Parameters influencing the behavior of a new Friction Damper Device

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Parameters Influencing the Behavior of a New Friction Damper Device

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ABSTRACT

This work presents a study on the parameters that govern the performance of a new Friction Damper Device (FDD). The device was designed to dissipate seismic input energy and protect buildings from structural and nonstructural damage during moderate and severe earthquakes. The device consists of 3 steel plates that rotate against each other in different directions, and in between these plates, friction pad material discs are inserted. The damper is attached to structures by using inverted Chevron bracing system and in this work pre-stress bars were used as bracing members. The clamping force in the pretensioned bolt controls the frictional moment at the onset of sliding.

The device has been tested intensively in order to verify its performance. The experimental program included two phases:
1- Testing the damper alone with Instron machine, examining three different friction-pad materials.
2- Testing a scaled steel frame model with inserted damper device.

In both phases the following parameters were tested: forcing frequencies, normal forces, displacement amplitudes, pre-stressing forces and degradation under long-term cyclic excitation.

The tests proved that the damper performance is:
- Independent of forcing frequency within the range of 2-7 Hz;
- Linearly dependent on displacement amplitudes;
- Linearly dependent on normal forces;
- Very stable over many cycles.

The new device is characterized by the use of special friction pad material, which has been tested for up to 400 and 500 cycles without showing degradation of friction forces more than 5%. Besides, the steel plates were not damaged or scratched so that they can be used for many times.

The comparison of results obtained from the experimental and numerical models showed a good agreement. The parameters influencing the frame with FDD were identified in advance by studying the frame's response to static and dynamic loading. The numerical studies demonstrated that the overall frame response was mainly affected by the geometry of the damper, frictional sliding moment and stiffness of the added brace.

The device is very easy to manufacture and implement in structures. It is a very economic device due to material availability. It can be easily replaced if it is damaged, which is extremely unlikely, or can be readjusted after use.

Keywords: friction damper, passive control, experimental tests, nonlinear dynamic analysis, damping system.

1. INTRODUCTION

Passive control devices have been successfully used to reduce the dynamic response of structures subjected to earthquakes or strong wind gusts. Friction devices have been used as a component of these dampers because they present high energy dissipation potential at a low cost and are easy to install and maintain. Several friction devices have been tested experimentally - Pall [9], Sumitomo [1], Fitzgerald [5], Constantinou [3], Dorka [4], Grigorian [6], Nims et al [8], and some of these have been implemented in buildings around the world. Several researchers worked to develop seismic design procedures for these dampers; Cherry and Filiatrault [2] have proposed a simple and practical design method that attempts to optimize the slip force in friction damped braced frame structures.

The present paper is on the development of a new friction damper that can be easily manufactured, installed in a short time without a need of qualified staff, and is inexpensive. It makes use of a material that not only provides a very stable performance over many cycles but can also resist wear and adhesive wear and does not damage the steel plate surfaces, so it allows multiple use.

2.DAMPER DESCRIPTION AND MECHANISM OF WORK

The novel friction damper consists of 3 steel plates rotating against each other and in between these plates, there are two circular friction pad discs, in order to have dry friction lubrication in the unit, ensuring stable friction force and reducing noise of the movements.

The damper main parts are the central plate and two side plates, as shown in Fig.1. The central plate holds and connects the damper device to the girder of frame structure by a hinge in order not to introduce moment in the girder. The hinge connection will increase the amount of relative rotation between the central and side plates, which in turn increases the amount of energy dissipation in the system. The two side plates connect the damper to the bracing system and in this work, inverted V-bracing was used. This bracing consists of pretension bar members in order to avoid compression forces and therefore buckling. The bracing bars are pin-connected at both ends to the damper and to the column bases.

The reason for using two side plates instead of one was to increase the frictional surface area and to provide the necessary symmetry in to obtain plane behaviour of the device. The bolt connects the three plates of the damper to each other. This adjustable bolt is used to control the normal force applied on the friction pad discs and the steel plates.

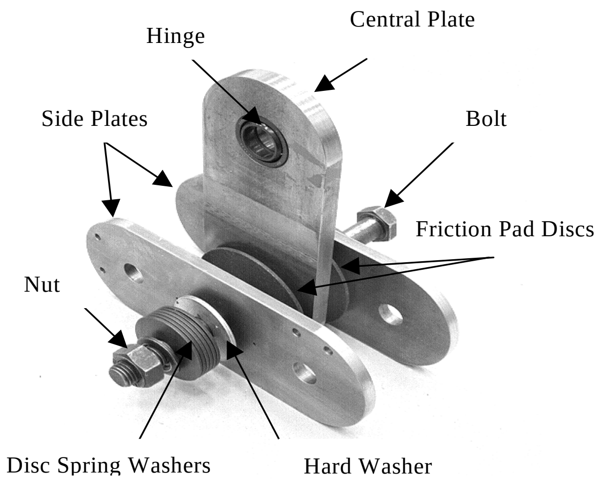

Figure 2: Details of the friction damper device

In order to keep a constant clamping force, several discs spring washers (Belleville washers) are used. Hardened washers were placed between these springs and steel plates to prevent any marks on steel plate due to the disc springs when they were in compression.

When a lateral external force excites a frame structure, the girder starts to displace horizontally due to this force. The bracing system and the frictional forces developed between the frictional surfaces of steel plates and friction pad materials will resist the horizontal motion. This process of moving from phase to phase is repeated upon reversal of the direction of the force application. Fig.2 explains the mechanism of the damper device under an excitation force in different directions.

As it is shown, the damper is very simple in its components which make it easy to assemble and very flexible in arrangement. It can be arranged in many configuration of bracing system, as well as in many types of bracing system. The simplicity of the damper design allows constructing a device with multi units, based on the requirements of the designed friction force and the space limitations. Beside the time required to install the device within a building is relatively short.

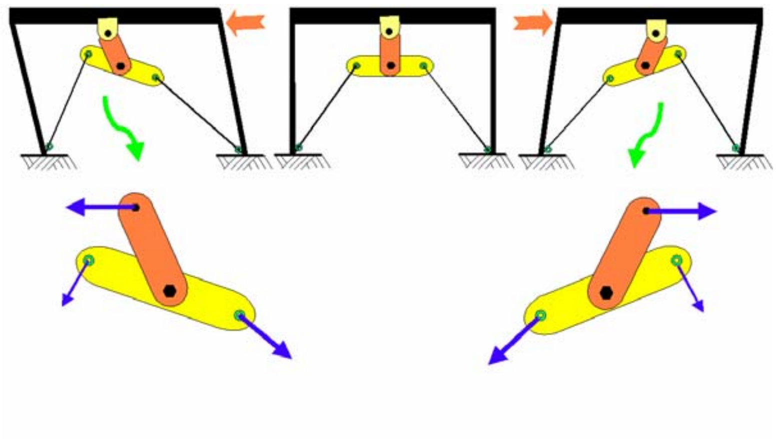

Figure 2: Mechanism of the friction damper device.

3. EXPERIMENTAL PROGRAM

In order to verify the frictional component of the proposed friction damper device, a number of qualification tests have been performed in the laboratory. The experimental program included two phases:

1. Testing the damper device with three different types of friction materials
2. Testing a scale model steel frame with implemented friction damper device.

The testing of damper with different friction materials was done with Instron machine to verify the parameters which affect its performance. These included cyclic tests of the damper from which the proper material was selected and used in the Phase 2 testing which was performed by a shaker. These experimental studies were carried out in the laboratory of the Department of Structural Engineering & Materials, Technical University of Denmark. Full details of the experimental program are given in Mualla [7].

Figure 3: Setup of the damper tests with Instron machine

In order to evaluate the damper performance, a series of tens of dynamic cyclic tests were performed with three different types of materials: brass, highly frictional material and friction pad material. Brass was chosen because of its low cost and its wide availability as a commercial material.

In general, the friction damper performances are affected by certain parameters. The parameters that were studied in these tests are as follows: frequency dependency, displacement amplitude, bolts clamping force and long running tests. The damper was tested with displacement amplitudes of 5, 10, 15 and 20 mm with 0.3 Hz forcing frequency. Fig. 4 shows the applied displacement and resulting hysteresis loops of the brass shims. It's clearly shown that, when the amount of the area was increased due to the increase of the displacement, the friction force was almost constant without showing any fluctuation or disturbances.

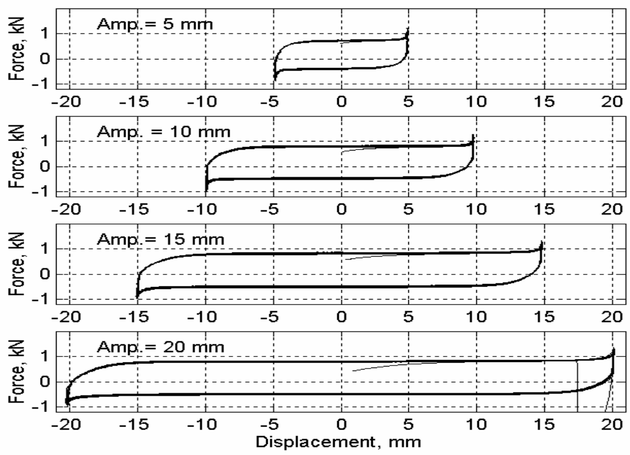

Figure 4: Effect of using different displacement amplitudes on the hysteresis loops of brass shims.

The high forces observed at the end of each cycle were due to the relative velocity of the plates reaching its minimum value. The visual inspection of the faying surfaces shows scares and adhesive wear between steel and brass.

Friction Pad Material

The performance of the damper can be improved by using another material having both the ability of resisting wear as much as possible and a stable hysterises for large number of cycles. Such improvement is likely to be achieved by providing a more suitable material combination. An asbestos-free friction material (Friction Pad Material, FPM) was found. This material is a composite one, with a friction coefficient of 0.35-0.45.

In order to study the damper performance with the FPM under long running cyclic test, the damper was subjected to up to 400 cycle with 0.5 Hz frequency and 4 kN clamping force. The results were very encouraging, no fading was noticed, and the noise caused by friction was much less than other materials. FPM tests showed negligible damage to their friction surface and the most important, the steel plates surfaces were free of scars or damages, except that a thin layer of powder film was found on the plate surfaces.

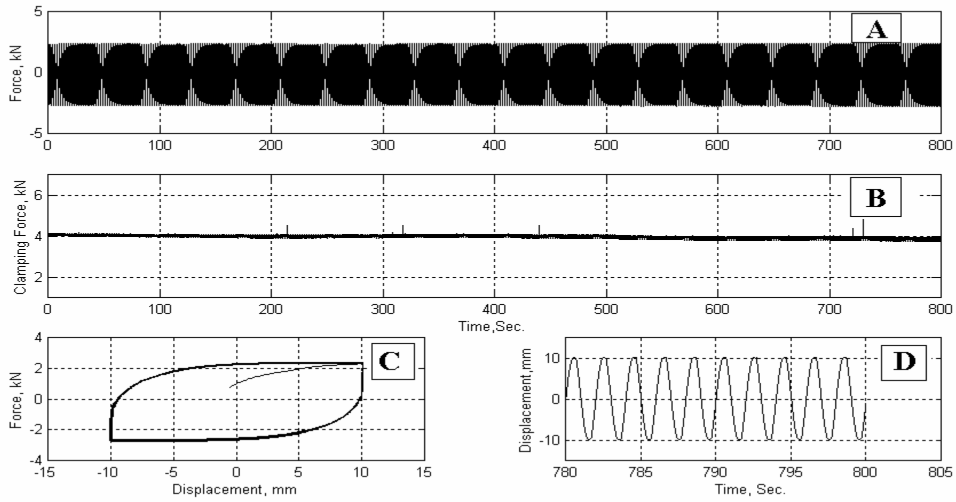

Fig. 5: [A] Force history for 400 cycles, [B] Bolt Clamping Force history
[C] Force – Displacement hysterises. [D] Displacement history for the last 10 cycles.

A single-story, one-bay steel frame model was built and tested statically and dynamically in order to verify the effectiveness of the friction damper concept experimentally. These tests were planed to ascertain the damper performance under practical condition prior to introducing it for use in buildings. The overall dimensions of the model frame are 1.125 m in height and 1.10m in span. The natural frequency of this frame was 6.8 Hz.

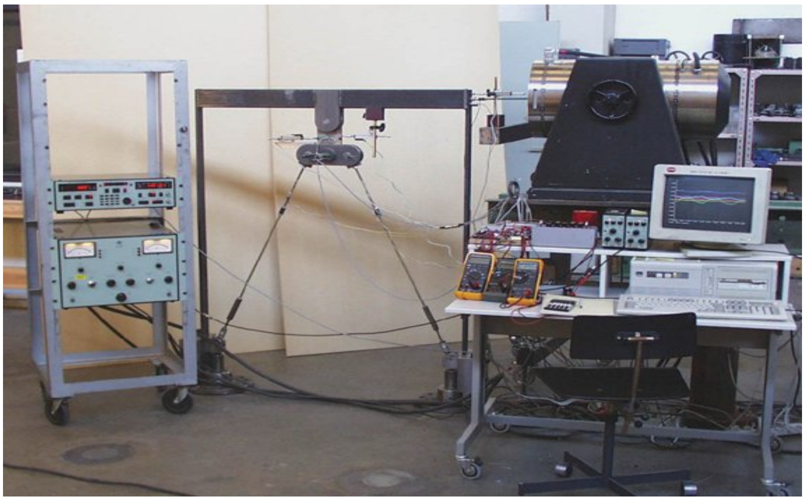

Figure 6: Experimental setup of frame with FDD

FREQUENCY INDEPENDENCY

One of the most important parameter in verifying the friction damper devices is the frequency dependency. The frame was tested by 2.0, 3.0, 4.0, 5.0, 6.0 and 7.0 Hz forcing frequency while keeping constant the values of all the other parameters. The results which represent the moment, M, in the damper and the relative rotation between the plates, Theta, show clearly that the device is almost independent for this range of frequencies as shown in Fig 7. This justifies the use of the Coulomb law for friction modeling. It is worth mentioning that some dependency was observed in the measuring tests of sliding coefficient of friction when high velocities were applied.

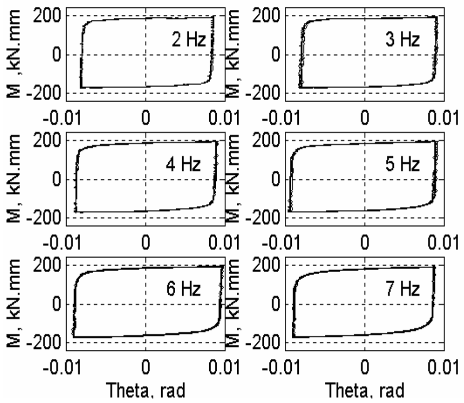

Figure 7: Effect of different frequencies, 2-7 Hz on Moment – Theta relation

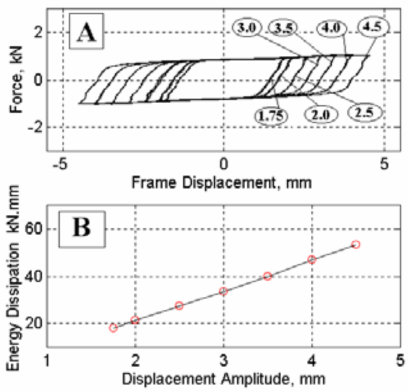

Figure 8: [A] displacement amplitude [B]Energy dissipation – displacement relation.

The influence of the displacement amplitudes on the damper behaviour was also studied. In these tests the frame displacement was controlled to 1.75, 2, 2.5, 3, 3.5, 4 and 4.5 mm as shown in Fig. 8A. The energy dissipation, which is the enclosed area of the force – displacement curve for each amplitude was plotted versus the frame displacement in Fig. 8B. It is clearly shown that the linearity effect of this parameter makes the mathematical modelling very simple.

ENERGY DISSIPATION

The performance of the damper is also evaluated by the amount of input energy that can be dissipated. The scaled frame was excited by harmonic loading with 3 Hz frequency and force amplitude of 0.8 kN. It is clearly seen, from Fig. 9, that the amount of energy dissipated by the friction damper, was about 89 % of the input energy. This high percent proves the efficiency of the friction damper devices in absorbing and dissipating a large amount of input energy.

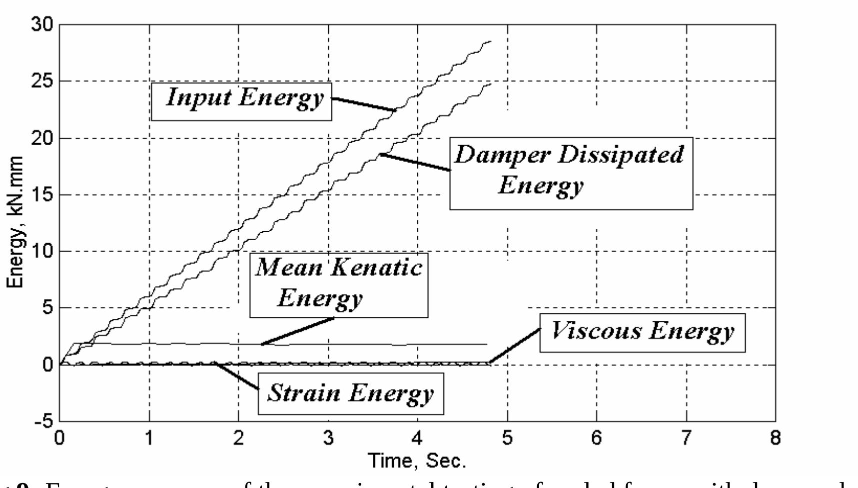

Fig.9: Energy response of the experimental testing of scaled frame with damper device

4. Comparison of experimental & numerical models

The experimental results were compared with those obtained using the numerical model described in [7]. This was to verify the modelling of the implemented friction damping system with the single story steel-frame scaled model. The frame was excited with a forcing frequency of 3.0 Hz, an 0.86 kN exciting force and 2.0 kN prestressing force in left bar and 2.2kN in the right bar. It is worth noting that, from practical point view, it is difficult to apply exactly the same prestressing forces in bracing bars, therefore it was decided to use different presstressing forces.

The results of comparing the experimental and numerical models show that they are, in general, in a good agreement, though several remarks were worth noting.

The numerical model, Figure 10 B captured the frame displacement amplitude at a steady state response, but the difference was observed on the slope representing the time when sticking occurred. The slope was slightly higher in the experimental test than in the numerical test.

The noticeable difference was the relative rotation, θ, which was smaller in the experimental test than in the numerical test. One reason was the friction between the clamping bolt, which is subjected to double shear force, and the thickness of the three steel plates. It had been assumed that the hinges on the central plate and bracing connection would behave purely as hinges because of the plain bearing. This was not entirely the case. Another important point is that no device was available for directly measuring relative rotation. The measurements were therefore obtained indirectly using potentiometer readings divided by the distance of the head from the bolt center line. On the other hand, the moment was also measured through indirect readings, i.e. calculated by using the forces in the bracing bars were known, but there was some differences between their experimental and numerical results. The rotation of the side plate was measured indirectly by subtracting the two rotational measurements. Each of these points played a role in the differences noted.

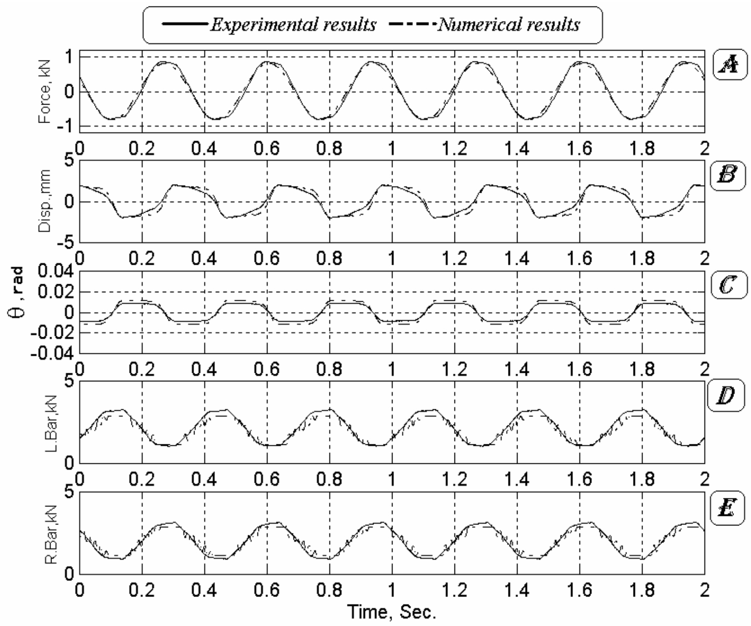

Figure 10 : Time history comparison of the results between experimental and numerical model of 3.0 Hz forcing frequency and 0.86 kN exciting force.
(A) : Exciting force, kN.
(B) : Frame displacements, mm.
(C) : Relative rotation, Theta, rad.
(D) : Left bar forces, kN.
(E) : Right bar forces, kN.

Figure 10 show the results of the comparison in terms of time history and frame displacement.

The prestressing bracing bars behaved the same in the experimental tests, though there was a slight difference in peak forces. There are several possible reasons for this: the calibration may not have been entirely accurate because the hall temperature of the laboratory varied because of doors being opened, which affected the readings recorded by the strain gages. Finally, it is worth mentioning the occasional difficulty in maintaining the same amount of prestressing forces in the bars. Performing different types of tests showed that the characteristics of the frame and the damper restoring force are evidently bi-linear (as expected) even if the steel frame is in the elastic range.

Finally, it is very worth to mention that only one pair of friction pad material disks were used for all the tests performed during this second phase. The steel plates, which had smooth surfaces, were not harmed or damaged. No scars or wear were noted, along with a slight film of powder, which was easily removed because it had not adhered to the steel plates in the same way as the brass. Therefore the steel plates can be used for a long time.

5. FDD system efficiency

The first conclusion on the efficiency of this damper device is derived from the reduction in response displacement of a frame under El Centro earthquake motion when the storey drift dropped by 59%, from 2.74 % (0.129 m) to (0.0534 m) 1.136 % of the storey height. Other tests and examples including different earthquake records are described in more depth later in this chapter.

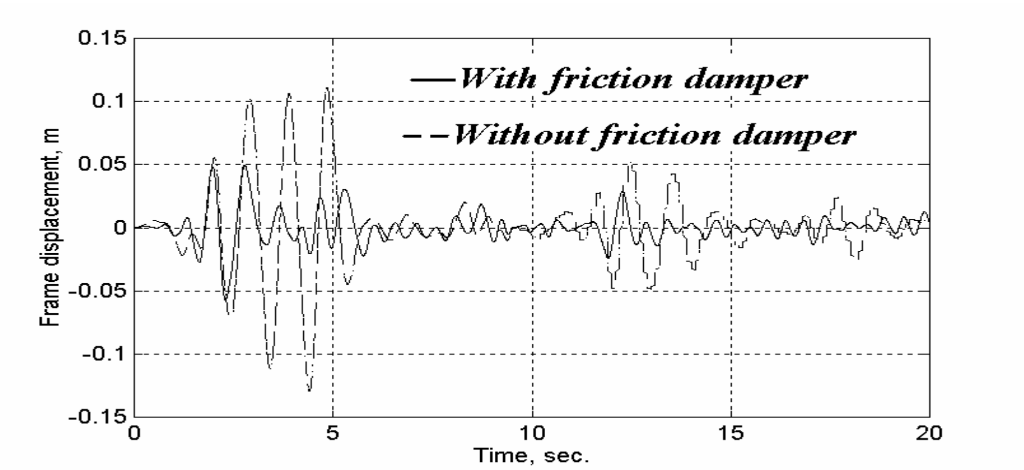

Figure 11: Basic frame response with and without FDDs, El Centro earthquake motion.

Another way to evaluate the FDD system is through the energy balance concept. As shown in Figure 11, the energy terms, which are the strain energy, kinetic energy, viscous energy, damper dissipated energy and input energy, are calculated separately. The accuracy of the calculations is verified by comparing the sum of the energies mobilised (energy supply) with the input energy (energy demand). Very good agreement is observed, showing that most of the input energy was dissipated by the FDD system.

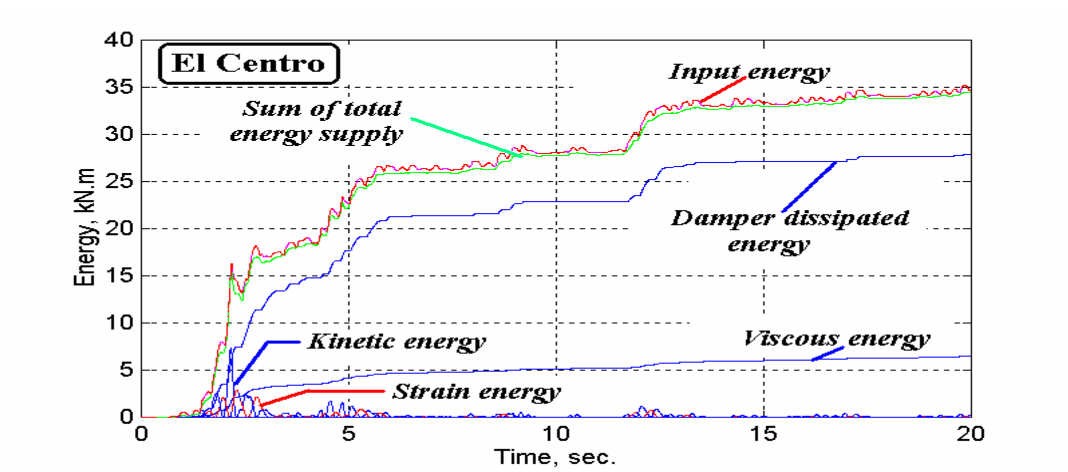

Figure 12: Basic frame response with FDD, El Centro earthquake motion.

6. Sensitivity studies

One of the most positive features of the FDD system is that its principal properties (energy dissipation and stiffness) can be studied statically. Other dampers (i.e. tuned mass dampers) must be studied dynamically. In these analyses, three different frame geometries were used to investigate the effect of the system and damper parameters on the damper response. The parameters studied in each frame were: damper size (*r and ha)*, frictional moment M_f, prestressing force in bracing F_{prst} and bracing cross sectional area A_b.

A frame geometry with a span of 6.0m and height of 3.0m so that span/2height = 1 was used in this sensitivity study. K_f = 6888 kN/m. Damper dimensions *r* and h_a take equal values from the array [0.1 0.2 0.3 0.4 0.5 0.6] m. E = 0.21e+9; A_b = 113.1mm^2 and F_{prst} = 24.0 kN, M_f = 4.0 kN.m and D_{max} = .015*height = 0.045m.

The plots in Figure 13 represent the effect of the damper's geometry on Energy Dissipation,*ED*, maximum Displacement,D_{max}, minimum prestressing forces in bracing F_{min} and stiffness of the damper & bracing, K_{bd}. The peak values of maximum *ED* correspond to damper dimension values for which $r = h_a$, that is, the slope of the bracing.
The most expedient effect was obtained for the r/h_a ratio equal to the bracing slope span/2height, see Figure 13. Obviously $r = h_a$ gave the maximum *ED* and K_{bd} and minimum values of F_{min}. However, the damper dimension had no influence on D_{max}. (earlier tests carried out by the author before the present work implied the expedience of using such a ratio). In order to give a three-dimensional representation of the interaction of the six design parameters, a total of thirty-six tests were carried out under force control up to a maximum static force of 90 kN for each of the sensitivity studies. The horizontal surfaces in Figure 13, show the limits of the maximum allowable displacement and minimum bar forces.

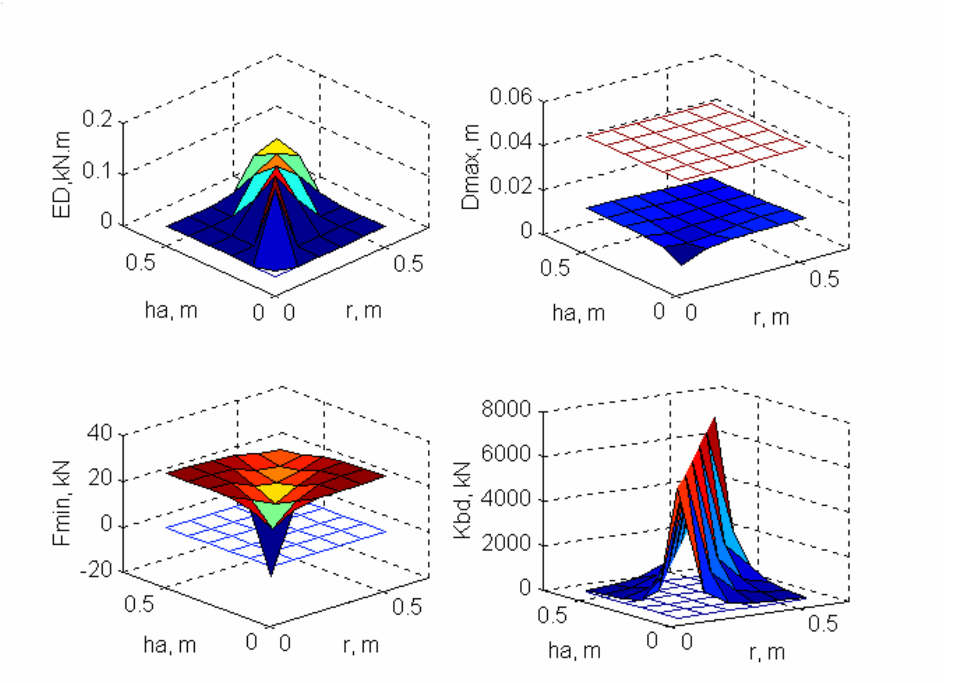

Figure 13: Effect of *r* and h_a on *ED*, D_{max} F_{min}, and K_{bd}.

The effect of M_f and F_{prst} is illustrated in Figure 14 for the following input data: M_f = [2 3 4 5 6 7 8], F_{prst} = 6* M_f, $r = h_a$ = 0.2m and A_b = 113.1mm^2. The optimum M_f was 4.0 kN.m, which gave the highest *ED*, but at the same time, the maximum displacement was reduced only modestly. Assuming F_{prst} = 6* M_f, this may be more than necessary for F_{min} and can be replaced by F_{prst} = 3.7* M_f kN.

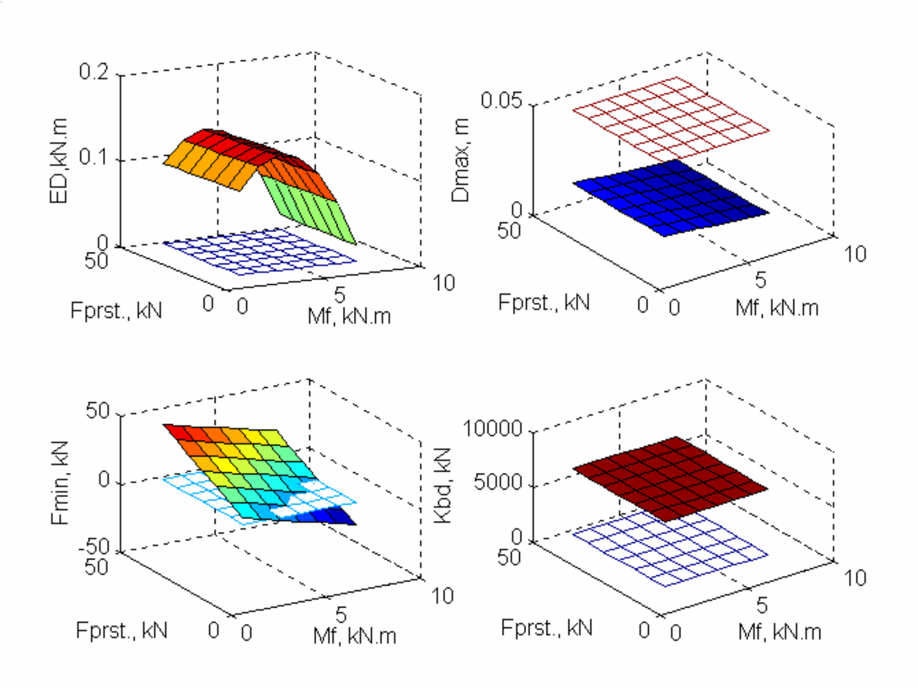

Figure 14: Effect of M_f and F_{prst} on ED, D_{max} F_{min}, and K_{bd}.

The study of the influence of damper size and A_b on damper response were studies, see Figure 15. A_b = [28.27 50.2 6 78.53 113.1 201.06 314.16] mm^2. These A_b values represent bar diameters of 6, 8, 10, 12, 16 and 20mm, respectively. The largest energy dissipation is obtained for smaller damper sizes in combination with maximum A_b.

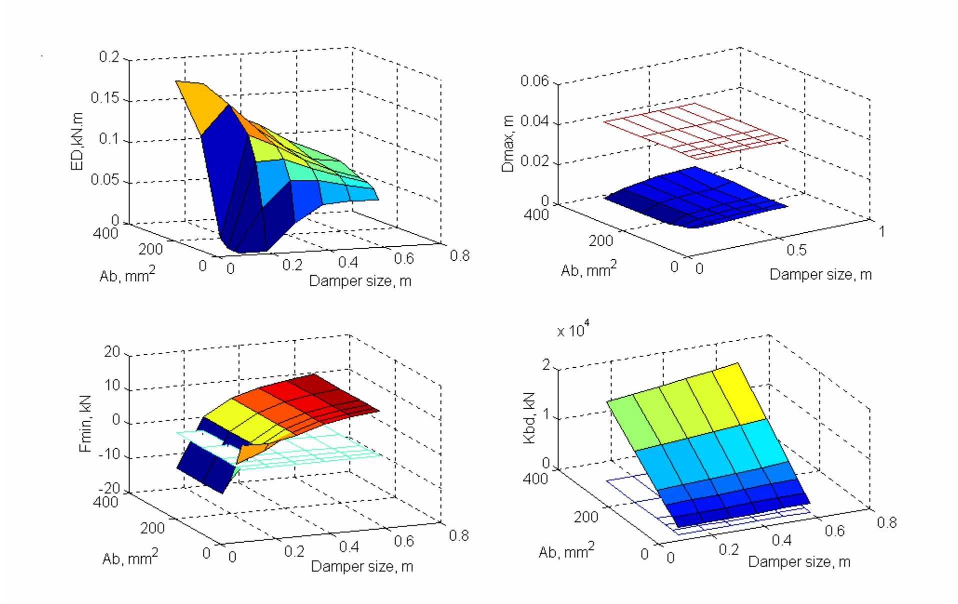

Figure 15: Effect of damper size and A_b on ED, D_{max} F_{min}, and K_{bd}, Frame #4.

The major conclusions from the study of these three different frame geometry are:

- A small damper size can give maximum *ED*
- The r/h_a ratio should be the same as span/2height of the frame
- F_{prst} should be 5.5- 6 M_f kN and 3.6-4 M_f kN for span/2height = 0.5 and 1.0 respectively to avoid bars buckling.
- The stiffness of the damping system K_{bd} is very sensitive to the r/h_a ratio. For a fixed A_b, maximum K_{bd} value could be obtained for an r/ha ratio equal to the span/2height.
- An optimum value of M_f exists that leads to maximum *ED*.
- Large A_b combined with small damper size results in high energy dissipation
- The minimum bracing bar force F_{min} is not influenced by the bar cross-section area but is very sensitive to damper size.

7. CONCLUSIONS

A new friction damper device was proposed to retrofit buildings subjected to dynamic loads. The device is very easy to manufacture and implement in structures. It's a very economic device because of the material availability. It can be easily replaced if it is damaged, which is extremely unlikely, or readjusted after use.

Intensive experimental tests were performed to study its parameters such as, forcing frequencies, displacement amplitude, bolt-clamping force and prestressing bar force. The successful performance of the damper in providing stable hysteresis loops is due to the use of Friction Pad Material which causes no damages to the steel plates beside the very stable performance over many cycles without any degradation in the friction force. Tests showed that the device is a velocity independent for certain range, and linearly dependent on displacement amplitude and normal forces, which make this damper easy for mathematical modeling.

One can conclude that, the use of supplemental damping provided by this friction damper dissipates a large amount of kinetic energy in a structure, and, thereby eliminates the utilisation of structural ductility while the structure remains elastic without damage.

The experimental and numerical studies reported clearly demonstrate that the new FDD presents a viable alternative to the conventional ductility-based earthquake-resistant design both for new construction and for upgrading existing structures. It can be easily and economically produced and installed in building frames to prevent them from collapsing and severe damage during strong earthquakes.

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