DEVELOPMENT AND TESTING OF AN IMPROVED FLUID DAMPER CONFIGURATION FOR STRUCTURES HAVING HIGH RIGIDITY

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It is generally recognized that structures having high rigidity can be characterized as having relatively small displacements when a shock input occurs. These small deflections are such that the implementation of added damping components has proven to be very difficult. Research was performed combining fluid dampers with a simple mechanical toggle brace assembly that magnifies the small displacement of the structure, while simultaneously producing the required damping force. Test results are provided with the toggle braces and fluid dampers installed on a 32,000 lb. structure, subjected to seismic ground motion transients on a large seismic shake table.

INTRODUCTION

The concept of adding damping devices to a structure to improve performance under shock and vibration inputs has been thoroughly proven by widespread applications over the past century. These applications range from automotive suspensions, to buildings and bridges, to military structures subjected to weapons' effects.

Depending on the application, optimal damping levels vary widely. For example, automotive suspensions typically have damping in the 20-30% critical range, utilizing the so-called "hydraulic shock absorber" to provide the required damping levels. Tall buildings subjected to wind inputs are often equipped with various types of dampers to provide 5-10% total damping, which includes only 1-3% from the structure itself. Military systems are inherently rugged, yet are often optimized under weapons' grade shock by adding very large amounts of damping, often equivalent to 100%-2000% of critical. Taylor and Constantinou (1994) [8] and Taylor and Lee (1987) [9] provide additional background and historical data on the use of added damping in structures. Constantinou, et al. (1996) [1] and Soong and Dargush (1996) [6] report on the use of dampers within building and bridge structures.

The implementation of damping devices within relatively stiff structural systems has proven to be very difficult. This is due to the small displacements that occur when a structure of this type is subjected to a shock and/or vibration input. The problem becomes even more difficult if the damping element is required to span building bays, where the inherent flexibility of attachments and brace elements becomes a major issue. To eliminate excessive brace and attachment deflections, these elements must be made massive in both the cross sectional area and bending moment of inertia. However, even when a design can accommodate heavy, oversized structural members, inherent flexibility in the damping device itself becomes a design issue. For example, consider the simple rectangular building bay shown in Fig. 1, which includes a simple diagonal brace with an integral fluid damper. This bay is 10 feet high and 30 feet wide. Assuming that the building is relatively rigid, structural engineers would expect roughly .5% lateral drift (expressed as a percentage of the story height), before yielding would occur. This lateral drift is depicted in exaggerated form in Fig. 1 by dashed lines.

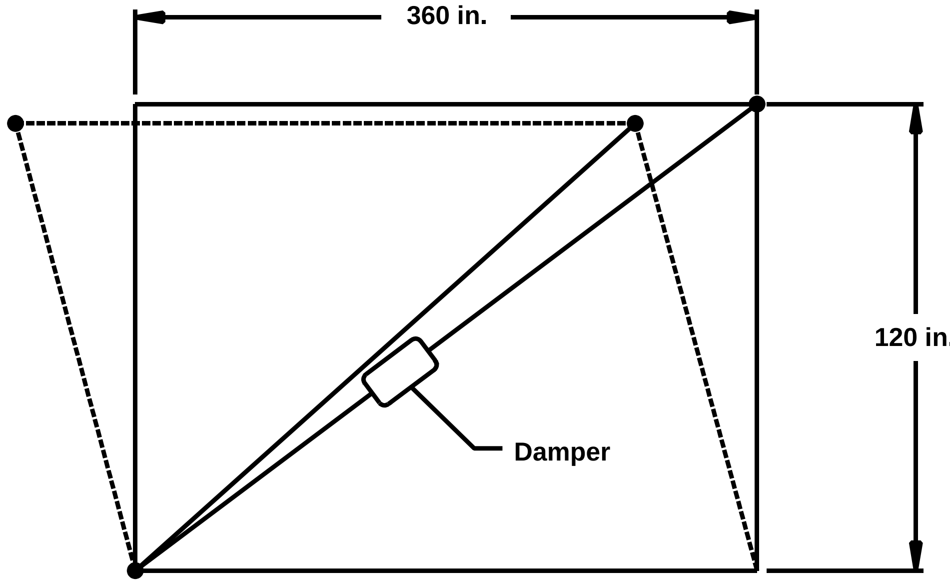

FIGURE 1
BUILDING BAY WITH DAMPER

Using simple geometry and solving for the diagonal brace lengths under both positions shown reveals a total of only .56 in. shortening of the diagonal under the defined input.

A typical design specification for a fluid damper of this type would require a total deflection based on the following summation:

Dynamic motion under ± .5% story drift	=	± .56 in.
Seismic design code safety factor (100%)	=	± .56 in.
Provision for thermal expansion/contraction	=	± .13 in.
Total required deflection capability	**=**	**± 1.25 in.**

A simple fluid damper block layout is shown in Fig. 2, which generates damping forces by the orificing of fluid through a piston head configuration. For a typical building bay (based upon the dimensions of Fig. 1), the damper would have an output force in the range of 50,000-100,000 lb. Taylor and Constantinou (1994) [8] reported that operating pressures for "real world" building dampers vary from 2,000-10,000 psi. Damping pressures below the 2,000 psi value result in an excessively large device. Pressures above 10,000 psi require special and costly design considerations. When one designs a damper suitable for small deflections, operating at pressures of 2,000-10,000 psi, compressibility of the working fluid and pressure expansion of the damper's cylinder wall cannot be ignored. Both of these effects act together such that the damper will require a finite amount of displacement to elevate fluid pressure to operational levels. This effect is known as the "rise deflection" or "nose angle" of the damper's force-deflection curve, and is verified by testing the damper with a step function velocity input. A reasonable approximation of this effect can usually be made by multiplying the fluid's compression fraction at maximum damping pressure times the total length of the fluid column when the damper's piston is fully offset in one direction. Taylor (1971) [7] reports that various manufacturers of silicone damping fluids have published compression values of 5% volumetric compression at 8,000 psi. For our example, with plus or minus 1.25 in. displacement, the largest rise deflection will occur when the piston is fully offset in one direction, then displaced in the opposite direction. If we assume an 8,000 psi operating pressure, and use the 5% compression value for silicone, the damper will have a rise deflection of:

$$.05 \times (2 \times 1.25) = .125 \text{ in.}$$

Thus, to reach full damping force will require .125 in. of damper displacement. Actual dynamic displacement to yield is .56 in. for the stiff structure defined. Therefore, the damper has essentially wasted nearly a quarter of the structure's displacement just to build up to its full damping force value. A second problem is that when the damper is operating in the deflection range associated with its rise deflection, the damper response provides very little energy dissipation. This is due to the relatively low force that is provided, and the fact that the initial response of the fluid is somewhat elastic in nature, even with the damping orifices providing resistive flow. If the designer wished to keep the structure elastic under wind or repetitive seismic inputs, deflection would be limited to a lesser value than the .56 in. to yield. This will even further reduce damper effectiveness.

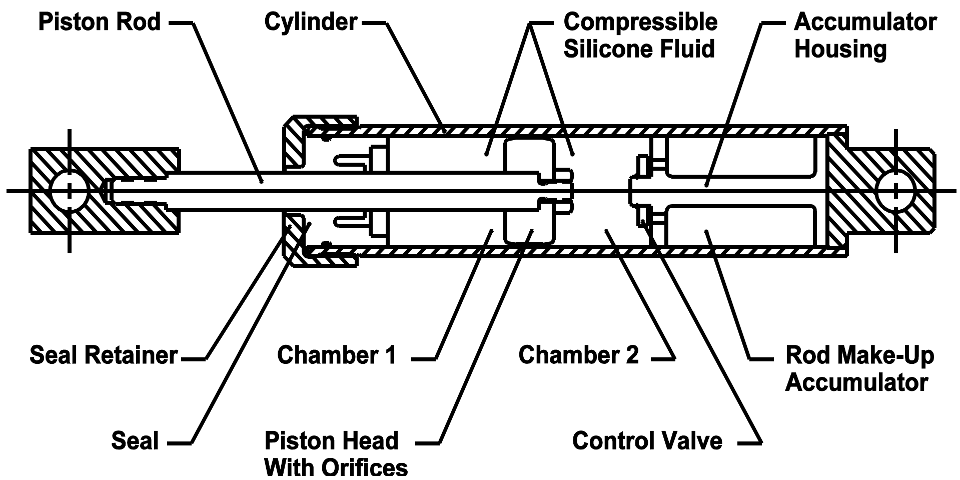

FIGURE 2
FLUID DAMPER

DEVELOPMENT OF IMPROVED DAMPER CONFIGURATIONS

The most direct solution to providing adequate damper performance in a rigid structure is simply to use a large bore damper acting at very low pressure to minimize the rise time effects. This solution is impractical in that the damper becomes difficult to package due to its large envelope, coupled with an equally high cost. A second direct solution is to find a less compressible fluid. This solution has also proved impractical since all currently available products with lower compressibility are either toxic, flammable, or temperature sensitive.

A more effective solution involves the use of a lever style mechanism that multiplies the deflection of the building while simultaneously reducing the required amount of applied force at the damper mounting points. This approach has been studied previously by various researchers. Figure 3 depicts a typical solution, which in this case is Taisei Corporation's "DREAMY" System, as reported by Hibino, et al. (1989) [3].

The system of Fig. 3 combines a substantially braced column with a driving arm connected to the column and upper floor with hinge pins. The end result is that a simple mechanical lever is used to increase the effective damper stroke. Unfortunately there are major impediments to actually using a design such as this in a building or bridge structure. Of primary concern is that the entire mechanism must be designed to have very little flexing or strain in its elements. Otherwise, flexing of the mechanism itself will be of the same level as the rise deflection of a direct acting damper, thus gaining no design improvement. The requirement for a rigid mechanism necessitates that the hinge points use extremely close fits, preferably with tapered roller bearings or similarly close clearance bearings. In addition, all of the mechanical links of the mechanism must be relatively large and heavy to prevent flexing under load. A second problem with the

DREAMY System involves out-of-plane motions. Since seismic and wind motions are rarely going to be applied along a single building axis, a bracing system must accept substantial out-of-plane motions without buckling or binding. As can be observed from Fig. 3, the same hinge points that must be close fitting to allow in-plane response must not bind in the out-of-plane direction, which is very difficult to do without excessive costs.

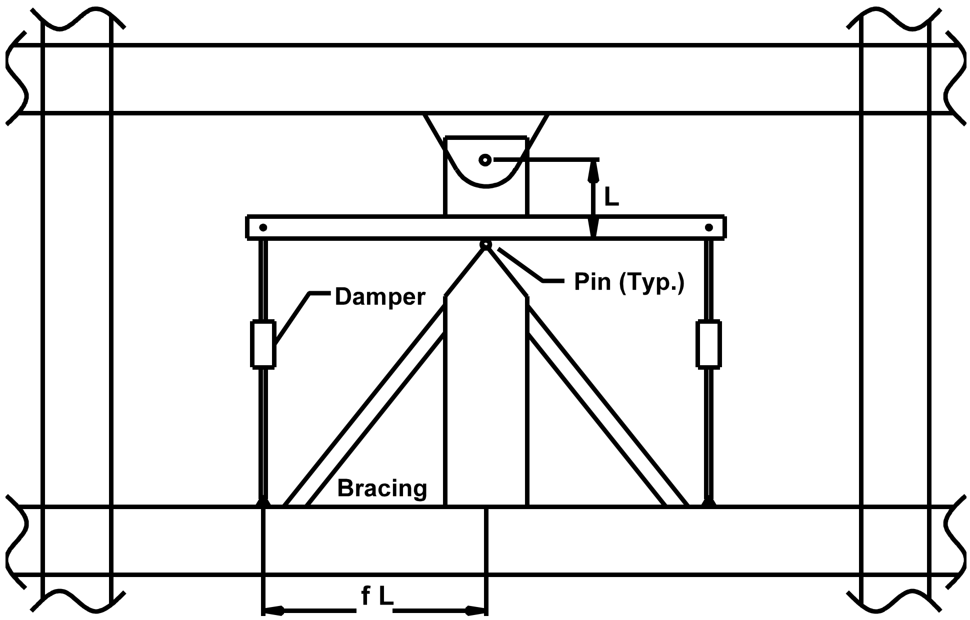

FIGURE 3
ILLUSTRATION OF DREAMY SYSTEM

THE TOGGLE BRACE MECHANISM

This research project involved the development of an improved mechanism that would eliminate problems associated with conventional design approaches to damper installation within a relatively stiff structure. Early in the design process it was recognized that a similar problem with mechanisms exists in the action (operating mechanism) design of small arms, particularly those encompassing semiautomatic or fully automatic firing modes. In this weapon type, action mechanisms must be lightweight out of necessity, yet rigid enough to firmly seal the weapon's breech when the weapon is fired. In addition, the action must be able to close and unlock the breech to allow firing, cycle to allow extraction and ejection of the fired cartridge, plus feed and chamber another round. All of these functions must be obtained with a low applied force.

A review of small arms designs revealed two successful applications of toggle mechanisms to accomplish the above tasks. One is the so-called lever action, used in the Volcanic, Henry, and Winchester repeating rifles, circa 1845-present. The second is the Luger (Parabellum) pistol, first adapted by the Swiss Army in 1900, and used by German forces in World Wars I and II. Certain similarities exist between these two weapons, due to the fact that the basic design for the pistol's action was originally purchased from Hugo Borchardt, who had been employed by Winchester Arms as an engineer in the 1890's. Figure 4 is a schematic of the so-called "toggle breech," from George Luger's patent of 1900, depicted in the full recoil position. When the breech slide returns to battery (forward), the toggle is nearly fully extended and serves as an inertial breech lock.

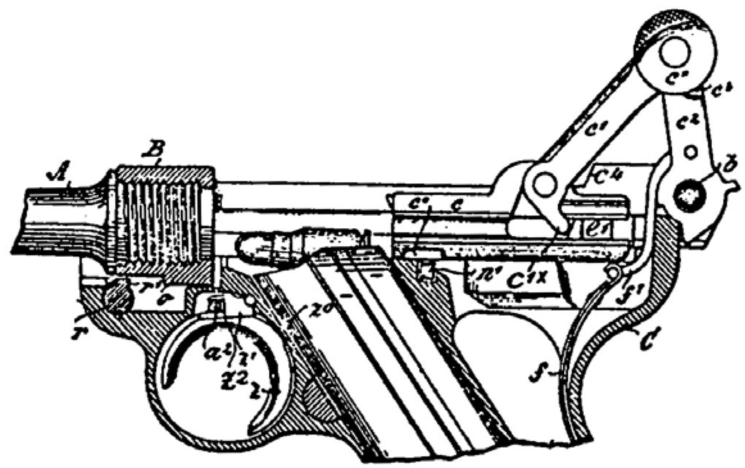

FIGURE 4
TOGGLE BREECH MECHANISM – MODEL PO8 LUGER PISTOL

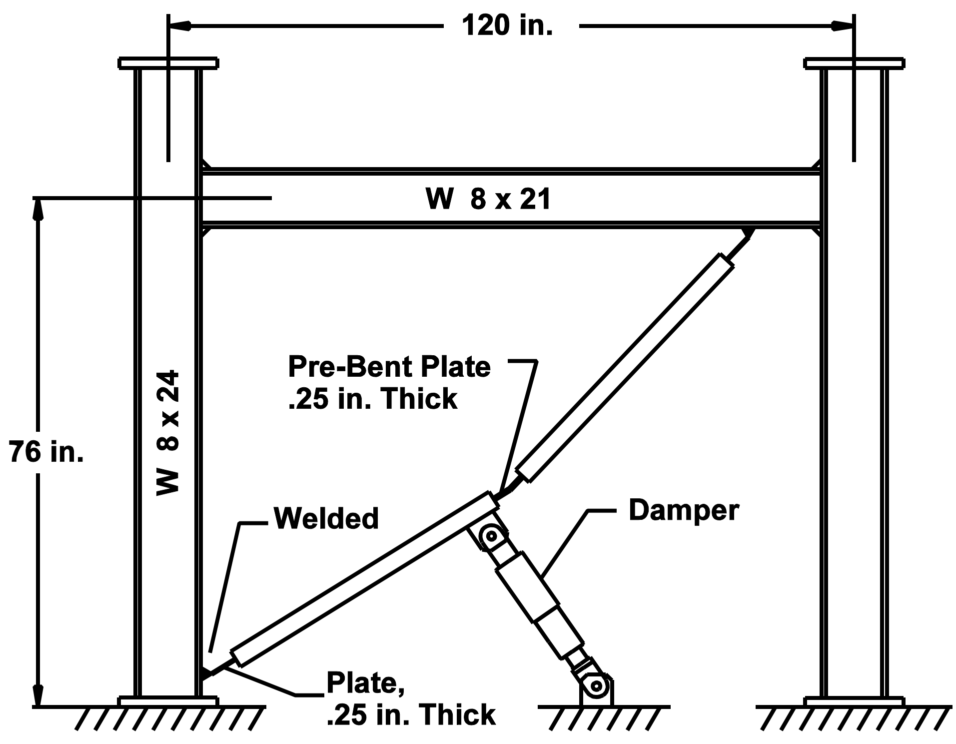

FIGURE 5
TESTED FRAME WITH TOGGLE BRACE-DAMPER SYSTEM

Adapting this mechanism to a building frame involves using the toggle as a diagonal brace, with one end of the damper installed proximate the toggle pivot, and the opposite end attached to the building frame. The basic design is depicted in Fig. 5, which also is the actual frame tested for this report. In this configuration, a relatively small lateral deflection in the building frame will cause a much larger deflection at the damper, due to the toggle mechanism multiplying deflections at the damper mounting point. Various rigid body geometric studies were performed which demonstrated useable deflection magnifications in a full-sized frame of between 3 and 4. Since desired damper energy dissipation is of a specific value, using the toggle brace to multiply deflections reduces the required force from the damper itself, since absorbed energy per cycle is the integral of damper force with respect to displacement. Note that the configuration tested in Fig. 5 resulted from using readily available materials and components for construction. In an actual structure, connection detailing would fasten each brace connection at a beam to column junction to minimize bending stress.

The design of Fig. 5 also addresses the condition of out-of-plane buckling, because the low angular deflection of the toggle allows the use of simple flexural connections. In this case, the required flexure was determined to be a section of one-quarter inch thick steel plate, welded in place between two pieces of structural tube that make up the toggle. Similar plate flexures are used to attach the toggle mechanism to the building frame. The use of flexures allows low force hinging in the plane of damper motion, while providing substantially stiff resistance to out-of-plane motion. In fact, if the flexure is made deep enough, its out-of-plane bending moment of inertia can be of any value, even to the point where the hinge is more resistant to out-of-plane motion than the structural tubing forming the balance of the toggle brace.

The toggle brace damper system of Fig. 5 is obviously much less costly to construct than the DREAMY System of Fig. 3, requiring only a few simple structural shapes and plain welds for construction.

TEST STRUCTURE

The test structure for the toggle brace consisted of two identical frames of the configuration depicted in Fig. 5, with a 32,000 lb. concrete block mass attached on top. The test structure was designed to be essentially a half length frame, with the majority of tests conducted with beam to column connections providing a fundamental frequency of 3.2 Hz in the horizontal direction. This fundamental frequency is representative of a relatively stiff structure. A single damper was installed in each of the test frames, thus providing a total of 2 dampers in the structure. Component level tests on each damper revealed essentially linear damping, with a constant of 90 lb-sec/in. over the velocity range of 0-20 in/sec. Each damper measured 1.75 in. diameter, 18 in. extended length, and had available deflection of plus or minus 2 in.

The entire structure was erected on a large seismic shake table located at the State University of New York at Buffalo. A total of 31 transducers were installed on the structure, including 18 accelerometers, 11 displacement transducers, and 2 load cells. Banded white noise excitations in the 0-50 Hz range were input to the structure by the shake table to obtain the related transfer functions of the frame, both with and without dampers. Analysis of the transfer functions indicated that the test structure behaved essentially as a single degree of freedom system, with a fundamental frequency of between 3.0 and 3.2 Hz for all tests. The variance of the fundamental frequency appeared to be due to connection stiffness during the test series, and this in turn was dependent on bolt tension in the various frame connections from test to test. Damping ratios were obtained from the transfer functions, and were found to be 4.5% critical for the bare structure, and 21.5% critical for the structure with dampers installed.

Performance of the structure was evaluated using eleven different earthquake records at various intensities, with a total of 80 separate tests performed. All tests were successfully completed, without anomaly. No damage or permanent deformation was noted in the frame, braces, or dampers during the tests. Table I lists selected earthquake motions from the testing matrix. All tests were performed in prototype scale, which involved compressing the motion in time by a factor of the square root of 2, thus satisfying the similitude requirements for a half length scale model.

TABLE I
Earthquake Motions Used In Shake Table Testing And Characteristics In Prototype Scale
(All Components Are Horizontal)

EARTHQUAKE	RECORD	PEAK ACCEL. (g)	PEAK VEL. (in/sec)	PEAK DISPL. (in)
El Centro S00E	Imperial Valley, CA May 18, 1940, component S00E	0.34	13.16	4.27
Taft N21E	Kern County, CA July 21, 1952, component N21E	0.16	6.19	2.64
Hachinoche NS	Tokachi-Oki earthquake, Japan, May 16, 1968, component NS	0.23	14.06	4.68
Mexico N90W	Mexico City, September 19, 1985, SCT Building, component N90W	0.17	23.81	8.34

SEISMIC TEST RESULTS

Table II provides test results for the structure, with the earthquake inputs listed in Table I. The data listed in Table II includes the following information:

1. **Excitation**

   This includes the specific earthquake transient and intensity factor. By example, a 50% intensity factor indicates the record's acceleration was multiplied by a factor of 0.5 for the test listed.

2. **The Recorded Peak Shake Table Acceleration, Velocity, and Displacement**

   Accelerations and displacements were directly recorded. Velocities were obtained by numerical differentiation of the displacement record with respect to time.

3. **Frame Motions**

   The reported drift is the measured displacement of the upper beam to column connection with respect to the column base. Joint acceleration is the measured horizontal acceleration at the upper beam to column connection. Values listed are the average of discrete motions for the two frames.

   Structural symmetry was very good for a structure of this size having high stiffness. Drift values from side to side were within 10% of each other for all cases with dampers, and within 15% for the undamped cases. Similarly, joint accelerations from side to side were within 15% of each other for cases with dampers, and within 20% for the undamped cases.

4. **Damper Response**

   Damper force and end to end displacement are reported, measured along the damper centerline. Values are the average of the two dampers, installed one per frame. All measured side to side damper displacements were within 13% of each other, with measured forces within 15%.

TABLE II
Seismic Test Results

EXCITATION	PEAK TABLE MOTION			FRAME MOTION		DAMPER MOTION	
	ACCEL. (g)	VELOCITY (in/sec)	DISPL. (in)	DRIFT (in)	ACCEL. (g)	DISPL. (in)	FORCE (lb)
El Centro, 25%	.084	2.27	.40	.23	.222	No Dampers	
El Centro, 50%	.150	4.34	.81	.16	.187	.39	768
El Centro, 100%	.320	8.74	1.63	.40	.377	.93	1641
Taft, 100%	.165	4.42	.86	.35	.309	No Dampers	
Taft, 100%	.155	4.03	.86	.17	.191	.39	680
Taft, 200%	.309	7.84	1.72	.35	.351	.82	1351
Hachinoche, 25%	.059	2.10	.48	.10	.110	No Dampers	
Hachinoche, 50%	.107	4.10	.97	.22	.225	No Dampers	
Hachinoche, 50%	.118	4.03	.97	.13	.147	.30	557
Hachinoche, 100%	.234	8.14	1.94	.25	.284	.58	1060
Mexico City, 100%	.188	16.34	3.94	.18	.199	.48	427

Results include one baseline excitation of the structure without dampers for each transient except Mexico City. The Mexico City earthquake tends to violently resonate lightly damped structures, and test personnel elected not to put the structure (and test lab) at risk by testing without dampers. Previous researchers have reported that the addition of linear fluid dampers to a structure subjected to earthquakes provides a reduction in both stress and deflection. Thus, the allowable seismic input can be greatly increased when fluid dampers are added, provided that total damping ratios in the 20-30% critical range are obtained. The results from Table II clearly show the expected improvement for a structure with this level of fluid damping.

Compared to other damper installations, results clearly demonstrate the ability of the toggle brace to very effectively multiply the structural drift. The average of all tests in Table II show that damper displacement is 2.372 times the measured drift. By comparison to other tested damper configurations, such as Constantinou and Symans (1992) [2], Reinhorn, et al. (1995) [4], Seleemah and Constantinou (1997) [5], the required damper force with toggle bracing is substantially smaller. This is due to the toggle brace's ability to multiply structural drift at the damper. The flexural connections used throughout the tests proved both efficient and reliable. Post test inspection revealed no cracking in any of the flexures, even though the flexures were simply welded in place, then subjected to a total of 80 individual earthquake inputs.

CONCLUSIONS

Structures having high rigidity experience relatively small deflections and interstructural velocities under conditions of seismic or similar types of transient shock. Because of this, the conventional application of energy dissipation devices may not be feasible or cost effective. An improved damper configuration has been investigated, utilizing a toggle mechanism to magnify internal structural deflections, allowing a more effective implementation of added damping devices.

Experimental results were obtained from a 32,000 lb. test structure utilizing two fluid dampers and two toggle brace elements. The frame was relatively rigid, with a 3.2 Hz fundamental frequency in the horizontal direction. During all tests, horizontal drift of the structure was less than 0.5 in. Simple welded flexural connections were used for the toggle hinge and end attachments. Because of the anticipated improvement expected with the toggle brace mechanism, a relatively small 1.75 in. diameter fluid damper was used, with an available deflection of plus or minus 2 in.

The test structure was subjected to transient excitation on a large seismic shaking table. Test inputs included some eighty individual earthquake transients, varying both in wave form and intensity. The results demonstrated the ability of the toggle mechanism to magnify displacements significantly. This provides excellent damper performance, even though maximum measured horizontal deflection was only 0.5% of the structure's vertical height. Conventional approaches to damper installation would not have been possible on the tested structure, due to the relatively small deflections.

The braces and flexural connections demonstrated sufficient out-of-plane stiffness such that no out-of-plane motion was observed. The flexure design, though very simple, proved to be completely reliable. Damper performance was excellent, with comparable results to those obtained by other researchers on more flexible structures, using direct acting dampers in conventional diagonal or chevron bracing. The toggle brace's ability to multiply deflections allowed a smaller diameter, longer stroke damper to be utilized. On a stiff structure, such as that tested here, the cost for a high force, short stroke damper used with conventional bracing would be much higher, and probably cost prohibitive as a design solution.

In summary, the toggle brace damping system appears to be an excellent solution to the implementation of added-on damping devices to rigid structures of all types. Advantages include relatively low damper cost, a simple bracing element design, and low installation cost. Patents are now pending on the design and concept.

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