EXPERIMENTS ON THE SURVIVABILITY OF SMALL PASSENGER VESSELS IN COLLISIONS

B Deakin, Wolfson Unit MTIA University of Southampton, UK

SUMMARY

Small passenger vessels frequently operate in close proximity to much larger ships, particularly in ports and on inland waterways. The smaller vessels' operations often take them across the main shipping routes, where large vessels operate with restricted ability to manoeuvre. There is a potential risk for a small passenger vessel to be struck by a larger ship, and for a disastrous outcome.

This paper describes a modest series of model tests to study the mechanisms involved, and the potential for flooding or capsize. The aim of the work was to attempt to establish the parameters affecting the survivability of passenger vessels, in terms of design parameters or stability characteristics. Models of two monohulls and a catamaran were subjected to collisions while stationary in a towing tank. The impact location, relative headings, speed, model configuration and stability were varied.

The results indicated that, for each configuration, a critical collision speed could be established, above which sinking or capsize would result. Comparison of the critical speeds enabled the relative safety of each configuration to be assessed. Stability and freeboard were found to have an influence on the critical speed, and the work provided some valuable information regarding the stability characteristics and behaviour of these vessels.

1. INTRODUCTION

This paper describes a programme of model tests, commissioned by the Maritime and Coastguard Agency, to study the stability and safety of small passenger vessels when subjected to a side impact collision with a much larger vessel. The full report of the study [1] is available from the MCA website.

Three types of vessel were studied. An older type of class V passenger vessel, partially decked and certificated on the basis of a heeling test, a more modern, wider, fully decked vessel which could comply with damage stability requirements, and a catamaran. An example of the older type of vessel had suffered a collision with disastrous consequences, and the aim of the project was to determine the degree to which the outcome of the collision depended on the stability.

2. TEST TECHNIQUE

2.1 TEST FACILITY

The tests were conducted in a towing tank 60 metres long by 3.7 metres wide by 1.8 metres deep. It is equipped with a manned towing carriage with a maximum speed of 4.5 m/s.

2.2 SIMULATION OF THE LARGER VESSEL

Small passenger vessels operate in close proximity with very large ships of various types, including container ships, bulk carriers and cruise ships. Their displacement might be two or more orders of magnitude greater than that of the passenger vessel. This difference in the displacements would have required modelling the passenger vessel at a very small scale, or conducting the tests in a very large facility for which the budget was inadequate.

With such large potential differences in the displacements, in the early stages of the collision there would be little reduction in the speed of the larger colliding vessel. It was considered reasonable, therefore, to represent it by a fixed structure attached to the towing tank carriage.

In a collision with the stem of a large vessel, the impact might occur with a vertical or raked stem, or with the upper part of a bulbous bow. A vertical stem represented the most general form, and the simplest to model. It was represented by a vertical wooden strut, sleeved with a neoprene fender to avoid structural damage to the passenger vessel models. The strut extended below the water surface to a depth greater than the draught of the models.

2.3 COLLISION METHOD

The collision strut was fixed to the forward end of the carriage at the centre of the towing tank. The passenger vessel model was placed at rest in the towing tank, ahead of the towing carriage, at the required orientation. Three orientations were studied: beam on, at 45 degrees with the stern towards the collision, and at 45 degrees with the

A low power laser was attached to the back of the carriage and aligned with the centre of the tank to enable the model to be placed accurately in line with the strut. Three locations were used for the impact point of the strut on the model: amidships and 25% of the length forward and aft of midships.

The carriage was run at the desired speed and stopped after the strut had pushed past the model and lost contact with it, or when it was apparent that the model was trapped on the strut in an unchanging situation.

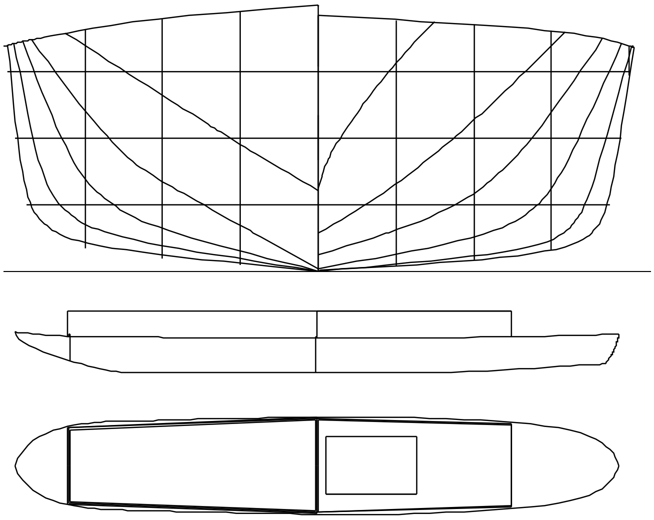


Figure 1. Narrow vessel model

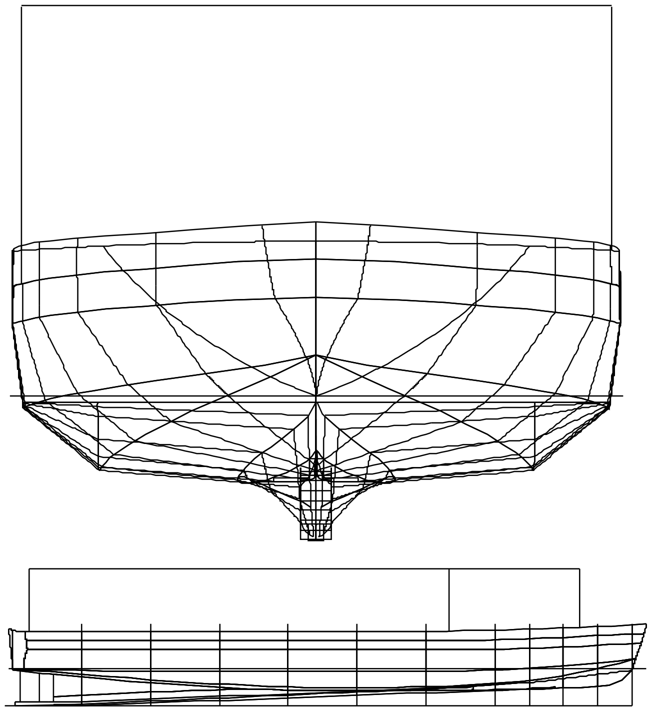


Figure 2. Wider vessel model

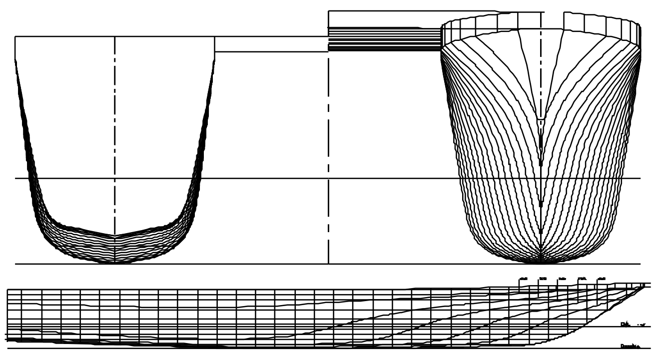


Figure 3. Catamaran model

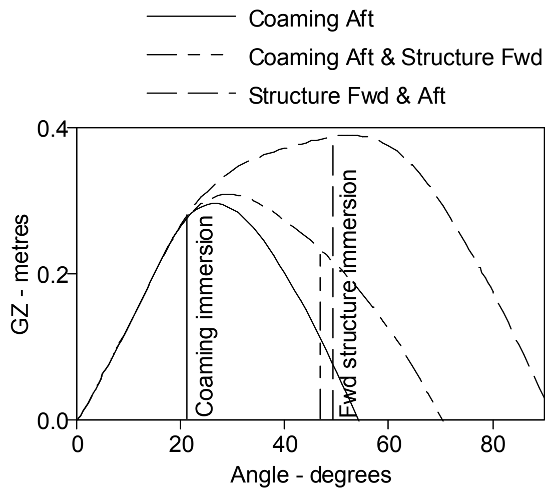


Figure 4. Stability of the narrow vessel

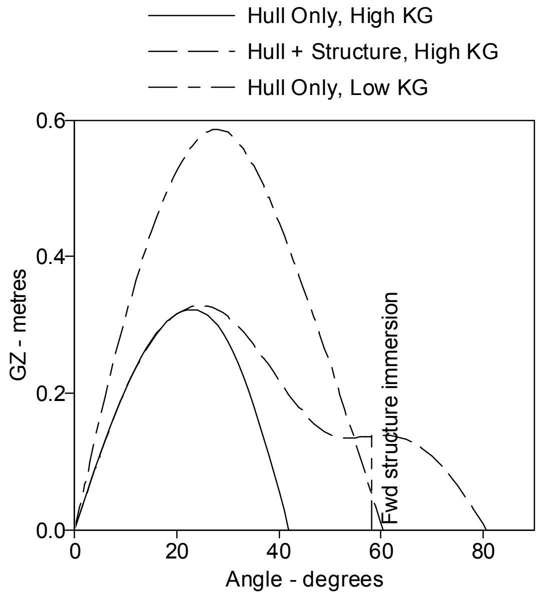


Figure 5. Stability of the wider vessel

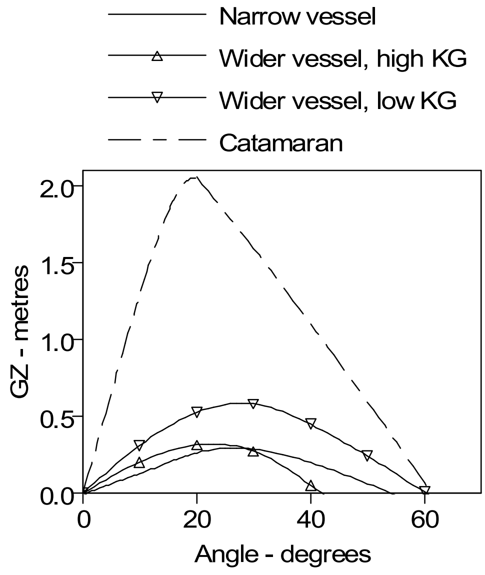


Figure 6. Comparison of the stability of the three models without superstructures

3. PASSENGER VESSEL MODELS

Principal dimensions of the vessel are presented in Table 1, drawings in Figure 1 to Figure 3, and the stability characteristics in Figure 4 to Figure 6.
bow towards the collision.

All dims in metres	Narrow Vessel	Wider Vessel	Catamaran	
			Bow trim	Level trim
Length OA	26.9	24.4	32.7	32.7
Length BP	25.9	22.8	29.5	29.5
Mld Beam	4.35	5.94	8.32	8.32
Draught	0.89	1.37	1.24	1.26
Freeboard	0.65	1.10	1.79	1.77
Displacement	50	108	90	98
LCG (fwd)	-1.16	-0.76	-1.13	-2.38
VCG	1.54	2.84 & 2.22	3.27	3.28
Model scale	1:16	1:16	1:20	

Table 1. Principal dimensions

3.1 NARROW VESSEL

This model was based on a vessel that had operated on the Thames. A model hull was constructed, at a scale of 1:16, of wood strip planks on frames, sheathed with GRP inside and out. It included the skeg and rudder but no other appendages. One level of superstructure was constructed in two modules, fore and aft, with an open top allowing downflooding at any point along its perimeter. The basis vessel was partially decked, with an undecked compartment extending through most of the aft part of the vessel with a very low coaming to the window height. This arrangement resulted in a low angle of downflooding, giving an effective range of stability of 22 degrees, and precluded compliance with the stability requirements for decked vessels. A plywood deck was constructed to enable this compartment to be made watertight, increasing the range to 55 degrees.

The model was ballasted to a representative displacement and centre of gravity. The ballast was adjusted for each configuration tested to maintain constant displacement and centre of gravity.

3.2 WIDER VESSEL

A more modern type of vessel was selected by MCA staff, and was representative of many small passenger vessels in operation. Principle differences to the other vessel are wider beam and a fully decked configuration enabling compliance with a single compartment damage standard, and giving a range of intact stability of 40 degrees.

The vessel comprised two decks of accommodation above the main deck, giving a relatively high centre of gravity and a stability curve not unlike that of the narrow vessel, despite the greater beam. It was decided, therefore, to conduct tests on the model in the loaded condition presented in the vessel's stability booklet, and in a second condition with the same displacement but a lower centre of gravity.

The model was constructed, at a scale of 1:16, of wood strip planks on frames, sheathed with GRP inside and out. It was fully decked and a simple open topped superstructure was constructed to represent the first level of accommodation on the full scale vessel.

3.3 CATAMARAN

Following tests on the models described above it was decided to conduct tests on a catamaran for comparison. An existing mould, manufactured for a model for another project, was used to construct the symmetric hulls of a conventional catamaran. The vessel is a 33 metre fast ferry operating in the UK on protected waters in close proximity to large ships, and therefore was considered a suitable example for this study.

The model was constructed, at a scale of 1:20, of GRP and Kevlar. It comprised the two symmetric, round bilge hulls, and a flat bridge deck. No appendages or superstructures were fitted.

The model was ballasted to represent a fully laden level trim condition, and a bow trim condition, using the stability information booklet for guidance on displacement and centre of gravity. Despite a difference in the GM values, the differences between the stability curves for these conditions was negligible, with less than 0.01 metre difference in the maximum GZ, and less than 1degree difference in the range. The displacement was 8% greater in the level trim condition, and hence the righting moment was also 8% higher.

4. GENERAL OBSERVATIONS OF THE FORCES INVOLVED

4.1 ORIENTATION AND POINT OF IMPACT

The behaviour of the models was very dependent on the longitudinal location of the impact and the orientation of the model relative to the course of the colliding vessel, or strut. To simplify discussion of this aspect a notation will be adopted as defined in Figure 7.

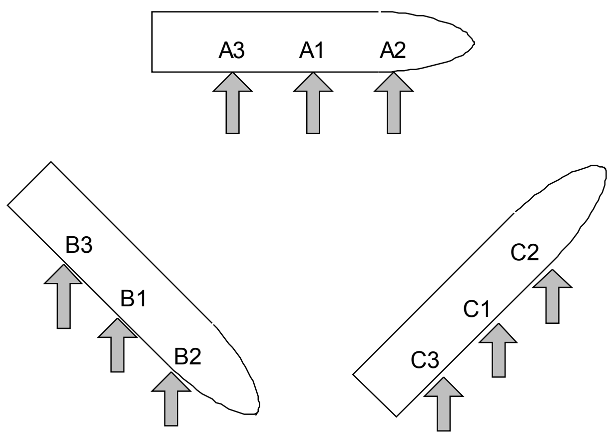


Figure 7. Notation used to define the collisions

It is understandable that the vessel is likely to be rotated and pushed aside by a collision of the type denoted C2, particularly if it has a raked keel or a substantial skeg that results in a centre of lateral resistance aft of midships. These features are common on passenger vessels and indeed were features of both the monohull vessels modelled. Impacts C2 and A2 therefore were the least troublesome for these models and resulted in no significant heeling. The catamaran has no skeg and the keel line is curved with the deepest point amidships. Its response in yaw was slightly different to the monohulls as a result, but impacts forward of midships did not result in capsize.

Similar results were obtained for impact B3, but the aft location of the centre of lateral resistance due to the keel and skeg arrangements of the monohulls reduced their rotational response, and one capsize occurred with the narrow model.

With the models oriented beam on to the collision the highest rate of capsize was for impacts A1, with the models at times being held on the strut, perhaps in the capsized state. For impacts A2 and A3 the model rotated and the number of capsizes was significantly less than for A1.

In impacts B2 and C3 the model moved sideways to some extent and the impact point moved towards the centre of the model. These impacts gave the highest rates of capsize for the models at these oblique headings, with the exception of the catamaran which, as mentioned above, did not capsize when stuck towards the bow in impact B2.

4.2 TRANSIENT PHASE OF THE IMPACT

The behaviour following the collision may be divided into a transient phase in which the passive vessel is set in motion by an impulsive force, followed by a quasi-static phase in which the vessel responds to more steady forces.

In many cases the roll response was immediate on impact, and it appears that the transient phase has a major effect on the behaviour because the initial roll angle affects the subsequent development and balance of forces.

In this phase it appeared that the model responded to three principal moments that governed its initial roll response. These are illustrated in Figure 8.

The force, denoted F, of the strut applied to the side of the model and the height at which this force is applied. The height is at the point of impact, and is dependent on the section shape of the hull and superstructure, and the shape of the stem of the colliding vessel.

The reactive inertial force, I, due to the acceleration of the model in the direction of travel of the strut, acting at the centre of gravity. The height at which this force acts is dependent on the height of the centre of gravity.

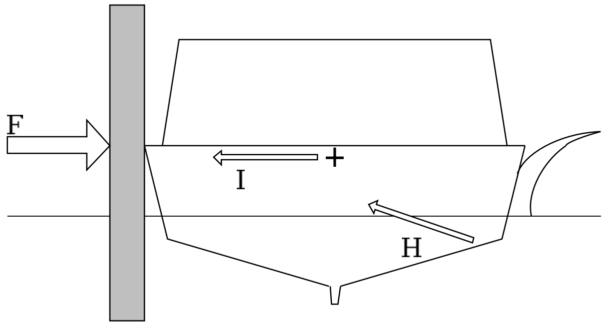


Figure 8. Forces acting during the transient phase

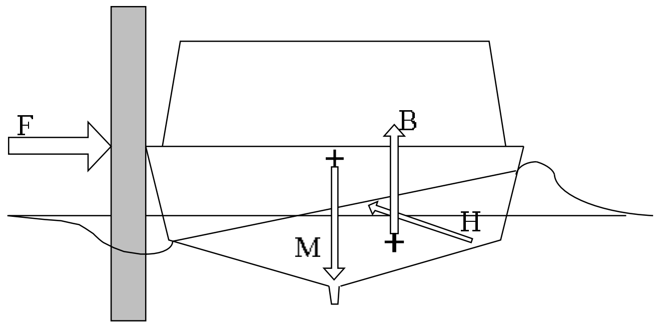


Figure 9. Forces acting during the quasi-static phase

The reactive force, H, due to the water resisting movement of the model, acting through the centre of pressure. On impact, the water alongside the vessel, on the side away from the impact, is displaced under pressure resulting in generation of an instantaneous wave along the topsides. This may be likened to the response to a slam, and is similar in appearance to the spray sheet on the hull of a planing boat. On the side adjacent to the impact there will be a negative pressure. The resultant is not a horizontal force acting at half the draught. Its magnitude and direction are difficult to predict, and are dependent on the shape of the hull. It should not be confused with the resistance components normally associated with a hull moving steadily through water.

The relative magnitudes and lines of action of these forces govern the initial response of the vessel, in particular whether it rolls towards or away from the colliding vessel. If the colliding vessel has a raked stem, or the passive vessel a high superstructure, the force F is likely to be above the centre of gravity and will impart a roll moment away from the colliding vessel. Conversely, if the passive vessel has a high centre of gravity and is struck low on the hull, the moment is likely to result in a roll towards the colliding vessel. If there is no rotation or deformation the lateral acceleration of the passive vessel will be of extremely high magnitude, as it will adopt the speed of the colliding vessel immediately. Any rotation or deformation will increase the time taken to accelerate with a proportional reduction in the acceleration and hence the inertial force associated with it. If the colliding vessel is of a similar displacement to the passive vessel,

the speed of the colliding vessel, and hence the acceleration of the passive vessel, will be reduced.
The hydrodynamic pressures complicate the issue so that such simplified predictions of the roll direction in any particular case would be unreliable.

Figure 17 and Figure 18 show tests where the model rolled rapidly on impact towards and away from the strut respectively. The different behaviour is believed to result primarily from the presence of the superstructure.

4.3 QUASI-STATIC PHASE OF THE IMPACT

Once the passive vessel has been accelerated to the speed of the colliding vessel, the inertial force associated with the acceleration is reduced to zero, and the flow around the hull becomes steadier. A wave pattern is set up around the hull as illustrated in Figure 9.

On the pressure side a wave crest is formed and on the suction side a wave trough, so that the vessel floats on an inclined water surface. Its hydrostatic stability on this inclined surface generates a roll moment towards the colliding vessel because of the transverse displacement of the centre of buoyancy from the centreline.

On the pressure side the wave may rise above the deck edge at some point, and this appears to have a significant effect on the roll moment, resulting in a roll away from the colliding vessel. With an undecked configuration it may result in downflooding, as illustrated in Figure 12. The times indicated for the sequence refer to full scale.

As in the transient phase, the hydrodynamic forces resulting from the flow around and under the hull are difficult to predict and complicate the overall force balance. As for a vessel moving forward in normal operation, the hydrodynamic resistance will include viscous, form and wave making components.

The behaviour of the models indicated that, in some cases, the forces may be in balance, with the model held at a constant attitude against the strut, or nearly in balance, with the model rotating slowly around the strut, predominantly in yaw.

An additional force in the system is the friction between the two vessels. This may apply a vertical force component at the point of contact, affecting the angle of inclination of the resultant force F. In the model tests the neoprene fender on the strut resulted in greater friction than would have been the case with a smooth strut, and undoubtedly affected the roll rotation in some tests. In a real collision the deformation of the vessels might result in considerable resistance to relative vertical movement at the point of contact, and so there was no justification for modifying the strut.

Tests on the catamaran further highlighted the difference between the transient and quasi-static phases. In some beam-on cases the model was capsized at 5.4 knots, with the capsize initiated during the transient phase of the collision. In other cases the model was held fast against the strut and pushed beam-on at speeds of up to 9 knots without excessive heeling. The latter cases arose following a stern-to presentation, where the impact did not cause capsize and the model subsequently yawed beam-on to the strut.

5. DETERMINATION OF CRITICAL SPEEDS

The behaviour was highly dependent on the speed and so attempts were made to determine the critical speed of impact, that is the lowest speed at which capsize occurred, for each configuration. Initially, tests were conducted on both monohull models at all combinations of orientation and impact point, at 2, 4 and 6 knots. It was apparent from these tests that collisions at 2 knots posed no threat to the stability of the vessels. The differences between the behaviour at 4 and 6 knots was dramatic in some cases, and so subsequent tests were conducted at finer speed increments. Whilst repeat tests proved the method to give reliable and consistent results, the behaviour of the model at the critical speeds was dependent to some extent on the precise orientation and impact point, and subsequent response in yaw. In most cases therefore it was considered that the resolution of the test method did not justify tests at increments of less than 0.5 knots.

Collisions of type A2, B3 and C2 resulted in very few or no capsizes, and so the tests concentrated on the remaining six combinations of orientation and impact point.

A large number of test runs were required to address the matrix of 5 variables: model, configuration, orientation, impact point and speed. Over 200 runs were conducted, from which were derived the critical speeds for the worst combination of orientation and impact point for the 9 model configurations. These are presented in Table 2.

The lowest critical speeds were found to be 4 knots for both the monohulls and 5.4 knots for the catamaran.

6. DIRECTION OF CAPSIZE

The capsizes of the wider monohull without the superstructure fitted were all towards the strut. With the superstructure fitted all capsizes were away from the strut. This indicates that the height of the point of contact of the colliding vessel is a dominant parameter.

For the narrow vessel the results were less clearly defined. With the superstructure fitted all capsizes were away from the strut, although not necessarily because the strut impacted the superstructure See Figure 15. Without superstructures there were capsizes in both directions. It appeared to be largely dependent on whether the pressure wave rose above the deck edge. This in turn was influenced by the orientation and point of impact. For example, in a collision of type B2, the model rotated rapidly in yaw, the bow being pushed ahead of the strut and generating a large wave that could overwhelm the deck forward and result in a capsize away from the strut. The lack of consistency in these events suggests that quite small differences in orientation or impact point can make dramatic differences to the balance of forces and hence the behaviour.

All collisions with the catamaran model resulted in heeling way from the strut, despite the fact that the model had no superstructure and the impact was at the deck at side, slightly below the vertical centre of gravity. With the catamaran trimmed by the bow the forward part of the deck was submerged at the higher speeds tested, and in some cases the model trimmed and rolled to a large angle but recovered.

7. EFFECTS OF IMPACT LOCATION AND YAW

Impacts at different points along the hull result in different yaw rates, and these can have a strong influence on the behaviour, particularly in the quasi-static phase. When the narrow model was struck beam-on amidships, Figure 13, it was pushed sideways without yawing and capsized very rapidly towards the strut. When struck aft of midships from the stern quarter, as in Figure 15, it capsized away from the strut, after yawing to a beam-on attitude. The difference appeared to be that, in the latter case the stern was pushed through the water much faster than the bow, with the pressure wave concentrated well aft. The wave rose above the deck edge and the roll then increased rapidly. In the former, beam-on case, the pressure wave was distributed along the full length of the model, and this appeared to generate sufficient buoyancy to roll the model towards the strut.

The hydrodynamic forces acting in these scenarios undoubtedly have an effect on the roll behaviour, but are more difficult to understand. When the deck edge immersed on the pressure side of the model it frequently resulted in capsize away from the strut. This may be due to an increase in the resistance to sway and a change in the direction of the resultant force.

8. EFFECTS OF THE SUPERSTRUCTURE

As described above, the presence of a superstructure may raise the effective height of application of the collision force, and affect the direction of capsize.

If the superstructure remains intact, its buoyancy has a considerable effect on the trim and stability of the vessel. In these tests the superstructure was open topped in all cases, allowing flooding when the side panels became submerged. The structural integrity of the vessel, and any windows and doors, will govern the downflooding in real cases, and a particular vessel might fare better or worse than the models as tested.

Presence of an intact superstructure increases the range of stability and reduces, or eliminates, the dynamic effects of immersion of the deck edge. It increases the angle of maximum GZ so that the vessel retains greater righting moments at large angles of heel.

9. EFFECTS OF STABILITY CHARACTERISTICS

Comparison of the stability curves reveals some common characteristics and some highly variable ones. For example, the narrow vessel and the wider vessel with a high KG have similar maximum values of GZ, while the catamaran has a much larger value. The wider vessel with the low KG has a similar range of stability to the catamaran but still with a much lower maximum KG. It was hoped that these selective differences would assist in the identification of the most influential characteristics. A summary of the stability characteristics is presented in Table 2.

There is clear evidence from the tests that, for a given vessel configuration, increased stability provides increased resistance to capsize. Comparison of runs 88 and 121 for the wider vessel provides a good example, because the capsize mechanisms were observed to be the same. See Figure 16 and Figure 17. Run 88 was with the lower stability condition, where the critical speed was 4.5 knots. Run 121 was with the higher stability condition and the critical speed was 6 knots. The difference between the test configurations is merely that ballast weights were relocated to reduce the height of the centre of gravity. The GM increased by 51%, the maximum GZ by 83%, and the range of stability by 43%.

This finding is less clear however, when all of the test configurations are studied together. Figure 10 presents three plots of the critical capsize speeds for each configuration against the range of stability, the maximum GZ and the GZ curve area. Although there are some indications of trends, particularly with respect to range of stability, the data do not enable reliable trend lines to be defined.

The stability of the catamaran, with a righting energy (that is the product of the area under the GZ and the displacement) an order of magnitude higher than that of the narrow vessel, gave only a modest increase in the critical speed. This indicates that righting energy is not an important parameter in this type of incident. This may be explained by the fact that, assuming the collision is with a much larger vessel, the available capsizing energy may be several orders of magnitude greater than the available righting energy. In the model tests the capsizing energy was effectively infinite because the carriage speed was not reduced on impact. Thus any increase in the righting energy, such as may be brought about by normal design changes, would be insignificant in comparison to the capsizing energy unless the collision is with a small vessel travelling at low speed.

Attempts were made to determine trends by comparing other parameters including GM, freeboard, displacement, length, beam, speed squared, and a number of non-dimensional variations and ratios of them. None of these attempts resulted in clear trends.

An example is presented in Figure 11 to show a possible trend between freeboard and critical speed. Speed squared has been used because it is believed to be more representative of the forces involved, and both have been divided by the cube root of displacement so that the data are independent of vessel size. An interesting aspect highlighted by these data is that all of the cases with relatively low freeboard capsized towards the strut.

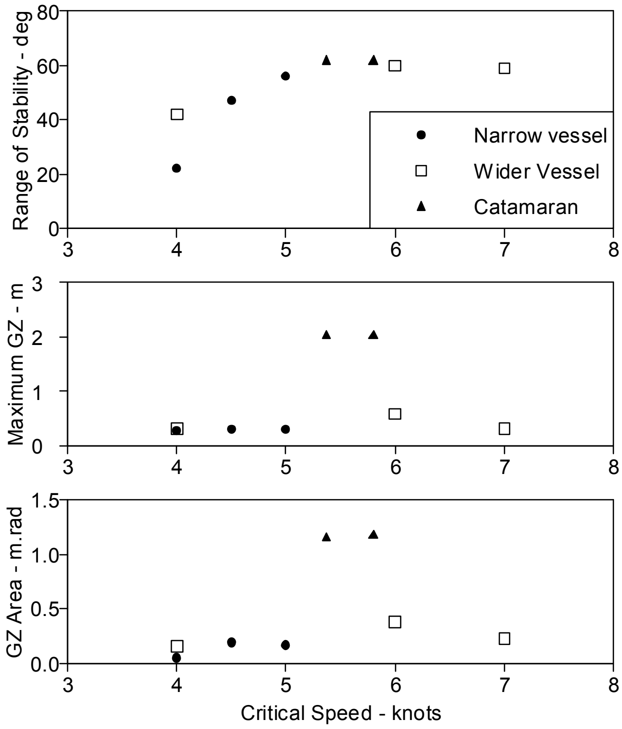


Figure 10. Variation of critical speed with stability

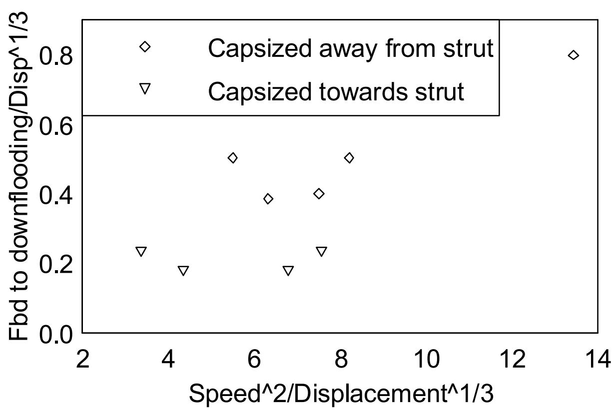


Figure 11. Variation of critical speed with freeboard

The highest critical speed, by a significant margin, was with the wider vessel fitted with a superstructure. The stability characteristics of this configuration were not particularly high, being similar to those of the narrow vessel with the full superstructure. This suggests that maintaining high freeboard and avoiding downflooding are worthwhile design aims.

10. VALIDATION OF THE TEST METHOD

One of the test cases simulated a well documented incident. The behaviour at the appropriate speed appeared to correlate well with that reported at full scale, and is consistent with the extent and nature of the impact damage sustained. This evidence supported the validity of the test method.

11. APPLICATION OF RESULTS TO OTHER VESSELS

It was hoped that, if increased stability was shown to provide increased resistance to capsize, it would be possible to recommend some guidance on appropriate levels of the important stability characteristics for certain types of operation. Unfortunately, while the tests indicate that increased stability does indeed provide increased safety, the results are specific to each model. This makes general guidance impossible with the modest data set produced by this study.

It is notable that all models were capsized, and that substantial changes to the model configuration generally led to modest increases in the critical speed. This perhaps underlines the importance of collision avoidance, as it cannot be assumed that any vessel will withstand a collision with a larger vessel, regardless of the perceived adequacy of its structure and stability.

All small vessels therefore are vulnerable to collision and the findings of this study are relevant to all small commercial vessels and recreational craft. It provides further evidence that stability and freeboard are important factors for the safety of the vessel, but it is unfortunate that the scope of this study has not enabled firm guidance on the characteristics required.

The nature of this type of incident and the subsequent behaviour of the passive vessel is that there is no gradual scale of severity of response. The vessel either capsizes or it does not. In the former case the result will be instant and catastrophic, with loss of life almost inevitable. In this respect a collision induced capsize is similar to other stability casualties where incident databases consistently reveal that, although stability incidents do not represent a large proportion of the total number of marine accidents, they do result in a large proportion of the deaths. If the vessel does not quite capsize, there may be structural damage, perhaps affecting buoyancy and stability in the medium term, and personal injury, but the vessel may survive or there may be adequate time to evacuate. There is unlikely to be any indication to the crew that their margin of safety from capsizing was small.

12. CONCLUSIONS

A simple test method was developed that appears to correlate well with full scale experience, albeit on the basis of only one casualty report.

This study enabled a better understanding of the behaviour of small vessels in collisions. It identified the forces involved and how they may be affected by various design parameters.

The critical speeds, above which capsize may occur, were identified for a range of model configurations for 3 vessel types.

It was demonstrated that both stability and freeboard are parameters affecting the critical speed.

Notwithstanding the above conclusion, the study did not reveal clear relationships for stability parameters that applied to all configurations tested. It has not been possible, therefore, to derive guidance on the levels of stability required to provide a common level of safety from capsize for small vessels in general. It is not necessarily the case that such relationships do not exist, rather that, if they do exist, the limited scope of this study was insufficient to determine them.

13. ACKNOWLEDGEMENTS

The author is grateful to the MCA for permission to present this material, and to the MAIB for their assistance in providing information on the casualty vessel.

14. REFERENCES

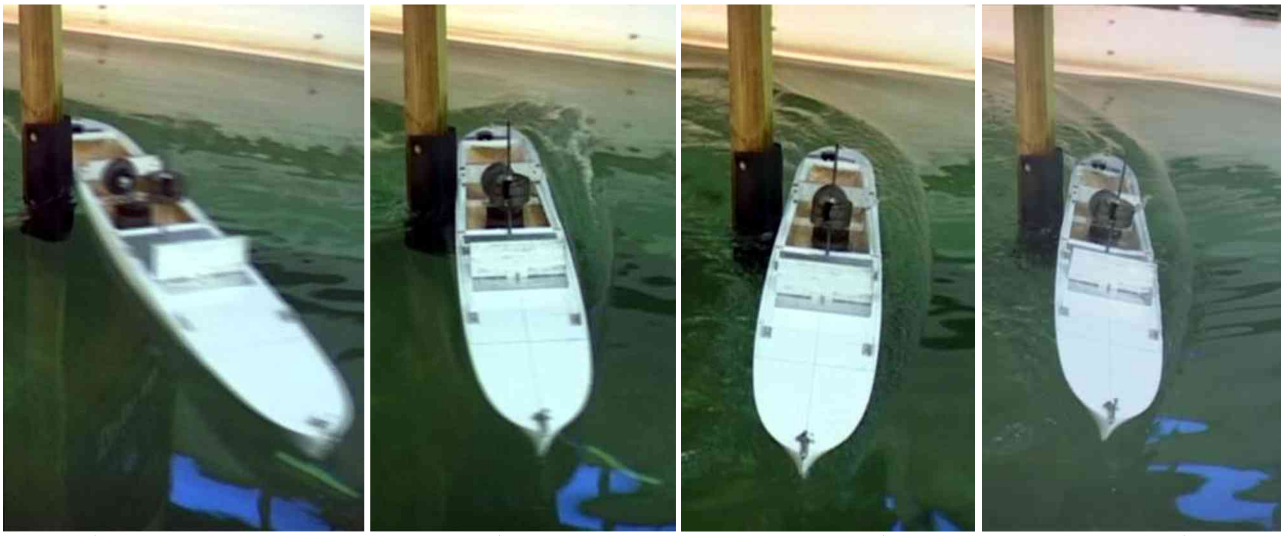
1. Wolfson Unit MTIA, MCA Research Project 524 – The Parameters affecting the Survivability of Small Passenger Vessels in Collisions, February 2004. www.mcga.gov.uk/c4mca/volume_vii_research_project_524_stability.pdf

15. AUTHORS' BIOGRAPHY

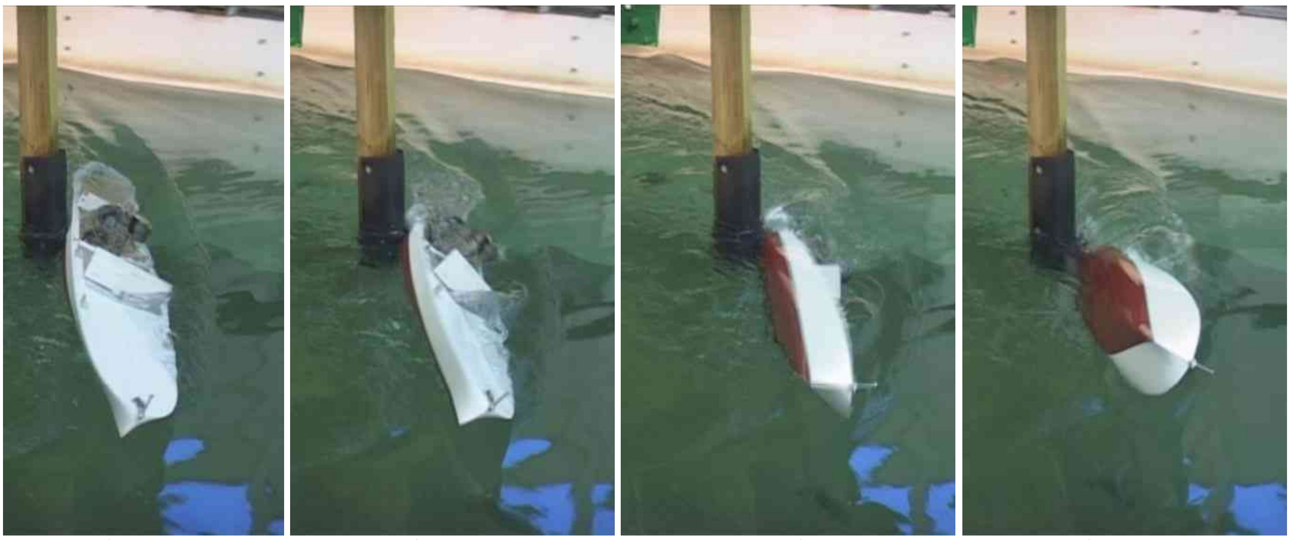
Barry Deakin has been employed as a consultant engineer at the Wolfson Unit since 1978. He has considerable experience of experimental work in towing tanks and wind tunnels, and specialises in the stability and capsizing of small vessels.

Run No.	Critical Speed	Capsize Direction Relative to Strut	Impact Type	Deck	Superstructure		GM	Range of Stability	GZ Max	GZ Area	Righting Energy
					Aft	Fwd					
	knots						m	deg	m	m.rads	tonne. m.rads
Narrow Vessel											
146	4.0	towards	A1	Open Aft	Off	Off	0.72	22	0.280	0.046	2.3
138	5.0	towards	A1	On	Off	Off	0.72	56	0.300	0.166	8.3
134	4.5	away	C3	On	Off	On	0.72	47	0.308	0.191	9.6
128	5.5	away	B2	On	On	On	0.72	49	0.388	0.229	11.5
Wider Vessel											
88	4.0	towards	B2	On	Off		1.18	42	0.320	0.152	16.4
121	6.0	towards	B2	On	Off		1.79	60	0.585	0.378	40.8
110	8.0	away	B2	On	On		1.18	59	0.320	0.223	24.1
Catamaran											
Bow trim											
173	5.8	away	A1	On	Off		7.49	62	2.055	1.187	107
Level trim											
174	5.4	away	A1	On	Off		6.75	62	2.050	1.159	114

Table 2. Critical capsize speed and stability summary for each test configuration



0 seconds 1.6 seconds 6.4 seconds 10.4 seconds



12 seconds 12.8 seconds 13.6 seconds 14.4 seconds

Figure 12. Simulation of the documented incident. Collision speed 4.5 knots.

Figure 13. Narrow vessel, decked, 6 knots, 1.6 seconds after impact

Figure 14.Narrow vessel, with full superstructure, 5.5 knots, 6.4 seconds after impact

Figure 15. Narrow vessel, with aft superstructure, 4.5 knots, 6.4 seconds after impact

Figure 16. Wider vessel, high VCG, 4 knots, 4.0 seconds after impact

Figure 17. Wider vessel, low VCG, 6.5 knots, 4.0 seconds after impact

Figure 18. Wider vessel, high VCG, with superstructure, 8 knots, 9.6 seconds after impact

Figure 19. Catamaran, 6 knots, 3.6 seconds after impact