Plane frames equipped with friction damper devices subjected to seismic action

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Abstract

The present paper analyzes the dynamic response of frames equipped with an anti-seismic friction damper developed by the company *Damptech ApS*. The NSCD algorithm (Jean, 1999) was programmed in *MATLAB* to efficiently deal with the non-regular character of the friction law that governs the behavior of this kind of systems. For validation of the program, known experimental and numerical results were reproduced and hysteresis cycles and maximum displacements were compared. An extensive campaign of numerical computations was carried out to study a laboratory frame model equipped with the friction damper, under a harmonic excitation force. A real frame under the accelerogram of the El Centro earthquake was also considered and a performance criterion was established that allowed to obtain an optimal moment for the frictional hinge. Each friction damper has two prestressed bracing bars; the cases of axially rigid and axially compliant bracing bars were considered. For the analyzed frames of one, three and five floors for both rigid and deformable bracing bars under the action of the El Centro earthquake, it was concluded that the optimal frictional moment is approximately independent of the number of floors. An important reduction of the relative displacements and absolute accelerations of the floors of the frames with friction dampers was also observed when comparing with the situation where these devices are absent.

Keywords: Anti-seismic system, Friction, Dissipated energy, NSCD algorithm

1. Introduction

Earthquakes are geological events in which a large amount of deformation energy accumulated over a long period of time in the earth's crust is released within a short time interval. Some of this energy is transmitted to buildings that, when they are not able to dissipate it at a reasonable speed, can be damaged, partial collapsed or even totally collapsed. The way in which and how quickly this energy is dissipated determines whether the structure can be rehabilitated or the need for its demolition. In order to ensure the safety and comfort of users and equipments in buildings, it is necessary that the structures of such buildings be able to dampen the vibrations transmitted by earthquakes in a timely manner. The most common means of achieving this goal is to provide structures with efficient intrinsic or external energy dissipation mechanisms. One of these mechanisms, object of this paper, is the passive damping by exploring the sliding friction at interfaces where the vibration process produces relative linear or angular sliding velocities. The friction damping method has advantages over viscous damping such as low cost of manufacture, lower maintenance requirements and environmental sustainability ((Bhaskararao and Jangid, 2006); (De la Cruz, López-Almansa, and Oller, 2007)).

There are several damping and structural control methods. They are generally grouped into four categories: *i*) passive systems, *ii*) semi-active systems, *iii*) active systems, and *iv*) hybrid systems. Passive systems include: seismic isolation in which the structure and the ground movement are decoupled, and energy dissipative systems designed to prevent the structure from being subjected to high deformations by means of an efficient dissipation of the energy transmitted by the earthquake.

There is a wide variety of passive seismic protection systems. The rotational friction device, designed by Mualla (Nielsen and Mualla, 2002) and developed by the company *Damptech ApS* (for more information see (Damptech-a)), is the focus of the present work (see figure 1). Alongside this Danish company, there are others that sell friction dissipation devices such as *Pall Dynamics Limited* (for more information see (Pall Dynamics)). This solution is recurrent in residential buildings in countries such as USA, Canada, Japan, Australia and New Zealand. Trends in modern architecture increasingly require consideration of large open spaces with few vertical structural elements, which may lead to solutions not acceptable by seismic design codes, therefore requiring the adoption of efficient seismic protection solutions such as friction dampers.

(a) Photography of a damping friction device (Damptech-b).

(b) Photography of a damping friction device (Damptech-b).

Figure 1: Damping friction device developed by the company *Damptech ApS*.

Eurocode 8 (EN1998-1:2004) still doesn't pay much attention to the method of frictional dissipation vibration control, so it is difficult to find guidelines of design for this type of devices and designers have a lot of field of action. In the case of structures without damper devices, the "capacity design" concept proposes in order to maximize the power dissipation capacity it is beneficial to form a sufficient number of plastic hinges without transforming the structure into a mechanism (Bento and Lopes, 1999). For this to occur it is essential that these plastic hinges form at the ends of the beam and never at the pillars so that they have sufficient ductility, that is, stable hysteresis cycles, so that the overall strength of the structure is not compromised. The approach in this paper is different: it aims to avoid the formation of plastic hinges on the structural elements by providing the structures with additional non-structural means that dissipate the energy transmitted by the earthquake.

2. Plane frame equipped with friction damper with *rigid bracing bars*

The energy dissipation mechanism of the system proposed by Nielsen and Mualla (2002) consists of a friction hinge inserted into a truss that deforms for relative movements between consecutive floors. Energy dissipates when a relative angular velocity occurs between the "rigid" elements attached to this hinge. The system schematically represented in figure 2, is the simplest version of the device, applied to a plane frame with one degree of freedom (one floor). The frame mass m is considered concen-

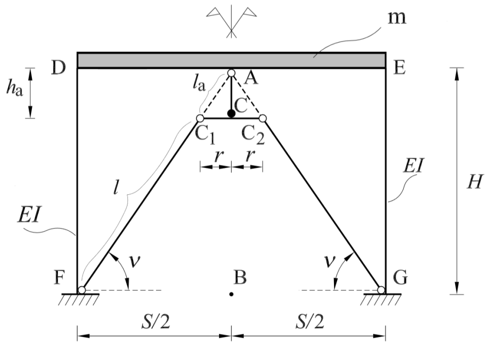


Figure 2: Geometry and mechanical properties of the damping system and the frame. Friction hinge: C (full circle). Hinges without friction: A, C_1, C_2, F (from bar $\overline{FC_1}$, G (from bar $\overline{GC_2}$).

trated at floor level. This mass is supported by two columns H, each with a cross section of bending stiffness EI, with the span of the frame equal to S.

This paper explores the behavior of this type of structures under the action of the North-South component of the El Centro earthquake (occurred in 1940 at the Imperial Valley Irrigation District, California, United States of America). The analyzed frame is the same considered by Mualla and Belev (2002) with two columns with a height $H = 4.6$ m, a span $S = 7.6$ m, a mass $m = 45918.4$ kg, a horizontal rigidity $k = 1760499.7$ N/m and a viscous damping factor of $\zeta = 5\%$. Further ahead, results are also obtained for three and five story frames (which have the same mass, column height per floor and span length as the one story frame). The influence of the earthquake on the displacements of each floor relative to the base, the absolute accelerations of the floors and the basal shear force is then analysed.

We start by determining the optimum maximum moment on the friction hinge of the frame based on the minimization of two performance criteria applied to the El Centro earthquake:

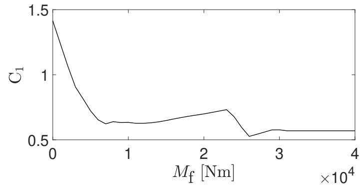
$$C_1 = \sqrt{f_1^2 + f_2^2} \rightarrow \min \quad \text{e} \quad C_2 = \sqrt{f_1^2 + f_2^2 + f_3^2} \rightarrow \min$$

where

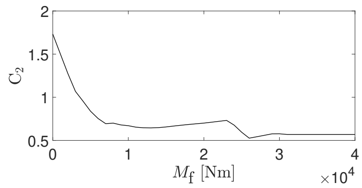
$$f_1 = \left|\frac{x_{N\ \mathrm{f\ max}}}{x_{N\ 0\ \max}}\right|, \quad f_2 = \left|\frac{\ddot{X}_{N\ \mathrm{f\ max}}}{\ddot{X}_{N\ 0\ \max}}\right|, \quad f_3 = \left|\frac{F_{\mathrm{bf}}}{F_{\mathrm{b0}}}\right| = \left|\frac{k\ x_{1\ \mathrm{f\ max}}}{k\ x_{1\ 0\ \max}}\right| = \left|\frac{x_{1\ \mathrm{f\ max}}}{x_{1\ 0\ \max}}\right|.$$

The values f_1, f_2 e f_3 reflect the weights (1) of the maximum relative displacement between the ground floor and the top floor, (2) the maximum absolute acceleration at the top floor, and (3) the shear force at the ground floor.

Figure 3 shows criteria 1 and 2 as a function of the moment on the friction hinge in the case of a single-story frame. The optimum moment M_{f} is considered to have similar values in both criteria: $M_{\mathrm{f\ opt}} \simeq 13000$ Nm.



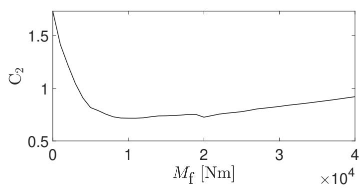
(a) Criterion C_1.



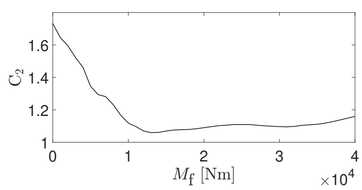
(b) Criterion C_2.

Figure 3: Criteria 1 and 2 for a *single-story* frame with rigid bracing bars ($M_{\mathrm{f\ opt}} = 13000$ Nm).

Since the optimal values for M_{f} are similar in both criteria, in figure 4 only criterion 2 is represented for the three- and five-story frames (we chose to show only C_2). Also in these two cases the optimal value is again $M_{\mathrm{f\ opt}} = 13000$ Nm.



(a) *Three-story* frame.



(b) *Five-story* frame.

Figure 4: Criteria 2 for three- and five-story frames with rigid bracing bars ($M_{\mathrm{f\ opt}} = 13000$ Nm).

Once the optimum moment of each frame is known, we next quantify the impact of the presence of this friction damping device in the vibration control of these frames. For the single-story frame, figures 5 and 6 represent the evolution of ground displacement and absolute acceleration *without* and *with* the optimized friction damping device. Consideration of an optimized friction damping represents a reduction of 86% in relative peak displacement and 38% in absolute peak accelerations.

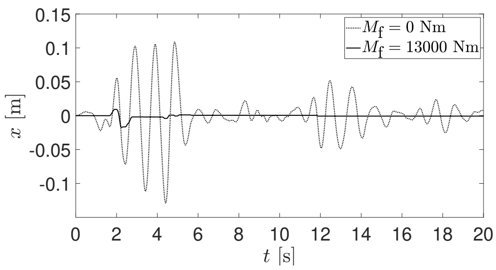


Figure 5: Floor displacement relative to the ground in a *single-story* frame with rigid bracing bars, without and with the optimal friction moment value.

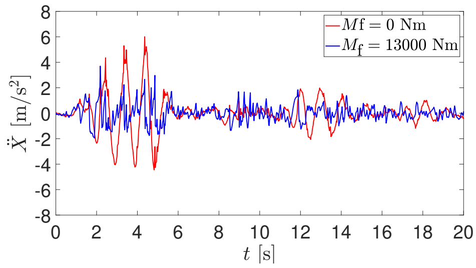


Figure 6: Absolute acceleration at the top floor in a *single-story* frame with rigid bracing bars, without and with the optimal friction moment value.

Figures 7 and 8 represent the evolution of ground relative displacement and acceleration (also of the last floor) *without* and *with* the optimized friction damping device for the three-story frame. The adoption of an optimized friction damping device results in a reduction of 81% in relative displacements and 37% in absolute accelerations.

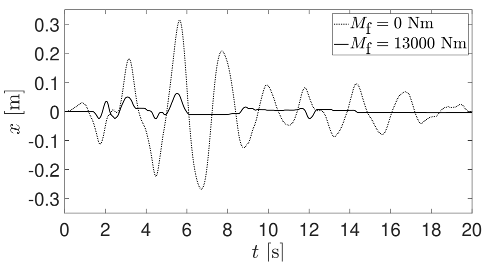


Figure 7: Relative displacement between the ground and the top floor in a *three-story* frame with rigid bracing bars, without and with the optimal friction moment value.

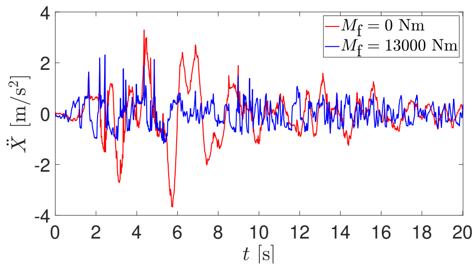


Figure 8: Absolute acceleration at the top floor in a *three-story* frame with rigid bracing bars, without and with the optimal friction moment value.

Figures 9 and 10 illustrate the evolution of the relative displacements of the three floors of this frame in the absence of the friction damping device ($M_f = 0$ Nm) and when the maximum moment on the friction hinge takes the optimized value $M_f = 13000$ Nm. A large reduction in the displacement amplitude can be observed when the friction damping device is present. In figure 10 we may also observe that the graphs corresponding to the 2^{nd} and 3^{rd} floors are coincident (for all practical purposes).

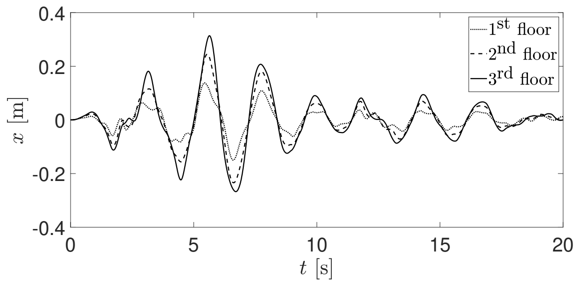


Figure 9: Floor displacements relative to the ground in a *three-story* frame with rigid bracing bars for $M_f = 0$ Nm.

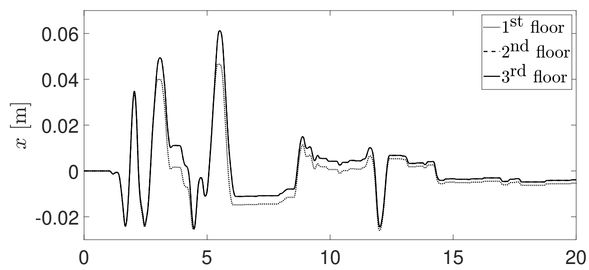


Figure 10: Floor displacements relative to the ground in a *three-story* frame with rigid bracing bars for $M_f = 13000$ Nm.

Figures 11 and 12 represent the evolution in time of the relative displacement between the ground floor and the top floor, and the absolute acceleration (also top-floor) *without* and *with* the optimized friction damping device for the five-story frame. In this case it is observed that the consideration of an optimized friction damping leads to a reduction of 65% in the maximum relative displacement and 15% in the maximum absolute acceleration.

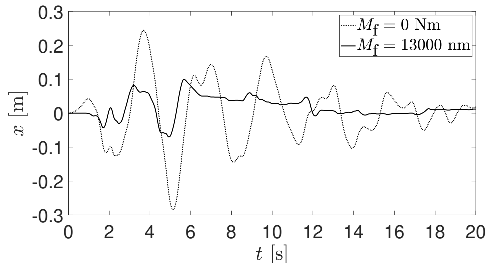


Figure 11: Relative displacement between the ground and the top floor in a *five-story* frame with rigid bracing bars, without and with the optimal friction moment value.

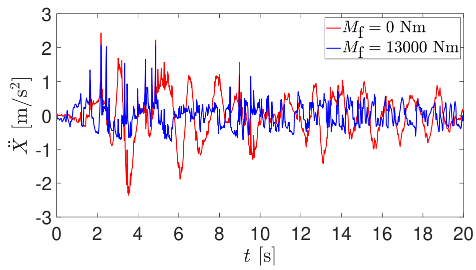


Figure 12: Absolute acceleration at the top floor in a *five-story* frame with rigid bracing bars, without and with the optimal friction moment value.

Figures 13 and 14 represent the relative displacements of the five floors of this frame in the absence of the friction damping device ($M_f = 0$ Nm) and when the maximum moment on the friction hinge takes the optimal value. A large reduction in the displacement amplitude of all floors can be observed when considering the presence of a friction damping device. In figure 14 we may also observe that the graphs corresponding to the 3rd, 4th and 5th floors are coincident (for all practical purposes).

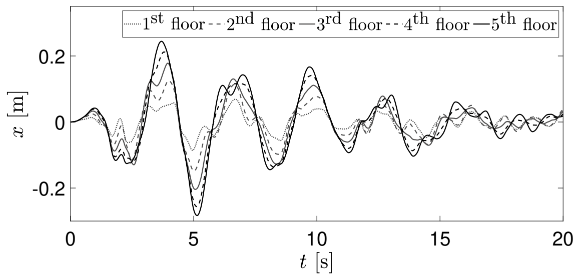


Figure 13: Floor displacements relative to the ground in a *five-story* frame with rigid bracing bars for $M_\text{f} = 0$ Nm.

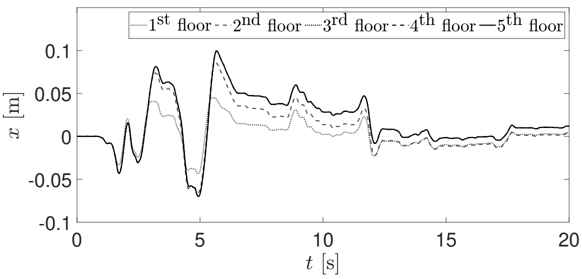
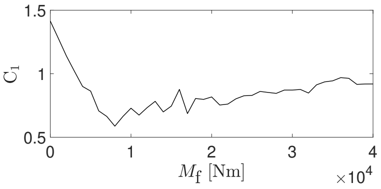


Figure 14: Floor displacements relative to the ground in a *five-story* frame with rigid bracing bars for $M_\text{f} = 13000$ Nm.

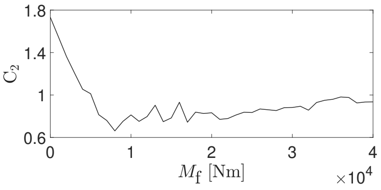
3. Plane frame equipped with friction damper with *axially compliant bracing bars*

As in the response of a frame subjected to a seismic action is also studied in this section but now considering that the bracing bars are not rigid. This frame has the characteristics already given in section 2, except that the two bracing bars are now compliant, with a cross section area $A_b = 603$ mm^2. The optimum moment in the friction device is determined based on the minimization of the same two seismic performance criteria (C_1 and C_2) applied again to the El Centro earthquake.

Figure 15 represents criteria 1 and 2 as a function of the moment at the friction hinge in the case of a single-story frame. Despite the irregularities of the graph it is considered that the optimum moment for a one-floor frame is approximately 13000 Nm.



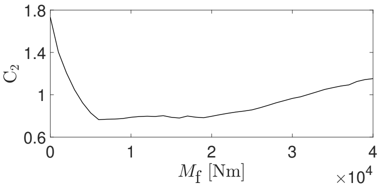
(a) Criterion C_1.



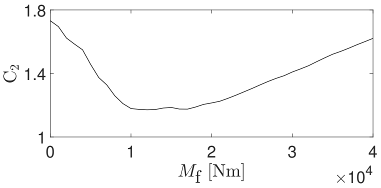
(b) Criterion C_2.

Figure 15: Criteria 1 and 2 for a *single-story* frame with axially compliant bracing bars ($M_\text{f opt} = 13000$ Nm).

Figure 16 represents criterion 2 as a function of the maximum moment at the friction hinge in the case of three- and five-story frames. In these two cases, it is also considered that the optimal moment is $M_\text{f opt} = 13000$ Nm, which coincides with the value obtained when the bracing bars were considered to be rigid. In the report (Mualla and Belev, 2002) the value obtained for the optimal moment was $M_\text{f opt} = 22000$ Nm based on a criterion similar to criterion 2. However, the authors do not mention which algorithm they used in the numerical analysis of the friction damping device.



(a) *Three-story* frame.



(b) *Five-story* frame.

Figure 16: Criterion 2 for a three- and five-story frame with axially compliant bracing bars ($M_\text{f opt} = 13000$ Nm).

Figures 17 and 18 represent, as a function of time, the relative displacement and absolute acceleration in the one floor frame *without* and *with* the optimized frictional damping device. It can be observed that the consideration of this device reduces

55% the maximum relative displacement and 36% the maximum absolute acceleration.

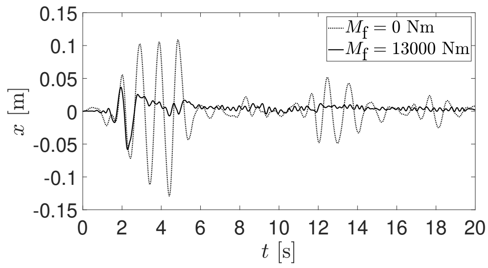


Figure 17: Floor displacement relative to the ground in a *single-story* frame with axially compliant bracing bars, without and with the optimized friction device.

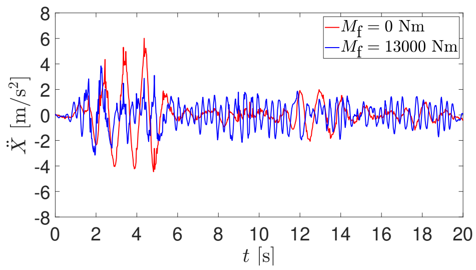


Figure 18: Absolute acceleration at the top floor in a *single-story* frame with axially compliant bracing bars, without and with the optimized friction device.

Figures 19 and 20 represent, as a function of time, the relative displacement between the top floor and the ground floor and the absolute acceleration (also of the top floor) in the three-story frame *without* and *with* the optimized friction device. It can be observed that the consideration of this device is reflected in a reduction of 77% in the peak relative displacement and 30% in the peak absolute accelerations.

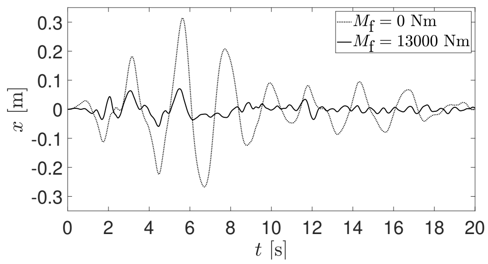


Figure 19: Relative displacement between the ground and the top floor in a *three-story* frame with axially compliant bracing bars, without and with the optimized friction device.

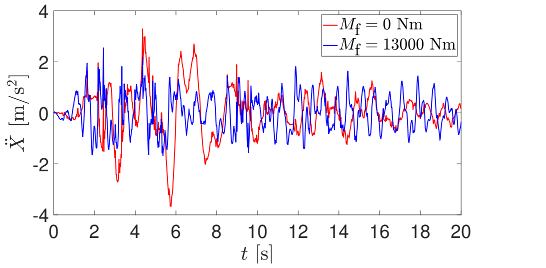


Figure 20: Absolute acceleration at the top floor in a *three-story* frame with axially compliant bracing bars, without and with the optimized friction device.

Figures 21 and 22 represent, as a function of time, the relative displacements of the three floors of this frame in the absence of the friction damping device ($M_f = 0$ Nm) and when the moment of the friction hinge takes the value that we assumed to be the optimized value $M_f = 13000$ Nm. A large reduction in displacement amplitude is observed when considering the presence of a friction damping device.

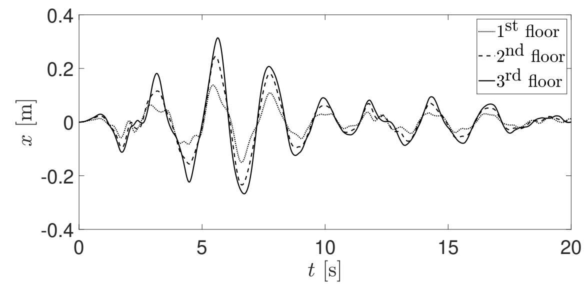


Figure 21: Floor displacements relative to the ground in a *three-story* frame with axially compliant bracing bars for $M_f = 0$ Nm.

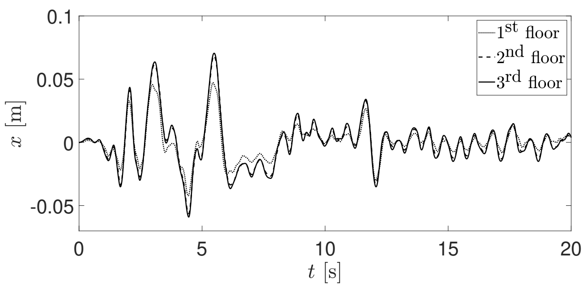


Figure 22: Floor displacements relative to the the ground in a *three-story* frame with axially compliant bracing bars for $M_f = 13000$ Nm..

Figures 23 and 24 represent, as a function of time, the relative displacement between the top and the ground floor and the absolute acceleration (also of the top floor) in the five-story frame *without* and *with* the optimized frictional damping device. The consideration of a friction damping device represents a 61% reduction in relative displacements and a 5% reduction in absolute accelerations.

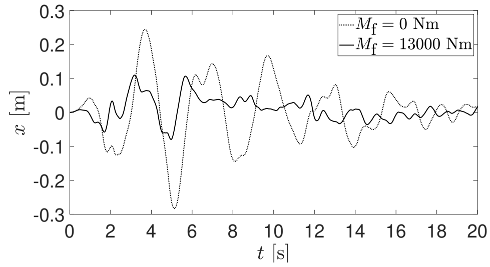


Figure 23: Relative displacement between the ground and the top floor in a *five-story* frame with axially compliant bracing bars, without and with the optimized friction device.

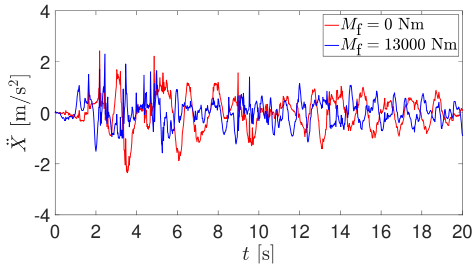


Figure 24: Absolute acceleration at the top floor in a *five-story* frame with axially compliant bracing bars, without and with the optimized friction device.

Figures 25 and 26 represent, as a function of time, the relative displacements of the five floors of this frame in the absence of the frictional damping device ($M_f = 0$ Nm) and when the moment at the friction hinge takes the optimal value. A reduction in the range of the displacements of all floors may be observed when considering the installation of a optimized friction damping device.

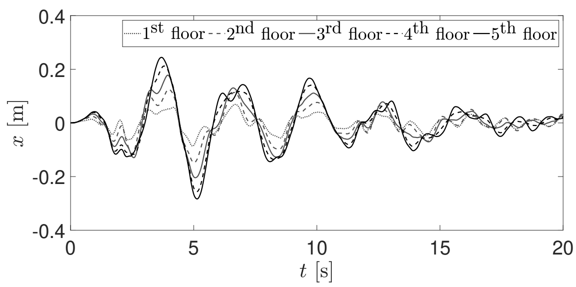


Figure 25: Floor displacements relative to the ground in a *five-story* frame with axially compliant bracing bars for $M_f = 0$ Nm.

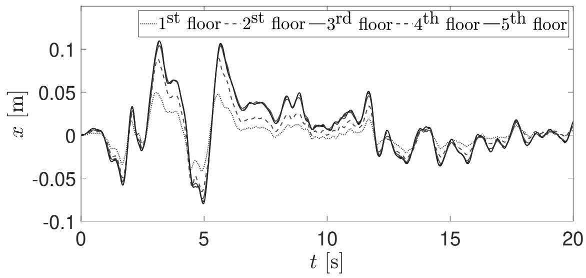


Figure 26: Floor displacements relative to the ground in a *five-story* frame with axially compliant bracing bars for $M_f = 13000$ Nm.

4. Conclusions

This paper addresses the dynamic behavior of plane frames equipped with friction energy dissipators subjected to harmonic forces or foundation movements. The assessment of the dynamic behavior is done by a set of extensive numerical simulations.

The numerical simulations are based on the NSCD algorithm, especially designed to take it to account the non-smooth character of the friction law. The NSCD algorithm was programmed in *MATLAB*. The program was validated by comparing some numerical results with known analytical estimates.

This paper was divided into two main chapters: one using a simplified model for the frictional damper with rigid bracing bars and another with axially deformable bracing bars. In both chapters, an extensive numerical calculation campaign was carried out to study real-sized frames with a variable number of floors subjected to a seismic action. One of the objectives of this paper was to evaluate the optimal frictional moment on the friction hinge based on two criteria that take into account both users' comfort and users' and frame's safety. For the analyzed frames, the optimal frictional moment should be equal to 13000 Nm regardless the number of floors. If the frames are equipped with this optimized system, it is also concluded that there is a large reduction in the maximum relative displacements and maximum floor accelerations compared to the situation where this system is not present. This proves the efficiency of this type of system which has several economic and environmental advantages over the viscous damping system.

Suggestions of future works may include:

- The development of a computational program that performs the analysis of *three-dimensional* structures equipped with friction energy dissipators subjected to dynamic actions applied simultaneously in various directions.
- The application of the program mentioned in the previous point to the analysis of *irregular structures* in plan and in elevation in or-

der to evaluate the efficiency of this passive damping system in the control of vibrations of structures more vulnerable to the seismic action.

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References

Bento, R. and Lopes, M. *Modelação Fisicamente Não Linear de Estruturas de Betão Armado*. Disciplina de Modelação e Análise Estrutural, Instituto Superior Técnico, 1999.

Bhaskararao, A. and Jangid, R. Seismic analysis of structures connected with friction dampers. *Engineering Structures*, 28:690–703, 2006.

Damptech-a. http://www.damptech.com/. Visitado em outubro 2019.

Damptech-b. https://www.damptech.com/for-other-purposes. Visitado em outubro 2019.

De la Cruz, S., López-Almansa, F., and Oller, S. Numerical simulation of the seismic behavior of building structures equipped with friction energy dissipators. *Computers and Structures*, 85:30–42, 2007.

EN1998-1:2004. Eurocode 8: Design of structures for earthquake resistance. -Part 1: General rules, seismic actions and rules for buildings, CEN, Bruxelles, Belgium, November 2004.

Jean, M. The non-smooth contact dynamics method. *Computer Methods in Applied Mechanics and Engineering*, 177(3–4):235–257, 1999.

Mualla, I. and Belev, B. Performance of steel frames with a new friction damper device under earthquake excitation. *Engineering Structures*, 24: 365–371, 2002.

Nielsen, L. and Mualla, I. A Friction Damping System - Low order behavior and design. BYG.DTU R-030, Danmarks Tekniske Universitet, 2002.

Pall Dynamics. http://www.palldynamics.com/FrictionDampers.htm/. Visitado em outubro 2019.