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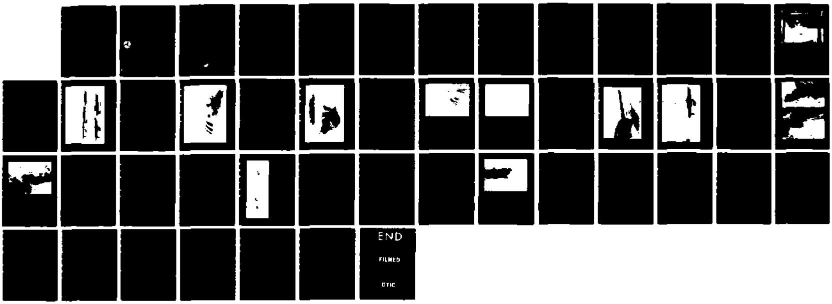

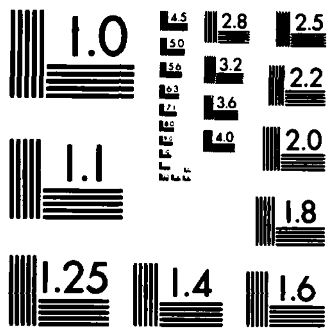

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Report No. CG-D-37-84

AD-A158 907

INVESTIGATION OF THE USE OF DROGUES TO IMPROVE THE SAFETY OF SAILING YACHTS AND LIFE RAFTS

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Prepared for:
U.S. Coast Guard
Research and Development Center
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Groton, Connecticut 06340

INTERIM REPORT

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16. Abstract

Model tests were conducted to investigate the use of drogues to improve the safety of sailing yachts and life rafts. The tests investigated the hazard of capsize by a breaking wave. The boats were assumed to be in a survival type storm with all sail off and not being controlled by the crew.

The models were built to a scale of 1 to 32 and were weighted to give the proper dynamic characteristics. Two methods of breaking wave simulation were used: 1) A horizontal jet of water discharged at the model; 2) A breaking wave formed by the wake of a towed boat.

A mathematical model was prepared which first simulated the motion of the boat-drogue system in non-breaking waves and then simulated a breaking wave strike.

The tests indicated that the hazard of breaking wave capsize could be greatly reduced by the use of a properly engineered drogue. However, a systematic investigation of the parameters affecting the boat/drogue system, i.e. loads on the boat and drogue, line elasticity, wind and wave forces, has yet to be undertaken. More study and testing is required before a specific design can be recommended.

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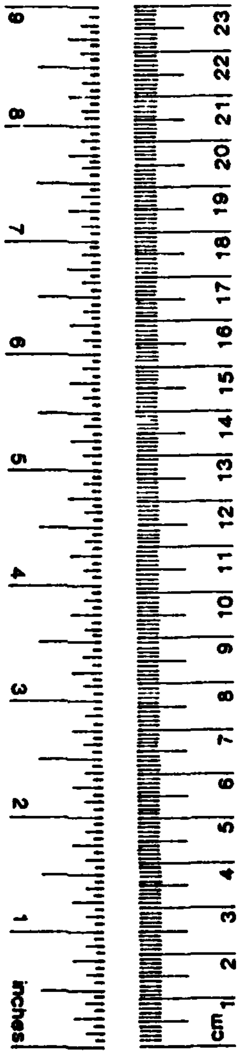
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

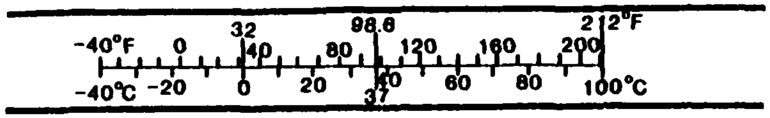
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

A major hazard to small craft and liferafts is the possibility of being struck by a large breaking wave. Such a wave strike can capsize the vessel and can impose loads large enough to cause serious structural damage. There is a long and continuing history of breaking wave capsizings in all the ocean regions where severe storms are encountered. The most notorious event was the 1979 Fastnet Race in which 24 boats were sunk or abandoned and 15 lives were lost. A broad spectrum of boat types and designs have succumbed to breaking wave strikes in the recent past, including a 47 ft. traditional schooner, a 60 ft. trimaran, a 52 ft. steel lobster boat and a wide variety of smaller craft.

In a typical instance the boat is either lying ahull, with all sail off, or running off before the sea in a survival type storm when she is suddenly struck by a breaking wave. The boat either rolls down beyond 90 degrees or pitchpoles end over end. In many cases structural damage is done to the rig, rudder, deck and cabin top, and in some instances the basic hull is damaged. A number of breaking wave capsize events are described in Reference 1. For the tests described in this report, it was assumed that all sail was off and the boat was not under the control of the crew.

It seems that the incidence of breaking wave capsize has increased in recent years. This is probably the result of more small boats going to sea. There is some concern that modern sailing yachts such as participated in the 1979 Fastnet Race are more vulnerable to breaking wave capsize than older traditional designs. This subject was investigated in model scale and reported in References 2 and 3. It was found that while certain design features such as light displacement, large beam, and high center of gravity might under some circumstances have a negative effect on capsize performance, a slightly larger wave would capsize all the designs. This is confirmed by the fact that the record of actual capsizings includes a wide variety of boat designs.

This report describes model tests to evaluate the use of a drogue to prevent breaking wave capsizing. Model test results together with limited full scale experience indicates that a properly engineered drogue may greatly reduce the chance of breaking wave capsize.

A very important parameter of the model testing is the simulation of the breaking wave. In recent years much has been learned about the detailed characteristics of storm waves through the use of modern instrumentation and recording equipment. Some of these data are reported in References 4, 5 and 6. However, very little is known about breaking waves of the type that would capsize a small boat or life raft. The incidence of dangerous waves within a given storm, the breaking wave profile, or the momentum of the high velocity water in the wave crest has not been investigated in any depth. Progress has been made in the computer simulation of a breaking wave (Reference 7) but this work has not been related to measurements taken in breaking waves generated by a storm.

Despite the lack of specific breaking wave data, the dynamics of a breaking wave are generally understood. Observations and photographs of storm waves give a good idea of what may be encountered by a small boat in a storm. Figure 1 shows a computer simulation of a deep water breaking wave.

In this type of wave the top portion of the wave curls over and breaks. The fast moving water from the crest surfs down the forward face of the wave. Such a wave would be hazardous to a small boat in the phases shown in Frames C thru F. Photographs show that storm waves may also break as shown on Figure 2, in which the entire wave breaks, or in Figure 3, in which only a small portion of the crest breaks. All types can be dangerous because of the velocity or momentum contained in the surface water and the shape of the wave face.

SCALING

To simulate the dynamic behavior of a full scale boat by testing a small scale model it is necessary to scale all the forces acting on the boat by the same ratio. The important forces are the pressure forces, the gravity forces, the viscous forces and the inertia forces. For these tests the models were constructed so that all the forces were properly scaled except the viscous forces. Thus the model scale tests are conducted at the correct Euler No. and Froude No. but not at the correct Reynolds No. Since in a breaking wave capsize the flow is turbulent and since small variations in drag are not important, it is believed the Re variation should not affect the results.

The models and the wave characteristics were scaled as follows:

Length	L
Area	L^2
Force	L^3
Displacement	L^3
Moment (Stability)	L^4
Moment of Inertia	L^5

For a 1/32 scale model, the period in roll would be 0.62 seconds where the full scale boat has a roll period of 3.5 seconds. The non-dimensional trajectory of the model should be the same as that of a full scale boat for any dynamic maneuver. The time to complete the maneuver would vary as $\sqrt{L}$. Thus for a 1/32 scale model, the time to capsize would be 1/5.66 that of a full scale boat.

For the tests described in this report two different types of wave simulation were used. These are discussed separately under Series I and Series II below.

TEST PROCEDURE, SERIES I

For this series, the breaking wave was simulated by a horizontal jet of water discharging into a static pool of water. The horizontal jet was generated by permitting a quantity of water to fall vertically and then deflecting the water from a vertical to horizontal direction by a curved ramp. A drawing of the test setup is shown in Figure 4 and by a photograph in Figure 5. Several hoppers of different heights were used during the tests to provide different jet velocities. The hopper shown in Figure 4 would provide a horizontal velocity of approximately 7 ft/second. The horizontal jet of water was intended to simulate Frames E and F of the type of breaking wave shown in Figure 1, and to simulate the type of wave shown in Figure 3.

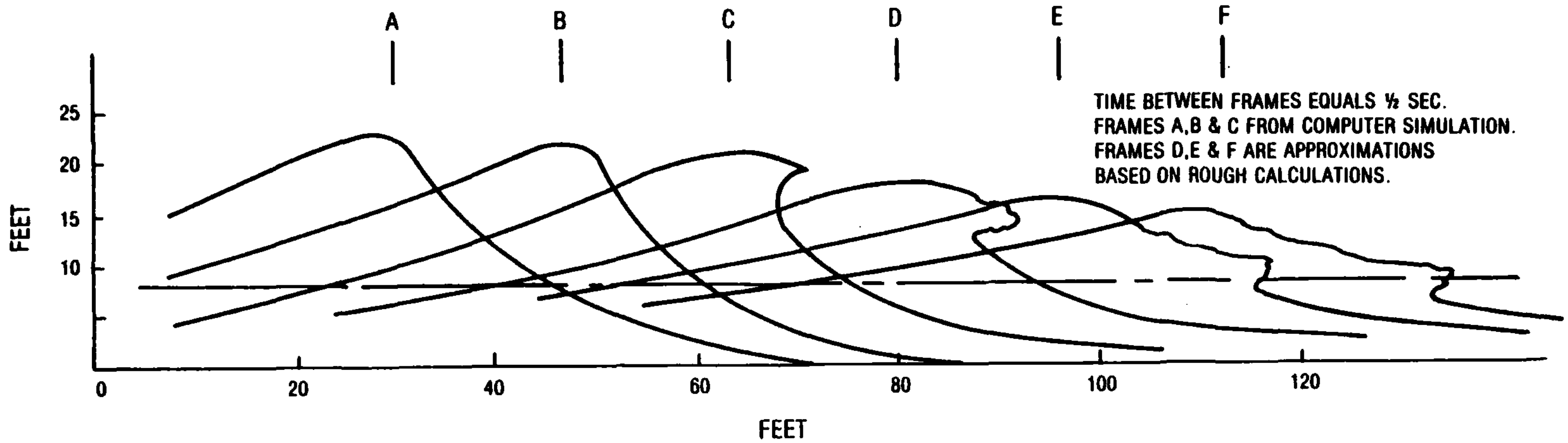


FIG. 1 BREAKING WAVE PROFILE

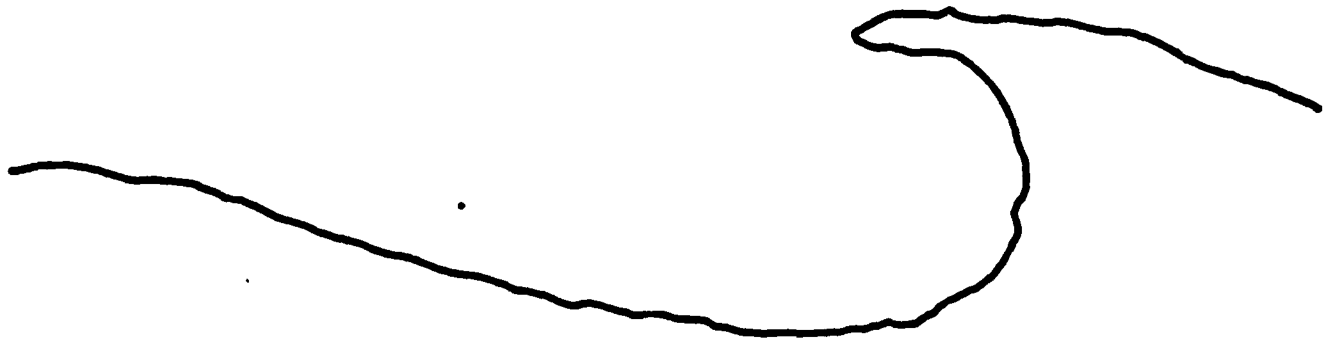


FIG. 2 BREAKING WAVE (Entire)

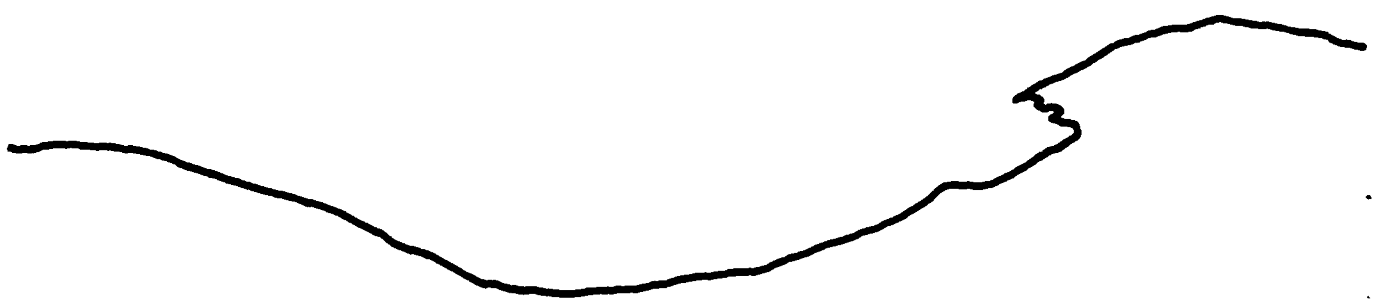


FIG. 3 BREAKING WAVE (Crest Only)

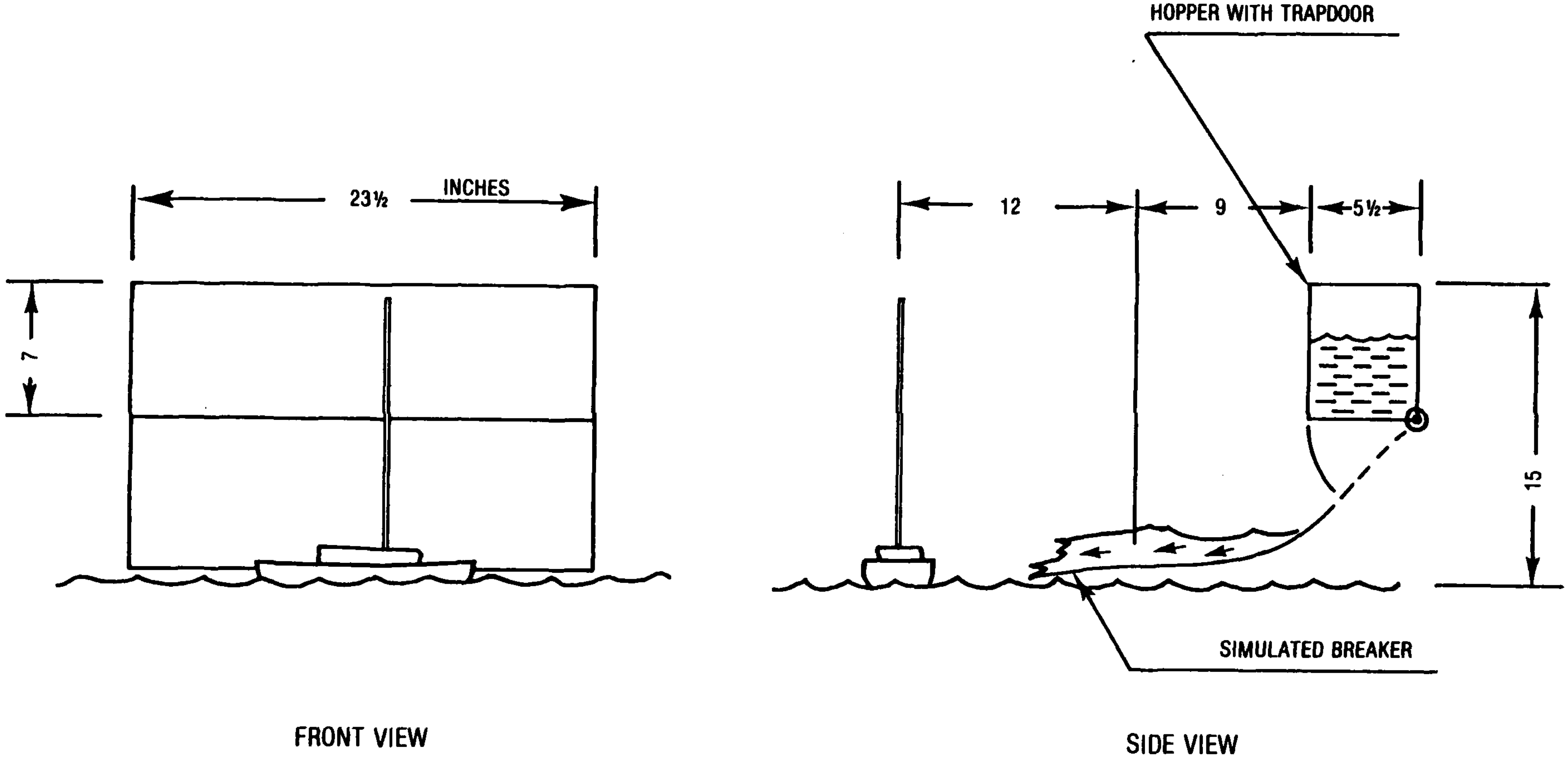


FIG. 4 BREAKING WAVE SIMULATOR (Schematic)

FIG. 5   BREAKING WAVE SIMULATOR (Photograph)

A variety of models were used for the tests. All were sailing yachts. They differed widely in size and design and represented over 50 years of yacht development. Figure 6 shows several of the models. On the left is the Standfast design which is a modern design used by other investigators. Most of the models were built to a scale of 1 to 32. Figure 7 compares the Standfast model to the full scale vessel. The models were made of balsa and were weighted with lead to give the correct dynamic characteristics.

To conduct a test, the model was placed in front of the discharge ramp of the hopper and held in position at a specified angle and distance. The hopper was filled with a measured amount of water. The lights were extinguished and the strobe light was turned on at a flash rate of 18 flashes per second. The trap door was then tripped releasing the water from the hopper. At the same time the model was released to float freely. When the wave front reached the end of the ramp, it tripped a switch which opened the camera lense for 1/2 second. Figure 8 shows the photo record for a typical capsize. This record could then be analyzed to obtain displacement, velocity and acceleration as a function of time.

For this series of tests most of the effort was devoted to studying the influence of yacht design on capsize performance. It was found that by far the most important variable was the size of the boat. Changes in design which might reasonably be applied to practical sailing yachts had a small effect; but a moderate increase in the momentum of the simulated wave crest would capsize all the designs. This work is reported in References 8 and 9.

In the concluding phase of this work, tests were run to evaluate the effect of deploying a drogue from the stern of the model. It was assumed that the geometry shown in Figure 9 would represent a severe condition. The boat was positioned so that the wave front struck at 45° from astern and the drogue was displaced 15° from the wave direction. The model drogue consisted of a simple plastic disk with a wire shaft. The drogue towline was nylon monofilament which, at model scale, exhibited essentially no elasticity or stretch. It was found that a drogue with a diameter of less than 10 to 15% of the length of the boat; i.e. 3 to 4-1/2 ft. for a 30 ft. boat, would not exert enough force to pull the stern into the wave face. As a result the boat would broach and capsize. However a drogue with a diameter equal to or greater than 10 to 15% of the length of the boat would pull the stern into the wave and prevent capsize. An example of such behavior is shown in Figure 10. Unfortunately, when elasticity was introduced into the model towline in an attempt to simulate a full scale nylon line, the model broached and capsized.

This testing clearly suggested that the proper application of a drogue might prevent capsize. More realistic test conditions were required to carry the work forward from this point.

TEST PROCEDURES, SERIES II

This series of tests was conducted in a shallow tidal bay in Fisher's Island Sound, Connecticut. The same models were used and several additional models were added including two different trimaran designs, a catamaran and a proa built to a scale of 1 to 32, and two six man liferafts built to a scale of 1 to 32 and 1 to 13.

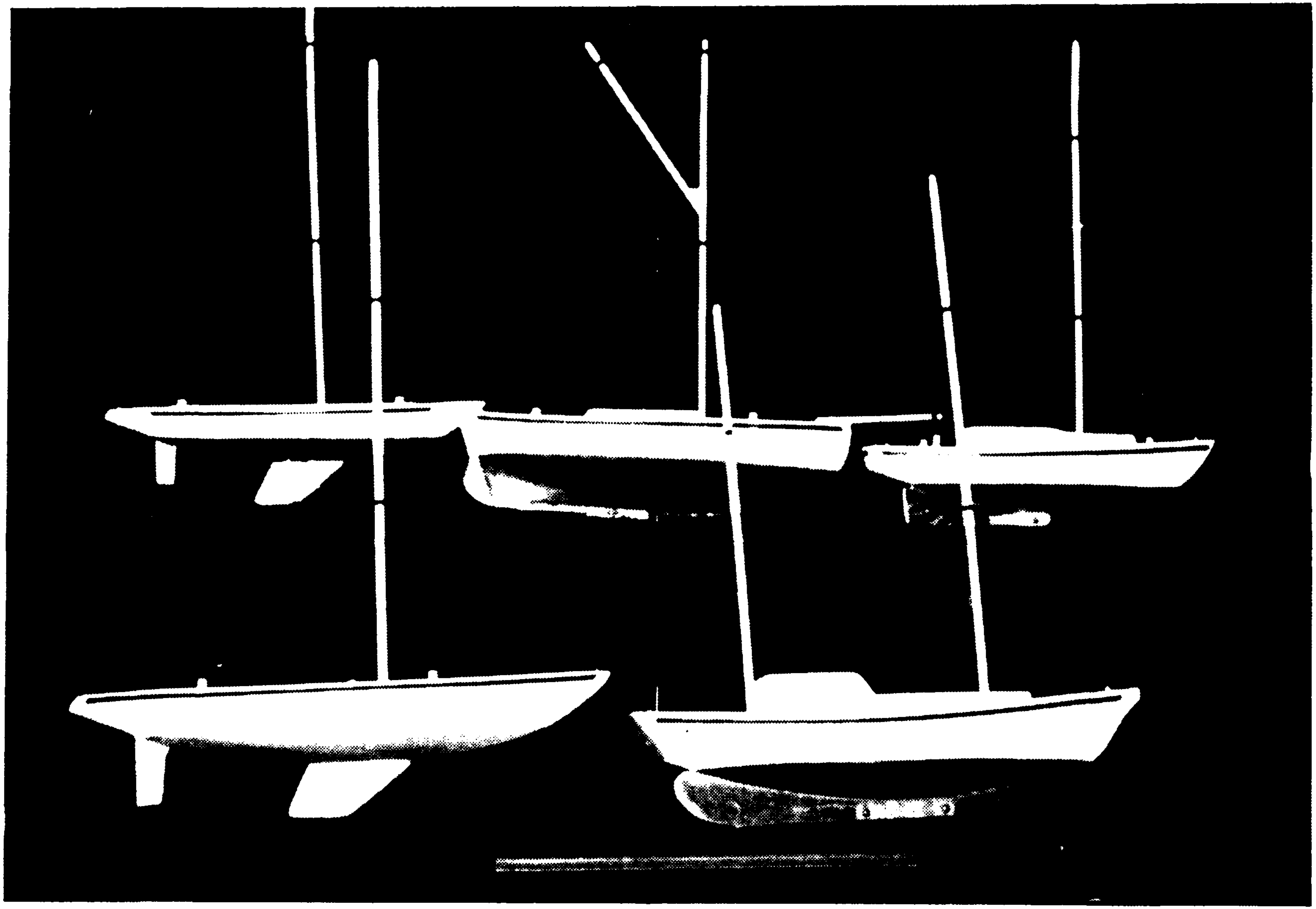


FIG. 6 YACHT MODELS

STANDFAST SAILING YACHT DESIGN

	FULL SCALE	1/32 SCALE MODEL
LENGTH (FT)	43	1.34
BEAM (FT)	11.6	.36
DRAFT (FT)	6.7	.21
DISPLACEMENT (LBS)	22000	.67
INITIAL STABILITY (FT LB / DEGREE)	1600	.0015
PERIOD IN ROLL (SECONDS)	4.1	.72
BALLAST (LBS)	11000	.34

FIG. 7 MODEL TO FULL SCALE COMPARISON

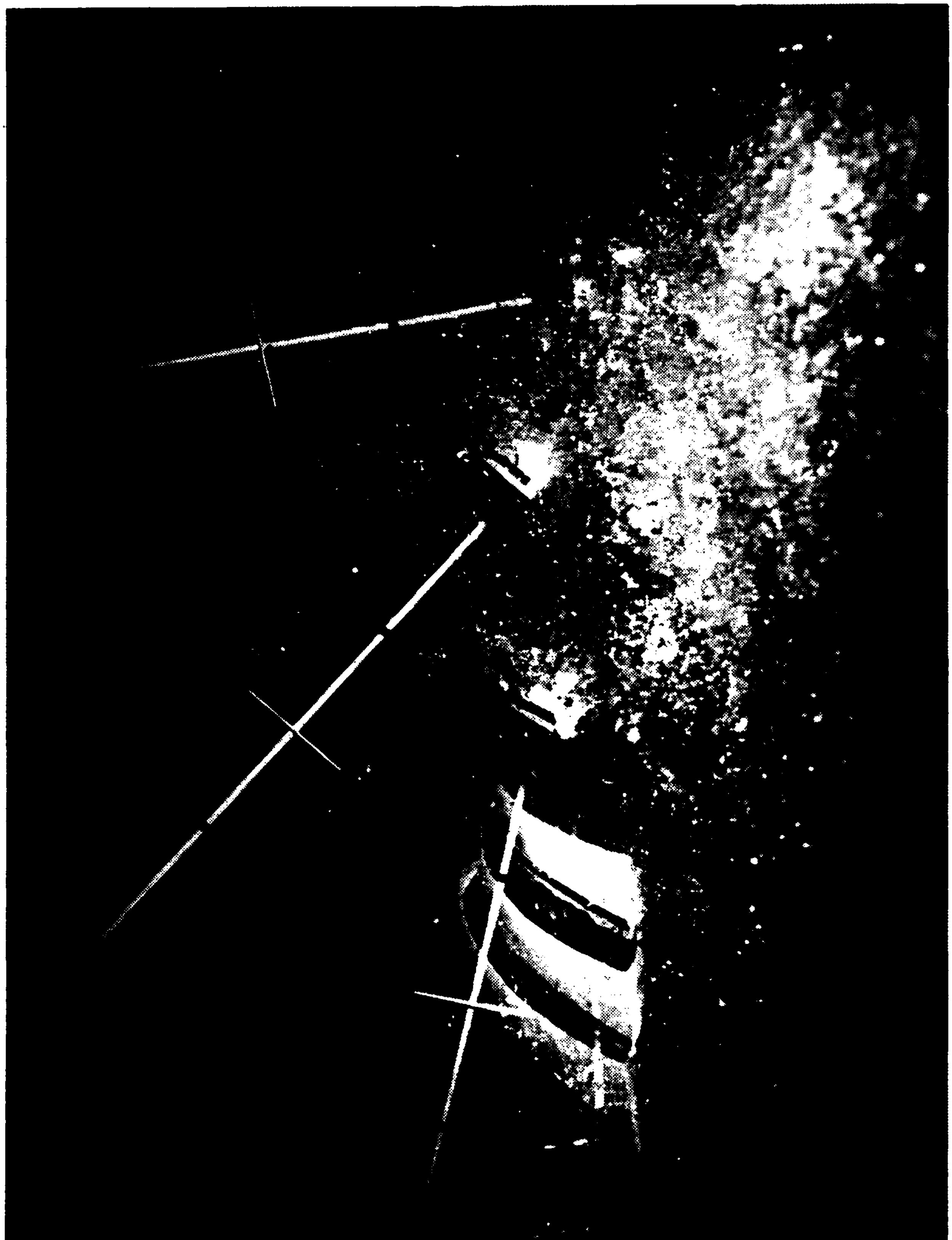


FIG. 8 TYPICAL CAPSIZE

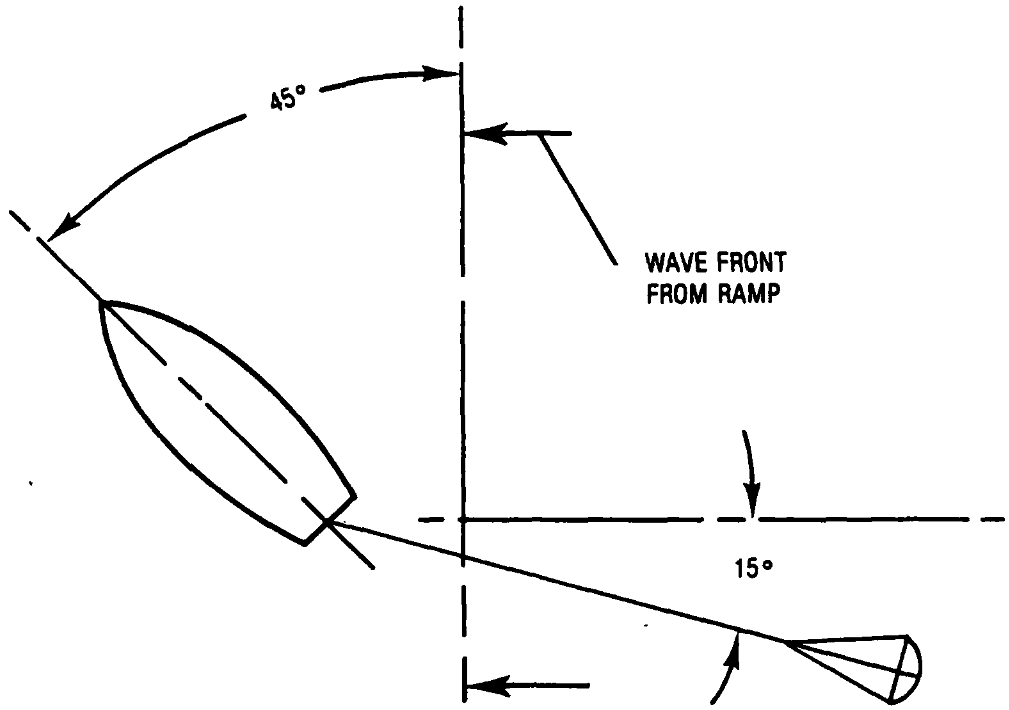


FIG. 9 POSITION OF BOAT AND DROGUE RELATIVE TO RAMP

FIG. 10 MODEL AND DROGUE IN BREAKING WAVE

For the initial testing the models were released to float free in natural waves. Under the proper wind and current conditions, the waves would reach a height of approximately one foot (32 ft. full scale) and would steepen until they formed the semblance of a whitecap. It was instructive to observe the waves and compare them with observations and pictures of large scale storm waves. The small waves would steepen and moving water would build up at the crest, but instead of cascading down the face of the wave as is often observed in ocean storms, the moving water would quickly mix with the underlying water and lose its forward velocity. It is believed that this is due to the apparent increase in viscosity of the water due to scale effect, i.e. the effect of Reynolds No. Because of this wave characteristic the models floating in wind formed waves were not subjected to any breaking wave strikes although the face of the wave occasionally approached near vertical.

The models were tested with and without a drogue. Without a drogue the models would lie almost abeam to the sea and would roll violently, but in no case did a monohull model show any tendency to roll beyond 90 degrees or to build up any appreciable velocity relative to the water. Figure 11 shows the model riding a steep wave. The loads on the hull and rigging appeared to be low. The monohull models would survive a scaled wind velocity of 100 mph. They would roll down and slide sideways on the bilge, but showed no tendency to roll over. One of the trimaran models, however, was equipped with an airfoil shaped beam to support the outriggers. This model would blow over as the scaled wind was increased above 60 to 70 mph.

This testing clearly showed that, although the ride may be uncomfortable, modern sailing yachts are capable of lying ahull in large non-breaking seas with no significant risk of capsize. This seems to be supported by actual experience.

For the next tests, the models were released with a variety of sea anchors or drogues. A sea anchor is defined as a drag device deployed from the bow and a drogue as a drag device deployed from the stern. It was immediately apparent that the boat rode much more easily with the drogue than with the sea anchor. With the sea anchor, the bow was driven off by each passing wave and the boat tended to sail from side to side. With the drogue, the boat would lie stern into the sea with little roll or yaw. This can be explained by the fact that on modern sailing yachts the windage is forward of the center of gravity and the center of lateral resistance of the underwater area is aft of the center of gravity. The boat wants to lie stern to the seas.

Figure 12 shows the model with a drogue deployed from the stern. The drogue did not prevent the stern from rising to a steep wave and there was no tendency of the boat to surf down the face of the wave.

Since it was not possible to capsize the models with naturally breaking waves, it was necessary to create a breaking wave of the appropriate height, velocity and form. After many unsuccessful attempts, a simple and highly effective solution was obtained. It was found that an 8 ft. dinghy with a 150 lb. man seated in the stern would form a continuously breaking stern wave if towed at 9 ft/second. The wave would travel at 45 degrees to the boat course. The height of the wave would be a maximum of about 8 inches

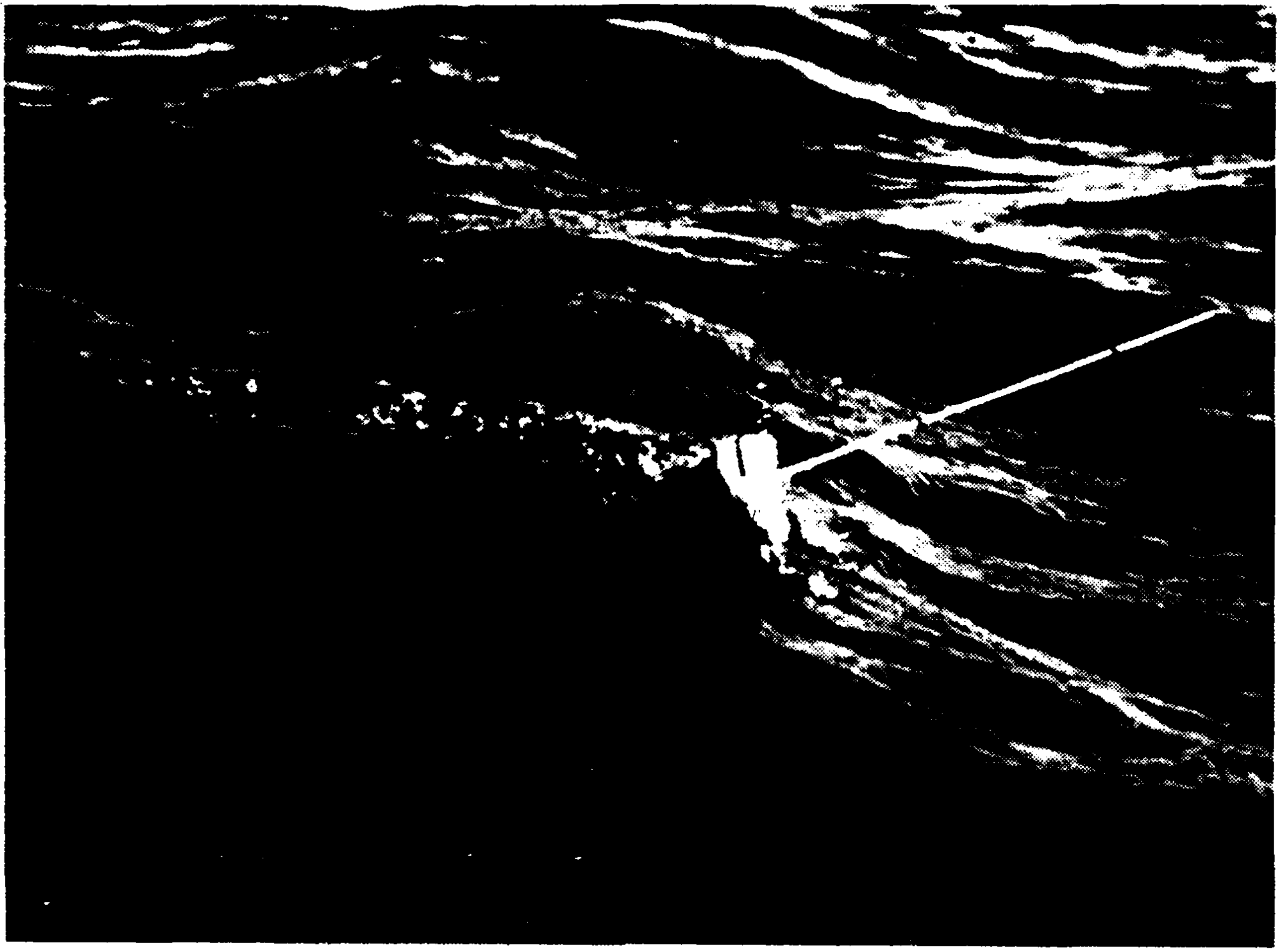


FIG. 11 MODEL ON STEEP WAVE

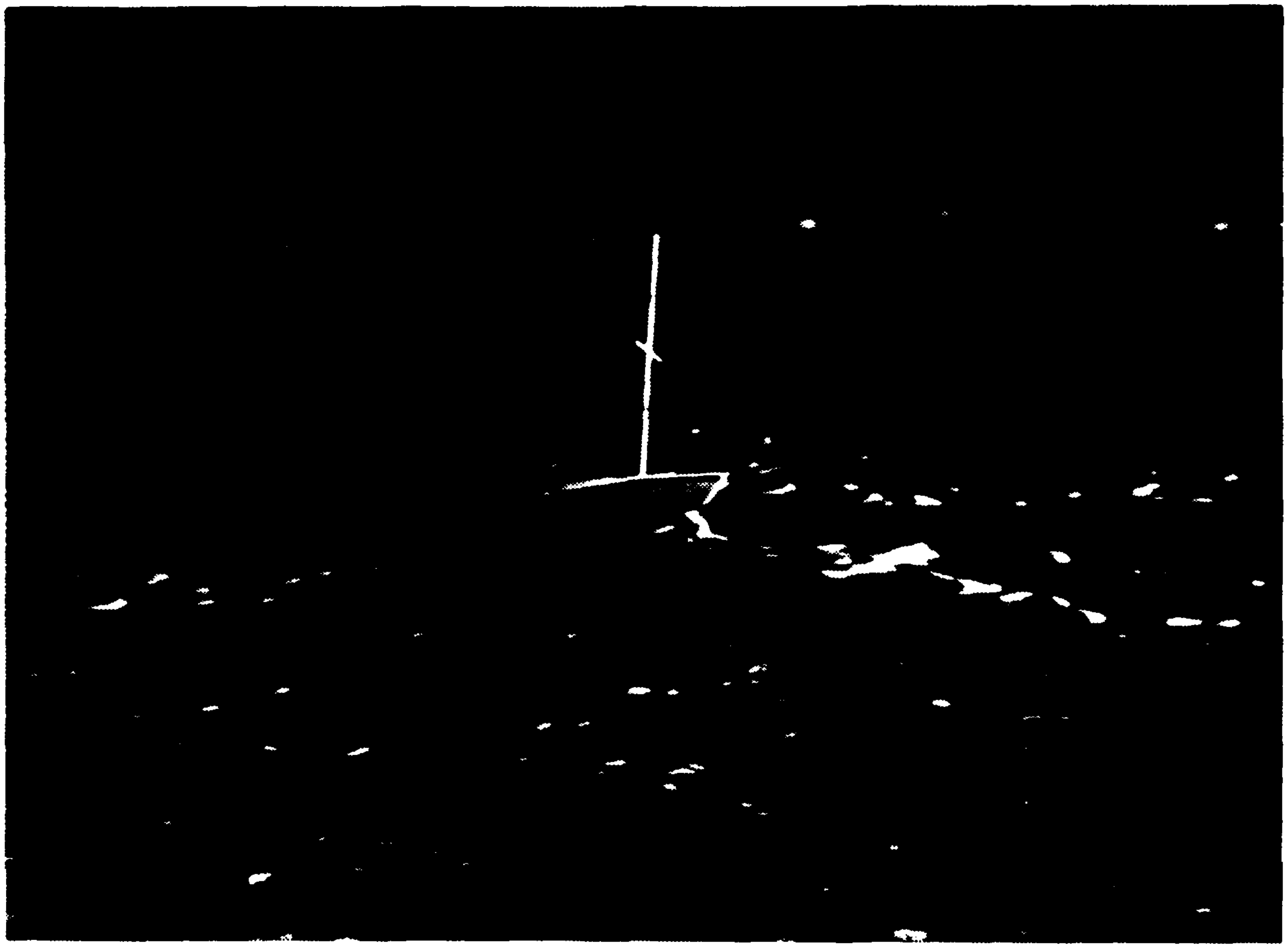


FIG. 12 MODEL WITH STERN DEPLOYED DROGUE

near the boat and diminish with distance. This wave would represent a 20 ft. breaking wave moving at about 21 knots. Figure 13 shows the dinghy creating the wave.

Two methods of testing were used. In the first, the model was mounted on a long pole and released into the breaking wave at the desired distance and angle. In the second the model was allowed to float freely and the dinghy was towed past it at the proper distance and direction. Motion pictures of 64 frames per second were taken from the dinghy and from the towboat to record the motion of the model during the wave strike. When a drogue was used, the load in the drogue towline was measured with the device shown in Figure 14. The towline was lead through an eye on the boat's transom and attached to a spring wire located behind the mast. Load on the drogue would cause the spring wire to bend. The instantaneous loading could be determined by measuring the angle between a vane attached to the spring wire and the mast as shown on the individual frames of the moving picture.

Two types of drogues were used, a disk type and a series type as shown in Figure 15. The disk type consisted of a thin plastic disk and a wire shaft. Vanes were provided on the forward face of the disk to prevent sideways motion. Various sizes and weights were tested. The series type consisted of a number of disk shaped plastic beads cemented to a thread with a weight on the end. The towline was made of nylon monofilament with a section of rubber band at the end to simulate the elasticity of the full scale nylon towline.

DISCUSSION OF RESULTS

Without a drogue all the models would be capsized by the breaking wave. When struck abeam they would often roll through 360 degrees. When struck on the quarter they would sometimes pitchpole end over end. Figure 16 shows typical events.

For a monohull sailing yacht it did not appear that the wind played much of a part in a breaking wave capsize. This conclusion seems to be confirmed by experiences in the Fastnet storm. With all sail off the rolling moment due to the wind is moderate and just before the breaking wave strike the boat is in the lee of a large wave. The period of the boat in roll is much less than the period of the large storm waves. Thus the boat has time to recover from the gust it experienced in passing over the previous crest. For a multihull however, the wind may be a significant factor in capsize performance because the outboard hull and support can generate lift.

With a drogue deployed, the models performed much better. Figure 17 shows the model being pulled through the breaking wave crest by a properly functioning drogue and towline. For the conditions under which these tests were conducted, it appeared that a disk drogue of 3 to 4-1/2 ft. diameter was required to prevent a 30 ft. boat from broaching and capsizing.

Preliminary tests were conducted with models of the six man life raft. In the 20 ft. simulated breaking wave, the unballasted liferaft with no drogue was violently tumbled. In a simulated 8 ft. breaking wave, the raft would be capsized by about half of the wave strikes. The provision of

FIG. 13 CREATING BREAKING WAVES

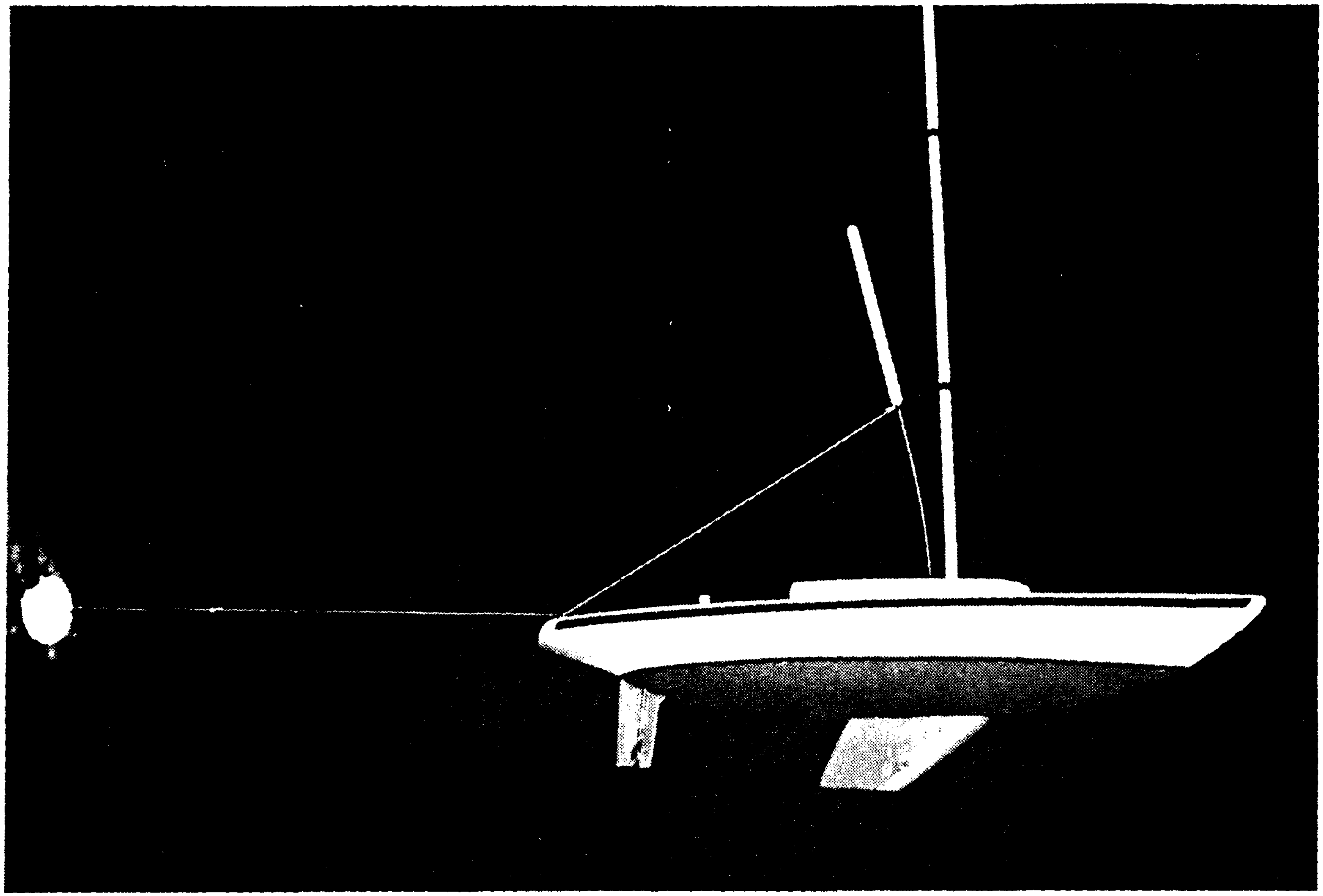


FIG. 14 LOAD WAND

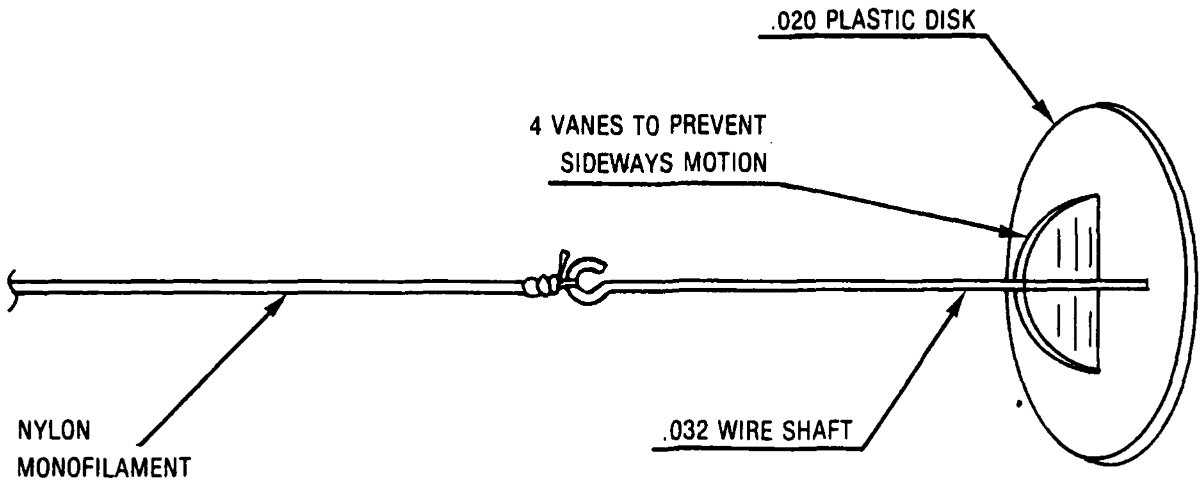


FIG. 15a TYPICAL DISK DROGUE

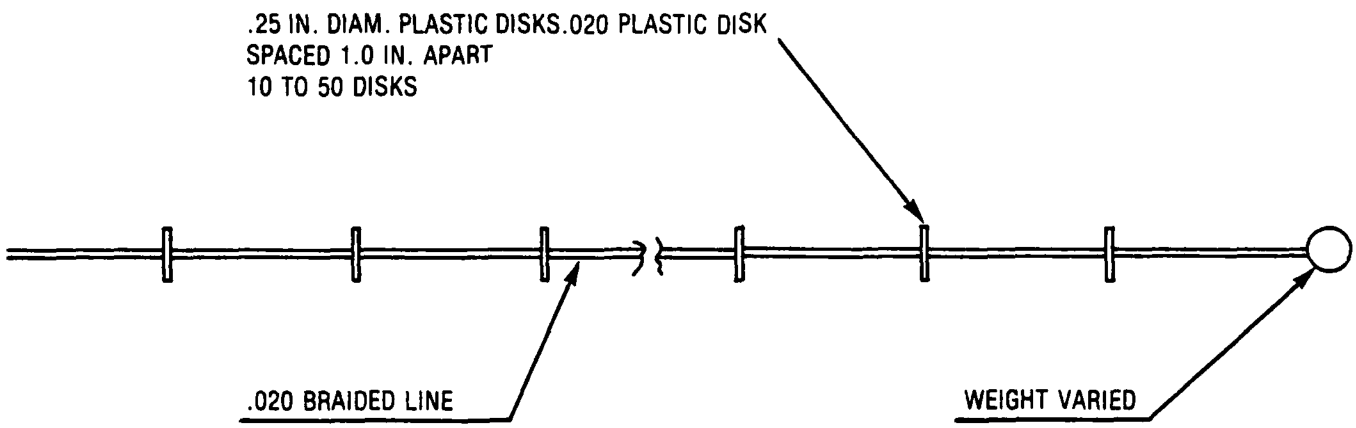


FIG. 15b TYPICAL SERIES DROGUE

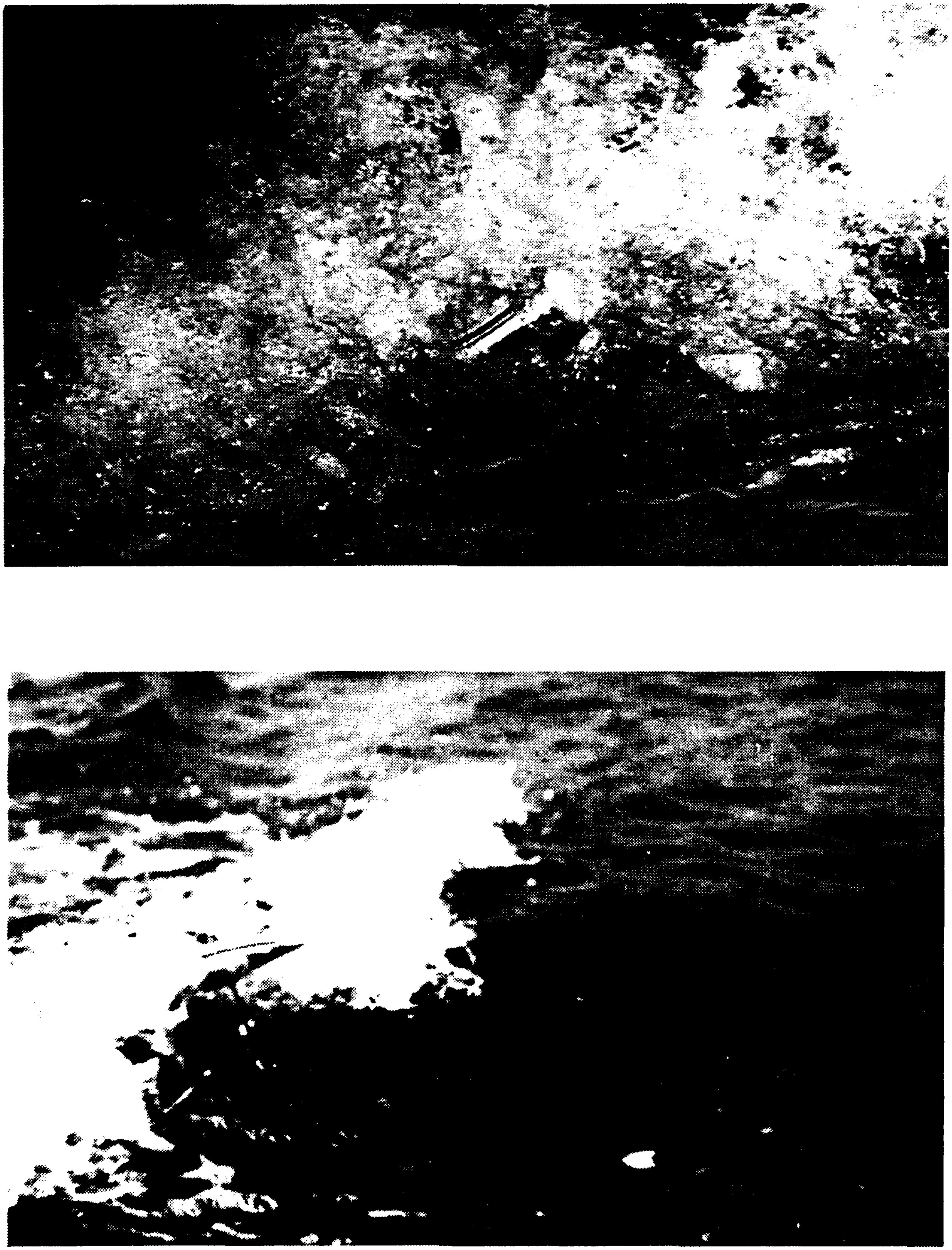


FIG. 16 CAPSIZE AND PITCH POLE

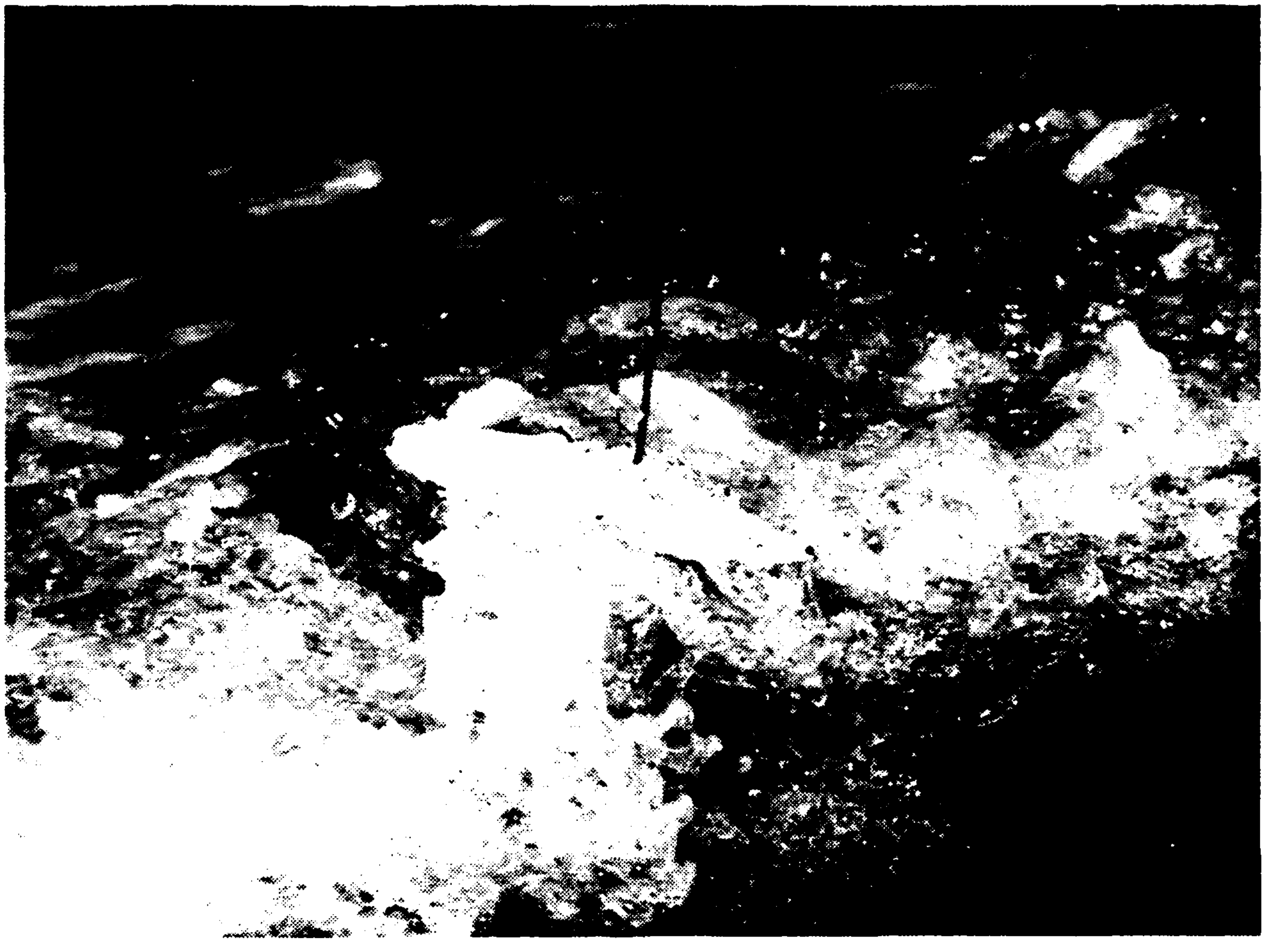


FIG. 17 DROGUE AND BREAKING WAVE

either a drogue or a hemispherical ballast bag prevented capsize in the 8 ft. wave. In the 20 ft. wave neither the drogue nor the ballast bag prevented capsize in most cases. However, with the hemispherical ballast bag, the raft would immediately right itself after capsize.

DROGUE AND BOAT DESIGN CONSIDERATIONS

Based on the limited testing accomplished to date, the following comments can be made regarding the drogue-boat system. Comments on the life raft system are contained in a following section.

Drogue Size - It is, of course, desirable to use as small a drogue as possible. The maximum loads will be lower and the equipment will be easier to deploy, retrieve and stow. A drogue can be considered to have the following three functions, and the size must be large enough to perform each separate function:

1) Under storm conditions, in non-breaking waves, the drogue must be large enough to hold the stern more or less into the wind. Without a drogue the boat will lie abeam to the sea. These model tests and actual experience suggest that a small drogue with a diameter less than 10% of the length of the boat will accomplish this. A large drogue would be required to hold the bow into the wind.

2) In steep non-breaking waves, the drogue must be large enough to prevent the boat from surfing down the wave face and possibly broaching. These model tests did not explore this condition very thoroughly and all that can be concluded is that the model showed no tendency to surf with a drogue diameter of 10% of the boat length. The mathematical model discussed in a latter section suggests that this diameter should be sufficient to prevent surfing.

3) In a breaking wave strike, the drogue must act in a powerful and immediate manner to pull the stern into the fast moving water of the wave crest. If the drogue is too small, if the drogue towline is too elastic or if there is too much slack in the towline, the stern will be driven down and the boat will broach and capsize. This is probably the most critical condition for which the drogue should be sized.

   If the boat is struck precisely from astern, a very small drogue might be adequate. If the boat is struck 30 degrees from astern, a smaller drogue would be required than if the boat were struck 45 degrees from astern. In the first series of tests using the horizontal water jet it was assumed that the drogue should be large enough to pull the stern into the wave if the boat were struck at 45 degrees. With no slack or elasticity in the towline, a drogue diameter of 10 to 15% of the boat length was found to be adequate.

In the second series of tests an effort was made to have the breaking wave strike the boat at 45 degrees from astern. This could not be controlled with any precision. The tests did show, however, that drogues with a diameter of less than 10 to 15% of the boat length would often permit the boat to broach and capsize, whereas larger drogues would generally prevent capsize.

DROGUE SHAPE

For most of this model testing a simple disk type drogue was used since it was convenient to handle in small scale, the dimensions could be controlled, and the drag coefficient is known.

In actual practice, two types of drogues are generally considered for use on small boats, a cone type and a parachute type. Various makeshift arrangements such as combinations of sails, anchors, tires and chain have also been tried.

CONE TYPE DROGUE

The classic drogue is the cone type. This has been used for many years by the Royal National Lifeboat Institution to stabilize their boats while running an inlet. There have been many other applications of the cone drogue. However a serious problem has been identified when a cone drogue is used on a small boat or life raft in a major storm. In large waves the towline goes slack when the boat is in the trough and pulls strongly when the boat passes over the crest. This is discussed in References 10, 11 and 12. When the towline is slack, the momentum of the water in the wake of the cone causes the drogue to turn inside out and tumble. When the towline again comes taut, the drogue may foul and even if it doesn't, the strain and abrasion is such that the possibility of damage in the 10 to 20,000 cycles of a major storm seems to be very high. There are many instances of a well built cone type drogue being destroyed in the early stages of the storm. Unreported tests in the circulating water channel at the U.S. Coast Guard Academy clearly demonstrate the violent motion of such a drogue under simulated storm conditions.

PARACHUTE TYPE DROGUE

There seems to be little experience with small parachute type drogues, i.e. less than 6 ft. diameter, under storm conditions. A small parachute drogue would suffer from the same tumbling problem that plagues the cone drogue. Also it is known that a parachute drogue (and some cone drogues) tend to be directionally unstable (Reference 13). When pulled they move sideways rather than axially.

In contrast, a large parachute, i.e. 18 to 26 ft. diameter, has been successfully used as a sea anchor and has survived a number of major storms with no structural damage. Most of the experience has been on multihulls. A good discussion of this application is contained in Reference 14. The drag is so high that the large parachute remains essentially stationary in the water. When the towline goes slack the parachute does not turn inside out or tumble but seems to pulsate gently. The major disadvantage of the large parachute is that it can develop a high load in the event of a breaking wave strike since it does not give or yield. A secondary disadvantage is that it can be difficult to deploy and retrieve.

SERIES TYPE DROGUE

This is a novel drogue arrangement that has been under development by the author for the past two years. The design is intended to overcome the disadvantages of the cone and parachute type. A typical configuration would consist of 100 cones, 8 inches in diameter spliced into 200 ft. of line with a 25 lb. anchor at the far end. The individual cones would be made of a lightweight sailcloth such as spinnaker material. Figure 18 shows a portion of a full scale drogue. Preliminary tests show that this system will not foul or tumble. The drag can be readily adjusted to give any desired value and it may be possible to provide overload protection. Ease of launching, retrieving and stowage aboard are potential added advantages.

DROGUE WEIGHT

Unless the drogue is weighted it will lie close to the surface. The surface water moves in a circular path. In 30 ft. waves the radius of the circular motion would be 15 ft. The drogue and boat could move together and apart by as much as 60 ft. It is desirable to keep the slack in the towline to a minimum since the drogue force must be applied quickly in the event of a wave strike. Also if the drogue is near the surface, it would be possible for the drogue to be picked up by a breaking wave crest and hurled toward the boat thus creating perhaps 100 ft. of slack in the towline. In view of these potential problems it would seem advisable to weight the drogue so that it would ride 30 to 40 ft. below the surface. A preliminary analysis indicates that a weight of 25 to 50 lbs. might be required. It is difficult to apply this weight to a cone or parachute drogue without introducing the possibility of deformation or fouling.

DROGUE LOADS

Using the equipment shown in Figure 14 a scaled maximum drogue load of 5000 lbs. was measured when the model was struck with a breaking wave moving at 21 knots. From analysis of these load data and from observation of the dynamic behavior of the boat when struck by a wave, a mathematical model was constructed which permits the drogue loads to be calculated for non-breaking regular waves and for a breaking wave strike. A discussion of this model and some typical results follow. The 5000 lb. maximum load discussed above was obtained with a scaled 32 ft. boat towing a 3-1/2 ft. diameter drogue. The breaking wave crest velocity was 21 knots. For a 30 knot wave crest velocity, the 5000 lb. load would extrapolate to 10,000 lbs. and for a 40 knot velocity the load could reach 18,000 lbs.

It would be desirable to develop a drogue system which would limit the maximum load. The series type drogue offers some possibility of accomplishing this, and tests are planned to gain information on the subject.

In addition to the maximum load imposed by a wave strike, the drogue system is subjected to a cyclic load each time a wave passes. A breaking wave strike will probably be encountered no more than a few times in the life of the drogue, but the cyclic load will occur 10,000 times or more in a single storm. For these tests the maximum measured cyclic load was less than 500 lbs., but the test conditions were not severe and did not represent a major storm. The mathematical model indicates that the cyclic load for a 32 ft. boat with a 3-1/2 ft. diameter drogue could exceed 1000 lbs.

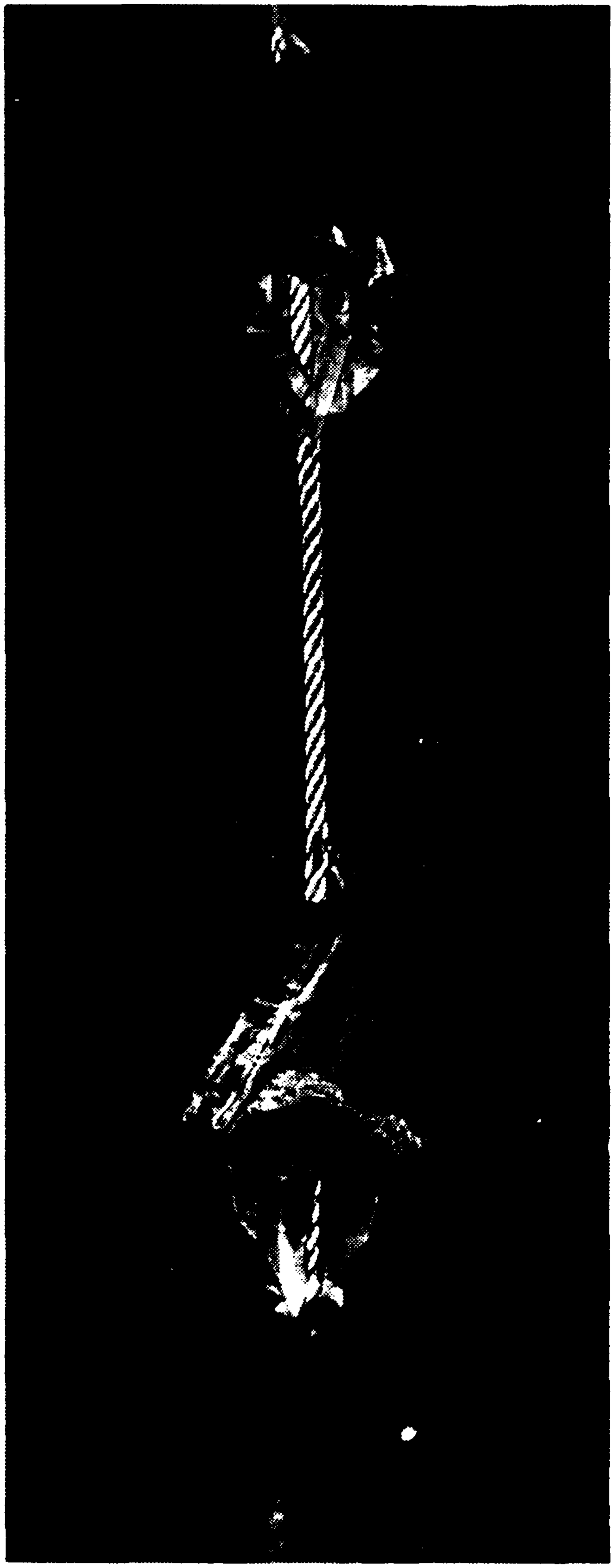


FIG. 18 SERIES DROGUE

DROGUE TOWLINE

The towline must be capable of carrying the loads discussed above with a reasonable safety margin. Particular care must be taken to avoid fatigue or chafe at the attachments. There are several considerations that effect the choice of towline length. If the drogue lies near the surface, it is probably desirable to position the drogue on the back face of the following sea. For a wave length of 300 ft. this would mean a towline length of 450 ft. In a typical storm in which the sea is confused, it is difficult to see how a rational choice could be made.

If the drogue is weighted to ride beneath the waves, the towline length will determine the depth at which the drogue lies. This is subject to analysis with the mathematical model but additional experimental input is required.

The series drogue with a weight at the end will ride partly on the surface and partly beneath the surface. Some limited testing shows that such a system can provide a faster load buildup than the cone or parachute type in the event of a wave strike. This is a desirable characteristic since if the drogue load builds up quickly, a broach can be prevented with a smaller total load.

Figure 19 shows the approximate geometry of a boat drogue system in large waves. A typical cone and a series type drogue are shown.

The degree of stretch or elasticity in the towline will affect both the cyclic load and the breaking wave load in the line. Greater elasticity will always reduce the cyclic load and often reduce the maximum load. U.S. Coast Guard testing, Reference 15, has determined that the dynamic elasticity of synthetic line is much less than the semi-static elasticity; i.e. when the load is applied rapidly the line does not stretch much, whereas if the load is applied gradually the line stretches. In a wave strike, the application of load is very rapid. This effect can be studied in the mathematical model.

BOAT DESIGN

Location of Drogue Attachment: As discussed in the previous section the tests clearly show that the drogue should be deployed from the stern. This is a somewhat unfortunate result because most boats are designed to take the sea on the bow, not on the stern. Discussions with sailors reveal an understandable reluctance to deploy a drogue from the stern and thus expose the transom, cockpit and companionway to a sweeping wave crest. The mathematical model derived from a continuation of the testing described in this report can provide design criteria for these structures so that no damage should be incurred. This is perhaps the most important input to yacht design for survival in Fastnet type storms.

Both the first and second series of tests showed a bridle rigged to the corners of the transom to be superior to a center line attachment. For a given drogue force, the bridle provides a much larger moment to turn the stern into the breaking wave face.

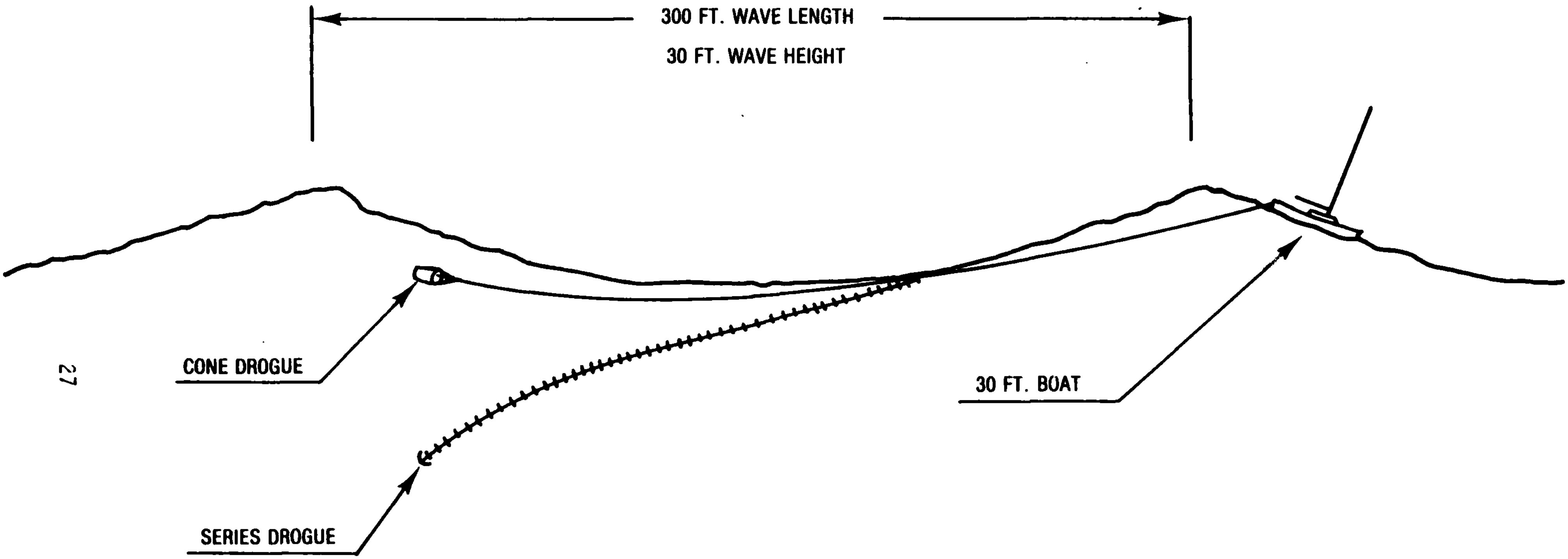


FIG. 19 TWO TYPES OF DROGUES IN 30 FT SEAS

The tests also showed the desirability of mounting the attaching eyes for the towline as high as possible above the waterline. When the drogue acts to counteract a broach, it not only turns the boat into the wave face but also provides a rolling moment in opposition to the capsizing moment from the wave. The higher the attachment, the greater the righting moment.

The upper outboard corners of the transom represent a good structural location since three surfaces intersect at this point. Attaching eyes are preferable to chocks with regard to possible chafe and fatigue.

CREW AND EQUIPMENT PROVISIONS

With a drogue deployed from the stern, the cockpit may not be habitable in a breaking wave strike. Figure 20 shows such a situation. Despite the fact that the boat was swept from stern to bow, the boat and drogue rode the wave quite gently in this instance. The safest place for the crew is in the cabin below, strapped in with aircraft type seat belts.

In the Fastnet Race several crewmen attempted to retreat to the cabin but were unable to stay there because heavy equipment had torn loose and was flying about in a dangerous manner. The retention system for heavy equipment and the latch system on drawers and containers should be designed to a specific acceleration requirement as is done in the design of a cabin for a commercial airplane. Further tests supported by the mathematical model can provide these design requirements.

LIFE RAFT AND DROGUE DESIGN CONSIDERATIONS

A drogue on a liferaft is intended to perform the following functions:

1) Reduce the drift rate and keep the raft directionally stable.

2) Prevent surfing.

3) Reduce the possibility of capsize by a breaking wave.

The tests described in this report were only exploratory. No attempt was made to evaluate drogue size, loads, or design.

For the scaled 86 inch diameter 6 man life raft, a 2 ft. diameter disk type drogue was tested. This system showed reasonable performance in limited testing. However, the raft also performed well with the hemispherical ballast bag and no drogue. No design conclusions can be drawn at this stage in the program. It may be that a suitably ballasted raft does not benefit much from the use of a drogue.

Full scale tests of life rafts with and without drogues are presented in References 10 and 11.

MATHEMATICAL MODEL

In a major storm the wave pattern is disorderly. In fact it is frequently described as chaotic. A dangerous breaking wave is formed by a combination of

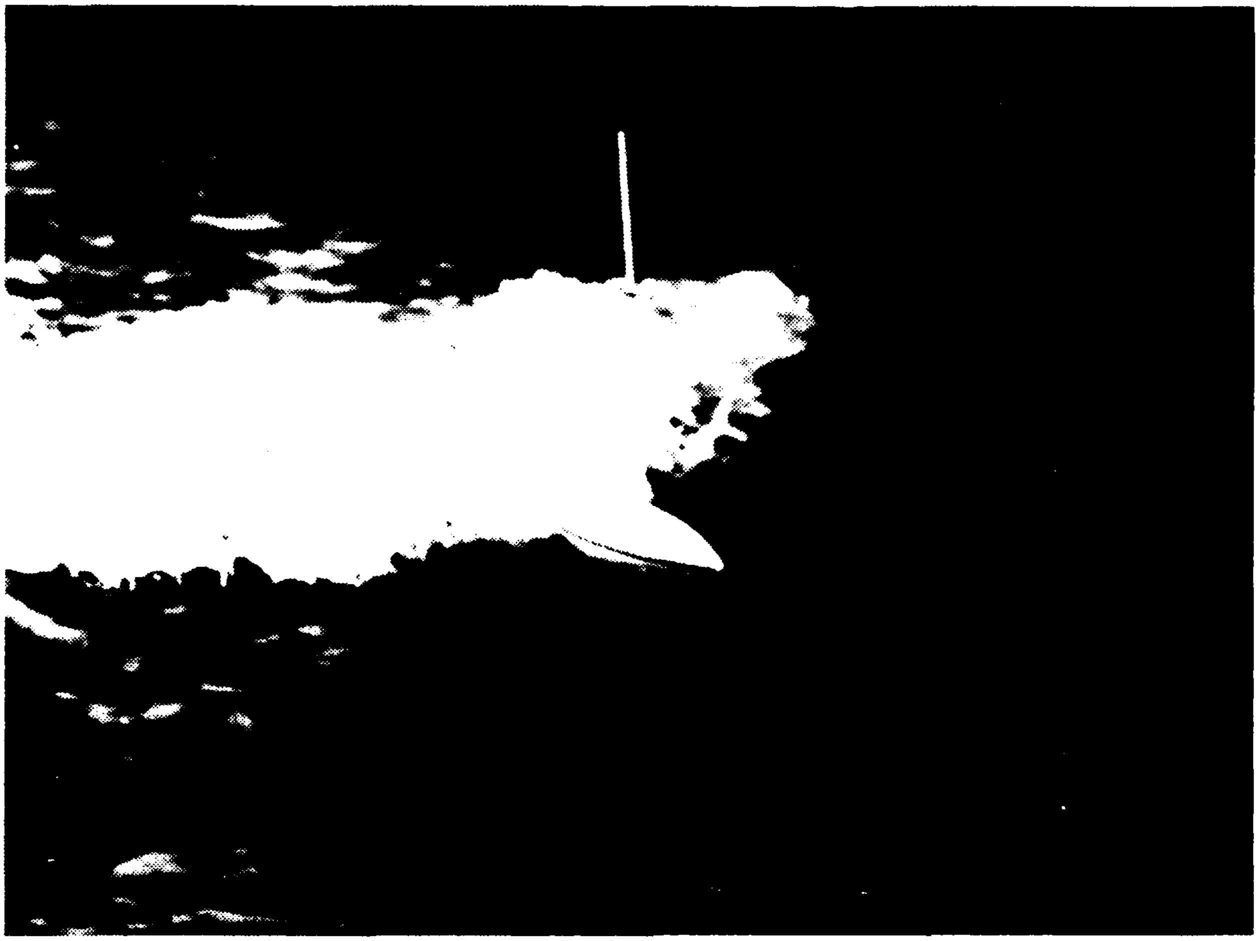


FIG. 20 BREAKING WAVE STRIKE ON STERN

many influencing factors including the interaction of random waves, the wind velocity, the rate of change of wind velocity and others. Each breaking wave is different. Even if the detailed characteristics of the breaking wave were known, a precise mathematical treatment of the interaction of the wave with a boat would be a highly complex problem, probably beyond the range of our present computational capability. However, a careful analysis of the moving pictures taken during this series of model tests has led to the formulation of a simplified mathematic model which has the potential of providing highly useful results when supported by sufficient experimental data.

The model described in the following pages is considered to be a first step. So far it seems to work well in describing what has actually been observed, both model scale and full scale. Each element of this program can be further refined as more information is obtained.

Wave: The surface of the wave is modeled as a simple sine wave.

$$y = W_h \sin(rt - \frac{2\pi x}{l})$$

where y = vertical position of wave surface

W_h = One half of wave height (ft.)

r = Circular frequency in radians per second, $\frac{2\pi}{P}$ where P is the wave period in seconds

t = time in seconds

x = horizontal position of the wave face

l = wave length

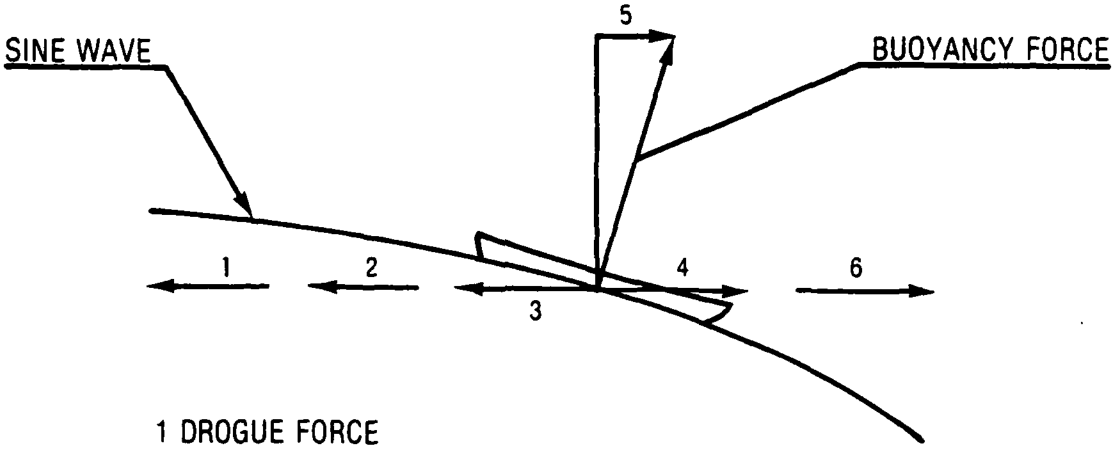
It is intended to consider other equations for the wave surface.

BOAT AND DROGUE

The assumed forces on the boat are shown on Figure 21.

1. Drogue Force = $\frac{w}{2g} A_1 C_{d_1} V_1^2 + na_1$

w = specific weight of water
g = acceleration of gravity
C_{d1} = drag coefficient of drogue
V_1 = velocity of drogue
n = effective mass of drogue including entrapped water
a_1 = acceleration of drogue
A_1 = cross section area of drogue



1 DROGUE FORCE
2 INERTIA FORCE
3 HULL DRAG
4 AIR DRAG
5 HORIZ. COMPONENT OF BUOYANCY FORCE
6 FORCE FROM BREAKING WAVE CREST

FIG. 21 FORCES ACTING ON BOAT

Drogue Force (F_1) = Towline Force (F_t)

Inertia Force (F_2) = Hull Drag (F_3) + Air Drag (F_4) + Buoyancy Force (F_5) + Breaking Wave Force (F_6) + Towline Force (F_t)

$$\frac{W_1}{2g} A_1 C_{D_1} V_1^2 + n a_1 = K(X_2 - X_1) = -m a_2 + \frac{w_2}{2g} A_2 C_{D_2} (Vw - V_2)^2 + \frac{W_4}{2g} A_4 C_{D_4} Va^2 - mg\frac{dy}{dx} + \frac{W_6}{2g} A_6 C_{D_6} (V_3 - V_2)^2$$

Drogue Force = Towline Force = $k(X_2 - X_1)$

k = towline elasticity, lbs/ft
x_2 = horizontal position of boat
x_1 = horizontal position of drogue

2. Inertia Force = $m\ a_2$

m = mass of boat
a_2 = acceleration of boat

3. Hull Drag = $\frac{w}{2g} A_2\ C_{d2}\ (v_w - v_2)^2$

w = specific weight of water

A_2 = Area of maximum transverse underwater section of boat

Cd_2 = drag coefficient referenced to underwater section

v_w = surface velocity of wave

v_w = $rW_h \sin (rt - 2\pi\ x_{2/1})$

v_2 = velocity of boat

This term is the conventional hull drag of a boat moving forward or backward through the water. No distinction is made for forward or backward motion.

4. Air Drag = $\frac{w_a}{2g} A_4\ C_{d4}\ v_a^2$

w_a = specific weight of air

A_4 = Windage cross section area of boat from astern including mast, rigging, etc.

Cd_4 = Drag coefficient of total windage area

v_a = velocity of air

This term is modeled as a function of the position of the boat on the wave. When the boat is on the crest, it receives the full air drag, when it is in the trough it receives a specified fraction of the full air drag.

5. Horizontal component of the buoyancy force. The buoyance force is assumed to be equal to the displacement; effect of vertical acceleration is neglected, and the buoyancy force is assumed to act normal to the wave surface at x_2, the location of the boat

   Buoyancy force = mg = displacement

   Horizontal component of buoyance force = $-mg \frac{dy}{dx}$

   $\frac{dy}{dx}$ = slope of wave at boat location x_2

   m = mass of boat

6. Force from Breaking wave Crest

   From the small scale tests it was concluded that the "worst case" breaking wave strike could be represented by the entire above water portion of the boat being swept from the stern by water moving at the phase speed of the wave, i.e. moving at wave crest velocity.

   $$\text{Breaking Wave Force} = \frac{w}{2g} A_6 C_{d6} (v_3 - v_2)^2$$

   A_6 = Above water transverse cross section area of boat. Same as A_4 except mast and rigging omitted since these elements would not be swept by wave crest.

   Cd_6 = Drag coefficient of above water section of boat

   v_3 = Breaking wave crest velocity

   $$v_3 = \frac{1r}{2\pi}$$

   v_2 = boat velocity

To operate the program, the boat and drogue are allowed to move on the wave under the influence of forces 1 through 5 for four or more complete wave cycles. This permits the starting transient to damp out. Then, at a specified position on the forward face of the wave as defined by the wave slope, the boat is struck by force 6, the breaking wave crest. Force 6 is allowed to continue until the total drogue load has passed the peak value.

Figure 22 shows a typical set of computer results. Appendix A contains the program used for these computations.

Also shown in Figure 22 are the actual scaled drogue loads measured on a model boat compared with a computer simulation. The drag coefficients necessary to achieve this correlation seem reasonable, but much more experimental confirmation is required. It is believed that this simplified computer simulation will be a very useful tool when supported by further testing.

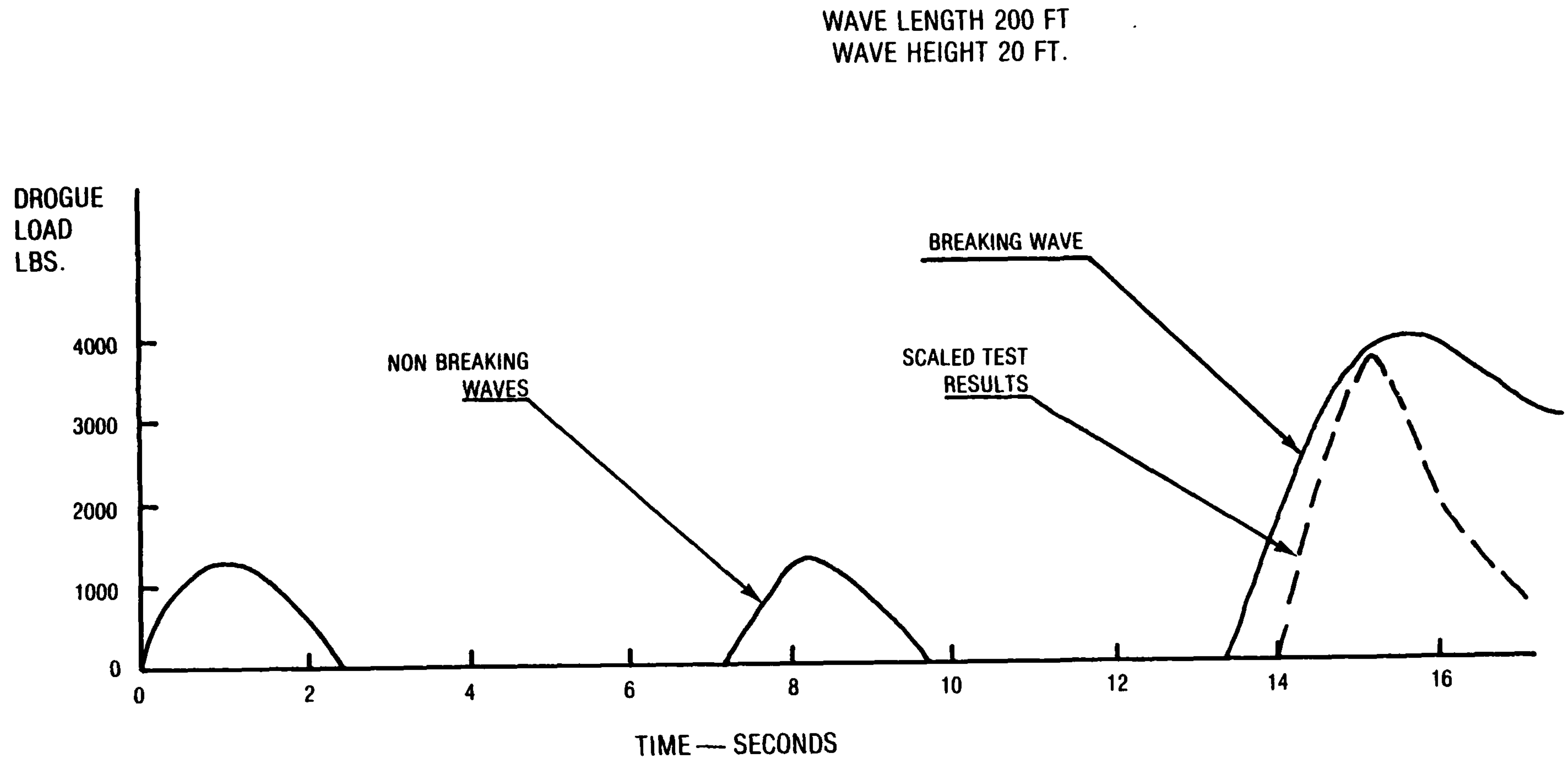


FIG. 22 COMPUTER SIMULATION OF 30 FT BOAT WITH 3 FT DIA. DROGUE

CONCLUSION

The results of the tests described in this report strongly suggest that the hazard of breaking wave capsize of sailing yachts in the 30 to 50 ft. size range can be greatly reduced and possibly eliminated by the use of a properly engineered drogue together with relatively moderate changes in boat design.

The dynamics of the boat drogue system are complex and there is a potential of generating very high loads in the drogue towline.

Current drogue designs may not be satisfactory:

1. The drogue may fail as a result of chafe and fatigue.

2. In the event of a breaking wave strike the drogue load may not build up quickly enough to prevent a broach.

3. When the boat is struck by a very fast moving wave crest, the drogue load may be excessive.

A mathematical model has been constructed which, when supported by adequate test data, should permit the boat drogue system to be properly engineered.

A series type drogue offers promise of providing a reasonable solution to the above problems.

RECOMMENDATIONS

1. The tests discussed in this report used very small models, approximately 1 to 32 in scale. It would be desirable to conduct similar tests with larger models. A scale of 1 to 10 would permit the models to be tested in natural storm waves with a height of approximately 4 ft. Such waves more closely simulate ocean waves and the dynamics of the models with and without a drogue can be determined with greater accuracy.

2. Enough information is presently available to permit the construction of several experimental full scale drogues. Useful data could be obtained by towing these drogues and by deploying the drogues from a drifting boat in moderate wind and sea conditions.

3. The mathematical model is a valuable tool and should be refined and improved based on input from the above tests and other sources.

4. Preliminary testing was accomplished on the liferaft model. It appears that the technique described in this report can provide useful information on the capsize of liferafts, with and without drogues and/or water ballast systems such as the hemispherical ballast bag. Further life raft tests should be conducted.

5. No testing was accomplished on a typical fishing boat hull. A small model (1 to 53 scale) of a 73 ft. commercial shrimper has been constructed. It would be desirable to conduct some exploratory testing.

6. The goal of this program is to develop a design specification for the boat-drogue system, and to test a full scale article under as severe conditions as can reasonably be obtained.

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APPENDIX A

COMPUTER PROGRAM TO PREDICT CAPSIZE FORCES

```
      program capsize2
c.......this is a program written by D.Jordan to predict forces
c.......on sailboats in capsizing conditions...................
      real k,kk,l,m,n,mult
      integer z
      open (unit=3,name='cap.in',type='old')
      open (unit=4,name='cap.out',type='new')
c
c.......initialize..........................................
c
      rb=0.9       !resist factor of boat (drag/vel rel. to water**2)
      m=310.0      !mass of boat (displacement/g)
      n=25.0       !effective mass of drogue incl. entrapped water
      g=32.2       !graviatational acceleration
      pi=3.14159
      h=0.1          !step size for time
c
c.......set-up..............................................
c
      read (3,*) ncase      !number of cases to be run
      do 20 j=1,ncase
      x1=0.0       !position of drogue in horizontal axis
      v1=0.0       !velocity of drogue (ft/sec)
      x2=0.0       !position of boat on horizontal axis
      v2=0.0       !velocity of boat (ft/sec)
      z=0          !programming factor,z=1 for breaking wave
      read (3,*) slmin,slmax   !minimum, maximum slope
      read (3,*) k,dd,db,da
c.......k=towline elas,dd=drogue drag,db=boat drag struc.k by wave
c.......da=air drag
      read (3,*) wh,l,r
c.......wh=wave height, l=wave length, r=wave frequency
      c=wh/2.0
      v3=l*r/(2.0*pi)          !wave celerity
      write (4,25) j,slmin,slmax,k,dd,db,da,wh,l,r
   25 format(/,1x,'  case=',i2,'  min slope=',f6.3,'  max slope=',f6.
     %3,'  towline elas=',f5.1,/,1x,'  drogue drag=',f4.1,'  boat drag=
     %',f4.1,'  air drag=',f5.1,/,1x,'  wave height=',f5.1,'  wave leng
     %th=',f5.1,'  wave freq=',f4.2,/)
      write (4,50)
   50 format (2x,'time',2x,'drog pos',2x,'drog vel',2x,'boat pos',
     % 2x,'boat vel',2x,'water vel',2x,'slope',2x,'z',2x,'line force')
```

```
c
c.......calculate...............................................................
c
        do 10 i=1,600
        t=i*h
        x1=x1+h*v1
        x2=x2+h*v2
        quan1=r*t-2.0*3.14*x2/l
        quan2=-2.0*3.14/l
        if (x2 .lt. x1) then
        kk=0.0        !allows for slack in towline
        else
        kk=k
        end if
        vw=c*r*sin(quan1)  !velocity of water on wave surface
        sl=c*quan2*cos(quan1) !wave slope
        fa=0.7*da+0.3*da*sin(quan1)  !instant air drag wrt boat pos
        fw=db*(v3-v2)**2  !force on boat from breaking wave
        v1=v1+h*(kk/n*(x2-x1)-dd/n*v1**2)
        mult=abs(vw-v2)/(vw-v2)
        v2=v2+h*(-g*c*cos(quan1)*quan2+fa/m-kk/m*(x2-x1)+rb/m*
     %  (vw-v2)**2*mult)
        if (t .lt. 30.) then
        go to 10                !allows system to reach steady state
        else if (z .eq. 1) then
        v2=v2+h*fw/m
        else if (t .gt. 40. .and. sl .gt. slmin .and. sl .lt. slmax
     %.and.vw .gt.5) then
        v2=v2+h*fw/m
        z=1
        end if
        ti=2.0*t
        it=iifix(2.*t)
        dt=abs(ti-it)
        if (dt .lt. 0.0001) then
        fd=kk*(x2-x1) !force on towline (lbs)
        write (4,100) t,x1,v1,x2,v2,vw,sl,z,fd
  100   format(2x,f4.1,3x,f7.2,3x,f6.2,4x,f7.2,3x,f6.2,5x,f6.2,2x,
     %  f6.3,2x,i1,3x,f8.2)
        end if
  10    continue
  20    continue
        stop
        end

$
```

END

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