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TIME-HISTORY ANALYSIS OF FRICTIONALLY DAMPED STRUCTURES

BY

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Abstract. During major seismic actions, a significant amount of energy is induced to structures. The means by which this energy is dissipated, determines the level of structural degradation. Special emphasis is placed on avoiding loss of human lives due to the earthquake action. In order to achieve this, the structures are designed ductile so that energy is dissipated by the system's elements by bending, twisting or degradation. This dissipative mechanism involves significant degradation of the structures thus leading to significant post-earthquake rehabilitation costs. If the amount of energy induced in the structure can be controlled or, if part of it can be dissipated mechanically by independent structures, the seismic response of the buildings is improved and the potential damage greatly reduced. These objectives can be achieved *via* new techniques such as base isolation or enhancement of energy dissipation capacity of the structures using damping devices. When possible, design codes suggest the use of the last technique as a cheaper and more viable way to improve the behaviour of structures subjected to earthquakes.

The hereby paper proposes a time history analysis of structures equipped with frictional dampers, highlighting the benefits resulting from the use of such devices.

Key words: time-history analysis; friction dampers; slip load.

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1. Introduction

Recent earthquakes have shown that the ductile design of structures, even in developed countries, leads to substantial degradation of structures as result of the seismic action.

For new structures avoiding the overall collapse is not enough. There are cases when the value of non-structural elements and/or equipment exceeds the value of the building itself. Some buildings, such as hospitals, police and fire-fighters stations, government buildings or telecommunications structures should operate without stops. In this context, a cost – benefit analysis suggests a performance based design. Such a design philosophy explicitly evaluates how a building is likely to perform, given the potential hazard it is likely to experience, considering uncertainties inherent in the quantification of potential hazard and uncertainties in assessment of the actual building (SAP 2000, 2009). Design codes that incorporate such design philosophies are: Vision 2000 (Sundararaj & Pall, 2004), ATC - 57 (Pall & Pall, 2004).

If the energy induced in the structure by the earthquake action can be controlled or can be mechanically dissipated by devices independent of the structure, the seismic response of the building is improved, thus substantially decreasing the potential damage. This can be achieved by means of base isolation or damping devices. An immediate effect of dampers usage is the increase of critical damping ratio up to 20...30% (compared to 5% – value usually used for structures).

Energy dissipation systems should be considered in a somewhat broader context than isolation systems. For the taller buildings (where isolation systems may not be feasible), energy dissipation systems should be considered as a design strategy when performance goals include the Damage Control Performance Range (Skuber & Beg, 2003).

Among the dissipating devices are the frictional ones too. Due to their low production and maintenance cost this type of damping devices are widely used both for new and retrofitted structures.

The purpose of the present paper is to underline the benefits resulting from the use of frictional dampers in terms of the reduction of structure's maximum displacement and acceleration when subjected to previous earthquakes recordings.

2. Slip Load of Friction Damper

During a significant earthquake action the friction dampers are designed to slip *prior* to yielding of structural members. Generally, this interval is in-between 130% of wind shear and 75% of member's yield shear force. Parametric studies have shown that the slip load of the friction damper is the principal variable with the appropriate selection of which it is possible to tune the response of structure to an optimum value. Optimum slip load gives minimum response. Studies have also shown that variations up to ±20% of the optimum slip load do not affect the response significantly (Pall & Pall, 2004).

Among the advantages resulting from the use of such devices in seismic protection of structures are the following:

a) high reliability and low cost;

b) rectangular hysteretic curve, with a large energy damping capacity (Fig. 1); for the same amount of damped energy fewer dampers are required when compared to other solutions (*e.g*. viscous dampers) (Vezina & Pall, 2004);

c) significant contribution to structures stiffness and damping capacity;

d) behaviour relatively independent of speed and temperature;

e) given the fact that this type of devices are not designed to damper wind induced forces fatigue failure is avoided.

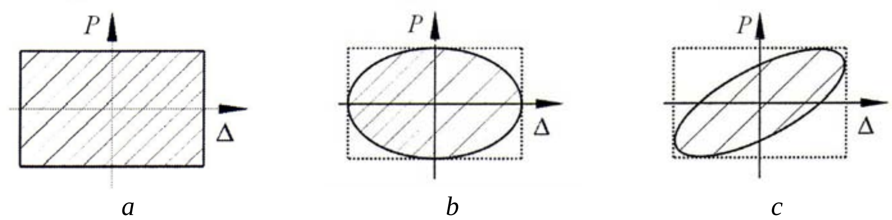


Fig. 1 – Hysteretic curves for different passive dampers: *a* – friction dampers; *b* – viscous dampers; *c* – viscoelastic dampers.

3. Case Study

The behaviour of a damper, placed in a bracing system, is a nonlinear one. The amount of damped energy or critical damping ratio is proportional to system's displacement. The analysis recommended to be used in evaluating the behaviour of structures equipped with frictional dampers is a nonlinear dynamic time-history one. Using this type of analysis, the response of the structure during and after the seismic action can be properly assessed. Modelling dampers, given their hysteretic characteristics, is simple. The hysteretic curve is similar to the rectangular loop of an ideal elasto-plastic material. The slip load of the friction-damper can be considered as a fictitious yield force (Sundararaj & Pall, 2004).

3.1. Analysed Structure

Having in view the above considerations, the software package SAP2000 (2009) was used to assess the response of a 2-D structural steel frame.

Three design scenarios were taken into consideration: unbraced structure (Fig. 2), braced structure (Fig. 2) and frictionally damped structure (Fig. 3). To model the characteristics of this class of devices the nonlinear elements – plastic (Wen) were used.

Fig. 2 – Unbraced and braced steel frame.

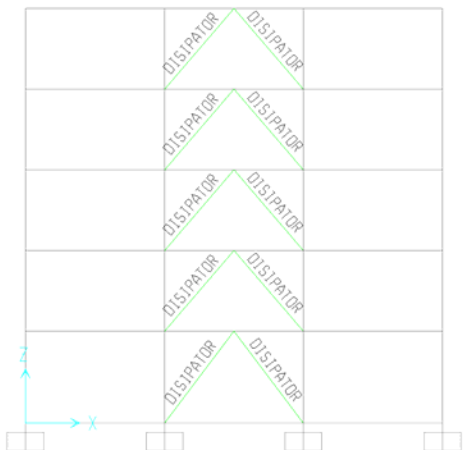


Fig. 3 – Structure equipped with friction dampers.

For the case of braced structure the cross-section of the braces are circular with an outer diameter of 120 mm and inner diameter of 100 mm.

Further details regarding span's length, levels height, and other structural characteristics such as materials characteristics and loading scenarios can be found in the work elaborated by Skuber and Beg (2003).

3.2. Analysis Scenarios

The dynamic nonlinear time-history analysis objectives are the following:

a) compare the response of structures in all three design versions (unbraced, braced, frictionally damped) when subjected to Vrancea 1986 recording;

b) highlight the influence of slip load's magnitude on the structural response of the frame in terms of maximum speed and acceleration;

c) compare the response of the structures when applying different earthquake recordings. At this stage four different accelerograms were used: El Centro (USA, 1940), Vrancea (Romania, 1986), Northridge (USA, 1994) and Kobe (Japan, 1995), scaled to 0.2 g.

3.3. Results of the Analysis

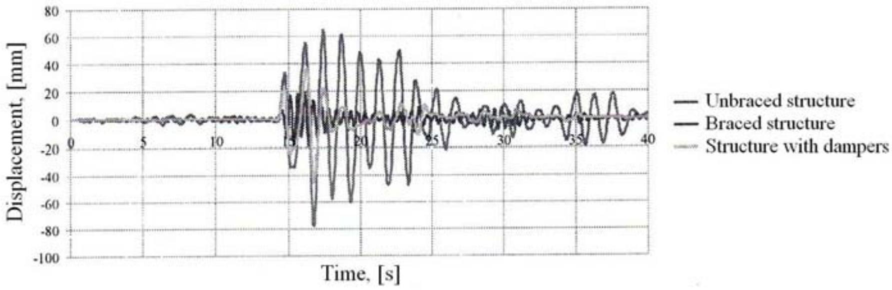
In the first part (Table 1) the dynamic characteristics of the structures are listed (periods of vibration and mass participation factors in each mode of vibration). The response of the structures will be presented, later on, in terms of maximum displacement and accelerations. Given the type of analysis – 2-D (*XZ* plane) analysis and direction along which the action is applied – *X*-direction, the response characteristics will be presented accordingly.

Table 1
Dynamic Characteristics of the Structures

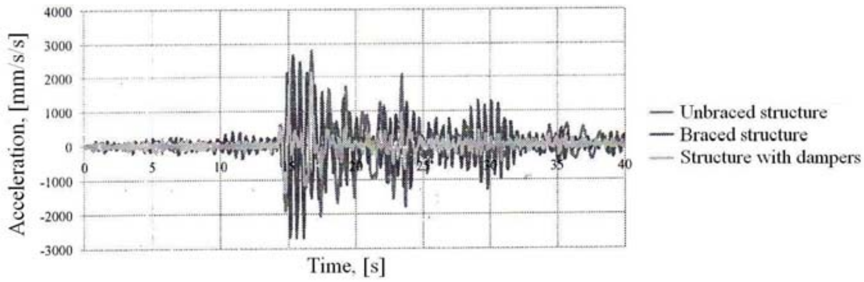
Unbraced structure		Braced structure		Structure equipped with friction dampers	
Period, [s]	*UX*	Period, [s]	*UX*	Period, [s]	*UX*
1.276266	0.82	0.512305	0.88	0.870457	0.85
0.410755	0.11	0.17281	8.53E-02	0.28748	9.88E-02
0.217345	4.12E-02	0.105034	2.43E-02	0.161967	3.18E-02
0.146044	1.92E-02	0.078036	7.98E-03	0.113946	1.28E-02

As expected, the fundamental period of vibration for the braced structure decreases due to the increased rigidity. In the third case, the period decreases due to the added stiffness resulting from the use of dampers.

It can be noticed (s. Fig. 4), a significant response reduction for the structure equipped with dampers when compared to the original design. When the top displacements of the unbraced structure reach maximum the corresponding ones out the structure equipped with dampers are twice smaller. It can also be observed that, even though the solution to limit the maximum displacement using braces leads to smaller top displacement, the maximum accelerations increase (compared with the structure equipped with dissipative devices). This can lead to unpleasant effects for the occupants of such structures when subjected to a seismic action. This leads to the conclusion that the use of friction dampers leads to an improved seismic response of buildings.



a



b

Fig. 4 – The response of the structures to Vrancea ’86 earthquake: *a* – top displacement; *b* – top acceleration.

In terms of device’s behaviour during seismic action (shown in Fig. 5) they have a rectangular hysteretic curve specific to such class of dampers. This confirms the fact the model used to describe the behaviour of friction dampers is suitable.

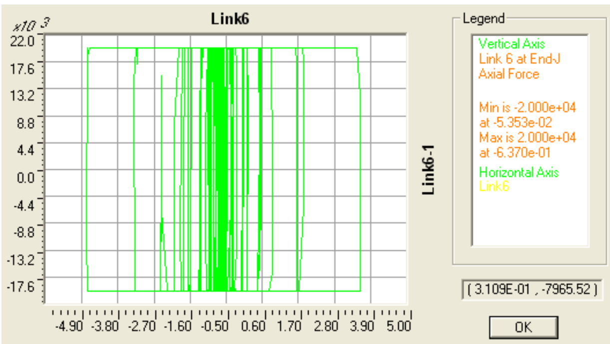


Fig. 5 – Hysteretic curve for a damper placed in a brace at ground floor (slip load 20 kN).

As mentioned in the introduction, the most important input parameter that controls the behaviour of a structure equipped with friction dampers is the slip load. The response was evaluated when the slip load varied between 8 kN and 20 kN, and had a constant value throughout the height of the structure.

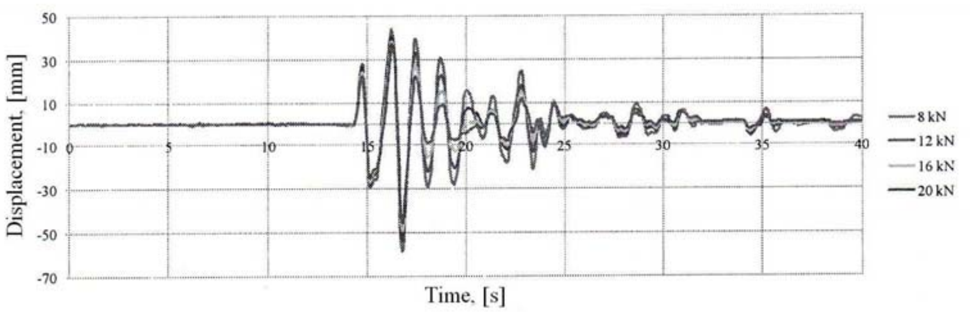


Fig. 6 – The variation of the top displacement *vs*. the slip load.

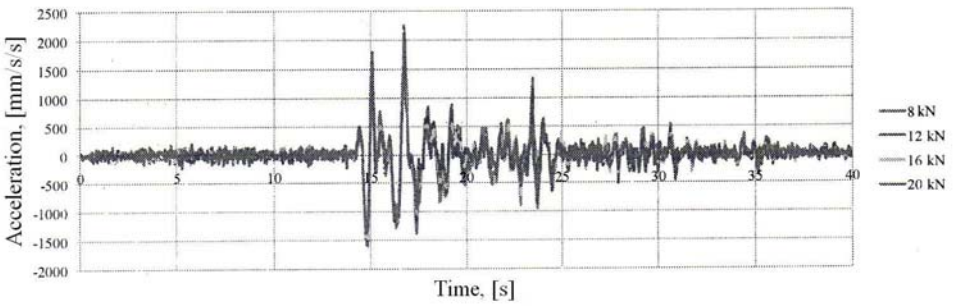
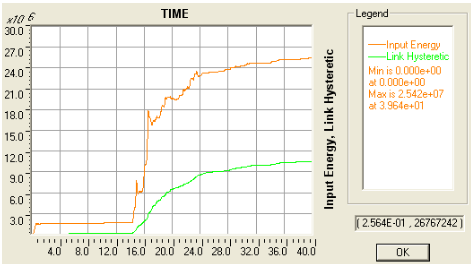
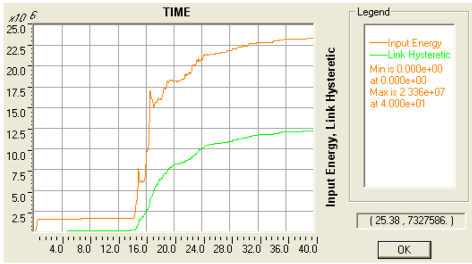


Fig. 7 – The variation of the top acceleration *vs*. the slip load.

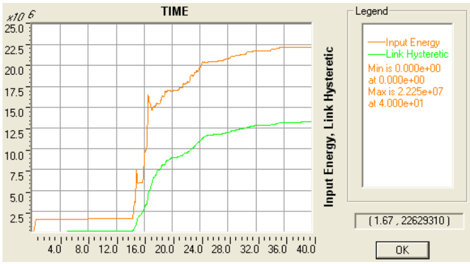
The most important conclusion resulting from the analysis of Figs. 6 and 7 is that in this case, the increase of the value of the slip load leads to an improvement of the response. Another way, besides the maximum displacements and accelerations, to quantify the effect of the dampers upon the behaviour of the structure is by the energy dissipated, graphically represented in Fig. 8.

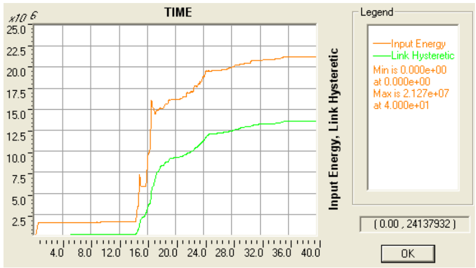
Given the random characteristic of the seismic action, which can lead to an overall unsatisfactory structural response, a comparison between the unbraced structure and the frictionally damped one is performed. The structures are subjected to four different recordings (stated in the introduction). All the accelerograms are scaled to a peak ground acceleration of 0.2 g. The slip load of the dampers is of 16 kN.





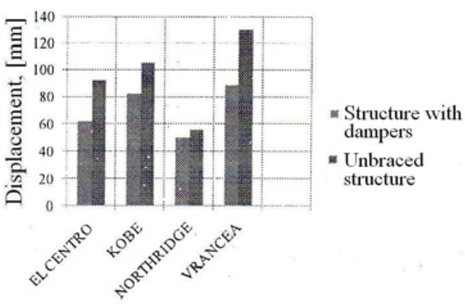
a *b*

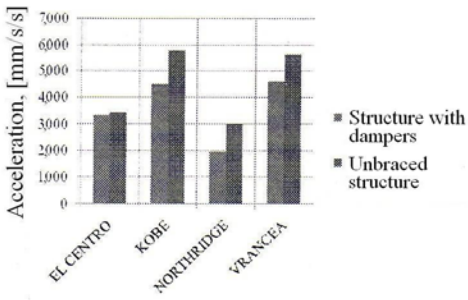




c *d*

Fig. 8 – The variation of dissipated energy with slip load:
a – 8 kN; *b* – 12 kN; *c* – 16 kN; *d* – 20 kN.





a *b*

Fig. 9 – Maximum response of the structure when subjected to different earthquake recordings: *a* – maximum displacements; *b* – maximum accelerations.

4. Conclusions

The dynamic nonlinear time-history analysis of the 2-D steel frame confirmed that the use of dampers, in this case friction dampers, significantly improve the behaviour of structure.

Whether the response in terms of maximum displacements, whether the response in terms of maximum accelerations is employed, the use of friction dampers greatly enhances the response of structures subjected to previous earthquakes recordings (in some cases by an order of magnitude of two or three).

Given their low fabrication cost, their relative independence to the environmental conditions or characteristics of the action, the friction dampers are a viable alternative to the classic approach of earthquake protection of buildings.

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ANALIZA TIME-HISTORY A STRUCTURILOR AMORTIZATE PRIN FRECARE

(Rezumat)

Pe parcursul unei acțiuni seismice majore, o cantitate semnificativă de energie este introdusă în structură. Modalitatea în care energia indusă este disipată determină nivelul degradărilor structurale. Un accent deosebit se pune pe evitarea pierderii de vieți omeneşti. Pentru a se putea realiza acest deziderat structurile sunt proiectate ductil, astfel încât energia indusă în sistem să fie disipată prin încovoierea, torsiunea, degradarea elementelor structurale etc. Acest obiectiv presupune degradări semnificative ale structurii, fapt ce conduce la costuri de reabilitare post-seism. În cazul în care cantitatea de energie indusă în structură poate fi controlată sau o mare parte din

aceasta poate fi disipată mecanic, independent de structura de rezistență, răspunsul seismic al structurii este îmbunătățit, valoarea potențială a pagubelor fiind mult diminuată. Aceste obiective pot fi îndeplinite prin adoptarea noilor tehnici de protecție antiseismică cum sunt cele de izolare a bazei şi creştere a capacității de disipare a energiei folosind dispozitive disipative. Atunci când este posibil, codurile de proiectare, sugerează utilizarea celei din urma abordări ca o modalitate ieftină şi viabilă de a îmbunătăți răspunsul structurilor supuse acțiunii seismice.

Se realizează o analiză time-history a structurilor echipate cu disipatori cu frecare, evidențiind beneficiile ce rezultă din utilizare unor astfel de dispozitive.