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NUMERICAL PREDICTIONS OF SHAKING TABLE TESTS ON A FULL SCALE FRICTION-DAMPED STRUCTURE

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ABSTRACT
This contribution presents results from an international research co-operation devoted to evaluating the performance of a three-storey test frame building equipped with a novel friction damper system recently developed at the Technical University of Denmark. The capability of the system to dissipate energy has been extensively studied in previous research both experimentally and numerically. The robust hysteretic performance of the friction damper device (FDD) was attributed to the proper selection of friction pad material.

The full-scale three-storey test building of the NCREE, Taiwan was employed as a primary frame structure in which the FDDs were inserted. The shaking table testing was carried out for different sets of the damper slip resistance along the height of the building. The performance of the damping system was verified under far-field and near-fault acceleration records scaled to different intensity levels. Finite element plane frame models of the primary and friction-damped structures were created and numerical simulations were performed using software for non-linear time history analysis. Based on the recorded response histories as a comparison basis, the models were refined to reflect important features of the "as-built" building and damping system.

The herein reported experimental and numerical studies demonstrated the efficiency of the new damping system which could be considered a promising alternative over the conventional ductility-based earthquake-resistant design both for new construction and for seismic upgrade of existing structures.

Keywords: Full Scale testing; Vibration control; Non-linear Dynamic analysis; Friction damper

INTRODUCTION

Due to its proven efficiency, the concept of seismic protection based on supplemental damping is gaining momentum within the engineering community worldwide. The key objective of this concept is to reduce or eliminate the ductility demand upon the primary structure, which implies substantially lower structural and nonstructural damage. Friction dampers are often employed as components of passive response control systems because they typically offer high energy dissipation capacity at relatively low cost and easy installation and maintenance.

There exist a large variety of devices capable of absorbing seismic energy. The research reported herein is focused in particular on the performance of a new **F**riction **D**amper **D**evice (FDD) developed by I. H. Mualla, Mualla [1]. It is meant for application in moment-resisting frame structures. The complete damping system includes FDDs supported by secondary structure (braces, panels, etc.) inserted within each storey. Comprehensive cyclic testing of a damper prototype and 1/3 scale damped frame model were carried out in the Technical University of Denmark (DTU). Several materials were evaluated for possible implementation in friction pads and the most promising of them was chosen.

However, further research was needed to verify the performance of the damping system in full-scale application under seismic ground shaking. The present contribution reports on the first findings of a joint research program on a three-storey building equipped with FDDs and tested at the advanced large-scale facility of the National Centre for Research on Earthquake Engineering (NCEER) of Taiwan during the first half of year 2001.

DESCRIPTION OF THE DAMPING SYSTEM

The novel friction damper consists of three steel plates and a prestressed bolt, which holds the plates together (Fig. 1). In between the steel plates, two circular friction pad discs made from composite material are inserted.

Figure 1: Friction damper device before testing

Several discs springs (Belleville washers) are used to maintain the bolt clamping force constant. Hardened washers are placed between these springs and side (horizontal) plates to smooth the pressure exerted by the disc springs. The central (vertical) plate connects the damper device to a

frame girder by a pin. The two side plates are connected at their tips to the supporting brace members. In the present research inverted-V (chevron) brace was used. The bracing members are prestressed in order to avoid buckling.
When ground shaking at the base or external lateral force excites a frame structure, the resulting interstorey drift of each storey produces a torque about the FDD center that is resisted by the frictional forces at the friction pad interfaces. Upon reaching the frictional resistance of the device in torsion M_f, slip and relative rotation between the damper plates take place (Fig. 2), thus dissipating a portion of the kinetic energy of the structure. The sticking and sliding modes of the FDDs succeed each other until the end of motion.

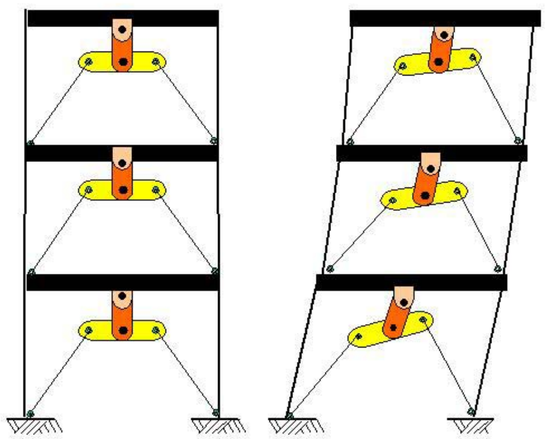

Figure 2: Principle of action of damping system

As shown above, the damper has a very simple mechanism that makes it easy to assemble and install. It can be arranged within a building in different configurations with or without bracing system. The simplicity allows for constructing devices with multiple units in order to match the required design frictional resistance and space limitations.

MAJOR RESULTS OF PREVIOUS RESEARCH

The experimental evaluation of a damper unit was carried out in DTU under displacement and forcing frequency control. For three options, namely brass shims and pads made from two different frictional materials, the influence of various parameters such as the frequency of excitation, displacement amplitude, bolt clamping force and number of loading cycles was examined. The best material capable of sustaining up to 400 cycles without property degradation was chosen for the second phase of testing in which the damper was inserted in a 1/3 scale portal frame model through inverted-V brace and subjected to harmonic lateral loading applied at the girder end. Complete details of the testing procedure can be found in [1]. This phase of testing revealed that the device was almost frequency-independent within the 2-7 Hz range of forcing frequency and the amount of dissipated energy per cycle was proportional to the displacement amplitude. Those findings justify the use of the Coulomb law for friction modelling and imply that the FDD can be classified as displacement-dependent according to Chapter 9 of FEMA [2].

Most of the previous numerical studies were focused mainly on single-degree of freedom structures with supplemental FDD and chevron brace as a secondary structure. The basic theory and underlying assumptions are given in Mualla [1], Mualla and Belev [3]. Approaches with increasing level of sophistication were employed in the simulation of the seismic performance of the friction-damped frame: bilinear hysteresis representation, finite element model and a refined model taking into account the possible large rotations of the device plates. DRAIN-2DX, Prakash et al. [4], and other software for non-linear time history analysis were used. The numerical analyses revealed important aspects of the seismic response of the damping system, which are summarised in Mualla and Belev [3].

SHAKE TABLE TESTING SET-UP

During the first half of year 2001, an international team conducted intensive research program on a three-storey building equipped with FDDs at the advanced large-scale shake-table testing facility of the NCEER. The test building has a steel moment-resisting frame structure with 3.0 m storey height and 4.5 m bay width in the direction of shaking (Fig. 3). The column and girder cross sections are H200x200x8x12 and I200x150x6x9, respectively. The columns are fixed at their bases and the beam-to-column joints are fully welded. Due to the fact that the columns bend about the weak axis of their cross section, the structure is relatively flexible in the direction of testing with estimated fundamental period of vibration 0.936 s. Heavy concrete blocks are used to simulate the floor weights. The total mass of the building including the auxiliary base perimeter frame measured by weighing was 38.3 tons.

Two FDD units were installed within each storey. Their dimensions and mechanical characteristics were chosen based on preliminary numerical analyses. The brace members were made from 20 mm diameter round steel bars pin-connected to the damper plates and frame joints. The prestressing was performed by tightening the bar turnbuckles. All installation works were carried out by a couple of technicians and took one day only. After the testing was completed, the FDDs and their supporting braces were removed within half a day. This was an implication that the dampers can be easily inspected or replaced in real applications.

The displacements and accelerations of the two frames of the model named "east" and "west" frames were measured by displacement transducers and accelerometers attached to each floor and base level. Strain gages were mounted on important locations in the columns, bracing bars and beams. Two LVDT were mounted on each damper to measure its rotations. The total number of all channels employed was 82.

The seismic response of the bare frame structure and its friction-damped peer was evaluated using the 5x5 m shaking table facility capable of simulating horizontal ground motions with peak acceleration up to 3g. It was decided to use several earthquake records of far-field and near-fault types from the 1940 Imperial Valley (USA), 1995 Kobe (Japan) and 1999 Chi-chi (Taiwan) events.

Figure 3: Test building equipped with FDDs

The bare frame structure was subjected to low intensity (PGA = 0.04g - 0.05g) quakes only because unwanted inelastic response under stronger shaking was expected. For this reason, the recorded displacement histories were further scaled up to obtain an extrapolated prediction of the peak response under higher intensity quakes. The performance of the damped structure was examined for 14 cases of seismic input with PGA varying from 0.05g to 0.30g. Several arrangements of the damper slip resistance along the height of the building were used but each arrangement was kept unchanged for a couple of tests of different intensity. For example, the Kobe Takatori record was first applied with PGA = 0.1g followed by consecutive shaking with PGA of 0.05g, 0.15g and 0.175g without readjusting the bolt clamping forces and M_f values. This was a simulation of a series of quakes including aftershocks and could be also viewed upon as a possible situation in which damper parameters deviating from the design ones were introduced due to a mistake of the installing staff. None of the friction pads or other FDD components was replaced during the series of 14 tests.

EXPERIMENTAL EVALUATION OF THE DAMPING SYSTEM

The lower intensity tests of the damped frame did not result in activating the devices to a large extent but confirmed that the braced structure response was predominantly in the direction of shaking with no torsional effects observed. The higher intensity tests with PGA = 0.15g - 0.30g demonstrated the remarkable efficiency of the damping system in reducing the lateral displacements and interstorey drifts of the test building. The enhanced performance is evident from Tables 1 and 2, in which the peak storey drifts of the bare frame structure (W/O FDDs) and its friction-damped peer (With FDDs) are compared.

TABLE 1
STOREY DRIFT COMPARISON FOR EL CENTRO 0.30G TEST

Storey	Storey drifts (mm)		Reduction (%)
	W/O FDDs	With FDDs	
First	80.4	17.4	78.4
Second	79.2	19.0	76.1
Third	50.1	14.3	71.1

TABLE 2
STOREY DRIFT COMPARISON FOR KOBE 0.175G TEST

Storey	Storey drifts (mm)		Reduction (%)
	W/O FDDs	With FDDs	
First	44.4	8.9	80.4
Second	43.9	8.2	81.1
Third	29.9	5.9	80.2

The roof displacement histories for the El Centro 0.20g and Kobe 0.175g cases are plotted in Figs. 4 and 5, respectively. The recorded response of the damped structure (With FDDs) is compared against the predicted elastic response of the bare frame (W/O FDDs) for the same PGA level.

NUMERICAL PREDICTIONS OF THE SEISMIC PERFORMANCE

Finite element plane frame models of the bare and friction-damped frames were created prior to the experimental program in order to support the planning of the shake-table test and assist in the FDD design. The friction action of the FDD was conventionally modelled with non-linear spring with rigid-plastic moment-rotation relationship. The brace bars were represented with Element 09 of DRAIN-2DX code, Prakash et al. [4], as tension-only links with specified axial stiffness and initial prestress force. At this stage, however, the emphasis was placed on choosing brace stiffness and M_f values that would provide adequate performance under the records considered for seismic input. The major constraint was the requirement to limit the storey drifts up to 2 cm (1/150 of the storey height) because the building had already experienced such deformation in previous tests without damage. An important indicator for the efficiency of the damping system that was watched in these preliminary analyses was the amount of energy dissipated in sliding friction as a percentage of the total input energy fed into the structure by a ground motion. The impact of the brace prestressing on the frame members and connections was also evaluated in combination with the gravity loads and seismic ground motion.

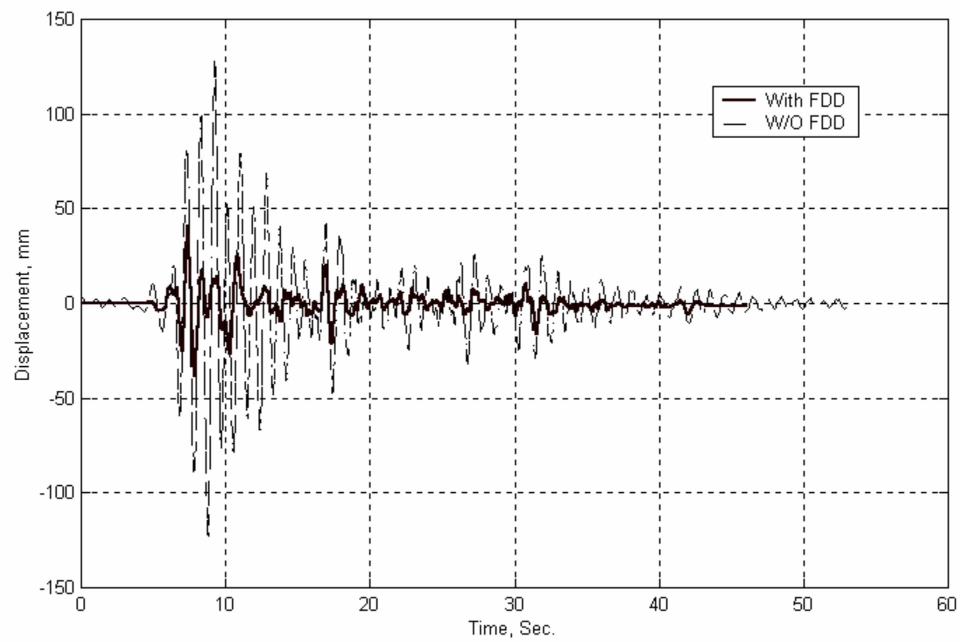

Figure 4: Roof displacement histories, El Centro 0.20g case

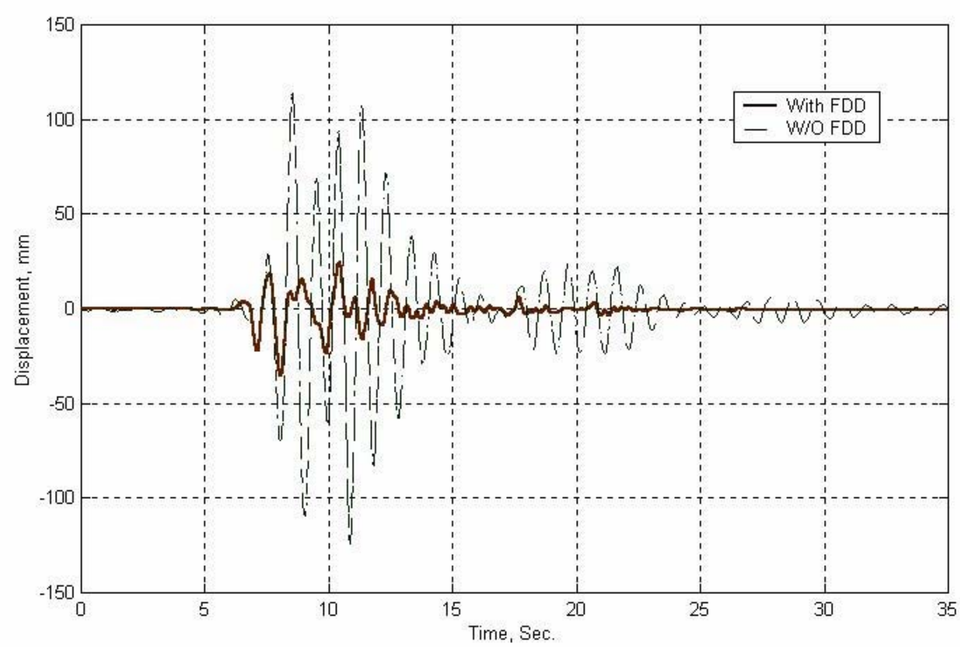

Figure 5: Roof displacement histories, Kobe 0.175g case

After the experimental phase was completed, the models were further improved based on extensive comparison studies. The average of the measured response histories for the "east" and "west" frames of the test building was used as a comparison basis throughout the numerical studies. The model refinement was needed to reflect some features of the "as built" damping system and test building as a whole. First the bare frame model was revised with the purpose of defining more precisely the mass, stiffness and damping parameters. Good agreement between the measured and simulated response was achieved only after the effect of the beam-to-column joint semirigidity was included. Based on the approach of Schneider and Amidi [5] to column panel zone modelling, bilinear rotational springs were introduced to account for the shear deformations of the column flanges at the beam-to-column joints when the columns bend about the weak axis. The modal damping ratios for the first and second modes of vibration were set to 1.5% and 0.5%, respectively, to reflect the findings of system identification analyses of other researchers for the same test building. Figure 6 compares the experimental and predicted roof displacement histories.

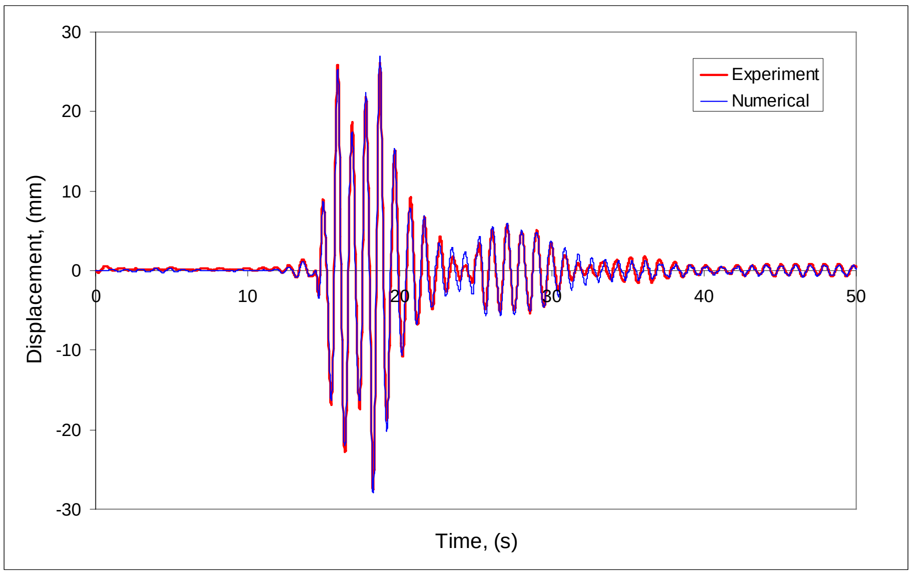

Figure 6: Roof displacement histories for the bare frame, El Centro 0.04g case

The damped frame model was also improved through using better estimates of the flexural and shear stiffness of the FDD plates. Additional calculation based on the clear elongation length of the bracing bars showed that they have 25-30% larger axial stiffness when the rigid gusset plates and actual locations of the bottom pins are taken into account. The measurements of the diagonal slope revealed that certain deviations from the design values were introduced, especially in the first storey brace, which could be considered eccentric at the column bases with an equivalent horizontal offset of 100 mm from the column centerlines inward. All of the modifications described above influenced the brace stiffness, periods of vibration and seismic response. A comparison of the recorded and simulated seismic responses of the friction-damped frame is presented in Fig. 7.

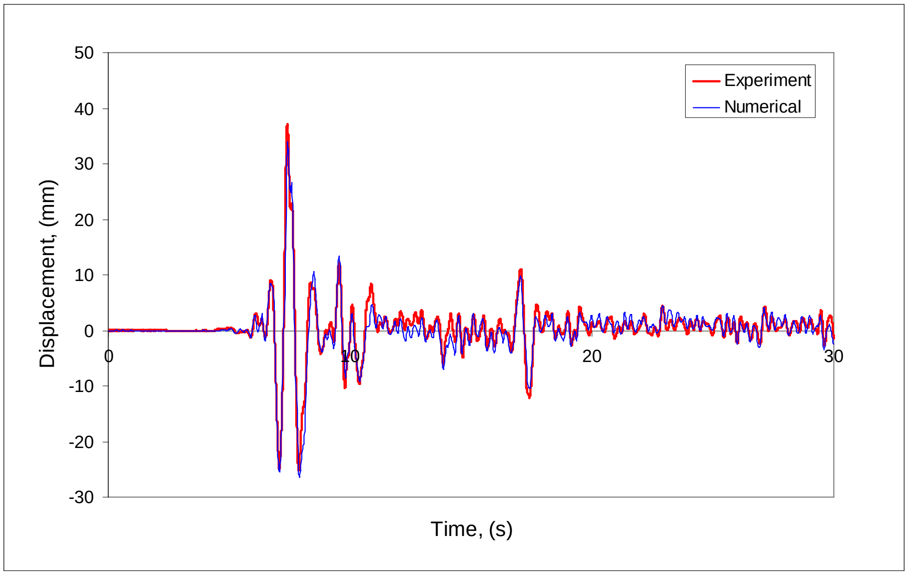

Figure 7: Roof displacement histories for the damped frame, El Centro 0.20g case

REMARKS AND CONCLUSIONS

Previous cyclic tests on scaled frame model not reported herein have indicated that the new FDD is frequency independent within the 2-7 Hz range and its energy dissipation capacity is proportional to the storey drift amplitude and bolt-clamping force, which simplifies the mathematical modelling.

The rigorous full-scale testing at the shaking table facility of NCREE proved the excellent capacity of the proposed damping system to significantly reduce earthquake-induced building vibrations. Durability was another aspect under examination. During the series of 14 tests no damage occurred to the dampers, bracing bars, frame members and connections. The friction pad material also performed very well and no scratches were observed on the sliding interfaces. The first full-scale application of the FDD was very promising in terms of speed of installation as well. The device is easy to manufacture and implement in structures.

The results of the numerical analyses gave a further confirmation that the seismic performance of such friction-damped frames could be predicted reasonably well by conventional software for non-linear time history analysis such as DRAIN-2DX. However, future work is needed for developing a practical design methodology for application of FDDs in multi-storey frame structures.

The seismic protection based on passive energy dissipation eliminates the stringent requirements for structural ductility, reduces damage and business interruption following a major earthquake. Thus an alternative to the conventional ductility-based earthquake-resistant design is made possible both for new construction and for upgrading existing structures.

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