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SHORT COMMUNICATION

Seismic Applications of Energy Dampers

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ABSTRACT

Damping devices based on the operating principle of high velocity fluid flow through orifices have found numerous applications in the shock and vibration isolation of aerospace and defence systems. The study aims to investigate the feasibility of using energy dissipating fluid viscous dampers in structures to protect against seismic loads and to prove analytically and experimentally that fluid viscous dampers can improve the seismic capacity of a structure by reducing damage and displacement without increasing stresses.

Both steel and concrete structures were considered. Extensive analytical and experimental investigations have led to the hazard mitigation applications on buildings bridges. A series of experiments were performed to demonstrate the benefits of fluid viscous damping devices in steel moment frame and reinforced concrete building models and a steel bridge model were tested, and all exhibited improved resistance to a variety of seismic loads. Furthermore, fluid dampers would be used as elements of seismic isolation systems for enhancing their energy dissipation capability.

Keywords: Dampers, models, floor displacement, relative displacement, hysteretic, forced deformation, energy dissipation, shock, vibration, viscous dampers, energy dissipating fluid, seismic loads, fluid dampers

1. INTRODUCTION

The applications of fluid viscous dampers to vibration control dates back to the 1993's in the USA, when these were first used on aircraft as a mean of controlling vibration-induced fatigue in airframes. Fluid viscous dampers were installed into the tail section of this carrier-based F-16 supersonic jet, within the aircraft's arresting hook. When the aircraft lands, the arresting hook engages cables on the aircraft carrier deck, and the fluid viscous damper is used to prevent shock loads from being transmitted to the aircraft[1]. By 1999, Sinha and Choudhury[2] used such dampers with a little modification (high compressible silicon fluid) called energy dissipating fluid (EDF) viscous dampers in various models, including existing structures (both steel and concrete) in India. The system may be very profitable in high altitude warfare like the war in the Kargil region of Jammu & Kashmir in India, because it is not only shock proof (whether it is an artificial or a natural shock) but also the safest and reliable against sudden disaster of the structure under any circumstances.

Comparatively, various energy dissipating devices have been proposed as add-on devices to buildings for improving their seismic resistance. Most notable of these devices are the mild steel dampers, frictional dampers, and viscoelastic dampers. Experimental studies have demonstrated that these dampers are

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effective in reducing drifts while maintaining shear forces at the same level or, under certain conditions, less than those of structures without dampers. However, due to their hysteretic or strong viscous behaviour, these devices introduce substantial axial force component which is in phase with the maximum bending moment in columns.

Energy dissipation fluid viscous dampers may be designed to have as linear viscous devices so that they introduce damping forces which are out-of-phase with drifts and column-bending moments. These can be very effective in reducing drifts and shear forces without introducing axial column forces which are in phase with the column-bending moments. These significant properties of EDF viscous dampers have been confirmed in shake table testing of a series of a single storey and a three-storey model structures. The experimental results demonstrated reductions in the drifts and shear forces, of the order of two to three, in comparison to the responses of the models without dampers for a wide range of earthquake input motions.

2. CONSTRUCTION OF ENERGY DISSIPATING FLUID VISCOUS DAMPERS

The construction of an EDF viscous damper is shown in Fig. 1. It consists of a stainless steel piston with bronze orifice head and an accumulator. It is filled with silicon oil. The piston head utilises specially shaped passages which alter the flow characteristics with fluid speed so that the force output is proportional to $/u/^x$, where u is the piston rod velocity and x is the predetermined coefficient in the range 0.5 to 2.0. A design with x equal to 1 results in a linear viscous damper.

This behaviour dominates for various frequencies of motion below a predetermined cutoff frequency (related to the characteristics of the accumulator values). Beyond this frequency, the EDF viscous dampers exhibit strong stiffness in addition to substantial ability to dissipate energy. The existence of the cutoff frequency is desirable, since the lower modes of vibration are only damped, while the higher ones are both damped and stiffened so that their contribution is completely suppressed.

The orifice flow may be compensated by a passive bimetallic thermostat which allows operation of the device over temperature range 40 °C-70 °C. The performance characteristics of the device are considered state-of-the-art[2]. The device with fluidic control orifices, bimetallic thermostat, and special silicon oil originated within products used in classified applications of the air defence force[3].

The EDF viscous dampers tested initially had all the aforementioned characteristics and these were designed to behave as linear viscous dampers. Each damper had stroke of ± 51 mm, length of 280 mm and weighed 100 kg. These were used in the tested building model described in squel and a bridge model.

Figure 2 shows recorded loops of force versus displacement of one damper at 23 °C. The purely viscous nature of the device is apparent. Figure 3

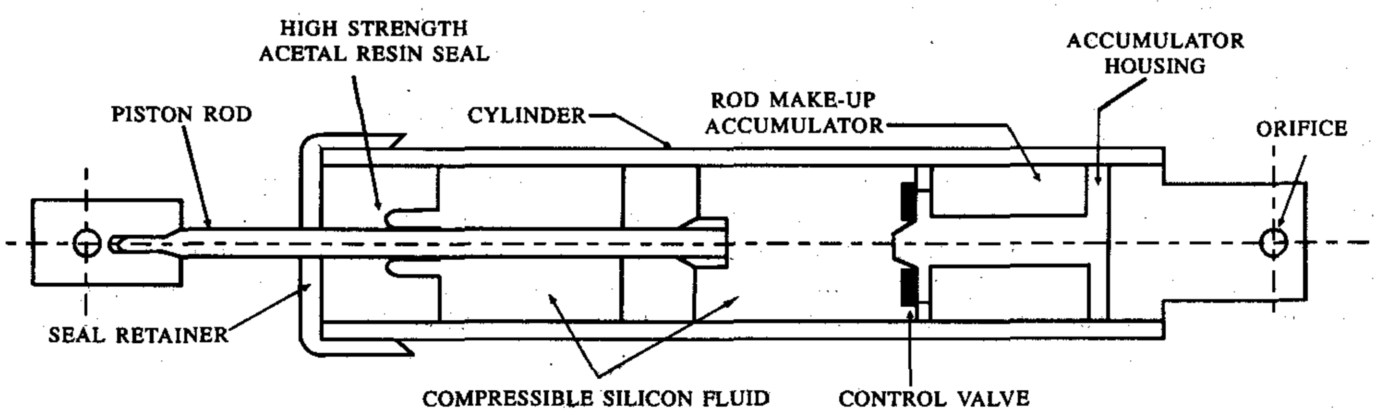


Figure 1. Construction of fluid viscous dampers

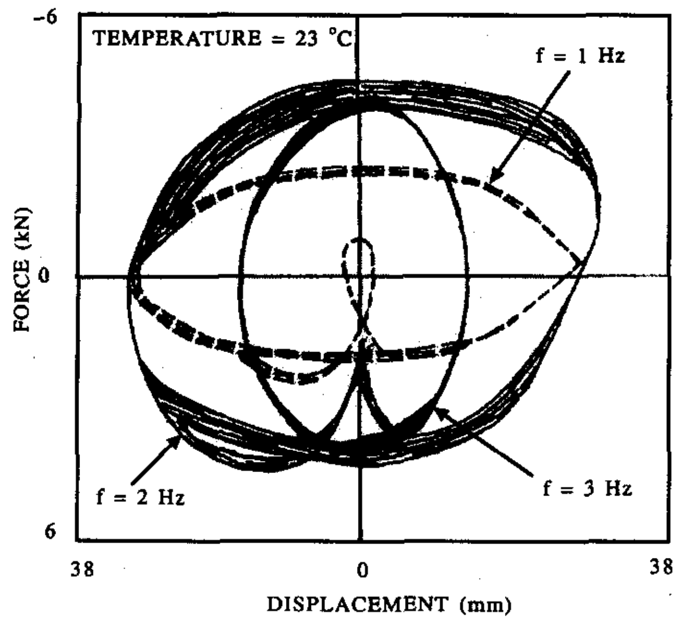


Figure 2. Loops of force versus displacement of fluid viscous dampers.

shows recorded data on the peak output force versus peak velocity of input at 0 °C, 25 °C and 50 °C. It can be seen that the experimental results may be fitted with straight lines of slope C_0 which represents the damping constant. The behaviour of the device was completely unaffected by the amplitude of motion. The values of C_0 in Fig. 3 demonstrate the small dependence of the characteristics of the device on temperature[3].

3. PROPERTIES OF VISCOUS DAMPERS

3.1 Steel-frame Structures

Based on the extensive analytical studies, a comprehensive test program has been designed and carried out involving experimental studies of the EDF viscous damper properties as functions of strain, excitation frequency, and ambient temperature. Structural tests with added EDF viscous dampers were conducted on a variety of structural models. They included a 1/4-scale, nine-storey model and 2/5-scale, five-storey model.

The EDF viscous dampers were tested on a nine-storey, three bay, 1/4-scale model structure[4] (Fig. 4). These dampers were tested with thirty earthquake events using eight different simulated earthquake signals. For all of the earthquake tests, the structural responses (both acceleration and displacement) were reduced compared to the moment-frame response. In some cases, the dampers reduced

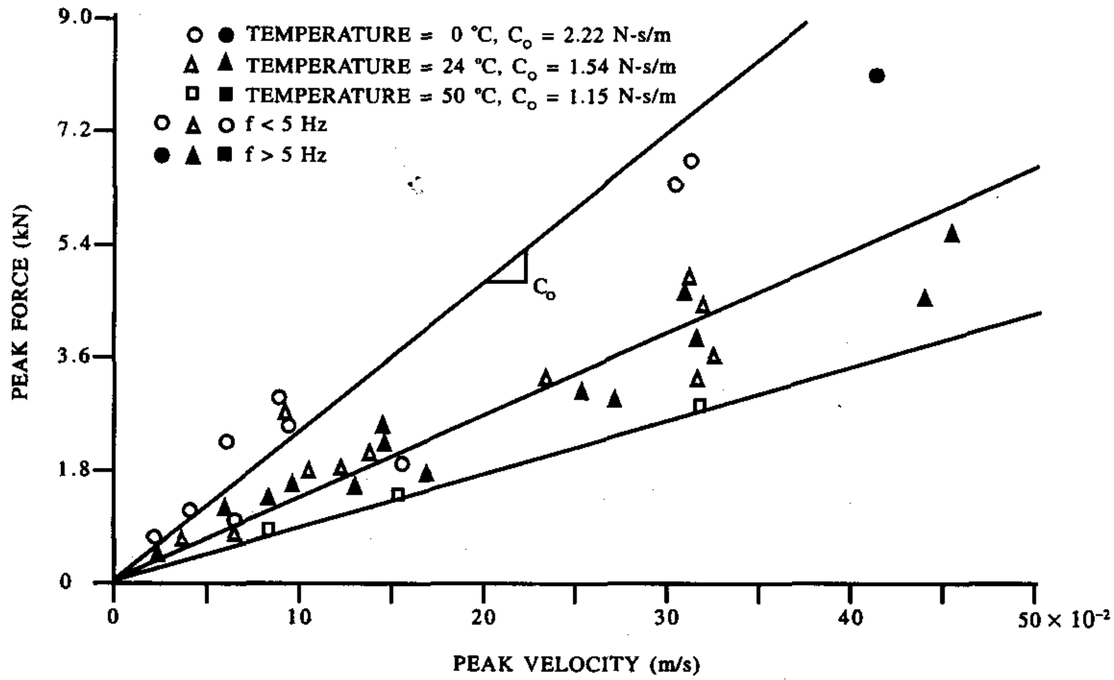


Figure 3. Mechanical properties of tested viscoelastic dampers

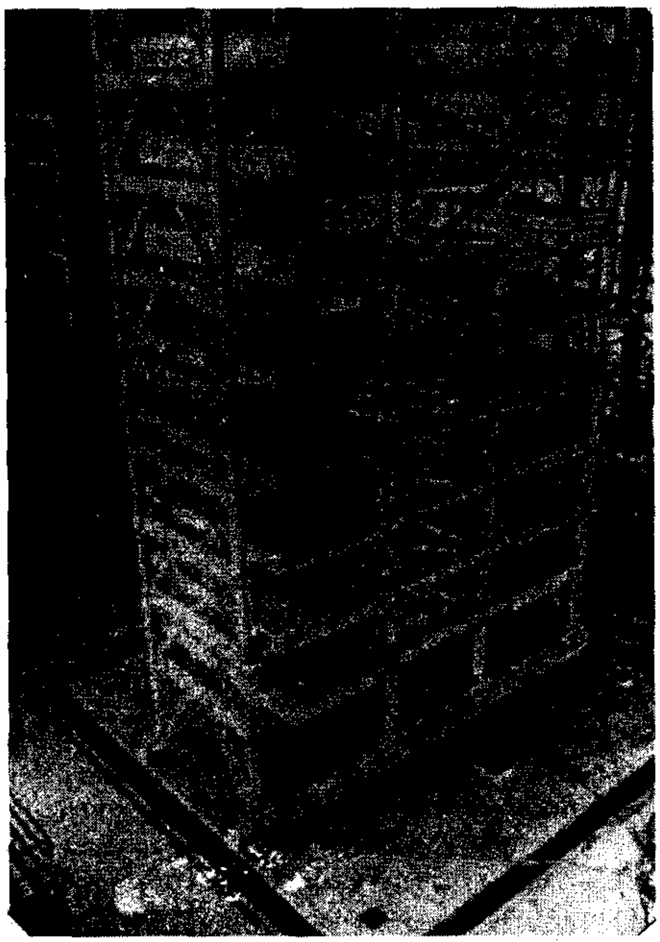


Figure 4. Nine-storey 1/4-scale model test

Figure 5. Five-storey 2/5-scale model test

the structural acceleration by as much as one-half, and simultaneously reduced the interstorey drifts by a similar level. Thermocouples embedded in the viscous material illustrated a temperature rise of about –12.23 °C for the 150 Latur (Maharashtra) earthquake. Temperature decreased relatively rapidly after the earthquake test was completed.

The effect of ambient temperature on damper performance was evaluated on a five storey, 2/5-scale model steel structure[4] (Fig. 5). Structural response results as shown in Fig. 6 depicts that even at high temperatures, the viscously damped structure can achieve a significant reduction of structural response as compared to the case with no added dampers. Testing at strong earthquake ground motion for earthquake intensity of 0.6 g at Dibrugarh (Fig. 7), demonstrated that structural response is significantly reduced and remained elastic with the EDF viscous dampers as compared to inelastic deformation from analytical simulation without dampers[2]. Testing demonstrated that EDF viscous

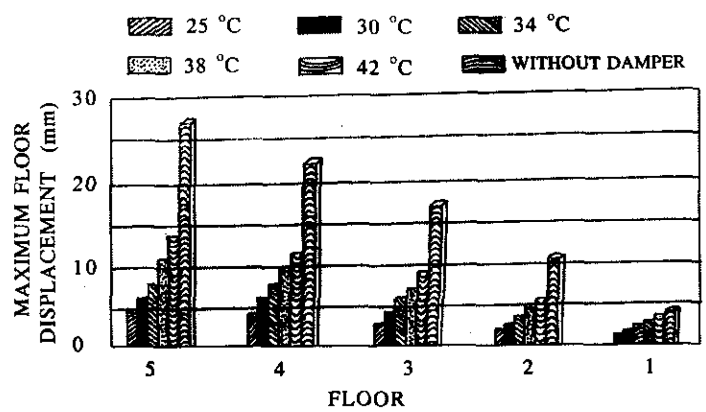


Figure 6. Damper effectiveness–maximum floor displacements.

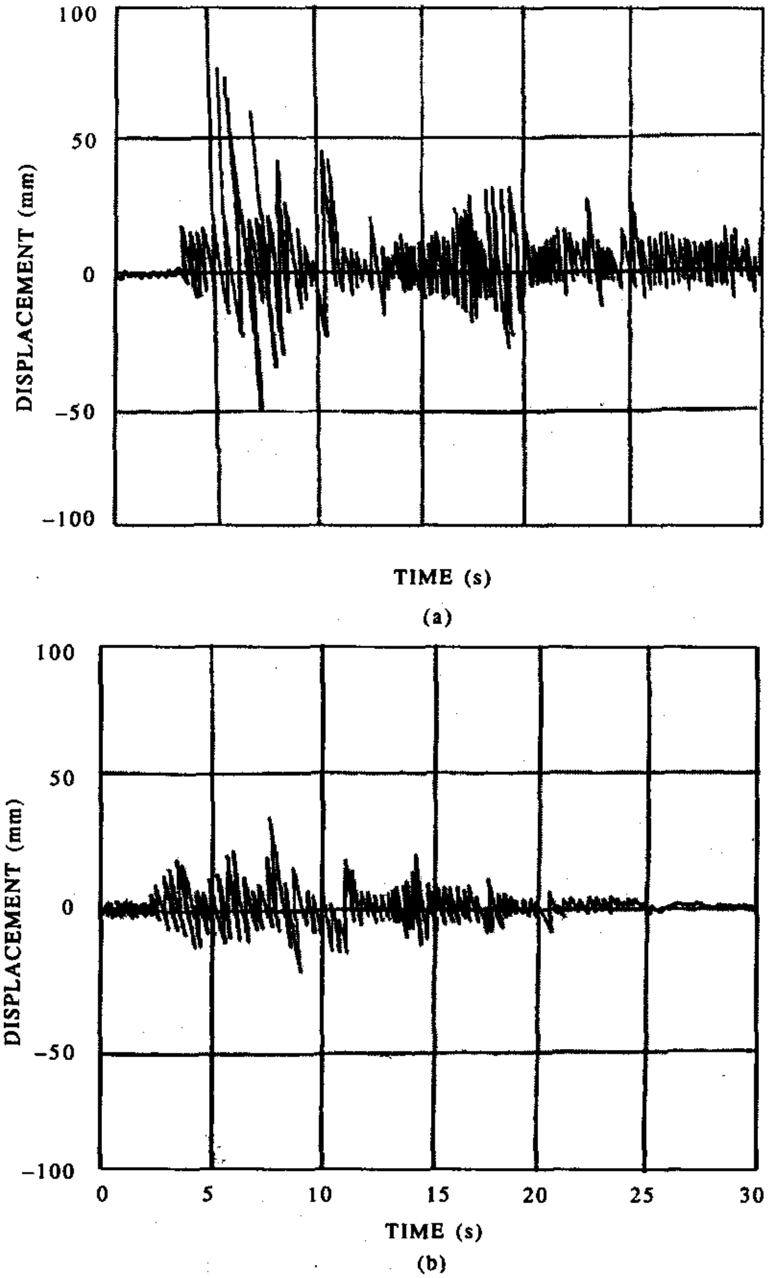


Figure 7. (a) Analytical simulation (without damper) and (b) experimental result (with damper) for the earthquake intensity of 0.6 g occurred at Dibrugarh.

dampers are effective for strong, moderate, and weak earthquake ground motions (Fig. 8). The model strain energy method for damper design was shown to simple and reliable. The seismic response of a viscously damped structure can be predicted using the conventional linear dynamic approach. On the basis of the above studies, a design procedure for viscously damped structures was developed and shown as a flow chart in Fig. 9.

A full-scale version of the 2/5-scale model was tested (Fig. 10), using a large vibration generator to excite the structure. This study showed that the model strain energy method provided comparable results for both the model-scale and the full-scale structures (Table 1).

As mentioned earlier, a seismic upgrade project using EDF viscous dampers is currently underway

Table 1. Maximum response values of steel structures

	Earthquake intensity (g)	Roof drifts Full-scale structures (mm)					Roof drifts Model-scale structures (mm)				
		1st	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th
Without damper	0.63	21.3	19.6	17.5	15.4	14.8	15.3	14.6	13.8	11.2	9.6
With damper	0.60	14.5	12.3	11.2	9.2	7.8	12.6	10.8	9.6	8.2	7.6

for the Administrative Building of Brahmaputra Board (6-storey) located in Guwahati. As shown in Fig. 11, it is approx. 64 m high and nearly square in plan, with 51 m × 51 m on typical upper floors. The exterior cladding consisted of full-height glazing on two sides and metal siding on the other two sides. The exterior cladding, however, provides little resistance to structural drift. The equivalent damping in the fundamental mode is less than 1 per cent of critical.

The building has been extensively instrumented, and useful data has been obtained during a number of recent small to moderate earthquakes. A plan for seismic upgrade of the building was developed, in part, when the response data indicated large and long-duration motion, including torsional coupling, during even moderate earthquakes.

The final design called for installation of two dampers per building face per floor level, which would increase the equivalent damping in the fundamental mode of the building to about 17 per cent of critical, providing substantial reduction to building response under all levels of ground shaking[2].

3.2 Reinforced Concrete Structures

The seismic response of a reinforced concrete structure is, by and large inelastic, which is often accompanied by permanent deformation and damage. The addition of EDF viscous dampers in this case can dissipate energy at the early stages of cracking of the concrete elements and reduce the development of damage. With proper selection of dampers, this damage can be substantially reduced or even eliminated. The quantification of the influence of viscous and

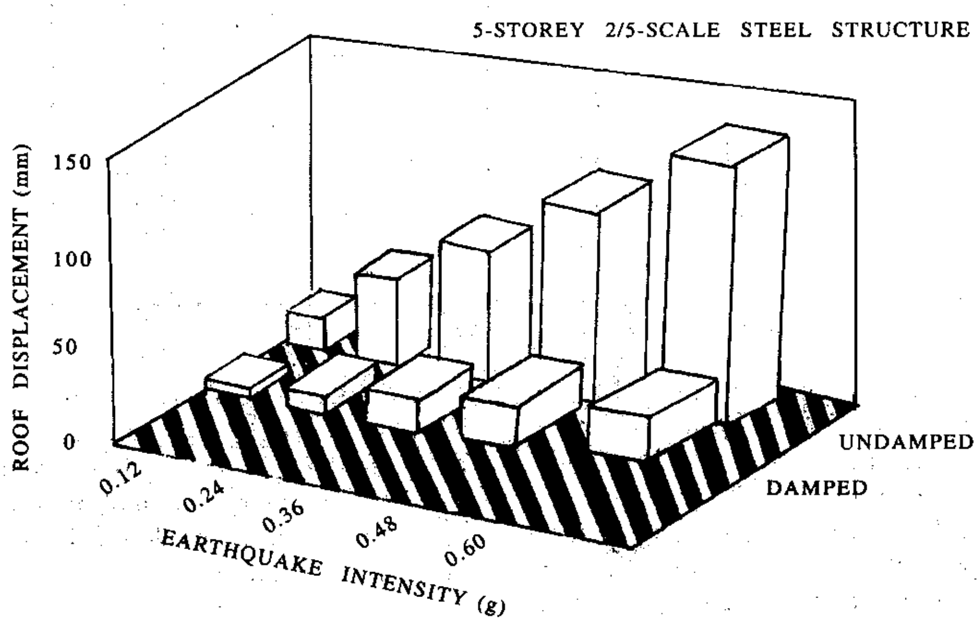


Figure 8. Relative displacement at roof

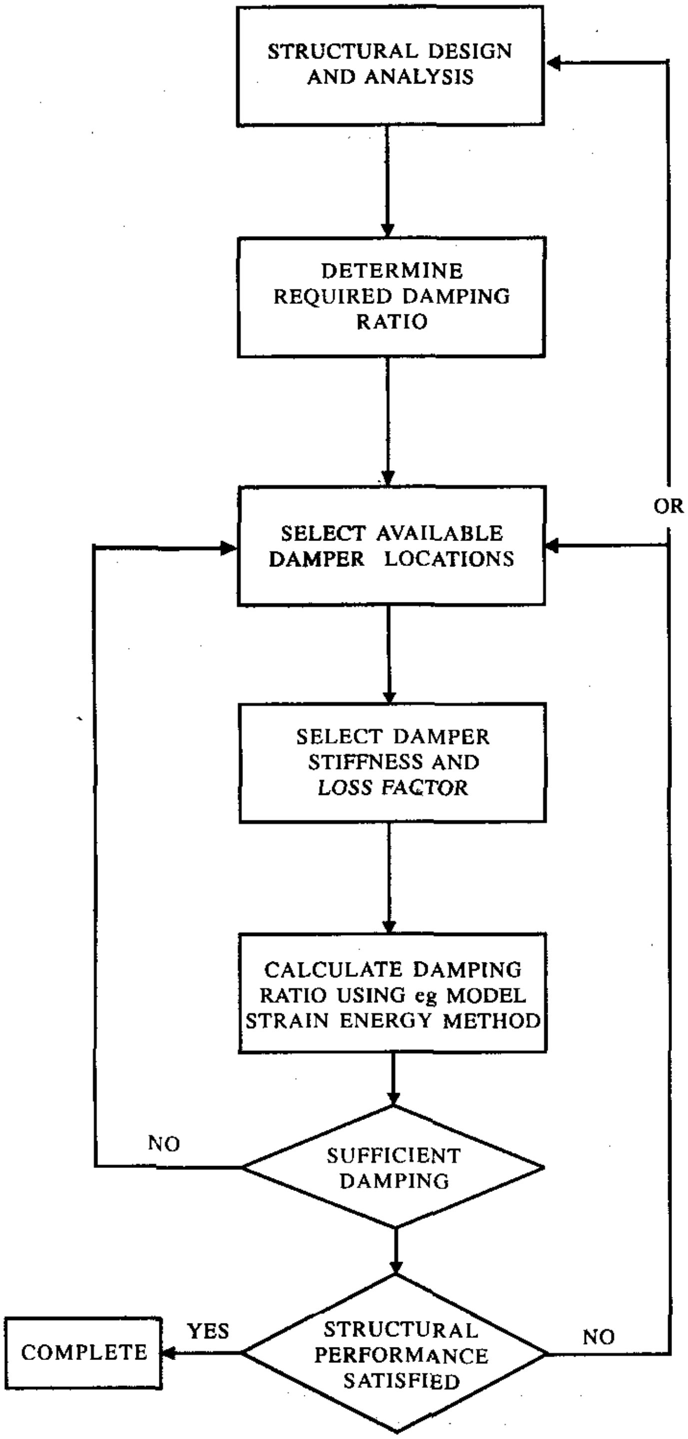


Figure 9. EDF viscous damper design flow

elastic stiffness properties of dampers during the *inelastic response of reinforced concrete structure* was the subject of several analytical and experimental investigations.

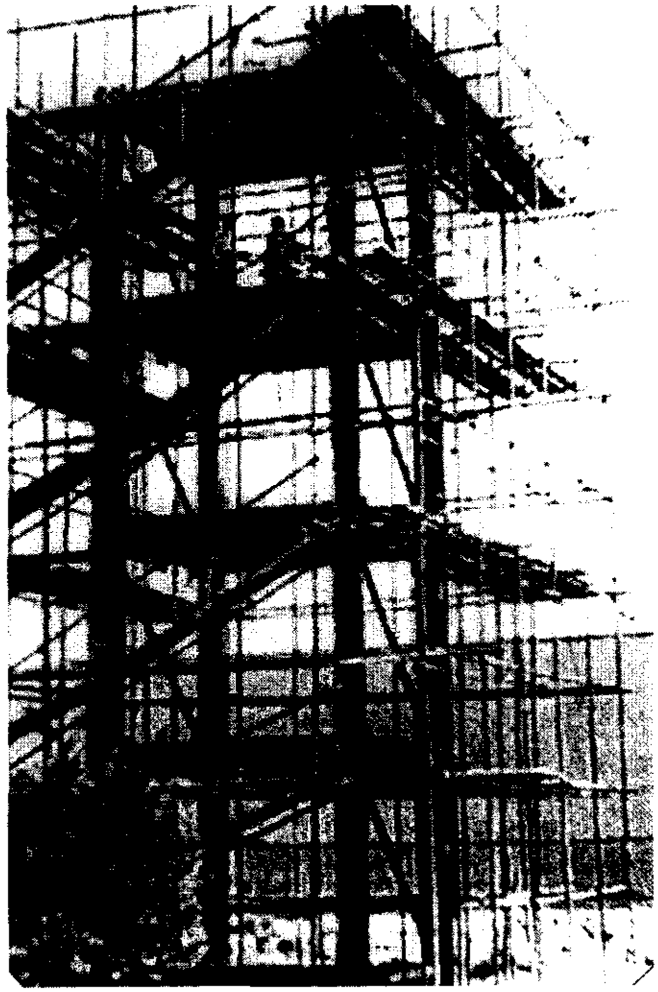


Figure 10. Full-scale structural test

A one-third scale model of a three-storey lightly reinforced concrete building was tested under simulated base motions using a shaking table[2]. The structure was tested using a series of simulated ground motions obtained from the scaled 1984 Assam earthquake, N25E component, normalised for peak ground accelerations of 0.07 g, 0.23 g and 0.32 g, representing minor, moderate, and severe ground motions, respectively. The structure was strengthened by adding the EDF viscous diagonal braces in the interior bay of each frame as shown in Fig.12. The model was tested without dampers and with dampers installed at braces at an angle of about 35°.

Some selected experimental results for the earthquake intensity of 0.23 g occurred in Assam

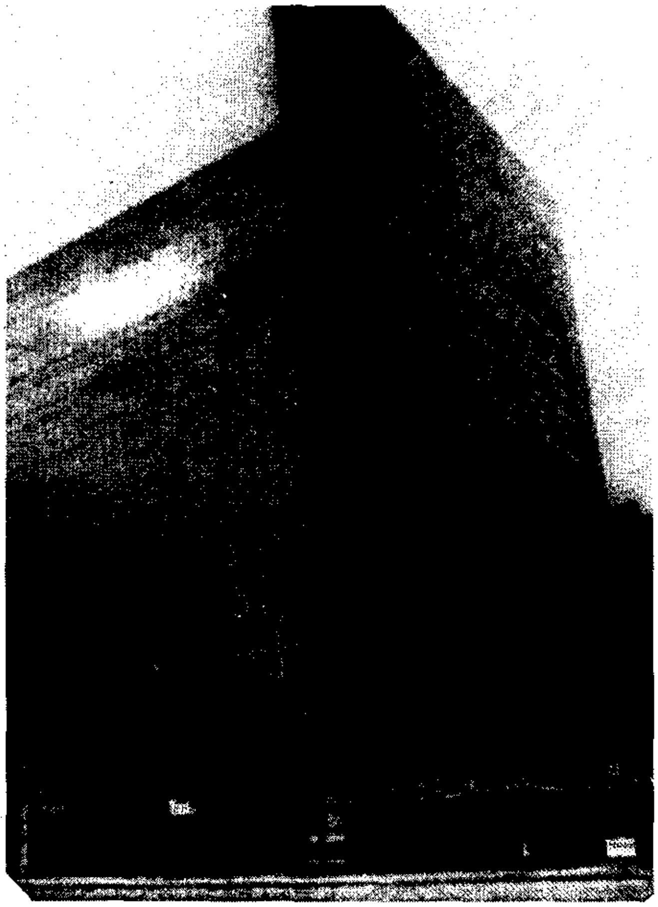


Figure 11. Brahmaputra Board Office at Guwahati

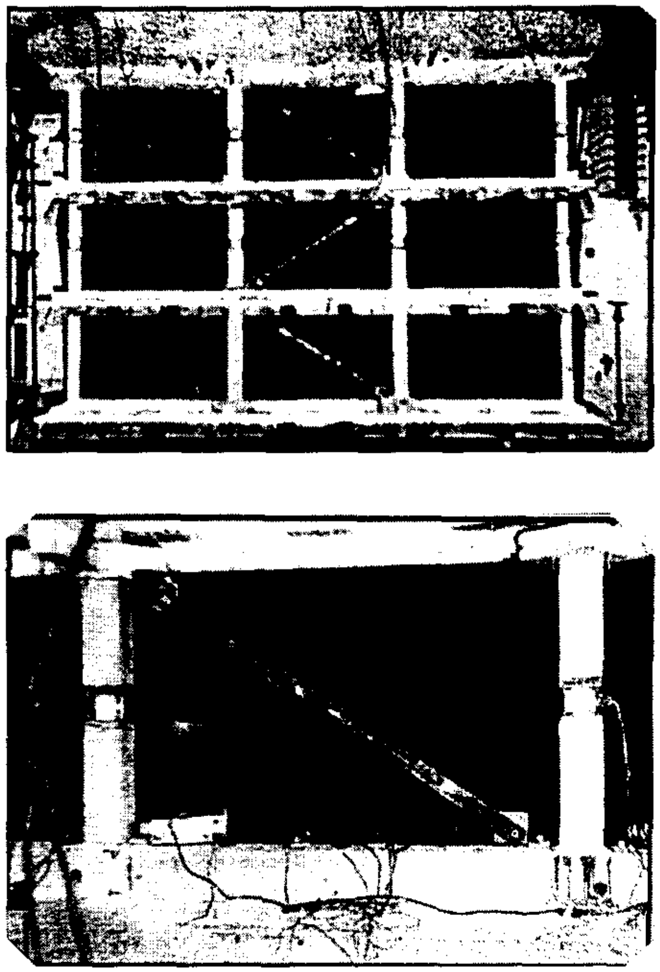


Figure 12. Details at reinforced concrete model with dampers.

are summarised for one type of dampers tested from the viewpoint of energy dissipation.

The interstorey drifts and storey shears in the columns are substantially reduced at all floors as indicated in Table 2. The deformations are reduced approximately three times, while the shear forces are reduced two times. These forces are much smaller than the ultimate strength of the columns, moreover, they are smaller than their yielding strengths. A sample set of force-deformation curves at the first floor (Fig.13) indicates that the column forces and deformations are substantially reduced, while most of the energy dissipation (area of hysteretic loops) is transferred from the columns to the EDF viscous dampers. Although some inelastic deformations are experienced by the columns in the presence of the EDF viscous braces, the column response is substantially improved.

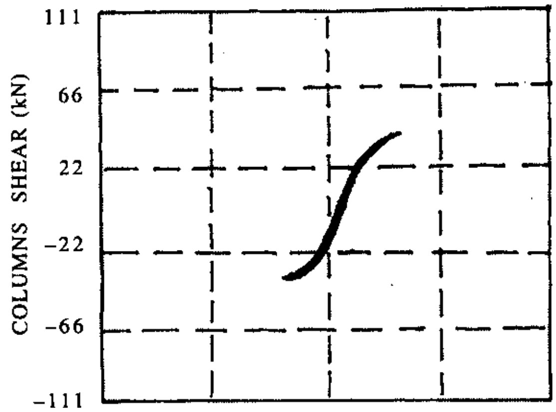
The EDF viscous dampers, after the overall energy balance as shown in Fig. 14, for the earthquake intensity of 0.23 g occurred in Assam were used in the experiment [Figs 14(a) and 14(b)]. The added EDF viscous dampers dissipate a majority of the input energy, leaving only a small amount of hysteretic energy to be dissipated by the structural members. Similar energy calculations for some

Table 2. Maximum measured storey response for 0.23 g Assam excitation

	Interstorey drifts (mm)			Column storey shears (kN)		
	1st	2nd	3rd	1st	2nd	3rd
Without damper	1.67	9.8	4.2	91	72	47
With damper	4.9	3.7	1.6	34	25	18

earthquakes occurred in some other places are also given in Fig. 14, showing that the overall energy input may vary depending on the match between the structural frequencies and the earthquake frequencies.

These experimental results verify analytical predictions of the performance of the EDF viscous dampers installed in reinforced concrete frames and show great potential for applying this technology to seismic strengthening of reinforced concrete structures.



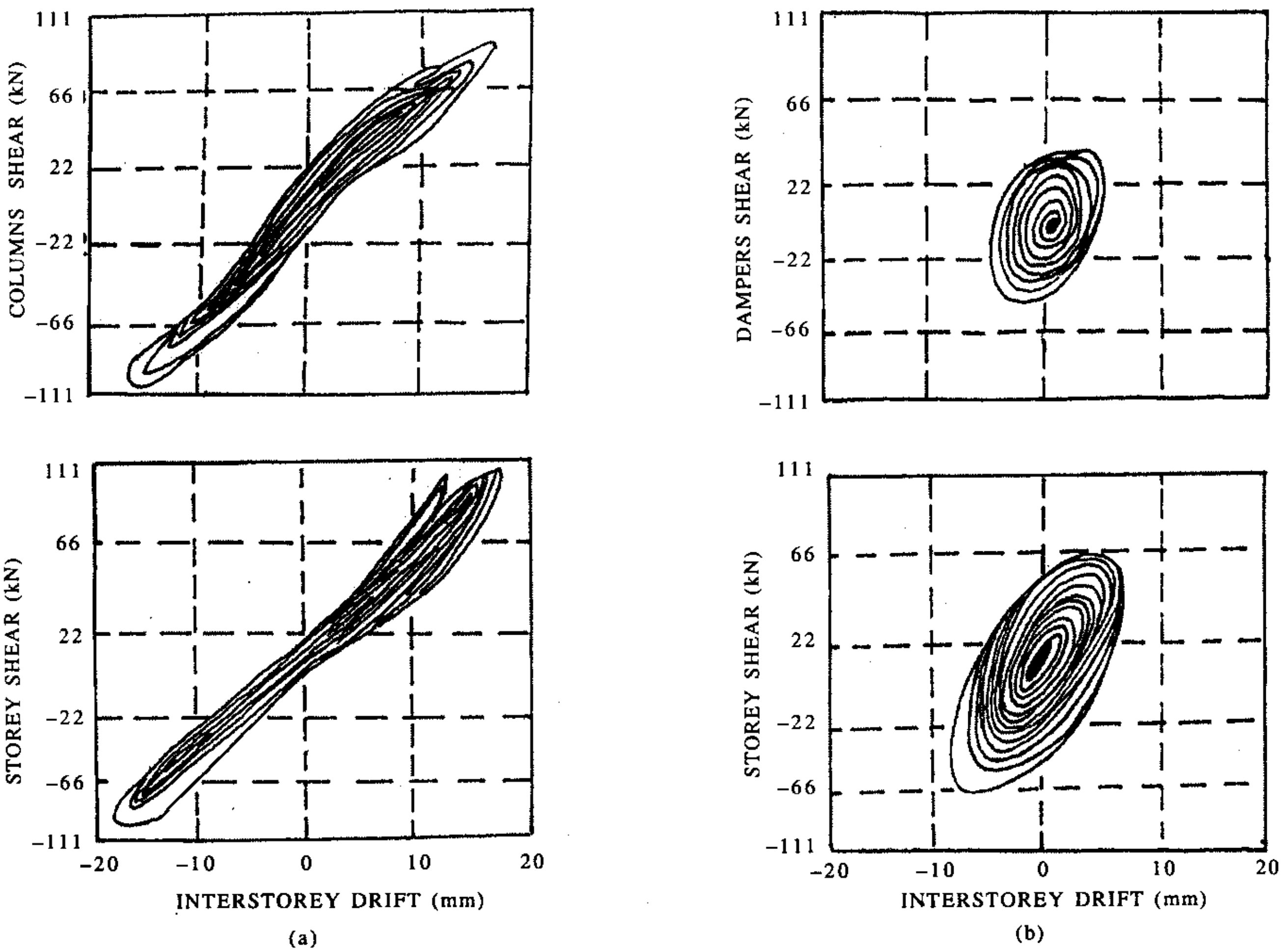


Figure 13. Force-deformation curves under 0.23 g Assam earthquakes. (a) without dampers and (b) with dampers

4. CONCLUSIONS

From the collected data, points that emerged are:

- The experimental results agree with the analytical predictions of the performance of the EDF viscous dampers installed in reinforced concrete frames and show great potential for applying this technology to seismic strengthening of reinforced concrete structures.
- This study demonstrated the ability of dampers to dissipate the significant amount of energy

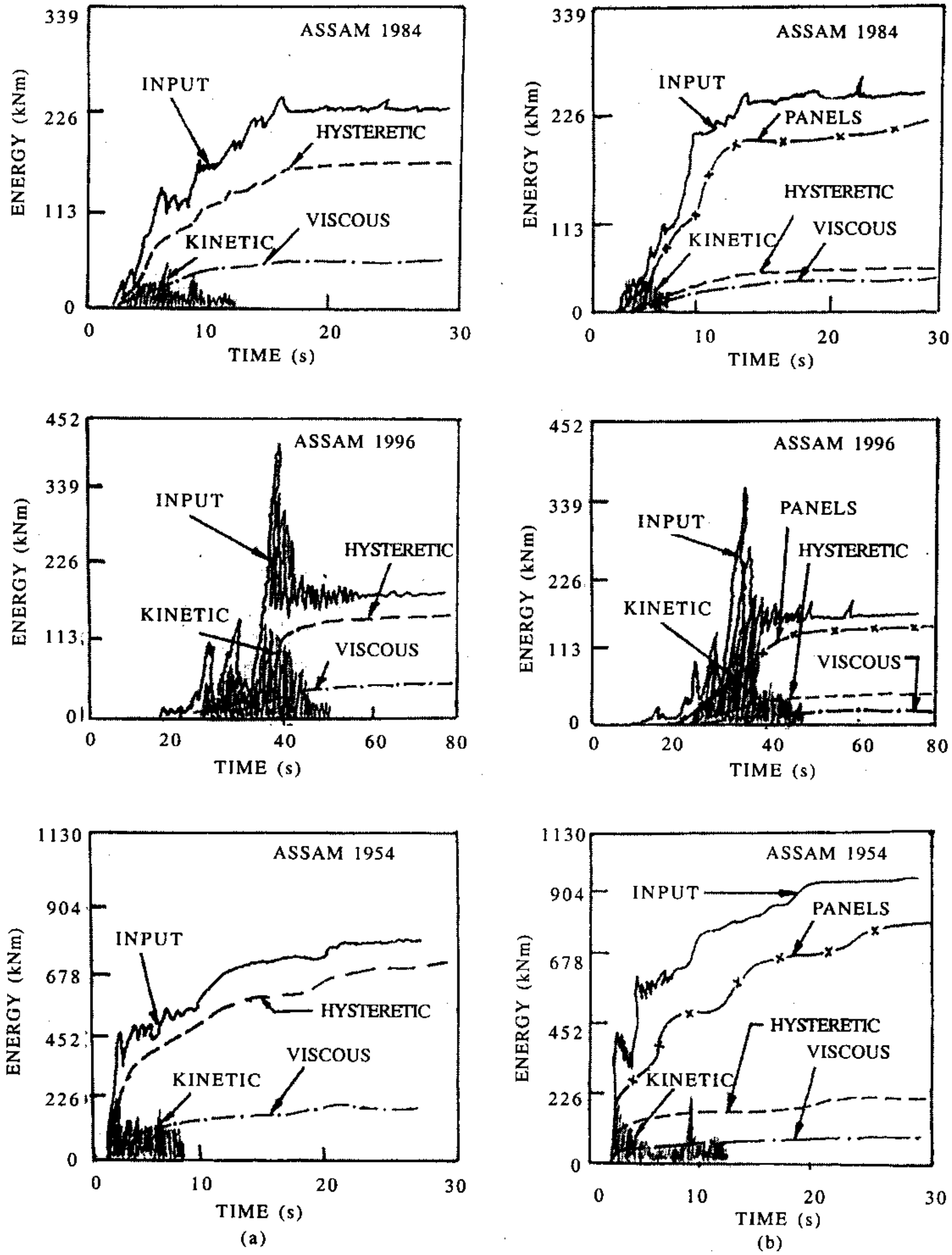


Figure 14. Contribution of energy terms. (a) No added dampers and (b) added dampers

and reduce concrete cracking.These results were further verified during testing of a three-storey, three-bay, 1/3-scale nonductile concrete structue conducted at the National Water Academy, Pune, in 1999.

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Contributor

Dr Shambhu Sinha obtained his ME from the Indian Institute of Technology (IIT) Kharagpur, in 1996 and PhD from the University of Pune in 1999. He worked as Scientist at the Council for Scientific and Industrial Research (CSIR), New Delhi, from 1993-99. Presently, he is working as Research Officer at the Central Water & Power Research Station (CWPRS), Pune. He has more than 10 years of work experience in the field of earthquake engineering, soil dynamics, structural dynamics, and deep water geotechnical investigation with the collaboration of Japan Concrete Institute (JCI) and Japan Soil Research Institute (JSRI). He also contributed towards building of low-cost earthquake-resistant housing structures in various remote and hilly areas. He introduced high rise structure design with strengthening method in a seismic-vulnerable zone, which resulted in 40 per cent savings. He has suggested solutions for landslides and sinking problems of Himalayan mountainous region. He was also associated with the critical study of the stability analysis of gravity dam in Himalayan region, where the dam induces seismic waves, causing minor/major tremors surrounding the region.

He is a fellow of the International Society of Earthquake Engineering and Research. He has published more than 80 research papers in the national/international journals. His name is enlisted with the Marquis Who's Who in the World–2004 (21st Edition), from the original Who's Who in America, the leading biographical reference publisher of the highest achievers and contributors across the country and around the world. His name, recognised along with those of the world's top achievers, including many high profile names (Nobel laureates). Inclusion in a Marquis Who's Who publication is considered by many as signal mark of achievement. He is the only Indian to achieve this target, sincerely (see website www.marquiswhoswho.com).