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Performance of steel frames with a new friction damper device under earthquake excitation

Imad H. Mualla [a,*], Borislav Belev [b]

[a] CTO of DampTech Ltd., Technical University of Denmark, B.118, 2800 Lyngby, Denmark

[b] Department of Steel and Timber Structures, University of Architecture, Civil Engineering and Geodesy, 1421 Sofia, Bulgaria

Abstract

A study on the dynamic response of single-storey steel frames equipped with a novel friction damper device (FDD) is presented. Extensive testing was carried out for assessing the friction pad material, damper unit performance and scaled model frame response to lateral harmonic excitation. Numerical simulations based on non-linear time history analysis were used to evaluate the seismic behaviour of steel frames with inserted FDD. The governing parameters were identified and their influence was traced and summarised along with implications for practical design. The application of the new FDD presents a feasible alternative to the conventional ductility-based earthquake-resistant design both for new construction and for upgrading existing structures.

Keywords: Damper device; Vibration control; Seismic protection; Friction; Energy dissipation

1. Introduction

Passive control systems have been successfully used for reducing the dynamic response of structures subjected to earthquakes or strong wind gusts. Friction dampers have often been employed as a component of these systems because they present high energy-dissipation potential at relatively low cost and are easy to install and maintain. A lot of friction devices have been tested experimentally, e.g. Pall and Marsh [1], Aiken and Kelly [2], Fitzgerald et al. [3], Constantinou et al. [4], Grigorian and Popov [5], Nims et al. [6], and many of them have been implemented in buildings around the world. Much research was devoted to developing the theory of passive control systems as well. Recent developments on analysis and design of friction-damped structures include the works of Filiatrault and Cherry [7,8], Colajanni and Papia [9], Dorka et al. [10], Fu and Cherry [11], etc. Kasai et al. [12] proposed common simplified theory for predicting the seismic responses of multi-storey structures with viscoelastic or elasto-plastic devices. Chapter 9 of NEHRP Guidelines [13] contains design provisions for building rehabilitation with passive energy dissipation systems employing displacement-dependent and velocity-dependent devices. Definitely, due to its proven efficiency and simplicity, the concept of seismic protection based on friction damping systems is gaining momentum within the engineering community worldwide.

This paper presents a novel friction damper device (FDD) which is economical, can be easily manufactured and quickly installed. It makes use of material that provides very stable performance over many cycles, resists adhesive wear well and does not damage the steel plate surfaces, thus allowing multiple use. This passive control device is designed to dissipate seismic input energy and protect buildings from structural and non-structural damage during moderate and severe earthquakes. The effectiveness of the damping system employing such FDDs in single-storey frames is evaluated both experimentally and numerically.

2. Damper description and principle of action

The damper main parts are the central (vertical) plate, two side (horizontal) plates and two circular friction pad discs placed in between the steel plates as shown in Fig. 1. The central plate has length h_a and is attached to the girder midspan in a frame structure by a hinge. The

* Corresponding author. Tel.: +45 45251725; fax: +45 45883282.
E-mail address: ihm@damptech.com (I.H. Mualla).

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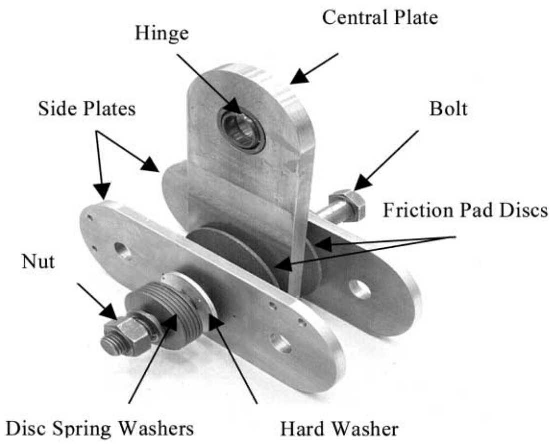

Fig. 1. Components of FDD.

hinge connection is meant to increase the amount of relative rotation between the central and side plates, which in turn enhances the energy dissipation in the system. The ends of the two side plates are connected to the members of inverted V-brace at a distance *r* from the FDD centre. The bracing makes use of pretensioned bars in order to avoid compression stresses and subsequent buckling. The bracing bars are pin-connected at both ends to the damper and to the column bases.

The combination of two side plates and one central plate increases the frictional surface area and provides symmetry needed for obtaining plane action of the device. A pretightened bolt connects the three plates of the damper to each other. This adjustable bolt is used to control the compression force applied on the interfaces of the friction pad discs and steel plates. In order to maintain a constant clamping force, several discs spring washers (Belleville washers) are used. Hardened washers are placed between these springs and the steel plates to prevent any marks on steel surface caused by the spring washers when they are under compression. Steel grade S235 was used for the device plates. In order to reflect the current fabricating practices and simulate industry standards, local structural steel fabricators manufactured all of the steel specimens and no special attempt was made to control the flatness or the dimensions of the damper.

When a lateral force excites a frame structure, the girder tends to displace horizontally. The bracing system and the forces of friction developed at the interface of the steel plates and friction pads will resist the horizontal motion. Fig. 2 explains the functioning of the FDD under excitation. As is shown, the device is very simple in its components and can be arranged within different bracing configurations to obtain a complete damping system.

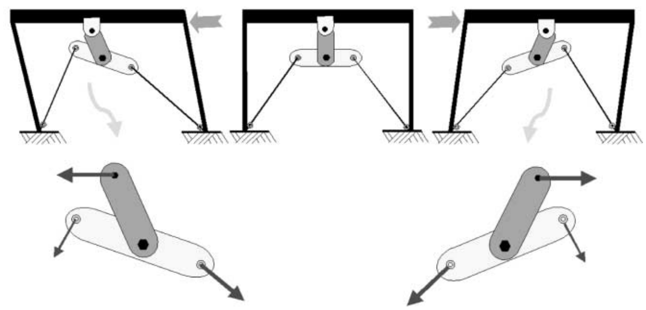

Fig. 2. Principle of action of FDD.

3. Experimental evaluation

In order to evaluate the frictional component of the proposed FDD, a number of qualification tests were performed in the laboratory of the Department of Structural Engineering and Materials, DTU. The experimental program included two phases:

1. testing the damper unit with three friction pad materials; and
2. testing a 1/3 scaled steel frame model with inserted FDD.

The testing of damper unit with different friction materials was done to verify the parameters affecting its performance. From these cyclic tests the proper material was selected and further used in Phase 2 testing. Full details of the experimental program are given in Mualla [14].

The damper specimen described above was tested under displacement and forcing frequency control using an Instron hydraulic testing machine of type 8502. Displacement, forcing frequency and applied force control were possible through a controller unit. 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 as an option because of its low cost and its wide availability as a commercial material. The influence of the following parameters was studied: excitation frequency, displacement amplitude, bolt clamping force and number of loading cycles.

A single-story, one-bay steel frame model was built and tested statically and dynamically in order to verify the effectiveness of the proposed damping system concept experimentally. These tests were planned to ascertain the FDD performance under practical condition prior to introducing it for use in buildings. The overall dimensions of the model frame were 1.125 m in height and 1.10 m in span (Fig. 3). The columns were made of steel strips with 50×15 mm cross section. The beam has a 90×50×5 mm rectangular hollow section and was rigidly connected to the columns by all-around butt-welding.

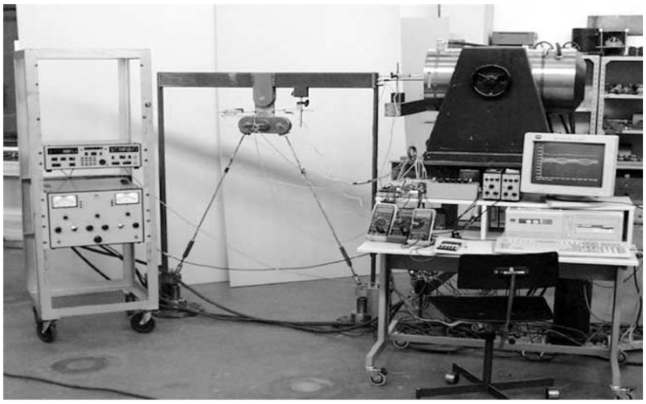

Fig. 3. Experimental setup of scaled frame model with FDD.

The frame was excited laterally with a harmonic force applied at the girder end.

One of the most important aspects in verifying friction damper devices is their 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 the values of all the other parameters constant. The results for the moment resisted by the damper versus the relative rotation between the plates shown in Fig. 4 clearly demonstrate that the hysteretic behaviour is almost frequency-independent for the above range of frequencies. This justifies the use of the Coulomb law for friction modelling. It is worth mentioning that some dependency was observed for the coefficient of sliding friction when high velocities were applied.

The influence of the displacement amplitudes was also studied through a series of tests with stepwise increasing the lateral displacement from 1.75 to 4.5 mm. The frame response is shown in Fig. 5(a), where the numbers in circlets refer to the displacement amplitude. The energy dissipated per cycle, which equals the area within the force–displacement loop was plotted versus the frame displacement amplitude in Fig. 5(b). The proportionality of the above quantities makes the mathematical modelling very simple. A direct proof for the efficiency of the damping system was the fact the FDD dissipated about 89% of the input energy when the model frame was excited by harmonic loading with 3 Hz frequency and force amplitude of 0.8 kN.

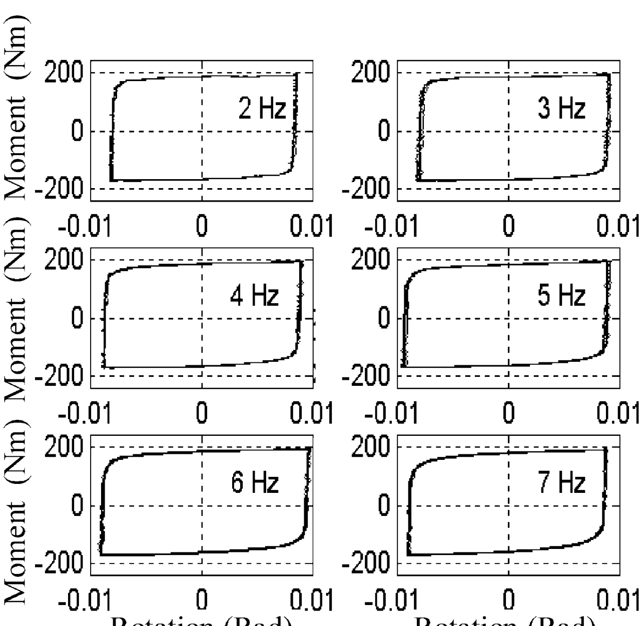

Fig. 4. Effect of forcing frequency on moment–rotation loops.

4. Numerical evaluation

4.1. Basic theory and model description

The friction-damped frame under consideration consists of a single-storey moment-resisting primary frame (PF) and a damping system with two components—the FDD itself and the supporting bracing members as shown in Fig. 2. The parametric studies on the seismic response of such structures often employ approximate simplified models usually based on different linearisation techniques and on the concept of equivalent viscous damping. Another possible approach to modelling is the bilinear–hysteresis SDOF system representation. The bilinear force–displacement relationship stems from the action in parallel of rigid-plastic friction damper and perfectly elastic PF and braces. The equivalent yield strength F_s, initial elastic stiffness K_t and post-yield stiffness K_p are defined as follows:

$$F_s = (M_f/h_a)/(K_t/K_{bd}) \quad (1)$$

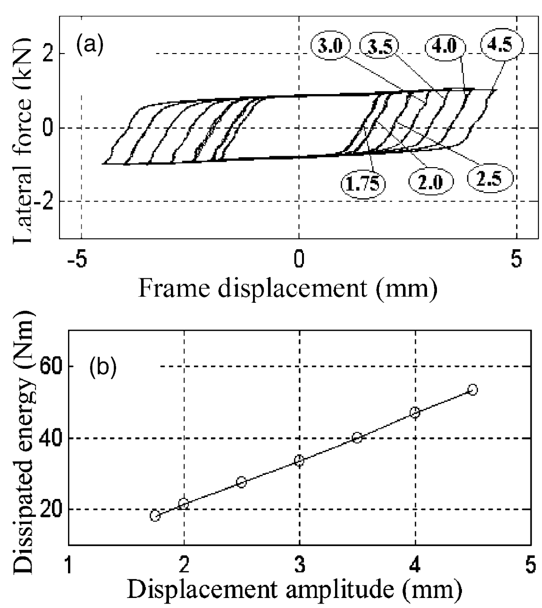

Fig. 5. (a) Effect of displacement amplitude. (b) Energy dissipation–displacement relation.

$$K_t=K_f+K_{bd} \quad (2)$$

$$K_p=K_f \quad (3)$$

where K_f and K_{bd} are the lateral stiffness of the PF and the stiffness of the damping system, respectively. M_f is the rotational frictional strength of the device.

The normalised damper strength is defined by the ratio

$$\eta_M=M_f/M_u \quad (4)$$

where M_u is the torque demand imposed by the ground shaking upon the FDD if it is locked and does not slide during the excitation. It has been derived in [14] that

$$\eta_M=(M_f/h_a)/(S_dK_{bd}) \quad (5)$$

where S_d is the elastic displacement demand computed under the above assumption. The case of η_M=0.0 corresponds to the unbraced PF and η_M=1.0 to the braced frame with locked FDD. It has been confirmed in [14] that the energy dissipation and response reduction capability of the damping system are governed mainly by η_M and the stiffness ratio

$$\mathrm{SR}=K_{bd}/K_f. \quad (6)$$

It is assumed that viscous damping is supplied by the PF members only, thus leading to damping ratio ξ_0. If the mass of the bracing members and FDD is neglected, the resulting damping ratio for the braced frame is

$$\xi_b=\xi_0\sqrt{K_f/K_t}. \quad (7)$$

The bilinear hysteresis model has two typical limitations. The first one stems from the assumed perfectly elastic response of the PF, which is not the case for a range of low η_M values, depending on the particular ground acceleration record. The second one arises from the assumed linear behaviour of the prestressed braces that would require rather high prestress force for a range of large η_M values in order to prevent braces from going slack. However, the previous studies indicated that best FDD performance is achieved for η_M that is in-between the two unfavourable ranges. The simplified bilinear model of the friction-damped frame is time efficient for parametric studies and allows NONLIN [15] or any similar software for non-linear analysis of SDOF systems to be employed.

Finite element plane frame models of the PF and friction-damped structure were also created and numerical simulations were performed using DRAIN-2DX [16] and other software for non-linear time history analysis. The frictional resistance of the FDD was represented by a non-linear spring with rigid-plastic moment-rotation relationship. The prestressed brace members were modelled with Element Type 09 as unidirectional tension-only links defined by their axial stiffness and initial tension force. Additional software named FRIC that employs a refined model accounting for the possible large rotations of the FDD plates and resulting change in the brace geometry was developed [14] and used for parallel computations.

4.2. Criteria for the efficiency of the damping system

For the purpose of numerical evaluation, several response indicators were estimated and plotted: energy dissipated by the damper as a percentage of the total seismic input energy, maximum response displacement, maximum total base shear, and maximum base shear in the PF only. The last parameter is proportional to the maximum response displacement if the frame remains elastic during the excitation. In addition, to quantify the damper capability to reduce the base shear and lateral displacement demands, these were normalised to the corresponding response quantities of the elastic unbraced PF, thus obtaining the so-called ‘response reduction factors’ R_f and R_d.

A brief review and discussion on the available criteria for the supplemental damping efficiency were given in Belev [17]. Following [11,12], a set of response curves in the R_d–R_f space can be plotted through varying the strength and stiffness of the damping system for a given seismic input, and the optimal solution is achieved at the point that is closest to the origin. If we define a seismic performance index SPI, this criterion could be translated into

$$\mathrm{SPI}=\sqrt{R_d^2+R_f^2}\rightarrow\mathrm{min}. \quad (8)$$

From a designer’s viewpoint, (8) is meaningful because it favours damping system parameters that significantly reduce both displacement and base shear demand. However, R_d and R_f are actually ratios of extreme response quantities that may not necessarily be proper descriptors of the overall seismic performance and complete response history. For this reason, it was suggested in [17] that an additional performance indicator R_e be included, defined as

$$R_e=(E_i-E_h)/E_i \quad (9)$$

where E_i and E_h are the total input energy and the energy dissipated by the hysteretic device at the end of the ground shaking, respectively. Generalising the criterion (8), the optimal design solution corresponds to the response point in the R_d–R_f–R_e space that is closest to the origin:

$$\mathrm{SPI}=\sqrt{R_d^2+R_f^2+R_e^2}\rightarrow\mathrm{min}. \quad (10)$$

Further, if the design recognises that the three performance indicators are of different importance (the target performance for new and retrofitted buildings may be different), appropriate weight factors w_d, w_f and w_e may be included in (10), thus modifying it to

$$\mathrm{SPI}=\sqrt{w_d^2R_d^2+w_f^2R_f^2+w_e^2R_e^2}\rightarrow\min. \tag{11}$$

4.3. Description of the case study frame

Single-storey frames with different geometries and damper parameters have been analysed in [14] using FRIC and DRAIN-2DX software. The case study frame considered herein was taken from the work of Filiatrault and Cherry [8]. It is a portal steel frame with 7.6 m span and 4.6 m height. The beam is assumed infinitely rigid and the columns are fixed at their bases. The column cross sections are wide-flange I-shapes with moment of inertia 34×10^6 mm^4. For the assumed weight of 450 kN, the period of vibration is 1 s, and the damping ratio is 5% of critical. The frame was equipped with an FDD that has dimensions r=0.165 m and h_a=0.2 m.

4.4. Influence of the damper strength

The energy dissipation and response reduction were studied as a function of the normalised damper strength η_M for a fixed SR value. Further, a family of curves corresponding to different SR values were plotted to illustrate the effect of brace stiffness on the performance of the friction-damped frame. A change in SR leads to shifting the period of vibration and damping ratio, and, as a consequence, to change in S_d. Three K_{bd} values were used. The first one denoted by K_{bd} corresponds to circular cross-section of 16 mm diameter with area A_b =201 mm^2, the second 2K_{bd} and third 3K_{bd}–to A_b =402 and 603 mm^2, respectively.

The numerical analyses were carried out using the bilinear model of the friction-damped frame and NONLIN software [15]. The input accelerogram was El Centro 1940, NS component with PGA=3.417 m/s^2 and 20 s duration. The performance of the friction-damped frame is displayed on Fig. 6 from which the following observations were made:

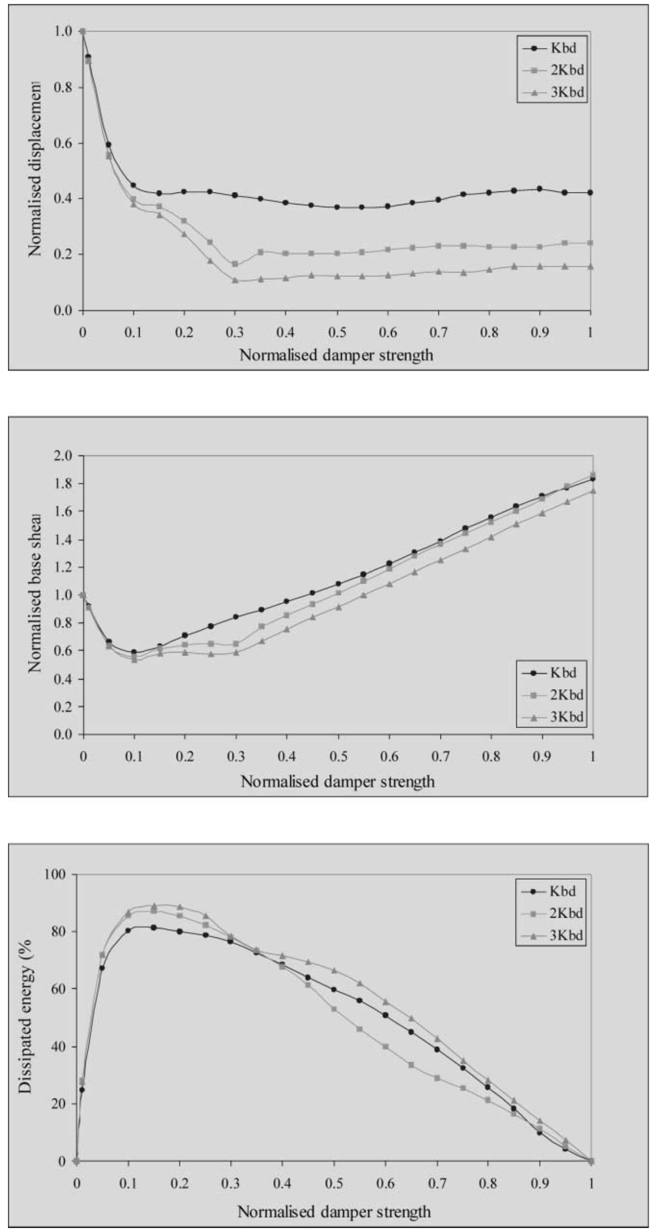

Fig. 6. Performance of the friction-damped frame: (a) displacement reduction; (b) base shear reduction; (c) energy dissipated by FDD.

1. The response reduction exhibits strong dependence upon η_M and K_{bd}. For η_M larger than 0.3, maximum displacement reduction can be obtained but this is accompanied by a steady increase in the base shear. Very large η_M values may not be physically meaningful for the specified small cross-sections and mild steel grade for the braces. High-strength cables would be more suitable for providing adequate brace prestress when large damper frictional strength is required.
2. The largest percentage of input energy is dissipated for η_M within the range from 0.05 to 0.20 for all K_{bd} values studied. However, the peak of dissipated energy plot does not necessarily indicate the best performance of the damped frame, as it is sometimes accompanied by increase in the total seismic energy input.

4.5. Influence of the brace prestress force

The use of slender bracing members in building structures is economical but requires certain brace configurations such as X-bracing in order to avoid controlled prestressing. For the case of V- or inverted V-bracing, either prestressed or rigid members are only applicable within conventional frames. The installation of a damping system including a FDD and inverted V-brace should follow the same principle, but due to the nonlinear (rigid-plastic) behaviour of the damper, the brace buckling (going slack) might not endanger the structural safety during an earthquake. Furthermore, the authors felt that the sensitivity of the friction-damped frame to the brace-prestressing accuracy is an important issue, which was studied through numerical simulations in [18].

The same single-storey frame and seismic input were considered and DRAIN-2DX software was employed. For the case of A_b=201 mm^2 and fixed M_f=7.0 kNm, the prestress force F_p required to prevent the brace bars from buckling (going slack) under El Centro NS ground motion was computed, and then the responses of the friction-damped frame with different levels of brace prestressing (20%, 40%, 60%, 80% and 100% of F_p) were simulated and compared. The lateral displacement histories for the two extreme cases–20% and 100% of F_p, are plotted in Fig. 7. The comparison shows that using partial prestressing for the brace members does not increase dramatically the response displacements. However, depending on the steel grade of the PF certain yielding of the frame members should be expected. The comparison of the damper rotation histories for the same two cases also showed close similarity and the increase in the rotation demand due to partial prestressing was minor.

4.6. Influence of the ground shaking intensity

The design of passive control systems is usually based on a given target seismic intensity. In fact, the design PGA or PGV correspond to an agreed probability of exceedance, thus implying that the performance and sensitivity of the system shall be carefully examined under varying (lower and higher than the design level) intensity of the seismic input. For the friction damping system, this issue was investigated in [19] using a limited numerical study on the response of the case study frame under the El Centro NS ground motion scaled by acceleration scale factors I=0.5/0.75/1.0/1.25 and 1.5. For the assumed brace cross section A_b=603 mm^2, the optimal M_f =22 kNm was estimated first based on (8) for the original El Centro NS acceleration history. This combination of stiffness and strength of the damping system resulted in R_d=0.11 and R_f=0.59. Fig. 8 shows the FDD rotation histories for original (I=1.0) and scaled (I=0.5 and 1.5) seismic input. Although optimised for I=1.0, even for I=1.5 the damping system successfully counterbalanced the sharp increase in input energy at the expense of much larger rotations between the damper plates. Additional analyses for the latter case assuming mild steel grade S235 with nominal yield strength of 235 MPa for the PF columns indicated that limited member yielding under seismic events with intensity larger than the design level is favourable to the FDD performance and decreases the residual displacements.

5. Conclusions

A new friction damper device developed for seismic protection of structures was described and evaluated experimentally and numerically. The excellent and stable hysteretic behaviour is to a great extent attributed to the choice of proper friction pad material. Intensive experimental tests were carried out to single out the influence of various parameters such as the forcing frequency, displacement amplitude, bolt clamping force and brace prestress on the model friction-damped frame. They showed that the device is velocity independent within a certain range and linearly dependent on the displacement amplitude that simplifies the mathematical modelling.

Numerical analyses on single-storey steel frame models indicated that (1) when the strength and stiffness of the damping system are properly selected, the response displacement and base shear could be reduced dramatically; (2) for the case study frame and assumed seismic input, the partial prestressing of the brace bars did not result in excessive response displacements or damper rotation; (3) the performance of the friction-damped frame under seismic event with PGA 50% higher than

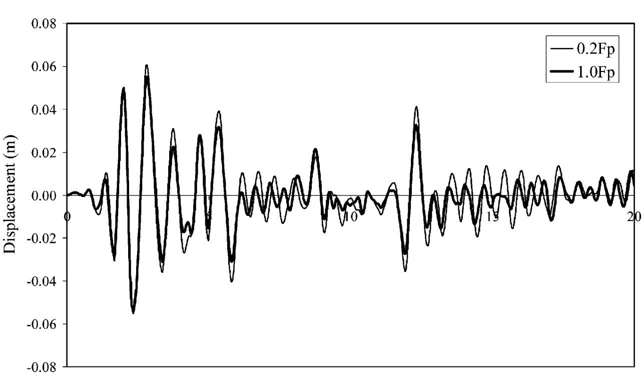

Fig. 7. Influence of brace prestress force on response displacements.

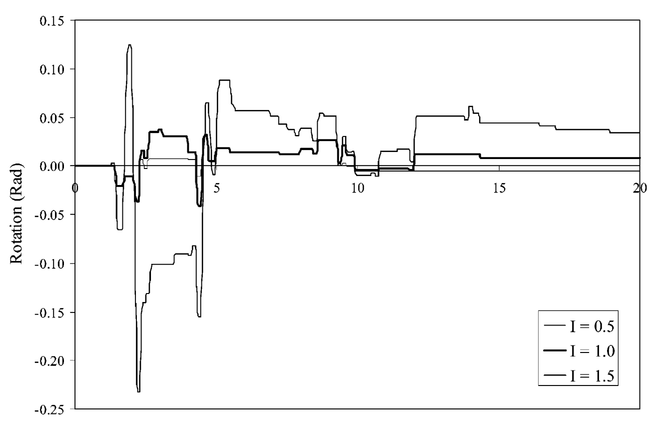

Fig. 8. Impact of ground shaking intensity on FDD behaviour.

the design level remained satisfactory at the expense of much larger rotation demand upon the FDD.

The experimental and numerical studies reported clearly demonstrate that passive response control systems based on the new FDD present a viable alternative to the conventional ductility-based earthquake-resistant design both for new construction and for upgrading existing structures. The device can be economically produced and installed in structural frames to protect buildings from structural and non-structural damage in moderate and severe earthquakes.

Further research is needed to justify the above conclusions for a broader set of seismic acceleration histories and to develop design procedures for multi-storey structures with supplemental friction dampers.

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