INVESTIGATION OF MINIMUM STABILITY REQUIREMENTS FOR BALLASTED, MONO-HULL SAILING CRAFT

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ABSTRACT

In this paper the results are presented of an investigation of the minimum stability requirements for ballasted, mono-hull sailing craft. This study was carried out in support of the work of Working Group 22 of Technical Committee 188 of the International Standards Organization, presently preparing a new International Standard for the stability of small craft of length less than 24 metres. This Standard is of particular importance as it will be one of about 30 Standards presently being developed for use in conjunction with the European Directive on Recreational Craft.

The paper first of all addresses recent sailing yacht casualties in an attempt to determine potentially dangerous stability characteristics in mono-hull sailing craft. To support the development of stability criteria based on this analysis, the stability data of so-called category I yachts (considered suitable for sailing anywhere in the world), of which more than 5 vessels were built and/or with a long operational history without any stability-oriented problems, are also considered. A proposal is then made for the minimum value of the vanishing angle of positive stability and the righting moment at 90 degrees of heel, for the four stability categories considered.

The development of a so-called Dynamic Stability Factor is also presented. This takes into consideration various factors of importance in a dynamic sense, such as the roll moment of inertia, the loss in waterplane inertia due to the wave through amidships, etc. In the Stability Standard under development it is stipulated that a sailing vessel must possess a minimum value for this factor, dependent on the stability category to be assigned.

1. INTRODUCTION

In Europe effective barriers to trade exist due to the fact that various countries impose technical regulations based on national legislation, involving approval of all recreational craft. Particularly France and Italy impose such regulations. In other member states technical standards exist, not backed by national legislation, thereby not creating obstacles to trade but, since these are not enforced, no guarantee exists against the production and placing on the market of potentially dangerous products. For these reasons, the International Council of Marine Industry Associations (ICOMIA), in 1988, decided to propose to the European Community that a Directive on Recreational Boats be prepared, to remove existing barriers to trade and to ensure that all recreational craft comply with certain technical requirements. This Directive on Recreational Boats was recently completed and passed by the European Parliament. It requires that as of June 1996, all recreational boats that are to be marketed in the European Union comply with the requirements set therein and in the associated technical standards being developed by various working groups of Technical Committee (TC) 188 of the International Standards Organization (ISO), or acceptable alternatives thereto.

Working Group 22 of TC188 is preparing ISO Standard 12217 on Stability and Buoyancy. This Standard is divided into 2 parts. Part 1, almost ready to be issued as a Committee Draught (CD), addresses non-sailing vessels, while Part 2 addresses sailing vessels. In this latter Part, sailing vessels are divided into 3 types, viz:

- sailing vessels (mono-hull and multi-hull) reliant on the use of crew weight for capsize recovery;
- sailing vessels (mono-hull and multi-hull) reliant mainly on hull form for stability.
- Mono-hull sailing vessels reliant mainly on both hull form and ballast for stability;

This sub-division recognizes the different mechanisms involved in capsize recovery and safety against capsize, i.e. crew weight such as in the case of sailing dinghy's and the like, the use of form stability only such as in the case in multi-hulls and some types of mono-hulls, and the use of ballast in combination with form stability, as in the case of most mono-hull sailing yachts with a length in excess of about 7 metres.

2. STABILITY REQUIREMENTS AS LAID DOWN IN THE LAST WORKING DRAUGHT OF ISO STANDARD 12217

For sailing vessels reliant on the use of crew weight for capsize recovery, requirements have to be met with respect to flotation and stability in the swamped condition. For sailing vessels reliant mainly on hull form for stability, requirements have to be met with respect to downflooding height to prevent undue ingress of water when upright and when heeled and, in addition, requirements are set on the size of the maximum sail area and on the area under the static righting moment curve up to the angle of maximum righting moment. Also, these sailing vessels must meet certain buoyancy requirements in the capsized condition because once capsized they usually cannot be righted.

For mono-hull sailing vessels reliant mainly on both hull form and ballast for stability, requirements have to be met with respect to downflooding height and angle, and with respect to the ability to recover from an inversion and a knockdown. After considerable discussion in the Working Group, it was decided that this latter requirement is complied with if a certain minimum value of the angle of vanishing positive stability is met and if, at the same time, a certain minimum righting moment at 90 degrees of heel is met. The requirement of a minimum angle of vanishing positive stability is necessary to ensure that the degree of stability in the inverted position is not too great and that the vessel, once it should become inverted, can right itself through the action of a moderate force or moment. The requirement of a minimum righting moment at 90 degrees of heel is to ensure that the vessel is able to right itself from a knockdown to an angle of around 90 degrees.

Although the degree of stability in the inverted condition is generally associated with the significance of the so-called negative area under the righting moment curve, it is strictly associated with the slope of the righting moment curve at a heel angle of 180 degrees, i.e. the value of "GM" at 180 degrees. In waves, however, it is more appropriate to view the degree of stability in the inverted position over a range of heel angles. In that case the average GZ value of the negative part of the righting moment curve is often used to ascertain the degree to which an incident wave can right the vessel again.

For all sailing vessels that cannot be righted by the crew, the Working Group considered it necessary to impose further requirements to safe-guard against unwanted dynamic behaviour in a seaway. Accordingly, in the case of mono-hull sailing vessels reliant mainly on both hull form and ballast for stability, requirements have also to be met with respect to the value of a so-called Dynamic Stability Factor which is dependent on various expressions for factors influencing dynamic behaviour such as the roll-moment of inertia and the loss in stability due to forward speed.

The set values for the various requirements in the Standard depend on the Stability Category to be assigned to the vessel. Stability Category I, intended for vessels that can sail anywhere in the world, demands that the highest values are met, while Stability Category IV, intended for vessels sailing in restricted waters such as small lakes and rivers, demands that relatively low values are met for the various requirements. Stability Categories V and VI are assigned to those vessels not meeting the requirements in the Standard. Category V is assigned to those vessels with low inherent stability which will float when swamped, while Category VI is assigned to those vessels with low inherent stability which will sink when swamped. Special graphic symbols to be placed on the vessel as a warning when they are assigned to Category V or VI are in preparation.

No specification is given in the Draught Standard with respect to the geographical areas that pertain to Stability Category I through IV. Instead, design criteria are given for values of the significant wave height and wind speed that vessels in each category are expected to be able to endure without impairing the safety of the vessel. These categories are defined in Table 1.

3. NETHERLANDS STABILITY STUDY TO SUPPORT THE WORK OF WORKING GROUP 22 OF TC188

To support the work of Working Group 22, the Netherlands carried out a study of the stability characteristics of mono-hull sailing vessels reliant on both hull form and ballast for stability. This study, supported by the Government, the National Association of Water Sports Industries (HISWA) and some 70 individual companies involved in the design and building of recreational craft in the Netherlands, was particularly aimed at analyzing the characteristics of so-called stability casualties and yachts with a well-proven performance record. Attention was mainly focussed on the minimum requirements with respect to the value of the angle of vanishing positive stability and the value of the righting lever at 90 degrees of heel, for each of the 4 stability categories. In addition, attention was given to the calculation methods involved in determining the Dynamic Stability Factor and the minimum value thereof to be imposed.

Table 1. Stability categories as defined in the present draught of ISO Stability Standard 12217.

Stability Category	Significant Wave Height in metre	Wind Speed in m/sec
I	0 to 8	25
II	0 to 4	21
III	0 to 2	17
IV	0 to 0.5	13
V	Vessels of low inherent stability which will float when swamped	
VI	Vessels of low inherent stability which will sink when swamped	

The technical content of this paper is almost solely the outcome of the study, mentioned above, carried out in the Netherlands. the results obtained have been made available to Working Group 22 through the author of this paper who is the Netherlands representative in the Working Group. Discussions as to the minimum values for the various requirements to be adopted in the Standard will be finalized no earlier than in the latter part of 1995. Accordingly, the values and expressions given here are by no means to be identified with those of the final Standard.

4. COLLECTION OF YACHT STABILITY DATA

Requests for stability data on mono-hull sailing vessels of all kind were requested from more than 65 sources world-wide. In particular, information was requested on yachts that had experienced a serious knockdown, a capsize, a sinking or other stability-oriented casualty. Together with data collected by other members of Working Group 22, 115 sets of rigorous yacht and stability data were collected over a period of about 8 months. About 30 sets of data involved yachts and vessels that had suffered a stability-oriented casualty of one kind or another.

All of the stability data collected constituted so-called "rigorous" data, obtained by taking into consideration deck camber, deck houses and structures, and floodable recesses such as cockpits. During the course of this study significant discussion ensued concerning the error involved in considering a flush deck, without taking into account the effect of deck camber, deck structures and cockpits. The reason for this is that the Offshore Racing Council (ORC), responsible for the International Measurement System (IMS), has on file stability information of thousands of yachts based on inclining experiments, which could have been made available for this stability study through the Chief Executive of ORC, also a member of Working Group 22. This stability information however does not include the effects of deck camber, deck structures or cockpits. The outcome of these deliberations was to request ORC to carry out a systematic series of stability calculations for a number of IMS yachts with deck camber, systematically varied deck structures and cockpits, and sealed masts. The results of these calculations, sponsored by the Netherlands, will allow for the development of approximate expressions for the effect of deckhouses, cockpits, etc, on vanishing angle of positive stability and righting lever at 90 degrees of heel. With these approximate expressions the respective IMS stability entities (defined as LPS and RM90) can possibly be refined to obtain more accurate values, perhaps even for use in the context of ascertaining whether or not the requirements to be imposed by ISO Standard 12217 are met.

Some of the casualty data was supplied on the basis that it be used in a statistical sense only, i.e. that the name or type of yacht, its designer and builder not be mentioned in a report or paper. For this reason the information here given should be considered as representative only, and no effort is made to provide a full set of pertinent yacht data.

Although many yachts were identified as having been knocked down and capsized, only the necessary particulars were obtained for about 30 sailing vessels. Table 2 lists particulars of some of these so-called casualties.

Table 3 lists particulars of 30 so-called category I yachts of which more than 5 vessels were built and/or with a long operational history without any stability-oriented problems. The category I designation was given by either the designer and/or the builder. That is, the designers and/or the builder of these yachts consider these vessels to be suitable to sail anywhere in the world. The latter table lists those 30 vessels that have the lowest value of the angle of vanishing positive stability and/or the lowest value of the righting lever at 90 degrees of heel. The total data base consists of another 55 vessels with greater stability values.

The data collected was for the so-called "minimum sailing"

Table 2. Particulars of yachts that have suffered stability-oriented casualties.

#	L_{OA}	B_{OA}	B_{WL}	T_C	D	Δ_{tot}	GM	GZ_{90}	ϕ_V
#1	6.50	2.85	2.15	0.25	1.20	1.50	0.85	0.34	110
#2	7.01	2.70	2.18	0.35	1.10	1.82	0.88	0.17	103
#3	7.32	2.72		0.30	1.03	1.70		0.11	99
#4	7.49	2.74	2.22	0.39	1.23	2.30	0.81	0.20	112
#5	8.08	3.20	2.79	0.41	1.37	4.55	1.35	0.56	133
#6	8.56	2.96	2.44	0.42	1.36	3.11	0.88	0.28	112
#7	9.14	3.14	2.47	0.44	1.41	3.77	0.85	0.27	117
#8	10.1	3.40	2.76	0.49	1.50	4.51	1.33	0.58	132
#9	10.5	3.58	2.85	0.50	1.50	5.30	1.08	0.28	109
#10	11.1	3.59	3.10	0.70	1.58	12.2	1.15	<0	68
#11	14.3	3.83	3.22	0.45	1.58	7.92	1.75	0.33	114
#12	17.4	3.60	3.54	0.41	1.45	14.7	1.89	<0	65
#13	18.0					14.3		0.26	98
#14	19.7	4.96	4.58	1.01	2.41	30.3	1.45	0.59	122
#15	19.8	5.94				64.9	1.86	<0	75
#16	26.7	7.01				136		<0	57
#17	27.3	7.01	6.78	2.21	3.22	124	1.86	<0	88
#18	28.0	6.40				167	0.61	<0	57

Notes

#1	Knocked down/capsized and sank with loss of life (various vessels);
#2, 4, 6 and 9	Knocked down in moderate to high seas and recovered with minor damage (more than one vessel in each class);
#3	Knocked down/capsized: most vessels recovered with minor damage: some were swamped (various vessels);
#5	Rolled 360 degrees in extreme seas: recovered with loss of rig;
#7	Knocked down, inverted and recovered after about 45 minutes: sank with loss of life (various vessels of same type were subject of similar casualties);
#8, 14	Knocked down in extreme seas: recovered with extensive damage;
#10, 12	Capsized and sank in shallow water due to wind gust (vessels were retrieved);
#11	Knocked down & inverted: after one hour righted and swamped, and subsequently sank with loss of life;
#13	Capsized and sank;
#15, 16, 17, 18	Capsized and sank with loss of life.

Table 3. Particulars of yachts designated as category I by their designers/builders, of which more than 5 were built and/or with a long operational history without any stability-oriented problems.

#	L_{OA}	B_{OA}	B_{WL}	T_C	D	Δ_{tot}	GM	GZ_{90}	ϕ_V
#1	7.99	2.80	2.28	0.35	1.37	2.50	1.07	0.58	135
#2	9.00	3.20				3.10		0.44	128
#3	9.40	3.37	2.82	0.48	1.43	4.32	0.99	0.53	132
#4	10.5	3.60				6.96	1.20	0.56	131
#5	10.5					6.25	1.31	0.54	130
#6	10.7	3.49	2.85	0.56	1.69	6.21	0.88	0.62	135
#7	11.5	3.81				8.67	1.39	0.54	129
#8	12.0	3.89	3.28	0.58	1.73	8.41	1.19	0.44	121
#9	12.7	4.07				10.7	1.31	0.65	132
#10	13.1	4.16				12.1	1.44	0.58	129
#11	14.1	4.20	3.72	0.94	2.50	18.5	0.90	0.55	130
#12	15.5	4.17			2.94	31.8	0.63	0.28	126
#13	16.1	4.80				18.6	1.38	0.65	126
#14	16.9	4.33				27.3	1.00	0.40	124
#15	17.0	4.70			3.25	42.4	0.98	0.32	123
#16	17.5	4.47	3.87	1.23	2.31	21.4	0.86	0.40	118
#17	17.7	5.05	4.30	1.02	2.43	30.6	1.36	0.53	121
#18	18.5	5.25				26.7		0.52	119
#19	19.9	4.96			2.95	77.2	0.87	0.14	107
#20	20.5	5.26	4.65	1.10	2.44	41.1	1.33	0.54	122
#21	21.1	5.22	4.70	1.25	2.17	42.2	1.24	0.23	104
#22	21.5	5.49			3.03	87.4	1.13	0.10	102
#23	21.6					48.7	1.28	0.19	101
#24	21.7	5.71	5.55	1.69	3.18	74.9	1.03	0.50	102
#25	22.1	5.75	5.14	1.06	2.51	40.6	1.89	0.65	118
#26	22.8	5.30	4.42	1.26	2.55	38.1	1.10	0.22	102
#27	23.1	6.00	4.91	0.91	2.51	45.0	1.53	0.15	97
#28	24.0	6.07		1.02	2.88	56.6	1.32	0.32	111
#29	28.1	6.80	6.37	1.46	3.00	98.6	1.75	0.37	106
#30	28.2	6.48	5.89	1.48	3.00	85.9	1.21	0.25	103

condition. In this condition all tanks are considered 10% full with sails hoisted and a minimum crew on-board. For a sailing vessel this is generally considered to be the condition in which stability is least.

During the course of collecting this data it became clear that serious knockdowns and capsizes happen more frequently than often supposed. Detailed information was obtained from the Royal National Lifeboat Institution (RNLI) in Dorset, England, revealing that every year the services by RNLI lifeboats to sailing yachts that have suffered a capsize number at least 20. A similar number of capsizes are reported by the equivalent Netherlands Institution. In all, it was not difficult to pin-point over 100 recent stability-oriented casualties. It was extremely difficult, however, to obtain the required stability data of these vessels to render them suitable for analysis.

5. ANALYSIS OF YACHT STABILITY DATA

A plot of the angle of vanishing positive stability (ϕ_V) against overall length, for all vessels specified in Tables 2 and 3, is shown in Figure 1. The lines shown herein approximately divide the points for most of the casualties (indicated by pluses) from those for "good" category I vessels (indicated by squares). A number of observations can now be made as follows:

- Three casualties are located amongst the so-called "good" category I vessels. A study of the particulars given in Table 2 for case studies 5, 8 and 13, reveals that these three yachts experienced a knockdown in high seas and recovered, with extensive damage. Although the yachts associated with case studies 2, 4, 6 and 9 also recovered, the sea conditions in these latter cases were nothing like the extreme conditions associated with cases 5, 8 and 13.
- The stability characteristics of the yachts associated with case studies 5, 8 and 13 in Table 2, are as good as those of the "good" category I vessels. Accordingly, it stands to reason that the "good" category I vessels could also have been knocked down in conditions experienced by these three vessels. It also follows that a high value of the vanishing angle of positive stability will therefore not prevent a knockdown from occurring but will ensure that the yacht is capable of righting itself, even after having been totally inverted.
- The minimum required value of the angle of vanishing positive stability is clearly dependent on the size of yacht. For overall length values in excess of about 22 metres, the minimum value of ϕ_V would seem to be in the order of about 100 degrees. For lengths of 10 metres and less, this value would seem to be about 130 degrees. This trend with size has previously been discerned. The analysis of the 1979 Fastnet race casualties has shown that in the same adverse conditions the smaller boats were generally more vulnerable, as could be expected (see list of references). It stands to reason therefore that stability

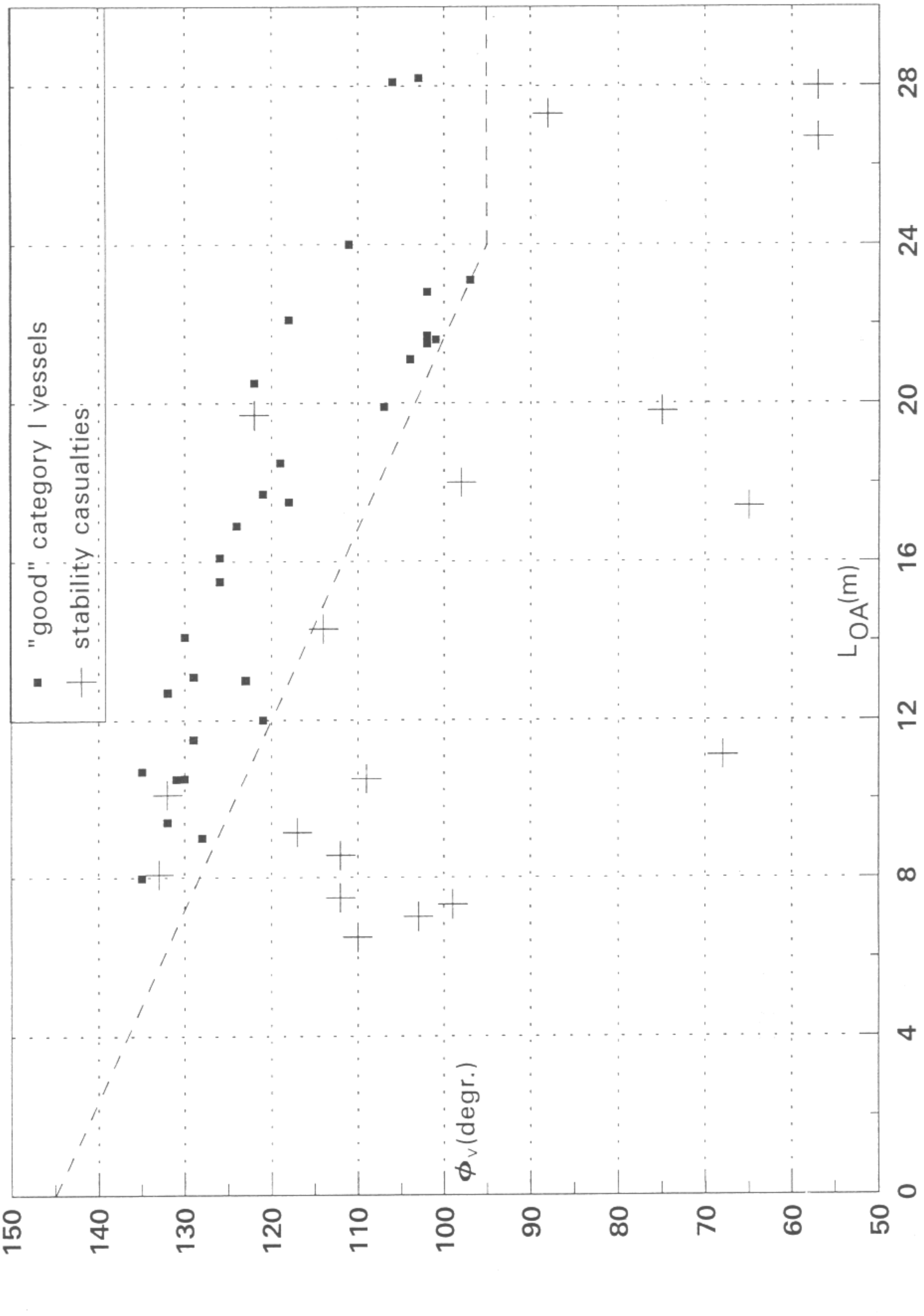

Figure 1. A plot of the angle of vanishing positive stability against overall length for stability-oriented casualties (pluses) and "good" category I vessels (squares).

requirements for small vessels must be significantly greater than for larger vessels. The past practice in this respect is responsible for the trend found in Figure 1.

In connection with this last observation, it should be noted that the requirement of a lower value of the angle of vanishing positive stability for larger vessels is not because these vessels recover from an inversion more easily, but rather because a larger excitation force is required to cause a knockdown in the first place. If the premise for developing stability criteria were to be such that an inversion has to be avoided irrespective of the chance of getting knocked down, then the only correct criterion to be applied is one demanding a specific minimum vanishing angle of positive stability for all vessels, irrespective of their size. On the basis of accepting a specific, small risk in setting safeguard criteria however, the adopted approach of requiring a lower stability threshold for preventing inversion for larger vessels, used here and in the past, can be defended.

It is not possible on the basis of the plot in Figure 1 to define a boundary for the minimum required angle of vanishing positive stability. The line drawn reveals insufficient latitude between the so-called casualties and "good" category I vessels.

The energy associated with a knockdown is probably more dependent on the mass of the yacht. Accordingly, a plot of vanishing angle against displacement mass is presented in Figure 2. In this figure a greater latitude is seen to exist between the casualty points and the points for the "good" category I vessels, due to the fact that the so-called casualties mostly constitute yachts with a small displacement. A less arbitrary line can now be defined to distinguish between the casualties and the "good" boats considered. This line is shown.

The value of the righting lever at 90 degrees of heel (GZ_{90}) was studied in a similar way. A plot of the righting lever against length or displacement was found not to provide a meaningful relationship, as only a cloud of points evolved. A plot of the actual righting moment at 90 degrees of heel however is seen to result in a very meaningful trend. Figure 3 gives this plot of the value of the righting moment against overall length. This righting moment is calculated from $\Delta.GZ_{90}$, where Δ is the mass of displacement in tonnes of 1000 kg. Again a relatively well-defined line can be drawn to distinguish between the casualties and the "good" category I yachts.

6. NETHERLANDS-PROPOSED CRITERIA FOR VANISHING ANGLE AND RIGHTING MOMENT AT 90 DEGREES OF HEEL

On the basis of considerable consultation with various designers, builders and experts in the Netherlands, a proposal was forwarded to Working Group 22 consisting of criteria for both vanishing angle of positive stability and the righting moment at 90 degrees of heel, for each of the four stability categories. These criteria are shown in Figures 4 and 5.

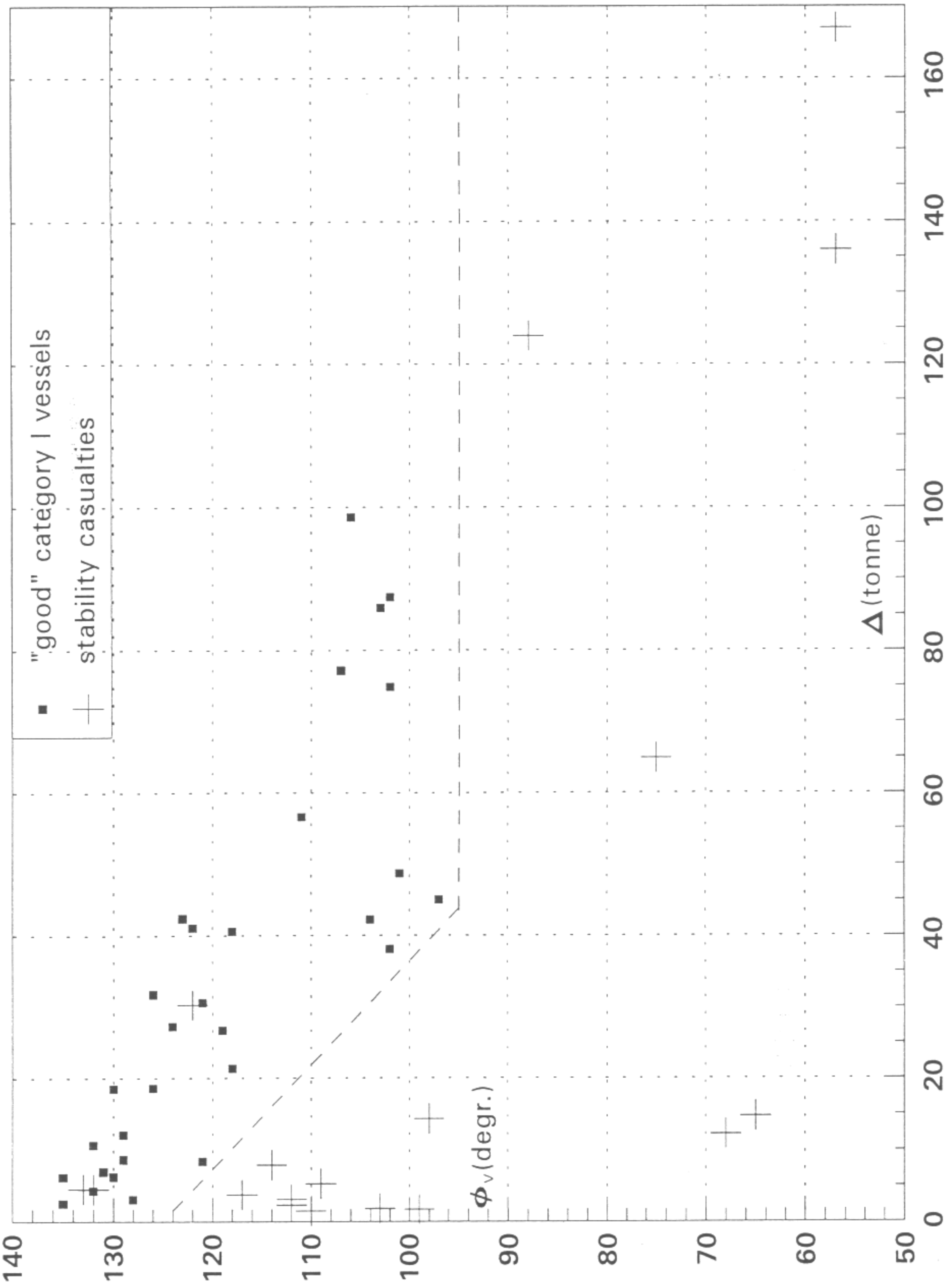

Figure 2. A plot of the angle of vanishing positive stability against displacement mass for the same vessels as presented in Figure 1. Here a well-defined line can be defined differentiating between casualties and the "good" category I vessels.

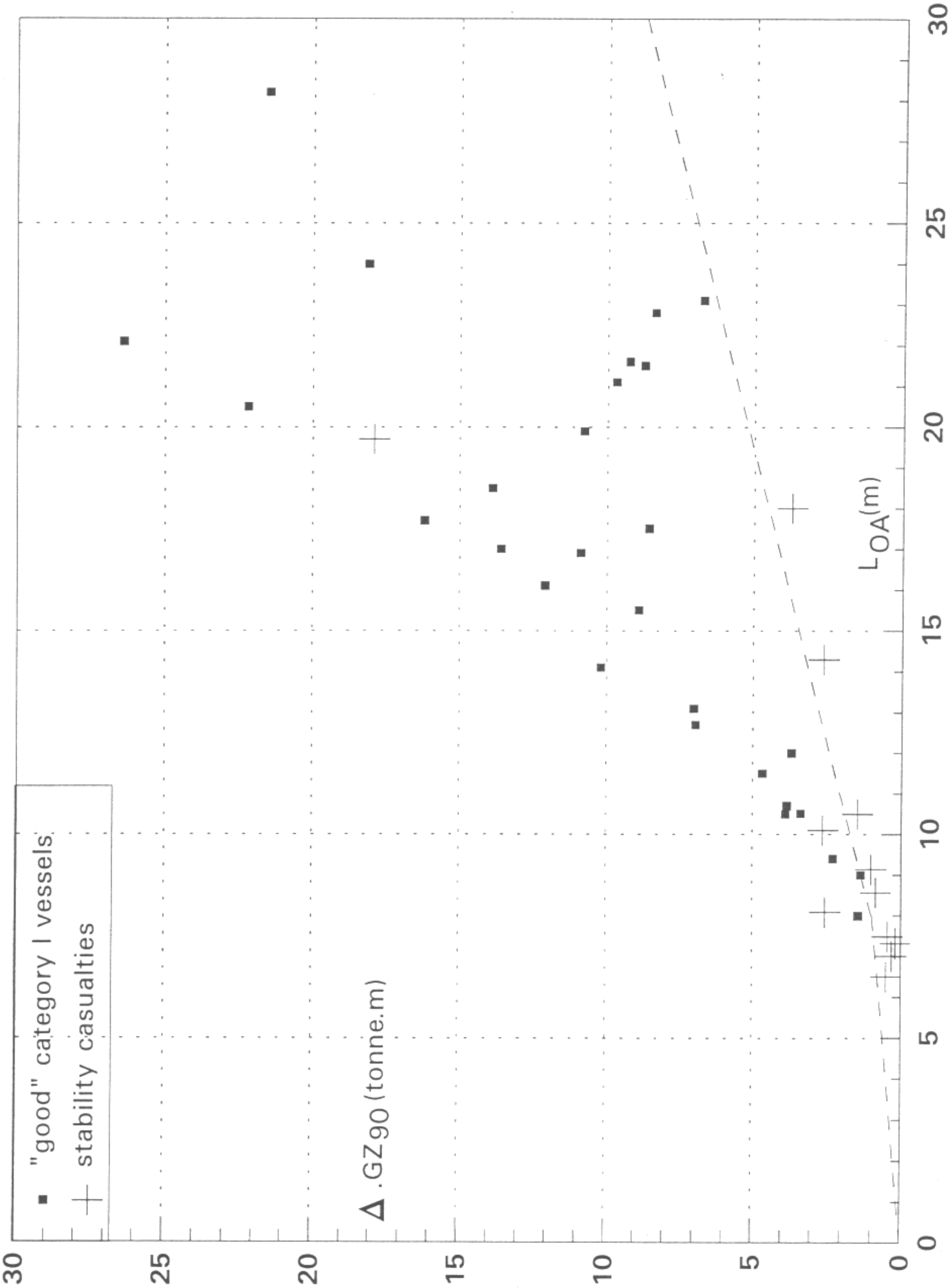

Figure 3. A plot of the righting moment (in tonne.m) against overall length for the same vessels considered in Figures 1 and 2. Here, also, a well-defined line can be defined differentiating between the casualties and the "good" category I vessels.

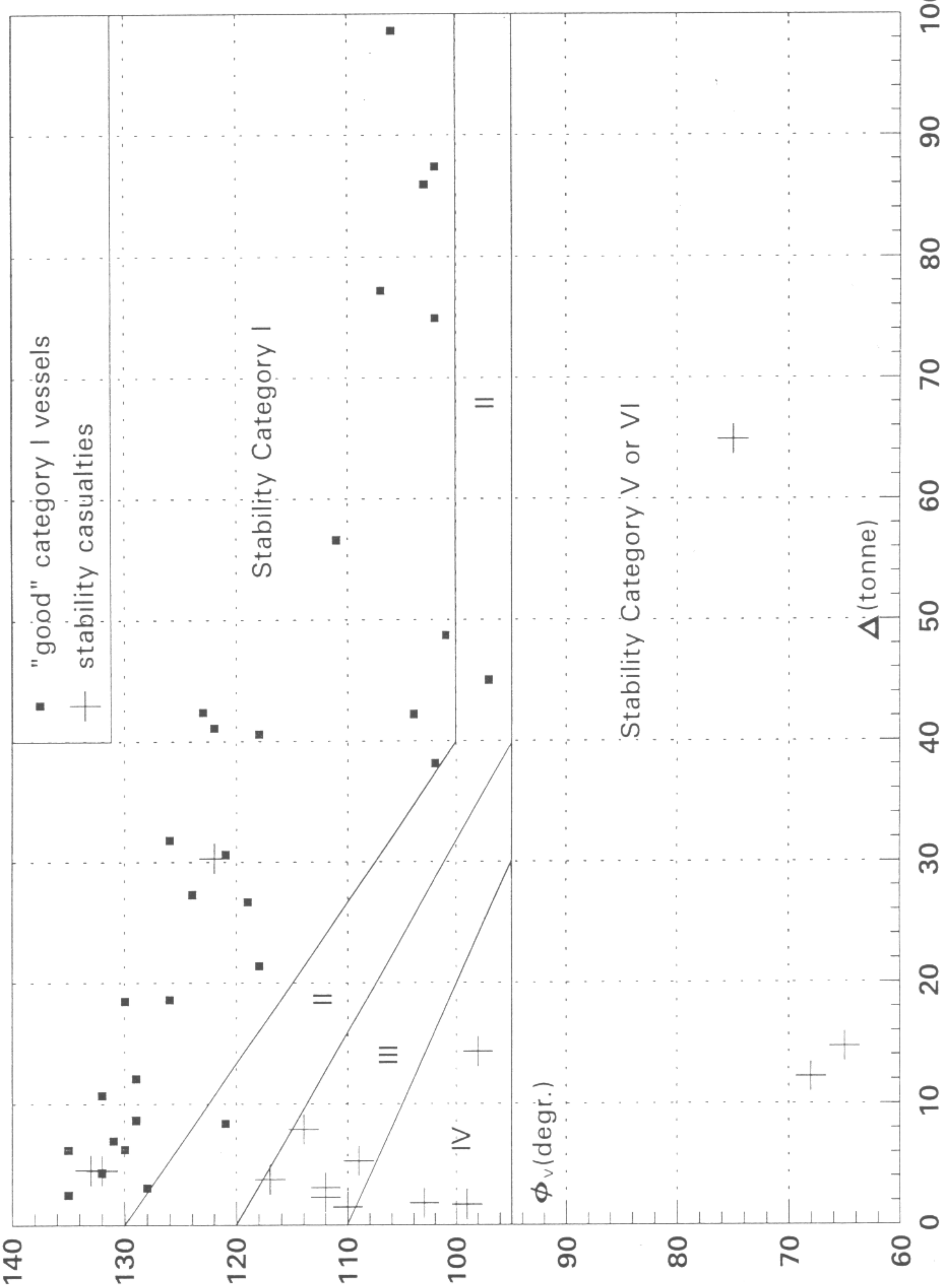

Figure 4. Netherlands proposal forwarded to Working Group 22 for the minimum value of the angle of vanishing positive stability as a function of displacement mass, for stability categories I through IV.

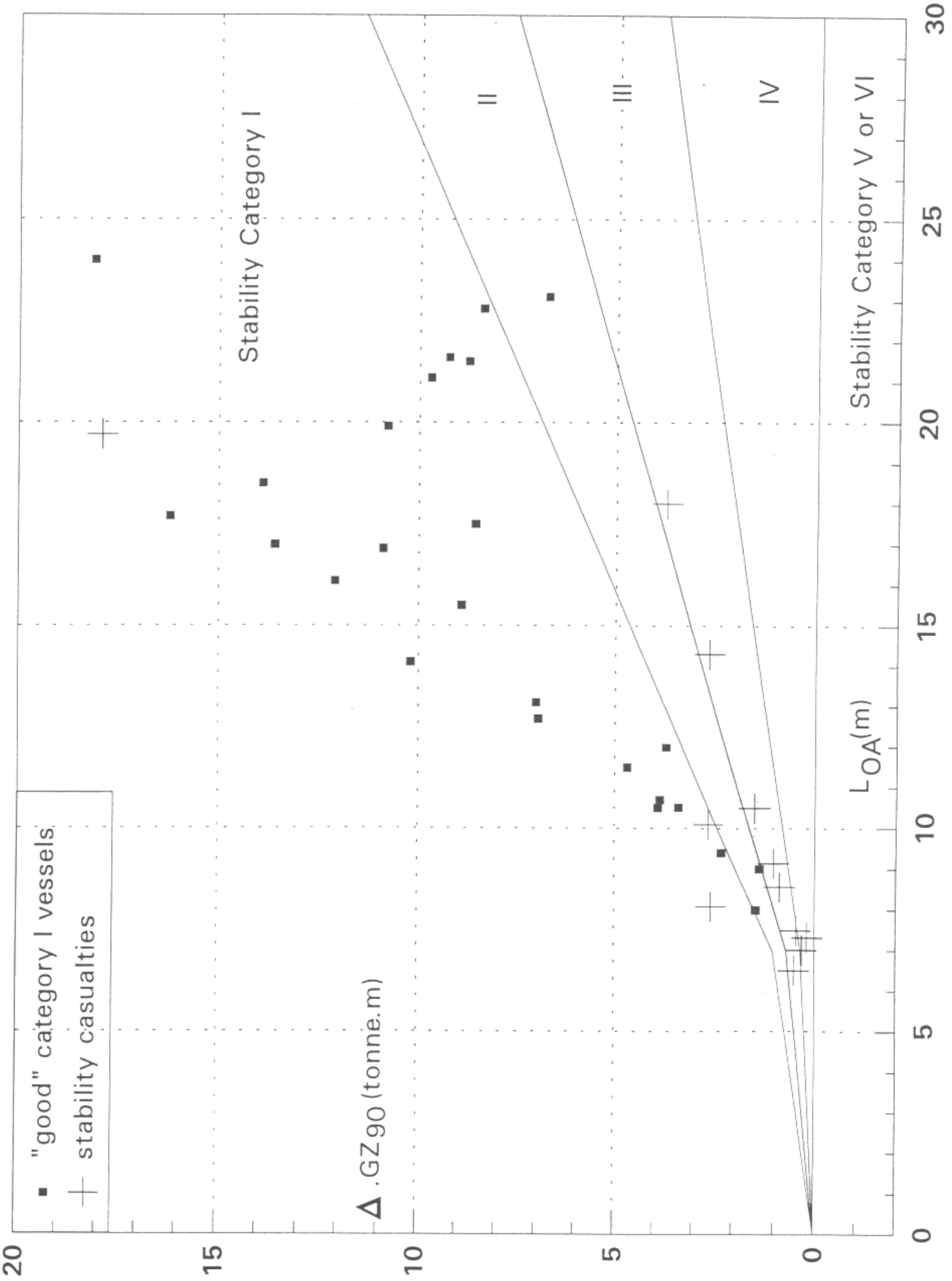

Figure 5. Netherlands proposal forwarded to working group 22 for the minimum value of the righting moment at 90 degrees of heel as a function of overall length, for stability categories I through IV.

In analytical form it is proposed that:

for the angle of vanishing positive stability, in degrees:

$\phi_V > 130 - 0.750\Delta$	for $\Delta < 40$ tonne	category I
$\phi_V > 100$	for $\Delta => 40$ tonne	"
$\phi_V > 120 - 0.625\Delta$	for $\Delta < 40$ tonne	category II
$\phi_V > 95$	for $\Delta => 40$ tonne	"
$\phi_V > 110 - 0.500\Delta$	for $\Delta < 30$ tonne	category III
$\phi_V > 95$	for $\Delta => 30$ tonne	"
$\phi_V > 95$		category IV

For the righting moment at 90 degrees of heel, in tonne.m:

$\Delta.GZ_{90} > 1.05 + 0.45(L_{OA} - 7)$	for $L_{OA} => 7$ m	category I
$\Delta.GZ_{90} > 0.15L_{OA}$	for $L_{OA} < 7$ m	"
$\Delta.GZ_{90} > 0.70 + 0.30(L_{OA} - 7)$	for $L_{OA} => 7$ m	category II
$\Delta.GZ_{90} > 0.10L_{OA}$	for $L_{OA} < 7$ m	"
$\Delta.GZ_{90} > 0.35 + 0.15(L_{OA} - 7)$	for $L_{OA} => 7$ m	category III
$\Delta.GZ_{90} > 0.05L_{OA}$	for $L_{OA} < 7$ m	"
$\Delta.GZ_{90} > 0$		category IV

The demarkation between categories I and II, between II and III, and between III and IV are based, in part, on information provided by designers, builders and others concerning the category of various well-known yachts of which the stability particulars were available.

7. THE PROPOSED MONO-HULL DYNAMIC STABILITY FACTOR

Working Group 22 is proposing to utilize the concept of a single factor accounting for the stability and buoyancy properties of mono-hull sailing yachts in a dynamic sense. This is a consequence of the realization that traditional stability requirements only address static stability behaviour, i.e. the characteristics of the craft at specific angles of heel, having attained those angles of heel infinitely slowly. Recent research in various countries has revealed that the danger of capsize is, at best, only partly described by static stability parameters such as the value of the angle of vanishing stability and the value of the righting moment at 90 degrees of heel. Parameters such as the roll moment of inertia, for example, also need to be taken into account, which fact was proven, amongst others, through the study carried out by the United States Yacht Racing Union (USYRU), now called the US Sailing Association, and The Society of Naval Architects and Marine Engineers (SNAME) joint committee on "Safety from Capsizing" in 1985 (see list of references).

The calculation of capsize and capsize-recovery behaviour in unsteady wind and wave conditions is realistically beyond the capabilities of yacht builders and others involved in the pleasure boating industry. Even most naval architects and boat designers need to turn to specialists in the field for such calculations, requiring the use of specially-developed mathematical models. In addition, screens, rules and regulations set by national and international bodies responsible for the safety of yachts and ships must, out of necessity, be simple and easy to use. Particularly when these screens, rules and regulations are to be enforced by law, such as is to be the case in the European Union for pleasure craft up to a length of 24 meters from 1996 onwards, the need to be able to check compliance with the set criteria quickly and cheaply, is of the utmost importance. All these facts are a handicap for those developing a methodology by which the safety against the danger of capsize and other hazardous behaviour in adverse wind and wave conditions can be assessed.

The approach adopted by Working Group 22 is to quantify known factors that have an influence on the dynamic loss of stability, capsize, capsize-recovery behaviour, and other dangerous dynamic behaviour, and to adopt a relatively simple and approximate formula using these factors to calculate a craft's ability to cope with the dangers. Each of the factors is normalized such that if the value attained is less than unity this indicates a low safety margin whereas, if the value is greater than unity, this indicates a relatively high safety margin. The series of factors normalized in this manner describe, on a relative scale, the properties of the craft under consideration and the product of all the factors will yield an overall value which is indicative of overall safety against the hazardous phenomena occurring. Through a comparative study of known casualties, and of craft which are known to possess adequate safety, it is possible to identify the minimum value of the overall value, depending on the type of craft, the area of operation or design category.

This approach is similar to so-called risk-analyses in which the probability of occurrence of each factor of importance is determined and the final probability of the unwanted phenomena occurring is calculated by multiplying all of these probabilities together. An application of this technique to the capsize of craft in beam seas was recently presented by Umeda, Ikeda and Suzuki in 1992, and by Dahle and Myrhaug in 1993.

The method adopted by Working Group 22 is similar to that recently adopted by the UK Department of Transport for commercial sail training vessels, and by the Royal Ocean Racing Council (RORC) and Royal Yachting Association (RYA) in 1987 for a specific category of yachts. Some of the factors in the proposed method described in this paper are taken from these methods or are a further development thereof, while other factors are newly developed to describe specific aspects of the complex dynamic stability problem not covered before.

Mention should here be made of the significant amount of work that was carried out by John Moon, member of Working Group 22, in preparing various documents on this subject, parts of which are based on the work he conducted in helping to develop the Channel Handicap System Screening System for the RORC, and the modified form thereof for use with sailing school yachts for the RORC and RYA.

8. IDENTIFICATION OF KNOWN FACTORS THAT DESCRIBE THE DYNAMIC STABILITY OF SAILING YACHTS

To date, 9 separate factors describing certain aspects of dynamic stability behaviour in the case of mono-hull sailing craft, have been identified, as follows:

- **FBS or Base Size Factor**. This factor accounts for the size of the subject craft in relation to the level of the wind and wave forces. It is considered to be of prime importance since seaworthiness and dynamic response in adverse wind and wave conditions are directly related to size or inertia of the subject craft. This is the only factor that is not normalized to obtain values around 1.0, either non-dimensional or otherwise. As such it gives the dynamic stability factor a basic order of magnitude. It is a function of the length of the hull. This factor is in line with casualty statistics, such as those given in the report of the 1979 Fastnet Race Inquiry already referred to. In that particular event 11 out of 40 (28%) yachts in Class I (large yachts) experienced knockdowns, 14 out of 40 (35%) in Class II, 28 out of 52 (54%) in Class III, 25 out of 46 (54%) in Class IV, and 30 out of 47 (64%) in class V (composed of the smallest participating yachts).

- **FDL or Displacement Length Factor**. This factor accounts for the displacement volume or mass-inertia of the subject craft. This is necessary, in addition to the Base Size Factor, since the latter factor is defined in terms of a length scale. The displacement-length factor accounts for the fact that a light displacement craft, for its length, experiences a greater motion response to wind and wave forces. The value of this factor is normalized such that it varies between 0.8 and 1.2.

  The FDL factor is derived from a combination of a screen developed by the Australian Yachting Federation (AYF) and from a comparison of the yacht's length-displacement ratio to the value that is considered to constitute the "norm" when related to size. The definition given in Paragraph 9.2 is as originally adopted by the RORC and RYA.

- **FBD or Beam Displacement Factor**. This factor accounts for the fact that a craft with a wide beam, in relation to the displacement, possesses a greater motion response to wave-induced forces, particularly at some initial angle of heel. At the same time, however, a low beam in relation to displacement, is indicative of a lack of form stability. Accordingly, this factor is defined in such a way that a high beam-displacement ratio is identified as a risk, while a low beam-displacement ratio is not given undue credit. The value of this factor varies between 0.8 and 1.05. The FBD factor is based on an original screen developed by the USYRU.

- **FSDBL or Sail Area Displacement Beam Length Factor.** This factor accounts for the size of the rig in relation to the ability of the hull to carry sail. The size of the spars and the presence of a large sail area increases the wind-induced loads on the yacht. Accordingly, this factor gives credit to craft with small rigs in relation to the displacement and the beam-length ratio. The beam-length ratio is entered here since the ability to carry sail has to be related to the stability of the craft. Since it is considered unnecessary to give too much credit for very small rig sizes, the value of this factor is normalized so that it also varies between 0.8 and 1.05.

  The FSDBL factor, as presented in Paragraph 9.4, was originally adopted by the RORC and RYA.

- **FSR or Self Righting Factor.** The area under the static righting moment curve, between the heel angle of 90 degrees and the angle of vanishing positive righting moment, can be considered to be related to the ability of the craft to recover from a capsize. The FSR factor is therefore expressed as a function of this area value. This is one of the more important factors and is therefore normalized so that its value varies between 0.6 and 1.2

  The FSR factor, as defined, constitutes a new proposal by the author. The earlier expressions for this factor were based on the calculated angle of vanishing positive stability only. Details of the formula proposed is given in Paragraph 9.5.

- **FAA or Relative Area Factor.** The property of a craft, after a capsize, to adopt an unwanted stable, inverted attitude in waves, is related to the significance of the "negative" area below the righting moment curve, from the angle of vanishing righting moment to 180 degrees of heel. It has been shown that the ratio of the "positive" area below the righting moment curve up to the angle of vanishing positive righting moment, to the "negative" area under the righting moment curve from the angle of vanishing positive righting moment to the inverted position (at 180 degrees of heel), is indicative of the degree of stability in the inverted position. Accordingly, this ratio is used for this purpose. The FAA factor is normalized so that it, too, can attain values between 0.6 and 1.2.

- **FSSL or Stability Speed Loss Factor.** At higher speeds the wave formation along the hull is such that the inertia of the waterplane is significantly decreased. The associated decrease in transverse stability, for round-bilge hull forms is well documented. The beam-draft ratio of the canoe body is the main parameter involved.

A relatively simple formula for this factor was developed by the author, based on the results of tests with 39 models of various kinds of mono-hull yachts carried out at the Delft University of Technology. The details thereof are given in Paragraph 9.7. This factor is normalized such that it can attain values between 0.7 and 1.0.

- **FRMI or Roll Moment of Inertia Factor**. Capsize studies have resulted in the finding that a high roll-moment of inertia decreases the likelihood of a capsize due to wave-induced forces broadside to the craft. A factor has been proposed by Rolf Eliasson, member of Working Group 22, for this effect, described in Paragraph 9.8. It has been proposed to limit this factor to yield values between 0.8 and 1.2. This is based on the consideration that, in comparison to the Self-righting Factor (FSR) and the Relative Area Factor (FAA), for which limits of 0.6 and 1.2 are proposed, this factor is less important.

  Further work is required in applying this factor for various craft, to obtain more insight into the validity of the assumptions made. It would appear however that the proposed formulae represent a significant improvement over previous screens for the roll moment of inertia. Working group 22 will be seeking to simplify the method as outlined in Paragraph 9.8 however.

- **FDA or Downflooding Angle Factor**. Significant downflooding during a knockdown or capsize will influence the degree to which capsize recovery remains possible. Accordingly, the heel angle at which downflooding occurs, and the degree to which water enters the hull, needs to be taken into account. As such, this factor needs to be a function of not only the downflooding angle but also of the volume or mass of water that can enter the hull during a capsize. An appropriate factor for this effect is currently in development.

9. CALCULATION OF THE MONO-HULL DYNAMIC STABILITY FACTOR

The value of the dynamic stability factor is obtained by multiplying the factors described above, viz:

$$FMDS = 5*FBS*FDL*FBD*FSDBL*FSR*FAA*FSSL*FRMI*FDA$$

where FMDS = Mono-hull dynamic stability factor.

After the various factors are finalized, further work is required to determine the minimum values of FMDS for each design category. Presently, the following minimum values for FMDS are being considered:

- stability category I: 40
- stability category II: 25
- stability category III: 10
- stability category IV: no requirement

9.1. FBS OR BASE SIZE FACTOR

This factor is simply the average of the length of the craft on the waterline and the length of the hull, as defined in ISO Standard 8666, viz:

$$FBS = (L + L_{WL})/2$$

where L = Length of hull (see ISO 8666),
L_{WL} = Length of canoe body on the waterline.

The value of FBS is expressed in meters. It is not normalized since it is considered to be the prime factor influencing dynamic stability behaviour because it is the size or inertia of the subject craft that determines its level of motion response to some excitation force. The value of FBS sets the scale for the resulting value of the dynamic stability factor. Note that long forward and aft overhangs result in a larger value of FBS.

9.2. FDL OR DISPLACEMENT LENGTH FACTOR

The displacement-length factor, FDL, is defined as follows:

$$FDL = 0.6 + 0.4*DLR/N1$$

in which the non-dimensional displacement-length ratio, DLR, is defined as:

$$DLR = \nabla/L_{WL}^3$$

where ∇ = total volume of displacement in m^3,
and L_{WL} = length of canoe body on the waterline in meters.

The normalization function, N1, is defined as:

$$N1 = (1-0.024*L_{WL})/85.8$$

This is the definition as adopted by the RORC and RYA, although written somewhat differently. The minimum value of FDL is 0.8 while the maximum value is 1.2. Figure 6 gives the value of the function 0.4*DLR/N1 for a range of DLR values. The minimum and maximum values permissible for 0.4*DLR/N1, is 0.2 and 0.6 respectively. As can be seen from Figure 6, a small craft with a length of 5 meters on the waterline can only attain the maximum value of 0.6 when the length-displacement ratio $L_{WL}/\nabla^{1/3} = 4$. This is a heavy displacement craft. A craft with a length of 25 meters, on the other hand, can attain the maximum value of 0.6 when $L_{WL}/\nabla^{1/3} = 5.2$, which corresponds to a moderate displacement craft.

9.3. FBD OR BEAM DISPLACEMENT FACTOR

The beam-displacement factor is defined as:

$$FBD = N2*(1.05*B_{max}/\nabla^{1/3})*B_{WL}/B_{max}$$

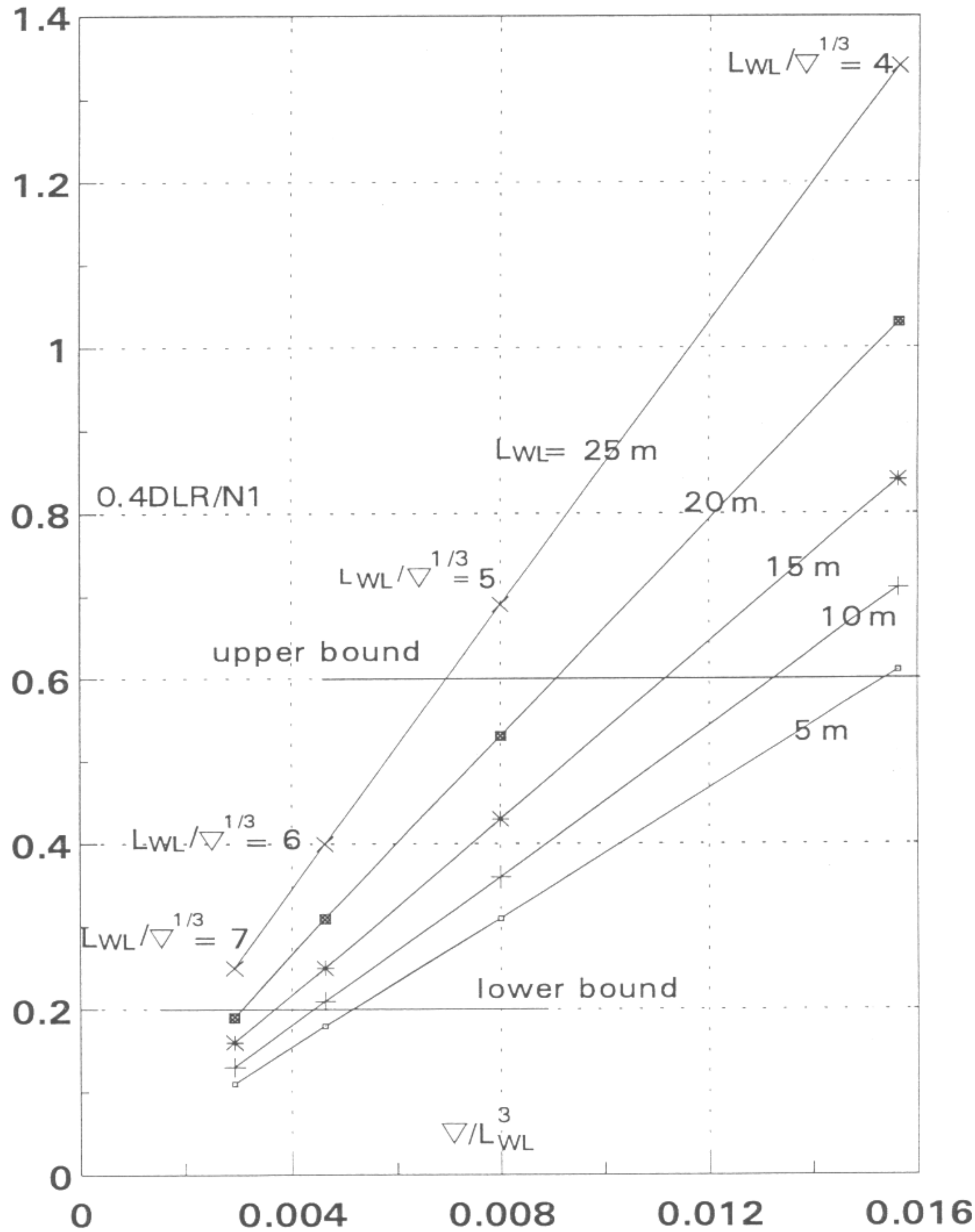

Figure 6. Value of the function 0.4*DLR/N1 for a range of DLR values, for L_{WL} values of 5, 10, 15, 20 and 25 meters.

where B_{max} = maximum beam of the hull in meters,
∇ = total volume of displacement in m^3,
and B_{WL} = maximum beam on the waterline in meters.

The normalization function N2 is defined by:

$$N2 = 0.595*(1.05*B_{max}/\nabla^{1/3}), \quad \text{for } 1.05*B_{max}/\nabla^{1/3} < 1.45$$

$$N2 = 1.25*(1.05*B_{max}/\nabla^{1/3})^{-1}, \quad \text{for } 1.45<=1.05*B_{max}/\nabla^{1/3}<=2.20$$

and $$N2 = 13.31*(1.05*B_{max}/\nabla^{1/3})^{-4}, \quad \text{for } 1.05*B_{max}/\nabla^{1/3} > 2.20$$

The maximum value of FBD is 1.05 and the minimum value is equal to 0.8. This, also, is identical to the definition as adopted by the RORC and RYA.

Figure 7 gives the value of FBD for a range of values of $1.05*B_{max}/\nabla^{1/3}$, for discrete values of B_{WL}/B_{max}. From this figure it follows that, in essence, the ratio B_{WL}/B_{max} determines the level of FBD in the most important part of the beam-displacement ratio range (for $1.45 <= 1.05*B_{max}/\nabla^{1/3} <= 2.20$). Only when relatively small and large maximum beam values are encountered is FBD influenced by the beam-displacement ratio value itself. In those cases a significant decrease in FBD is prescribed, in accordance with the finding that too small a maximum beam results in low form stability, while too large a maximum beam, particularly when incorporating large topside flare, results in too large a vulnerability to wave-induced capsize, as confirmed by Claughton and Handley (1984). Note that the value of B_{WL}/B_{max} is indicative of the amount of topsides flare.

Figure 8 gives the permissible variation in B_{max}/L_{WL} as a function of length-displacement ratio in the "neutral" region of $1.05*B_{max}/\nabla^{1/3}$. The equivalent B_{max} values are seen to be relatively high, and relatively normal B_{max}/L_{WL} values of around 0.20 to 0.3 can only be attained for moderate to light displacements. A modification of this factor so as to obtain such B_{max}/L_{WL} values at both heavy and moderate displacements might be considered, leading to a revision of the formulae for this factor.

9.4. FSDBL OR SAIL AREA DISPLACEMENT BEAM LENGTH FACTOR

The sail area-displacement-beam-length factor adopted by the RORC and RYA is:

$$FSDBL = 0.7 + 0.3*(0.55*DBL^2+21.5*DBL+15)/SA$$

in which DBL is the displacement-beam-length factor defined by:

DBL = $\nabla*B_{WL}/L_{WL}$, in m^3,

and SA = area of mainsail and foretriangle of genoa, in m^2.

This factor is not normalized in a non-dimensional way. It is a direct formula relating sail area to the displacement-beam-

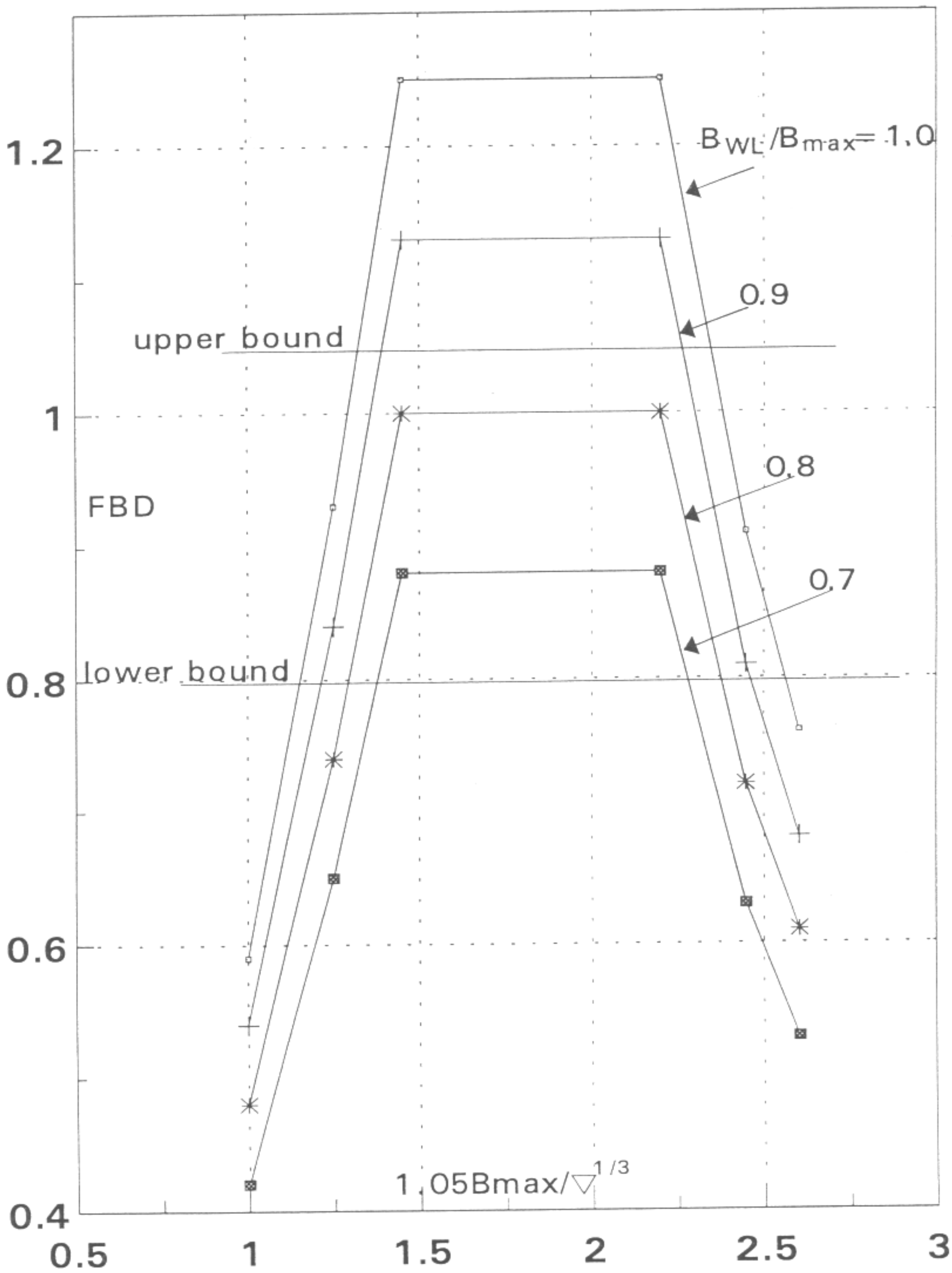

Figure 7. Value of FBD for a range of values of $1.05*B_{max}/\nabla^{1/3}$ and B_{WL}/B_{max}. Note that in the region $1.45 <= 1.05*B_{max}/\nabla^{1/3} <= 2.20$, the beam-displacement factor is, in effect, only dependent on topsides flare.

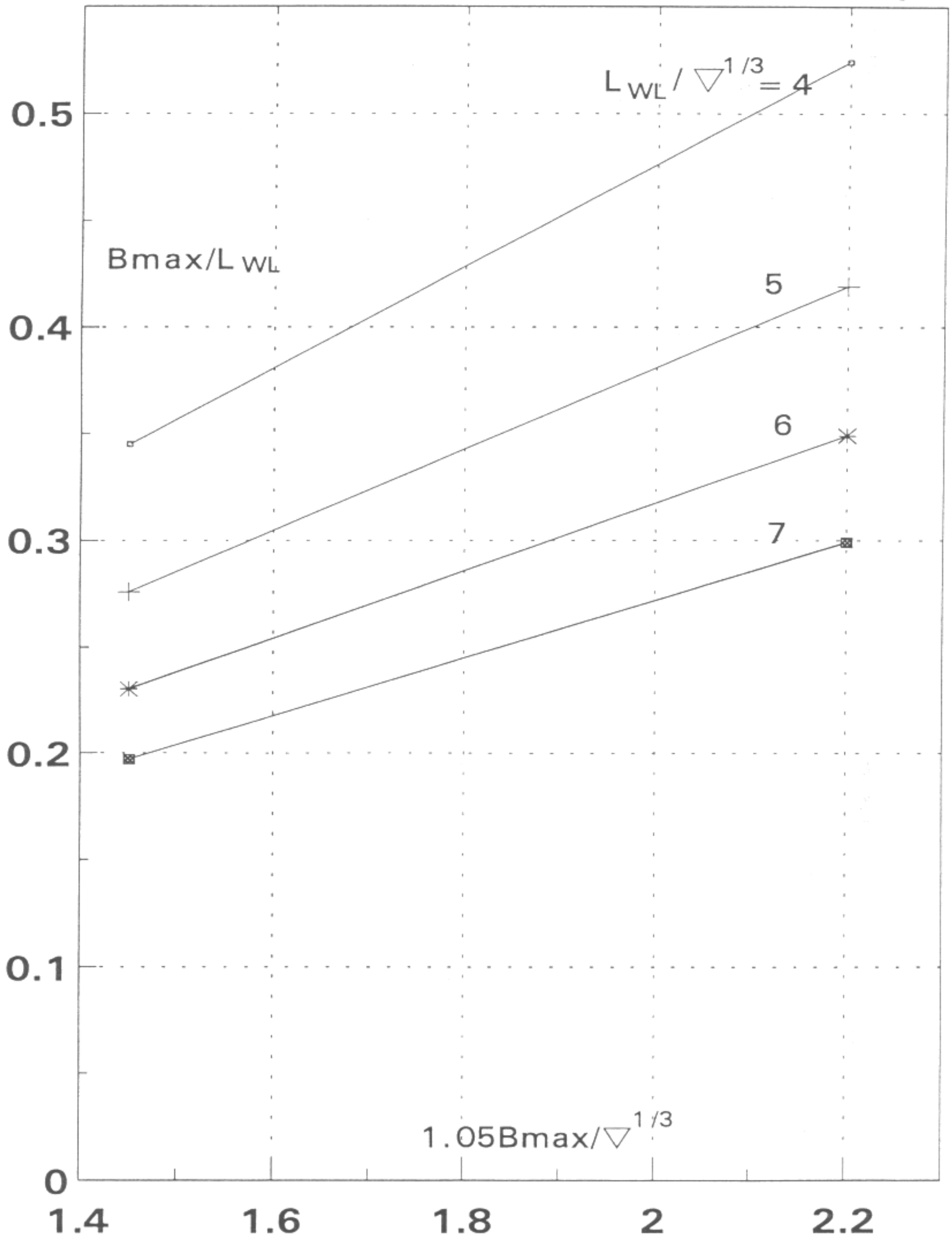

Figure 8. The FBD factor allows a specific variation in B_{max}/L_{WL} as a function of length-displacement ratio in the "neutral" region of $1.05*B_{max}/\nabla^{1/3}$ (i.e. for $1.45 <= 1.05*B_{max}/\nabla^{1/3} <= 2.20$).

length factor. On adopting FSDBL = 1.0 for example, we obtain:

$$SA = 0.55*(\nabla*B_{WL}/L_{WL})^2 + 21.5*(\nabla*B_{WL}/L_{WL}) + 15$$

The minimum value of FSDBL is 0.8 and the maximum value is 1.05. Figure 9 shows the permissible value of the variable part of FSDBL as a function of sail area in m^2 and the displacement-beam-length factor, $\nabla*B_{WL}/L_{WL}$. Note the strong decrease in FSDBL with decreasing $\nabla*B_{WL}/L_{WL}$, for constant sail area.

From the relationship for SA when FSDBL = 1.0 it can be seen that the units of the left-hand side are not consistent with the units on the right-hand side of the equation. This indicates that the relationship has been derived from a specific data base and is possibly not valid for all types of mono-hull sailing craft. Accordingly, it might be advantageous to investigate the possibility of replacing this factor with a more consistent relationship involving the so-called "power to carry sail" factor defined as:

$$SA*H/\nabla = c*GM/V_{AW}^2$$

where H = height of center of effort of sail plan above center of lateral resistance,
GM = metacentric height,
and V_{AW} = apparent wind speed.

The coefficient c herein is a function of the lift and drag coefficients of the sails and the heel angle under consideration. It is possible, by adopting a specific apparent wind speed, a realistic set of lift and drag coefficients and, for example, 30 degrees of heel, to arrive at a more universal relationship then the relationship adopted by the RORC and RYA. It is proposed that this is developed as an alternative proposal.

9.5. FSR OR SELF RIGHTING FACTOR

The self-righting factor, as adopted by the RORC and RYA is a simple expression involving the righting lever GZ at 90 degrees of heel, viz:

$$FSR = 0.6 + 1.35*GZ_{90} - 0.68*GZ_{90}^2$$

Here GZ_{90} = righting lever at 90 degrees of heel.

It has been suggested that this be modified to:

$$FSR = 0.6 + GZ_{90}$$

In both cases the minimum value of FSR is 0.6 and the maximum value is 1.2.

No account is here made of the angle of vanishing positive righting moment which is equally important when considering capsize recovery. For example, If GZ_{90} were to be of a reason-

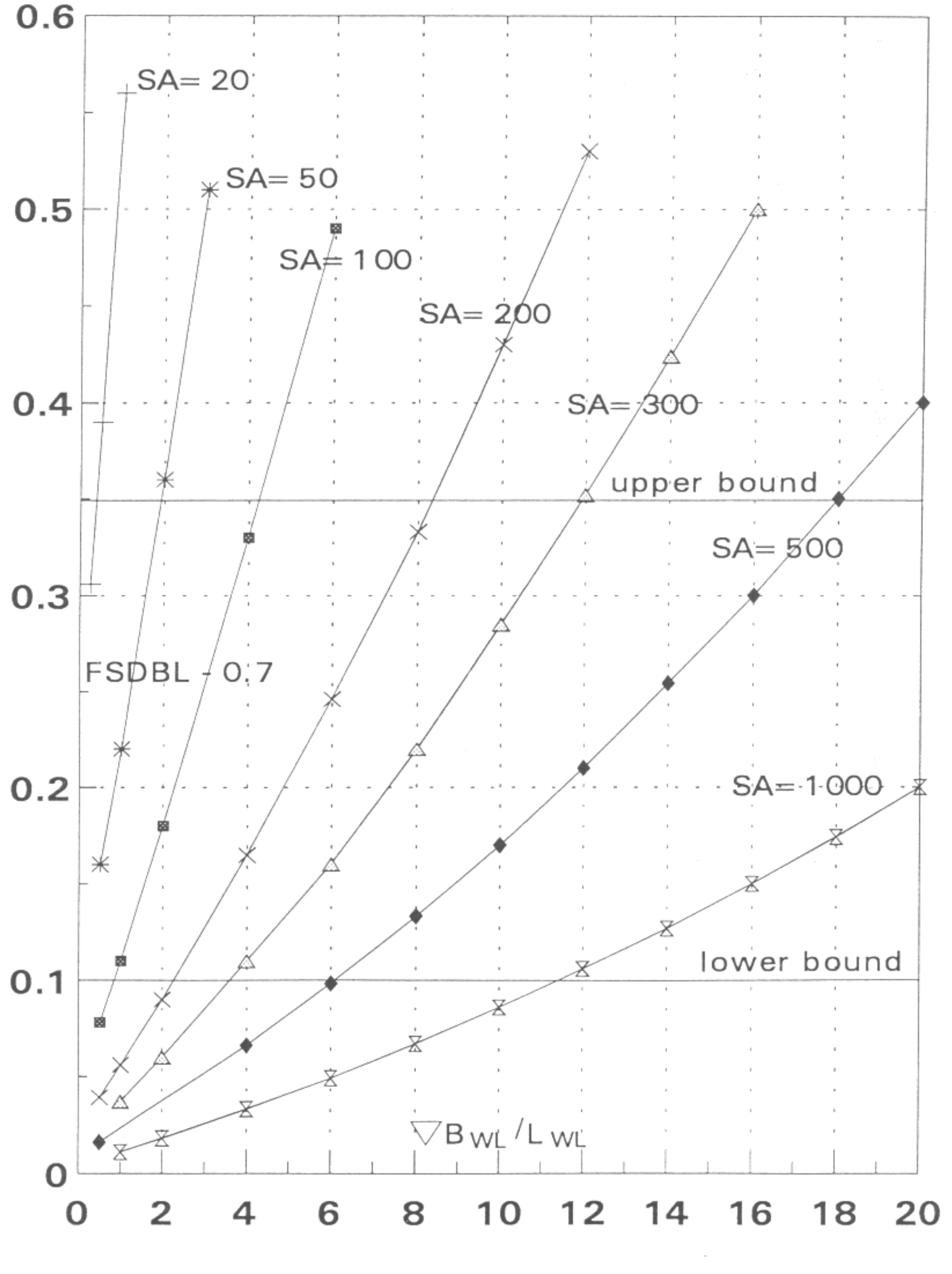

Figure 9. The permissible value of the variable part of FSDBL as a function of sail area in m^2 and the displacement-beam-length factor, $\nabla * B_{WL}/L_{WL}$.

able magnitude but the angle of vanishing positive righting moment were to be, say, only 95 degrees, the craft would probably not be able to recover from a knockdown (after the mast hits the water at a heel angle slightly in excess of 90 degrees). Accordingly, due consideration should be given to the product of GZ_{90} and the angle of vanishing positive righting moment ϕ_V, particularly if the angle of vanishing stability does not appear in any of the other factors making up the dynamic stability factor. A more appropriate formula for FSR might be:

$$FSR = 0.6 + 0.05*GZ_{90}*(\phi_V - 90)$$

where GZ_{90} = righting lever at 90 degrees of heel in meter, and
ϕ_V = angle of vanishing positive righting moment in degrees.

The value of $GZ_{90}*(\phi_V - 90)/2$ is approximately equal to the area under the righting moment curve between a heel angle of 90 degrees and the angle of vanishing positive righting moment. This area is a more accurate measure of the ability of a craft to recover from a knockdown or capsize.

The previously stated minimum and a maximum values for FSR of 0.6 and 1.2, respectively, should be maintained. This is one of the more important factors describing dynamic stability behaviour and its importance is well established through imposing the relatively low minimum value of 0.6.

9.6. FAA OR RELATIVE AREA FACTOR

This too is one of the more important factors. The formula thereof according to the RORC and RYA is:

$$FAA = 0.6 + 0.122*AA - 0.006*AA^2$$

where AA = the positive area under the righting moment curve between zero heel angle and the angle of vanishing positive righting moment, and the area under the righting moment curve between the angle of vanishing positive righting moment and a heel angle of 180 degrees.

A simplification of this formula has been proposed, viz:

$$FAA = 0.6 + 0.085*AA$$

Here, also, the minimum and maximum values are 0.6 and 1.2, respectively. Work is here yet required to develop reasonably accurate screening expressions for the angle of vanishing positive righting moment and the ratio AA, based on pertinent geometry and static stability parameters. The formulae yet to be developed for this purpose are to be somewhat conservative. When these screens are not met, a full GZ curve needs to be calculated, as is the case in other parts of the proposed Standard. The development of this factor will require further work.

9.7. FSSL OR STABILITY SPEED LOSS FACTOR

Considerable doubt and a lack of understanding persists as to the nature of this factor. It should be realized that while the transverse stability of well-designed hard-chine craft at planing speed is often higher then the results of static stability calculations indicate, the transverse stability of round-bilge craft at moderate to high speed is often less. The pronounced wave trough along the length of the hull is one of the prime causes of this. This feature is addressed by the FSSL or stability speed-loss factor.

At the Delft University of Technology, a series of 39 models of different sailing yachts have been tested over a full range of speeds, heel and leeway angles. In a recent publication by Gerritsma et al (1992), the loss in transverse stability of these models, representative of all types of ballasted mono-hull sailing yachts, was investigated. For moderate beam-draft ratios the reduction in righting moment lever was found to be relatively small. For beam-draft ratio values of 10 or more, however, this reduction was found to be appreciable. For Delft Model 31, with a waterline beam-canoe body draft ratio of 15.8, a waterline length of 10 meters, and a GM value of 2.78 meters, the reduction in transverse stability was found to be an average of 29%, from 0 to 30 degrees of heel.

The derivation of the FSSL factor, developed by the author of and forwarded to Working Group 22 in September 1993 for consideration, is outlined below.

Gerritsma and co-workers (1992) found that the following formula for the effect of speed on the transverse stability of mono-hull sailing yachts with a length of 10 meters on the waterline fitted the test data sufficiently accurately:

$$MN_{10} * \sin\phi / L_{WL} = D2 * \phi * F_N + D3 * \phi^2$$

with $D2 = -0.0406 + 0.0109 * (B_{WL}/T_C) - 0.00105 * (B_{WL}/T_C)^2$

and $D3 = 0.0636 - 0.0196 * (B_{WL}/T_C)$

Note that in this representation, $MN_{10} * \sin\phi$, is the so-called residual stability part of the value of the righting lever GZ for the equivalent yacht with $L_{WL} = 10$ m, at some angle ϕ. This is defined as:

$$MN_{10} * \sin\phi = GZ_{10} - GM_{10} * \sin\phi$$

where

GM_{10} = metacentric height determined in the conventional way at zero speed in meters, for the yacht scaled up (or down) to a waterline length of 10 meter;

ϕ = heel angle in radians;

L_{WL} = length of canoe body (hull without appendages) on waterline at zero speed and zero heel, equal to 10 meter;

F_N	=	Froude number based on forward speed and L_{WL}, viz: $F_N = V_B/(g*L_{WL})^{1/2}$, where:
V_B	=	forward speed in m/sec;
g	=	acceleration due to gravity (9.81 m/s^2);
B_{WL}	=	maximum beam on the waterline at zero speed and zero heel angle, in meters,
and T_C	=	maximum draft of the canoe body at zero speed and zero heel angle, in meters.

This expression is valid up to a heel angle of 30 degrees, which is the greatest heel angle considered during the model tests with the 39 models. The D2 term in this expression accounts for the loss in stability due to forward speed, which is hereafter called $MN_{10(speed)}$, i.e.

$$MN_{10(speed)}*\sin\phi = -(0.0406-0.0109(B_{WL}/T_C)+0.00105(B_{WL}/T_C)^2)*\phi*F_N*L_{WL}$$

On expressing this loss in GZ as a fraction of the total GZ, we can write:

$$FSSL = 1 + MN_{10(speed)}*\sin\phi/GZ_{10}$$

This is the basis for the calculation of the Stability-Speed-Loss factor FSSL.

The relation for $MN_{10(speed)}$ can be simplified by adopting a heel angle of 30 degrees and a Froude number of 0.40 (which value corresponds to the case the wave trough along the hull of the yacht is most pronounced). We then obtain, after some simplification:

$$FSSL = 1 - \frac{(0.00850 - 0.00228*(B_{WL}/T_C) + 0.000220*(B_{WL}/T_C)^2)*L_{WL}}{GM_{10}*\sin(30) + MN_{10(V=0)}*\sin(30)}$$

The value of MN at zero forward speed, $MN_{10(V=0)}$, is given by the expression:

$$MN_{10(V=0)} = L_{WL}*D3*\phi^2/\sin\phi$$

Accordingly, after rounding-off the various coefficients to 2 significant numbers, we obtain:

$$FSSL = 1 - \frac{(0.0085 - 0.0023*(B_{WL}/T_C) + 0.00022*(B_{WL}/T_C)^2).L_{WL}}{GM_{10}/2 + (0.017 - 0.0054*(B_{WL}/T_C))*L_{WL}}$$

Since L_{WL} = 10 m, we finally obtain:

$$FSSL = 1 - \frac{0.085 - 0.023*(B_{WL}/T_C) + 0.0022*(B_{WL}/T_C)^2}{GM_{10}/2 + 0.17 - 0.054*(B_{WL}/T_C)}$$

A numerical example follows.

Model 31 of the Delft standard series of mono-hull sailing yacht, for which the loss in transverse stability was measured to be the greatest of the 39 models, has the following full-scale parameters: B_{WL}/T_C = 15.82 and GM_{10} = 2.78 m (for L_{WL} = 10 m). This yields:

$$FSSL = 1 - \frac{0.085 - 0.023 * 15.82 + 0.0022 * 15.82^2}{1.39 + 0.17 - 0.054 * 15.82}$$

or $$FSSL = 1 - 0.272/0.706 = 0.615$$

For a more moderate design, with GM_{10} = 1.5 m (L_{WL} = 10 m) and B_{WL}/T_C = 4, for example, we obtain a value of FSSL = 0.96.

A minimum value of 0.7 and a maximum value of 1.0 is proposed for FSSL. Note that the maximum value of 1.0 will only be attained at values of B_{WL}/T_C around 4 to 6, for high metacentric height values.

Note that when B_{WL}/T_C = 0, the value of FSSL becomes:

$$FSSL = 1 - 0.085/(GM_{10}/2 + 0.17)$$

which value is 0.5 when GM_{10} = 0.

Figure 10 shows the effect of B_{WL}/T_C on FSSL for GM_{10} values of 0.5, 1.0, 1.5, 2.0 and 3.0 meter. From these graphs it follows that for B_{WL}/T_C values less than about 5.0 the value of FSSL decreases slightly. To avoid this, it is proposed to limit the minimum B_{WL}/T_C value for the evaluation of FSSL to 5.0. Similarly, it is proposed to limit the maximum value of B_{WL}/T_C for the calculation of FSSL to:

$$(B_{WL}/T_C)_{max} = (50*GM_{10})^{0.606}$$

to avoid numerical difficulties associated with zero or negative values of the denominator of the expression for FSSL.

In conclusion therefore, the proposal for FSSL becomes:

$$FSSL = 1 - \frac{0.085 - 0.023*(B_{WL}/T_C) + 0.0022*(B_{WL}/T_C)^2}{GM_{10}/2 + 0.17 - 0.054*(B_{WL}/T_C)}$$

with $(B_{WL}/T_C)_{min} = 5$

and $(B_{WL}/T_C)_{max} = (50*GM_{10})^{0.606}$

where the minimum value of FSSL is 0.7. Finally, it should be realized that the value of GM_{10} can be obtained for the yacht of interest by multiplying the actual value of GM by the ratio $10/L_{WL}$, where L_{WL} is the actual length of the waterline of the canoe body of the craft of interest, viz:

$$GM_{10} = GM*(10/L_{WL})$$

9.8. FRMI OR ROLL MOMENT OF INERTIA FACTOR

A proposal for the roll moment of inertia factor FRMI was prepared by Rolf Eliasson, a member of Working Group 22, in

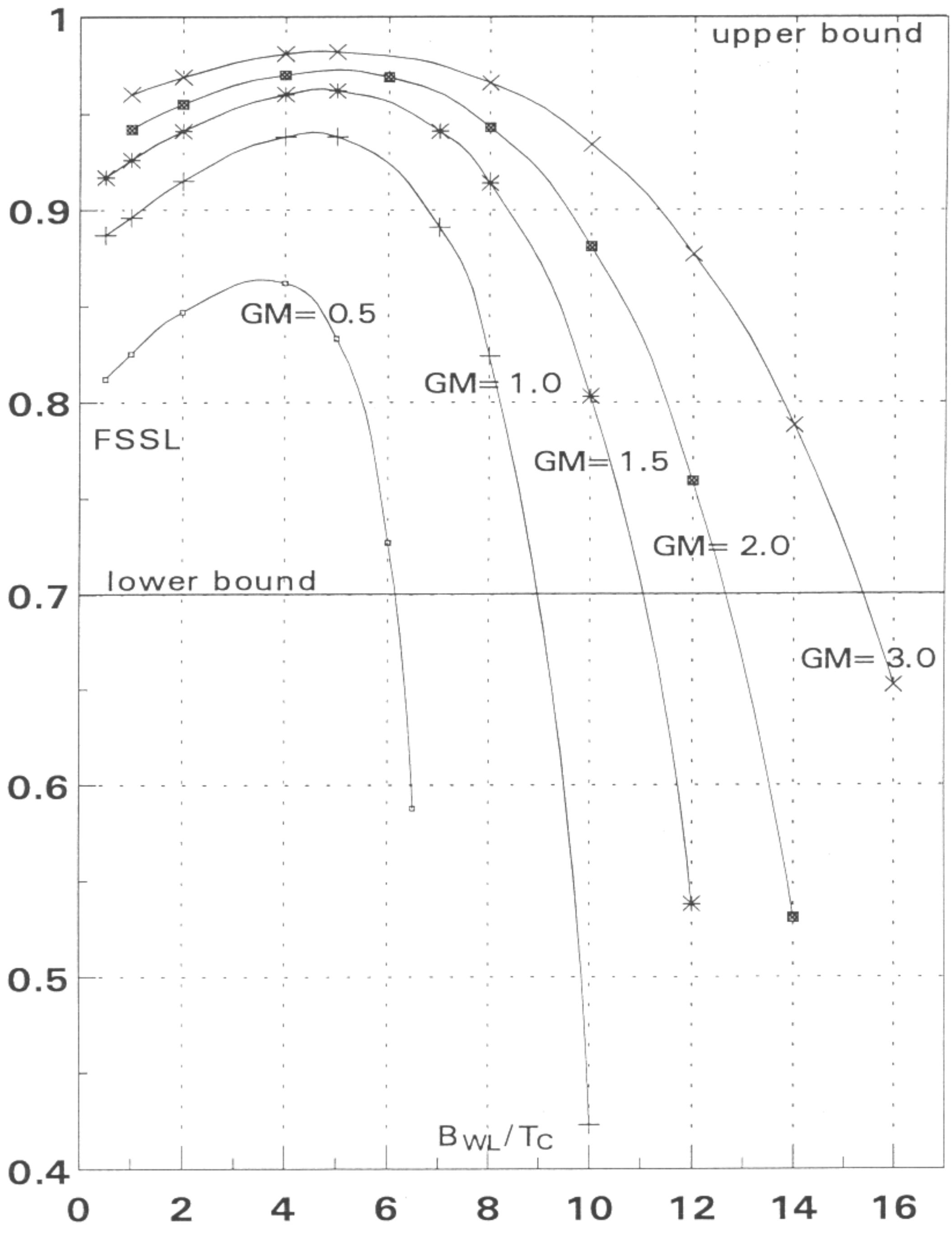

Figure 10. The value of FSSL as a function of B_{WL}/T_C for GM_{10} values of 0.5, 1.0, 1.5, 2.0 and 3.0 meter.

January 1994. This is based on an approximate calculation of the roll, mass-moment of inertia around the centre of the flotation plane, as follows:

$$I_{xx(tot)} = I_{xx(rig)} + I_{xx(hull)} + I_{xx(keel)}$$

where $I_{xx(tot)}$ = total mass moment of inertia about the longitudinal axis at the intersection of the symmetry plane of the yacht and the waterplane;
$I_{xx(rig)}$ = mass moment of inertia of mast and standing and running rigging;
$I_{xx(hull)}$ = mass moment of inertia of the hull;
and $I_{xx(keel)}$ = mass moment of inertia of keel (and ballast therein).

The approximate formulae for the individual moments of inertia are as follows:

$$I_{xx(rig)} = \Delta_{rig}*((H_M+H_H)^2/6 + 2*(H_M/2+H_H)^2/3 + H_H^2/6)$$

where Δ_{rig} = total mass of mast and rigging, in kg;
H_M = height of top of mast above base of mast (at deck or coach roof), in meter;
and H_H = height to base of mast above waterplane, in meter.

$$I_{xx(hull)} = \Delta_{hull}*(F_M^2/3 + 2*((F_M/2-T_C/2)^2/3+2*(B_{WL}/2+B_{max}/2)^2)/3)$$

where Δ_{hull} = total mass of yacht in minimum sailing condition, excluding mass of rig and keel, in kg;
F_M = freeboard amidships, in meter;
T_C = maximum draft of canoe body, in meter;
B_{WL} = maximum beam of canoe body on the waterline, in meter;
B_{max} = maximum beam of hull, as defined in ISO 8666, in meter.

$$I_{xx(keel)} = \Delta_{keel}*((T_K+T_C)^2/6 + 2*(G_{ballast}+T_C)^2/3 + T_C^2/6)$$

where Δ_{keel} = total mass of keel, inclusive of ballast therein (or in bulb), in kg;
T_K = depth of bottom of keel below bottom of canoe body, in meter;
and $G_{ballast}$ = depth of centre of gravity of ballast in keel (or bulb) below bottom of canoe body, in meter.

In this calculation of the roll mass moment of inertia, the mass of rig, hull and keel is assumed to be distributed in discrete locations to facilitate this approximate calculation. The mass of the mast and rigging is assumed to be concentrated at the base thereof (one-sixth), at mid-height (two-thirds) and at the top thereof (one-sixth). Similarly, the mass of the keel and ballast therein is assumed to be concentrated at the bottom of the keel (one-sixth) at the centre of gravity of the ballast itself (two-thirds) and at the top of the keel (1/6th). The mass of the hull is assumed to be concentrated at deck level, amidships, (one-third) and at a distance from the center of roll equal to $((F_M-T_C)^2/4+(B_{WL}+B_{max})^2/4)^{1/2}$ (two-thirds).

The non-dimensional roll gyradius is then calculated from:

$$k_{xx} = (I_{xx(tot)}/\Delta_{tot})^{1/2}$$

where Δ_{tot} = total mass of displacement, in kg.

The non-dimensional roll-gyradius - beam ratio (GBR) is then:

$$GBR = 2*k_{xx}/(B_{WL}+B_{max})$$

The roll moment of inertia factor FRMI is then defined by normalizing GBR as follows:

$$FRMI = (10.67*GBR*\nabla^{1/3}/(B_{WL}+B_{max}) - 0.2)^{1/2}$$

Although the original proposal was to adopt minimum and maximum values for FRMI of 0.6 and 1.2, respectively, it is suggested that this minimum value is too low and that a more suited minimum value is 0.8. This is based on the relative importance of the various factors on hazardous behaviour.

Further work is required in applying this factor for various craft, to obtain more insight into the validity of the assumptions made. It would appear however that the above formulae represent a significant improvement over previous screens for the roll moment of inertia, as proposed by USYRU and SNAME, and others (see Deakin, 1991).

9.9. FDA OR DOWNFLOODING ANGLE FACTOR

A factor for the dynamic effect of the degree of downflooding on capsize recovery is currently in development. Downflooding or the amount of water taken on board during a capsize will influence capsize recovery behaviour. Accordingly, a parameter for the amount of water taken on board must be part of this factor. The downflooding angle, as a parameter, is less significant in this regard.

10. FINAL REMARKS

The subject matter dealt with in this paper, in the context of ISO Standard 12217, is still in development. All of the criteria presented will remain subject of discussion in the Working Group for another 9 months or so. Also, it should be remarked that once the Working Group has presented its so-called CD (Committee Draught) version of the Standard, this will be sent to all ISO member countries for formal consideration. It is quite likely that proposals will be forthcoming recommending modifications, additions and deletions. As such, this paper should be considered as a presentation of the current state of affairs with respect to the development of a relatively small part of the Standard. Furthermore, the opinions and remarks presented here are by no means those of Working Group 22, but those of the Netherlands delegate only.

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