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THE LOADING OF A SHIP IN A SEAWAY

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THE LOADING OF A SHIP IN A SEAWAY

Strain and Deflection Measurements aboard the M.S. SAN FRANCISCO of the Hamburg-America Line

by

George Schnadel

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Translated by M. C. Roemer, E.M.B., Washington Navy Yard

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The measurements and investigations which I here report form only a small portion of the high sea trial trip of 1934. In spite of the segregation of the various subjects of research, as oscillations, vibrations, and wave measurements, the portion falling under strength investigation is so extensive that I am able to report on only a small part of it, namely longitudinal strength, within the limits of this paper.

The most important data on the test ship are compiled in Table 1.* The longitudinal section gives the most important details (Figs. 1 and 1a). The ship, after a number of consultations with Director Gödeken of the Hamburg-America Line, was chosen for the test, after examination of the plans had shown it to be suitable for the aims of the trial trip. The ship was required to be a simple built-up box girder whose strength deck should be continuous over the greater part of its length. Only light superstructures were to be built on the strength deck, while the freeboard deck was required to lie below the strength deck in order to permit arrangement of a continuous measuring range for deflection measurements and part of the strain measurements in the tween-decks. No larger and faster vessel of suitable structure was available for the planned itinerary.

The course from Hamburg to the west coast of America was chosen for the voyage, inquiries among nautical experts having revealed that the possibility of encountering heavy storms and high seas on the North Atlantic and the North Pacific is particularly great in autumn. The course and the chief observed positions may be seen in Fig. 2. Those points are also indicated on the map, at which important measurements were made.

While we found only slight seaway and little wind for long distances, we were decidedly fortunate on the return voyage in the Atlantic. We there encountered heavy swells several times and two very violent storms of 20 and 30 hours duration, the seas running highest on Dec. 11, 14, and 15. Weather reports and ship's telegrams indicated that the storm area was of an unusually wide extent. It extended from Newfoundland into the North Sea, and from Iceland to the neighborhood of the Azores. The barograph indicated a rapid fall in atmospheric pressure. The lowest pressure was below 719 mm mercury, the lowest recording limit of the barograph. During this period the wind velocity measured with the anemometer at a height of 25 meters attained 30 meters per second, corresponding to a wind of 9 to 11 on the Beaufort scale. In the squalls, the wind rose to 40 meters per second, and for just a few hours in the night from Dec. 14 to 15, and on Dec. 11, and 12, the wind attained 12 on the scale. Dr. Weinblum and Dipl. Ing. Weiss will report on the height of the seas and its measurement. It is sufficient to state here that observation of the seas from the bridge with an eye level of about 14 meters showed waves with a height of at least 15 meters. Actually stereophotographic grammetric records showed a maximum distance of from 16 to 18 meters from the highest to the lowest point.

*All Tables and Figures are given in the Appendix.

During the most important measurements the ship lay to, viz., from Dec. 11, 1934, 11h 15m, to Dec. 12, 2h 15m and on Dec. 14 from 11h 40m to 13h 37m, and from 16h up to Dec. 15, 20h 15m.

It is to be noted in particular that with increasing wind velocity the seaway rose very rapidly, reaching its maximum height in as little as 4 or 5 hours. On the morning of Dec. 11, the sea was higher than expected from the wind force 9 to 11. This probably is connected with the fact that the SAN FRANCISCO was at the end of the path of the wind and had reached the waves that had been caused by the greater force of wind 11 to 12.

The photographic records show individual views of the seas at some distance from the ship. Therefore they are of primary importance for statistical purposes. For strain and stress measurements, Weiss' measuring apparatus proved to be especially useful, because with it it was possible to obtain a continuous record, provided with time markings, of the position of the ship in the waves. It is also possible to reconstruct the actual waves from the position of the ship in the waves and from measurements of the pitching angles. Mr. Weiss is reporting this. For the present, the contours formed by the waves on the ship's side will suffice for strength investigations. The differences between the highest hump and the connecting line of the lowest points may be designated as the apparent wave height in this test method, since the actual height of waves, when they are long, is indeed much greater. I shall later show the relation between wave heights and stressing of the ship.

Professor Horn will report on the acceleration measurements and on the rolling and pitching angles. For strength measurements, however, it is essential to note that the greatest measured accelerations due to heaving oscillations amounted to about 1.5 m/s^2, those due to pitching oscillations to about 4.5 m/s^2 at the ends of the ship, so that due to superposition it was possible to establish values up to 5.3 m/s^2. The influence on stresses and strains will be alluded to in connection with the consideration of a concrete instance. In this category are also the vibrations of the ship's hull which are caused by impact of the waves, emersion of the propeller and working of the engines. In pitching, a maximum double amplitude of 24° was measured. Simultaneously the bottom received a violent shock when the bow hit the water. Parts of the foregoing investigations were for special purposes, but at the same time they served to determine the external forces acting on the ship and to study the effect of heaving and pitching oscillations on the stressing of the hull. In order to grasp the wave effect and the so called Smith effect and the disturbance of the waves by the hull, pressure recorders were installed on the shell plating which recorded the water pressure on the bottom caused by the seaway. A total of eight pressure recorders was provided, but it was possible to operate only a part of these continuously since it was necessary while under way to fill some of the tanks with water in order to safeguard the seaworthiness of the ship. I shall report on these measurements elsewhere.

The pressure recorders, some of the accelerometers, and the extensometers were operated with the scratch process. The greater part of the instruments were supplied by the Deutsche Versuchsanstalt für Luftfahrt. In addition, the Hamburg Model Basin had also supplied instruments of its own design for strain measurements. The long-time strain recorders having an operating time of about 18 hours were installed at points which were not easily accessible during heavy weather. In contrast, the short-time instruments were used in constantly accessible compartments, such as the measuring passage. In spite of the difficulty of observation, the long-time instruments were found to be absolutely reliable. When properly adjusted, they operated satisfactorily under the most difficult circumstances.

For the determination of strains and stresses arising from longitudinal bending moments a number of strain gauges were installed on the strength deck. The disposition of the instruments may be seen in Fig. 3. Here distinction is made between two groups, one arranged in longitudinal direction, and a second group at 45°. The first group serves exclusively for the determination of bending strains ϵ_x and the corresponding bending stresses σ_x . These are, as is well known, independent of shear. The second group together with the longitudinal strains further permits determination of the shearing stresses. At every station measurements were made on two sides, i.e. on the top side as well as the bottom side of the plate. For determining longitudinal stress and shear at one station, four measurements were made. Actually six strain measurements are required at each point in order to determine a full stress condition in a thin plate subjected simultaneously to bending stresses. However, determination of all those stress components which are of only relatively small values was dispensed with from the start since their influence on the remaining components is negligible, in order to avoid superflous measurements. The order of magnitude of this influence may be easily estimated and introduced into the calculation so that results will be sufficiently accurate. In general, the differences will be within the limit of test accuracy. The disposition of various instruments may be seen in Figs. 4 and 5. The instruments above deck were protected by watertight cases.

For determining the stresses in the lower flange and in the neutral axis, additional measurements were made. I shall here cite only those on the shell plating, Fr. 69/70. In order here to distinguish the bending stresses in the plating from the thin plate stresses, the second strain gauge was set up next to the first one on blocks of the thickness of the shell plating. The blocks magnify the bending strain in the shell plating threefold, so that it is possible to distinguish between the thin plate stresses and the bending stresses. Fig. 6 shows the disposition of the instruments.

The motors of all the scratch instruments were driven by a special transformer. Since at times nearly 50 scratch instruments were in operation simultaneously, each of which required a cable with three conductors, it was necessary to lay about 1500 meters of cable. The central station was found to be unfortunately very cramped, since because of lack of space the wave measuring apparatus of Mr. Weiss also had to be installed in the already small compartment.*

At first the instruments were connected in groups, but later it was found necessary on the days of the storms to guard each apparatus individually against short circuit, so that even after several days of the most violent storms only a limited number of instruments had ceased functioning. In the evaluation it would be possible to bear the failure of a few of the instruments if the opposite instrument registered, since the ratio of the bending stresses at the same station and for a given stress value was approximately constant.

For measuring deflections, the D.V.L. Optograph was used, which was installed in a special passage on the port side of the ship (Fig. 8). The passage was situated on the upper deck, and in addition to serving for deflection measurements, also served for supervision of the short-time instruments installed in this passage as lower deck apparatus. To determine deflections eight brilliantly lighted bulbs were continuously photographed, so that for each point of light a continuous curve was obtained. The bulbs were diaphragmed in order to give the sharpest possible images of the light. The optograph was first attached at Frame 87 under the superstructure bulkhead, and later at Frame 80, since the first point of attachment was not sufficiently rigid. The instrument has two objectives, so that it was possible to photograph forward and back from the middle without getting too great distances from the points of light. Every station has a wholly definite reduction factor dependent upon the distance between objective and point of light, which was determined by experiment. Fig. 9 shows the arrangement of the optograph lights.

All continuously operating instruments such as strain gauges, optograph, pressure recorders, recording accelerometers, wave measuring apparatus, Petravic Gyro, were synchronously connected. Every instrument had a time contact which was connected with a contact clock in the central station which gave a time signal every ten seconds. Thus, for each reading, a time base was established, so that all simultaneous measurements could be compared with an error of less than one second. A minor difficulty with the scratch recorders was caused by the fact that a considerable parallax between the time record and the recorded measurement is caused by the design of the apparatus. In order to keep the records for various hours and days separate, longer time marks were made with one contact at irregular long intervals. Exact records were kept of these marks which permit placing each reading in chronological order, even at a later time.

Considerable difficulty arose from the circumstance that the records of the long-time scratch recorders could be observed only after a great lapse of time.

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*The preparatory work for installation of all the measuring apparatus, in the office and aboardship was done by Dipl. Ing. Hennig.

Therefore the possibility was discussed while still aboard ship of avoiding delay in analysis by distant recording of the data. As a result of conference with an experienced technician this method seems promising.

STATISTICS OF MAXIMUM STRESSES

In order to obtain a general idea of the stressing of the ship in a seaway it appeared necessary first to prepare a statistical table of the magnitude and frequency of stresses. The table was intended to show to what extent strength calculations hitherto made agreed with actual conditions. Therefore it was necessary to infer wave heights and if possible the wave lengths also. Deflection readings and strain readings at Fr. 89/90 were selected as the basis of the table. At this station a complete photographic image of about 100 meters of the scratch record was available for all the days of the storm. Fig. 10 shows a section of the spool. The station is situated forward of the superstructure and consequently is little influenced by it.

When the ship is lying to with bow to wind and sea, a wave passes the ship on an average of every 10 to 12 seconds. With the storm lasting a total of 50 hours this makes about 9,000 waves with 18,000 changes in load. About 14 hours were measured, with 5,000 load changes. Naturally it would be useless to discuss moments, deflections and wave contours to this extent. In order to obtain an idea of the whole, notwithstanding, all small stresses were discarded and only the essential points were selected.

For comparison with the customary strength calculation, a complete calculation of strength was carried out with three waves of 5 m, 6.55 m height (L:20 = standard wave) and 8 m height, and the bending moments and deflections, including shear deflections, were determined.

For comparison with the calculated deflections only the optograph stations farthest forward and farthest aft were taken, and by plotting several bending curves the coefficient was determined by which the mean value must be multiplied to find the deflection in the midship section referred to the entire ship's length. By comparing this deflection with the calculated deflection, the "effective wave height" that has stressed the ship is obtained for any given time.

In a similar manner the effective wave height was determined from the strain measurement mentioned. From the measurement a definite stress was obtained. It was determined after taking into consideration the transverse stress σ_y. This gives an effect of about 5%. This stress was compared with a number of opposite measurements on the under side of the plate and the average coefficient determined, with which a reading on one side must be multiplied in order to get the longitudinal stress for the mid-plane of the deck. From this, then, by multiplying by the section modulus it was possible to determine the bending moment at Fr. 89/90 and the corresponding effective wave height. Naturally the wave heights found from strain and deflection at one point can not agree exactly, since the bending stresses at one point include local and dynamic influences, which have varying effects on the bending curve.

Finally the corresponding wave length was computed from the wave oscillation periods. For this purpose, the wave periods were determined from the optograph and strain gauge readings, taking the time difference between two maximum deflections or strains with the ship on a wave crest as the period.

The period is not determinable from the difference in time between the maximum deflections in the wave trough, since here violent shocks distort the picture. From the wave period the wave length was then calculated which agrees satisfactorily with measurements in the trial check-up. These wave lengths were also incorporated in the statistics.

Table II presents the results of this investigation. It contains the maximum stress in the strength deck at Fr. 91 as set up by the seaway, in each case for wave crest (+) and wave hollow (–). Next to this is entered the ratio of stresses on the crest and in the hollow, and finally the bending moments corresponding to the stresses were calculated with reversed sign by multiplication with the appropriate section modulus. Furthermore, the deflections measured with the optograph were entered, and likewise the wave lengths calculated from the period. The greatest effective wave heights of more than 4.35 m, corresponding to a wave height of L/30 are especially brought out. Examination of this table yields results important in strength calculation. The maximum stresses, bending moments, and deflections for the ship in the wave hollow are considerably greater than for the ship on the wave crest. The greatest stresses occur with wave lengths which approximately correspond to the ship's length, here 131 m.

To supplement Table II, an additional one, Table III, was set up. This contains only the highest measured values with the test apparatus stopped. During this time the long-time extensometers recorded on the same part of the record. Thereby the maximum extensions and compressions during the intervals between tests were recorded. No optograph records and no wave periods are available for this purpose. The table therefore is limited to determination of the bending moments and the corresponding effective wave height. The essential result obtained is that the greatest effective wave height for the ship on the wave crest occurs when H_w = 5.6 m = L/23.5, and in the wave hollow when H_w = 7.2 m = L/18. The effective wave height for the calculation of a ship, on the strength of our measurements must therefore be assumed higher for the wave hollow than for the wave crest. This surprising fact will be explained thoroughly in the following.

In the charts we note that the differences between the deflections on the wave crest and wave hollow are especially great when the stress curve in the chart ascends rapidly. This rise is an indication that impact loading of the ship oc-

[illegible] in the [illegible] [illegible] the upper bound of [illegible]

curred. Heavy impacts rarely occur when the ship is lying to. Therefore it was possible to note them on the recording strain gauge while the testing apparatus was at rest where a fine scratched line projected beyond the heavily marked mid portion. The shocks thus noted have been marked in the statistical table. Hereby it is shown that impact loading calls forth the ~~critical~~ stresses with the ship in the wave trough. It is easy to comprehend that a shock at the bow always sets up compressive stresses in the deck like those actually occurring with the ship in the wave hollow. As shown by observation and by experience during the storms, such impacts also occur in wave lengths which are considerably greater than the ship's length. Therefore the effective wave length attains values up to 6 m in waves of great length also, corresponding to a ratio $L/H_W = 22$. They are somewhat below the values attained when wave length and ship's length coincide. In running before the wind and waves, or as the seaman expresses it, in scudding before the wind, these large moments due to shocks do not occur, as shown in Table III for the night of Dec. 10–11, 1934. In this case the maximum bending moment on the wave crest is even greater than that in the hollow. From this we may draw the important conclusion that the relative velocity of the ship has a great influence on stress due to shocks. In general, I note that the largest waves mostly rolled up in groups of two, three, or four, while smaller waves intervened. The appearance of such groups of the largest waves was generally connected with a violent squall. Once, in bringing the ship to, she was caught broadside on. Two waves were sufficient to cause her to roll at an angle of more than 20°. The third wave struck the ship somewhat forward, so that the list was not further increased.

One might ask here, whether the measured maximum stresses might even be exceeded in exceptional instances. Discussions with the Captain, the Chief Engineer, and the First Officer revealed that in several cases seas even steeper and higher had been observed. Based on this discussion it may be assumed that the maximum values measured during the day may still be exceeded by 10% in unfavorable cases.

up to this date

EVALUATION OF MEASUREMENTS OVER A SHORT PERIOD

In order to obtain a better idea of the bending stresses of a ship in a seaway, four types of loading are to be differentiated in the following.

1. The static loading due to the position on the wave,
2. The loading due to oscillations, such as heaving and pitching,
3. Loading due to vibrations,
4. Loading due to shocks.

The three first types of loading have already been studied previously. The significance of the fourth has hitherto not been understood.

It is quite impossible in the limits of this paper to present the evaluation and detailed investigation of the most important test data. Therefore I have selected a certain period of time and investigated the loading of the ship in running through a number of waves. When the calculation had already proceeded to an advanced stage, it became evident that it might have been more to the point to have selected a different time period, since the record chosen was that of the night of the second violent storm, in which several accelerometers had run down and several other instruments damaged or short circuited. The available results are sufficient, however, to expose the relationship of load, stress, and deflection.

In order to calculate the stresses and deflections it was necessary to undertake investigations of the influence of the superstructures amidships. The results of this investigation are compiled in Fig. 11, where the distribution of the moment of inertia and the section modulus over the length of the ship, and the location of the calculated neutral axis are plotted.

During the measurement the ship lay to. At first the wind and waves came from the southwest. Then the storm gradually swung around to the northwest and freshened more and more. At the time of the measurement it had a force of 11.

In the following the data of wave measurements, of the recording strain gauges and of the optograph at time 23 h 56 m 15 s to 25 s are compared.

(a) WAVE MEASUREMENT

From the results of wave measurements the position of the ship in the waves was determined for the time 11h 56m 20s, and the preceding and succeeding times in 1/5 sec. intervals. The position of the ship in the large time intervals (one second) is presented in Fig. 12. Here it is seen that at 11h 56m 16s the ship was on a wave crest. The measured wave length corresponds approximately with the ship's length (131 m) in good agreement with the wave length (126 m) computed from the period T = 9 s. The height of the wave measured from the line connecting the two hollows to the crest amounts to about 7.6 m. Since the ship's length and the wave length nearly coincide, we have the actual height of the wave. The possible error in this measurement amounts to about +0.4 m, since on the average the differences between measurements amounted to 0.8 m. After 3 seconds the bow of the ship was struck by another wave, resulting in a violent shock. The difference in height between the wave crest and the wave hollow here amounted to only about 5.4 m, i.e. considerably less than 3 seconds previously.

In order to obtain a check on the accuracy of measurement with Weiss' instruments, the displacements and moments of trim were figured out, which the measurements yielded over certain time intervals (Fig. 12a). Since the ship uninterruptedly performs heaving and pitching movements, it is generally impossible for displacement and weight, weight moment and displacement moment to agree. Rather must they oscillate about a position of equilibrium. The result of the calculation shows that a maximum moment of trim fluctuates from 80,000 to 120,000 m t,

[illegible]

corresponding approximately to 2.5 to 3.0 m change in depth of immersion forward, with a period of T = 6 sec. This period agrees pretty well with that of a natural pitching oscillation. No full oscillation exists in the case of heaving oscillation, obviously because of the shock on the ship's bottom. It is true that the ship has a position of equilibrium with a residual weight of 800 to 1,000 tons corresponding to about 0.5 m heaving amplitude. The position of equilibrium for the heaving oscillation, however, lacks about 1,000 tons displacement. It might perhaps be well to attribute the difference of 1,000 tons which corresponds to an emersion of about 0.5 meters to the error in measurement already mentioned. To me, however, this does not seem to be correct, since in integrating over the length the mean error of measurement must become smaller. Therefore I assume that here the influence of the disturbance of the rotation of the waves by the ship's hull plays a part, which necessarily evidences itself in a dynamic buoyancy. An explanation is to be expected from analysis of the measurements of water pressure.

(b) STRAIN MEASUREMENTS [2]

For comparison with the result of wave measurement the scratch records of the recording strain gauges over the same period were marked out and photographed (Fig. 13). The records show zero strain for the ship floating in calm water. In order to take the stress condition into account, a constant strain must be set down for each station. The records therefore reproduce the pure wave influence, so that the wave effect can be determined from them alone. For this purpose the bending moments were computed from the strains (Fig. 14). The strain at each point was found as the mean value of the readings on the top and bottom side of the plate. The deviation from the mean value gives the local bulging of the plating. $E = 2.15 \cdot 10^6$ kg/cm² was taken as the modulus of elasticity, and an increase of 2% in stress due to prevention of cross contraction on the stringer was allowed for. For the stations situated farther inboard this effect was computed at 5%.

As already stated, in the neighborhood of the bridge structure the location of the neutral axis was checked by the strain measurements at Fr. 69/70. By separating the plate bending stresses from the longitudinal bending stresses it was possible to determine the neutral axis which agreed with the original calculation. Fig. 15 shows the result of the investigation.

The moments of wave pressure were plotted with the moment of the ship in still water as zero axis. For comparison with the moments found by measurement the moment curves calculated as usual with various wave heights are added. From this the effective wave heights for wave hollow and wave crest can be determined. For the wave crest an effective wave height of 4.25 m is obtained in place of the

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[2] The scratch recorders were operated chiefly by Engineer Rosenberg.

measured wave height of 7.6 m. The effective wave height is therefore smaller than the decrease in wave height according to the theory of Gerstner-Hagen, which would give about 5.6 m. The stress measurement therefore shows a not inconsiderable increase in the effect [3], which is probably attributable to the restricted rotation of the wave elements.

Conditions are different for the ship in a wave hollow. Here the impact effect results in a very considerable increase in stresses and bending moments. Although the wave record indicates a lower wave height of 5.4 m, bending moments are found which correspond to a wave height of about 6 m, thus in contrast to the ship on a wave crest, an increase in moments and stresses. Here the restriction of rotation of the wave particles by the ship's hull apparently results in increasing the pressure on the ship's bottom forward, thus causing an increase in stresses. The whole investigation bears out the result already obtained from the statistical table that the calculated wave heights for the ship in a wave hollow must be taken higher than for the ship on the wave crest. Furthermore, the shapes of the bending moment curves show that especially when a shock occurs against the middle third of the ship's length, the moment curves are rather flat. This indicates that when a shock occurs the shear forces lie farther toward the ends than would appear in ordinary strength measurements, and that the shape of the waves ought to be chosen somewhat differently for determining shock. However, it will be necessary to conduct further investigations in this connection.

For the particular case of the SAN FRANCISCO it is important to determine the absolute moments and deflections. The weight distribution was determined after checks had carefully been made of the cargo condition and the contents of the tanks. From this the bending moments in calm water were then determined. Weight distribution, displacement, load, and bending moments of the shipform in calm water are represented in Fig. 16. In connection with the weight distribution it is noteworthy that the ends of the ship bore especially heavy loads, since there was only a small amount of cargo for the refrigerator compartments. This caused a considerable tensile stress in the strength deck. The moments with regard to the load condition are plotted in Fig. 17. The moments on the wave crest are now greater than in the wave hollow. The extreme load condition is especially noticeable. But contrary to former views, this type of loading does not seem dangerous, since the compressive stresses in the strength deck and in the bottom are not excessively high.

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[3] In shipbuilding circles the effect is usually called the Smith effect, since Smith was first to apply it in the calculation of stresses (TINA 1883).

(c) INFLUENCE OF HEAVING AND PITCHING OSCILLATIONS AND OF VIBRATIONS

At this point, the effect of pitching and heaving oscillations on the measured strains for the time period chosen will be treated briefly. Here the bending moments will first be computed for a heaving oscillation with an amplitude of 1 m, corresponding to an active force of 2,840 tons, and for a pitching oscillation with an acceleration of 2.5 m/sec^2 at the stem. ~~a change of 2.5 m in emersion of the stem,~~ corresponding to a moment of trim of 95,000 mt. The distribution of load and virtual mass and the corresponding bending moments may be seen in Fig. 18. Since a maximum exciting force of 1,000 tons and a maximum moment of trim of about 80,000 mt on the wave crest, and 120,000 mt in the wave hollow were determined, there results in the present case of the ship a maximum additional moment of about +1,800 mt for the heaving oscillation and -2,300 mt, or as the case may be, +3,500 mt for the pitching oscillation on the wave crest or in the wave hollow, respectively. These moments increase the static moments caused by the position of the ship among the waves. In this connection it is to be noted that the calculation is based on the normal line of flotation. On exact calculation, the increase in stress will be smaller on the wave crest, and somewhat larger in the wave hollow. Nevertheless, it is established that these moments due to dynamic loading of the oscillations attain only an order of magnitude of 15% of the static bending moments in good agreement with previous calculations by Horn. The difference between stresses on the wave crest and in the wave hollow can therefore not be attributed to the stresses due to oscillations either. The stressing of the ship due to vibrations, likewise, according to measurements at Fr. 89/90 reaches only about 10% of the stress due to bending. The stress due to vibrations is not considered in the moments, the frequency in the case of the SAN FRANCISCO amounted to about 84/min.

The greatest pitching and heaving oscillations were observed on Dec. 2. Colleague Horn is reporting on the oscillation phenomena. The influence on the bending moments and deflections will be separately treated in a subsequent paper, since because of lack of time I am unable to take it up here.

(d) DEFLECTION MEASUREMENTS WITH THE OPTOGRAPH [4]

Fig. 19 shows a record of the D.V.L. optograph. The record covers all stations. The records of stations aft are particularly prominent because the optograph was installed slightly forward of amidships. The deflection at each point is to be multiplied by a multiple from Table IV in order to find the distance of the point from the tangent to the elastic line in the place in which the optograph was set up. The peculiar property of the optograph of recording the angle

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[4] Optograph measurements were made by Engineer Frank.

between the tangent and the point measured, to a certain extent precludes the possibility of vitiating the test result by vertical turning of the optograph. It must be noted, that just as in the strain measurements, every point in the image is displaced with respect to the time markings. The displacement may change with horizontal rotation. This causes an error in the chronograph record, which may be eliminated, however, if there is a possible means of measuring time in horizontal direction, vibrations, for example. We have applied this means in the present case, so that it is possible to coordinate very accurately the deflection records and stress records. Naturally it is impossible completely to avoid small errors. In order to get an idea of the sensitivity of the set-up, I merely wish to mention that the loosening of a fastening screw by 1/1,000 mm with respect to another apparently shifts test point 1 horizontally by about 60 mm. This causes a horizontal displacement as compared to the chronographic mark in the image of about 5 mm. Therefore the set-up in strain and deflection tests must be arranged very carefully.

The deflections measured with the optograph are plotted in Fig. 20. The line of flotation of the ship in calm water is taken as the base. For comparison the calculated elastic curves for 5 m and 6.55 (L/20) m wave height for wave crest and wave hollow are also included. In the calculated elastic curves, the deflection due to shear is also considered. It is evident that calculated and measured deflections are in the same ratio as the calculated and measured bending moments, with sufficient accuracy. Wherever small deviations exist, they may be attributed, on close observation, on the one hand to the difficulty of determining time, and on the other to the great fulness of some moment curves which somewhat magnify the deflection. In conclusion, the maximum deflections due to wave movement on wave crest and wave hollow are plotted over the deflection in calm water, in order to show the influence of extreme loading and to obtain the absolute deflections. (Fig. 21). In the case of the deflection measurements the influence of vibrations is not included in the charts.

SUMMARY

By summarizing the results of measurements for longitudinal strength obtained up to this point the following conclusions are obtained:

(a) The waves encountered by a ship at sea exceed the heights and gradients hitherto accepted. For an effective maximum wave height of about 5.5 m the actual height amounts to about 9 to 10 m with a length of 130 m.

(b) For calculating the stresses in a ship on a wave crest the observed wave heights must be decreased. The decrease is greater than that allowed in the so-called Smith effect. The decrease may probably be attributed to the disturbance of the rotation of the wave elements by the ship's hull. A conclusive explanation will be obtained from the evaluation of measurements of pressure on the bottom.

1 – 2 – 3 – 4 – 5

(c) In the wave hollow, the stresses on the bottom forward are greater than when the ship is on a wave crest, due to the impact action of the waves.

(d) The method of calculating the longitudinal strength of ships should be changed. In order to find the actual stresses in a seaway a greater wave height should be assumed for a ship in a wave hollow, than for one on the crest. The ratio of wave heights for ships with low engine power can be derived from the present tests. For faster large ships the ratio must be increased.

(e) The customary methods of calculating bending moments, bending stresses, and of deflections from moments and shear are adequate for practical purposes. For purposes of calculation the wave length must be taken as equal to the ship's length, as hitherto.

In addition to the measurements which I am here reporting, another series of further findings are to be expected from the test data. I here have in mind the investigations of the magnitude and location of shear stresses in the hull. Other measurements indicate the magnitude of bending stresses in the shell plating due to water pressure and the change in stress caused by the butts of the plates. They are particularly valuable for comparison with the tests of the Navy in the Material Testing Bureau at Berlin-Dahlem. Additional series of tests give the stresses in the frames and the double bottom in a seaway. The torsional stress of the ship was also continuously studied.

Although the results exceed my own expectations, there still is much lacking to explain all that is required by the engineer to make correct designs. The influence of the size and the speed of the ship and the "effective wave height" depending thereon can only be learned by additional measurements of large, fast vessels.

I here express my thanks to the Deutshe Forschungsgemeinschaft, the D.V.L., the German Navy, the Hamburg-America Line, the yards of Blohm and Voss, Deutsche Werft, Deutsche Werke and Deschimag, the German Lloyd, the Gesellschaft der Freunde der Technischen Hochschule, Berlin, the Siemens Apparate, Ltd. and the Siemens-Schuckert Works, of Berlin and Hamburg, as well as the Schiffbautechnische Gesellschaft for their support of my efforts. My thanks are also given to the navigating and engineering staffs of the ship, who always willingly assisted our investigations.

The following took essential part in the measurements: Dipl. Ing. Henning, Eng. Rosenberg and Eng. Frank, and in the analyses as well, Dr. Eng. Pophanken and Candidates Izzet, Steinbrück, Többicke and Umlauf. I thank them here for their indefatigable cooperation. In conclusion I thank all those who participated in the test voyage, but particularly my colleague, Dr. Horn, for the comradeship and cooperation which contributed materially to our success.

TABLE 1.

Motorship SAN FRANCISCO.

Class: G.L. +100 A (E) with Freeboard.
Length between perpendiculars: 131 meters.
Overall Length: 136.80 meters.
Greatest Moulded Breadth: 18 meters.
Height of side to Freeboard Deck: 9.06 meters.
" " " " Strength " 11.50 meters.
Displacement (Dec. 14, 1934) : 13,070 T.
Corresponding draft, forward: 6.90 meters.
" " aft : 7.61 meters.
Block coefficient: 0.744.
Engine: 1 – 5 Z dw 2T MAN 4,200 EHP at n = 90.
Speed: 13.2 Knots.

TABLE II. STATICTICS

Optograph roll 14^{II} gives values for f, H''_w. Scratch instrument M46, Fr. 89/90 gives values for σ , M, H'_w and H''_w: Effective wave heights, computed from stress or bending.

Time	Stress + Tension – Compr. Kg/cm²	σ Hollow / σ Crest	Bending Moment M 1000 mt	Deflection f + Hollow – Crest cm	f Hollow / f Crest	Period sec.	Wave Data Length m	H'_w from σ m	H'_w (Hollow) / H'_w (Crest)	H'_w from f m	H'_w(Hollow) / H'_w (Crest)	Remarks
11. XII. $11^h\,55'$	— 477	1,23	+ 20,0	+ 5,3	1,29	10,5	175	3,8	1,19	3,8	1,15	
	+ 387		— 16,2	— 4,1				3,2		3,3		
	— 845	1,57	+ 35,3	+ 8,9	1,75	9,0	126	6,6	1,47	6,2	1,40	Stoß!
	+ 540		— 22,5	— 5,1				4,5		4,3		
	— 566		+ 23,7	+ 5.5		10,5	175	4,5		4,0		
$11^h\,24'$	— 370	1,37	+ 15,5	+ 4,0	1,38	15,0	350	3,0	1,37	2,9	1,26	
	+ 270		— 11.3	— 2.9				2,2		2.3		
	— 567	1.50	+ 23.7	+ 6.5	1.71	7.9	100	4.5	1,40	4.5	1.41	
	+ 378		— 15,8	— 3,8				3,2		3.2		
$11^h\,39'$	— 540	1,50	+ 22,6	+ 5,3	1,47	11,0	190	4,3	1,43	3,9	1,26	
	+ 360		— 15,0	— 3,6				3,0		3,1		
	— 405		+ 16.9	+ 4.9		9,8	150	3.3		3.5		
$11^h\,40'$	— 360	0,93	+ 15,0	+ 3,3	0,75	9,0	126	2,9	0,85	2,5	0,70	
	+ 387		— 16,2	— 4,4				3,3		3,6		
	— 405		+ 16.9	+ 5,1		13,8	300	3,3		3,6		
$11^h\,40/1'$	— 560	1,12	+ 23,4	+ 6,8	1,13	11,3	200	4,5	1,07	4,7	0,94	
	+ 500		— 20,9	— 6.0				4,2		5,0		
	— 675		+ 28,2	+ 8,3		11,3	200	5.4		5,5		Stoß!
$18^h\,02'$	— 675	1,50	+ 28,2	+ 8,0	1,48	10,8	180	5,4	1,42	5,5	1,25	Stoß!
	+ 450		— 18,8	— 5,4				3,8		4,4		
	— 566	2.10	+ 23.7	+ 6.2	1.68	11,5	205	4,6	1,95	4.4	1.52	Stoß!
	— 270		— 11.3	— 3,7				2.3		2,9		
	— 450	1,04	+ 18,8	+ 6.8	1,55	13,8	300	3,7	1,03	4,6	1,24	Stoß!
	+ 432		— 18,1	— 4,4				3,6		3,7		
	— 765	1,70	+ 32,0	+ 8,5	1,73	10,8	180	6,1	1,60	5,8	1,41	Stoß!
	+ 450		— 18,8	— 4,9				3,8		4,1		
14. XII. $18^h\,51'$	— 500	1,24	+ 20,9	+ 5,8	1,93	9,8	150	4,0	1,21	4,1	1,52	
	+ 405		— 16,9	— 3,0				3,3		2,7		
	— 450	2,08	+ 18,9	+ 5,1	3,00	9,8	150	3.6	2,00	3,6	2,57	
	+ 216		— 9,0	— 1,7				1,8		1,4		
	— 380	1,00	+ 15,9	+ 4.7	1,62	11,3	200	3,0	0,97	3,3	1,27	
	+ 380		— 15,9	— 2,9				3,1		2,6		
	— 405	1,50	+ 16,9	+ 4,8	2,18	13,3	275	3,3	1,50	3,4	1,89	
	+ 270		— 11,3	— 2,2				2,2		1,8		
	— 400		+ 16,7	+ 4,3		8,6	110	3,2		3.1		
$18^h\,52'$	— 690	2,19	+ 28,8	+ 7,3	2.61	9.7	·150	6.4	2,16	5,1	2,22	
	+ 315		— 13,2	— 2,8				2,5		2,3		
	— 315		+ 13,2	+ 2,8		17,9	500	2,5		2,2		
$21^h\,07'$	— 270	0,75	+ 11,3	+ 4,0	1,33	8,6	115	+ 2,2	0,73	2,9	1,21	
	+ 360		— 15,1	— 3.0				3.0		2,4		
	— 620	1,64	+ 25.9	+ 8,7	2.81	9,1	130	5.0	1,61	5,8	2,32	Stoß!
	+ 378		— 15.8	— 3,1				3,1		2,5		
$23^h\,56'$	— 270	0,75	+ 11,3	+ 3,4	1,13	11,3	200	2,2	0,73	2,4	1,00	
	+ 360		— 15,1	— 3,0				3,0		2,4		
	— 270	0,50	+ 11,3	+ 3.2	0.60	12.0	225	2.2	0.48	2.2	0.49	
	+ 540		— 22,6	— 5,3				4,6		4,5		
	— 810	1,97	+ 33.8	+ 9.0	3.00	9,0	126	6,4	1,88	6,3	2.62	Stoß!
	+ 412		— 17.2	— 3,0				3,4		2,4		
15. XII. $12^h\,22'$	— 425	1,18	+ 17,8	+ 5,1	1,11	10,0	156	3,4	1,13	3,6	0,97	
	+ 360		— 15,0	— 4,6				3,0		3.7		
	— 540		+ 22.6	+ 6,6		8,8	121	4,3		4,5		Stoß!

Stoss = Impact

TABLE III. STATISTICS

Maximum Storm Values
Station M 46

Time and Date	Stress			Bending Moment M		Effective Wave Height		Remarks
	σ Crest Kg/cm^2	σ Hollow Kg/cm^2	$\frac{\sigma \text{ Cr.}}{\sigma \text{ Hol.}}$	Crest 1000 mt	Hollow 1000 mt	Crest m	Hollow m	
Nacht vom 10. XII. zum 11 XII.	+ 500	— 460	0,92	— 20,9	+ 18,85	4,2	3,6	
11. XII. 12^{h}15 bis 14^{h}13 . . .	+ 520	— 720	1,38	— 21,8	+ 30.10	4,4	5,7	Stoß!
		(— 630)	(1,21)		(+ 26,40)		(5,0)	
„ 14^{h}30 bis 17^{h}30 . . .	+ 505	— 720	1,43	— 21,1	+ 30,1	4,3	5,7	
„ 18^{h}40 bis 23^{h}00 . . .	+ 650	— 920	—	— 30,1	+ 39,5	5,6	7,2	Ermittelt aus M 48
11. XII. 23^{h}20 bis 12. XII. 14^{h}07	+ 600	— 920	1,42	— 27,2	+ 38.40	5,3	7,2	Stoß!
		(— 695)	(1,07)		(+ 29,10)		(5,5)	
14. XII. 12^{h}00 bis 13^{h}30 . . .	+ 435	— 560	1,29	— 18,2	+ 23,4	3,6	4,5	
„ 14^{h}30 bis 15^{h}37 . . .	+ 540	— 560	1,04	— 22,6	+ 23,4	4,6	4,5	
„ 16^{h}49 bis 18^{h}32 . . .	+ 640	— 720	1,12	— 26,8	+ 30,1	5,6	5,7	
„ 18^{h}59 bis 21^{h}00 . . .	+ 450	— 765	1,70	— 18,8	+ 32,0	3,8	6,1	Stoß!
		(— 630)	(1,40)		(+ 26,4)		(5,0)	
„ 21^{c}25 bis 23^{h}50 . . .	+ 585	— 765	1,31	— 24,5	+ 32,0	5,0	6,1	
14. XII. 0^{h}20 bis 15. XII. 9^{h}15	+ 560	— 720	1,29	— 23,4	+ 30,1	4,8	5,7	
15. XII. 9^{h}35 bis 11^{h}30 . . .	+ 560	— 810	1,45	— 23,4	+ 33.9	4,8	6,4	Stoß!
		(— 660)	(1,18)		(+ 27,6)		(5,2)	
„ 12^{h}30 bis 13^{h}30 . .	+ 450	— 675	1,50	— 18,8	+ 28,2	3,8	5,3	Stoß!
		(— 630)	(1,40)		(+ 26,4)		(5,0)	
„ 14^{h}00 bis 17^{h}00 . . .	+ 540	— 720	1,33	— 22,6	+ 30,1	4,6	5,7	Stoß!
		(— 650)	(1,20)		(+ 27,2)		(5,1)	
„ 18^{h}00 bis 20^{h}01 . . .	+ 470	— 540	1,15	— 19,7	+ 22,6	4,0	4,3	
„ 21^{h}01 bis 22^{h}16 . . .	+ 450	— 450	1,0	— 18,8	18,8	3.8	3,6	

Note: The shock component has been deducted from the values in brackets.

Stoss = Impact

Ermittelt aus M48 = Derived from M48

TABLE IV.

Position of Test Stations 1 to 8 with Respect to the Optograph (Fr.80).

Station	1	2	3	4	5	6	7	8
Distance fr. Optograph, m. + = Forward, - = Aft.	— 56,7	— 45,9	— 35,1	— 26,1	+ 16,2	+ 27,9	+ 36,7	+ 45,8
Scale	1 : 12,4	1 : 10,6	1 : 8,0	1 : 6,0	1 : 8,2	1 : 13,4	1 : 16,7	1 : 20,5

---

[*] Die Optographenmessungen wurden von Herrn Ing. Frank ausgeführt.

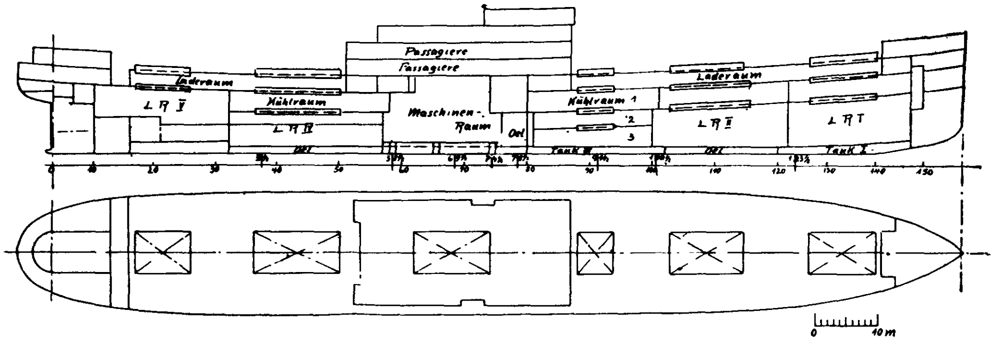

Fig. 1. Longitudinal Section of the SAN FRANCISCO.

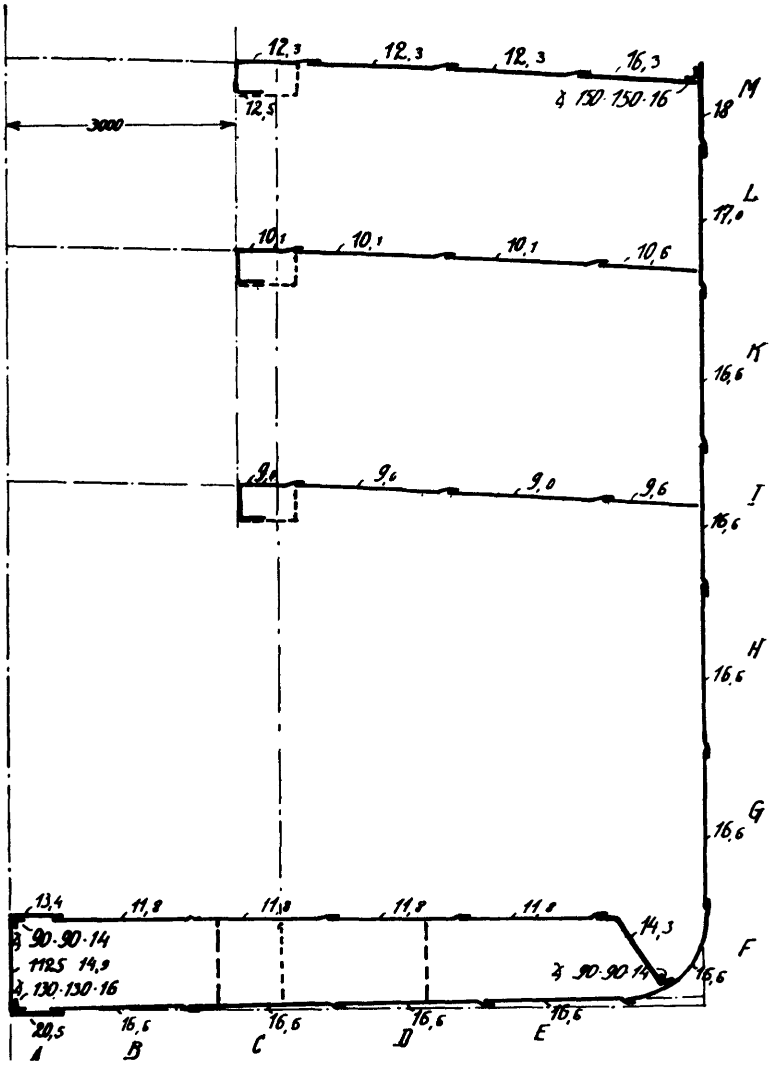

Fig. 1a. M.S. SAN FRANCISCO, MIDSHIP SECTION

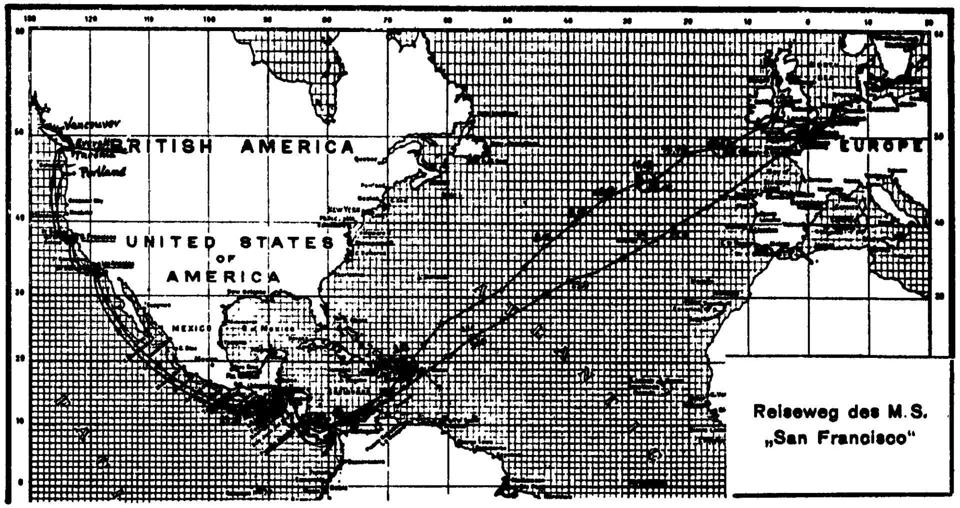

Figure 2.

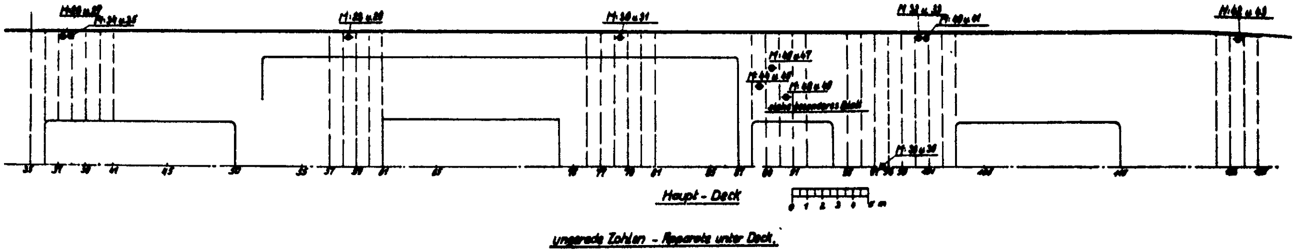

Fig. 3. Diaposition of Extensometers on Strength Deck.

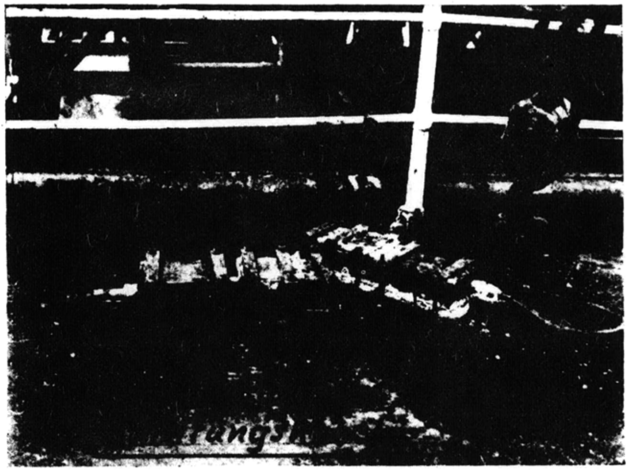

Fig. 4. Extensometer Fr. 37/38 with Housing.

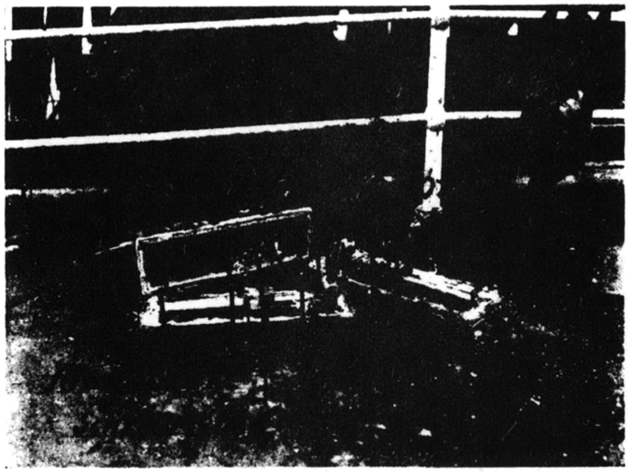

Fig. 5. Extensometer Fr. 37/38, Housing removed.

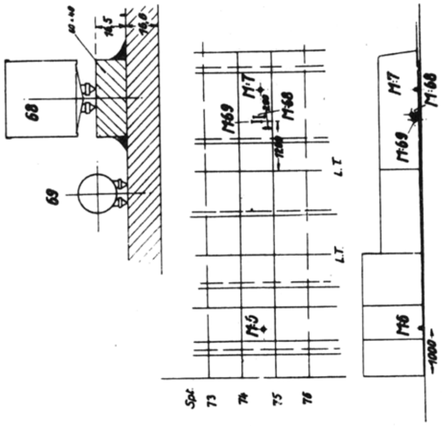

Fig. 6. Extensometer on Shell Plating.

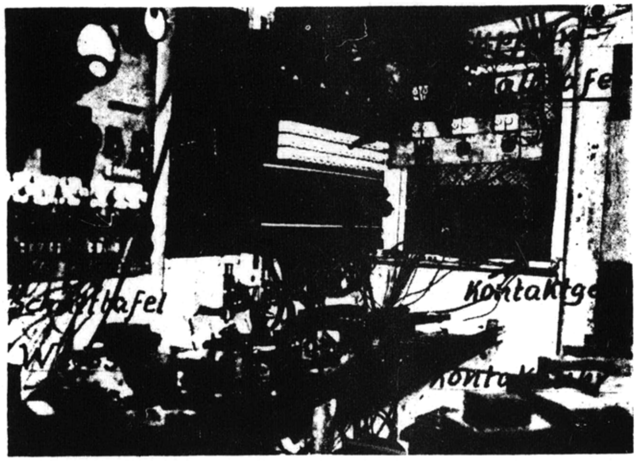

Fig. 7. Central Station.

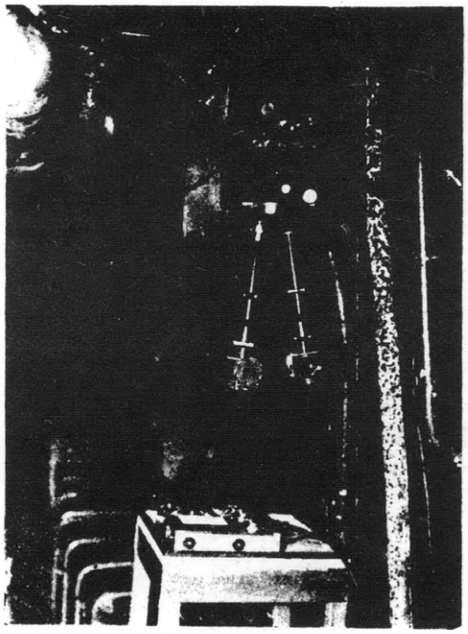

Fig. 8. DVL Optograph.

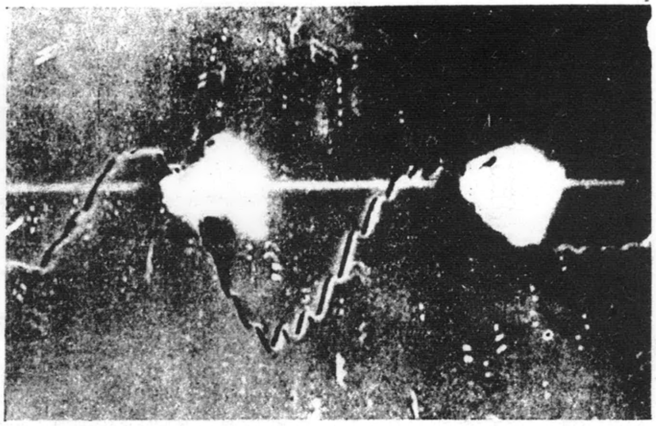

Fig. 10. Scratch Extensometer Record, Fr. 89/90
(Magnified about 170 times).

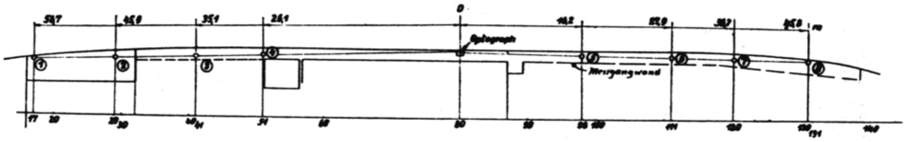

Fig. 9. Arrangement of Optograph Stations.

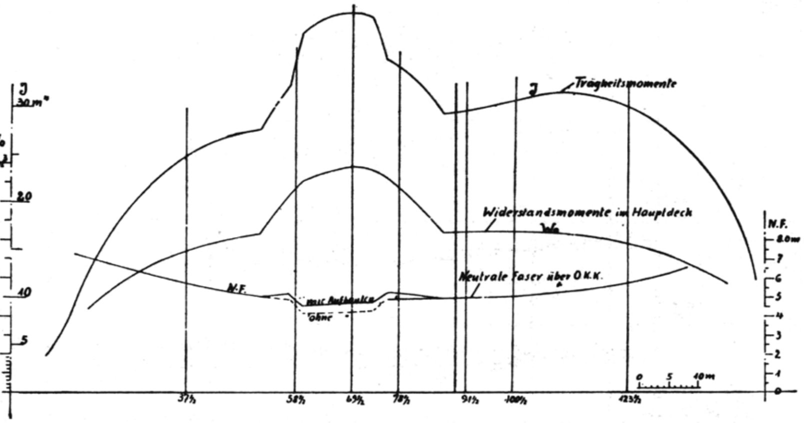

Fig. 11. Moments of Inertia, Resistance Moments and Neutral Axis.

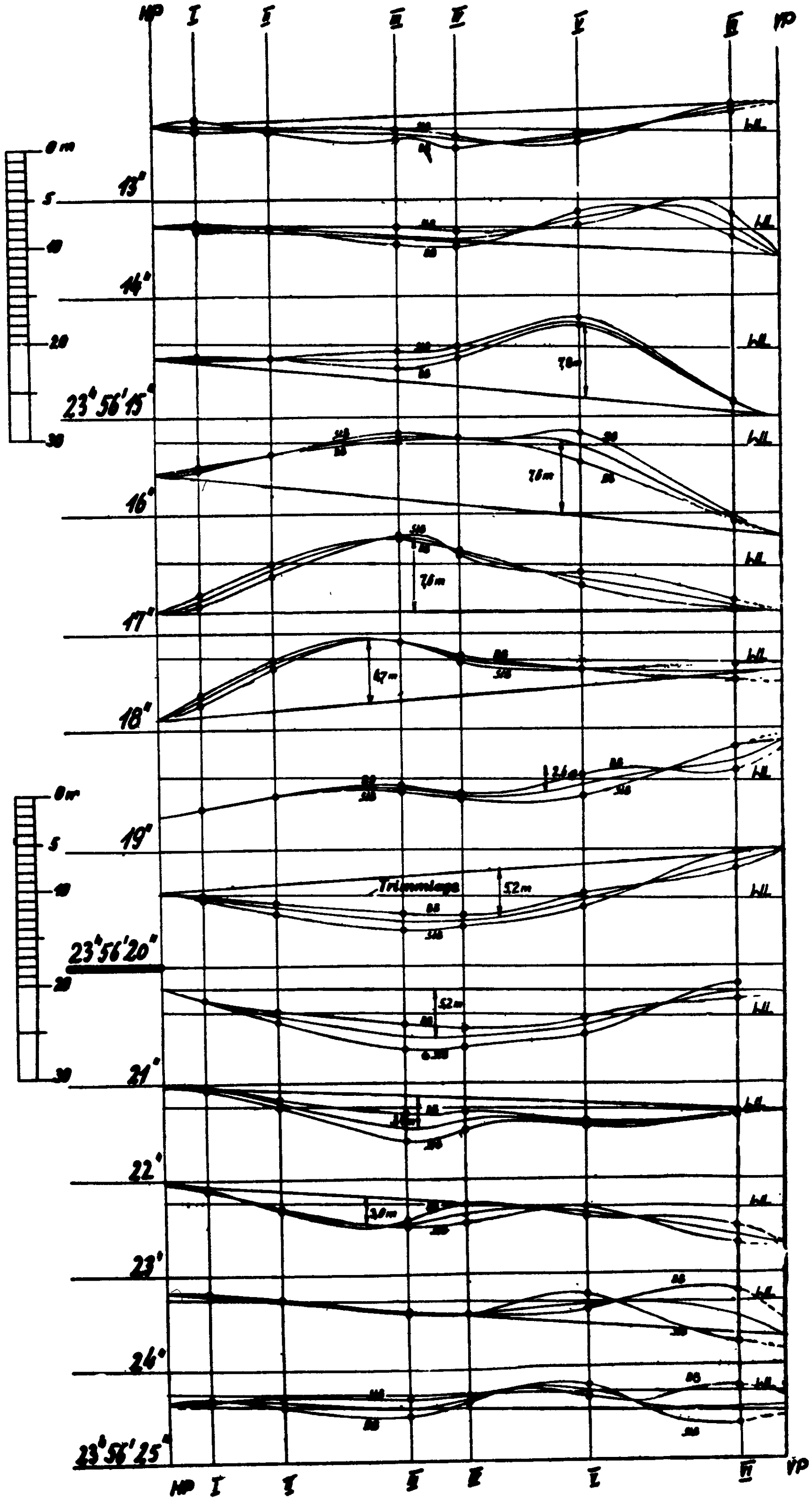

Fig. 12. Result of Wave Measurement on Ship's Hull.

Time: $23^{h}56'13''$ - $23^{h}56'24''$ on Dec. 14, 1934.

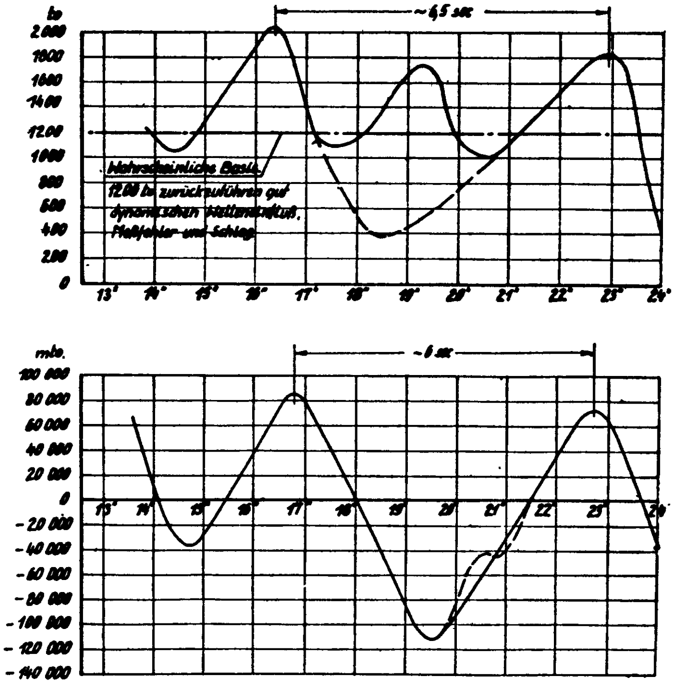

Fig. 12a. Residual Weight and Moments of Trim according to Wave Measurement.

(See following pages for Figs. 13 to 13g)

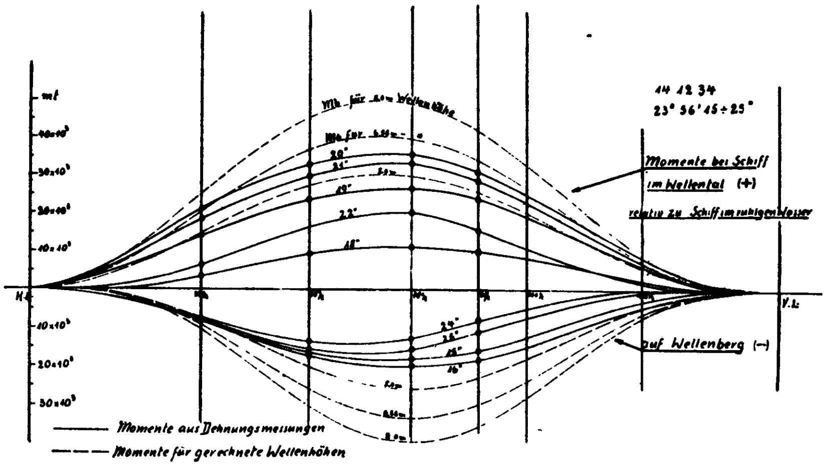

Fig. 14. Moments due to Seaway only.

Fig. 13.
Scratch Records.
M = 1 mm = .006 mm.

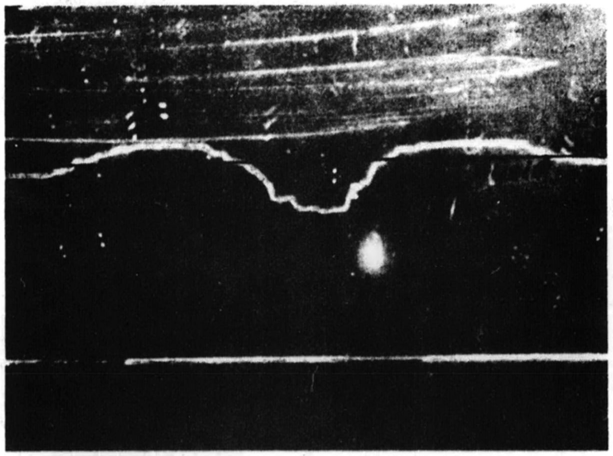

Fig. 13a. Test Station 26. Fr. 37/38 on Deck.

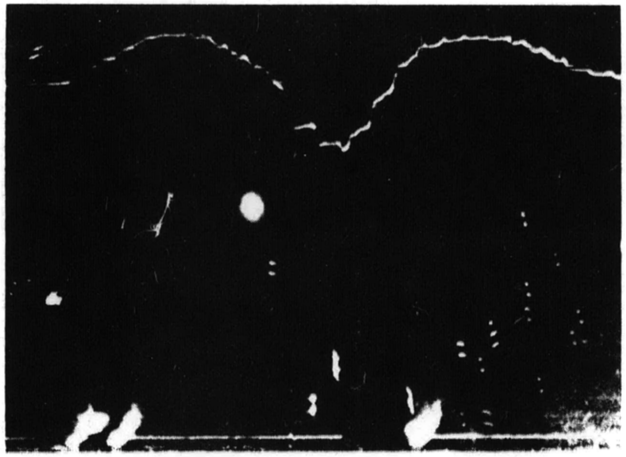

Fig. 13b. Test Station 27. Fr. 37/38 below Deck.

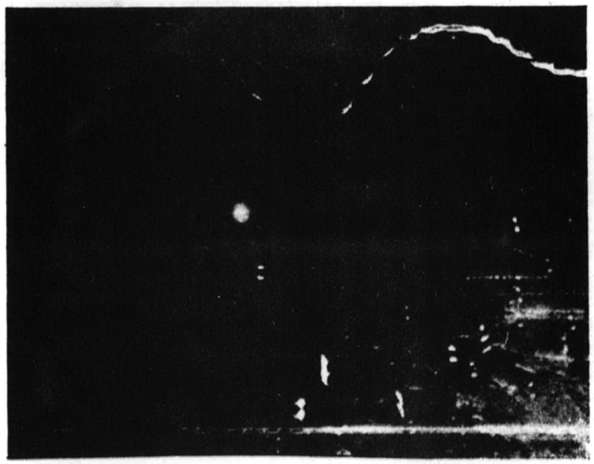

Fig. 13c. Test Station 29, Fr. 58/59 below Deck.

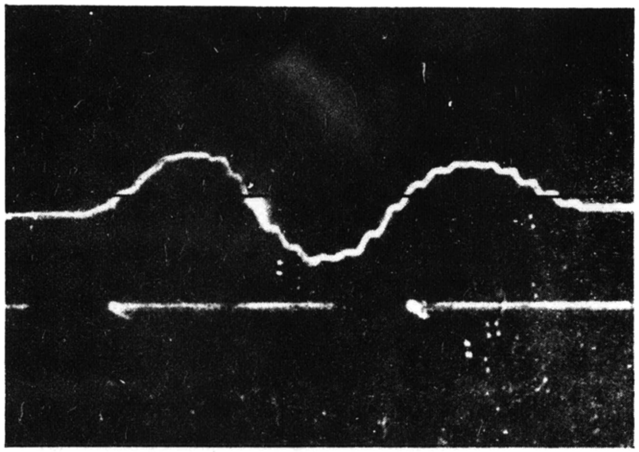

Fig. 13d. Test Station 30, Fr. 78/79 on Deck.

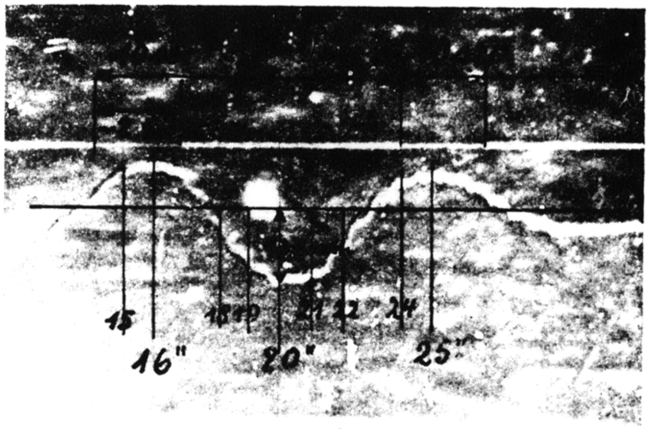

Fig. 13e. Test Station 31, Fr. 91/92 below Deck.

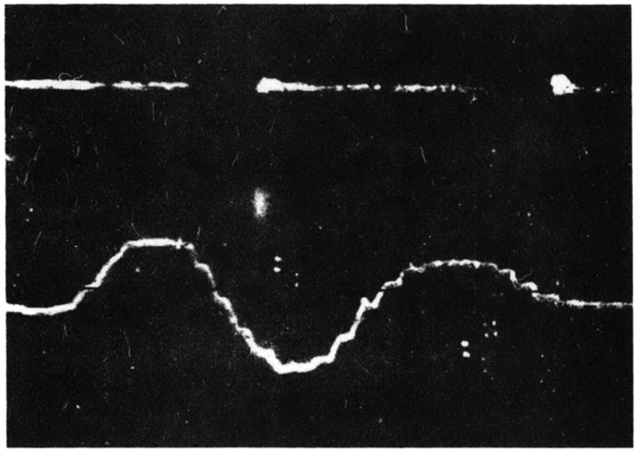

Fig. 13f. Test Station 48, Fr. 91/92 on Deck.

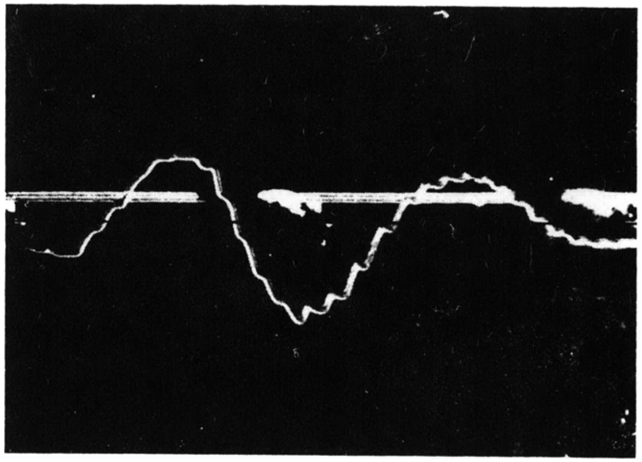

Fig. 13g. Test Station 49, Fr. 91/92 below Deck.

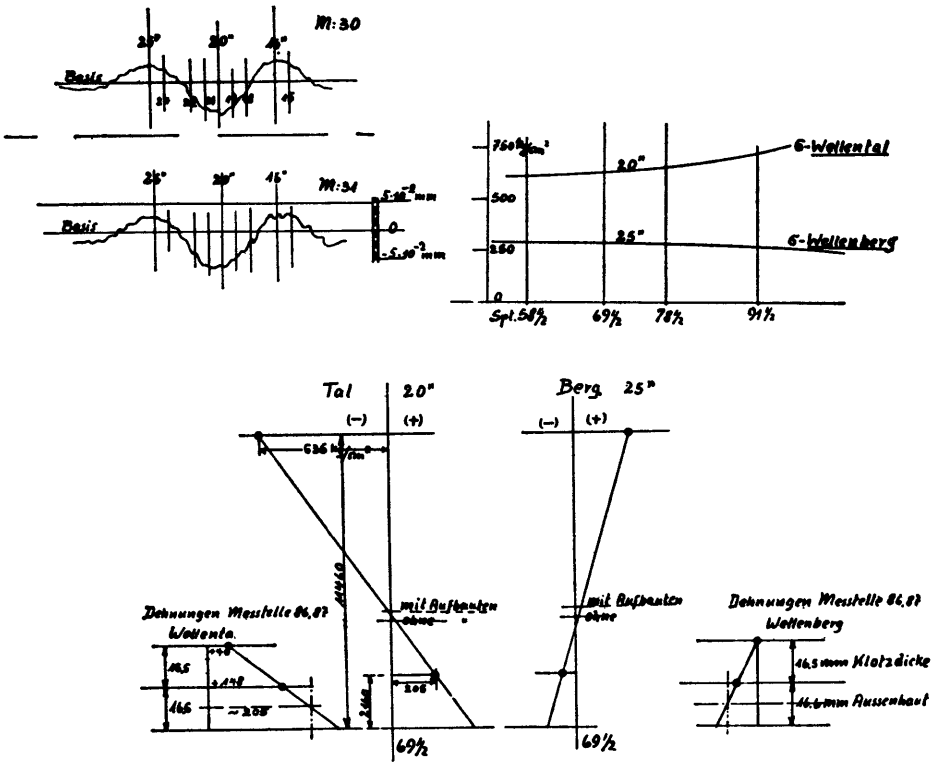

Fig. 15. Determination of the Neutral Axis.

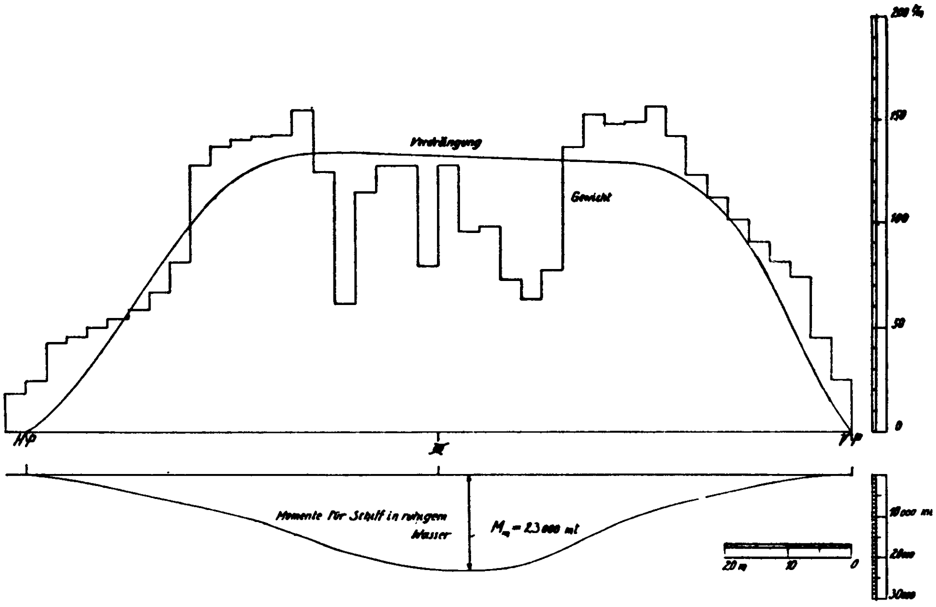

Fig. 16. Weight, Bouyancy and Moment in Quiet Water.

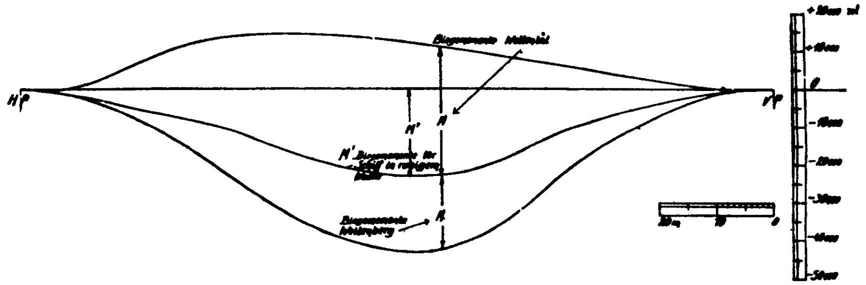

Fig. 17. Absolute Bending Moments.

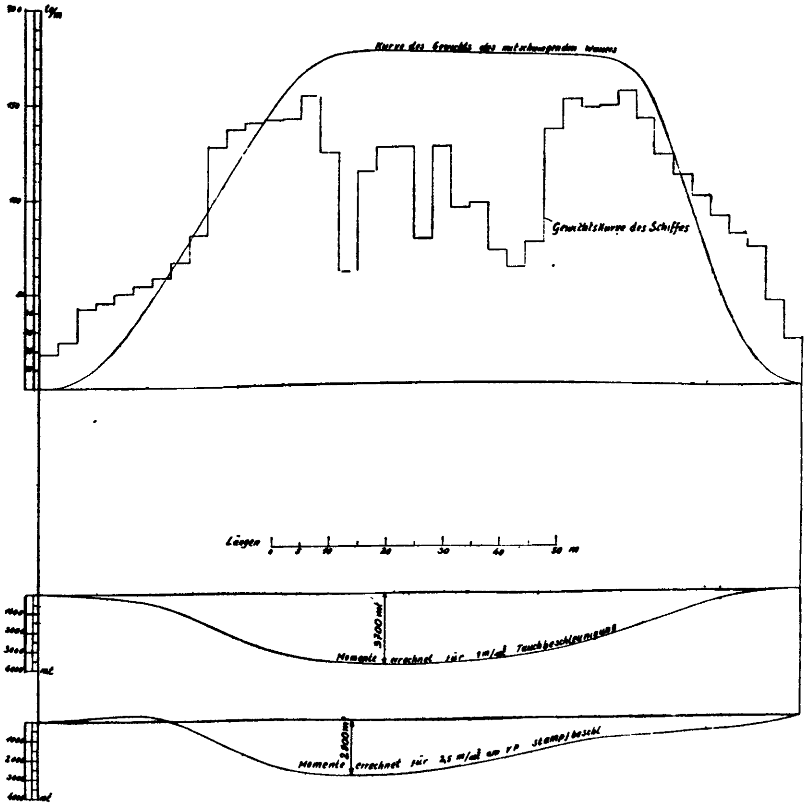

Fig. 18. Weight, Virtual Mass, and Moments due to Heaving and Pitching Oscillations.

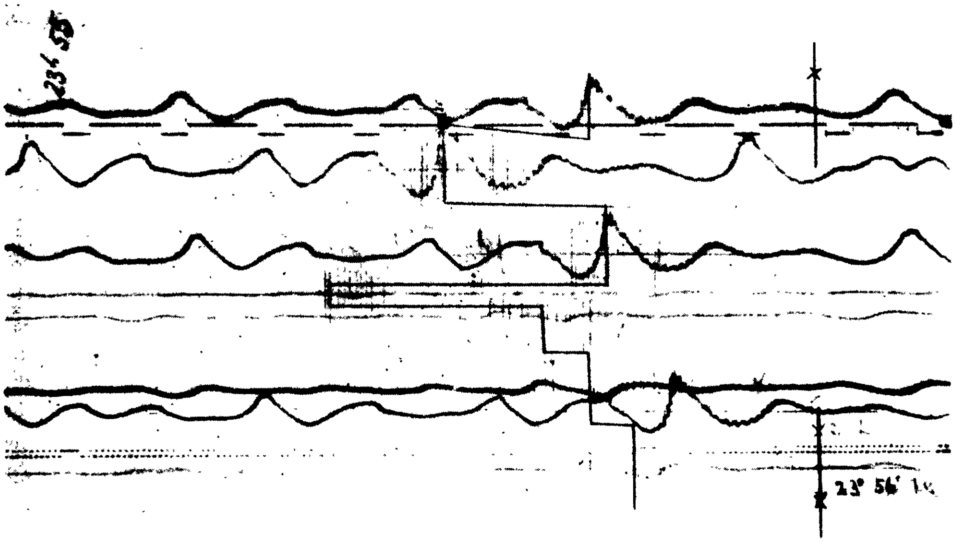

Fig. 19. Optograph Record (reduced ca. .88 times).

(See following page for Fig. 20).

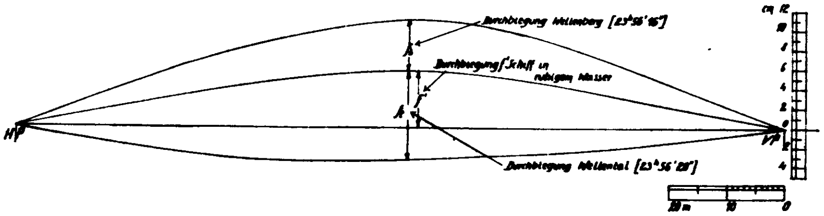

Fig. 21. Absolute Deflection.

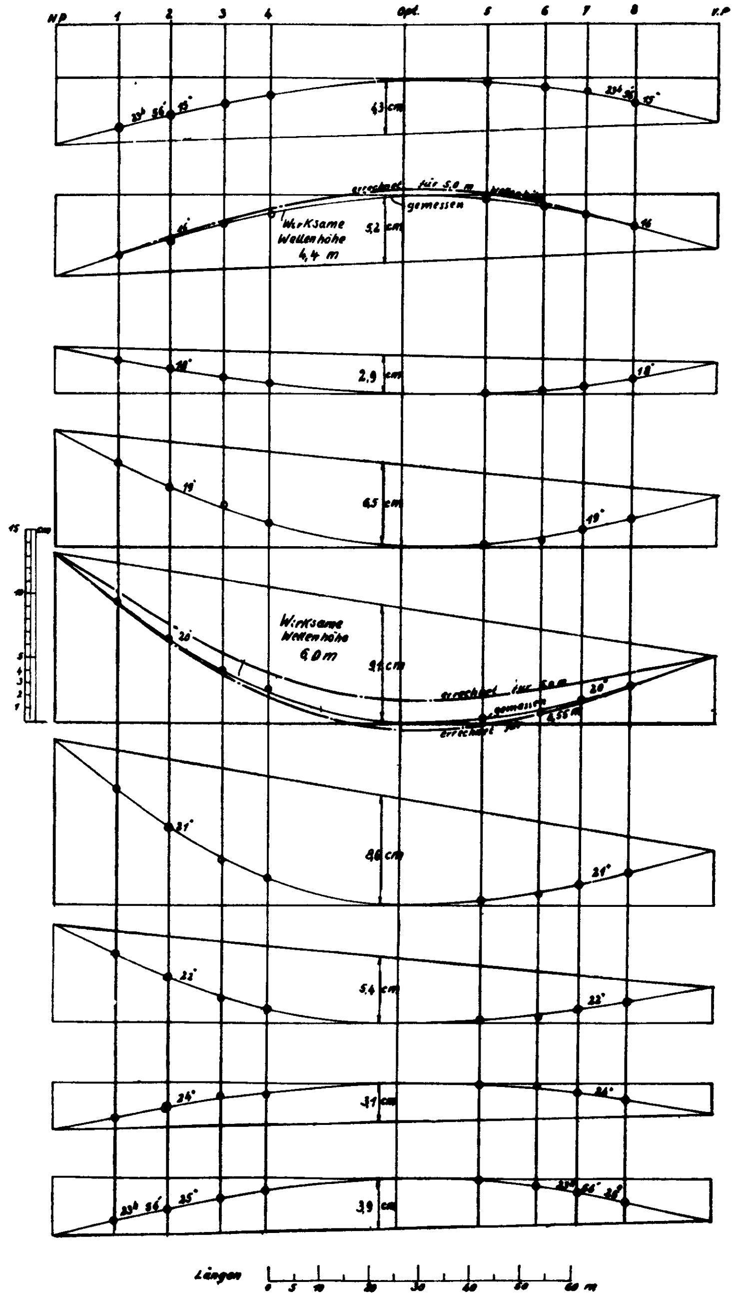

Fig. 20. Deflections due to Seaway only, from Optograph Measurement.