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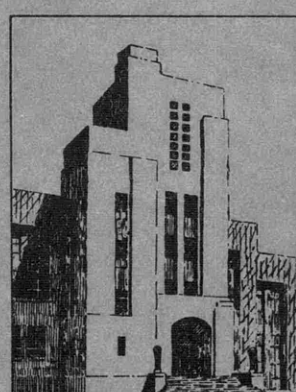
THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

MODEL TESTS OF TURRETS AND FOUNDATIONS AND THEIR INFLUENCE ON FULL-SCALE DESIGN

BY R.T. McGOLDRICK



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DAVID TAYLOR MODEL BASIN

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PERSONNEL

The experimental work discussed in this report extended over a period of several years, beginning about 1937. Those chiefly concerned were: with the static model work, Comdr. R.D. Conrad, USN, Comdr. J.M. Farrin, USN, C. Trilling, and E.E. Johnson of the U.S. Experimental Model Basin; with the dynamic model testing program, Captain W.P. Roop, USN, R.T. McGoldrick, Dr. B.L. Miller, and F.B. Bryant of the David Taylor Model Basin, and C.J. Lissenden and J.L. Moorehouse of the Scientific Section of the Philadelphia Navy Yard; with the recent turret observations on the firing trials of BB55 and BB56, Comdr. J. Ormondroyd, USNR, E.E. Johnson, H.R. Thomas, and R.T. McGoldrick of the David Taylor Model Basin; with the static loading tests on cruiser turrets, E.E. Johnson and L.D. Anderson of the David Taylor Model Basin.

The report is the work of R.T. McGoldrick.

FOREWORD

A number of technical reports have been issued from time to time during the past five years by the U.S. Experimental Model Basin and the David Taylor Model Basin, describing the results of a series of model and full-scale tests made in an effort to improve and refine the design of turret structures and their foundations on vessels of the United States Navy.

Although this work is still underway, the present time appears to be a suitable one to summarize the results, to consolidate the present position, and to redefine the objectives, as it were, so that future work may be on a sound and logical basis. This report is the result of an effort to accomplish this task.

To those familiar with turret design and construction in general, the treatment of the turret and its foundation in this report may seem rather elementary. It has been made so purposely to facilitate studies of the problem by persons who are not naval architects but who have sufficient knowledge of the theory of elasticity and the design and behavior of structures in general to enable them to make useful contributions in this field, provided they can familiarize themselves with the background.

DIGEST*

The design of turret structures and their foundations on men-of-war has reached its present stage of development by a process of gradual evolution in which common sense, good engineering judgment, and practical experience have played as large and as important a part as theoretical analysis.

The David Taylor Model Basin has been concerned with the basic features of turret foundations for many years, and more recently with the whole assembly including the turret; the references on pages 43, 44, and 45 of this report describe numerous theoretical and experimental studies of this problem. As a result of this work, the design of the turret foundation has been considerably modified, and ideas have crystallized as to the essential points to consider in the design of such elements as the roller tracks, holding-down clips, and gun girders. With the renewal in the 1930's of heavy turret construction on battleships, a new demand for research in this field arose, so that the Taylor Model Basin in collaboration with the Design Section of the Philadelphia Navy Yard proceeded to extend its testing techniques to include dynamic as well as static loads. Thus turret models are now subjected to transient loads closely simulating those acting on the full-scale turret.

Experiments have also been made with a view to finding a substitute for the present roller-bearing design. Model tests with a rollerless bearing with force-feed lubrication (6) have indicated that such a bearing has distinct possibilities for turret service.

In this report the basic design problem is outlined in the light of the studies made at the Taylor Model Basin, and design criteria for use in designs employing the flanged tapered roller are recommended. Further model and full-scale research in this field is suggested in Reference (6) and later in this report.

The general method of mounting guns in turrets is illustrated in Figure 3, reproduced here, and the details of the immediate support of the gun in Figures 4 and 5, on pages 6 and 7 of the report. These vitally affect the dynamic loads upon which the design of the foundation is based, and a thorough knowledge of the action, especially of the recoil system, is necessary to an understanding of the problem as a whole.

Turret rollers are proportioned chiefly on the basis of experience with designs in service and of model tests. As an explicit guide, two empirical index numbers were used, one based on deadweight load only and the other based on deadweight plus recoil load, as shown in Figure 9. The first index number based on dead weight is W/NLD, where W is the dead weight in tons, N is the number of rollers, L is the length of the rollers in inches, and D is the roller diameter in inches. In practice

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* This digest is a condensation of the text of the report, containing a description of all essential features and giving the principal results. It is prepared and included for the benefit of those who cannot spare the time to read the whole report.

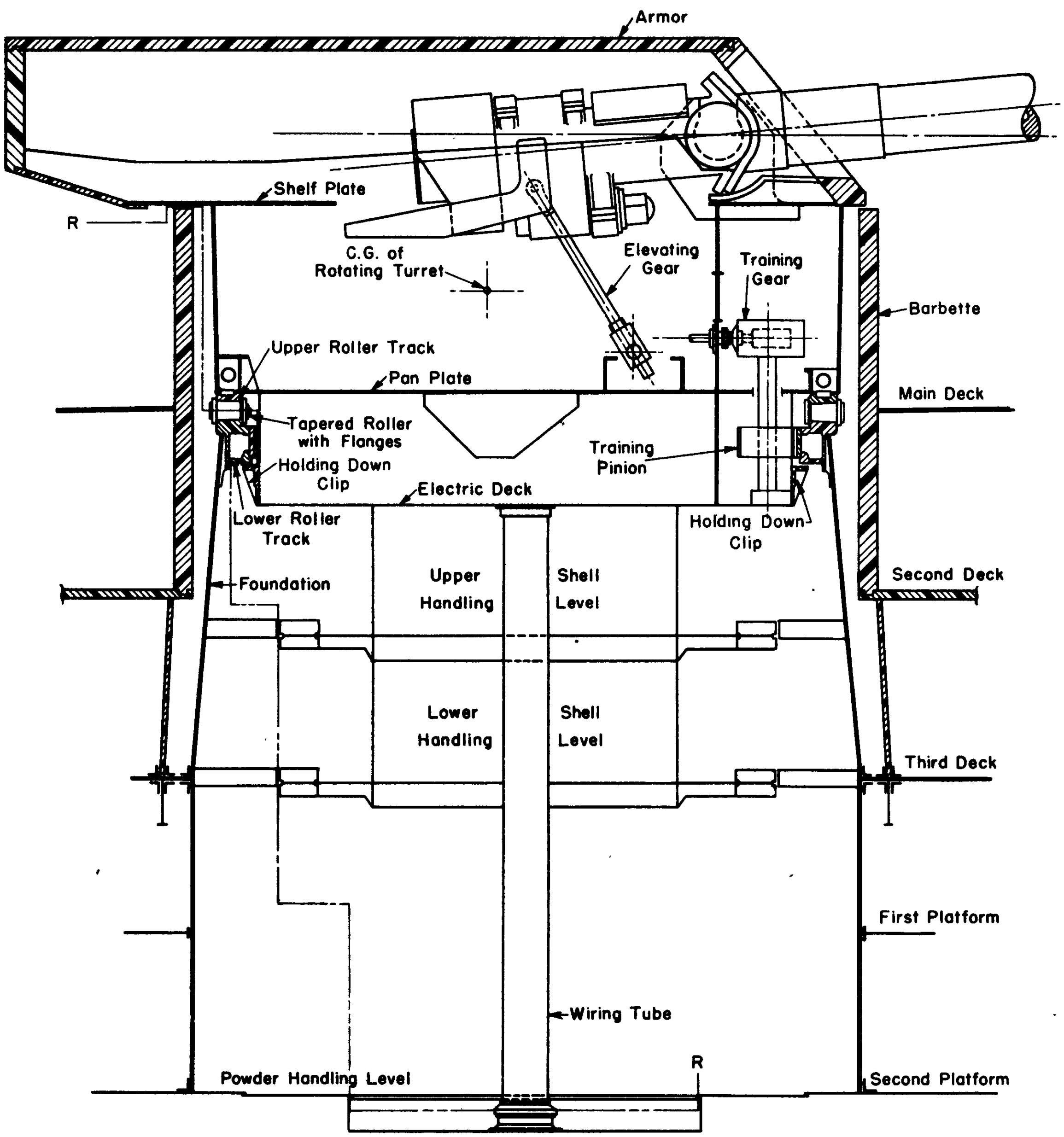
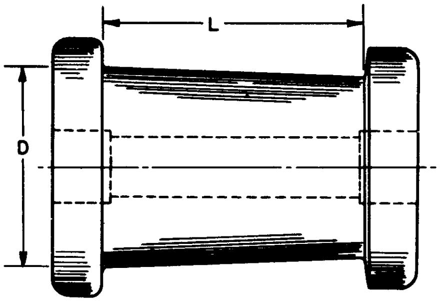


Figure 3 - Vertical Section through a Typical Modern Major-Caliber Turret Installation

This is a triple 16-inch, 45-caliber high gun turret of BB56. Here the lower roller track is supported on an unstiffened tubular foundation extending down to the lower platforms in the ship. This foundation, above the third deck, is entirely clear of the barbette or heavy stationary armor. The rotating turret structure in which the guns are installed and which is heavily armored above the barbette is supported on a tapered roller bearing. Both the fixed and the rotating structures are protected by the barbette, which is a cylindrical shell of armor extending from the armored deck up to the armored part of the turret.

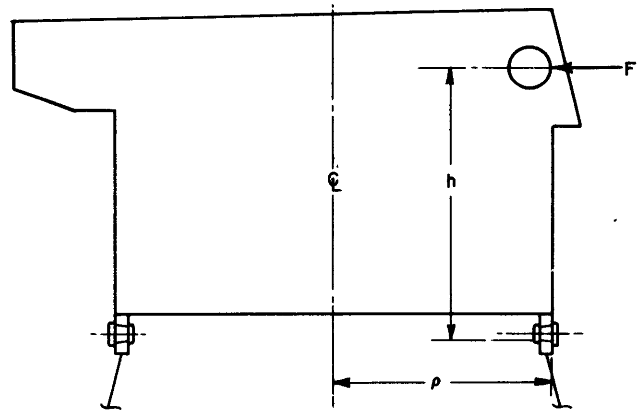
The training pinion is built into the turret and engages a ring gear attached to the lower roller track. The rollers have wide flanges so that in addition to carrying the vertical or deadweight load they resist the tendency of the turret to move horizontally under the recoil load. To prevent lifting of the turret from its bearing when recoil occurs, the rotating structure carries holding-down clips which project under the lower roller track. A close clearance is maintained between the clip and the lower track.

All parts inside of the line R-R rotate; all other parts remain stationary.



Index Number = $\frac{W}{NLD}$

where W is the dead weight in tons
N is the number of rollers
L is the length of the rollers in inches
D is the diameter of the rollers in inches



Index Number = $\frac{W + 2F\frac{h}{\rho}}{NLD}$

where F is the trunnion load in tons, and other factors are as shown

Figure 9 - Diagrams Illustrating Empirical Index Numbers for Roller Design

this index number is kept below 0.130. The index number based on recoil load is $\left(W + 2F\frac{h}{\rho}\right) \div NLD$, where N, L, D, and W are as before, F is the trunnion load in tons, and h/ρ is the ratio of the distance between the lower track and the trunnion center to the track radius. This index number is kept below 0.390.

Turret installations in U.S. Naval vessels are in general giving satisfactory service. Aside from the general aim of refinement in design and reduction in weight, there might seem to be little purpose in carrying out further investigations in this field, even admitting that much information is lacking as to the actual loads on individual members. There are two immediate reasons, however, for re-examination of the methods used. In the first place, there are in progress a general tightening in the basic specifications and an adaptation of the principles to new assemblies designed to meet the changing pattern of naval warfare. In the second place, roller track indentations occurred in some turrets of recent design. This has led to a series of evaluations of the dynamic load factor.

Various rules may be observed in designing scale models of structures subject to dynamic loads and in loading them according to the basic design requirements. In Reference (13) are demonstrated the rules that must be observed in order that displacements at corresponding points in model and prototype be in the ratio of the scale factor, and likewise that stresses at corresponding points be the same at corresponding times. The time element is of the utmost importance in dynamic testing, and all events in the model test must occur at a different rate than in the full-scale case in order to comply with the requirements of similitude. The rules for similitude according to the foregoing conditions are summarized in Table 4.

TABLE 4

Relations of Similitude in Dynamic Testing

Measured Quantity	Prototype	Model	Measured Quantity	Prototype	Model
Length	L	λL	Natural frequency	N	$\lambda^{-1}N$
Area	A	$\lambda^2 A$	Deflection	d	λd
Volume	V	$\lambda^3 V$	Velocity	v	v
Mass	M	$\lambda^3 M$	Acceleration	a	$\lambda^{-1}a$
Weight density	ρ	ρ	Force	F	$\lambda^2 F$
Modulus of elasticity	E	E	Spring constant	k	λk
Stress	σ	σ	Damping constant	C	$\lambda^2 C$
Time	T	λT	Ratio of damping to critical damping	C/C_c	C/C_c

The proportioning of model load to the square of the scale factor gives stresses equal to those in full scale and deflections proportional to the scale factor λ.

The dynamic test of the 1/8-scale BB56 turret model, carried out as shown in Figure 12, confirmed the fact previously established by static model tests that the BB56 design provided an adequate factor of safety. Stresses in the turret foundation at standard load nowhere exceeded 7000 pounds per square inch. No roller-track indentations were observed at the standard load or at 30 per cent overload. Deflections of the foundation at the level of the lower track at standard load, measured in a horizontal plane, did not exceed a value corresponding to 1/2 inch on the prototype.

The BB56 dynamic model foundation was carried down to a point corresponding to the second platform in the ship. In the absence of definite knowledge as to the flexibility of the supporting ship structure below that point, the model was placed on timbers and was held down to the concrete floor of the test shop by foundation bolts. It later became apparent that the support for the model lacked the rigidity of the ship structure, since subsequent observation on BB56 showed that the prototype turret frequency, 330 cycles per minute, was much higher than the value of 140 indicated by the model test.

A dynamic load factor of 1.7 was deduced from the model test. However, this value was based in part on data obtained with the static model which had been tested on a very different supporting structure, so that this result is not conclusive. Facilities were not available at the time of the dynamic test for applying the required static loads to the dynamic model. It should be a general rule to provide for the application of static loads to dynamic models on the same supporting structure to be used in the dynamic test so as to obtain reliable experimental values of dynamic load factors.

On the basis of the recent observations described in the foregoing, the Taylor Model Basin has come to the following conclusions:

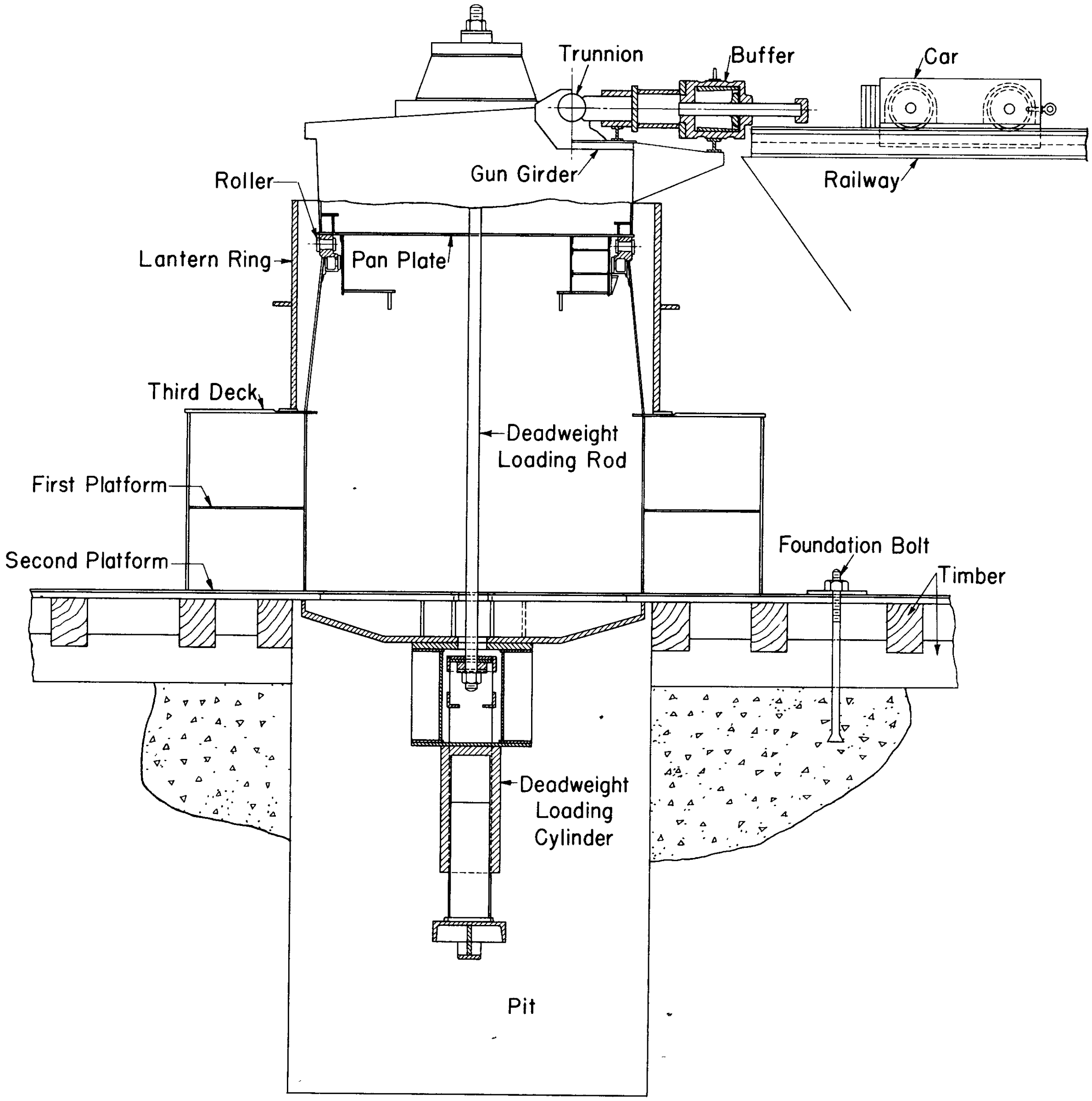


Figure 12 - General Arrangement for Dynamic Turret Model Test

The weight of the turret was simulated by heavy weights wedged into the structure between the gun girders.

The recoil was simulated by the car, which ran down a long, inclined track and struck the buffer at high velocity.

1. With tracks of the present scantlings, the "egg-shaped" bending deformation of the lower roller track in its own plane is relatively unimportant.

2. Torsional action in the lower roller path is relatively more important than bending and needs further study, if reduction of the track section is under consideration.

3. With present scantlings foundation stresses in general under recoil loads are well below values ordinarily allowed in design.

4. Experimental evidence based on deflections and stresses in the foundation places the dynamic factor nearer to 1.3 than to the value 2.0 frequently used in design. It is believed that an overestimate of the recoil load has caused an underestimate of the dynamic load factor.

In the light of the information obtained from the work previously described, and reported in detail in the references, the Taylor Model Basin makes the following general recommendations for the design of turrets having the present type of roller bearing. In many cases these represent current practice, but they are summarized here for the sake of completeness.

FOUNDATION. Although the early practice of reinforcing the foundation with vertical stiffeners was abandoned some time ago, foundation stresses are still quite low. However, as long as a minimum thickness of plating for the foundation is necessary for splinter protection, designing for higher allowable stresses is not feasible.

If a stress estimate is desired, the Bureau of Ordnance value of design trunnion load, including 25 per cent additional for peaking, should be multiplied by 1.3. The bending and shear stresses in the foundation should be evaluated as for a static load by the use of the ordinary formulas for beams.

The best method of estimating maximum deflection is to use the spring constant experimentally determined in firing trials of turrets of a similar class and to calculate the deflection under an assumed static load equal to 1.3 times the Bureau of Ordnance value of design trunnion load. Spring constants based on frequency observations are not yet acceptable for this use.

LOWER ROLLER TRACK. The present lower roller track design appears to provide ample strength, and although some weight could undoubtedly be saved here it would be small in comparison with the other weights involved. The chief deficiency of this part at present is in torsional rigidity, but no reports of damage due to torsion have been received. Indentation has been controlled by increasing the surface hardness of the track. The present hardness number of 200 Brinell is the minimum allowable. As commercial practice in roller bearing design goes as high as 600 Brinell, the possibilities of utilizing greater hardness should be considered.

ROLLERS. Provided all the available space is filled with rollers, the number of rollers to be used is not as important as might at first sight be expected, for although increasing the number decreases the load per roller, this is counteracted by a concentration of load due to the decreased diameter of the roller. One of the chief advantages of smaller rollers is in reducing the tilting moment, and so the torsional action on the ring. The number selected for the BB61 class, namely 72, seems to be near the optimum for the present basic design.

Strictly speaking, the clearance between the roller flanges and the roller tracks would have to be reduced to zero before the shock loads on the tracks would be zero, but the close tolerance now specified, 3/64 inch each, upper and lower, or 3/32 inch total, results in an approximation to zero close enough so that the resulting shock effect can be ignored.

The safe roller load may be checked by the empirical formulas given on page 12 of this report.

UPPER ROLLER TRACK. The present design is satisfactory except for the hardness of the surface, which should have the same value as for the lower track.

GUN GIRDERS. In designing these parts the design trunnion load should be used directly without the application of a dynamic factor differing from unity. The scant experimental evidence on hand indicates that stresses in the gun girders on BB56 are low, but as the walls of these girders must be elastically stable, weight-saving here should not be undertaken without investigation of that point. The welded box girder construction used on BB55 and 56 appears to be satisfactory.

HOLDING-DOWN CLIPS. The present design of holding-down clip provides adequate strength and rigidity. The clip clearance should be adjusted to the minimum value that will not interfere with ease of training; this value is about 3/32 inch. The smaller the clearance the smaller will be the shock load on the roller tracks.

In recent years considerable attention has been given to the possibility of a radical departure from present turret design practice, chiefly with a view to finding a method of nearly frictionless support superior to the present flanged rollers. Although the present type of tapered roller bearing is ideally suited for purely axial loads, its action under radial loading is less perfect, and alternative arrangements based on commercial practice have been suggested.

In machine design practice a tapered roller bearing for combined radial and thrust load would have the axes of the rollers parallel to the shaft axis. Since in the heavy gun turret the radial load is dynamic while the dead weight or thrust load is mainly static the need is primarily for a radial bearing with weight-carrying as a secondary consideration.

Bearings having characteristics superior to those now in use in turrets are undoubtedly possible but the development work on them may be long and tedious, and it must be supplemented by the satisfactory performance, on experimental vessels, of full-scale installations, before it can be expected that the designs will be adopted for combatant vessels.

The basic information necessary for design of the present conventional heavy gun turret is now available to designers and further model tests of the type described in References (9), (15), (17), and (18) appear to be unnecessary until new major features appear. Necessary experiments with rollers and track materials could be carried out on a much larger and a much simpler scale.

However, when radically new designs become necessary model tests are most valuable; it now is generally agreed that these should be dynamic tests rather than static tests. In the meantime the following conclusions may be drawn:

1. The value of trunnion load as now estimated by the Bureau of Ordnance, including a margin of 25 per cent for peaking, should be multiplied by 1.3 to allow for dynamic effect in estimating the loads on the stationary structure below the lower track level.

2. The dynamic factor recommended for the foundation is not applicable throughout the structure. For load or stress estimates in the gun girders the dynamic factor should be 1.0.

3. Owing to shock, the rollers and tracks may be subjected to overload; with the close clearances now used, however, this effect may be ignored.

4. Specification of materials and heat treatment may be depended on to eliminate track indentations; higher hardness values in the tracks would be of benefit.

5. The stresses in the BB56 turret structure are amply low under the load of the 3-gun salvo. However, reduction of scantlings is recommended only in the case of the gun girders in view of the smallness of possible saving in total weight.

6. Further model tests on complete heavy gun turrets of the conventional design, similar to that of the BB55, 57, and 61 classes are unnecessary, but experiments with some of the elements, such as the rollers, would be useful.

7. Dynamic model tests are recommended where any radical changes in design are contemplated, such as for example the high-angle 6-inch-gun cruiser turrets.

8. More complete surveys by vibration test are desirable on single vessels of each type.

9. Possible substitutes for the present flanged-roller method of turret support are worthy of study.

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MODEL TESTS OF TURRETS AND FOUNDATIONS AND THEIR INFLUENCE ON FULL-SCALE DESIGN

ABSTRACT

Static and dynamic turret model investigations undertaken in recent years by the David Taylor Model Basin in collaboration with the Design Section of the Philadelphia Navy Yard are reviewed. This program was undertaken principally as a check on the structural design of the turrets for the new post-war battleships, BB55 and 56.

The discussion is expanded to include a brief survey of present methods in turret design and theories of the dynamic actions in the turret structure under the recoil forces.

General recommendations are made for criteria to be used in the basic design of the principal structural elements of the turret in the light of recent model investigations and observations on structural firing trials of new vessels. A brief outline is given of various proposed substitutes for the present roller-bearing type of turret support.

A dynamic load factor of 1.3 is recommended for use in estimates of dynamic stress in the turret foundation but it is pointed out that a universal dynamic load factor for the whole structure does not exist. Serious consideration of substitute designs for the roller-bearing support is recommended.

INTRODUCTION

The design of turret structures and their foundations on men-of-war has reached its present stage of development by a process of gradual evolution in which common sense, good engineering judgment, and practical experience have played as large and as important a part as theoretical analysis.

John Ericsson had little more than experience with old wheeled broadside mounts and pivot guns to add to his own ingenuity and skill in devising the first turret, and it was 60 years later before anything approaching scientific data was available to the designers of turret structures in modern ships.

In the old pivot guns (1)(2)* the recoil load and the horizontal loads caused by movement of the ship were taken by a central pivot, or by a pivot at the front of the carriage, and the gravity load was carried by flangeless tapered rollers fastened to the gun carriage and running on a circular track; see Figure 1. The need for passing ammunition from spaces below the turret and for installing control gear below the guns eventually eliminated the pivot and the central support from the turrets in the vessels of the United States and other navies (3), and required the use of a turntable which could take the horizontal as well as the vertical loads.

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* Numbers in parentheses indicate references on page 43 of this report.

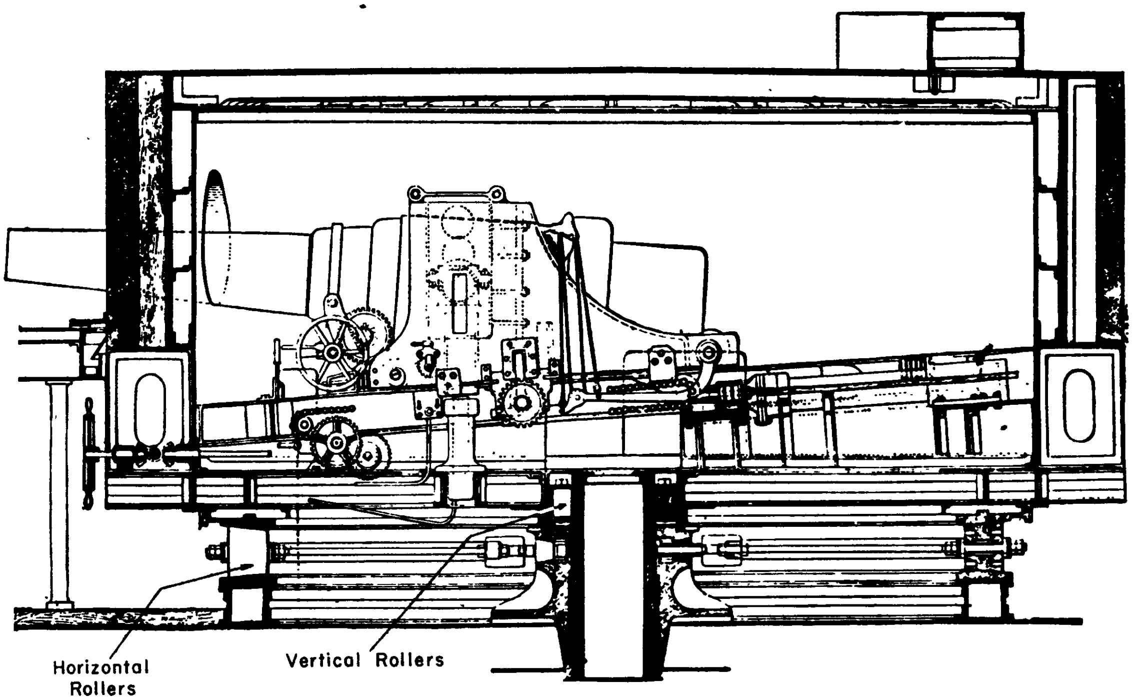


Figure 1 - Turret Carriage for 24-cm Gun, German Design, Pattern of 1874

This cut is taken from page 262 of Reference (2). Note that the recoil load is taken by a set of vertical rollers around the top of a massive kingpin held by a heavy casting at the deck. The section shows the metal in the horizontal rollers cut away, presumably for flexibility.

As the great advantage of a turret is its ability to carry both guns and armor and to permit rapid and precise train in azimuth to suit battle conditions, the means by which the heavy loads are carried to the turntable and the facility with which this unit functions lead to the conclusion that the structural design of the turret as a whole centers around the bearing by which this huge mass is supported.

For many years past, the circular roller bearing with flanged and tapered rollers has been the standard type for turrets of major-caliber guns in the United States Navy. The rollers carry the vertical or gravity load, and the flanges transmit the horizontal or recoil load from the turret to the foundation when the guns are fired.

It is rather surprising that this standard turret design has proved generally satisfactory in spite of the fact that, whereas the bearing is of a type designed primarily for vertical loads, the severest action to which the bearing is subjected is the horizontal load due to recoil. A roller bearing designed mainly for such a radial load would have the axes of its rollers parallel to the bearing axis or nearly so, and would permit very little lateral play;* with the horizontal rollers actually

* Gun mounts having a combination of both horizontal and vertical cylindrical rollers, of small diameter and without taper, have been successfully used on heavy cruisers of the U.S. Navy; see Reference (4) and Figure 16b on page 40.

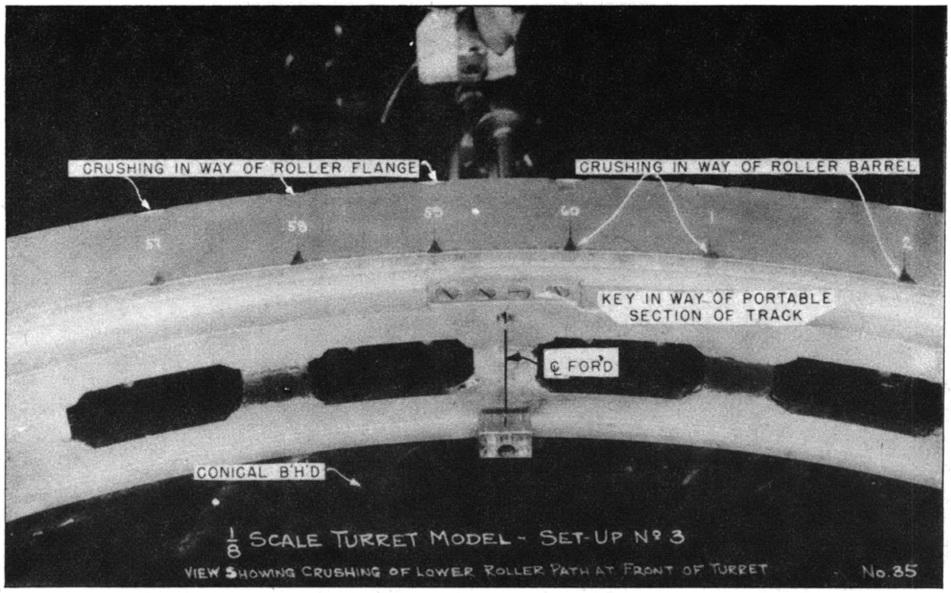


Figure 2 - Indentations on Lower Track of a Turret Model

The indentations illustrated in this photograph were actually produced by static loading and were probably not much affected by roller clearance. However, they give an indication of the action described.

This is taken from Figure 33 of EMB Report 458; Reference (9).

used, the lateral motion is limited only by the pressure of the roller flanges against the edges of the tracks after the flange clearance is taken up. The precision of modern methods of fire control requires that this clearance be small, but if it is too small, difficulty is encountered in training. If it is too large, a shock load occurs when the clearance is taken up. This would accentuate indentations at the edges of the roller tracks, as shown in Figure 2. Moreover, the presence of even a small amount of unrestrained motion complicates the movement of the turret during firing and makes an estimate of the dynamic loads on the foundation most difficult. While from a practical standpoint it may be unnecessary to have exact knowledge of all such detailed actions in the structure, as long as adequate strength is assured, in general a design that eliminates unpredictable loads is certainly superior to one that does not.

So far as known, the first systematic and comprehensive attack on the problem of experimentally determining the forces, motions, and deformations of major-caliber turret structures on U.S. Naval vessels was undertaken by the National Bureau of Standards on the USS CALIFORNIA in the year 1919, at the request of the Bureau of Construction and Repair. The results of these tests, which in general confirmed the design criteria and procedure which had been in use up to that time, will be found in Reference (5).

The David Taylor Model Basin has been concerned with the basic features of turret foundations for many years, and more recently with the whole assembly including the turret; the references on pages 43, 44, and 45 of this report describe numerous theoretical and experimental studies of this problem. As a result of this work the design of the turret foundation has been considerably modified, and ideas have crystallized as to the essential points to consider in the design of such elements as the roller tracks, holding-down clips, and gun girders. With the renewal in the 1930's of heavy turret construction on battleships, a new demand for research in this field arose, so that the Taylor Model Basin in collaboration with the Design Section of the Philadelphia Navy Yard proceeded to extend its testing techniques to include dynamic as well as static loads. Thus turret models are now subjected to transient loads closely simulating those acting on the full-scale turret.

Experiments have also been made with a view to finding a substitute for the present roller-bearing design. Model tests with a rollerless bearing with force-feed lubrication (6) have indicated that such a bearing has distinct possibilities for turret service.

In this report the basic design problem is outlined in the light of the studies made at the Taylor Model Basin, and design criteria for use in designs employing the flanged tapered roller are recommended. Further model and full-scale research in this field is suggested in Reference (6) and later in this report.

PART 1. GENERAL CONSTRUCTION OF TURRETS

This discussion is limited to turrets proper as distinguished from gun mounts, although the two types of gun installation have much in common. The chief distinction is that the turret rotates on a foundation which has no connection to the upper decks, above the waterline, which are subject to damage; the foundation is completely enclosed inside a stationary circular belt of armor called the barbette. The gun mount, on the other hand, rotates on a circular track secured to the weather deck, and all protective armor above the roller track rotates with it. Although turrets of the type shown in Figure 3 are now in use on naval vessels to carry 6-inch and 8-inch guns, and although foundations for 5-inch mounts are now being built in cylindrical form, the emphasis in this report is on the heaviest type of turret, such as that installed on recent battleships, because of the more severe problems encountered.

The general method of mounting guns in turrets is illustrated in Figure 3, and the details of the immediate support of the gun in Figures 4 and 5. These vitally affect the dynamic loads upon which the design of the foundation is based, and a thorough knowledge of the action, especially of the recoil system, is necessary to an understanding of the problem as a whole.

This report is concerned only with the behavior of the structure of the turret and of its foundation in service and does not deal with operating mechanisms such as the gun-firing devices, the elevating and training machinery, the shell hoists and powder cars, or the rammers. The part of the rotating structure which is assembled in the turret shop and installed in the ship as a unit will be spoken of as the turret weldment; this includes the gun girders, the upper roller track, the pan plate,

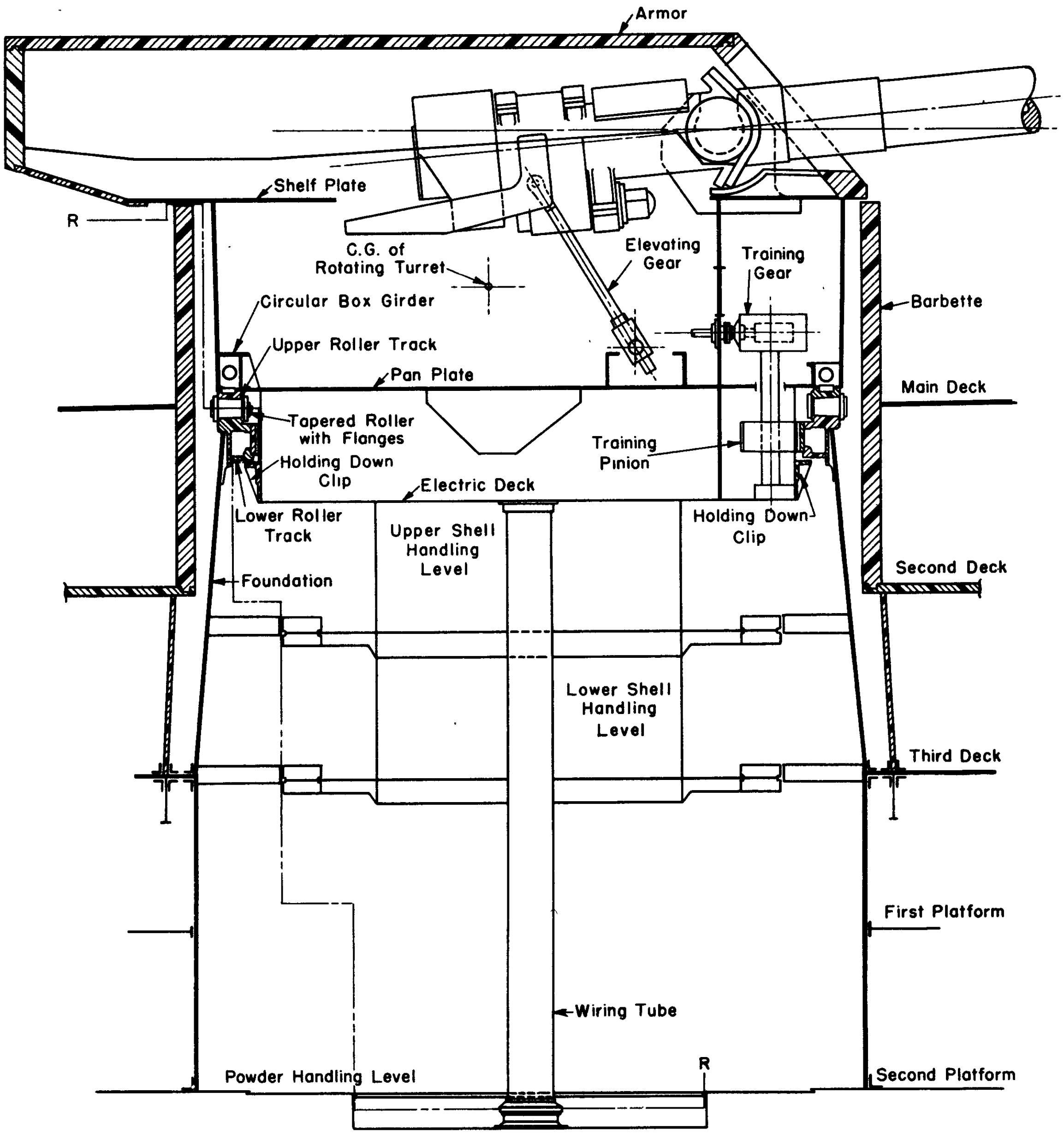


Figure 3 - Vertical Section through a Typical Modern Major-Caliber Turret Installation

This is a triple 16-inch, 45-caliber high gun turret of BB56. Here the lower roller track is supported on an unstiffened tubular foundation extending down to the lower platforms in the ship. This foundation, above the third deck, is entirely clear of the barbette or heavy stationary armor. The rotating turret structure in which the guns are installed and which is heavily armored above the barbette is supported on a tapered roller bearing. Both the fixed and the rotating structures are protected by the barbette, which is a cylindrical shell of armor extending from the armored deck up to the armored part of the turret.

The training pinion is built into the turret and engages a ring gear attached to the lower roller track. The rollers have wide flanges so that in addition to carrying the vertical or deadweight load they resist the tendency of the turret to move horizontally under the recoil load. To prevent lifting of the turret from its bearing when recoil occurs, the rotating structure carries holding-down clips which project under the lower roller track. A close clearance is maintained between the clip and the lower track.

All parts inside of the line R-R rotate; all other parts remain stationary.

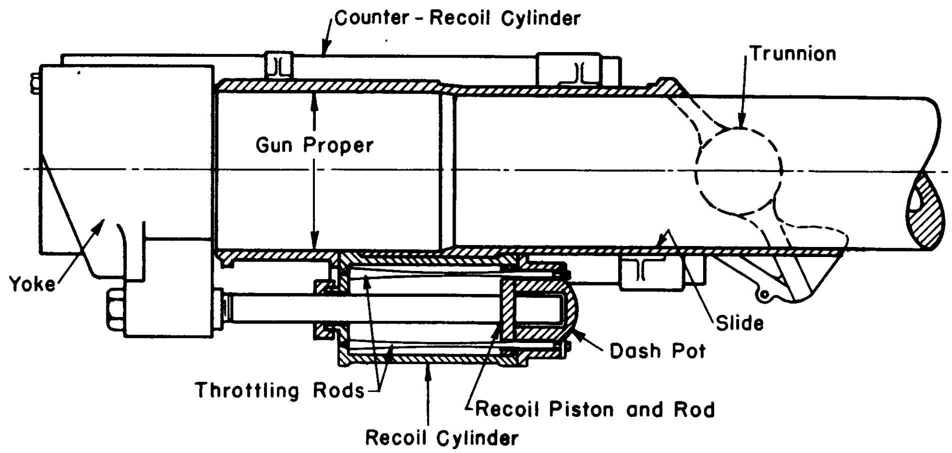


Figure 4 - Mounting and Recoil System of a Major-Caliber Gun

Here the gun is in its outer or "battery" position, ready to fire.

The gun proper is a hollow tube of varying outside diameter, largest at the rear or breech end. The gun is carried by a heavy casting called a slide, bored out to a neat fit to permit the gun to move inside it, parallel to its axis, but with the smallest practicable lost motion.

On each side of the slide is a projecting trunnion which supports the weight and transmits the recoil forces. The trunnions rotate in bearings in trunnion blocks or deck lugs, which are attached firmly and rigidly to massive gun girders built into the rotating turret structure.

Thus the slide, although its inner end is depressed or elevated to elevate or depress the gun, remains in a fixed position relative to the turret in a horizontal plane.

The gun moves axially to the rear when it is fired, as shown in Figure 5, but its motion is checked and stopped by the recoil system. This consists of a yoke at the breech end of the gun to which are fastened piston rods moving in the recoil and counter-recoil cylinders. The cylinders themselves are attached to the gun slide; throttling rods in the recoil cylinder check the motion of the gun, and springs or compressed air in the counter-recoil cylinders return the gun to its firing position. All loads from the gun are transmitted by the recoil system through the gun slide and trunnion bearings to the gun girders and thence to the turret structure.

and all rotating structure above and below that plate. The turret weldment which is stress-relieved as a unit does not include the hanging structure below the pan, which is attached by a bolted joint.

BASIC DESIGN CRITERIA

The turret structure must be designed to withstand both static and dynamic loads; the former are due to the dead weight of the entire rotating structure and the latter are due to gun recoil and to vibration and rolling and pitching of the ship. The ballistic impact loads due to shell and bomb hits on the turret are considered in the design of the armor and its support but not in the design of the roller bearing or of the foundation. These loads are still unpredictable, but it is known that the momentum imparted to the turret by the impact of a single major-caliber projectile is less than that of the full salvo of all the guns in the turret.

The forces acting on a typical heavy gun turret are illustrated in Figure 6.

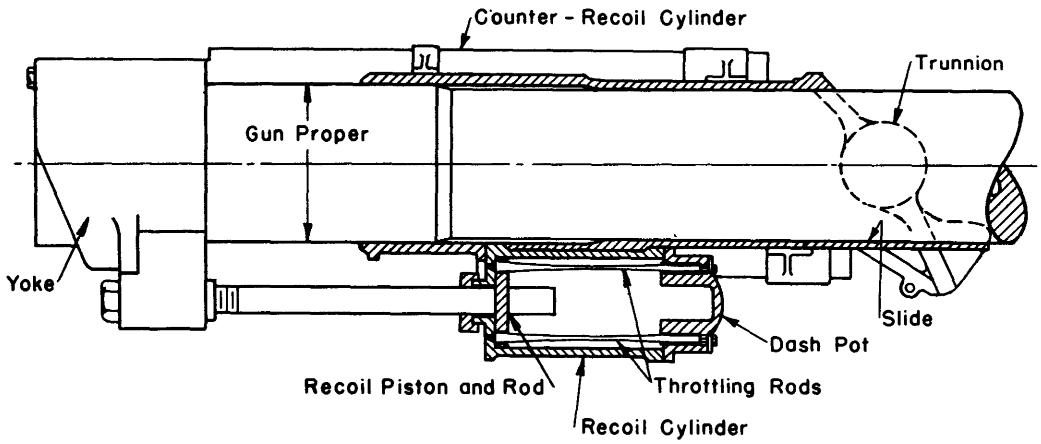


Figure 5 - Mounting and Recoil System of a Major-Caliber Gun

Here the gun is in the recoil position, immediately after it has been fired.

Note that the piston in the recoil cylinder is now at the extreme end of its stroke, and that all the liquid in the rear end of the cylinder has passed through the throttling holes to the other end.

The springs or compressed air in the counter-recoil cylinder will now return the gun to its normal or firing position, and the dash pot in the right-hand end of the recoil cylinder will cushion the shock at the end of the counter-recoil stroke.

The slide remains fixed in position through this sequence of events.

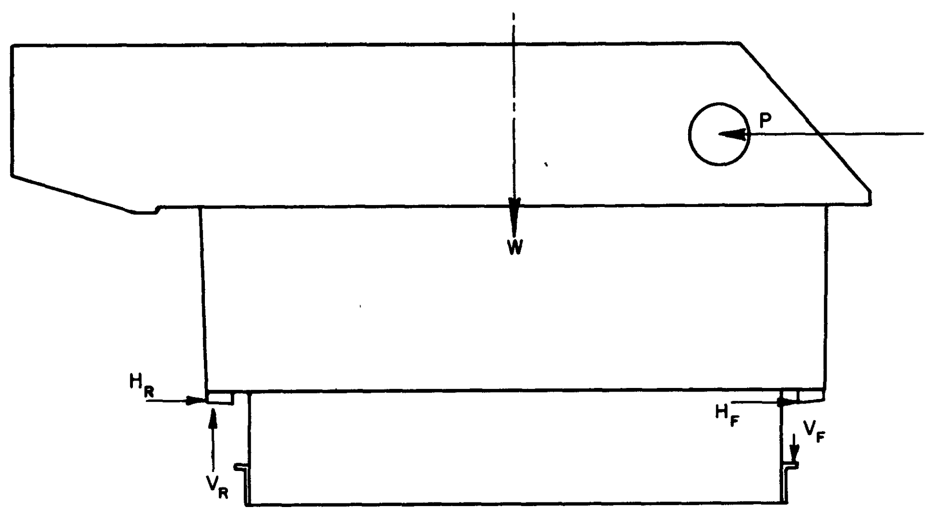


Figure 6 - Diagram Illustrating the Forces Acting on the Turret

W is the dead weight

H_F is the horizontal reaction on the front of the upper roller track

H_R is the horizontal reaction on the rear of the upper roller track

P is the trunnion load

V_F is the force on the holding-down clip

V_R is the vertical reaction on the upper roller track

Static or Deadweight Loads

The dead weight of a large modern turret is of the order of one-twentieth of the total displacement of the vessel and this ratio will probably continue to increase. Weight estimates of the guns, the turret armor, the weldment, and the machinery are available at a very early stage in the design of the ship. The design of a foundation of the simple form shown in Figure 3 to carry the deadweight load listed in Table 1 offers no particular difficulties, especially as the turret foundation considered as a column has an extremely low slenderness ratio.

TABLE 1

Load and Roller Data for Typical Turrets

Vessel	Guns per Turret	Rotating Weight tons	Bureau of Ships Design Trunnion Load for Full Salvo tons*	Time of Recoil seconds	Length of Recoil Stroke inches	Number of Rollers	Maximum Diameter of Rollers inches	Length of Rollers inches
CL43	3 6-inch	160	190	0.143	21	84	4	5.5
CA37	3 8-inch	270	300	0.25	32	72	5 1/2	7
BB44	3 14-inch	980	1050	0.26	44	42	12	15
BB56	3 16-inch	1680	1890	0.25	48	60	13	17.5

The recoil loads listed in this table are the design values furnished by the Bureau of Ordnance. They are obtained by adding 25 per cent to the estimated brake recoil force.

* All tons in this report are long tons of 2240 pounds.

Dynamic Loads

The foundation, the roller bearing, and the weldment in general are designed mainly to withstand the recoil load caused by an all-gun salvo.

All forces exerted by the gun on the turret act at the trunnion bearings; the total of such loads, excluding dead weight, is called the trunnion load. The principal component of the trunnion load is the brake recoil load; this is the force developed in the recoil system, acting at the angle of elevation of the gun. The trunnion load is the resultant of all the forces exerted on the turret by the gun except the dead weight; it includes not only the brake load but also the force in the counter-recoil cylinder, and the friction in the gun slide and the packing glands.

The main recoil cylinder is designed to produce a constant reaction during the entire recoil stroke. The Bureau of Ordnance design specifies the length of stroke, the duration of stroke, and a constant retarding force acting during this time.

This constant retarding force is considered to represent an estimate of the trunnion load, and the curve of trunnion load as a function of time is assumed to be a rectangle. However, because of the many uncertain factors affecting the recoil system it is customary to add 25 per cent to the estimated trunnion load to obtain the design trunnion load, and it is this design value which is used by the Bureau of Ships. At the same time it is assumed that the time of recoil and the length of stroke remain at the designed values. The values so obtained for the BB56 turret design, for a three-gun salvo at zero elevation, were: design trunnion load, 4,200,000 pounds; time of recoil, 0.25 second; length of recoil stroke, 48 inches, as shown in Table 1.

After recoil the gun is returned to the initial or battery position by the hydro-pneumatic counter-recoil system, as shown in Figure 5. The time of counter-recoil is several times that of recoil, and the trunnion loads involved are much smaller. Moreover, as counter-recoil does not begin until after the foundation has reached its peak deflection, counter-recoil loads are omitted from the basic turret design calculations. However, at the end of the counter-recoil stroke the gun is brought to rest in the battery position by a dash pot; its short stroke results in a considerable reaction opposite in direction to the recoil. The load produced, however, is only about half that of direct recoil, so that this item also is neglected.

When the gun is elevated the friction in the slide is less than at zero elevation and the weight of the gun has an axial component which does not otherwise exist. However, in the preliminary design calculations by the Bureau of Ordnance, the trunnion load is assumed to change with gun elevation only with respect to its direction. The recoil brake loads are then checked at the Proving Ground by engine indicators. The Bureau of Ships is not concerned with the design of recoil mechanisms otherwise than to have assurance that the trunnion loads used in the design calculations are reasonably correct and that all estimates, corrections, and margins are applied to all designs in a uniform manner.

Although dynamic loads due to vibration and movements of the ship are small in comparison with the trunnion loads, they cannot be entirely overlooked. A heaving acceleration of the ship equal to the acceleration of gravity would put a vertical load on the rollers equal to twice the weight of the rotating structure. Fortunately, heaving or pitching accelerations in excess of 1/2 *g* are rare. A 30-degree roll of the ship at a 15-second period would put a transverse load on the trunnions of the high turret BB56 of about 0.6 of the weight of the guns. As each gun plus slide, yoke, and attachments weighs 150 tons, this load is sufficient to be taken into account in the design of the lateral support of the trunnion blocks. The similar load of the turret on the rollers is considered not to exceed that caused by recoil when the turret is trained directly abeam.

Vibration accelerations in excess of 1/4 *g* are rare in operating experience and hence in a structure designed to withstand high recoil loads there is little danger from vibratory stresses. While vibratory stresses in the structure are usually well below the endurance limit there is evidence that relatively low vibratory loads when long continued are capable of producing track indentations. Aside from stress considerations vibratory loads may cause serious difficulties in the use of the turret range finders and large amplitudes may be developed in the cantilever structure suspended below the pan plate. However, the cure of such troubles is better handled separately from the problem of general turret design.

Thus the principal loads on which the turret design is based are the vertical load due to the dead weight of the rotating structure and the horizontal recoil load of an all-gun salvo.

DETAILED DESIGN OF BASIC ELEMENTS

In BB55 and BB56, used here as an example, the superposed Turret 2 has a higher conical foundation than the other two. The rotating structures of all three turrets are identical except for the vertical distance from the powder-handling level to the lower shell-handling level. Since the moment of the recoil load with respect to the base of the foundation is greatest in the high turret, this turret is taken as the example in making the basic design calculations.

The method used in the preliminary design of the BB56 turret foundations, briefly summarized here, may be found in detail elsewhere (7). The foundation, including both conical and cylindrical portions, is a shell of uniform thickness. As it was desired to have the foundation act as a splinter bulkhead for all the vulnerable apparatus inside it, 60-pound STS plating was selected on the basis of experience as the plating of minimum thickness necessary for this purpose. Stress computations were then made for a foundation of this thickness considered as a tubular cantilever, under a combined deadweight column load and a transverse bending load due to recoil; see Figure 7. The turret was assumed to move as a unit with the top of the foundation,

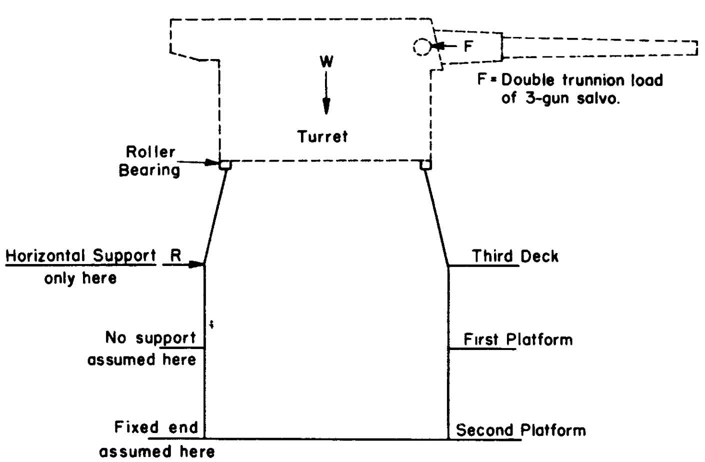


Figure 7 - Forces Assumed in Estimating Bending Moment in Foundation, Turret 2, BB56

The turret was assumed a rigid structure, attached to the top of the elastic conical and cylindrical foundation through the roller bearings, without clearance, and so as to prevent egg-shaped deformation in the lower roller path.

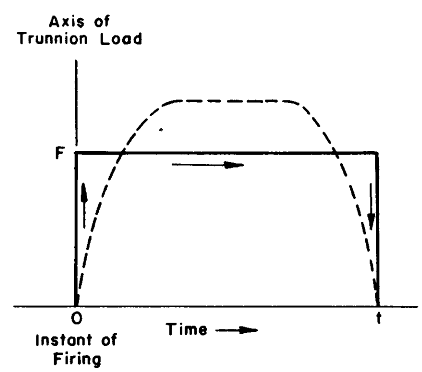


Figure 8 - Diagram Representing Trunnion Load as a Rectangular Pulse

The assumed load, as shown by the full line, rises instantaneously to the magnitude F and continues for the time t. During this interval the guns are recoiling their full distance. Actually the load-time curve is more nearly like the broken line.

while the latter acted as a spring of negligible mass, the whole constituting an elastic system having one degree of freedom. If the trunnion load consisted of a rectangular pulse of duration exceeding half the natural period of transverse vibration of the system, the resulting deflection under the assumed conditions would be twice that which the trunnion load would produce as a static load, as explained in Reference (8). The dynamic load factor under these conditions would be 2.0. The load to which this factor has been applied in practice is the estimated brake load plus an allowance of 25 per cent, as explained on page 9.

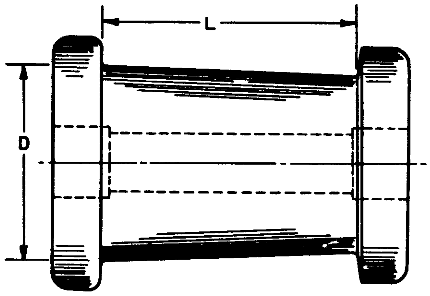
The foundation was treated as a combined column and beam, in which the column load was equal to the dead weight of the rotating structure and the beam load was twice the trunnion load for a 3-gun salvo. The conditions of support assumed for the beam were, as illustrated in Figure 7, fixed end at the second platform, no support at the first platform, simple transverse support at the third deck, and overhanging end above the third deck. Bending stresses were then calculated by simple beam formulas and added to the column stresses. The maximum shearing stress was derived by calculating an average value based on the total area of section and then doubling this to allow for an estimated unequal distribution, as in the case of a cylindrical tube. Since the combined stresses were found to be within ordinary design limits, allowing an adequate factor of safety, the assumed 60-pound plating for the foundation was considered satisfactory. The strength of the important riveted connection at the third deck, as shown in Figure 3, was checked by the same basic theory.

The design of the lower roller track on BB55 and 56 was based on three main criteria: (a) sufficient hardness of the track surfaces to prevent indentations due to concentrated loads from the rollers, (b) sufficient constraint against bending in the ring to avoid excessive egg-shaped deformation in a horizontal plane under the recoil load, and (c) sufficient torsional rigidity to prevent excessive tilting of the track surfaces under load.

(a) A hardness number of 200 Brinell was considered satisfactory on the basis of static model tests made at the Philadelphia Navy Yard (9).

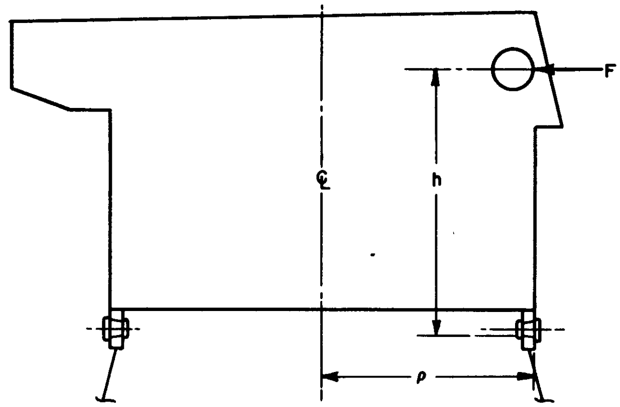
(b) In early calculations for stiffness, the static bending load was assumed to be twice the design value of the 3-gun trunnion load, and the lower track was considered as an unrestrained ring with 3/5 of the double trunnion load acting on the rear half and 2/5 on the front half; see Reference (10). The net reaction exerted on the ring by the foundation was represented by two equal forces, one at each end of the transverse axis through the center of the ring; these forces were equal to the total shear load on the foundation.

However, as the upper track was heavily reinforced in a horizontal plane by the pan plate, and as the presence of the rollers with their flanges severely limited the amount of relative motion between the two tracks, it appeared safe to assume that the upper track would prevent undue deformation of the lower track.



Index Number $= \frac{W}{N\,L\,D}$

where W is the dead weight in tons
N is the number of rollers
L is the length of the rollers in inches
D is the diameter of the rollers in inches



Index Number $= \frac{W + 2F\frac{h}{\rho}}{N\,L\,D}$

where F is the trunnion load in tons, and other factors are as shown

Figure 9 - Diagrams Illustrating Empirical Index Numbers for Roller Design

(c) Torsional strength of the lower track, made in the form of a substantial box girder, was considered ample on the basis of previous model tests such as those made at Newport News (11).

The rollers were proportioned chiefly on the basis of experience with designs in service and of model tests. As an explicit guide, two empirical index numbers were used, one based on deadweight load only and the other based on deadweight plus recoil load, as shown in Figure 9. The first index number based on dead weight is W/NLD, where W is the dead weight in tons, N is the number of rollers, L is the length of rollers in inches, and D is the roller diameter in inches. In practice this index number is kept below 0.130. The index number based on recoil load is $\left(W + 2F\frac{h}{\rho}\right) \div NLD$, where N, L, D, and W are as before, F is the trunnion load in tons, and h/ρ is the ratio of the distance between the lower track and the trunnion center to the track radius. This index number is kept below 0.390. With these considerations as a guide, a bearing having 60 rollers was selected in which each roller had a length of 17 1/2 inches and a diameter of 13 inches. The roller flange thickness was checked for shear strength; in this calculation the distribution of load among the rollers was based on the assumption that each roller carried a share proportional to the cosine of the bearing angle measured from the turret axis.

Detailed stress analysis was omitted in the preliminary design of the upper roller track for BB55 and BB56, owing to the substantial reinforcement provided by the heavy pan plate and by the circular box girder above the pan plate; the primary function of this girder was to increase the torsional strength of the upper track. The track profile was made to conform to that of the lower track, but a solid section was used.

The rotating turret weldment is a structure of considerable complexity, made up of a relatively deep dish-shaped structure into which there are worked three pairs of longitudinal vertical members to carry the trunnion blocks of the guns, as shown in Figure 10. It was questionable whether the fact that this structure was welded, whereas previous structures had been riveted, rendered the strength analysis more complicated, but there could be no doubt that the resulting structure was better fitted for the duty it was to perform. The weldment was designed as a statically loaded structure supported at the rollers and subject to the deadweight load combined with a horizontal load equal to twice the 3-gun trunnion load. The distribution of loads in such a structure is largely indeterminate, and therefore bold assumptions had to be made as to the load taken by the individual members. Those used conformed with the prior assumption as to the loads on the rollers, as given in the preceding paragraph. The use of a 40-pound pan plate was found to provide adequate strength under these conditions.

The gun-girder design represented a departure from previous U.S. battleship practice in that, owing to the increased center-to-center distance of the guns, two

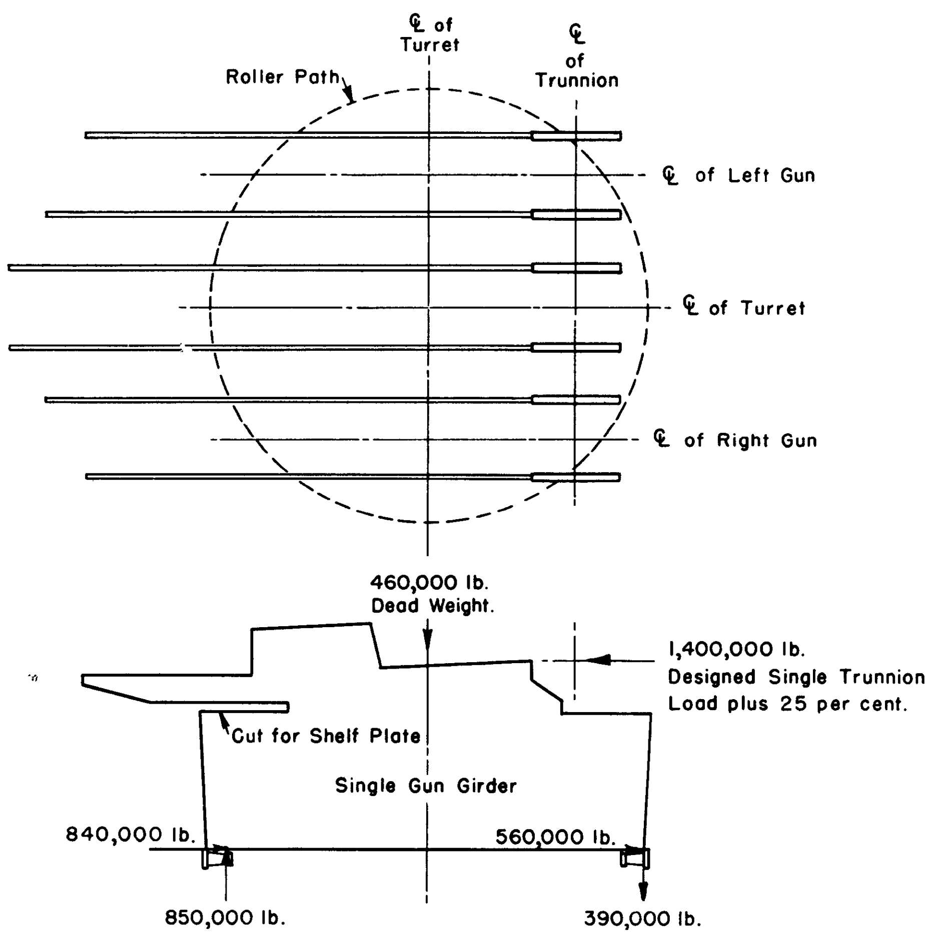


Figure 10 - Forces Assumed to Act on a Gun Girder of a BB56 Turret during Action of Horizontal Recoil Forces

plate girders were provided between guns instead of the single plate formerly used. This put the trunnion load from every gun directly in line with a girder. In the preliminary calculations the doubled design trunnion load of each gun was assumed to act as a static load divided equally between the two trunnions. For an elevation of 45 degrees the equivalent static load* was assumed to be the same as for zero elevation, except that the direction of the load was changed. It was further assumed in the preliminary calculations that the gun girders carry the dead weight of the turret less the weight of the turret armor as a load uniformly distributed over their length.

The reactions on the gun girders from the roller tracks were calculated from considerations of static equilibrium. Figure 10 shows the distributed and concentrated loads assumed to act on the gun girders for zero elevation. Bending and shearing stresses were calculated by the beam theory and the elastic stability of the walls was investigated. The plating selected for the gun girders was 65-pound special treatment steel.

The loads on the front holding-down clips were estimated by assuming the doubled design trunnion load of three guns to act as a static force and by finding the forces required to prevent lift of the weldment.

PART 2. CHANGES IN DESIGN PRACTICE

NECESSITY FOR CHANGES

Turret installations in U.S. Naval vessels are in general giving satisfactory service. Aside from the general aim of refinement in design and reduction in weight, there might seem to be little purpose in carrying out further investigations in this field, even admitting that much information is lacking as to the actual loads on individual members. There are two immediate reasons, however, for re-examination of the methods used. In the first place, there are in progress a general tightening in the basic specifications and an adaptation of the principles to new assemblies designed to meet the changing pattern of naval warfare. In the second place, roller track indentations occurred in some turrets of recent design. This has led to a series of evaluations of the dynamic load factor.

CHANGES OF TYPE

Although there is little likelihood that guns of caliber larger than the present 16 inches will be used, a demand for heavier armor protection on top of the turrets is a distinct possibility. Naturally any appreciable increase in weight of the rotating structure would require a re-examination of the whole design. The rollers and roller tracks are already heavily loaded, and they would be the first items to be investigated. Moreover, with increased probability of direct bomb hits on the turret there is need for consideration of this type of load.

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* Here equal to the design trunnion load multiplied by 2.0.

New conditions of operation have created demands for entirely new types of turrets, and the exigencies of war allow little time for research and development. This emphasizes the need for improved theories of turret action. With adequate theories, changes could be made with confidence that the structural members could carry the loads, even in advance of practical experience with the design. Without adequate theories, model tests must be made, or the performance of the new construction in service must be awaited, with the loss of valuable time.

A case in point is the new 6-inch, 47-caliber turret designed for high-angle firing, illustrated in Figure 17 on page 41. The construction of the gun girders in this turret is a radical departure from previous practice. In this case a model test was considered necessary, chiefly to check stresses in the gun girders, the holding-down clips, and the foundation. As a result of the early tests on this model, the gun girders were reduced in size, to give more room inside the turret.

TRACK AND ROLLER INDENTATIONS AND ABRASION

Roller track indentations have been a matter of concern for many years. The systematic non-uniform spacing of rollers is an early expedient to prevent all the rollers from dropping simultaneously into depressions formed by long-continued vibration of the ship when underway, while the turret is resting in the zero or secure position. It has also been observed that vibratory loads produce pitting of the bearing races in commercial machinery even when the machine itself is not in operation. Here the vibration is induced in or transmitted to the foundation through some nearby machine or, in the case of the ship, through the hull structure.

High load concentrations on the tracks or races are inevitable in a roller-bearing design, since except for elastic deformations only line contact is made. In the case of turret tracks the load concentration is greatly aggravated by the forces acting on the rollers to make them tilt under the recoil load; this further concentrates the load nominally near points at the edges of the tracks, as illustrated in Figure 2. These high load concentrations are further intensified by the fact that

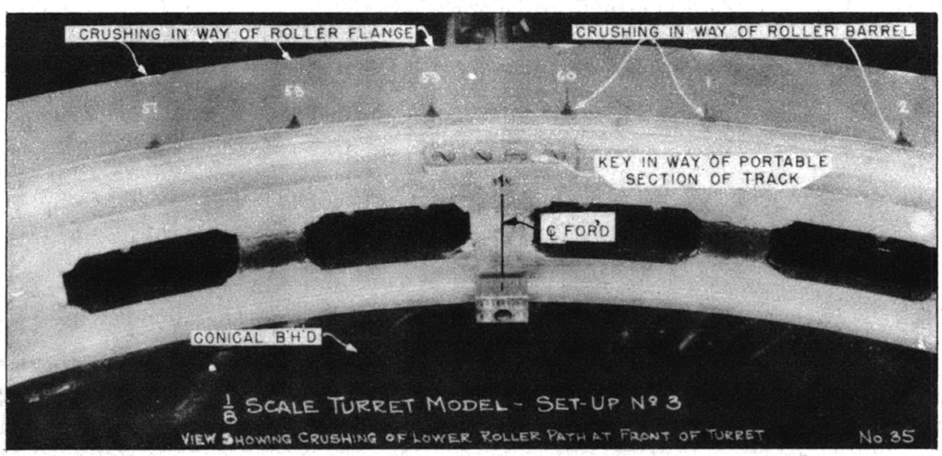

Figure 2 - Indentations on Lower Track of a Turret Model

after the flange clearance is taken up, the tracks are brought to bear against the roller flanges abruptly, which causes a shock load.

At the time when the roller-track design for BB56 was being considered there was renewed concern over indentations because the loads these tracks were expected to withstand were much greater than those involved in any U.S. battleship turrets previously built. Both static and dynamic model tests were made to clarify this point, and as a result a track hardness number of 200 Brinell was specified.

The track should always be harder than the rollers, as a flattened roller is readily replaceable while the track is not. However, a hardness number of 200 Brinell is much lower than the standard in commercial roller-bearing practice, where the hardness numbers in the races sometimes reach 600. Consequently it is not surprising that, according to recent reports, slight indentations have actually appeared in service on the tracks of BB56. Somewhere, however, there is a limit to higher Brinell numbers in the turret track, in view of shock service and fabrication difficulties.

The possibility of obstruction in train due to track indentations is perhaps the principal defect in the present standard design, although some difficulty has also been encountered owing to roller flanges scraping the sides of the tracks. In general the stresses elsewhere in the track structure now in current use are apparently still within safe limits.

REDUCTION OF SCANTLINGS

The stresses in many structural members of the turret and foundation structure are known to be low, and the question may be raised why scantlings should not be reduced to save weight. There are reasons why, in general, this may not be desirable. In the first place, in proportion to the great weight of the guns and armor, the weight of the strength members is already small. In the foundations, a certain plating thickness provides insurance against penetration by splinters in case of shell hits. In general, any reduction in scantlings of the strength members, even though it might not cause excessive stresses, would increase deflections. It is possible, however, that the foundation structure would be improved by an increase of flexibility. This is discussed more fully in a subsequent section, pages 25 and 26. Nevertheless, the normal course of development is toward reduction of weight.

Since the thickness of the foundation plating is first selected on the basis of splinter protection and then checked for strength, the foundation seems not to offer much opportunity for saving weight. The lower track casting, however, is a massive member; in BB56 it has a sectional area of about 270 square inches, a diameter of about 32 feet, and a total weight of about 90,000 pounds. The bending strength of this ring is less important than was formerly supposed, and some weight might be saved here. If this is considered, model tests should precede such an attempt, as will be pointed out later.

TABLE 2

Preliminary Design Weights of Principal Parts of One 3-Gun Turret, BB56

Item	Armor	Guns	Slides and other Ordnance Items	Ordnance and Operating Machinery	Weldment including Gun Girders and Upper Track	Projectiles stored on the Rotating Structure	Powder in Hoist	Total
Thousands of pounds	986	762	603	208	733	462	4	3758
Per cent of total	26.2	20.5	16.0	5.5	19.4	12.3	0.1	100

The chief structural members in the rotating structure in which weight might be saved are the gun girders, which are of massive construction. In a BB56 turret they total some 180,000 pounds. However, the elastic stability of the plating needs consideration in any proposal for reducing this weight.

Perhaps the most pressing need is for a redistribution of material in the structure. Whatever is done, any distinct improvement in structural design and construction must be preceded by more definite knowledge of the loads which the different parts are required to carry.

For information, Table 2 is included to give a breakdown of the principal components of the rotating weight.

VIBRATION

In the past, vibration has not been given much consideration in turret design. If hull vibration could be eliminated, the problem would not be serious, as most of the machinery in the turret itself is well balanced. In view, however, of the severe demands on the propulsion systems of modern warships it is not safe, in designing the turret, to ignore vibrations that may be induced through the hull. Difficulty due to vibration has been encountered in using turret range finders. In general, especially if the hull vibration is amplified by local resonance in the turret, the problem must certainly be considered in the turret design.

As the turret proper above the pan plate is a very rigid structure, most of its natural modes are beyond the range of hull frequencies encountered. On battleships the lowest natural mode of turret vibration is the cantilever vibration in which the whole turret moves horizontally by flexure of the foundation. Fortunately, the frequency of this mode appears to be lower than the range of disturbing hull frequencies. On the other hand, there is the possibility of resonant vibration of this type on cruisers. Considerable transverse vibration at the powder-handling level was observed at certain speeds in Turret 2 during the early trials of BB56. This was probably due to resonance of that part of the rotating structure suspended below the pan plate. The possibility of avoiding this type of resonance by transverse stiffening should be considered in any new design. The possibility of using neutralizing devices to reduce resonant vibration of the turret when its natural frequency falls within the range of hull vibration might also be considered (12). Natural frequencies of vertical vibratory motion are probably beyond the disturbing range, but this should be checked experimentally.

PART 3. RECENT MODEL INVESTIGATIONS

The chief reason for the use of scale models in turret design is that an accurate theory of the behavior of turret structures under dynamic loads does not exist. This being the case, it is considered not safe to make drastic changes in design practice without experimental confirmation of the wisdom of these changes. The cost of full-scale experimentation in this field is completely prohibitive. When preliminary designs were being considered for the turrets of BB56 there was some anxiety as to the behavior of the roller tracks. This was the immediate reason for initiating the model testing program in 1937, but the program was later extended to include models containing almost all of the structural elements of the system. In consequence, our knowledge of turret behavior has been greatly extended.

STATIC MODEL TESTS

Similitude

The principles of similitude applicable to model structures are expressed in symbolic terms in Reference (13). The basic fact is that if the model is made throughout to the same scale, static stresses in the model will be the same as static stresses in the prototype at corresponding points of the structures if the loads applied at corresponding points are in the ratio of the square of the scale factor. When model and prototype are of the same material this rule applies only when the dead weight of the structure is small in comparison with externally applied loads; otherwise, since the dead weight of the model will be to the dead weight of the prototype as their respective volumes, and hence as the cube of the scale factor, dead-weight loads will be too small in the model. With this exception, the conditions for similitude with static models are relatively simple. From the conditions of loading required to produce the same stresses at corresponding points of model and prototype of the same material it follows that deflections at corresponding points will stand in the simple ratio of the scale factor.

However, it must be remembered that these rules have hitherto presupposed that Hooke's law is satisfied at all times. Once plastic deformation begins, as when indentations appear on the roller tracks, similitude between model and prototype enters a new and different phase. This is particularly important because some of the turret model testing had as its main purpose the investigation of roller track indentations. For example, if the surface of the prototype is polished to obtain smooth operation, indentations almost unmeasurable are very plainly visible; however, a degree of polish on the model high enough to reduce the surface irregularities in the ratio of the scale factor would require special methods to attain, and the question whether it is necessary would need special attention. In general, the physical conditioning of the material used in model tests has not even yet been brought under full control, although work on this phase of the matter is very active (14).

Design

Various scale factors were used in the static turret model designs according to the type of the turret in order to use a single loading rig; the track diameters were made the same in all cases. The scale factor for the BB56 models (9)(15) was 1/8. As the chief items of interest were the rollers and roller tracks, the static model foundations were extended only to the first supporting deck below the lower track; this was represented by the relatively heavy test stand. The weldment was omitted below the electric deck as unessential, as was all of the structure above the gun girders, and the turret armor. The lower roller track was duplicated in detail except that the training gear was omitted. Holding-down clips were included, and were adjusted for the proper scale clearance.

Procedure

The static models were loaded at the trunnions by a hydraulic jack mounted on the test stand in such a way that loads could be applied to the trunnions in various directions corresponding to the angle of elevation of the guns. The vertical load needed to simulate the dead weight of the full-scale rotating structure was produced by a threaded tie rod and nut. This load was adjusted by use of extensometers attached directly to the tie rod. The loading system is described in detail in Reference (9) and is illustrated in Figure 11.

Observations were made not only of the deformations of the rollers and indentations of the roller tracks but of stresses and deflections in the foundation. The standard load was the doubled design trunnion load, including 25 per cent margin, for a 3-gun salvo at zero elevation, reduced by the model scale factor. The load was increased until failure finally occurred.

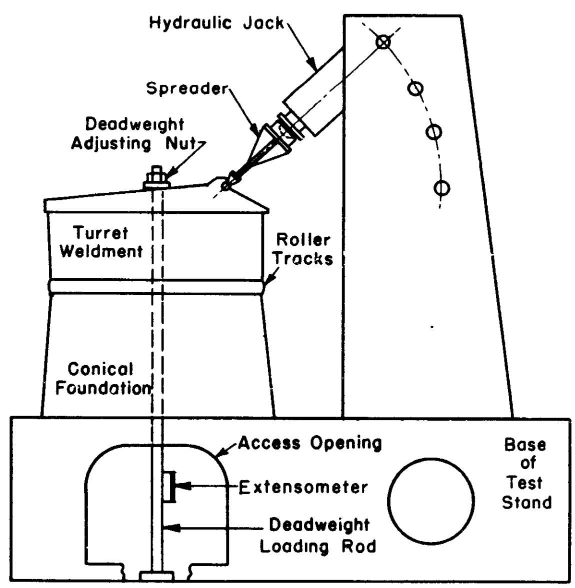

Figure 11 - Method of Loading Turret Models for Static Tests

Results

Of most interest among the static turret model tests were the results on the model of the BB56 turret described in EMB Reports 458 (9) and 466 (15). These indicated that the BB56 and BB57 track designs would be satisfactory, except that greater hardness of the track material was desirable. The tests also showed that the number of rollers could be increased to advantage; see Reference (15), page 10. As a result of these model tests a hardness number of 200 Brinell was specified for the BB56 tracks, and on the BB61 class the number of rollers was changed from 60 to 72.

The standard load gave a horizontal deflection of the lower track of 0.52 inch at the rear and 0.14 inch at the front, stepped up from model to full-scale values. The value which had been calculated by ring-flexure theory for the deflection at the rear of the lower track was twice as great as that observed in the model. This indicated that reinforcement of the lower track by support from the roller flanges, limiting the egg-shaped distortion, was great enough so that ring flexure should no longer be taken as the controlling feature of lower track design.

Failure was gradual, so that the failure load was not closely defined. It varied considerably with the type of holding-down clip, but was in all cases more than 25 per cent in excess of the doubled design trunnion load. The failures involved crushing of the roller tracks, with large angles of tilt in the rollers.

The observed stresses at the base of the conical foundation corresponding to the standard load were 21,000 pounds per square inch compression at the rear point, and 9400 pounds per square inch tension at the front point. The point of zero stress at the base of the conical foundation was not at the transverse diameter nor were the stresses proportional to the distance from the point of zero stress, as would be expected from application of the simple beam theory. The shear stress at the base of the foundation reached a maximum at two points about 45 degrees from the centerline instead of 90 degrees from it, as might be expected from ordinary theory. The shear stress corresponding to the standard load was 7000 pounds per square inch. Regardless of the unexplained distribution of the observed stresses none of them was considered excessive.

A comparison of peak deflections obtained from the static model tests with subsequent full-scale data obtained on firing trials is given in Table 3.

Conclusions from Static Tests

In addition to the guidance obtained from the static tests for decisions on details of the BB designs, certain ideas of general application emerged. The emphasis previously placed on horizontal bending of the lower roller track in its own plane is now seen to have been too great. The circumstances found in earlier work [(10), p.4, (16), p.2] to reduce bending deflections are so effective that they have removed bending of the ring in a horizontal plane from the primary considerations altogether. When advantage is taken of this to reduce the section of the ring, another limiting effect appears, namely, torsional rotation of the meridional sections of the ring.

TABLE 3

Peak Turret Foundation Deflections under
Recoil Load from a 3-Gun Salvo

Ship	Turret	Deflection Predicted from Static Model Test (based on dynamic factor 2.0) inches	Value Observed on Firing Trials of Vessel inches
BB55	Turret 2	0.52	0.255
BB56	Turret 2	0.52	0.27
BB44	Turret 3	0.25	0.23
CL43	Turret 1	0.11	0.09
The deflections were measured at the lower track level, at Station A-3, as in Figure 15 on page 34.			

This had been foreseen by Bengston (11) but the test which he devised referred to the BOISE design, in which the ring sections had not been reduced. In view of the large openings in the pan plate the reinforcing effect of the rotating structure against bending in the lower ring was not as great as in the BB's. In consequence, Bengston's test failed to show the expected torsion, as it was too small in proportion to the bending.

When this same question recurred on BB55 and 56, torsion became the limiting consideration, as pointed out by Conrad (9), pp. 2 and 3. The progress of design, however, has not yet led to a satisfactory criterion for torsional rigidity in the ring. This should form the subject of specialized tests and analysis.

In addition, the benefit of model tests was definitely extended to other members of the turret assembly, and in particular confirmation was obtained of the fact that a tubular cantilever needs no axial stiffeners. At the same time the simple beam theory of the tubular cantilever was shown to have serious deficiencies where precise calculations are involved; fortunately, great margins of strength in the turret foundation cantilever make high precision in calculations unnecessary.

A second major result of the static tests, however, was the attention which they directed to the question of impact effects. Dynamic load factors evaluated by Farrin (15) from comparisons of actual deflections of foundations measured on firing trials with static deflections of the models were found to be of the order of 1.3 instead of the traditional value of 2.0.

DYNAMIC MODEL TESTS

Although valuable information was obtained from the many tests made on turret models under static loading it became apparent that no static load could sufficiently represent the shock of service action on the foundation. Hence it was felt that if the model could be loaded in a manner similar to that in which the load is applied to the prototype, much greater reliance could be placed on the model results, particularly with regard to the serviceability of the roller tracks.

Dynamic Similitude

Various rules may be observed in designing scale models of structures subject to dynamic loads and in loading them according to the basic design requirements. In Reference (13) are demonstrated the rules that must be observed in order that displacements at corresponding points in model and prototype be in the ratio of the scale factor, and likewise that stresses at corresponding points be the same at corresponding times. The time element is of the utmost importance in dynamic testing, and all events in the model test must occur at a different rate than in the full-scale case in order to comply with the requirements of similitude. The rules for similitude according to the foregoing conditions are summarized in Table 4.

TABLE 4

Relations of Similitude in Dynamic Testing

Measured Quantity	Prototype	Model	Measured Quantity	Prototype	Model
Length	L	λL	Natural frequency	N	$\lambda^{-1}N$
Area	A	$\lambda^2 A$	Deflection	d	λd
Volume	V	$\lambda^3 V$	Velocity	v	v
Mass	M	$\lambda^3 M$	Acceleration	a	$\lambda^{-1}a$
Weight density	ρ	ρ	Force	F	$\lambda^2 F$
Modulus of elasticity	E	E	Spring constant	k	λk
Stress	σ	σ	Damping constant	C	$\lambda^2 C$
Time	T	λT	Ratio of damping to critical damping	C/C_c	C/C_c

The proportioning of model load to the square of the scale factor gives stresses equal to those in full scale and deflections proportional to the scale factor λ.

The rules given here involve certain assumptions; in particular, that gravity loads are negligible in comparison with dynamic loads, that the material is elastic, that stresses never exceed the elastic limit, and that forces can be applied to the model at the required rate, which is faster than the rate on the prototype. If the model has the same density as the prototype, the gravity loads will vary as λ^3, and not as λ^2 as called for in Table 4. If deadweight stresses are appreciable it is therefore necessary to preload the model to obtain this initial stress without, however, increasing its inertia. These rules cannot be met where viscous frictional forces are involved, since the foregoing condition for velocities would not give the same Reynolds number in both cases.

Design

The design of the dynamic test and of the models used followed the same general lines as in static work; all non-essential structural parts and all machinery were omitted from all the models. The chief differences lay in the load, which now was transient instead of static and at zero elevation only. In the dynamic models ship structure was added below the conical foundation and the inertia of the missing structural parts was simulated.

The weights were so located as to place the center of gravity of the model in the same relative position as in the full-scale turret. Strictly this is not sufficient for similitude, as model and prototype should also have the same mass moment of inertia, but the small error thus caused is ignored for the present. The load required to bring the initial deadweight stresses in the model up to the full-scale values was applied by a hydraulic jack below the foundation. It was transmitted through a long vertical tie rod which passed up through the center of the turret, as shown in Figure 12, so as to avoid restraint on the horizontal movement of the structure. The nominal scale factor λ was 1/8.

Procedure

Dynamic model tests call for the development of a very different technique (17)(18) from that used in the static tests, both in the manner of applying the loads and in the measurement of stresses and deflections. The transient force representing the recoil load on the trunnions of the prototype was applied to the model by a heavy car coming down an inclined track at high speed and striking a hydraulic buffer attached to the trunnions. To the cylinder wall of this buffer were attached two tapered splines which fitted into rectangular notches in the piston. The motion of the piston forced the braking fluid to escape from one side of the piston to the other through the notch area not occupied by the spline. The section given to the spline in such a buffer determines the braking force developed for a given piston velocity. The theory of such a buffer, which is similar to the recoil brake installed on the guns, and further details of the design, are given in References (18)(19).

In this case car mass, car speed, and buffer-spline taper were all calculated to reproduce to model scale the load-time relation given by the Bureau of Ordnance as the full-scale turret trunnion load for a 3-gun salvo at zero elevation, in which the duration of the load was reduced according to the time relation given in Table 4. The standard load for the model was 1/64 the full-scale brake recoil load for a 3-gun salvo, applied for a duration 1/8 of the time of recoil. No margin, such as the 25 per cent added for uncertainty of peak load value in the static tests, or increase for dynamic load factor was introduced; the reason for this shift from the standard used in the static tests, namely, the doubled design trunnion load, lies in the fact that the object of the dynamic test is the evaluation of a dynamic load factor, and the only fair basis for application of such a factor lies in the best known value of

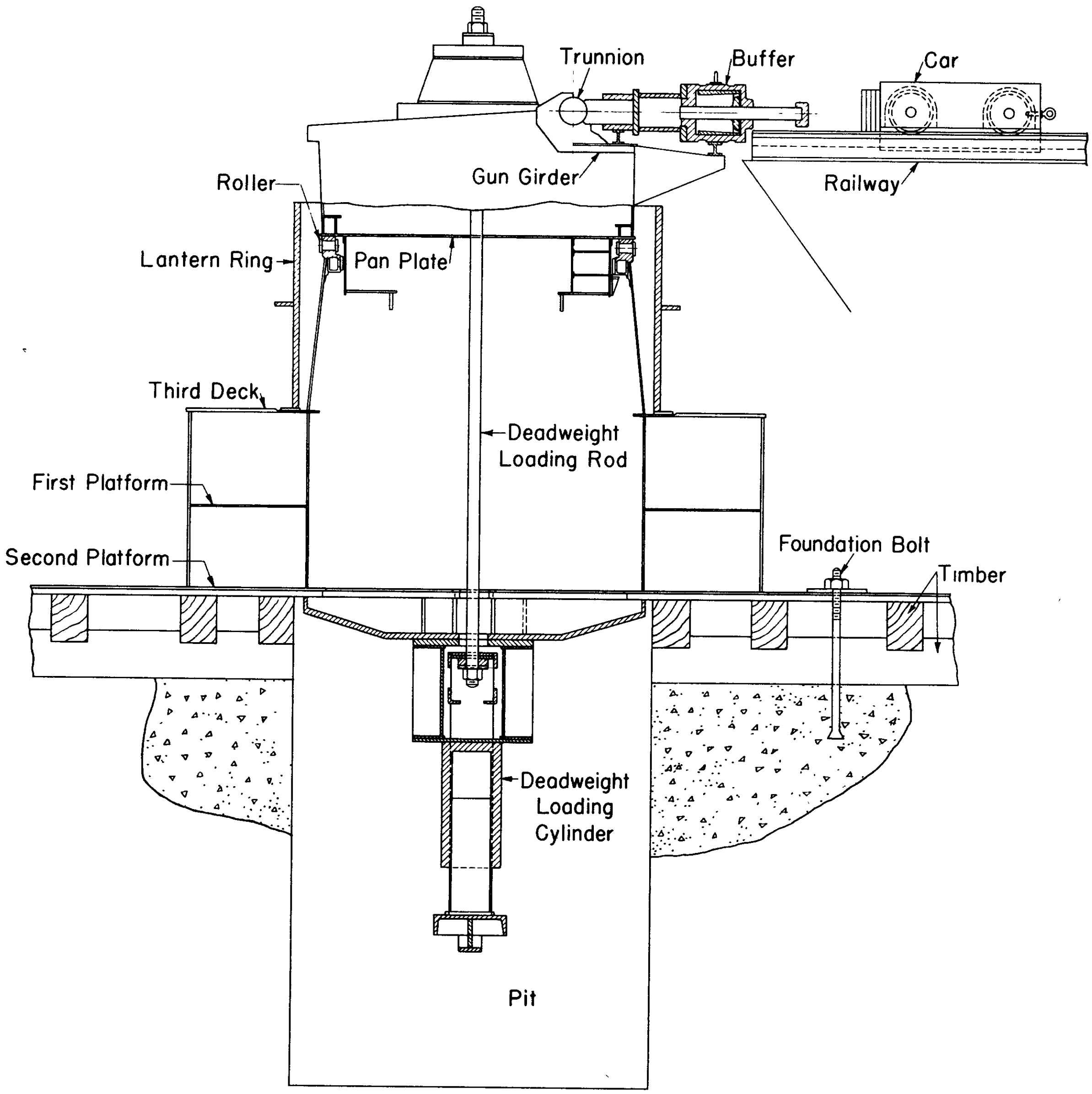

Figure 12 - General Arrangement for Dynamic Turret Model Test

The weight of the turret was simulated by heavy weights wedged into the structure between the gun girders.

The recoil was simulated by the car, which ran down a long, inclined track and struck the buffer at high velocity.

the actual load, without reservations, implicit or explicit. Application to the model of the standard load as thus defined should cause stresses equal to those caused by the service load on the full-scale turret.

With a loading system of this type it is difficult to vary the load and still keep the duration of the load and the time taken to reach peak load the same.

To attain this would require the installation of a different set of splines in the buffer cylinder for each load. Hence the complete conditions of dynamic similitude as far as loading was concerned were exactly met only for the standard trunnion load.

After each dynamic load was applied the turret model tracks and rollers were examined for indentations. Stresses at the base of the conical foundation at the front and rear points were measured as functions of time. Horizontal displacements at the trunnion level and at the track level were measured.

In addition to the impact tests of the dynamic model a vibration test was run. This was done with two aims in view: first, to determine the resonant frequency and damping characteristics of the assembly; second, to compare the effect on the roller tracks of the recoil loads and of a million cycles of repeated load of about one-tenth the magnitude of the recoil load.

Results

The dynamic test of the 1/8-scale BB56 turret model confirmed the fact previously established by static model tests that the BB56 design provided an adequate factor of safety. Stresses in the turret foundation at standard load nowhere exceeded 7000 pounds per square inch. No roller-track indentations were observed at the standard load or at 30 per cent overload. Deflections of the foundation at the level of the lower track at standard load, measured in a horizontal plane, did not exceed a value corresponding to 1/2 inch on the prototype.

The vibration test indicated a horizontal natural frequency of the model structure of 1250 cycles per minute. Corrected for the scale factor and for the mass of the guns, omitted from the model, the corresponding full-scale frequency would be 140 cycles per minute. The effective spring constant of the turret model foundation as determined from the vibration test was 3.1×10^5 pounds per inch. The corresponding full-scale value is 2.5×10^6 pounds per inch. The resonance curve indicated the damping of the turret structure to be 6 per cent of the critical damping value. The same ratio should apply to the prototype.

Continuous vibration for more than a million cycles, with a force amplitude applied at the trunnion level after allowance for resonance amplification, equal to one-tenth of the standard load, produced no indentations on the roller tracks of the BB56 model. However, preliminary tests made in the development of the dynamic testing technique showed that on a model with soft roller tracks such a vibration load produced greater track indentations than the single application of the full recoil load (17).

Discussion of Results with BB56 Dynamic Model

The BB56 dynamic model foundation was carried down to a point corresponding to the second platform in the ship. In the absence of definite knowledge as to the flexibility of the supporting ship structure below that point, the model was placed on timbers and was held down to the concrete floor of the test shop by foundation bolts. It later became apparent that the support for the model lacked the rigidity of the ship structure, since subsequent observation on BB56 showed that the prototype turret frequency, 330 cycles per minute, was much higher than the value of 140 indicated by the model test.

In static testing any flexibility in the support would simply mean greater absolute deflection, but as long as the load was maintained, stresses and relative deflections would not be affected. Under dynamic conditions it is clear that all inertia reactions are altered by the amount of motion. Thus if the foundation were on wheels, the whole structure would recoil, but there would be very little stress in the foundation. Hence the frequency, as a criterion for a good dynamic model, should always be examined.

A dynamic load factor of 1.7 was deduced from the model test. However, this value was based in part on data obtained with the static model which had been tested on a very different supporting structure, so that this result is not conclusive. Facilities were not available at the time of the dynamic test for applying the required static loads to the dynamic model. It should be a general rule to provide for the application of static loads to dynamic models on the same supporting structure to be used in the dynamic test so as to obtain reliable experimental values of dynamic load factors.

If stress in the foundation is used instead of deflection as a basis for calculation of the dynamic load factor, a comparison of the results on the BB56 dynamic model with those on the static model gives a dynamic load factor of 1.4. If the foundation is considered as a simple beam fixed at the second platform and simply supported at the third deck, as in the preliminary design calculations (7), the deflection so calculated, compared with the value measured under dynamic load on the model, gives a dynamic load factor of 1.1. It should be remembered, however, that any lack of rigidity in the supporting structure will result in model stresses which are too low; therefore 1.1 should be considered only as a lower limit and not as the probable value derived from comparison of foundation stresses.

In view of the softness of the substructure, the absence of track indentations in the dynamic model test is not altogether conclusive since lack of rigidity in the structure reduces the loads on the model roller tracks. The importance of rigidity of support as a determinant of dynamic response has been greatly emphasized by these tests and it will be discussed further at a later point of this report.

Value of Dynamic Tests

Dynamic testing of structural models is relatively new although in other fields dynamic model testing has been well established for a long time. The towing tests of ship models are all dynamic tests; so also are the tests on aircraft models in wind tunnels, and all vibration model tests. An especially novel feature of the present tests lies in the transient nature of the loads. An investigation of the conditions necessary for similitude should therefore be made a part of any new turret model testing program. Perhaps all the necessary conditions for similitude cannot be met simultaneously. The chief points to consider are the time rate of application of the load, the duration of the load, and the relation of rate and duration to the natural period of the structure.

Stress and deflection values can be observed on dynamic models in cases for which mathematical analysis would be hopelessly complicated and for which static tests would be entirely misleading. The difficulty of analysis increases rapidly as the number of degrees of freedom of a system increases, whereas the dynamic testing technique remains the same. This technique merely requires application of the load at the correct rate for the correct duration and at the correct point in the system, and measurement of the stress and deflection at the points corresponding to the desired locations in the full-scale structure.

The present considerations are restricted to the case in which the stresses are held within the elastic limit, but even with this restriction indications may be obtained as to the loads at which plastic deformation may begin. Ordinarily design stresses are well below this range.

PART 4. DYNAMICAL CONSIDERATIONS IN THE DESIGN AND CONSTRUCTION OF TURRETS

GENERAL ANALYSIS AND THE TREATMENT OF DYNAMIC FACTORS

Various theoretical treatments of the dynamics of the turret-foundation system under gun recoil load are mentioned in the list of references at the end of this report. The value of any theoretical analysis is limited by the validity of the assumptions that must be made before any mathematical treatment is at all possible. No attempt is made in this report to review these theoretical treatments or to present in detail an alternative mathematical analysis. On the contrary it is proposed to reduce the turret and its foundation to the simplest possible equivalent mechanical system consistent with the experimentally known facts.

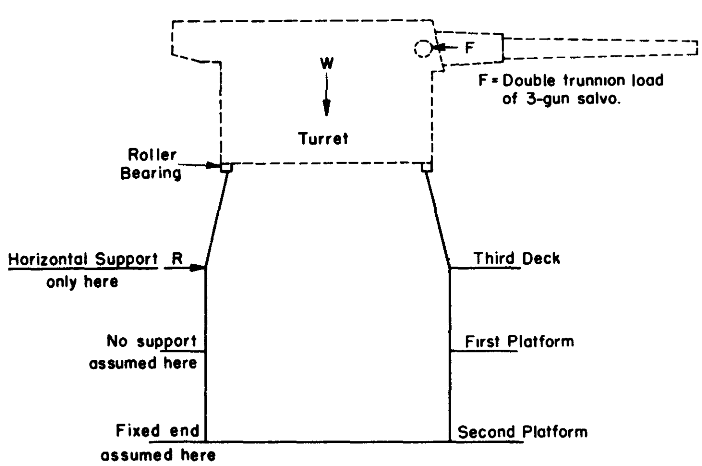

Figure 7 - Forces Assumed in Estimating Bending Moment in Foundation, Turret 2, BB56

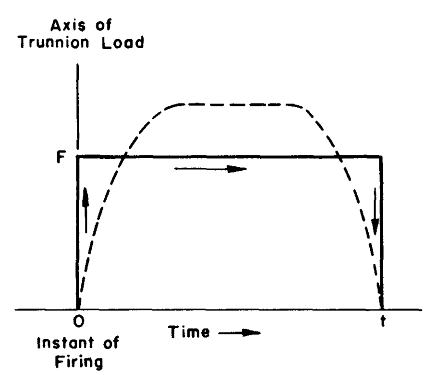

Figure 8 - Diagram Representing Trunnion Load as a Rectangular Pulse

The intention in design of the recoil system is to produce a transient force-time function at the trunnions which may be represented by a rectangular diagram. The trunnion load should then rise instantaneously to the design value, remain constant for an interval equal to the time of recoil, and then drop instantaneously to zero. If a force of this kind acts on a linear system of one degree of freedom such as may be represented by a single mass connected by a single spring to an infinite mass, and if the force lasts longer than one-half the natural period of the system, the maximum displacement of the mass, and the compression of the spring, have twice the static values that would exist under a steady force of the same magnitude as the transient force. As pointed out in Reference (8), this phenomenon may be described by saying that the system has under these circumstances a dynamic load factor of 2.0.

As a result of the foregoing principle it has been common practice in turret design simply to double the design trunnion load and thereafter to treat the turret and foundation as a system subject to known external static loads.

The point of view adopted in the present report is that the system does in fact closely approximate a simple system of one degree of freedom provided the equivalent or generalized system is properly defined; however, observed values of the dynamic load factor fall below the value 2.0. The practical dynamic factor is defined as the ratio of the observed stress at any point in the structure during recoil to the stress that would exist if the design trunnion load without margin were applied as a static load. Its value depends among other things on the manner in which the design trunnion load is found, but as long as the same practice is consistently followed the practical factors may be used.

The experimental basis for this point of view is the fact that if a vibration exciter is attached to the turret at the trunnion level, capable of producing simple harmonic forces in the horizontal direction over a wide range of frequencies, the turret-foundation system exhibits the familiar phenomenon of resonance as it occurs in a simple elastic system having one degree of freedom. While it is true that the turret may also vibrate vertically and at right angles to the direction of recoil it has only one degree of freedom in the direction of the trunnion load; see Figure 13. Therefore, following common practice in vibration analysis, the effective spring constant of the system is defined as the ratio of the static force that must be applied horizontally at the trunnion level to produce a certain deflection at that level, to the horizontal deflection produced. The effective mass m of the system is defined as a mass such that if concentrated at the trunnion level the natural frequency of the system would be the same

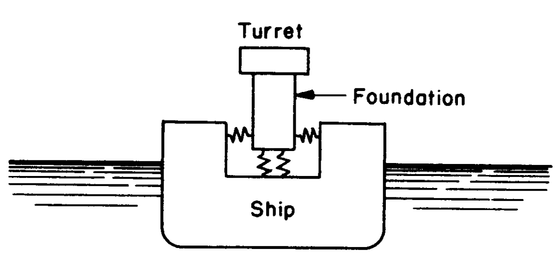

Figure 13 - Diagram of a Two-Body System with Connecting Spring

as that actually observed. In consequence of the simplified scheme, an estimate of the dynamic load factor can be obtained in terms of deflection instead of stress.

The effective values of the generalized linear system may also be defined in terms of energy as follows: The effective spring constant k is such that if the deflection at the trunnion level is Δ the elastic energy stored in the system is $\frac{1}{2} k\Delta^2$. The effective mass is such that if the velocity at the trunnion level is v the kinetic energy of the system is $\frac{1}{2} mv^2$. The effective mass and spring constants are further related by the equation giving the natural frequency of the system, $n = \frac{1}{2\pi} \sqrt{k/m}$. It makes no difference where the bending actually occurs; it is suggested that a part of the flexibility in the BB56 turret design is in the structure surrounding the foundation rather than in the action of the foundation cantilever. Since a certain degree of rotation about a horizontal transverse axis occurs, the effective mass m depends in part on the mass moment of inertia, so that the distribution of mass enters the calculations as well as the location of its center of gravity. The effective values of k and m are valid only for a given point in the system, in this case the trunnion level or the point of application of the recoil load; for a different point the values would be different.

Since the turret-foundation system is thus equivalent to a linear system of one degree of freedom and since the time of recoil is longer than one-half the natural period of the system, determined experimentally, the deflection at the trunnion level would be expected to be twice the deflection under a static trunnion load of the same value. The fact that it has a lower value is taken to show that the recoil load is not truly represented by a rectangular force-time diagram (8).

No correction should be made for the freedom of the rotating structure first, to slide on the rollers until the flange clearances are taken up and second, to tilt until the holding-down clip clearance is taken up. Neither of these actions occurred during the vibration tests by which the frequencies were found. They might produce local shock loads on rollers and tracks which would increase the ratio of dynamic to static stress at these points, but they do not greatly affect the dynamics of the structure as a whole.

In the generalized equivalent system the dynamic factor applicable to the spring is 2.0, as shown in Reference (8). This means that the stress in the spring would be twice what it would be in the static case. Directly at the point of application of the load, however, it is clear that the stress must be the same in either the static or the dynamic case, because at this point the stress is simply the force divided by the area to which it is applied, regardless of the motion. The dynamic factor here is 1.0. In general, in view of the fact that the load is sustained more than half a cycle of the lowest frequency involved, the dynamic factor must lie between 1.0 and 2.0, depending on the rate of load application in relation to the natural frequency of the part.

It is thus clear, however, that different values of the dynamic load factor will apply to different actions in the assembly. Thus at the rollers the rate of load application will depend on the motion of the turret and the intricate conditions of clearance and resilience. However, it is a safe assumption that the value 2.0 prevails from this point on, to all points below the lower track level.

The value 2.0 applies, however, only if the trunnion load rises with complete abruptness; any more gradual rise is to be treated as in Reference (8); and especially the factor is to be applied to the peak and not to an average load value.

EXPLANATION OF LOW OBSERVED DYNAMIC LOAD FACTOR

While the theory just mentioned indicates that the dynamic load factors should be nearly 2.0, the values determined experimentally are much lower. If the stress measured with dynamic strain gages at the base of the conical foundation during a 3-gun salvo on BB56 is compared with the computed stress due to a static bending moment equal to the trunnion load times the distance from the trunnion level to the base of the conical foundation, the ratio is only about 1.1 (20). Values as low as this were also found on cruisers by comparison of the deflections measured during structural firing tests with the deflections obtained under subsequent static loading tests (21)(22).

The discrepancy is believed to be due to some or all of the following causes:

First, delay in rise of the trunnion load-time curve. Indicator diagrams taken at the Naval Proving Ground show that the brake cylinder pressure-time diagram is decidedly rounded instead of absolutely rectangular as assumed. Non-simultaneous firing of the guns would further delay the rise in the trunnion load-time curve.

Second, overestimate of the actual trunnion load in calculating the dynamic factor. This estimate includes an addition of 25 per cent to the design value, intended to allow for peaking of the initial pressure rise.

Third, reduction of the strain in the foundation due to the motion of the ship when the guns are fired. This motion includes elastic deflection of the ship structure, as well as roll, yaw, and side slip of the ship as a whole.

It is impossible accurately to calculate the combined result of these various actions on the deflection of the turret. The third is the most obscure of these effects. It is clear however, that a yielding support under the foundation, as illustrated in Figure 13, will cushion the blow put on it by the turret just as the recoil system cushions the blow put on the turret by the gun; the reaction is hence reduced in intensity. However,

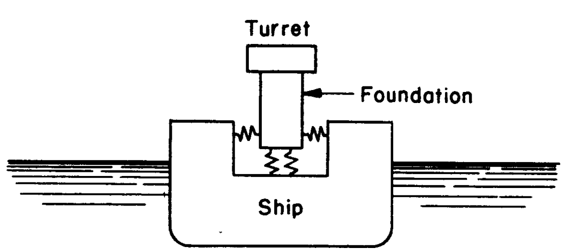

Figure 13 - Diagram of a Two-Body System with Connecting Spring

these considerations will apply only if the duration of the load is short in comparison with the period of the cushioning system. A load indefinitely sustained will still give a dynamic load factor not much less than 2.0 if abruptly applied, regardless of the natural period of the system.

ELASTIC DEFLECTION OF THE FOUNDATION

In this report the elastic deflection of the turret foundation is considered chiefly from the point of view of its effect on the dynamic load factor. The treatment does not extend to a stress analysis of the conical shell itself or to its buckling strength. Such an analysis can be attempted only for the part of the shell above the highest supporting deck because of the uncertainty of the support from this point down. This subject has been treated in detail by Westergaard (23). Experimental data have shown existing turret foundations to be amply rigid, and stress increments due to recoil to be well within safe limits. As previously explained, it is felt necessary to retain present shell thicknesses for splinter protection.

It will now be shown that if the supporting decks remained stationary but otherwise offered minimum restraint to the foundation (simple support) the flexibility of the foundation as derived by simple beam theory, plus allowance for shear deflection, could not account for the observed low spring constant to the turret, and hence that considerable flexibility of the surrounding structure is indicated.

The foundation acts like a combination of a beam and a column, both of very small ratio of length to depth. The beam action with which we are chiefly concerned may be considered independently of the column action. In a structure having a slenderness ratio near unity the transverse deflection due to shear is a very large part of the total deflection. The turret foundation passes through several decks or platforms to which it is attached by riveted or welded connections. The restraint offered to the foundation by these decks is a matter for conjecture. In examining this question a standard condition of support may be assumed and the elastic constant at the trunnion level, expressed as the ratio of the applied load to the deflection, may then be computed by the usual methods. A comparison of this constant with that deduced from the observed natural frequency will then give an indication of the flexibility of the surrounding hull structure, that is, the departure of the actual restraints from those assumed. Turret 2 of BB56 will be used as an example.

The assumption will be that of simple support at the lowest supporting deck, in this case the second platform, and simple support at the highest supporting deck, in this case the third deck, with no support between. This is not the usual assumption but it should be the limiting case of greatest flexibility and it will serve as a suitable basis of discussion. The circular form of the section in the horizontal plane is assumed to be everywhere maintained. Further, for the sake of simplicity, the foundation will be treated as of uniform circular section although actually it is conical above the third deck.

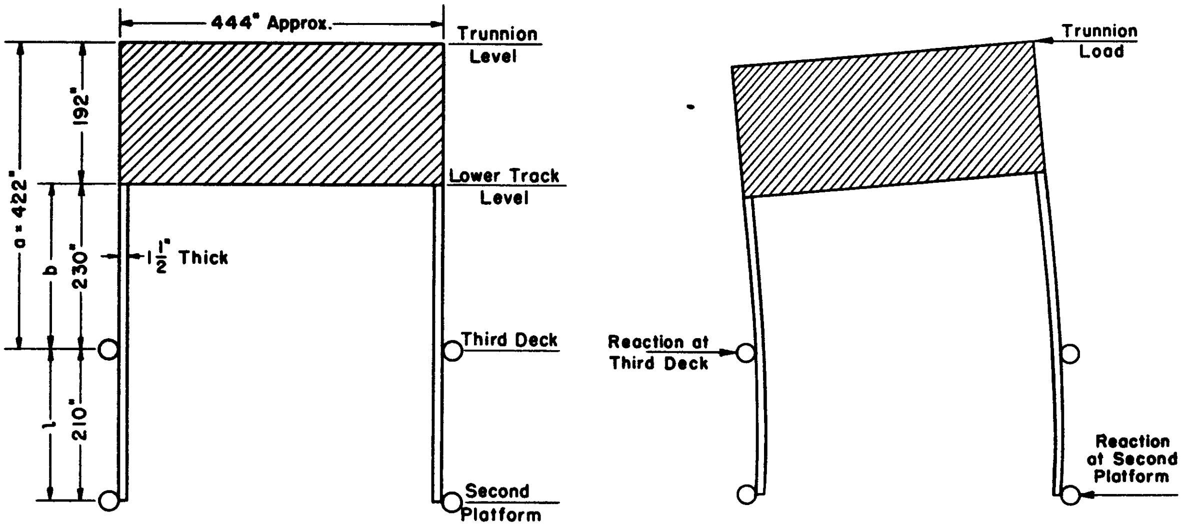

Figure 14a - Turret in unloaded condition

Figure 14b - Turret under trunnion load F with simple support at third deck and second platform

Figure 14 - Treatment of Foundation of Turret 2 on BB56 as a Simple Beam

The elastic constant, as referred to the trunnion level, will be derived from the elastic line of a cantilever beam simply supported at two points, with a transverse load applied on an overhanging rigid end; the cantilever has a uniform section for a length $l + b$, as shown on Figure 14, from which point upward the rigidity is infinite. The height of this rigid member, 192 inches, equals the height from the lower track level to the trunnion level. In Figure 14, a solid block represents the turret and a cylindrical shell the foundation. Circles represent the simple support at the third deck and the second platform, which are assumed to be fixed.

The following constants will be used in the treatment of the beam action of the foundation:

$E = 30 \times 10^6$ pounds per square inch	$a = 442$ inches
$G = 12 \times 10^6$ pounds per square inch	$b = 230$ inches
$I = 51 \times 10^6$ inches^4	$l = 210$ inches

$A = 2070$ square inches

If x represents the horizontal displacement relative to the third deck and y represents vertical distance above the third deck, then the bending deflection between the third deck and the lower track level, as given in the Handbook of the American Institute of Steel Construction, Formula 26, page 352, is

$$x = \frac{Fy}{6EI}(2al + 3ay - y^2), \text{ expressed in inches,}$$

where F is the load applied at the trunnion level. The slope is

$$\frac{dx}{dy} = \frac{F}{6EI}(2al + 6ay - 3y^2)$$

At the lower track level the horizontal deflection is obtained by substituting $y = b = 230$, giving

$$x = \frac{F \times 230 \times 42 \times 10^4}{6 \times 30 \times 10^6 \times 51 \times 10^6} = 105 \times 10^{-10} F$$

and the slope at this level is

$$\frac{dx}{dy} = \frac{F \times 60 \times 10^4}{6 \times 30 \times 10^6 \times 51 \times 10^6} = 0.65 \times 10^{-10} F$$

The deflection at the trunnion level due to bending of the foundation is the sum of the deflection at the lower track level and the increment due to the inclination of the rigid structure above the lower track level. Therefore

$$\Delta_b = (105 \times 10^{-10} F) + (192 \times 0.65 \times 10^{-10} F)$$

$$\Delta_b = F(105 \times 10^{-10}) + F(125 \times 10^{-10}) = 230 \times 10^{-10} F$$

In a circular tube of uniform thickness the deflection due to shear is given by the formula

$$\Delta_s = \frac{2V}{A}\frac{y}{G}, \text{ expressed in inches,}$$

where V is the total shearing load in pounds, A is the sectional area in square inches, and y is the distance from the fixed end in inches. In the case under consideration the deflection due to shear at the trunnion level will be the same as at the lower track level, and will be

$$\Delta_s = \frac{2F}{A} \times \frac{b}{G}$$

Substituting numerical values,

$$\Delta_s = \frac{2F \times 230}{2070 \times 12 \times 10^6} = 186 \times 10^{-10} F$$

Hence the total deflection at the trunnion level, due to bending and shear, is

$$\Delta = \Delta_b + \Delta_s = 42 \times 10^{-9} F, \text{ expressed in inches}$$

and the deflection at the trunnions in bending and shear, assuming simple support at both the lowest and highest supporting decks and no other support, is then equal to the load at the trunnions divided by k. From this operation

$$k = 24 \times 10^6 \text{ pounds per inch}$$

This value of stiffness is about 4 times the experimental value obtained from the observed natural frequency of the turret-foundation system and the comparison indicates considerable flexibility in the hull structure adjacent to the turret foundation. It may therefore be said with certainty that the horizontal deflection in the tubular cantilever is only a part of the whole deflection at the trunnion.

PART 5. FULL-SCALE TURRET DATA

In addition to model investigations, the Taylor Model Basin has in recent years made a number of observations on full-scale turrets now in service. All these investigations were far less elaborate than that made by the National Bureau of Standards on the USS CALIFORNIA (5), as the Model Basin measurements were confined chiefly to maximum values. The data collected, however, are believed to be reliable.

These data were taken during the structural firing trials of the USS NASHVILLE during November 1938 (24), of the USS WICHITA during August 1939 (25), of the USS WASHINGTON and USS NORTH CAROLINA during September 1941 (20), and of the USS BALTIMORE during June 1943 (26), and are being continued from time to time on other vessels. Some full-scale static loading tests were also made on the USS WICHITA (21) and on the USS PHILADELPHIA (22) at the New York Navy Yard in 1941. Observations of resonant frequency were made on Turret 2 of the NORTH CAROLINA in 1942, and on Turret 2 of the IOWA (27).

MEASURING TECHNIQUE

The instruments used in these measurements consisted chiefly of plunger-type scratch gages installed so as to indicate relative motions at the standard series of stations as shown in Figure 15. Most of the measurements were taken for all-gun salvos at zero elevation and a train angle of 270 degrees, i.e., with the turret firing on the port beam. The displacements measured were the maximum displacement of the

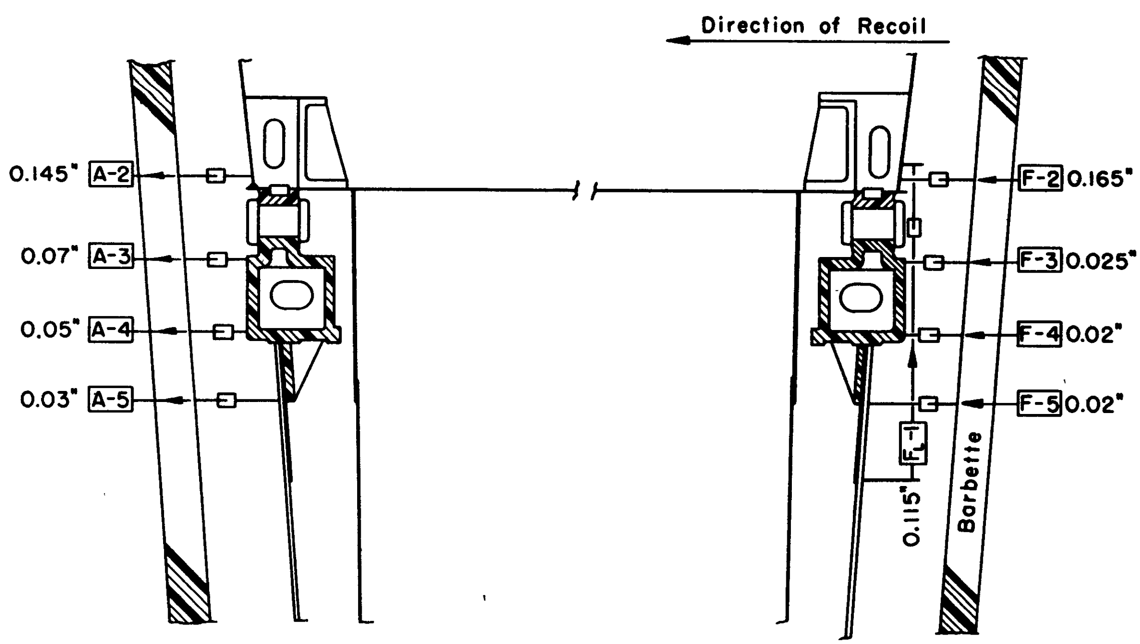

Figure 15 - Displacements of Turret 1 of USS WICHITA

The data given are averages from two 3-gun salvos. The displacements are maxima, measured from the zero position before firing. The arrows indicate the direction of the displacements.

upper and lower roller track relative to the barbette at both front and rear points, and the lift of the upper track at the front. On the USS WASHINGTON and the USS NORTH CAROLINA, strain-time records were obtained in addition at the base of the conical turret foundation by Tuckerman optical strain gages with photographic recording.

The natural frequency observations were made with the 5000-pound medium vibration generator designed and built by the Taylor Model Basin. Confirming data were obtained from the time records of vibration following firing.

GENERAL RESULTS OF RECENT MEASUREMENTS ON BOARD SHIP

Complete details of the tests may be found in previous reports referred to on page 34. A summary of the most important data is given in Tables 5, 6, and 7.

TABLE 5

Full-Scale Deflection under Service Load

All values are given in fractions of an inch for a 3-gun salvo.

Displacement Measured (Station designations refer to Figure 15)	USS NASHVILLE CL43 Turret 1	USS WICHITA CA45 Turret 1	USS NORTH CAROLINA BB55 Turret 2	USS WASHINGTON BB56 Turret 2	USS BALTIMORE CA68 Turret 1
Lift of upper track at front of turret, F_L-1	0.135	0.115	0.21	0.175	0.22
Maximum horizontal displacement at upper track at front, F-2	0.20	0.165	0.46	0.50	0.30
Maximum horizontal displacement at upper track at rear, A-2	0.165	0.145	0.445	0.46	0.28
Maximum horizontal displacement at top of lower track at front, F-3	0.04	0.025	0.22	0.195	0.03
Maximum horizontal displacement at top of lower track at rear, A-3	0.09	0.07	0.255	0.27	0.14
Maximum horizontal displacement at bottom of lower track at front, F-4	0.035	0.02	No data	0.18	0.03
Maximum horizontal displacement at bottom of lower track at rear, A-4	0.065	0.05	0.175	0.205	0.10

On BB55 the observed natural frequency was 330 cycles per minute when vibration was induced in the fore-and-aft direction. On this occasion the turret could not be trained to 270 degrees, the train angle at which observations were made during the structural firing trials. However, subsequent measurements on BB61 gave approximately the same frequency as for BB55 and the value was the same in both transverse and fore-and-aft directions.

Static loading tests were made on Turret 1 on the USS PHILADELPHIA (CL41) and the USS WICHITA (CA45) for comparison with data taken during the structural firing trials of the USS NASHVILLE (CL43) and the USS WICHITA (CA45) (24)(25). Since

TABLE 6

Observed Dynamic Load Factors for Turrets

Vessel	Observed Dynamic Load Factor	Basis of Estimate of Dynamic Factor
USS WICHITA (CA45)	1.1	Based on comparison of deflections of lower roller track during structural firing tests with same deflection during static loading test.
USS PHILADELPHIA (CL41)	1.4	Based on comparison of deflections of lower roller track during structural firing tests with same deflection during static loading test
USS WASHINGTON (BB56)	1.4	Based on comparison of stresses in foundation in dynamic and static model tests.
USS WASHINGTON (BB56)	1.1	Based on comparison of stress measured in foundation during structural firing test with value computed under trunnion load by simple beam theory.

TABLE 7

Stress in Turret Foundations under Service Load

All values are given in pounds per square inch for a 3-gun salvo.

Station	Turret 2	
	USS NORTH CAROLINA BB55	USS WASHINGTON BB56
Compressive stress at base of conical foundation at rear	7800	5500
Tensile stress at base of conical foundation at front	8100	5800

Note: On BB55 the dynamic strain gages were located 20 inches above the lower shell deck; on BB56 they were 10 inches below the upper shell deck. This made the ratio of moments of the trunnion loads on BB55 to BB56 as 15 to 12, with respect to the places of measurement.

in applying these static loads it was necessary to take the reaction on the barbette of Turret 2, only relatively small loads could safely be applied; these were of the order of one-quarter of the 3-gun salvo trunnion load. On the basis of deflection, these static tests gave dynamic load factors of 1.1 for the WICHITA and 1.4 for the NASHVILLE class. The results also indicated that the distribution of load on the foundation was very different under static load from what it was under recoil loads. It was found that under static load the barbette itself moves appreciably relative to the adjoining part of the hull.

CONCLUSIONS FROM THE FULL-SCALE OBSERVATIONS

On the basis of the recent observations described in the foregoing, the Taylor Model Basin has come to the following conclusions:

1. With tracks of the present scantlings, the "egg-shaped" bending deformation of the lower roller track in its own plane is relatively unimportant.

2. Torsional action in the lower roller path is relatively more important than bending and needs further study, if reduction of the track section is under consideration.

3. With present scantlings foundation stresses in general under recoil loads are well below values ordinarily allowed in design.

4. Experimental evidence based on deflections and stresses in the foundation places the dynamic factor nearer to 1.3 than to the value 2.0 frequently used in design. It is believed that an overestimate of the recoil load has caused an underestimate of the dynamic load factor.

PART 6. RECOMMENDED DESIGN CRITERIA FOR PRESENT TYPE OF HEAVY GUN TURRET

In the light of the information obtained from the work previously described, and reported in detail in the references, the Taylor Model Basin makes the following general recommendations for the design of turrets having the present type of roller bearing. In many cases these represent current practice, but they are summarized here for the sake of completeness.

1. FOUNDATION. Although the early practice of reinforcing the foundation with vertical stiffeners was abandoned some time ago, foundation stresses are still quite low. However, as long as a minimum thickness of plating for the foundation is necessary for splinter protection, designing for higher allowable stresses is not feasible.

If a stress estimate is desired, the Bureau of Ordnance value of design trunnion load, including 25 per cent additional for peaking, should be multiplied by 1.3. The bending and shear stresses in the foundation should be evaluated as for a static load by the use of the ordinary formulas for beams.

The best method of estimating maximum deflection is to use the spring constant experimentally determined in firing trials of turrets of a similar class and to calculate the deflection under an assumed static load equal to 1.3 times the Bureau of Ordnance value of design trunnion load. Spring constants based on frequency observations are not yet acceptable for this use.

2. LOWER ROLLER TRACK. The present lower roller track design appears to provide ample strength, and although some weight could undoubtedly be saved here it would be small in comparison with the other weights involved. The chief deficiency of this part at present is in torsional rigidity, but no reports of damage due to torsion have been received. Indentation has been controlled by increasing the surface hardness of the track. The present hardness number of 200 Brinell is the minimum allowable. As commercial practice in roller bearing design goes as high as 600 Brinell, the possibilities of utilizing greater hardness should be considered.

3. ROLLERS. Provided all the available space is filled with rollers, the number of rollers to be used is not as important as might at first sight be expected, for although increasing the number decreases the load per roller, this is counteracted by a concentration of load due to the decreased diameter of the roller. One of the chief advantages of smaller rollers is in reducing the tilting moment, and so the torsional action on the ring. The number selected for the BB61 class, namely 72, seems to be near the optimum for the present basic design.

Strictly speaking, the clearance between the roller flanges and the roller tracks would have to be reduced to zero before the shock loads on the tracks would be zero, but the close tolerance now specified, 3/64 inch each, upper and lower, or 3/32 inch total, results in an approximation to zero close enough so that the resulting shock effect can be ignored.

The safe roller load may be checked by the empirical formulas given on page 12.

4. UPPER ROLLER TRACK. The present design is satisfactory except for the hardness of the surface, which should have the same value as for the lower track.

5. GUN GIRDERS. In designing these parts the design trunnion load should be used directly without the application of a dynamic factor differing from unity. The scant experimental evidence on hand indicates that stresses in the gun girders on BB56 are low, but as the walls of these girders must be elastically stable, weight-saving here should not be undertaken without investigation of that point. The welded box girder construction used on BB55 and 56 appears to be satisfactory.

6. HOLDING-DOWN CLIPS. The present design of holding-down clip provides adequate strength and rigidity. The clip clearance should be adjusted to the minimum value that will not interfere with ease of training; this value is about 3/32 inch. The smaller the clearance the smaller will be the shock load on the roller tracks.

RECOMMENDATIONS FOR FURTHER EXPERIMENTAL WORK

ALTERNATIVE TYPES OF BEARING

In recent years considerable attention has been given to the possibility of a radical departure from present turret design practice, chiefly with a view to finding a method of nearly frictionless support superior to the present flanged rollers. Although the present type of tapered roller bearing is ideally suited for purely axial loads, its action under radial loading is less perfect, and alternative arrangements based on commercial practice have been suggested.

In machine design practice a tapered roller bearing for combined radial and thrust load would have the axes of the rollers parallel to the shaft axis. Since in the heavy gun turret the radial load is dynamic while the dead weight or thrust load is mainly static the need is primarily for a radial bearing with weight-carrying as a secondary consideration.

Bearings having characteristics superior to those now in use in turrets are undoubtedly possible but the development work on them may be long and tedious, and it must be supplemented by the satisfactory performance, on experimental vessels, of full-scale installations, before it can be expected that the designs will be adopted for combatant vessels.

Some of the most promising alternative proposals are outlined here.

1. A design proposed by the Philadelphia Navy Yard during the design stage on the BB55 and 56 turrets is shown in Figure 16a. A series of flangeless horizontal rollers run between upper and lower tracks having inside and outside flanges.

2. The combined vertical and horizontal roller design used in the 8-inch mounts of the SALT LAKE CITY and AUGUSTA class of heavy cruisers may be seen in Naval Gun Factory Plan 144301 (4). Figure 16b is a sketch showing a suggested re-design for battleship turrets.

3. An oil-film plain bearing, designed to take both recoil and deadweight loads, is shown in Figure 16c. This bearing was proposed by Captain E.F. Eggert, (CC), USN, (Ret.), and is described in TMB Report 514, Reference (6).

4. A combination oil-film plain bearing and roller bearing, in which the former takes the vertical or deadweight load and the latter takes the horizontal or recoil load, is shown in Figure 16d.

ADDITIONAL MODEL TESTS

The basic information necessary for design of the present conventional heavy gun turret is now available to designers and further model tests of the type described in References (9), (15), (17), and (18) appear to be unnecessary until new major features appear. Necessary experiments with rollers and track materials could be carried out on a much larger and a much simpler scale.

However, when radically new designs become necessary model tests are most valuable; it now is generally agreed that these should be dynamic tests rather than static tests. A case in point is the recent design for the 6-inch, 47-caliber-gun turret for high-angle firing in which, because of space requirements, the gun girders are of unusual shape and are attached only to the front of the turret weldment. This design is illustrated in Figure 17. A scale dynamic model of this turret has been built and is undergoing test at the Philadelphia Navy Yard.

The proposed substitutes for the flanged, tapered, roller-bearing design should be thoroughly explored in model form. These models need not be very elaborate. The rotating structure can be represented by relatively simple and inexpensive castings such as have already been used (6). The effect of rolling motion can be adequately represented on a tilting platform and the tests under recoil load can be made with the testing device already available at Philadelphia.

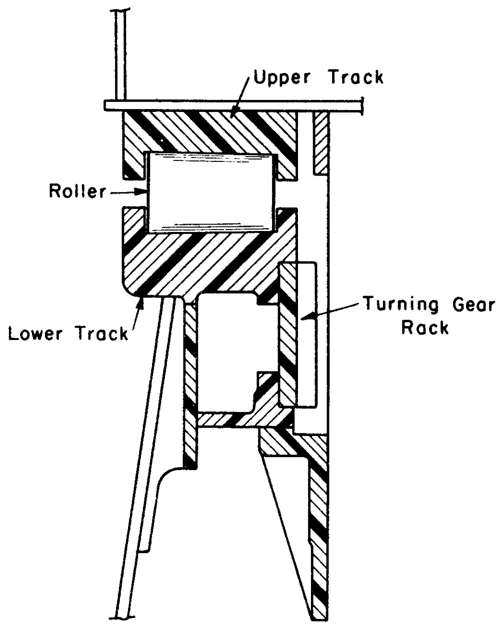

Figure 16a

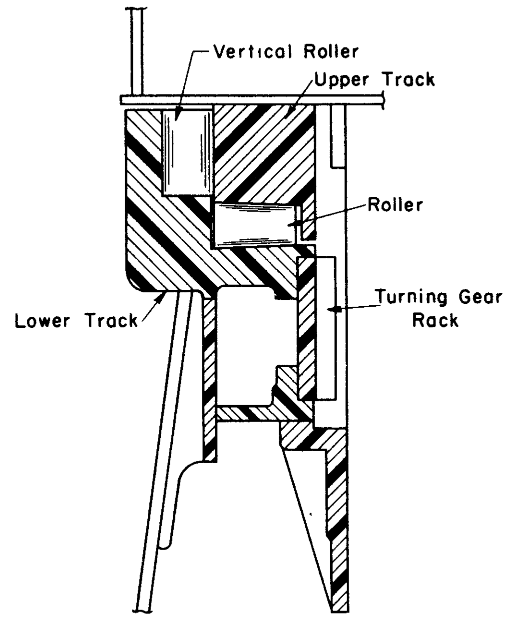

Figure 16b

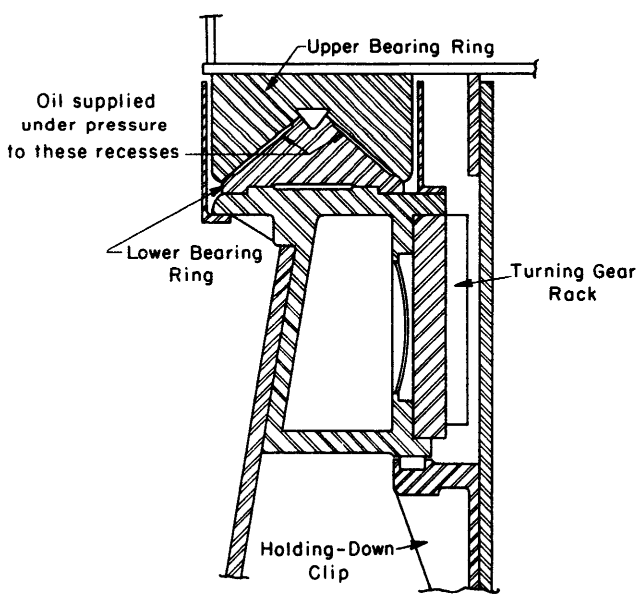

Figure 16c

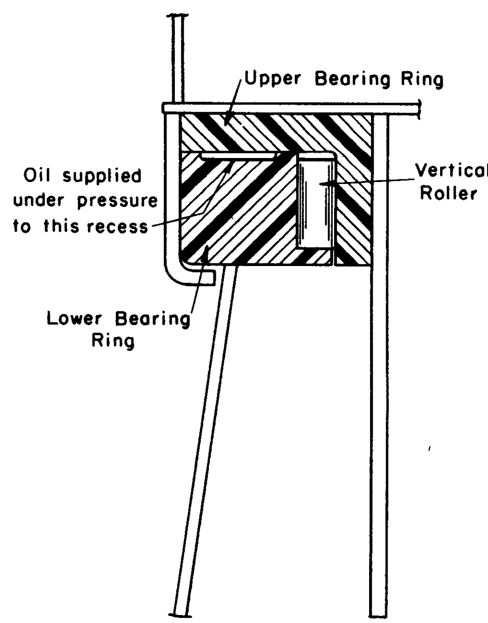

Figure 16d

Figure 16 - Four Types of Alternative Turret Bearings

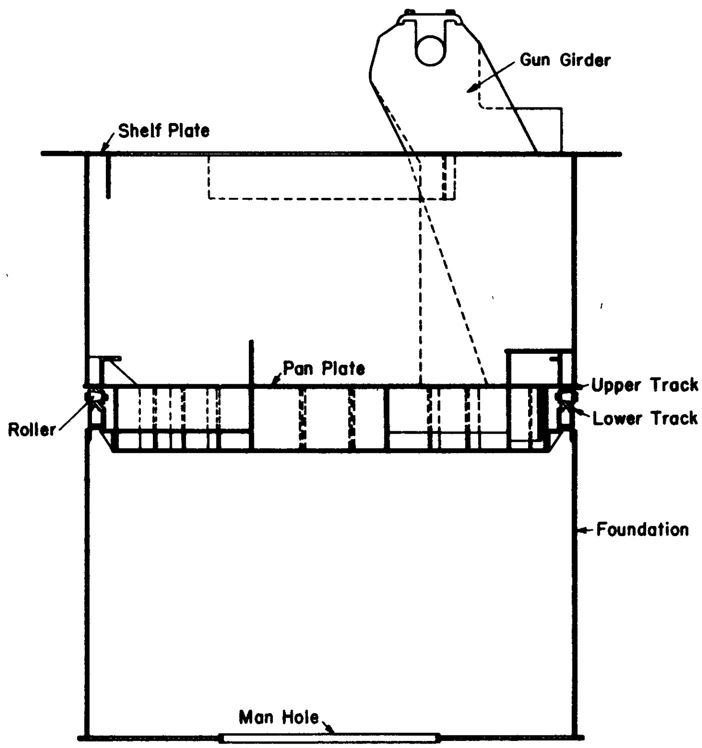

Figure 17 - General Arrangement of Model of 6-Inch,
47-Caliber-Gun Turret for High-Angle Firing

Some of the basic questions of turret behavior should be investigated. Projects are already in hand for study of elastic rigidity of the foundation cantilever and its adjacent supporting structure. A study of ring torsion has been started (28) and will be continued at a suitable opportunity.

The effect of clearance or play between the turret and the foundation needs further study and clarification, especially with reference to frictional resistance to relative movement between the turret and the foundation. Tilting of the rollers is not fully understood; it is strongly influenced by angle of elevation and, at low angles, by the holding-down-clip clearance and rigidity in the lower roller track.

FURTHER FULL-SCALE INVESTIGATIONS

The chief guide for improvement of existing designs is the performance of those now in service. Hence casualty or damage reports dealing with turrets should always be studied for a clue to possible improvements. This has been done hitherto by agencies other than the Taylor Model Basin.

There is still uncertainty as to the actual trunnion loads, and more exact experimental data would be of value. There is at present no method of measuring trunnion loads directly on the ship; about all that can be measured directly is pressure in the recoil and counter-recoil cylinders. It was found in the dynamic turret model experiments that considerable back pressure developed in the hydraulic brake cylinder, even though it was provided with an expansion chamber, and it was necessary to correct for this in estimating the trunnion load. It is not known whether this occurs also in the full-scale brake cylinders, but if it does the trunnion load is overestimated. This question should be investigated.

A cooperative project should be undertaken with personnel at the Naval Proving Ground, to investigate all the factors affecting the trunnion load, so that there might be more definite information as to the trunnion loads on which the whole turret design hinges. This should be done for modern guns of 16-inch, 8-inch, and 6-inch caliber. A study should also be made to determine whether for any reason the trunnion loads on the ship could differ appreciably from those measured at the Proving Ground.

Further elaborate investigations during firing trials such as were conducted on the USS CALIFORNIA (5) are probably unnecessary, but a seismic instrument designed especially for turret use, which could be installed with the minimum of interference with normal operations inside the turret, would facilitate the collection of valuable data for checking present ideas as to the displacements and accelerations that have to be dealt with. In the case of the TMB pallographs which were installed on BB55 and BB56 the range of travel of the seismic elements was smaller than the turret displacements, so that invariably the elements hit the stops. This rendered the records useless beyond this point. Accelerometers, because of the small relative movement between the element and the frame of the instrument, are usually designed for photographic recording or for oscillographic recording with large amplification. Neither of these systems is convenient for use inside turrets where very little space is available for experimental apparatus and personnel.

Although a satisfactory theory of the elastic behavior of the foundation is lacking, the stresses under present scantlings are known to be quite low and further stress analysis of the present foundations and tracks appears unnecessary except for comparison unless the design is appreciably changed. There may be need, however, of further information as to the stresses in the gun girders, the pan plate, and the holding-down clips, and especially as to the shock loads on the tracks. These are all influenced by the overall elastic constant of the foundation in the horizontal direction as well as by local conditions. In the overall value the separate contributions of shear deflection, bending deflection, and deflection of the surrounding hull structure are not required, so that the effective spring constant of turret foundations can be determined by measuring their natural frequencies when the ship or turret structures are excited by vibration generators. When only frequencies and modes are needed, vibration amplitudes of only a few thousandths of an inch are sufficient. This is possible on the largest turrets with the vibration generating equipment now available.

Determination of these frequencies and modes on cruisers of the NASHVILLE and WICHITA classes, on which experimental data have already been obtained, would furnish a valuable check on present ideas. Extensive investigation of these or other individual ships would be of value. Thus vibration generators might be used to find the natural frequency of the foundation system before and after installation of the turret, or perhaps to determine the effect on the frequency of the addition of known weights, such as guns or sections of armor. A thorough study of some one ship should be made to supplement the data now accumulating on the differences between different ships. Ultimately such studies should be made on a type ship of each class.

SUMMARY AND CONCLUSIONS

1. The value of trunnion load as now estimated by the Bureau of Ordnance, including a margin of 25 per cent for peaking, should be multiplied by 1.3 to allow for dynamic effect in estimating the loads on the stationary structure below the lower track level.

2. The dynamic factor recommended for the foundation is not applicable throughout the structure. For load or stress estimates in the gun girders the dynamic factor should be 1.0.

3. Owing to shock, the rollers and tracks may be subjected to overload; with the close clearances now used, however, this effect may be ignored.

4. Specification of materials and heat treatment may be depended on to eliminate track indentations; higher hardness values in the tracks would be of benefit.

5. The stresses in the BB56 turret structure are amply low under the load of the 3-gun salvo. However, reduction of scantlings is recommended only in the case of the gun girders in view of the smallness of possible saving in total weight.

6. Further model tests on complete heavy gun turrets of the conventional design, similar to that of the BB55, 57, and 61 classes are unnecessary, but experiments with some of the elements, such as the rollers, would be useful.

7. Dynamic model tests are recommended where any radical changes in design are contemplated, such as for example the high-angle 6-inch-gun cruiser turrets.

8. More complete surveys by vibration test are desirable on single vessels of each type.

9. Possible substitutes for the present flanged-roller method of turret support are worthy of study.

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