MODERN INSTALLATION FOR TESTING OF LARGE ASSEMBLIES UNDER STATIC AND FATIGUE LOADING

(Description of Installation at Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania)

by

Bruno Thürlimann and W.J. Eney

(Not for Publication)

Fritz Laboratory Report No. 237.7
INTRODUCTION

The need for testing materials by subjecting them to a great number of loading cycles was recognized some 80 years ago. Fatigue testing of small specimens to establish the endurance limit of a certain material is now commonly done with a great variety of machines (see e.g. (1), (2)). However, the endurance limit of the assembled structure or machine cannot be predicted from the fatigue tests on small samples for the following several reasons:

(1) The general phenomenon called size-effect does not allow a direct extrapolation of results obtained on a small specimen to the behavior of a large piece of material, especially in case of fatigue.

(2) The endurance limit can be lowered to a considerable degree by stress concentrations arising from the geometry of the structure.

(3) An exact stress analysis of a complicated detail is very often impossible. Therefore the calculated working stresses are only rough approximations of the actual values. Hence, the behavior in fatigue cannot be predicted without an actual test.

(4) During fabrication and construction, stresses not accounted for in the analysis may have been built in. These include (a) residual stresses due to uneven cooling of rolled structural shapes; (b) residual stresses due to welding and (c) stresses arising from shrinkage and creep in concrete members, etc.

*Refers to List of References
Consideration of these factors shows an urgent need for testing large component parts and entire machines and structures by subjecting them to a large number of loading cycles. Even in cases of purely static loading the necessity of testing complete assemblies has been recognized.

In conceiving and designing an installation for such purposes attention should be given to a few fundamental requirements:

1. The installation should be capable of testing specimens of a great variety of shapes and of considerable size. Rather than to fit the specimen to a given testing machine it is desirable to fit the test set up to the specimen.

2. It should be possible to apply any type of loading such as tension, compression, bending, torsion or combinations thereof. These loads should be either static or cyclic, allowing a simple changeover.

3. Direct measurement of the applied loads should be possible. In case of cyclic loading this can only be achieved by avoiding the resonance range of the test specimen.

4. One to two million loading cycles should be obtainable within reasonable time.

5. The equipment should function without the constant presence of an operator. Safety
devices for automatic shut-off in case of fracture or emergency are necessary.

Consideration of these points lead to the conception and the design of the new installation at the Fritz Engineering Laboratory, Lehigh University. This is the first such installation in the United States. It has been in constant operation since October 1955. The many new features incorporated in the Lehigh design, and the resulting great versatility making possible a completely new kind of fatigue testing of large structures is hereafter described.

Valuable information aiding in the design was obtained from a number of articles describing modern European Testing Laboratories(3),(4),(5),(6).

I. GENERAL ARRANGEMENT OF THE LEHIGH INSTALLATION

The general lay-out follows the principle of "unit construction". A typical set up is shown in Fig. 1. Such a set up is an assembly of a number of functional units which can be combined in a variety of arrangements. The "backbone" of the installation is a massive, reinforced concrete slab, built into the laboratory floor, and hereafter referred to as the test bed. Anchorages provided in this bed allow the attachment of steel frames. The framing is built around the test specimen providing the necessary supports and reactions for both the specimen and the hydraulic loading jacks. These jacks can be placed in any desired position. For static testing a "Pendulum Dynamometer" delivers a constant oil pressure to the jacks. For fatigue testing a "Pulsator" supplies a sinusoidally changing oil pressure.
It may be readily seen that such an arrangement offers a great variety of testing possibilities as illustrated in the following detailed description.

II. DESCRIPTION OF TEST BED AND FRAMES

Fig. 2 is a design drawing of the test bed and Fig. 3 shows it under construction. The bed is 70 ft. long, 14 ft. wide, and 6' - 5" deep. The width was dictated by the available space on the laboratory floor. Care was taken to structurally separate the bed from the building foundations and the rest of the laboratory floor. It is designed to resist a static bending moment of 9000 ft-kips, a maximum vertical shear of 600 kips and a horizontal force of 1000 kips. Its allowable torsional resistance is beyond 4000 ft-kips. Apart from strength, rigidity was an important design criterion for reasons which will be later indicated. Vertical anchorages are provided in a regular pattern, 4 by 5 ft., by pairs of 3-inch diameter high tensile bolts, extending throughout the whole depth of the slab. The top surface of the slab surrounding the anchorages is formed with heavy steel plates bolted to I-beams running longitudinally the full length of the bed.

In designing the anchorage system special attention was given to clearly separate the vertical and horizontal forces. This is illustrated in the typical column anchorage as shown in Fig. 4. The base plate of the column rests on the steel plate of the test bed. A collar, shrunk-fitted
into the column base-plate protrudes into a hole in the bed plate. The horizontal forces are transmitted from the column base plate through the collar into the bed plate and finally down into the horizontal I-beams. Each anchor is designed to resist a static horizontal force of 500 kips; the bed can resist a total of 1000 kips.

Vertical anchorage is made by a short threaded stud connecting the column base to the sleeve at the top of the anchor bolts (Fig. 4). In order to eliminate fluctuating stresses under cyclic loading the entire anchorage is pre-stressed by a simple hydraulic jacking system whenever a connection is made. During construction of the bed care was taken to prevent any bond between the anchor bolts and the concrete by wrapping the bolts with tar paper. In this way the bolts are prestressed over their entire length, eliminating any stress fluctuation and hence possible fatigue failures.

The steel framing is made up of simple individual structural members. They can be assembled into a multitude of combinations to suit conditions imposed by the size and shape of a given test specimen and to resist forces in any desired direction. A study of likely test set-ups resulted in the following choice of members, a design drawing of which is given in Fig. 6.

4 columns (12WF85), Length 15′-6″
4 columns (12WF85), Length 23′-0″
2 heavy cross beams (pair of 30WF116)
2 light cross beams (pair of 18x4f58.0)
4 short spreader beams (built-up box, 15″ deep)
1 long spreader beam (built-up box, 22″ deep)
4 thrust brackets (weldment, 6′-8″ high)
4 supports with shoes
4 diagonal braces (10WF33)
All connections between the different members are made by one inch diameter high tensile bolts (Fig. 7). These connections offer several advantages, such as better resistance to fatigue loading, ease of assembling and disassembling, use of ordinary structural tolerances in fabrication, complete rigidity eliminating slip and noise, and elimination of machining of pieces during fabrication.

Tightening of the bolts to the required torque of 800 ft-lbs. is done by a calibrated hand wrench. The use of an air wrench does not offer a great saving in time as the number of bolts involved in a given set-up is rather small. Furthermore, the hand wrench offers a better control of the torque which is especially desirable as the bolts are constantly re-used.

A careful study of the natural frequencies of some typical frame set-ups was made. This showed that under certain extreme conditions diagonal braces may become necessary in order to increase the resonance frequency of the framing sufficiently above the working frequencies of the loading equipment.

III. DESCRIPTION OF LOADING EQUIPMENT

All the loading equipment was purchased from the Amsler Testing Machine Co., Schaffhausen, Switzerland. The long experience of this firm and the successful use of their newest fatigue testing equipment in the most modern European Testing Laboratories (3), (4), (5), (6) are favorably reflected in the Lehigh installation.

In the following description an account of the different units is first given. Their combined application is then shown schematically in a typical test set-up.
1. Jacks:

Loads are produced by hydraulic compression jacks with lapped ram pistons. Precision machining reduces the friction to such a minimum that the oil pressure is an accurate indication of the load. The following assortment of jacks of various capacities was obtained (see Fig. 8): four of 5500 lbs.; four of 11,000 lbs.; two of 55,000 lbs. and two of 110,000 lbs. All jacks have a ram stroke of 5 inches. For proper adjustment and for resetting, built-in spindels and extension stilts are provided. Spherical seats at both ends of the jack assure proper axiality of loading. The same jacks can be used for static and/or cyclic loading. The maximum working pressure is about 2900 psi.

2. Pendulum Dynamometer:

This unit has the double function of delivering a static oil pressure to a jack or jacks and measuring the load in the case of static testing (Fig. 9). A large reservoir contains sufficient oil such that up to 8 jacks can be connected simultaneously. The load is measured with testing machine accuracy by the following arrangement. The hydraulic pressure applied to the jacks also acts on a measuring piston which in turn actuates a pendulum. A higher pressure on the piston is balanced by a higher swing of the pendulum. This movement is transmitted to a pointer indicating the load on a large dial. The measuring piston is constantly rotating about its own axis thereby practically eliminating all friction. This simple system assures a high and time independent accuracy.
Four different load ranges are available. An automatic load maintainer is built in, allowing application of constant loads over long periods of time. This device is very desirable for performing creep tests on large structures involving high loads. The entire machine is a compact unit which can be moved easily. It need not be bolted to the floor when operating.

Two Pendulum Dynamometers were obtained for the Lehigh installation.

3. Pulsator:

For cyclic loading a jack (or jacks) is connected to a "Pulsator" (Fig. 10). This machine consists essentially of a pump with one large piston of continuously adjustable stroke. The working principle is shown schematically in Fig. 11. The minimum pressure is supplied by a small piston pump (6) delivering oil into the main cylinder (5) over the regulating valve (7). By changing the force of spring (8) the minimum pressure is changed accordingly. The pulsating pressure is produced by the movement of the main piston (4). The stroke is controlled by a three-bar linkage system. Position A and B of bar (2) determine the maximum and minimum piston stroke. On its upward stroke the piston (4) forces oil from the Pulsator into the jack. On the downward stroke the elasticity of the test specimen pushes the oil back into the Pulsator. Therefore the same quantity of oil flows back and forth between Pulsator and jack. With no valves and by-passes such a system has very smooth and quiet operating characteristics producing an almost perfect sinusoidal pressure variation in the jack. The Pulsator has two operating speeds of
250 and 500 cycles per minute resulting into 1 million load cycles within 34 and 68 hours respectively.

Special mention should be made of the load measuring system. Measuring the pressure fluctuation within the Pulsator would be completely inadequate as considerable frictional losses occurring in the pipe connecting the Pulsator and jack would be included. The actual measurement is made by tapping the pressure directly at the jack by means of a measuring valve element. The maximum and minimum pressures are transmitted hydraulically to corresponding pressure gages mounted on the Pulsator. This arrangement results in an accuracy well within the limits proposed by the International Institute of Welding for hydraulic fatigue testing machines (7).

The Pulsator is driven by a 11 HP electric motor. Electric relays will shut it off automatically in case of fracture of the specimen, etc. The Pulsator constitutes a completely self-contained unit, requiring no attendance once it is operating. It can be freely placed without bolting to the floor. The power requirement for operation of a single Pulsator is 3 phase, 220 volts, 27 amperes.

The capacity of one Pulsator is limited by the maximum oil output per stroke of 300 cubic centimeters (about 18.3 in³) and the maximum operating pressure of 2900 psi.

The following table lists the theoretical piston stroke of a single jack when connected to one Pulsator:
<table>
<thead>
<tr>
<th>Jack Size</th>
<th>5500 lbs.</th>
<th>22000 lbs.</th>
<th>55000 lbs.</th>
<th>110,000 lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Stroke</td>
<td>8.88 in.*</td>
<td>2.33 in.</td>
<td>0.89 in.</td>
<td>0.45 in.</td>
</tr>
</tbody>
</table>

*However, limited by maximum stroke of jack to 5 in.

If more than one jack is used the available stroke for each jack is obtained by dividing the above figures by the number of jacks. By coupling the two Pulsators available at Lehigh the stroke can be doubled.

The actual jack stroke will be somewhat smaller due to deformations of the loading frames, the test bed and the compressibility of the oil. However, the first two losses are practically negligible due to the great rigidity of the framing and bed. Even for large test set-ups consisting of two Pulsators, multiple jacks and long connecting lines the compressibility losses will not exceed 15 to 20% of the above given figures.

4. Auxiliary Equipment:

For static testing connections between Pendulum Dynamometer and jacks are made by high pressure rubber hoses. If more than one jack is connected the oil from the Pendulum Dynamometer is fed into a "Distributor" into which the jacks are connected. For cyclic loading special steel tubing with articulated joints is required. Under operation a very small amount of oil leaking from the jacks is collected by rubber hoses, delivered into a reservoir and pumped back into the system by a leak-oil pump.

The use of an "Accumulator" makes application of alternating loads (changing through zero) possible. Its use is shown in the following description of a schematic test set-up.
5. Schematic Test Set-up:

Fig. 12 outlines schematically a test set-up for alternating bending of a large member. The test specimen (1) is mounted on the test bed (2). A lower jack (3) exerts a constant pressure upwards. This pressure is produced and maintained by the Pendulum Dynamometer (4) and applied through the Accumulator (5). Any movement of the jack piston can be absorbed by the nitrogen cushion of the Accumulator without a significant change in pressure. In actual operation the small pressure variation due to pipe friction is taken into account by measuring the maximum and minimum load of jack (3). An upper jack (6) is connected to a Pulsator (7). For example by varying the load in the upper jack from 0 to 100,000 lbs. and maintaining the load in the lower jack (3) constant at say 50,000 lbs. the resulting force on the specimen will alternate between 50,000 acting upward and downward. The limit loads can be set to any desired values varying from a static load to complete load reversal.

For cases requiring fluctuating loads, i.e., no passage through zero, only Pulsator and jack are required.

IV. ADDITIONAL EQUIPMENT

In order to round out the whole installation two additional pieces of equipment for testing of coupons and small-size specimens were installed.

1. Alternating Stress Testing Machine:

The 220,000 lbs. Alternating Stress Testing Machine is shown in Fig. 13. The machine comprises the following units
Pulsator, Accumulator, Testing Frame and Pendulum Dynamometer. All these units except the testing frame are easily demontable and can also be used in conjunction with the test bed. The machine can apply static, fluctuating or alternating loads to tension, compression or bending specimens. Fig. 14 shows schematically testing of a member under alternating tension-compression. The test specimen (1) is gripped between the fixed and movable head of the testing frame. A lower jack (2), built into the head of the testing frame applies a downward compressive load to the specimen. Pressure to jack (2) is supplied by the Pendulum Dynamometer through the Accumulator. Piston movements of jack (2) are absorbed by the nitrogen cushion of the Accumulator without a significant change in pressure. Fluctuating tension is superimposed on the compressive load in the specimen by an upper jack (3), actuating the movable frame (4). The pressure fluctuation is generated by the Pulsator. The effective loads on the specimen are given by:

Max. Load: \( P_{\text{max}} = P_{3\text{max}} - P_{2} \)

Min. Load: \( P_{\text{min}} = P_{3\text{min}} - P_{2} \)

where:

\( P_{2} = \) Load in Jack (2)

\( P_{3\text{max}} = \) Max. Load in Jack (3)

\( P_{3\text{min}} = \) Min. Load in Jack (3)

Tests requiring fluctuating loads are performed with the use of the Pulsator only. Finally for static testing the Pendulum Dynamometer is connected to the upper jack (3). The switch-over from one type of loading to another can be readily done. The maximum length of tension-compression specimens
between heads is 40 inches and the maximum span for bending specimens is 55 inches. For cyclic loading the frequencies are 250 and/or 500 cycles per minute. By a small adaptation it is also possible to work in the intermediate range if so desired.

2. High Frequency Vibrophore:

This high speed fatigue testing machine of 22,000 lbs. capacity works at frequencies between 8000 and 18,000 cycles per minute (Fig. 15). It is suitable for fluctuating and alternating load tests of small specimens under tension, compression, bending and torsion. The loads are measured with an accuracy of ±1.5%. The high speed is a very desirable feature for a rapid determination of the S-N curve of a given material, for development work on small specimens, as e.g. threads of screws, proper machining of tooth-gears, anchorage of wires and small cables, spot welding of thin plates, etc.

Auxiliary attachments extend the usefulness of the machine. By a programming device a pre-selected loading program can be imposed on the machine. Other attachments allow the measurement of the damping characteristic of a material and the dynamic modulus of elasticity. For testing at elevated temperatures up to 800° centigrade or at subnormal temperatures down to -190° centigrade special units are available.*

The high testing speed may appear questionable. However, considerable investigation has shown that the influence of high speed is practically negligible under usual conditions(8). It should also be mentioned that fatigue testing in general is in the first instance comparative testing of a qualitative nature.*

*For more complete description of Vibrophore see Ref.(9).
showing the superiority of one material, detail or structure over another. The extrapolation of quantitative results to actual service life is a disputed problem even in cases where special care is taken to simulate service conditions with a high degree of accuracy. Sometimes it appears that this situation is not sufficiently appreciated.

V. EXAMPLES OF TYPICAL TEST SET-UPS

To illustrate the versatility of the installation a few typical test set-ups will be described.

1. Static Bending Test:

Fig. 16 shows a steel column 36 feet long with perforated cover plates ready for testing in bending. The two 110,000 lb. jacks placed at third-point are connected to a Pendulum Dynamometer. The test was performed to determine experimentally the influence of the perforations on the bending stiffness. The simplicity of the set-up and the accessibility are clearly evident from the picture. It made possible the measurement of deflections by means of a high precision level.

2. Fluctuating Bending Test:

A test of a prestressed concrete girder 55 foot long under fluctuating loads is pictured in Fig. 17. The magnitude of deflections required the simultaneous use of two Pulsators. They were placed at the center of the set-up, coupled together mechanically, hydraulically and electrically. The test was run for 1 million cycles at working load. Then, the loads were successively stepped up until 3 million cycles were reached. Final fracture was obtained by further load increase.
The entire test including a number of intermediate static measurements was completed within 10 days.

The influence of inertia forces on the actually effective loads during such a test should be mentioned. These forces cannot be neglected in testing such large specimens. By considering the specimen subjected to a forced vibration of known frequency the magnitude of the inertia forces can be computed theoretically. The elastic constants entering the problem are determined from a static deflection test on the specimen. Arranging the cyclic test in such a way that the natural frequency of the specimen is sufficiently above the applied frequency this influence can be determined rather accurately. For the test shown the influence of the inertia forces amounted to 75 percent of the amplitude of the applied forces.

3. Fatigue Test of Composite Beam Bridge:

A section of a composite beam bridge consisting of two WF-beams (18WF50) and a 6 inch deck slab, 32 feet long and 10' 6" wide, can be seen in Fig. 18, ready for testing. The purpose of the test was to study the fatigue behavior of the stud shear connectors under cyclic loading, simulating traffic conditions.

4. Alternating Bending of Rail:

The 220,000 lb. Alternating Stress Testing Machine was used to subject a piece of rail, 60 inches long to alternating bending (Fig. 19). The load, applied at mid-span, alternated between 40,000 lbs. downward and 40,000 lb. upward at 500 cycles per minute. In this way the strength of fusion-welded joints, the influence of heat treatment on the fatigue properties, etc. can be determined.
5. Fluctuating Tension on Aircraft Bolts:

The same machine was used in development testing of large aircraft bolts of high strength steel and titanium. The test set-up is illustrated in Fig. 20, showing a 1-1/2 inch diameter bolt held between two fixtures. The spherical seat of the movable frame of the testing machine (see Fig. 14) allowed an accurate centering of the specimen. A check of the applied loads by means of SR-4 electrical strain gages, applied to the fixtures, and an oscilloscope gave close agreement with the pressure gage readings of the machine.

6. Alternating Torsion of a Ship Propeller Shaft:

A set-up of an alternating torsion test on a ship propeller shaft is shown by a model in Fig. 21. With the equipment available at Lehigh it is possible to apply an alternating twisting moment of ± 6,500,000 inch-pounds. This may illustrate the great versatility of the installation.

7. Field Testing:

The complete mobility of the loading equipment (jacks, Pendulum Dynamometer, Pulsator) makes field testing easily possible. Tests on road or airfield pavements (see Fig. 22), on foundation piles, ships, etc., under static and cyclic loading are possible.

VI. CONCLUSIONS

By the application of the "unit construction" principle an extremely versatile testing installation has been developed. Specimens ranging from small coupons up to large components and entire structures and machines can be tested under static
and cyclic loading with practically unlimited types of load combinations. Initial experience with the installation has shown its great versatility. It is believed that these completely new facilities for fatigue testing of large components and entire assemblies have wide applications in the fields of civil, mechanical, and aeronautical engineering. It is expected that Industry and Governmental agencies will find this installation at Lehigh useful in carrying out their research programs.

VII. ACKNOWLEDGEMENTS

The authors are indebted to the firm of Alfred J. Amsler & Co., Schaffhausen, Switzerland for instructive information leading to the general conception of the installation. The help of Dr. Jonathan Jones, former chief engineer, and Mr. Karl deVries, engineer, Fabricated Steel Construction, Bethlehem Steel Co., in the design of the test bed and the loading frames is gratefully acknowledged.
LIST OF REFERENCES


Fig. 1  General View (Fatigue Test of 42 ft. Prestressed Concrete Beam)

Fig. 3
Test Bed Under Construction
Fig. 2 Design Drawing of Test Bed
WF Column (12 WF 85)

3" φ Stud
Nut
Collar
Column Base

Floor Level

5.240 ± .004" dia.

12.000 ± .006"

5.260 ± .004" dia.  5.260 ± .004" dia.

Use tar paper to prevent bond between sleeves and shanks of bolts and the concrete.

Fig. 4 Design Drawing of Typical Column Anchorage
Fig. 5 Prestressing of Anchorage

Fig. 7 Calibrated Hand Wrench for High Tensile Bolt Connections
Fig. 6 Design Drawing of Steel Framing
Fig. 8  Jacks, Extension Stilts, Steel Tubing, Distributor, etc.
Fig. 9 Pendulum Dynamometer for Static Loading
Fig. 10  Pulsator for Cyclic Loading (Flywheel Covers Removed)
Fig. 11  Schematic Diagram of Pulsator
Case A
Resultant 50,000 lb.

Nitrogen

Case B
Resultant 50,000 lb.

Specimen 100,000 lb.

Fig. 12 Schematic Set-Up for Alternating Bending Test on Test Bed
Fig. 13
220,000 lb. Alternating Stress Testing Machine (Left to Right: Pulsator, Accumulator, Testing Frame, Pendulum Dynamometer)

Fig. 16
Static Bending Test of 36 ft. long Column with Perforated Cover Plates
Fig. 14 Schematic Diagram of 220,000 lb. Alternating Stress Testing Machine
Fig. 15  22,000 lb. High Frequency Vibrophore
Fig. 17
Fluctuating Bending Test of 55 ft. long Prestressed Concrete Beam

Fig. 18
Fatigue Test of Composite Beam Bridge, 32 ft. long and 10 ft. 6 in. wide
Fig. 19
Alternating Bending Test of Rail Section

Fig. 20
Fatigue Test of High Strength Aircraft Bolts, 1½ in. Diameter
Fig. 21 Model Showing Set-up for Alternating Torsion Test on Ship Propeller Shaft (Maximum Torque $\pm 6,500,000$ in.-lb.)

Fig. 22 Static Loading Test on Airfield Pavement