FLUID LOCK-UP DEVICES – A ROBUST MEANS TO CONTROL MULTIPLE MASS STRUCTURAL SYSTEMS SUBJECTED TO SEISMIC OR WIND INPUTS

by

Douglas P. Taylor, President

Taylor Devices, Inc.
90 Taylor Drive
North Tonawanda, NY 14120-0748

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Taylor Devices, Inc.
90 Taylor Drive, P.O. Box 748
North Tonawanda, NY 14120-0748
716-694-0800

ABSTRACT

Fluid Lock-up Devices have recently become quite popular for passive control of large structures subjected to earthquake or wind storm effects. The Lock-up Device, a variation of the Fluid Viscous Damper, allows unrestricted motion at low translational speeds. Yet, when a transient event occurs, the Lock-up Device activates, dynamically forming, in effect, a rigid brace connection between masses. After the transient event ends, the Lock-up Device reverts to low force output, permitting structural sections to thermally expand or contract without added stress. The operation of the device is completely passive, yet enables multi-mass structures to be dynamically braced, without resorting to the cost and complexity of an active actuator system.

INTRODUCTION

A Lock-up Device (LD) is a component from the general technology base of Fluid Dampers. Unlike a Fluid Damper, the LD does not dissipate energy. Rather, the LD effectively acts as a dynamic brace to literally "lock" multiple masses together under seismic or wind transients. When equipped with LDs, a multiple mass structure essentially acts like a single, monolithic mass when a transient event occurs.

In the structural engineering field, these devices have become widely used to restrict the motion of bridges located in the Eastern and Central United States, notably in areas classified as Seismic Zones 1-3. Many of these bridges also have the requirement to withstand wind loads from hurricanes and/or tornados, plus loads from truck or train braking, where bridge motion must be limited over a sustained period of several hours. Other applications are on buildings located close to one another and subjected to "pounding" problems, which can occur in any area of seismic or wind storm risk. Building applications to address these potential pounding problems include both fixed and base isolated structures.   A third major area of application is the use of LDs between discrete sections of a structure, thus allowing loads to be shared among individual masses during a transient event. Figure 1 depicts typical mounting locations for LDs on building and bridge structures respectively.

HISTORY

Because of the similarity in design between a damper and an LD, early hydraulic devices used to damp or limit motion in a structural system could conceivably be classified as either type of component. However, up until the end of World War II, most hydraulic components lacked the precision fits and sealing techniques to be considered as anything other than crude dashpots or restricted-flow hydraulic cylinders. To produce a realistic LD, high velocity orifices must be installed inside a relatively large component with controlled orifice flow areas less than one millionth of the cylinder bore area. This was not practical in production until the advent of computer-controlled machinery. Taylor [1] provides general information on the evolution and internal designs of hydraulic dampers from the 1890's to date.

The earliest successful and documented use of Lock-up Devices known to the author is found in a series of reports by J.H. Walls and E. Schnitzer respectively, published by the U.S. National Advisory Committee for Aeronautics (NACA) from 1951-1958 [2, 3 & 4]. The NACA, predecessor organization to NASA, was investigating ways to improve aircraft landing gears under conditions occurring on rough, unimproved airstrips. A review of the cited references in the reports

indicates that the research could well be a continuation of similar work begun by the German Luftwaffe (Air Force) in the late 1930's through the cessation of hostilities of World War II. The research approach was to construct a landing gear that would passively adapt to highly variable runways such that it would always prevent dangerous mechanical bottoming of the landing gear on any airstrip. The immediate reason for this was simply that bottoming often caused damage to the aircraft structure, which in turn could lead to loss of the aircraft and crew. The result of the research was a fluid-filled landing gear with fluid locking elements that would form a nearly rigid (but still elastic) brace connection between tire and airframe under severe landing conditions.

The NACA does not reveal why this research was performed, or who sponsored it. However, it may be more than a coincidence that the Great Berlin Airlift of the Cold War occurred in 1948 and 1949, just previous to the start of the NACA research. When the Berlin airlift began, there was only one airstrip in the U.S. occupied section of the city, at Templehof, with only a single short and very rough dirt runway. This runway needed almost continuous repair during the airlift to prevent damage to cargo aircraft.

In any event, the last report in the series was published in September 1958, and no record exists showing any subsequent development for aircraft. However, during the 1960's, the U.S. Navy developed a similar Fluid Lock-up Device which was used to restrict the motion of large shipboard electronics drawers. Under normal conditions, the drawer could be opened and closed manually by the ship's personnel with low force. However, under conditions of severe sea state or weapons detonation, the Lock-up Device would lock the drawer at any relative position until the transient had ended.
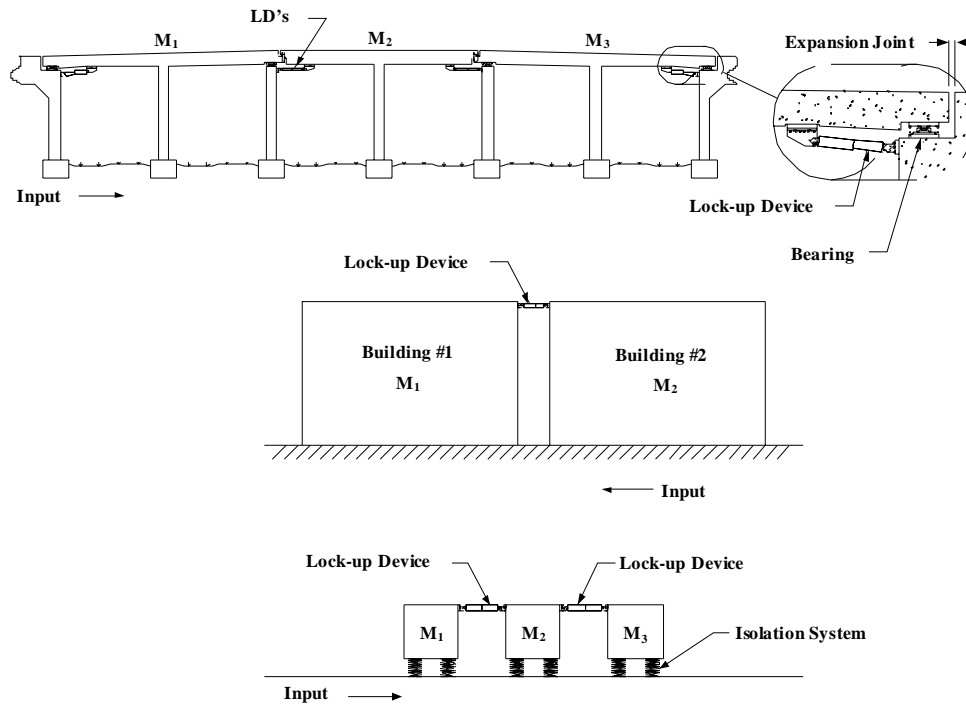

FIGURE 1
TYPICAL APPLICATIONS FOR LOCK-UP DEVICE TECHNOLOGY

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This approach protected both crew and equipment from the potential hazard of the heavy drawer coming loose or adrift during a shock event. These Lock-up Devices were manufactured in output forces ranging from 1,000–5,000 lbs. with available deflections of up to 30 inches. Several thousand devices were manufactured for this application in the period 1966-1980.

Another use for the NACA's Lock-up Device also dates to the 1960's in the design of commercially available hydraulic shock absorbers for industrial use. In this case, the shock absorber designers added lock-up orifices internally to the shock absorber to limit mechanical bottoming under overload conditions. Eventually, many successful industrial shock absorbers for large machines and moving steel mill equipment used passive lock-up orifices which engaged whenever the device was being used in its last 5% of linear travel before mechanical bottoming occurred.

A parallel technology to LDs was developed by various industrial hydraulics manufacturers of the 1960's. The resultant product, known generally as a snubber, was used on nuclear powerplant pipe supports to restrict motion in the event of pipe failure or related transients. Snubbers were constructed from an eclectic assortment of hydraulic parts and pipe fittings, generally including a hydraulic cylinder, an accumulator, and numerous spring-loaded flow control and check valves. In general, powerplant snubbers performed very poorly in service, largely due to their over-complex design and the poor radiation resistance of industry-standard gaskets, packings, and seals. The service records of powerplant snubbers essentially have eliminated this product for use outside the nuclear industry. Nitzel, et al. [5] provide general design and detail information on snubbers used by the nuclear power industry.

Today's applications for seismic and wind protection use the LD as a separate, stand-alone, passive component. In some cases, LDs may be used in conjunction with passive dampers in an isolation system; the LDs dynamically locking discrete masses to form an equivalent monolith, and the dampers dissipating the energy of the earthquake imparted to the resultant macroscopic mass. As will be seen in the next section, an LD is a simple, reliable, and passive device. It has no moving parts except for a piston assembly.


DESIGN DESCRIPTION

A cutaway drawing of a typical LD is shown in Figure 2. The drawing does not include complete detailing of all elements of the device, and is intended to be conceptual. Operation is extremely simple, i.e., motion of the piston head relative to the cylinder sweeps a viscous fluid or putty through orifices in the piston head. In most cases, the seal type and orifice configuration must be selected to be compatible with the specific fluid or putty material selected by the designer. In the case of fluid filled LDs, orifice style may be annular discharge only, restrictor orifice only, or a combination of both. Putty filled units usually use only the annular discharge orifice, due to difficulties involved with the putty itself being locally heated by the restrictor orifice.

Those readers familiar with fluid dampers can easily observe that an LD has identical parts to a monotube style fluid damper. This is entirely correct; the LD is nothing more than a damper, with orifices so small that the device does not displace very far when maximum load is applied. In actual use, the LD has such a short dynamic displacement that it does not absorb or dissipate energy, but rather acts inherently as a hydraulic lock. LD orifices are specifically designed to provide an output force that varies with velocity, usually to the first power or higher. This, coupled with a very low rod displacement speed for maximum force, insures that the LD will have virtually no ability to dissipate energy. Because the LD puts out maximum force at a very low speed, the device's flow orifices are very small in size. Most manufacturers utilize orifices with a very large length to diameter or length to width ratio. This design offers a high flow resistance, yet is relatively free from jamming or clogging during long-term service.

Figure 3 depicts the difference in response between a LD of 200 tons output force, and a typical seismic damper of 200 tons output used in conjunction with isolation bearings in a base isolated structure. It can be observed that the damper is designed to displace substantially as it absorbs and dissipates energy under seismic velocities. In comparison, the LD acts like a rigid link under any significant velocity transient, dissipating virtually none of the seismic energy, and directly transmitting applied seismic forces. In general, basic LDs are fully functional over a wide frequency band. For structural applications, the LD will easily respond to input frequencies from zero to more than 50 Hz.
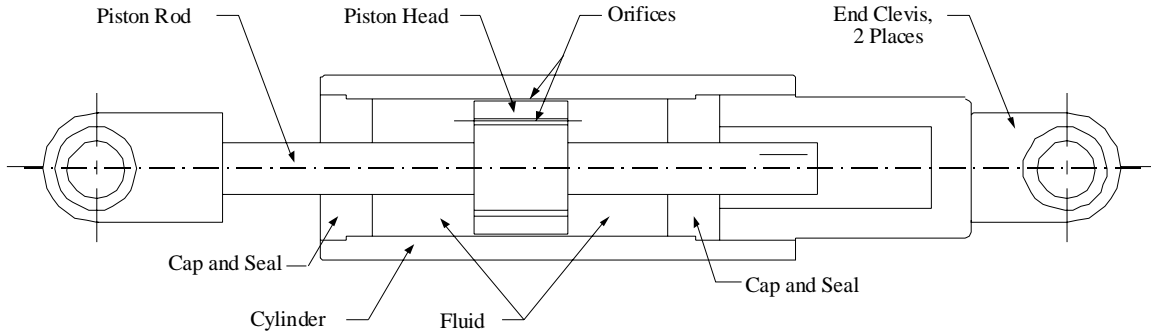
FIGURE 2
CUTAWAY DRAWING OF A TYPICAL LD

LD, Output Force = 40×10^6 V

Damper,
Output Force = $45,730$ V$^{.4}$
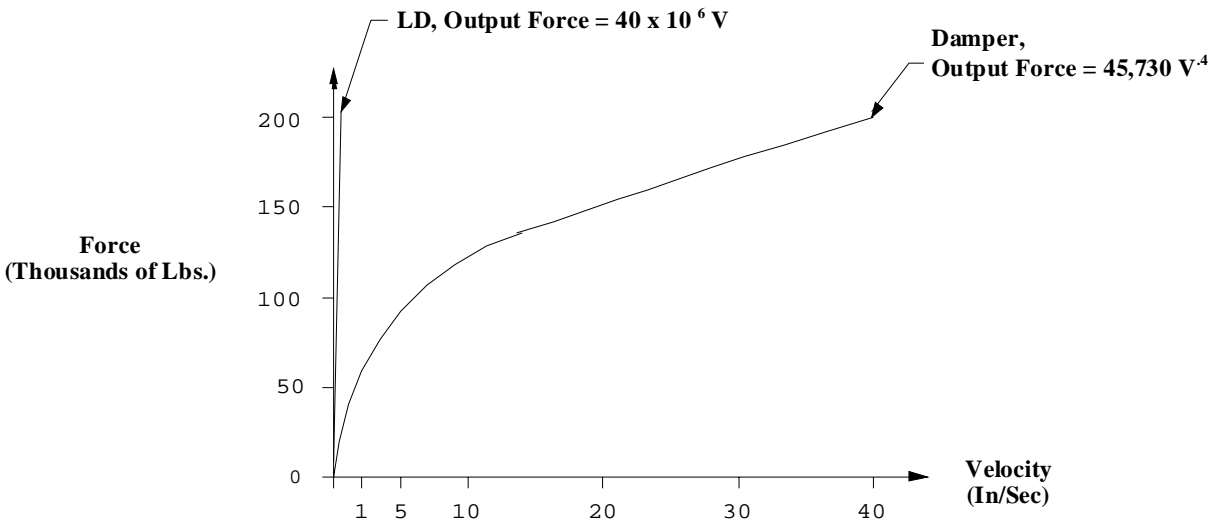
FIGURE 3
OUTPUT RESPONSE CURVES – LD COMPARED TO SEISMIC DAMPER

DESIGN VARIATIONS AND CONTROLLABLE PARAMETERS

There are several manufacturers of Lock-up Devices, and each offers differing designs and available options.

Fluid/Putty: The selection of either fluid or putty operating medium is the largest variation found among the devices. Each operating material requires dedicated seals and orifices manufactured to be compatible with the medium over temperature and time. In general, both fluid and putty mediums are materials from the silicone family, as distinct from conventional petrochemicals. The use of petrochemical fluids and putties is rare in today's LDs, due to environmental restrictions on volatile organic compounds (VOC) contained in this type of media. In any event, the manufacturer will be

required to provide full material safety data sheets on the working medium to insure compliance with national or local regulations. This is particularly necessary with putties, which often are modified with added solvents to keep them from freezing at temperatures below 0 degrees F. For example, in the 1950's when silicone putty was first developed, it was common to use benzene or freon based materials to enhance low temperature operation. Today, this would be both illegal and potentially disastrous to the environment. Additional information about the use of putty materials in LDs and damping devices can be found in the patents of Paul H. Taylor, U.S. patent numbers 2,668,049 and 2,846,211. In addition, Kendall [6] reports on the use of putties in energy absorbing devices intended for automobile crash protection. In comparison to putties, fluid filled LDs normally use a straight, unmodified dimethyl silicone, which is nonflammable, and cosmetically inert to humans.

Available Sizes: LDs are readily available in force levels of 1-2,000 tons. Available displacements range from plus or minus 1 inch to plus or minus 60 inches.

Construction Materials: Depending on seal materials selected, piston rods should be passivated stainless steel, which may be chrome plated for seal compatibility. The balance of the materials used to construct the LD are usually corrosion protected steel, either plated and/or painted to meet project requirements. Articulation of the LD is provided by spherical bearings at the mounting interfaces to the structure. The use of spherical bearings (ball end joints) allows multi-axis end rotation of the LD, preventing binding and providing ease of installation. These bearings can be stainless steel, plated steel, or polymer/moly coated steel, again depending on project requirements.

Lock-up Speed: The lock-up speed for an LD is generally defined as the translational velocity at which the LD will put out its rated force. In most cases, this will be a velocity that is 2 orders of magnitude below the anticipated range of seismic or wind induced motion measured across the mounting pins of the LD. Typical lock-up speeds are between 0.005 in/sec. and 0.01 in/sec. for bridge and building applications. Thus, a typical specification call-out would be for the LD to be tested at maximum force by applying that force, and measuring the resulting velocity, which must be below a specified maximum, or within a specified bandwidth.

Thermal Expansion Speed: The maximum anticipated speed of expansion and contraction for a structure is usually much lower than the lock-up speed, this being measured across the mounting pins of the LD as a resultant value. Typical maximum thermal motion speeds are generally in the range of 0.0001 to 0.001 in/sec., with allowable LD output forces being from 3% to 10% of the maximum rated force of the device. Thus, a typical specification call-out would be for the LD to be tested at a specified thermal motion speed with verification that the resulting output force is less than a specified value, usually 10% of the maximum rated force.

Lock-up Displacement: The lock-up displacement of an LD is that required for the device to go from zero force to full force. The reason that this displacement exists is because of the elasticity of the LD parts, and the elasticity (bulk modulus) of the fluid or putty. The dynamic spring rate of the device can easily be expressed as the rated force of the LD, divided by the lock-up displacement.

In most applications, the lock-up displacement is expressed as a maximum, and is generally in the range of 5% of the available device deflection. By example, if an LD has available displacement of plus or minus 4 inches, the lock-up displacement will be roughly equal to 5% (4 in.) = 0.2 in. As a general rule, for a given force level, the lock-up displacement can be altered by selecting a larger or smaller diameter LD, and thereby changing the relative elasticity of the LD parts and the working medium.

Service Life: The service life of a Lock-up Device is limited by three items, these are:

1. The cyclic life of the seals
2. Aging or cyclic degradation of the working medium
3. Corrosion of metallic parts

The most severe applications for LDs is on highway and railroad bridges, where at least one measurable cycle of thermal expansion and contraction occurs daily, along with traffic vibration and, in some instances, train braking loads. Assuming a 50 year life without maintenance, this is equivalent to a minimum of 18,250 cycles when only the thermal motion is considered. Manufacturers should submit test data documenting a minimum life of at least 20,000 full displacement cycles with no degradation of output.. These tests should, of course, be made with a fully operational device. Often, to facilitate a reasonable time for testing, the orifices inside the LD are enlarged by a factor of 100. This allows testing to take place at cyclic rates much faster than one per day, without the device locking up. Some optimistic manufacturers have suggested running this test without fluid or putty in the device. However, only a tiny amount of leakage (or extrusion in the case of putty) on each cycle can cause large reductions in LD performance over 50 years of cycling. In addition, putty-filled devices can experience liquidation or degradation of the putty itself under cyclic testing. Thus, the only realistic test method for cyclic life is to use a functional device.

Aging or cyclic degradation of the working media can be simply evaluated by the cyclic test unit in the case of fluid filled devices. However, in the case of putty filled devices, accelerated aging tests must be performed to assure that the putty will not harden over time by cross-linking its molecules, or out-gassing solvents. The normal method of age testing putty involves heating the material to 220-250 degrees F for 100 hours in a vented furnace. After the test, the putty is tested for apparent viscosity, and the results compared to pre-test properties.

Corrosion of metallic parts is usually tested in a salt fog chamber, using established and published procedures of the American Society for the Testing of Materials (ASTM), or the AMS standards of the Society of Automotive Engineers (SAE). The appropriate number of hours for the salt fog test is selected by the engineer of record. The worst case being that of highway bridge usage, where a value of 1,000 hours exposure is generally considered as a representative test.

Acceptance Testing: Similar to any life safety product,, each Lock-up Device manufactured must be acceptance tested to full force and velocity in both operational directions. Most users elect to specify additional load testing under thermal expansion/contraction conditions. In addition, all deliverable units should be tested to bottoming under full load in compression and extension to verify full stroking capability.

DESIGN CASE STUDY

A typical application for LD technology can be found on the new Sidney Lanier Bridge, being constructed in Brunswick, Georgia. This highway bridge is of the "signature" type, utilizing a cable-stayed suspension for the main span. The new structure will be the longest spanning bridge in Georgia, and will allow large ships to enter the Port of Brunswick. Total length of the bridge is 7,780 feet, with the main span measuring 1,250 feet between the suspension towers, with two 625 feet side spans. Cost of the complete main span is $65,000,000, and features a concrete bridge deck. Figure 4 depicts an artist's conception of the completed bridge.

The bridge designers were required to perform extensive studies to insure that the new bridge would be safe during conditions of hurricane-force winds. A second design consideration was low-level seismic transients, this region of Georgia being seismic Zone 1-2, compared with Zone 4 for Los Angeles and San Francisco, California. An area of concern for the designers was longitudinal wind and/or seismic motion of the main span's concrete deck. Under adverse conditions, the deck could impact the approach spans, causing damage to the costly expansion joints and the bridge structure itself. Calculations indicated that an LD was a good solution to the problem, with four LDs of 250 tons force each providing the required restraint force. Figure 5 is an envelope drawing of the LD, which was manufactured by Taylor Devices, Inc. of North Tonawanda, New York.

Basic specifications are:

1. Rated Force   =   250 tons

2. Available Stroke   =   plus or minus 8.0 inches

3. Thermal Expansion =   4 inches in 10 hours with an applied force of less than 25 tons

4. Lock-up Speed/Displacement:

Rapid application of 250 tons of force (in less than 0.5 seconds) shall not cause more than 0.25 in. total deflection, nor more than an additional 0.125 in. deflection during a 5 second sustained load. Test to be performed in one direction, followed immediately by testing in the opposite direction.

Figure 6 provides typical test results for the lock-up speed/displacement test for the completed LD. Figure 7 is a photo of the LDs ready for shipment to the job site.
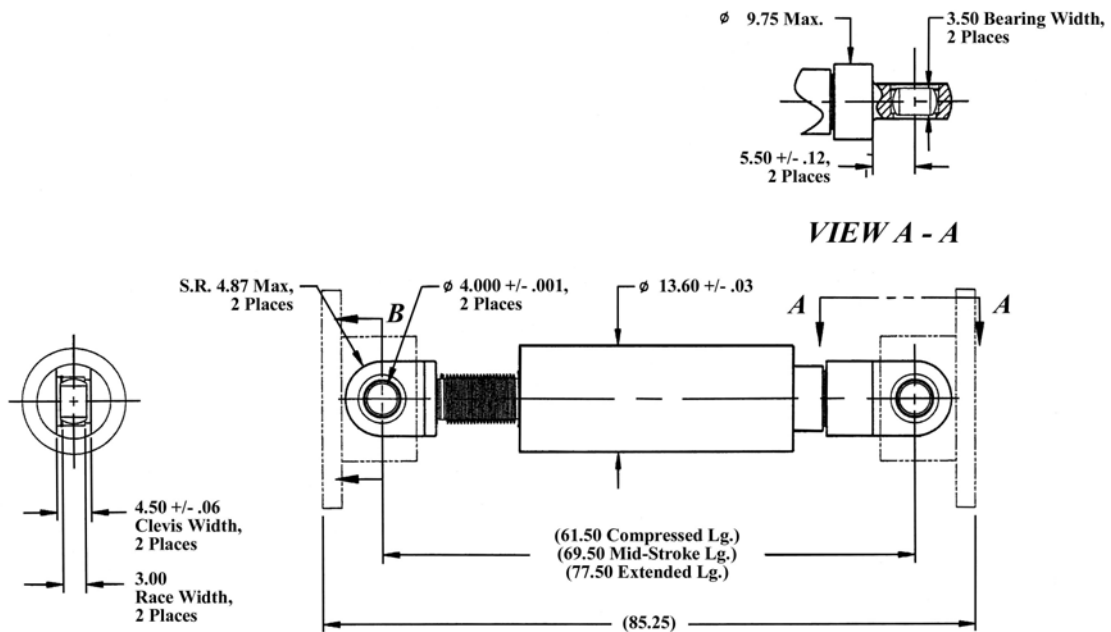

FIGURE 4
ARTIST'S RENDITION OF SYDNEY LANIER BRIDGE

FIGURE 5
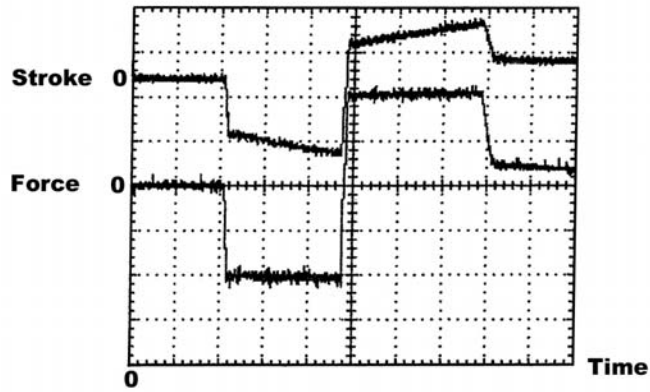**ENVELOPE DRAWING OF LD**

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FIGURE 6
LD TYPICAL TEST RESULTS

Calibration
Force: 243,212 lbs/division
Stroke   .20 in/division
Time: 2 sec/division

Results
Force Applied by Test: 504,665 lbs, both directions
Loading Tension Stroke: 0.230 in. (0.25 in. max.)
Loaded Tension Stroke: 0.090 in. (0.125 in. max.)
Loading Compression Stroke: 0.190 in. (0.25 in. max.)
Loaded Compression Stroke: 0.080 in. (0.125 in. max.)

FIGURE 7
LDs READY FOR SHIPMENT TO JOBSITE

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CONCLUSIONS

A Lock-up Device is essentially a form of a very stiff viscous damper, with an orifice so restrictive that virtually no energy is dissipated during a transient event. The Lock-up Device allows flexibly connected masses to act like a rigid, single mass during a shock event, yet allows the same masses to move freely during normal mode conditions.

Lock-up Device designs are extremely simple, and available sizes range from 1 ton to 2,000 tons of force, and displacements up to plus or minus 60 inches.

Present applications include bridges of all types, base isolated structures in high seismicity areas, and fixed base buildings subjected to wind storm or low level seismic transients.

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