Subject 8.

Forces and Moments on Ships in a Seaway

Chairman: Prof. Dr. Techn. C. W. Prohaska.
Reporter: Prof. E. V. Lewis.
Secretary: Mr. W. A. Crago.

Introductory Remarks *

SCOPE.

The subject of this session of the Conference is taken to refer to the forces and moments acting on the main hull structure of ships when the motions of ship and wave are taken into account—as distinguished from the forces and moments calculated under the conventional static assumptions. The subject embraces the effects of impact loads, which involves the elastic characteristics of the hull structure.

Reference to the seaway implies that consideration is to be given to the effects of the irregular patterns of the sea in contrast to regular waves of constant period and amplitude customarily used in model tests.

In preparing this report and the list of references at the end, individuals in model basins in several different countries were contacted and their suggestions incorporated herein. However, the writer would be grateful for any additional references which participants in the conference may be able to suggest in discussion, as well as descriptions of any as yet unpublished work.

BACKGROUND.

The subject of bending moments in waves has been studied rather intermittently ever since the beginning of iron shipbuilding. The most complete early analytical treatment was by A. Kriloff in 1895 and 1898 (Refs. B-4, 5), and it is only recently that significant advances have been made beyond his classic work. In 1905, J. H. Biles published the results of observations of hull stresses on HMS WOLF at sea (as well as in dry dock) (Ref. A-1), which have been followed by many other full-scale trials in the intervening years. Strangely enough the experimental approach in the model tank has been a very recent development. Apparently the first such tests were carried out in Japan by Sato in 1945, but results were not published at that time. Sato's report in Japanese has been translated into English recently and made generally available (Ref. C-1). Other experimental work has been done in the U. S. A., in Japan, and recently in England.

The successful introduction of the problem of dynamic forces and moments in waves into the model basin is undoubtedly the reason for the inclusion of the subject in the program of the Eighth I.T.T.C. However, for completeness this report will first outline briefly the state of knowledge in the areas of full-scale observation and of analytical investigation, and then will go into somewhat greater detail in the experimental aspects of the subject.

A list of references in the three areas is appended to the report. It is not intended to be an exhaustive bibliography except for part C, model studies.

FULL-SCALE OBSERVATIONS.

Early Work.

An admirable summary of early work on observed hull stresses (or strains) at sea is given in the Ocean Vulcan report (Ref. A-26). Outstanding was the work on the M. S. SAN FRANCISCO, which was notable for the completeness of the instrumentation and the fact that unusually severe sea conditions were encountered. The work showed among other things that the observed hull stresses in a severe storm were appreciably less than those predicted by conventional static methods of calculation without "Smith effect". Schnadel found that even after taking the Smith effect into account, the actual hogging stresses were less than the theoretical, but the sagging stresses were somewhat higher. He concluded that the discrepancy might be due to the ship mo-

(*) This report has been prepared under Stevens E. T. T. Project GE 1723, Research on Forces and Moments on Ship Hulls in Waves in Reference to Structural Design, sponsored by the Bureau of Ships, U. S. Navy, through the David Taylor Model Basin, under Contract Nonr 263(09).

TABLE 1.—SUMMARY OF TRIALS ON THE BEHAVIOUR OF SHIPS' STR

REPRODUCED FROM "S.S. OCEAN VULCAN SEA TRIALS, REPORT NO. R-8", THE ADMIRALTY SHIP V

	SHIP	TYPE	Registered Length (feet)	Gross Tonnage	Strain Gauges Used at Sea	Other Instruments Used	Trials Voyage(s)	I
1	*H.M.S. Wolf.*	Destroyer	211 (B.P.)	—	3 Stromeyer Gauges Mechanical Type Non-Recording		Runs off S.W. Coast of England	Ma
2	*S.S. Ancon.*	Dry Cargo	389.5	9332	1 Portable Gauge Mechanical Non-Recording 6" Base Length		New York to Colon and return	Apri
3	*S.S. Westboro.* *S.S. Faith.*	Dry Cargo Dry Cargo	409.5 320	5770 3400	Up to 22 Mechanical Gauges Self-Recording 30" Base Length	13 Presure Gauges	Double Crossing of N. Atlantic San Francisco to Vancouver	Spri
4	*S.S. London Mariner* *S.S. Kenmore.* *S.S. Ravonia.* *S.S. San Tirso.* *S.S. San Fraterno.*	Dry Cargo Dry Cargo Coaster Tanker Tanker	450.5 363.5 186.5 420.6 527.3	7896 3616 813 6236 11.929	Up to 4 Mechanical Gauges Non-Recording 24" to 36" Base Length		Westbound across N. Atl. Eastbound across N. Atlan Round Land's End to Liverpool London to Gulf of Mexico Gulf of Mexico to England	Spri Autu Spri
5	*S.S. Wesphalia.*	Dry Cargo	473.6	11.343	6 Carbon Resistance Electric. Strain Gauges Remote Recording by Oscillograph	Shaft Torsiometers	Double Crossing of N. Atlantic	Aug
6	*S.S. Gottingen.*	Dry Cargo	428.7	5498	Up to 25 Carbon Resistance Electric Strain Gauges Remote Recording by Oscillograph	3 Presure Gauges 3 Accelerometers 2 Rows Wave Profile Indicators	Bremen-Baltimore-Bremen	Aug
7	—	Dry Cargo	425	12.900 (Δ)	1 Mechanical Gauge Self Recording about 12" Base Length		Leith-St. J.-Halifax-Hambg Both East and Westward Round N. Coast of Scotland	Dece -Fe
8	— —	Passenger Liner Passenger Liner	550 600		1 Mechanical Gauge Self-Recording about 12" Base Length		England to Australia via Suez. Australia to England via Suez	
9	*U.S.S. Cuyama.*	Tanker	455	15.000 (Δ)	3 Potential Dividor Type Electric Strain Gauges Long Base Length of 300"	Mechanical Deflection Measuring Equipment	Voyages in Gulf of Mexico and N. Pacific including Honolulu and Port Arthur	Spr 50 St
10	*Several U.S. Naval Vessels.*	Different Types	—		Various Scratch Type Gauges, Long Base Gauge and Prototype E. R. S. Gauges	Optical Deflection Measuring Equipment Accelerometers	Various Voyages Primarily to test out instruments	Vari tes 1935
11	*M.S. San Francisco.*	Dry Cargo	432.4	6753	About 40 Mechanical Gauges Self-Recording about 12" Base Length	Optical Deflection Measuring Equipment 8 Pressure Gauges 12 Rows Wave Profile Indicators Accelerometers Gyroscope Angle Recorders Stereo-Cameras Anemometers	Hamburg to Vancouver (B. C.) and return to Liverpool via Panama Canal	Sept Dec
12	*M.S. Robert Ley.*	Passenger Liner			Details not known	Details not known Probably as above but with improvements and additions	No Trials Voyages	Prep tr W 1
13	*S.S. Beaverbrae.*	Dry Cargo	502.5	9956	5 Mechanical Type Gauges Non-Recording 4 with 72" Base Length 1 (Portable) with 3" Base		London-Halifax-London London-Halifax-London	Ma Dece to
14	*M.V. San Conrado.*	Tanker	465.0	7982	3 Mechanical Type Gauges Non-Recording 2 with 360" Base Length 1 (Portable) with 3" Base Length		Liverpool-Tampico-London	Spr
15	*M.S. Duisburg.*	Dry Cargo	463.6	7389	18 Mechanical Type Gauges 8" Base Length Local Cine Camera Recording	Local Panel Bending Gauge	Rotterdam to Bay of Biscay	Ap
16	*S.S. Samuel Gompers.* *S.S. George B. McFarland.*	Dry Cargo Dry Cargo	422.8 422.8	7216 7216	Up to 46 Wire Wound Electric Resistance, Strain Gauges using 4 Remote Recorders 1 Portable Mechanical Gauge 10" Base Length		San Francisco-(Alaska) -Tacoma S. Francisco-Guadalcanal Guam-San Francisco	Sum Sum
17	*M.V. Niso.*	Tanker	465.6	8273	2 Mechanical Gauges 100" Base 1 Portable Mechanical Gauge 18" Base 1 E. R. S. Gauge with Oscillograph Recording	6 Sets of Mechanical Deflection Measuring equipment 3 Pressure Gauges 1 Row Wave Profile indicator 1 Accelerometer Roll and Pitch Recorders Stereo Cameras	Glasgow-New York	Dece Janu

RY OF TRIALS ON THE BEHAVIOUR OF SHIPS' STRUCTURES AT SEA

ULCAN SEA TRIALS, REPORT NO. R-8", THE ADMIRALTY SHIP WELDING COMMITTEE, LONDON, 1953

Sea	Other Instruments Used	Trials Voyage(s)	Date	Weather	Maximum Stress Range (Out to Out) Tons per sq. in.	Potentiality of Trials Strain Gauge × Days	Author	References
		Runs off S.W. Coast of England	May 1905	Up to Force 7 Wind	7.9	15	J. H. Biles	A-1
ling		New York to Colon and return	April - May 1913	Moderate	1.5 2.2 at a Point of Stress Concentr.	15	J. E. Howard	A-2
	13 Presure Gauges	Double Crossing of N. Atlantic San Francisco to Vancouver	Spring 1919 1919	Rough Outbound, Moderate Homeward Bound Storm of unusual severity	Under 4.0 3.2	300* 50	Anon	A-4
n		Westbound across N. Atl. Eastbound across N. Atlan Round Land's End to Liverpool London to Gulf of Mexico Gulf of Mexico to England	Spring 1925 Autumn 1925 Spring 1926	Waves up to 360' long Waves up to 360' long by 20'-30' high Gale Rough Confused Seas Waves up to 680' long by 35' high	3.6 2.5 1.0 6.1 10.5	50 50 10 100 100	J. Lockwood Taylor	A-5
lec- Os-	Shaft Torsiometers	Double Crossing of N. Atlantic	August 1925	Moderate	1.9	120	Slemann	A-6
nce Os-	3 Presure Gauges 3 Accelerometers 2 Rows Wave Profile Indicators	Bremen-Baltimore-Bremen	August-Sept. 1926	Mostly moderate or calm Force 8 Wind for a few hours only	0.3 (No value for roughest conditions)	250*	Slemann	A-7
12"		Leith-St. J.-Halifax-Hambg Both East and Westward Round N. Coast of Scotland	Decemb. 1928 -Febr. 1929	Waves commonly 350' long by 16' high		50	B. C. Laws	A-8
		England to Australia via Suez. Australia to England via Suez	1930	Waves up to 300' long by 13' high Waves up to 250 long by 9' high	3.2	50 50	B. C. Laws	A-9
e 300"	Mechanical Deflection Measuring Equipment	Voyages in Gulf of Mexico and N. Pacific including Honolulu and Port Arthur	Spring 1930 50 Days Stalling	Winds up to Beaufort Force 6	6.3	200	W. P. Roop (U. S. Navy)	A-11
uge S.	Optical Deflection Measuring Equipment Accelerometers	Various Voyages Primarily to test out instruments	Various Dates between 1935 and 1940			—	W. P. Roop (U. S. Navy)	A-10, 12
h	Optical Deflection Measuring Equipment 8 Pressure Gauges 12 Rows Wave Profile Indicators Accelerometers Gyroscope Angle Recorders Stereo-Cameras Anemometers	Hamburg to Vancouver (B. C.) and return to Liverpool via Panama Canal	September tc Decem. 1934	Hurricane Force 12 Winds Waves up to 600' long by 45' high	8.2 (9.6 including Slam Stresses)	1800*	G. Schnadel	A-17 18 19
	Details not known Probably as above but with improvements and additions	No Trials Voyages	Prepared for trials in Winter 1939-40			—*	G. Schnadel	A-19
ges h Base		London-Halifax-London London-Halifax-London	March 1935 Decemb. 1935 to January 1936	Fresh Gale Strong Gale	2.3 4.9 8.1 at point of concentration	125 125	C. H. Stocks	A-16
ges h Base		Liverpool-Tampico-London	Spring 1937	Winds up to Beaufort Force 7-8 Waves up to 400' long by 28' high	4.3	100	I. C. Bridges	A-20
ges -	Local Panel Bending Gauge	Rotterdam to Bay of Biscay	April 1939	Mostly Calm Seas	1.7	120	W. Dalman & K. Remmers	A-21
		San Francisco-(Alaska) -Tacoma S. Francisco-Guadalcanal Guam-San Francisco	Summer 1944 Summer 1944	Up to Force 9 Wind in Enclosed Waters Mostly Moderate	3.0	300 400	E. D. Howe A. Boodberg B. York & M. P. O'Brien	A-22
00" Os-	6 Sets of Mechanical Deflection Measuring equipment 3 Pressure Gauges 1 Row Wave Profile indicator 1 Accelerometer Roll and Pitch Recorders Stereo Cameras	Glasgow-New York	Decemb. 1944 to January 1945	Moderately Rough Waves up to 20' high	3.2	50*	G. M. Boyd F. B. Bull & K. J. Pascoe (Admiralty)	A-23

1	*H.M.S. Wolf.*	Destroyer	211 (B.P.)	—	3 Stromeyer Gauges Mechanical Type Non-Recording		Runs off S.W. Coast of England	Ma
2	*S.S. Ancon.*	Dry Cargo	389.5	9332	1 Portable Gauge Mechanical Non-Recording 6" Base Length		New York to Colon and return	April
3	*S.S. Westboro.* *S.S. Faith.*	Dry Cargo Dry Cargo	409.5 320	5770 3400	Up to 22 Mechanical Gauges Self-Recording 30" Base Length	13 Presure Gauges	Double Crossing of N. Atlantic San Francisco to Vancouver	Spri 1
4	*S.S. London Mariner* *S.S. Kenmore.* *S.S. Ravonia.* *S.S. San Tirso.* *S.S. San Fraterno.*	Dry Cargo Dry Cargo Coaster Tanker Tanker	450.5 363.5 186.5 420.6 527.3	7896 3616 813 6236 11,929	Up to 4 Mechanical Gauges Non-Recording 24" to 36" Base Length		Westbound across N. Atl. Eastbound across N. Atlan Round Land's End to Liverpool London to Gulf of Mexico Gulf of Mexico to England	Spri Autu Spri
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6	*S.S. Gottingen.*	Dry Cargo	428.7	5498	Up to 25 Carbon Resistance Electric Strain Gauges Remote Recording by Oscillograph	3 Presure Gauges 3 Accelerometers 2 Rows Wave Profile Indicators	Bremen-Baltimore-Bremen	Augu
7	—	Dry Cargo	425	12.900 (Δ)	1 Mechanical Gauge Self Recording about 12" Base Length		Leith-St. J.-Halifax-Hambg Both East and Westward Round N. Coast of Scotland	Decer -Feb
8	— —	Passenger Liner Passenger Liner	550 600		1 Mechanical Gauge Self-Recording about 12" Base Length		England to Australia via Suez. Australia to England via Suez	1
9	*U.S.S. Cuyama.*	Tanker	455	15.000 (Δ)	3 Potential Dividor Type Electric Strain Gauges Long Base Length of 300"	Mechanical Deflection Measuring Equipment	Voyages in Gulf of Mexico and N. Pacific including Honolulu and Port Arthur	Spri 50 St
10	*Several U.S. Naval Vessels.*	Different Types	—		Various Scratch Type Gauges, Long Base Gauge and Prototype E. R. S. Gauges	Optical Deflection Measuring Equipment Accelerometers	Various Voyages Primarily to test out instruments	Vari tes 1935
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12	*M.S. Robert Ley.*	Passenger Liner			Details not known	Details not known Probably as above but with improvements and additions	No Trials Voyages	Prepa tri W 19
13	*S.S. Beaverbrae.*	Dry Cargo	502.5	9956	5 Mechanical Type Gauges Non-Recording 4 with 72" Base Length 1 (Portable) with 3" Base		London-Halifax-London London-Halifax-London	Mar Decer to J
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18	*S.S. Ocean Vulcan.*	Dry Cargo	425.1	7174	20 Complete Station E.R.S. Gauges Remote Recording by Cine Camera 2 Non-Recording Portable Gauges	Numerous Pressure Gauges Accelerometers, etc., See Table IV	8 Double Crossings of N. Atlantic	Dece Ma

NOTE.—Potenciality number is the multiple of the number of strain gauges available times the number of
Numbers marked thus:— * Indicate that instruments other than strain gauges were used extensivel
These other instruments are not included in the assessment of potentiality number.

		Runs off S.W. Coast of England	May 1905	Up to Force 7 Wind	7.9	15	J. H. Biles	A-1
ing		New York to Colon and return	April - May 1913	Moderate	1.5 2.2 at a Point of Stress Concentr.	15	J. E. Howard	A-2
	13 Presure Gauges	Double Crossing of N. Atlantic San Francisco to Vancouver	Spring 1919 1919	Rough Outbound, Moderate Homeward Bound Storm of unusual severity	Under 4.0 3.2	300* 50	Anon	A-4
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12"		Leith-St. J.-Halifax-Hambg Both East and Westward Round N. Coast of Scotland	Decemb. 1928 -Febr. 1929	Waves commonly 350' long by 16' high		50	B. C. Laws	A-8
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e 00"	Mechanical Deflection Measuring Equipment	Voyages in Gulf of Mexico and N. Pacific including Honolulu and Port Arthur	Spring 1930 50 Days Stalling	Winds up to Beaufort Force 6	6.3	200	W. P. Roop (U. S. Navy)	A-11
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ges h Base		London-Halifax-London London-Halifax-London	March 1935 Decemb. 1935 to January 1936	Fresh Gale Strong Gale	2.3 4.9 8.1 at point of concentration	125 125	C. H. Stocks	A-16
ges h Base		Liverpool-Tampico-London	Spring 1937	Winds up to Beaufort Force 7-8 Waves up to 400' long by 28' high	4.3	100	I. C. Bridges	A-20
ges	Local Panel Bending Gauge	Rotterdam to Bay of Biscay	April 1939	Mostly Calm Seas	1.7	120	W. Dalman & K. Remmers	A-21
		San Francisco-(Alaska) -Tacoma S. Francisco-Guadalcanal Guam-San Francisco	Summer 1944 Summer 1944	Up to Force 9 Wind in Enclosed Waters Mostly Moderate	3.0	300 400	E. D. Howe A. Boodberg B. York & M. P. O'Brien	A-22
00" Os-	6 Sets of Mechanical Deflection Measuring equipment 3 Pressure Gauges 1 Row Wave Profile indicator 1 Accelerometer Roll and Pitch Recorders Stereo Cameras	Glasgow-New York	Decemb. 1944 to January 1945	Moderately Rough Waves up to 20' high	3.2	50*	G. M. Boyd F. B. Bull & K. J. Pascoe (Admiralty)	A-23
R.S. ine ble	Numerous Pressure Gauges Accelerometers, etc., See Table IV	8 Double Crossings of N. Atlantic	Decemb. 1945 to May 1947	Conditions from Calm to Force 9 Winds Waves up to 700' long by 35' high	8.0	15,000*	Admiralty Ship Welding Committee	A-26

f the number of strain gauges available times the number of days at sea.
hat instruments other than strain gauges were used extensively.
ded in the assessment of potentiality number.

tions interfering with the wave structure and pressures (Refs. A-17, 18, 19).

Ocean Vulcan.

The well-known Ocean Vulcan sea trials (Reference A-26) had a different objective than most earlier full-scale investigations. The aim was to determine the maximum seaway loads on a typical cargo vessel, in order that the stresses in both a riveted and a welded ship could be compared in still water under realistic loadings. The determination of the sea loads was accomplished by measuring the pressures over the entire underwater hull, supplemented by accelerometer measurements. From these data the longitudinal load distribution was determined and hence the shear and bending moment curves calculated in the customary manner. Direct measurements of stresses or strains at sea were therefore secondary to the main objective of the trials and were included mainly for checking purposes. The following conclusions were reached from the sea trials (Ref. A-26):

"(1) The greatest range of vertical bending moment derived from these observations at sea was 190,000 tons-ft., corresponding to a range of stress of 8 tons per sq. in. at the top of the sheer strake amidship. There is no experimental evidence to show the actual division of this range between hogging and sagging, but theoretical considerations suggest that the sagging moment constituted about 55 per cent of the total range.

"(2) The above range of vertical bending moment was associated with waves 35 ft. high and between 600 and 700 ft. long. According to oceanographical data, waves of even greater severity may be encountered, but it is estimated that for the Ocean Vulcan the maximum bending moment range due to waves is never likely to exceed 260,000 tons-ft. This corresponds to a stress range of 11.0 tons per sq. in. at the top of sheer strake amidships.

"(4) Horizontal longitudinal bending moments were observed in almost all wave conditions, and sometimes caused stresses of similar magnitude to those due to the concurrent vertical bending. The maximum range of horizontal bending moment observed was 80,000 tons-ft. corresponding to a stress range of 2-1/2 tons per sq. in. at the sheer strake amidships. The horizontal and vertical bending moments were frequently in phase and this resulted in the stress range on one sheer strake (or bilge) being very different from that on the other.

"(5) The greatest horizontal bending moments occurred when the inclination of the wave advance relative to the ship's course was between 20 and 50 degrees. In head or following seas, which caused the highest vertical bending moments were relatively small.

"(6) Torsion moments derived from the records were small and therefore had little effect on the stresses on the hull girder."

Data on High Stresses.

The accompanying Table 1 (*) (from Ref. A-26) summarizes the reliable observed high stress reported by various investigators up to 1953. Additional data available since are tabulated in Table 2. It is significant that in no case did stresses reach really dangerous proportions, and they are well below the usual "allowable stresses". This is despite the fact noted in Reference A-26 that "the locations chosen for instrument stations were often at places of obvious stress concentration". However, there is no assurance that higher stresses have not been experienced when no recording instruments were available, and in any case, direct comparisons of observed stresses with conventional "allowable stresses" should be made with caution. The conventional static method of calculating longitudinal strength is meant to be a standard of comparison rather than a realistic prediction, and the same standard of strength can of course be obtained by any number of different combinations of assumed wave height and "allowable stress."

Statistical Data.

The irregularity of the sea and the difficulty of obtaining continuous stress data over long periods such as the life of a ship has served to emphasize the need for statistical techniques in interpreting data observed at sea. Outstanding work along this line has been done by Jasper (Refs. A-31, 32, 40). The greatest value of his work to date appears to be in defining the typical statistical patterns of alternating stresses experienced by actual ships, which will permit a better evaluation of the place of endurance strength in the structural failure of ship hulls. Unfortunately, the statistical methods cannot yet give a satisfactory answer to the question of the maximum bending moments or stresses to be expected in the life of a ship. (See Ref. A-40 and discussion.) Consequently, further developments in this area are urgently needed, as discussed in the section on Analytical Work.

Impact Loads.

Coming now to the consideration of impact loads, the effect of slamming on the main hull girder stresses (or strains) was clearly shown in the observations made on the Westboro (Ref. A-4), Westpha-

(*) Enclosed in the pocket attached to the rear cover of the book.

lia (Ref. A-6), San Francisco (Refs. A-17, 18, 19), and Ocean Vulcan (Ref. A-26). These results usually showed a sudden sagging stress followed by an oscillating stress superimposed on the normal stress caused by wave action. Records showed that for ships in ballast this vibratory effect usually continued for many seconds. The frequency of the oscillating stress corresponded with the natural frequency of vertical two-noded hull vibration, and its amplitude amounted to up to ± 1.5 tons per sq. in. (Refs. A-18 and 26). Since the recorded slams usually occurred immediately after a high peak of hogging stress, the initial impact actually decreased the stress momentarily. But the following vibratory stress served to increase the subsequent sagging peak.

More recent ship data on slamming have been obtained on the U. S. Coast Guard Cutters Casco (Ref. A-27) and Unimak (Ref. A-37), including actual measurements of slamming pressures. The maximum local pressure recorded on the Unimak was "of the order of 300 lb./sq.in." Instrumentation is described in Ref. A-34. Data have also been obtained by Warnsinck (Ref. A-30).

TABLE 2.—SUPPLEMENTARY DATA ON FULL-SCALE SHIP TRIALS

Ship	Type	Length Ft.	Strain Gages	Other Measurements	Voyages	Dates	Weather	Max. Stress Range Tons/In.²	Author	References
Nissei-Maru	Dry Cargo	420	11 resistance wire strain gages and 3 mechanical meters	Shaft RPM and torque; roll, pitch, yaw, heave; helm angles	1 round trip across Pacific	12/51 to 5/52	Calm to Force 9 winds	3.9	Exp. Tank Committee of Japan	A-20
Esso Asheville	T-2 Tanker	503	2 sets of SR-4 strain gages and DTMB 10" str. gage on deck near amidships	Heave and pitch accelerations	Along Atlantic seaboard, Central Amer. & Gulf Coast	8/52 to 4/54	Calm to Force 6 winds	5.2	N. H. Jasper	A-32
Casco	U. S. Coast Guard Cutter	300	4 strain cycle counters, 6 SR-4 gages, 1 inductance gage-deck & keel near amidships & fwd. qtr. *L*	Bottom pressure fwd; roll & pitch angles; heaving, rolling & pitching accelerations	North Atlantic Ocean	3-4/51	Moderate to heavy weather	2.1	N. H. Jasper	A-27
Unimak	U. S. Coast Guard Cutter	300	2 sets of SR-4 strain gages, main deck near amidships	Bottom pressures and deflections fwd. (8 locations); roll and pitch angles; pitch & heave accelerations	North Atlantic Ocean	10/54-11/54 and 1/55-2/55	Force 8 to 9 winds	2.64 (Recorded) > 3.0 (Counter)	N. H. Jasper & J. T. Birmingham	A-37
Mormacpenn, Mormacmail	C-3 Cargo Ships	465	1 mechanical stress counter main deck near amidships	Log data on wind and sea conditions	9 round trip voyages across North Atlantic	1955 to 1956	Calm to Force 11 winds	> 7.1	Panel S-10, SNAME	A-34
Gopher Mariner	Dry Cargo Ship	528	2 DTMB mechanical strain cycle gages and counters, main deck near amidships	Pitch and roll angles	North Atlantic Ocean (6 crossings)	2-5/54	Calm to Force 8 winds	> 8.9	N. H. Jasper	A-40
Fessenden	Destr. Escort		10" DTMB gage and counter		Atlantic Coast, U. S.	12/52-4/53 10-11/1954		> 6.2	N. H. Jasper	A-40
	Destroyer		SR-4 gages		North Atlantic Ocean	Winter 1955-56		> 8.9	N. H. Jasper	A-40
Minnesota	Cargo Liner	440	3 strain gages	Pitch and roll angles	Atlantic Ocean	1-3/55		5.65	Swedish Shpbldg. Res. Found.	A-25

Current Work.

Various current projects in which stress and/or slamming data are being obtained, but for which no results are yet available, may be listed as follows:

Cooperative tests on destroyers, Royal Netherlands Navy and U. S. Navy (DTMB), Ref. A-39.
Observations on two converted Liberty ships, one of which has been lenthened 25 ft., U. S. Bureau of Ships (DTMB) and U. S. Maritime Administration, including wave records. (Ref. A-42).
Long range observations abord an aircraft carrier (USS VALLEY FORGE) and destroyer (USS SPERRY), U. S. Navy (DTMB).
Cooperative project for observations aboard the high-speed cargo ship, M. S. CANADA, Swedish Shipbuilding Research Foundation and U. S. Navy (DTMB).
Observations aboard the C-2 cargo ships, S. S. AMERICAN FLYER and S. S. AMERICAN MANUFACTURER, Hull Structure Committee (Panel S-10), SNAME.
Observations aboard the M. S. GINGA MARU in the North Pacific, which have been only partly analyzed (Ref. A-33).
Statistical research on French ships, Génie Maritime, making use of stress counters (Ref. A-41).
Observations on the modern tanker HAVTAR, by H. O. Meyer (see Ref. A-28).
Observations on various merchant ships at sea, British Shipbuilding Research Association.

Analytical Work.

Early Studies.

It is well known that the classical method of calculating the longitudinal bending moments of ships involves the simple static summation of weights acting downward and wave buoyancy forces acting upward. The ship is assumed to be poised in a horizontal position on either wave crest or hollow, and its motions are completely neglected. The first refinement was introduced by Smith in 1883, when the effect of the actual pressure distribution in a wave was shown to reduce the calculated bending moments appreciably (Ref. B-2). The first complete formulation of the related problems of ship motions and bending moments was due to Kriloff (Refs. B-4, 5) who set up the equations of motion for the ship as a rigid body pitching and heaving in regular waves. The "Smith effect" was included, but the disturbance of the motions of the wave particles, and hence the pressure distribution within the wave due to the presence of the moving ship's hull, was neglected (Froude-Kriloff hypothesis). Linear coefficients were assumed in the equations, taking into account damping in rather crude form, mass inertia effects, but not virtual mass (entrained water).

Other work on bending moments was done by Read (Ref. B-3), Alexander (Refs. B-6, 7), Robb (B-8), J. L. Taylor (B-10), and others listed at the end of this report. A particularly important analytical advance was made by Hazen and Nims (Reference B-16). These investigators made use of a mechanical computation device which permitted greater flexibility in the calculations. Accordingly, they were able to evaluate the buoyancy forces and moments for successive positions of the ship (i. e., to use non-linear coefficients).

Recent Developments.

Further important advances were made in the analytical work forming a part of the Ocean Vulcan project (Ref. B-23). Here the entrained water was taken into account, refinements were introduced in the determination of damping forces (with the assistance of model tests for the determination of coefficients), and the numerical method of computation used permitted the "exciting forces" to be treated in a non-linear manner. However, pitch and heave were still treated as independent motions.

Meanwhile, refinements in the analytical treatment of ship motions were made, without specific application to the bending moment problem: Kreitner (1939), Haskind (1946), Ursell (1949), Weinblum and St. Denis (1950) (Ref. B-20), St. Denis (1951), Grim (1953), Havelock (1942-1955), etc.

Finally, Korvin-Kroukovsky (Ref. B-30) treated the coupled equations of pitching and heaving and provided a method of calculating the exciting forces which took into account the interaction between ship and wave motions. At the same time he introduced a numerical "strip" method of calculation which was ideal for the application to the bending moment problem, where the longitudinal distribution of forces are of prime importance. Although linear coefficients were used for the motions calculations, non-linearity could readily be introduced in the calculation of bending moments (Ref. B-38). The most significant finding was that the disturbance of the wave by the moving ship tends to intensify the Smith effect and reduce the bending moment further, as suggested by Schnadel some twenty years carlier (Ref. A-17). Further refinements in the calculations have since been carried out (Ref. B-41), and direct comparison between calculated bending moments and those determined by model experiments have been made by Jacobs under the sponsorship of the S-3 Panel, SNAME (Ref. B-35). Results are encouraging but do not yet appear to be quantitatively correct in respect to the effect of ship speed. Similar, but somewhat simplified, analytical work has been carried out by Fay (Ref. B-45). Calculations are now being made at Stevens on a destroyer for which model data are available. The bending moment has been found to be virtually a second order effect, so that it is more difficult to calculate than the motions.

Recent work by Radosavljevic (Refs. B-36, 37), confirms the importance of the Smith effect and evaluates analytically the effect of the sloping sides at bow and stern on ship motions. A portion of his work now available only in Serbian (Ref. B-33) deduces approximate formulas and diagrams for the estimation of the bending moment, taking into account Smith effect, virtual mass, and other dynamic effects.

Irregular Seas.

St. Denis and Pierson (Ref. B-26) presented a complete statement of a statistical method of dealing analytically with the behavior of a ship in realistic irregular storm seas. In this method both the sea pattern and the irregular ship response are represented by the summation of a very large number of regular waves or responses. Although the paper was primarily concerned with ship motions, the discussions brought out the fact that other ship responses—such as stresses or bending moments—could be treated in the same manner. An introductory study along this line was sponsored by the S-3 Panel, SNAME (Ref. B-44), showing good results in the predicted statistical properties of bending moments in irregular tank waves. The method was then applied to predicting the trend of midship bending moments with severity of sea and speed of ships, with the following results for the T2-SE-Al tanker in head seas corresponding to different ideal storm wave patterns:

1. There is an upward trend of bending moment with increasing severity of the sea.
2. There is a slight upward trend of bending moment with increasing speed up to 10 knots, followed by a falling off at higher speeds-if attainable.
3. For the most severe case considered—an ideal fully-developed sea corresponding to a 45-knot wind (Ref. B-26)—the predicted values of the highest 10 % bending moments (hog + + sag) were:
   (a) Less than the "standard" static range of bending moment in a $L/20$ wave (without Smith correction),
   (b) Greater than the bending moment ranges corresponding to stresses actually recorded in recent full-scale observations at sea.

It should be noted that the characteristic bending moments in regular waves of different lengths ("response amplitude operators") used in the above work were determined by model tests rather than by calculation. When the analytical procedures reach a satisfactory state, the entire procedure can of course be carried out by calculation.

Other work making use of the superposition method of St. Denis-Pierson to treat the spectrum of bending moments in a seaway has been done by Akita (Ref. B-40) but is at present available only in Japanese.

A previously noted weakness of the statistical approach to the prediction of actual stresses at sea is that it breaks down when an answer is sought as to the *highest* value of bending moment (or stress) to be expected over a very long period of time, such as the life of a ship (Ref. B-39). Even if a great deal of data on high stresses recorded at sea were available, it appears doubtful that a satisfactory answer could be obtained by statistical methods alone. Fortunately there are definite physical limits to the bending moment which can be exerted on the hull by the sea: wave steepness has an absolute maximum value, and the depth of the ship itself limits the possible severity of the distribution of the forces of buoyancy. These physical limits on the external loads may actually provide the key to the problem of maximum stresses by permitting the maximum loads to be determined on physical grounds. In this connection, an important suggestion of Hazen and Nims (Ref. B-16) should be noted:

> "With a wave of any given shape at any given position along the hull assume a position and velocity for the ship in the heave and the pitch coordinates. These assumptions may be considered sufficient to fix the forces acting on the ship since the unbalanced force and moment, and consequently the accelerations, are fixed thereby. By investigating a series of such conditions with the hull having a wide range of positions and velocities with respect to the water, it is possible that an envelope for moment curves would be defined which would represent the maximum moments that would be encountered by the hull for any position and velocity to which it might be subjected..."

Once having determined the most extreme bending moment physically possible, statistical methods could undoubtedly be used to determine the probability of occurrence of this extreme condition.

Impact Loads.

The analytical treatment of impact loads in a seaway is not new to this Conference because of a brief presentation by Dr. Vedeler in Washington in 1951 (Ref. B-24) and an important paper at Oslo in 1954, "On Slamming", by V. G. Szebehely (Reference B-27). Dr. Szebehely's paper summarized work on both the analytical and experimental approaches to the problem. First of all, he defined slamming as a sudden change of acceleration, which is followed by the elastic vibration of the hull. It was brought out in the discussion of the paper that the elastic vibration could take place without slamming, but there was general (but not complete) agreement that the sudden change of acceleration was a good basis for defining the phenomenon. Undoubtedly, further sea observations which include bottom pressure measurements forward will settle this matter.

Next, Dr. Szebehely set up criteria which in some combination make slamming likely:

(1) Forefoot emergence,
(2) Large relative velocity between bow and wave,
(3) Small angle between the keel line and the wave slope (in a longitudinal direction) at the instant of impact.

In regular waves all of the above were shown to depend upon the following:

(a) Draft forward,
(b) Amplitude of pich and heave,
(c) Phase lag between bow motion and wave.

A study of the kinematics of ship motions on the basis of simple uncoupled theory then established conditions under which slamming is to be expected in regular waves. These results were generalized in more useful manner in Ref. B-32, where the figures showed the strong correlation between the first two of the above conditions for slamming and a value for the tuning factor, $\Lambda = T_p/T_e$, of unity (where T_p is the natural pitching period afloat and T_e is the period of encounter). The results also showed greater likelihood of slamming in waves of ship length or longer than in waves shorter than the ship.

Lewis has pointed out (Ref. B-31) that in view of the fact that conditions for deck submergence are almost identical with those for bow emergence, this work shows that all of the most objectionable aspects of ship motions are thus associated with synchronism. This fact acquires especial significance in relation to irregular seas, which may be considered as the summation of a large number of regular wave components. One would expect intuitively that slamming in irregular seas would be associated with conditions in which there would be synchronism between the natural pitching period and the period of encounter with wave components of ship length or longer. The observed diminution in slamming and wetness accompanying a reduction of ship speed can thus be explained in a general way by the avoidance of synchronism with all components except those which are shorter than the ship.

The likelihood of shipping water over the bow or emergence of the forefoot in irregular seas can easily be evaluated by the techniques presented in Reference B-26. (See Refs. B-29, 31.) For an exact evaluation of the likelihood of slamming in irregular seas, however, an extensión of the statistical techniques is required to take account of the joint probabilities of the simultaneous occurrence of two or more of the basic conditions for slamming. An important paper by Tick (Ref. B-29) has evaluated the number of slams to be expected per second on the basis of Szebehely's first two conditions, namely:

(1) Forefoot emergence,
(2) Relative velocity between the bow and the water surface at the instant of impact exceeding a specified value.

It is believed that this work has provided a solution to the kinematic aspects of the slamming problem, although further refinements to take into account Szebehely's third condition, small angle between keel line and wave slope, may eventually improve it further. Meanwhile, experimental verification would be of great value.

Insofar as longitudinal strength is concerned, it has been pointed out that in addition to the increase in hull bending stress resulting from the superposition of slamming stresses, there are two other effects of slamming which may be significant in the structural failure of ships:

(1) The high strain rate associated with slamming (Ref. C-3),
(2) The large number of extra strain cycles resulting from the vibratory oscillations following a slam (Ref. A-37).

Finally, Szebehely's paper presented the impact theory applied to the calculation of the local forces associated with slamming. A series of calculations has been given by Bledsoe in Ref. B-42. A complete analysis of structural response to impact loads has been given by Taylor (Ref. B-18), and other work has been done by Ormondroyd, et al (Ref. B-21). Greenspon has calculated the local strains in the plating subject to slamming and compared them with observations (Ref. A-38). Among other important contributions to the subject of slamming are those of Kempf (B-11), Lehmann (B-15), Kent (B-19), and Watanabe (B-25).

MODEL TESTS.

Longitudinal Strength.

Experimental work done in recent years on the dynamic forces and moments experienced by ship models in waves has been in the areas of (1) loads and stresses on the main longitudinal hull structure and (2) local impact loads forward, or slamming. Considering longitudinal bending first, two distinct types of test have been made:

(a) Measurements of stress or strain in metal models in which the ship's structure is represented (with some simplification),
(b) Measurements of external bending moments at one or two specific sections in jointed wooden models.

In Sato's tests (Ref. C-1) a brass model was used, which represented the main structural features of the full-scale ship, a destroyer. Shell, deck and longitudinal members were scaled down from the ship, but the number of transverses was reduced for simplicity. Strains were measured at various points on deck and bottom shell by means of resistance wire gages and results presented for a station near the midship section.

Model tests sponsored by the Hull Structure Committee of the SNAME in the U. S. A. and published in 1954 (Ref. C-3) followed a different approach. A 5-ft. wooden model was cut at the midship section and the parts joined by aluminum alloy bars. The relative deflection of the two halves of the model was recorded by means of variable inductance pickups calibrated directly in terms of external bending moment, with the still water moment considered as the zero reference. In this method, data could be obtained of course only at the section at which the model was cut, but the concentration on the problem of external loads resulted in a simplification of the model set-up.

Model tests of either type are particularly advantageous on two counts: (1) The wave conditions of the test—whether simple or complex—can be much more easily measured than on actual ships at sea, (2) simplifying assumpations which are inherent in even the most advanced method of analytical calculation can in principle be avoided. The model test can thus be conceived as an analog computer in which the external loading can be readily explored over a wide range of wave and ship variables. Model tests are also of great value for checking and verifying theoretical methods of calculating bending moments.

Other model tests have been carried out, using the above two basic techniques, in Japan (Refs. C-4, 6, 13), and in the U. S. A. (Refs. C-8, 11, and 12). One of the most complete and valuable papers is by Ochi (Ref. C-13), although results so far available in English apply only to the ballast condition. For convenient reference a summary of all available published model tests is given in the accompanying Table 3. A case of a model test to determine hydrodynamic loads on appendages is given in Ref. C-9. Model tests for the purpose of studying conditions leading to slamming and/or the measurement of impact pressures will be considered separately later.

A number of significant conclussions have emerged from the relatively small number of model studies of seaway loads carried out to date. Some of these are:

1. Midship bending moments (or strains), measured at moderate speeds in regular head or following seas are consistently lower than those calculated by conventional static methods, even with Smith effect correction (Refs. C-3, 6, 12, 13).

2. Bending moments measured are very nearly proportional to wave height, until serious bow emergence and/or shipping of water occurs (References C-1, 3, 6, 8).

3. As speed increases from zero, the bending moment in regular head seas remains steady in most cases or even drops somewhat, then usually starts to increase when speed goes high enough (often beyond the normal speed for the ship) (Refs. C-1, 3, 6, and 13).

4. For destroyer models at high speeds an increase in sagging and a decrease in hogging moments is found (Refs. C-1, 11). This effect appears to be due to the influence of the model's own wave formation.

5. In following seas the effect of speed is relatively small (Ref. C-3).

6. In some cases the lowest bending moments accompanied violent amplitudes of pitching and heaving (Refs. C-3, 12).

7. No consistent trend of bending moment with wave length at constant speed appeared; in some cases very large moments occured at a wave length of 3/4 or 1-1/4 times the model length (Refs. C-8, 12, and 13).

8. In regular head seas the wave-induced bending moments were in general greater in sagging than in hogging (Refs. C-3, 13).

9. There was some indication that U-form forward results in slightly less bending moment than V-form for a typical cargo ship (Ref. C-13).

10. Bending moments for a moderate speed ship were less at 1/4 L forward of midships than at the midship section, as expected (Ref. C-8),

Tests have been completed at the Stevens E. T. T. on a jointed model of a destroyer, in which shear as well as bending was recorded at the midship section (Ref. C-11). Results are to be published in the near future. Also, a project has recently been initiated at Stevens under the sponsorship of the American Bu-

TABLE 3.—DATA ON MODEL TESTS FOR DETERMINING DYNAMIC FORCES AND MOMENTS IN WAVES

Experimenters	1 Sato	2 Akita, Ochi	3 Ochi	4 E. V. Lewis	5 Wachnik, Robinson
Date Work Completed Date Published Reference	1945 1956 (1951, Japan) C-1	1954 1955 C-6, 10	1956 1956 C-13	Jan. 1954 1954 C-3, C-12	May 1956 — C-8
MODEL Ship Type	Destroyer, similar "Asashio" class	Simplified: wall-sided, flat bottomed symmetrical	Cargo ship (a) U-form (b) V-form	T2-SE-A1 Tanker	Passenger-Cargo Ship
Block Coeff.	—	0.83	0.741	0.74	0.662
Material	Brass	Brass	Brass	Wood, jointed	Wood, jointed
Construction	Structure simplified (transv.)	Structure simplified (transv.)	Structure simplified (transv.)	Cut at midship section; parts connected by aluminum alloy bars	Cut at midships and 1/4 L forward; parts connected by aluminum bar
Sheer	True sheer	Forecastle	No sheer	Freeboard > ship	
Length, ft. m.	24.3 7.4	19.7 6.0	19.7 6.0	4.79 1.46	4.18 1.27
Restraint in Surge	Light spring	Complete restraint	Model self-propelled	Light spring	Constant towing force acting through long towing cable
BENDING MOMENT Method of measurement	Strain gauges	Strain gauges	Strain gauges	Relative deflection of two halves	Strain gauges on top and bottom of bar
Points of measurement	Near amidships deck and bottom	Near amidships deck stringer	Near amidships and various points along length on dk. stringer	Midship section	Midship section and 1/4 L forward
PRESSURES Method of measurement	None	Resistance wire pressure gauges		None	None
Points of measurement	"	5 points on CL	Several points on bottom and side	—	—
OTHER DATA	Wave, Pitch, Heave	Wave, Pitch, Heave	Wave, Pitch, heave, surge, bow accelerations	Wave, Pitch, Heave, bow and stern accelerations	Wave, Pitch,
WAVES Lengths	1.04 L	0.625-1.25 L	0.75-1.33 L	1.0 L; 0.75-2.5 L	.50-1.50 L
Heights	$L_w/18$, $L_w/36$	$L_w/26$ to $L_w/40$	$L_w/26$ to $L_w/75$	$L_w/20$ $L_{model}/48$	$L_w/20$ and $L_w/30$
SPEEDS Head Seas, Ft./sec. M/sec.	0-16.0 0- 4.9	0-9.2 0-2.8	0-9.8 0-3.0	0-4.4 0-1.3	0-3.0 0-0.9
Following Seas, Ft./sec. M/sec.	None —	1 speed	None	0-4.4 0-1.3	None
DRAFTS	Full load, no trim	Mostly light; some tests at deep draft; 4 trims	Light (56 % Δ), Trim by stern	Full load	Full load

reau of Shipping to compare models of three different degrees of fullness at various speeds. Other work now in progress includes a project in England sponsored by the BSRA, an investigation of a passenger ship model at the NSMB, Wageningen, The Netherlands, and a student thesis project by Kimball and Lutzi at M. I. T., U. S. A. Tests have also been made at the Transportation Technical Research Institute in Tokyo, Japan, of two jointed models of submarine chasers.

Irregular Seas.

Results of a limited number of model tests in irregular head seas were presented by Lewis in Ref. C-3. This work has been supplemented by a comparison with data predicted by the method of superposition in Ref. C-12. (See section on Analytical Work.) The irregular tank waves corresponded closely to a storm sea created by a 35-40 knot wind and tests showed bending moments which never exceeded values obtained by conventional static L/20 calculation (without Smith effect). However, they did at times exceed the static values with Smith correction. It was pointed out that more severe wave conditions and hence bending moments might be expected in case of stronger winds of longer duration, or with shoal water and/or adverse currents, which emphasizes the need for more complete data on ocean waves. Meanwhile, the value of model tests under realistic irregular sea conditions has been clearly demonstrated.

Slamming.

Most of the model tests mentioned above gave some information as to the conditions under which slamming can be expected (Refs. C-3, 4, 6, 13) and other tests have been conducted specifically to study this subject (Ref. C-7). In some cases data are given also on local slamming pressure measurements (References C-2, 4, 6, 13) and accelerations (Refs. C-3, 7, 13) associated with slamming.

The experimental work confirms experience in showing that slamming is more likely under light than deep draft conditions and more serious with U-than V-forms forward (Ref. C-13). Theory is confirmed by experimental evidence that in regular waves slamming is associated with speeds near synchronism in pitching, when phase relationships as well as amplitudes of motions are found to be unfavorable (Ref. C-13). Slamming is more likely in irregular seas (Ref. C-2), and in irregular head seas slamming occurred occasionally at full load draft for a model of the T-2 tanker (Ref. C-3). Maximum slamming pressures in regular wave tests at light draft were found along the keel line forward, the peak moving aft with increasing speed (Ref. C-2, and 13).

In some cases data are given on the effect of slamming on the midship stress or bending moment (Refs. C-3, 6, 13) and on the longitudinal distribution of these stresses (Refs. C-13, 10). Since the elastic response of the model is involved here, this aspect of the subject of model tests requires special consideration. In order to obtain accurate indications from model tests of the vibratory response of a ship to impact loads such as slamming, it is necessary of course to have dynamic similarity between model and ship. This implies that not only the model section modulus but the natural frequencies of hull vibration must be correct to scale. These conditions can only be met by building a detailed structural model using a material with a modulus of elasticity reduced in proportion to the scale ratio. This might be accomplished by the use of some plastic material with a very low modulus, and although such models have been discussed at times they have never actually been built. It is also important when vibratory effects are measured to make sure that test apparatus is capable of accurately recording high frequency signals.

The two types of models used to date in experimental work have distinctly different elastic properties. In the brass models the structure has been reproduced in sufficient detail so that correct scale response can be expected throughout to static or low frequency loads. However, the modulus of elasticity of brass is such that the models had a natural frequency response which was somewhat too high —though not so high as solid wood models used for acceleration measurements (Ref. C-7).

An approximate solution to the problem of dynamic scaling is that used at Stevens (Ref. C-3) with a wooden model jointed at the midship section. By choosing the correct length and cross section of the connecting bars it was possible to provide both suitable magnitudes of deflection and the correct scaled-down frequency of vertical vibration. Since the model was jointed, it could vibrate in only one mode, which approximated closely the 2-noded vibration of an elastic beam. Thus an approximate solution to the dynamic scaling problem was achieved in a simple manner. It was found that for the jointed model representing a loaded T-2 tanker (Ref. C-3) the vibration died out more quickly than some full-scale ship records indicate. This difference is believed to be mainly the result of the difference in damping between the loaded condition of the model and the ballast condition of the ship observations (Ref. A-26).

In spite of the above limitations, it is believed that the findings regarding hull stress distributions of Refs. 10 and 11, using brass models, are significant in a qualitative way. They indicate that the highest deck stresses associated with slamming occur somewhat forward of the midship section. The actual magnitudes of the vibratory response appear to be somewhat in doubt because of the above-mentioned question regarding dynamic scaling. Furthermore, the time required for the vibration to die out—which determines the extent to which the vibratory stress is additive to the normal wave stress—would certainly not be correctly represented in the brass models.

A sudden change in vertical acceleration was found to accompany slamming impacts, without perceptible change in the motion traces, except for a slight reduction in the amplitude of the succeeding oscillation (Ref. C-7).

CONCLUSIONS.

A survey of work completed and in progress on the subject of Dynamic Forces and Moments in a Seaway shows that notable advances have been made in our understanding in recent years. The joint efforts of many organizations and individuals may be expected to yield continued rapid progress through further full-scale observations, analytical work, and model tank tests. It is believed that the following items are particularly in need of attention:

1. Continuation of observations of hull stresses at sea, with simultaneous recording of the wave patterns, and correlation with model tests in irregular waves,
2. Continuation of work on the analytical calculation of bending moments in regular waves and comparison with model tests,
3. Investigation of extreme values of bending moments to be expected, from the points of view of:
   - (a) Oceanography—spectra of extreme storm seas encountered,
   - (b) Analysis—possible physical maxima of bending moments possible for specific ships, and
   - (c) Statistics—extreme value theory.
4. Continuation of research on the prediction of the probability of slamming in irregular seas, and verification by means of model tests and full-scale observations.

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ABBREVIATIONS.

INA	Institution of Naval Architects, London.
SNAME	Society of Naval Architects and Marine Engineers, New York.
Z.V.D.I.	Zeitschrift des Vereins Deutscher Ingenieure.
S.B.T.G.	Schiffbautechnische Gesellschaft.
N.E.C.I.	North East Coast Institution of Engineers and Shipbuilders, Newcastle-upon-Tyne.
E.M.B.	U. S. Experimental Model Basin (now David Taylor Model Basin, U. S. A.).
I.E.S.S.	Institution of Engineers and Shipbuilders in Scotland, Glasgow.
O.S.R.D.	U. S. Office of Research and Development.
DTMB	David Taylor Model Basin, U. S. A.
ETT	Experimental Towing Tank, Stevens Institute of Technology, Hoboken, N. J.
SNA of Japan	Society of Naval Architects of Japan (Nippon Kaiji Kyokai).
MIT	Massachusetts Institute of Technology, Cambridge, Mass.
ATMA	Association Technique Maritime et Aéronautique, Paris.
ATTC	American Towing Tank Conference.

Formal Discussion

Prof. E. V. Lewis (Written contribution).

A series of tests recently completed at Stevens on a destroyer model in waves may be of interest both from the point of view of the apparatus for measuring shear and bending moment at the midship section and of certain findings not previously reported. The test apparatus was described briefly in a presentation before the American Towing Tank Conference last September (Ref. 1), and a complete report on the project is now in preparation (Ref. 2). The work has been carried out under sponsorship of the U. S. Navy Bureau of Ships, under the technical cognizance of the David Taylor Model Basin (Contract NOnr 263 09).

Apparatus.

The model set-up for the destroyer tests was similar to that used in the case of the T2 tanker model previously tested (Ref. 1 and 3). However, a number of new features have been incorporated which may be of interest. First, the dynamometer connecting the two halves of the model has been made compact and self-contained in order to eliminate some of the hysteresis encountered in the T2 model. Second, it has been found possible at the same time to incorporate the measurement of vertical shearing force at the midship section as well as bending moment. The primary objective of the shear measurement was to make it possible to calculate the line of action of the net resultant force on each half of the model. It is believed that this will be helpful in checking the analytical calculation of dynamic bending moments. It also gives some indication as to how far from the midship section the maximum bending moment occurs.

The apparatus for the destroyer tests, shown in Figure 1, consists of a beam connecting the two halves of the model. The design was based on three considerations:

1. Sufficient flexibility in bending to provide measurable deflections on the variable inductance pick-ups being used.
2. Sufficiently low resistance to shear to provide measurable shear deflections.
3. A natural frequency of vertical vibration corresponding to the two-noded natural frequency of the full-scale ship.

SKETCH OF DYNAMOMETER USED IN MEASUREMENT OF BENDING MOMENT AND SHEAR

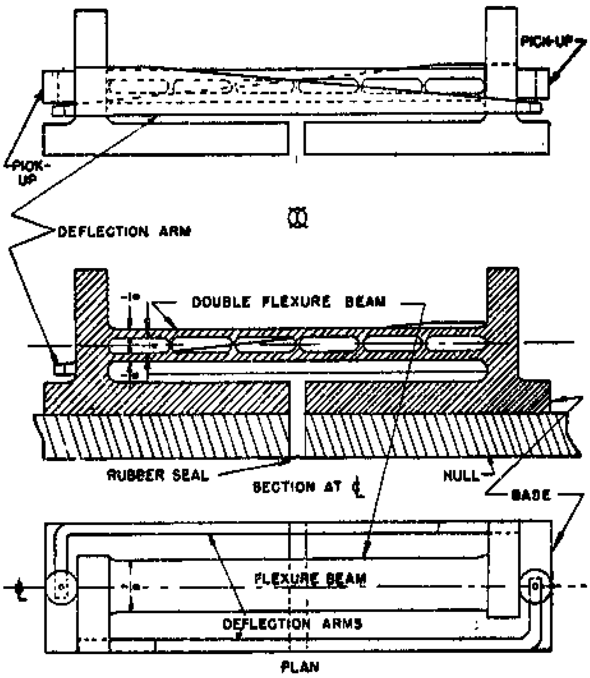

Fig. 1

These requirements were met by a 6 inch beam having two flanges connected only by light struts, as shown in the Figure. This design provided the right amount of rigidity in bending and the relatively greater flexibility in shear desired. Except for the deflection arms, the entire dynamometer was cut out of a single piece of 1 in. aluminum alloy. The gap between the two parts of the model was closed by means of a thin sheet rubber seal.

The two deflection arms shown, extending from each end to the other, permit relative deflections to be picked up by Schaevitz differential transformer units. When the model is subjected to a pure bending, the two deflections are equal and in the same direction. However, when the model is subjected to a pure shear load at the midship section, the deflections are in opposite directions. Consequently, the bending moment is proportional to the *sum* of the deflections and the shear to the *difference*. The signals are passed through two isolation transformers connected up so as to add and subtract the signals from the two pick-ups electrically. Bending moment and shear can thus be recorded directly on the oscillograph tape along with motion records.

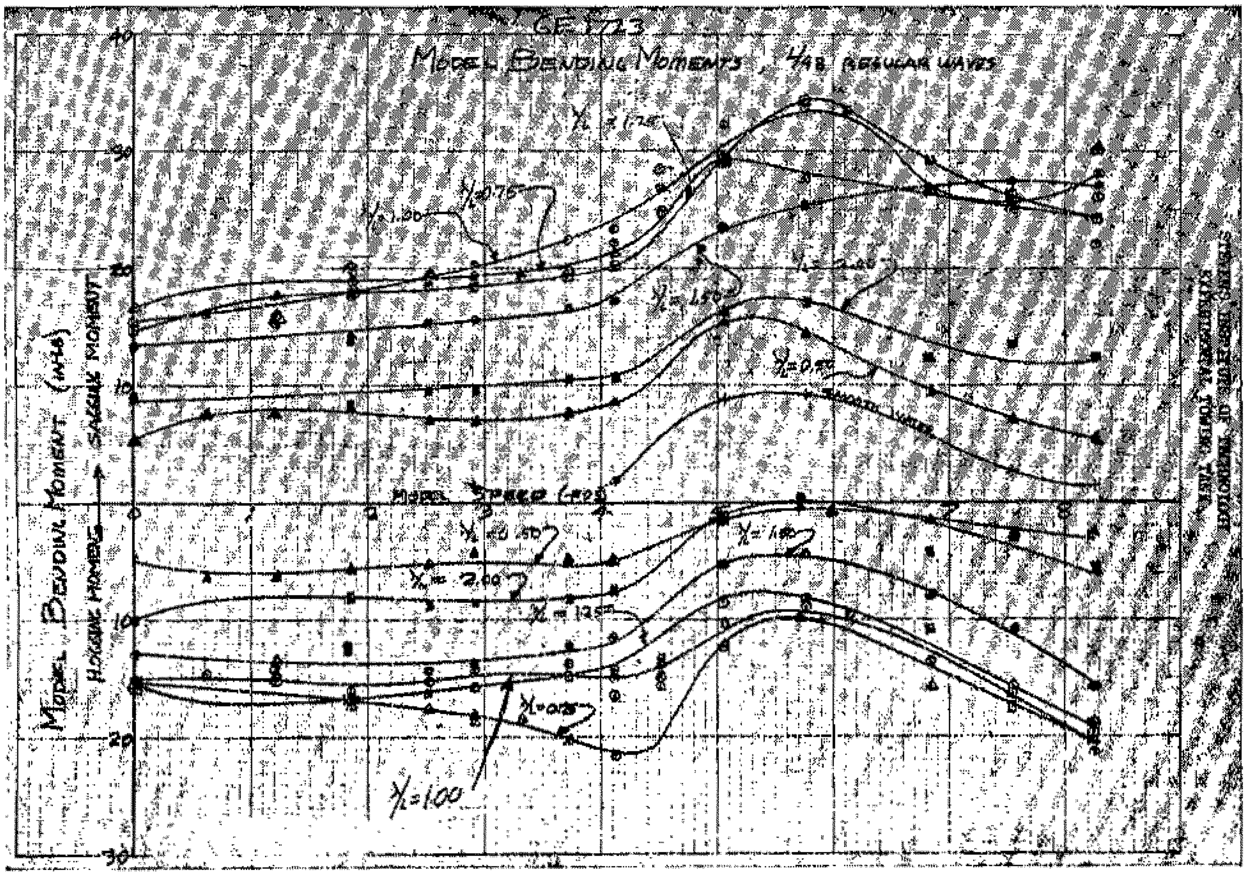

Fig. 2

For testing, the model was towed by the constant-speed towing carriage through the motions apparatus, which provides complete freedom in pitch, heave, and surge—under the influence of a constant towing force (Ref. 4). The following data were then recorded simultaneously on oscillograph tape:

1. Pitch.
2. Heave.
3. Surge (or vertical acceleration at bow).
4. Wave.
5. Bending moment.
6. Shear.

A few runs were made with the accelerometer instead of the surge record, in order to assist in the clear identification of slamming when it occurred.

Effect of Speed.

Experimental results at various speeds in waves of different lengths are shown in Figure 2, where bending moment values are plotted in reference to the still water bending moment as zero. The wave disturbance created by the forward motion of the model at high speed was so pronounced that it appeared it might be an important factor in the trends of measured bending moment. Accordingly, separate measurements were made of the bending moments at various speeds in calm water, and results were plotted also in Figure 2. The pronounced sagging moment found at speeds of 5-7 ft./sec. showed remarkable correspondence with the trend of the other curves, suggesting that the variation of bending moments with speed is strongly influenced by the superposition of a sagging moment caused by the model's own wave pattern. When the observed calm water sagging moment was subtracted from the sagging curves and added to the hogging curves, only a very gradual, slightly erratic, upward trend of bending moment with speed remained. The effect of the model's own wave at high speed is therefore clearly of considerable importance and should not be neglected in bending moment calculations for ships of this type.

It may be of interest to note that the total range of bending moment by static calculation is 118.2 in.-lb. in an $L/20$ wave of model length ($\lambda/L = 1.0$). Assuming that the moment varies directly with wave height, the static value is 49.2 in.-lb. for the $L/48$ wave of $\lambda/L = 1.0$. It will be noted that the experimentally determined bending moment does not ever reach this value, although it approaches it at the higher speeds.

Vibratory Effects.

An important feature of the experimental set-up was obtaining a frequency of vertical vibration afloat corresponding to the 2-noded natural hull frequency scaled down from the ship. As a consequence of this provision it is believed that the oscillation of the bending moment in the natural frequency, which was observed to be superimposed on the wave bending moment, has real significance for the full-scale ship. When the amplitude of the superimposed oscillation was plotted vs. tuning factor (T_p/T_e, where T_p is the natural period of pitching motion and T_e is the period of wave encounter), it was found that in most waves the vibratory response reached a maximum under conditions of synchronous pitching (tuning factor near unity). Here the amplitudes of motion were observed to be near a maximum and phase relationships most unfavorable for bow emergence and for large fluctuations in hydrodynamic forces. It should be noted that actual slamming—as indicated by sharp changes in the bending moment and acceleration records—was not observed in regular waves. Numerous slams were recorded at high speed in irregular waves, however (test results obtained in irregular waves will be included in the complete report, Reference 2).

In conclusion, it is believed that in model test to measure dynamic forces and moments in a seaway means should be provided for scaling the ship's vibratory response as closely as possible.

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Prof. M. A. Abkowitz (Written contribution).

The testing of ship models in waves to determine the dynamic forces and moments acting on a hull is developing increasing interest in the profession and the M. I. T. Tank is participating in this interest. Since the conference is basically for the purpose of discussing technique and instrumentation for model tests (tankery), I should like to mention some techniques and instrumentation used at the M. I. T. Towing Tank in conjunction with dynamic force measurements.

A five foot model of a North Atlantic passenger ship was cut at the quarter length (forward) and midlength and these sections were attached to the remainder of the model by a long, rigid aluminum bar of rectangular cross-section. The bar was firmly fastened to the hull along the inside bottom of the model and strain gages were mounted on the bar at the quarter length and midlength of the model. A strip of thin flexible plastic sheet around the cuts in the model was sufficient to maintain watertightness. With this setup, simultaneous measurement of the bending moment at the quarter length and midlength was measured while the model was pitching and heaving in regular waves [1]. In similar fashion, a five foot model of a large tanker was cut at three positions—10 % of the length forward of amidships, amidships, and 10 % aft of amidships—thus providing a means of simultaneously measuring bending moments at three locations near the midship station in various wave lengths and wave heights for several different ship loading conditions [2]. This test was designed to determine whether maximum loading occurred at midships. Using strain gages located at the root of bow anti-pitching fins (at the junction with the hull), the local bending moment loading on anti-pitching fins were measured as the model moved in waves. These measured results are to be compared to the dynamic bending moments on the fins as calculated theoretically in a report presently being prepared.

Among other techniques used recently at the M. I. T. Towing Tank were the duplication on a model of horizontal bow vibrations caused by certain appendages located at the bow of the ship, and the high speed photographing of the lines of flow about anti-pitching fins while model is pitching and heaving in waves.

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Dr. S. L. Smith (Written contribution).

In the first place I must say that I am very surprised to find this subject on the programme. At the last Conference in 1954 this was one of the additional subjects proposed by the Standing Committee but these were not accepted by the Conference as is most clearly stated in Decision 5 on page 323 of the Proceedings. In the recently circulated Preliminary Report of the present Standing Committee it is stated on page 3 that the decision to add this new Subject to the programme was taken by the Standing Committee at its meeting at San Sebastián in September last year. I should like to know whether it is in order for the Standing Committee to override the Conference in this way.

Be that as it may, I should like to say that Mr. Lewis' report gives a most interesting and informative review of the subject and the work now proceeding in different establishments. Much of the report deals with the general subject of strength of ships and in the Conclusions reference is made to further work required on ships at sea. Here again, whereas admitting that model techniques are influenced by the details of the work to be done, I feel strongly that this Towing Tank Conference should be concerned primarily with the model techniques. In this connexion I find Mr. Lewis' description on page 9 of the various types of model techniques for measuring wave bending moment most interesting.

At B. S. R. A. we have recently put in hand tests using the "split-model" technique to determine wave bending moments for an intermediate cargo ship form. The model is being run through regular wave trains in which the height and length of the waves are being systematically varied. The object is to compare these dynamic bending moments with those calculated on the usual static assumptions and to throw light on the problem generally. Comprehensive records of strain are also being measured on the actual ship during routine voyages.

Mr. Lewis touches on a very difficult problem in discussing the development of techniques for the investigation of slamming on the model scale involving as it does dynamic similarity between model and ship together with appropriate elastic response. The method of dealing with this at Stevens Institute is noted with interest namely: where the stiffness of the mid-ship joint on a split model was designed so as to make possible on the model scale the reproduction of an approximation to the 2 node vertical vibration. A difficulty here appears to be that a slam might well excite higher modes of vibration.

Our own work at B. S. R. A. has not yet reached the report stage, but there is one point to which we think attention might be directed and which would come within the purview of the Conference. I am referring here to the scaling of damping factors between model and ship and indeed the question of scale effect generally in this work. As far as can be ascertained little appears to be known about this and it may well prove to be significant.

Mr. D. I. Moor (Written contribution).

The writer wishes first to deprecate very strongly the inclusion of this subject in the Conference at all. Discussion of the model aspects of the subject, which alone appear to be within the scope of the Conference, could quite well be discussed under Subject 6. Indeed the techniques of Subject 6 are an essential pre-requisite to Subject 8. Discussion of the theoretical aspects should more properly take place before other bodies.

Extensive experiments to measure bending moments and impact forces in waves have been carried out at St. Albans during the last two years, and although this work cannot yet be published, it may be stated that some of the conclusions are different from those which might have been expected from other published work.

In particular it has been found that there are certain periods of encounter between model and waves (other than those at resonance) where the motions, propulsive forces and bending moments are highly unstable, with unexpectedly high peak values. An interesting phenomenon sometimes noticed in conjunction with these unstable ranges has been the forward propagation of a wave train from beneath the stem of the model.

If this unstable range has not been noticed elsewhere, it is possible that it has been concealed by the artificial restraints or freedoms imposed on *towed* models. The writer is firmly convinced that the only correct method is to self-propel the model, although it appears from Table 3 of the Introductory Remarks that, apart from St. Albans, only Ochi has adopted this procedure.

Since the conclusions from model experiments frequently appear to differ from those expected, or experienced at sea, a ship-model correlation is urgently required, and it is hoped that the British Shipbuiding Research Association will shortly publish a comparison between the results of experiments carried out on a model at St. Albans and corresponding observations on the full size ship at sea.

Informal Discussion

Capt. E. A. Wright.

In this model basin business we seem to learn more rapidly when we try somewhat new experimental techniques. Such was the case when Davidson did his well-known sailing yacht experiments, when Saunders first looked at the underside of ship-model in his circulating water channel, when Barrillon developed a rotating arm basin, when van Lammeren opened a seakeeping basin. This work on forces and moments in a seaway was originated apparently in Japan and in the U. S. by the Society of Naval Architects, and was developed by Stevens Institute of Technology, I believe, in this category of classic originality. The David Taylor Model Basin is a interested in the structure of ships as in the hydromechanics of ships. However, the most elusive unknowns are invariably the hydrodynamic loadings on the hull and it is quite necessary to measure these loadings in order to separate the hydrodynamic forces from the structure response, eventually to understand better these hydroelastic phenomena. I suggest that this Conference confine its deliberations to the hydrodynamic forces on models and then let the structure naval architects and engineers pick up from that point. As the Russian delegates have pointed out, the measurement of transitory inertia conditions in connection with virtual mass shows great importance in much of our work.

In addition to bending, torsion and shear in a seaway, there are of course many other problems, such as those in connection with rudders. A great deal has been and will be done in this regard. There are a number of manoeuvring basins and rotating arm facilities presently under construction which will, I believe, be in operation before the next I. T. T. C. I suggest therefore that the incoming Standing Committee consider the model experimental prediction of manoeuvring and route stability qualities. We have, of course, an outstanding candidate for Chairman of such a Committee in Mr. F. S. Burt, of the Admiralty Research Laboratory, for the leadership in this field.

This decade is a changing one and model basins are also changing. Tank superintendents have a real opportunity and responsibility. To influence the entire future course of hydrodynamics in ship design you should be aware of the way you are accepting this challenge.

Mr. G. A. Firsov (Translated from Russian).

In Russian tanks, three methods have been developed and are used to measure the forces exerted in models in the seaway:

(a) Measurement of the varying pressures exerted on the hull.
(b) Measurement of stresses which arise between or in the joints in a model which is separated into two different parts.
(c) Measurement of the vertical accelerations, which is essentially used with problems connected with hydroplanes.

The results so far have not been published, but it can be concluded that the forces experienced in a seaway are actually not too far from the results that can be obtained from the Froude-Kryloff theory. But the distribution of these forces is quite different from that which follows from this theory.

All these experiments are made in regular waves in a tank. To obtain results in an irregular seaway, the method of spectral analysis is successfully used even in those cases where the actions are not linear. They are primarily interested in such problems where the process which is the object of the investigation is connected with ship motions in a non-linear way, but the process in itself does not influence directly the motions considered. Some examples may be mentioned: the investigation of the twisting moments which arise on stabilizing fin shafts and the determination of stresses in some parts of the ship above the yielding point of the material. For the solution of this kind of problem it is necessary to transform the variables in the distribution probability function of the process of waves or ship motions. For this purpose, as it is well known, one must determine first the Jacobian, the terms of which in many cases can be determined only experimentally. Therefore, the tank must be adapted to determine these initial data.

Returning to the examples given we may mention a special installation in Leningrad tank for the measurement of moments in the shafts of fins, during tests that reproduced the motions of the fins when the ship is in a seaway.

To obtain the necessary data for the calculation of the ship stress in irregular sea, the ship must be put into the dock on the controllable supports.

In the opinion of the Russian delegation, this Conference must give more attention in the future to the problems connected with the stabilizing of ships and organize the corresponding committee.

Mr. L. N. Sretensky (Translated from French).

I want to present some remarks from a mathematical point of view on this subject.

If we take as an example the Mitchell integral, which gives the resultant of pressure forces, or the similar formula which gives the moment of these forces, we can obtain some numbers that can be considered as characteristic integrals of the ship.

But in some cases it would be interesting to know the values of the forces and moments acting on a part of the hull, limited by a given closed curve Γ. These forces may be computed by the formula of Bernouilli, but the calculations are very laborious.

I think that some results, both interesting and useful, may be obtained without such long calculations, if we apply to this problem some theorems which were developed by Tchebycheff for the theory of probabilities.

We may take as known the values of

$$\int_A^B f(x)\,dx \quad ; \quad \int_A^B x\,f(x)\,dx \qquad \int_A^B x^n f(x)\,dx$$

$f(x)$ being a positive function.

We want to know the value of

$$\int_a^b f(x)\,dx$$

the limits b and a being as follows:

$$A < a < b < B$$

Tchebycheff has given a solution to this problem, and the application of his theory to the problems of ship hydrodynamics may give useful data on the pressure distribution along the hull.

I have studied this question for Mitchell hulls, whose surfaces are represented by the equation of the type $y = X(x)\ Z(z)$, and have found with this method the inequalities concerned with the resultant of the hydrodynamic forces acting on a hull's belt, limited by two closed curves and any two water lines.

Mr. R. N. Newton.

I should like to make a few general observations regarding the determination of stresses due to bending.

It is clear that bending moment can be measured with accuracy by what is known as the jointed model technique. This is very practical. On the other hand, I don't think it is by any means established that measurements of stress or strain in the model basin can be scaled to the ship.

The real question which arises within the field of ship tanks is: what can we do with the information? We think that it is easier to change the motion than then again try the performance in another direction. Table 1 of the Committee Report shows the maximum stress range in rough way. It is rather difficult to visualize that any substantial reduction can be achieved and it would seem to me to be even more important to carry out structural tests and determine the more economical distribution of material and avoid stress concentration. For example, you will notice that in one of the ships given in Table 1 there is a concentration of 4 to 1.

Prof. Dr. Ing. F. Horn (Translated from German).

In the report of Prof. Lewis (Model Tests, Point 1) it is stated that midship bending moments measured at moderate speeds in regular head or following seas are consistently lower than those calculated by conventional methods, i. e., with the ship on static equilibrium on the wave. This result seems, at a first glance, somewhat unexpected, since it might be guessed that the dynamic action of the seaway should increase that bending moment. However, this result may be explained on theoretical grounds, as has been shown on a linear basis in my publication "Die dynamischen Wirkungen der Wellenbewegung auf die Längsbeanspruchung des Schiffskörpers", Springer, 1910. Recently there has come to my attention a Japanese report—by Prof. Watanabe, I think—and it contains practically the same reasoning. It should be mentioned that Prof. Watanabe had no notice of my work, published such a long time ago and scarcely diffused.

In both researches it is concluded that midship bending moments are strongly influenced by heaving. We may suppose the ship in a trough of a wave of the same length as the ship. In general, the heaving action deepens the ship to a lower position than the equilibrium point. Therefore, two forces appear: first, buoyancy of the zone between equilibrium and real water surface—linearity being supposed—, and second, the inertia, which equals the first mentioned force—acting against it—and that it can be calculated with the aid of the ship weight distribution and the acceleration due to the greater submergence.

Now, if we consider only a half of the ship, for instance, the forebody, we see that the static bending moment when the ship is in the trough works counter-clockwise, but the dynamic moment due to the above mentioned heave acts in the other direction, i. e., unloading the structure. And this because the centre of gravity of the fore part of the water surface is generally ahead of the fore half of the weight distribution curve. The same conclusion —that dynamic moments act against the static ones—might be obtained when considering the ship over the wave crest.

In special cases, when the relative positions of both centres of gravity are not as mentioned, dynamic effects may increase the load due to static bending moment. But, in any case, it is important to know this simple criterion—the relative position of both centres of gravity—in order to take into account the undesirable circumstances that could be met in those special cases, and to avoid them when possible.

Dr. M. St. Denis.

The report by Mr. Lewis does establish that there is one aspect of testing technique that has been ignored, and the other point that he makes is that this aspect is a rather difficult one.

Indeed the subject is rather new and this lack has resulted from the need of having to develop other testing techniques for the accurate measurements of what are secondary effects. Involving, as they do, differences in distribution, they are in opposition to integral effects—as you may call them—which come into the study of ship motion. A great amount of efforts have to be made in the development of new techniques.

The subject is small because it is difficult to work on it but we must not conclude that it is unimportant. Its aim is to inquire into the validity of the hydrodynamic assumption which underlines the structural designs of ships, and I suppose that everybody will agree that this is of fundamental importance. If there was sufficient reason to have five subjects dealing with resistance and propulsion of ships, there does seem to be sufficient reason for breaking down the much wider field of seagoing into two subjects. The laboratories must grow with time if they are to remain virile and if they are to be effective in playing a role in the solution of the new problems concerning the Navy and the Merchant Marine, which are, of ever growing complexity in this changing world.

Ir. J. Gerritsma.

This year a research on bending moments of a model in waves started in the Delft tank. This programme is not yet completed, but the available data allow a short description of the tests.

The usual method of measuring the bending moments on a model in waves is the use of a jointed model. In our case a plastic model has been used and the bending moments on the hull are determined by measuring the strain in the plastic; the strain is converted to the bending moment after calibration of the model in still water using pure bending moments of a known magnitude. The use of a plastic model has two advantages which I mention here:

(1) Bending moments can be measured in several cross sections simultaneously. In our case this was done in five sections.

(2) The model can be used also to study two node and perhaps three node vibrations in vertical or horizontal direction when an exciting apparatus is used.

Our tests were carried out with a 8 ft model with a block coefficient 0.70. The plastic hull had a thickness of 2 mm and was reinforced with four layers of fibre glass. The obtained accuracy of the geometry of the hull was quite satisfactory. The strain in the plastic was measured by strain gauges. Some tests were carried out in waves of model length and wave heights up to $L/20$. The results are in good agreement with Lewis' results of a T2 tanker.

A comparison of the measured moments and those obtained following the conventional calculation (without Smith effect) shows that the measured values are approximately 1/2 of the calculated values.

Capt. H. E. Saunders.

I realize that this problem is difficult. Nevertheless, we have struggled with the easiest part, that is, the measurement of forces and moments in a vertical plane. Now, naval architects and engineers who design ships have often realized that their problem lies neither in the design of structures which have been designed many times before, nor in the design of the ship for vertical forces and moments—because the world is full of calculations and papers full of pictures of ships which have operated sucessfully—but in the design of ships for other forces, and by those I mean torsional forces and moments. These problems will possibly be solved when we have models running in oblique waves. I trust that the planning for this project (if it is, as I hope, continued in future Conferences) will include a measurement of torsional forces and moments because the naval architects have in this respect almost no data on which to work.

We in the U. S. Navy have had trouble with torsional deformations which we suspect are at least responsible for most of the vibrations.

I should also like to make one further point at the risk of boring you with a statement which I gave to this Conference in 1951: that slamming can occur on the side of the ship, and the U. S. Navy has had occasion with several ships to make repairs in the bilges which have been bent by lateral slams.

Ing. Gen. J. Dieudonné (Translated from French).

The measurement of stresses on the structure of ships in a seaway is expensive and needs considerable instrumentation. Besides, if it is wished to extend these measurements for a moderately long time, the analysis of results is very difficult.

To be really well informed on stresses in ship structures in waves, it is necessary to have measurements taken over a long time, throughout the seven seas, and taking specially into account the data concerning very bad weather and the peak values.

The effects of the sea are very variable and the only way to assess them is the application of statistical methods; therefore, great number of results are needed.

We think that in order to advance in this study, the installation of counting strain gauges, during long periods of time, on board ship, is required. Apparatuses of this type have recently been developed in several countries. In France we have mounted such strain gauges in several ships on service.

Indeed, the position of the strain gauge as well as the judging of the measured values depends on the stress distribution in the different parts of the structure, but this study can be carried out independently, either with static loads, or, when possible, with measurements taken during a single sea run. Regarding the static studies on sea characteristics, it is difficult to predict the frequency and the importance of peak values, which are the most interesting from the point of view of the strength of the ship structure.

I find myself, therefore, in close agreement with Mr. Lewis when he says that further work on this question is needed.

Mr. A. F. Honnor.

I have no additional information to add to the subject under discussion, since no experimental work on the measurement of hull bending forces and moments has been carried out at the Admiralty Experiment Works during recent years. I am in the position of a customer in this instance, having in the past been concerned with the strength of ship structures and presumably shall be so again.

Fortunately, the ship designer is not totally devoid of information on which to base the structure design. This is provided by a mass of service reports detailing all instances of structural damage during the life of each ship or class of ship and this gives valuable guidance for the preparation of new designs. This of course does not mean that there is nothing to be learned from a new approach.

Mr. W. A. Crago.

It seems that techniques of model tests have been tried in various establishments. Such techniques have also been discussed by our tank, where we test the forces of moments generated in models of aircraft. In particular we had experience of helicopters with heads that had to be designed to have scaled characteristics in performance. Having had this experience, I would like to suggest that I don't believe that it is impossible to extend this sort of technique to the more difficult case of the ship where the forces are rather smaller, and therefore more difficult to measure.

Prof. E. V. Lewis.

I want to mention briefly the point that Mr. Moor raised about the unstable conditions encountered when at low speed a train of waves preceded ahead of the model. I quite agree that this is a difficult problem in model testing and that it represents a realistic condition actually encountered in the ship; the problem being to determine the behaviour after the conditions have started, but before the wave has been reflected back from the end of the tank. The question of reflections from the side of the tank is a separate matter which also comes into the picture and also causes a difficulty. I agree there are two separate aspects to this problem.

Prof. Dr. Techn. C. W. Prohaska.

I think it would be appropriate to say that the number of discussers have proved "la raison de vivre" of this subject. I am in complete agreement with Mr. St. Denis when he says that the subject may be small, but it is not unimportant. It might be indeed one of the most important, at least from a practitioner point of view.