a jack-up platform during a wet tow in severe seas. Steady wind and irregular waves were represented, and the model was tested in both the intact and damaged conditions. The tests identified the limiting height of the centre of gravity at which the model just remained upright throughout an entire three-hour (full scale) test. The results and conclusions from these model tests will be presented in a follow-up paper, together with results from a traditional quasi-static stability analysis.

5. ACKNOWLEDGEMENTS

These model tests were performed by the ‘BMT User Group’ in the Offshore Wave Basin at the Danish Hydraulic Institute under contract ERBFMGECT950050 of the EU-TMR Large Scale Facilities programme. The financial contribution from the European Union (EU) is appreciated. The assistance of DHI was also greatly appreciated.

6. REFERENCES

- [1] BMT Offshore Limited, 'Stability Criteria for Jack-ups in Transit. Phase 1: Review of casualties, seakeeping data and numerical methods', report to the Health and Safety Executive, project no. P45459, revised final report, 18 July 1994.
- [2] Standing, R.G., and Rowe, S.J., 'Stability and seakeeping review for jack-ups in transit', Proc. 4th Intl. Jack-up Conference, City University, London, September 1993.
- [3] The Health and Safety Executive, 'Offshore Installations: Guidance on design construction and certification', 4th Edition with amendments, 1993.

Table 1: Irregular wave conditions.				
H_s (m)	T_p (s)	T_z (s)	JONSWAP g	significant wave steepness
12	14	10.9	3.3	1/15.5
9	12	9.4	3.3	1/15.3

Table 2: Nominal main particulars of the full-scale jack-up.	
Length (m)	78.2
Breadth (m)	90.2
Draught (m)	6.6
Displacement (tonnes)	25,000

Table 3: Results from free decay tests on the intact model.			
Condition	Motion	Natural period (s)	Damping (percent of critical)
I2	Roll	23	7
I2	Pitch	22	8
I2	Yaw	50	13
I2	Surge	100	10
I2	Sway	71	9
I2	Heave	9	8
I1	Roll	15	4
I1	Pitch	15	5

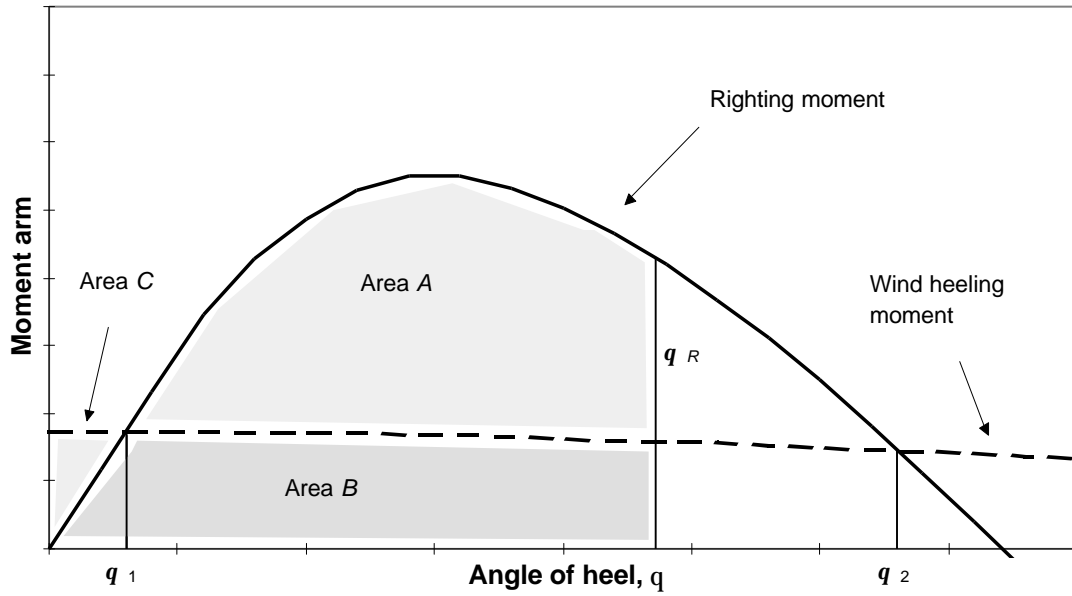


Figure 1: Wind heeling moment and righting moment arm curves, and parameters used in an intact stability analysis.

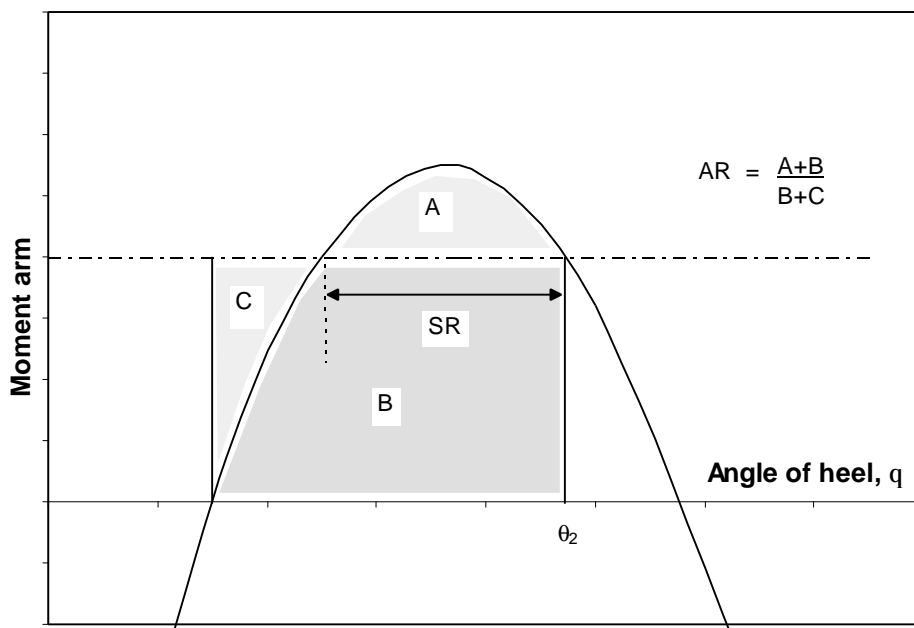


Figure 2: Definitions of AR , SR and q_2 .

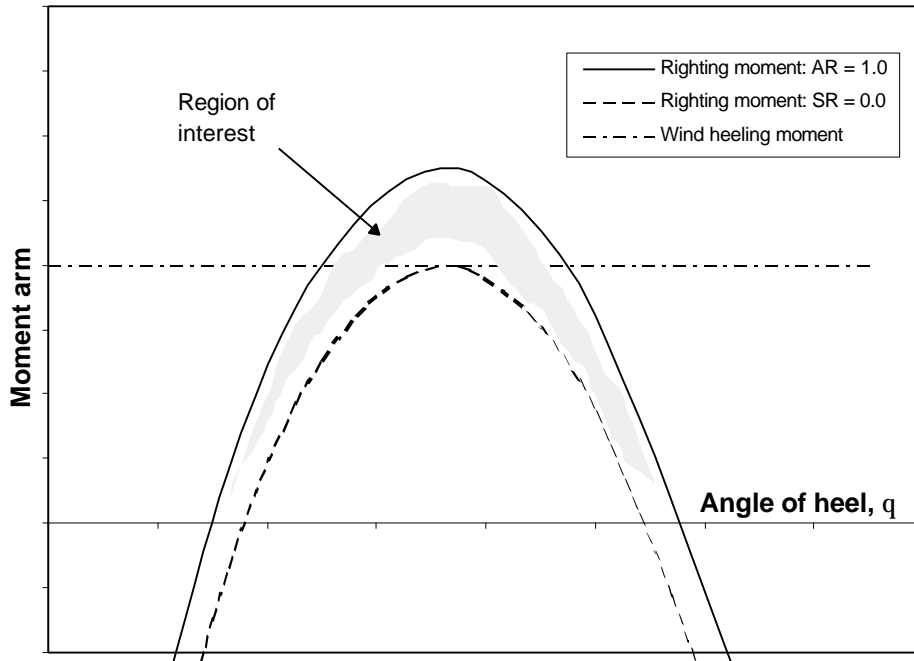


Figure 3: Primary area of interest: righting moment curves between $AR = 1.0$ and $SR = 0.0$.

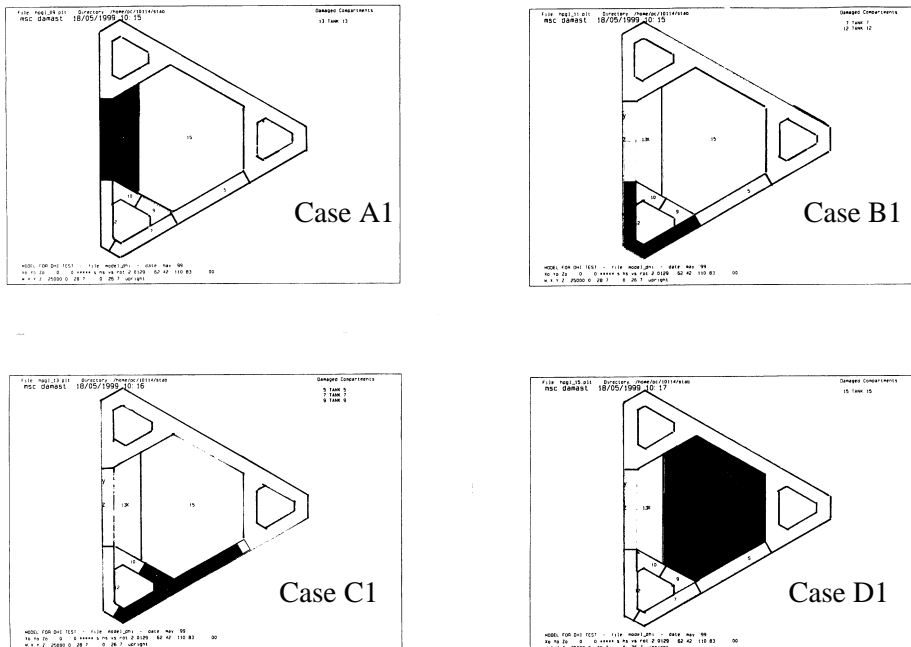


Figure 4: Damage conditions A1, B1, C1 and D1 (flooded compartments highlighted).

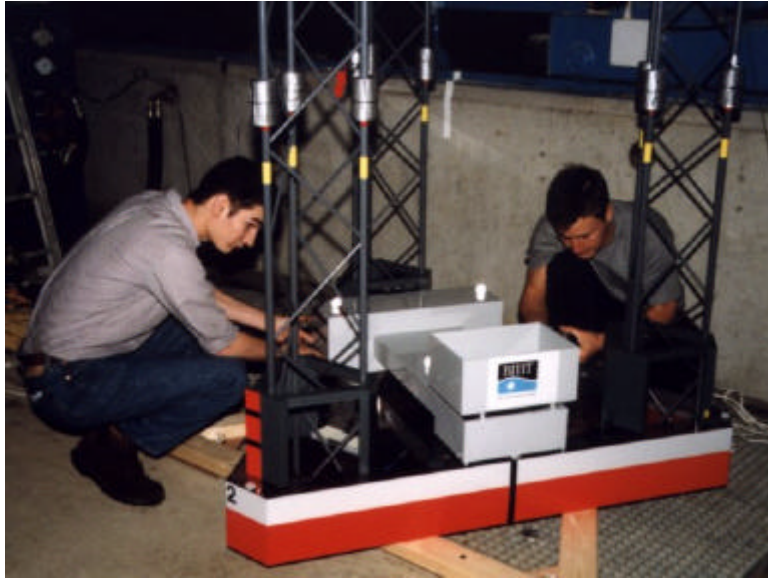


Figure 5: Model being prepared for testing.



Figure 6: Model with A1 damage in still water and during tests in 9m waves.