"OVIDIUS" UNIVERSITY OF CONSTANTA
DOCTORAL SCHOOL OF APPLIED SCIENCES
DOCTORAL FIELD: CIVIL ENGINEERING AND INSTALLATIONS

THESIS

„The seismic response of structures in braced frames equipped with friction dampers"

-SUMMARY-

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Constanța, 2020

Keywords: energy dissipation, nonlinear dynamic analysis, bracing, friction damper, artificial accelerogram, seismic energy response

Contents

Chapter 1. Introduction

1.1 The thematic context of the research

The approach from traditional design to the design of structures in seismic areas makes that material damage following a major earthquake is especially significant in the need to strengthen the structural elements involved in the dissipation of seismic energy (beams, walls) but especially of the destruction of non-structural components.
Globally in recent decades, there is a growing interest in the development of new seismic protection systems, as well as the improvement of existing ones. In Romania, there exists various national research projects, doctoral theses, and even patents on the subject of various seismic protection systems/devices.

1.2 Research objectives

The main objective of the thesis “Seismic response of structures in braced frames equipped with rotating friction dampers ”is the study of the seismic response of metal structures using friction dampers for seismic conditions in Romania, from point of view of both the traditional components of the response (displacements, accelerations, forces level cutters, etc.) but especially of energy components. By studying the energy balance of structure, the engineer can have a much deeper look at the effects of decisions regarding structural conformation and choice of the structural system, depending on the height regime and its location. The main devices used for reduction will be presented by the seismic response of structures, with their advantages and disadvantages. Achieving the goal, the main objective of the thesis was to clarify and solve the following secondary objectives:

- Understanding the concept of inherent and added structural depreciation;
- Study of the components of the energy balance for the case of multi-story structures. Here the analysis will focus on the effects of lateral stiffness and shock absorbers’ friction on the energy balance of multi-story structures with different regimes of height;
- Experimental determination of the hysteretic characteristics of friction shock absorbers’
- rotation;
- Study of the influence of stiffness and added damping on seismic input energy and a
- energy absorption capacity for metal structures with different regimes of height.

To fulfill these objectives, it was necessary to go through a rich bibliography, of which 6 are own scientific papers. For experimental tests presented in chapter 4, the author of the thesis had to design and build a universal testing apparatus because the adaptation of the trays of the Universal Testing Machine of the Faculty of Constructions in Constanța was more difficult to achieve.

1.3 Summary of chapters

Chapter 1. "Introduction" - describes the thematic context of the doctoral thesis, objectives, and research methodology. The reasons for meeting the allowed limits were set out of relative level displacements should not be reduced only through the use of section stiffening
and the fact that adding a more in-depth study to understand the concepts of energy and depreciation can provide the designer with new structural compliance solutions. In this chapter, the main and secondary objectives of the research were presented.

Chapter 2. "Energy dissipation in building structures" - presents notions of dynamics structures. It analyses the dynamics of structures with a degree of dynamic freedom, as well as structures with a degrees of dynamic freedom. This chapter describes the equations of motion that characterize the movement of structures with or without damping. The seismic response of a structure is also analysed in this chapter, for four values of damping, the response in terms of travel as well as in energy terms.

Chapter 3. "Seismic damping systems of structures" - presents the main devices used for seismic protection of structures and some examples of their application. A more extensive presentation is made for friction damping devices, the main objective of this thesis being the study of the seismic response of the structures equipped with these shock absorbers.
In this chapter the energetic approach of design for both structures with a degree of dynamic freedom as well as for those with degrees of dynamic freedom is also presented.

Chapter 4. "Experimental determination of hysteresis loops of friction dampers" - presents experimental studies performed for the determination of hysteresis curves for two friction dampers. At the same time the designed universal testing apparatus is presented and constructed by the author of the thesis.

Chapter 5. "Seismic response of structures equipped with friction dampers" - presents three case studies that analyse different features of the seismic response of metal structures.
Conclusions are presented for each case study.

Chapter 6. "Conclusions, personal contributions, and future research directions" - In this chapter the conclusions is formulated regarding the fulfillment of the objectives assumed in the first chapter. The conclusions of the theoretical studies, of the bibliographic ones as well as of the case studies are presented as made by the author. Personal contributions and their importance for the field are presented in structural engineering as well as future research directions.

2. Chapter 2. Energy dissipation in construction structures

2.1 General notions of structure dynamics

„The main objective of the structure dynamics is the elaboration of some methods for determining the efforts and deformations in structures subject to dynamic actions. Dynamic action is an action with size, direction, or point of application that varies over time. The dynamics of structures develop the calculation methods specific to the discipline of construction statics, considering the variation in time of the response of a structure as an effect of dynamic action.

2.1.1 Dynamics of systems with a degree of dynamic freedom

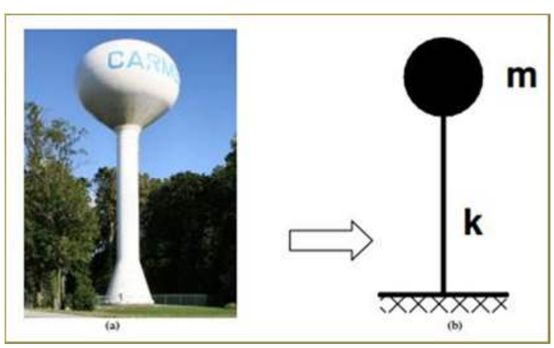


Figure 2.1.1 **"System with a single degree of dynamic freedom" (Stratan, 2014)**

„The number of degrees of dynamic freedom (GLD) required in dynamic analysis of a structure is the number of independent displacements required to define the displaced position of the masses relative to their initial position."

2.1.2 Dynamics of systems with a finite number of degrees of dynamic freedom

„The dynamic response of a system with several degrees of dynamic freedom (MGLD) driven by dynamic forces is made up of displacements (t), speeds and accelerations, j = 1… N. The dynamic forces can be considered distributed to the stiffness component, the damping component, and the ground component:
$\{f_I(t)\}+\{f_D(t)\}+\{f_s(t)\}=\{p(t)\}$(2.1.2)

...
$[m]\{\ddot{u}\}+[c]\{\dot{u}\}+[k]\{u\}=\{p(t)\}$(2.1.3)

which represents a system of N differential equations, the solution of which leads to the determination displacements {u (t)} generated by the dynamic action {p (t)}. "(Chopra, 2001) (Stratan, 2014)

3. Chapter 3. Seismic damping systems of structures

„In the last 20-30 years, more and more buildings are equipped with special devices with the role of dissipating the energy induced in the structure during seismic events. Seismic protective devices are introduced to improve the structure's response in terms of ductility or to absorb most of the seismic energy.

A possible classification of seismic damping devices is presented in the table3.1.1" (Ghindea, 2008):

***Table 3.1.1* „Classification of seismic damping devices" (Ghindea, 2008)**

<table>
<tr><td rowspan="3">Dispozitive dependente de deplasare</td><td colspan="2">Dispozitive liniare (LD)</td></tr>
<tr><td rowspan="2">Dispozitive neliniare (NLD)/ Histeretice (YD)</td><td>Dispozitive cu metale ductile (YMD)</td></tr>
<tr><td>Dispozitive cu frecare (FD)</td></tr>
<tr><td rowspan="2">Dispozitive dependente de viteză/ amortizori vâscoși (VD)</td><td colspan="2">Dispozitive cu fluid vâscos (FVD)</td></tr>
<tr><td colspan="2">Dispozitive cu resort și fluid (FSD)</td></tr>
<tr><td colspan="3">Dispozitive dependente de accelerații (TMD)</td></tr>
<tr><td colspan="3">Dispozitive modificatoare de input (Izolarea bazei)</td></tr>
<tr><td colspan="3">Combinații ale variantelor de mai sus</td></tr>
</table>

3.1.1 Devices that use the ductility properties of metals

„Deformation in the inelastic domain of ductile materials is a stable mechanism for seismic energy dissipation. In traditional design, the seismic energy dissipation is based on the ductility of the component elements of the structure. Starting from this concept, we came to the idea of installing separate structural elements (devices) to absorb seismic energy. In the 1970s, such devices were designed and tested.” (Cheng, 2008).

Figure 3.1.1 **„Building equipped with ADAS type shock absorber”** *(Cheng, 2008)*

3.1.2 Friction devices

Friction is an efficient, reliable, widely, and economically applicable mechanism for dissipating kinetic energy by converting it to heat. In the early 1980s, Pall, and Marsh (Pall, 1979) developed a friction damper to improve the seismic response of structures.

Limited-slip bolted joint (LSB)

The limited-slip connection developed by Pall and Marsh (Pall, 1979) in the early 1980s was initially used to improve the seismic response of large panel structures.

The Pall-type friction damper

The Pall-type friction damper is made of a set of perforated strips joined together using high-strength screws (fig. 3.1.2.a). The steel from which the strips are made is specially treated to improve friction. This friction damper is inserted at the intersection of the diagonals in X (fig. 3.1.2.b).

Figure 3.1.2 **„Pall-type friction damper**
a) în laborator, b) instalat” (Pall, 2006)

The Sumitomo -type friction damper

This shock absorber is designed and manufactured by Sumitomo Metal Industries Ltd., Japan. In this type of shock absorber, the friction force is generated by the graphite-copper alloy pads that slide on the inner surface of a metal tube.

Energy dissipating link (EDR)

„The energy dissipation connection is part of the category of friction dampers. In these shock absorbers, the friction force increases linearly with their deformation. This type of shock absorber has been patented by Fluor Daniel, Inc. "(Innaudi, 1996).

Damptech rotary friction damper

„This friction damper consists of 3 or more steel plates that rotate against each other, abrasive discs are placed between these plates. The main components of the shock absorber are the center plate and two or more side plates as shown in, Figure 3.1.3. The central plate connects the damping device to the beam of the frame type structure with the help of a rotatable joint so as not to introduce momentum in the beam "(Muala, 2001).

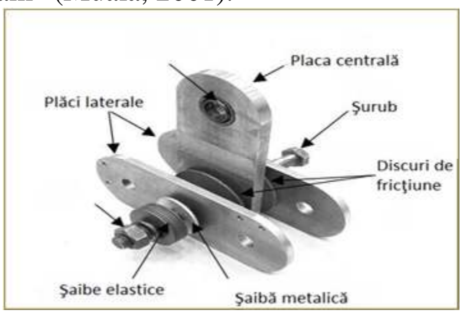


Figure 3.1.3 **„Details of Damptech friction damper"** *(Muala, 2000)*

SERB type friction shock absorber

„The SERB type damping device was invented in Romania in 2005 by V. Şerban (Serban, 2005) and is a stiffener with stiffening reinforcement whose behavior is divided into two distinct areas. " (Vacărescu et. Al., 2013).

3.1.3 Viscous shock absorbers

„These shock absorbers are, due to their high performance, one of the most modern methods of seismic protection. These shock absorbers do not require maintenance, no oil tanks, pressure lines, level indicators, or external accumulators are needed. The internal fluid is not replaced during service. "(Ionescu, 2017)

3.1.4 Magneto-rheological shock absorbers

This type of shock absorber is a semi-active device that has superior characteristics to the viscous fluid shock absorber.
Acceleration dependent devices

3.1.5 Shock absorbers with given mass

„In their simple form, Tuned Mass Damper (TMD) consists of a system consisting of a table (m_d), a spring (k_d) and a shock absorber (c_d), a system anchored or attached to the main structure of the building, usually at the top."(Cheng et al., 2008).

Devices that change the action on the structure

3.1.6 Base insulation

„These passive base insulation devices are a solution to the approach of passive control over the seismic response. Thus, the base insulation solution is the structural control solution by placing special devices that allow decoupling the superstructure of buildings from their infrastructure." (Ghindea, 2008).

3.2 The energy approach. Energy balance

The main objective of this subchapter is to present the concept of energy absorption capacity for structures subject to seismic action. Housner (Housner, 1956) theorises to provide structures with sufficient capacity to absorb seismic energy introduced into the structure. This proposal made it possible to quantify, through calculus, the quantity of sysmic engergy induced by earthquakes and the quantities of energy components. Thus, the energy balance equation was introduced:

$$E_i = E_K + E_{S,e} + E_D + E_{S,h} + E_{AD} \tag{3.2.1}$$

Energy balance

Each structure has its capacity to dissipate the seismic energy input. Many of the structural sizing provisions aim to ensure the highest possible energy absorption capacity and have the role of directing the possibility of forming plastic areas at the ends of the beams.
Housner (Housner, 1956) proposes to provide structures with sufficient capacity to absorb seismic energy introduced into the structure. This approach was developed by calculating the amounts of seismic energy induced by an earthquake and the amounts of energy components. Thus, the idea of energy balance was introduced together with the related equations.
The input energy, induced by the earthquake, in the case of structures designed in the elastic field is distributed as follows:

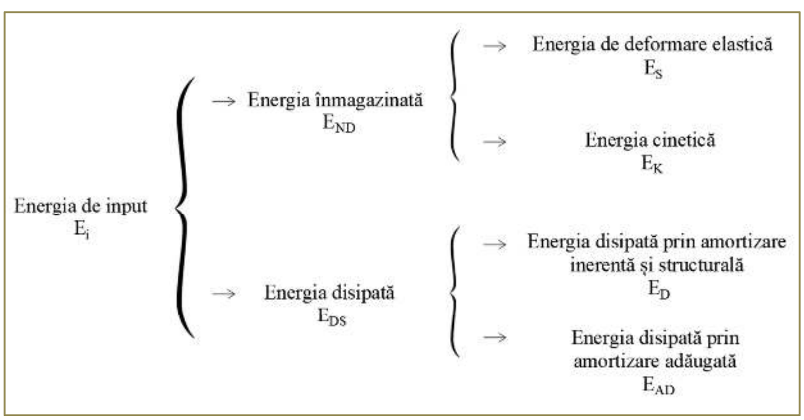


Figure 3.2.1 **Energy distribution in the structure**

3.2.1 Components of the seismic energy response of systems with a degree of freedom.

The energy response of a system with a finite number of degrees of freedom can be extracted from the response of a structure equivalent to a degree of freedom.

3.2.2 Components of the seismic energy response of systems with a finite number of degrees of freedom.

In this case, to simplify the calculation, the multi-story structural model is equivalent to systems with several degrees of dynamic freedom, the number being finite.
In the case of absolute input energy, it is composed of kinetic energy, elastic deformation, energy absorption capacity, and energy dissipated by vibration control devices.

4. Chapter 4. Experimental determination of hysteresis loops friction shock absorbers

4.1 Introduction. Testing apparatus description

This universal testing apparatus proposed and built by the author of the thesis (Oance, 2019) can be used as a universal tool for testing the tensile and compressive strength of various friction damper devices.
To determine the behavior of the devices tested on this device, it is necessary to secure them using screw fastening in the two fixing points provided with holes.

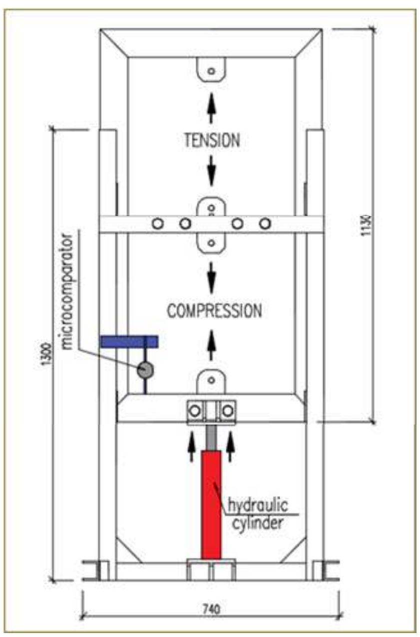


Figure 4.1.1 **Testing apparatus - front view**

Figure 4.1.2 **Universal testing apparatus**

The resulting assembly was equipped with a manual hydraulic pump, hydraulic cylinder, manometer, and electronic microcomputer (Figure 4.1.2).

4.2 Experimental tests on the rotating friction damper

The experimental test on a rotary friction damper according to the Damptech model built by the author of the thesis was performed using the Universal Testing Apparatus presented above in point 4.1.
The components of the shock absorber are metal strips, metal washers, washers made of materials with a high coefficient of friction, and prestressed bolts. The size of the components, their characteristics, and the value at which the bolts are prestressed determine the shape and size of the hysteresis loop.

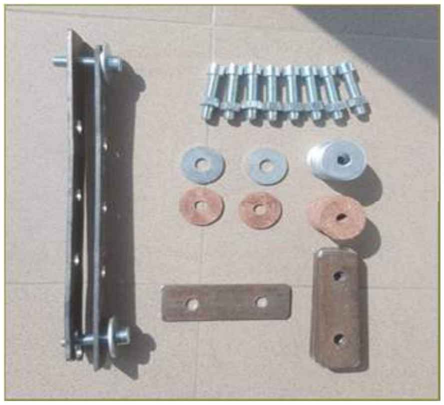


Figure 4.2.1 **Rotating friction damper components**

We performed a series of tensile tests, with forces up to 25kN. Figure 4.2.2
features the hysteresis loop ideal for the tried and tested rotary friction damper.

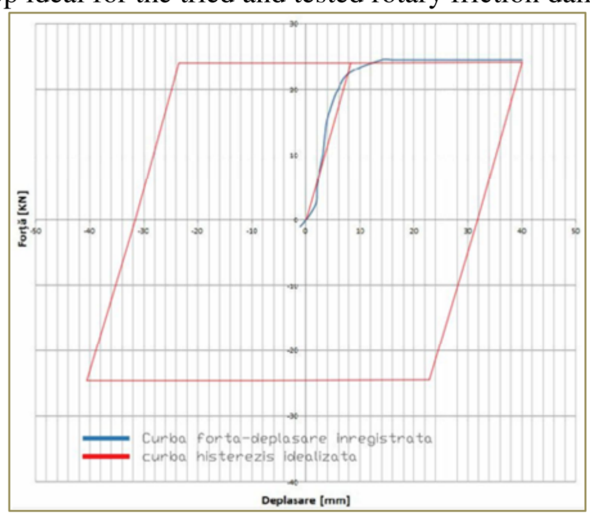


Figure 4.2.2 **Shock absorber hysteresis loop with rotational friction**

Analyzing the force-displacement curve obtained experimentally, it is observed that it has a shape similar to those obtained in the experimental studies conducted by the inventor. (Muala, 2010).Following the experimental test, the following can be concluded:

- The force applied to the shock absorber increases linearly to the maximum value, a value from which the displacement increases without registering an increase in force (a bearing is obtained);
- The hysteresis curve obtained can be associated with a rigid-perfectly plastic behavior, behavior that is easy to model in structural analysis software;

4.3 Experimental tests on the translation friction damper

The experimental test on a rotary-translation friction damper according to the model proposed and constructed by the thesis author was performed using the universal testing apparatus presented previously in point 4.1. For this experimental test, it was necessary to measure the displacement between the clamping points of the shock absorber, a displacement that varies depending on the force applied.

4.4 Conclusion

The experimental study required the design and construction by the author of the thesis of a universal testing apparatus, an apparatus that can be used for future tests. The purpose of the experimental tests was to validate the behavior of the friction dampers. Behavior between the two friction shock absorbers studied experimentally, depends on the coefficient of friction of the surfaces in direct contact and implicitly on the value of the „pre-tensioning'' of the screws that solidify the component elements of the shock absorber.

5. Chapter 5. Seismic response of structures equipped with friction dampers

5.1 General notions

„The design method requires that some components of the structural system be designed and detailed to allow the dissipation of seismic energy through inelastic deformations, while all other structural elements have sufficient strength to not exceed the elastic limits and to allow the development of the chosen energy dissipation mechanism "
(Paulay, 1997) (Figure 5.1.1).

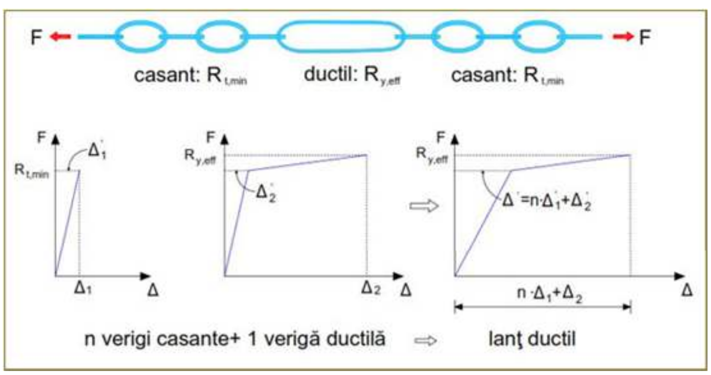


Figure 5.1.1 **The principle of limiting efforts with the help of ductile elements**

The collapse of the structure being avoided by design, the problem focuses only on the need for repairs and consolidation after each high-intensity earthquake.

5.2 Case study 1 - Study of the seismic response of structures in metal frames by introducing friction dampers

5.2.1 Description of the considered structures

In this first case study, the advantages deriving from the use of the bracing system provided with Damptech type friction dampers compared to; the classic non-braced, centrally braced, and eccentrically braced metal structures will be analysed.
Initially, an unbroken metal structure (SMNC) was considered with the following geometric characteristics: 5 openings of 6m and 6 levels, the ground floor has a height of 4.5m and the rest of the levels have a height of 3.5m (Figure 5.2.1). The building will be located in Bucharest, with occupational clasification as an Appartment block.
All structural elements are made of S355 steel with flow resistance f y = 355N / mm 2. Unbroken metal frames have excellent ductility, but hardlythe rigidity conditions imposed by the seismic design code P100-1 / 2013 can be met.
The next two structures analysed resulted in transforming the first structural system into a dual structure consisting of braced metal frames and centrally braced metal frames (SMCC) (Figure 5.2.2). and, respectively, a dual structure consisting of unbroken metal frames and eccentrically braced metal frames (SMCE) (Figure 5.2.3). The last structure analysed is a dual structure consisting of non-braced frames and braced frames equipped with friction dampers (Figure 5.2.4) in two variants: with shock absorbers with flow values of 50KN and 150KN respectively. Such a shock absorber is shown in Figure 5.2.5.

Figure 5.2.1**Unbraced structure (SMNC)**

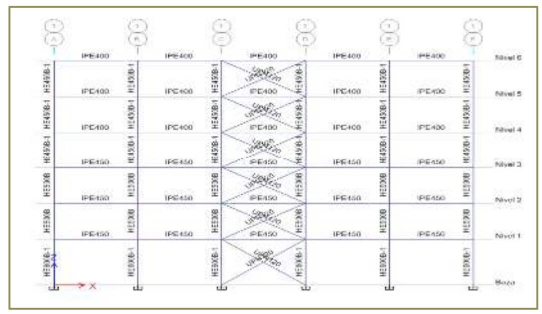


Figure 5.2.2 Centric brace structure (SMCC)

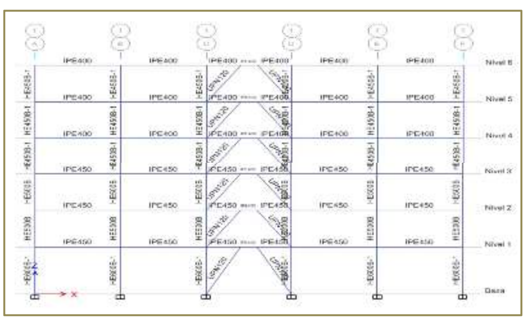


Figure 5.2.3**Eccentric brace structure(SMCE)**

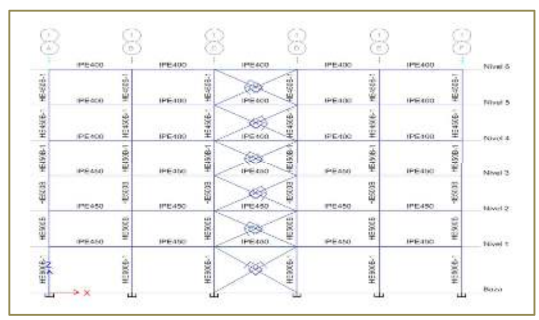


Figure 5.2.4**Frictionally damped structure(SMCA)**

Figure 5.2.5**Rotary friction damper (https://www.damptech.com/for-buildings-check)**

To evaluate the response of these four structures, a non-linear dynamic calculation of time-history type was performed. This type of analysis has the advantage that it can present the response of the structure during the seismic action (response in time). The friction dampers were modeled according to the characteristic behavior curve (Figure 5.2.6).

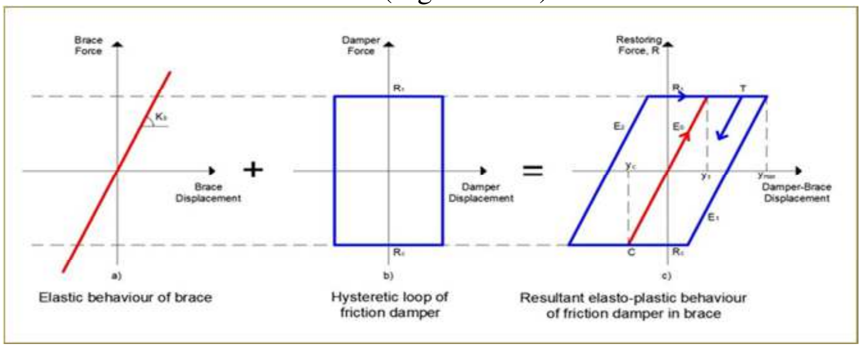


Figure 5.2.6 **Elasto-plastic curve of the diagonal equipped with friction damper** ***(Oance, 2019)***

5.2.2 Nonlinear dynamic analysis

In the nonlinear dynamic analysis, the plastic joints in the defined beams were of the moment-rotation type. P-M type joints (axial stress interaction - bending moment) ductile were defined for columns. For columns and beams, these plastic joints were assigned to the ends of the bar, in case of bracing, plastic deformations of type P (axial stress) were assigned to the middle of the bar. The ultimate plastic rotations are defined by FEMA 273 and ASCE 41-17.

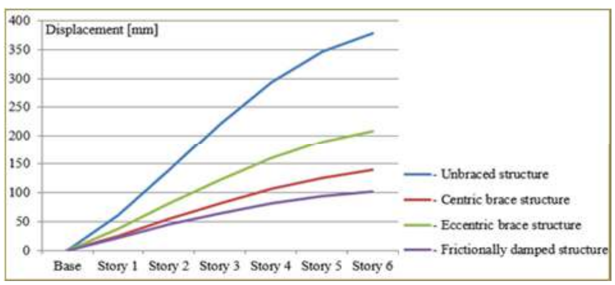


Figure 5.2.7 **Maximum displacements at the top of the structure**

The maximum displacement at the top of the structure equipped with friction dampers (SMCA) is 3.75 times smaller than the maximum displacement of the unbroken structure (SMNC) (Figure 5.2.7).

As a result of the analyses performed, it can be seen that the response of the structure equipped with friction dampers shows a significant improvement compared to the other structures analysed (response in terms of maximum peak displacement, relative level displacement, and peak accelerations).

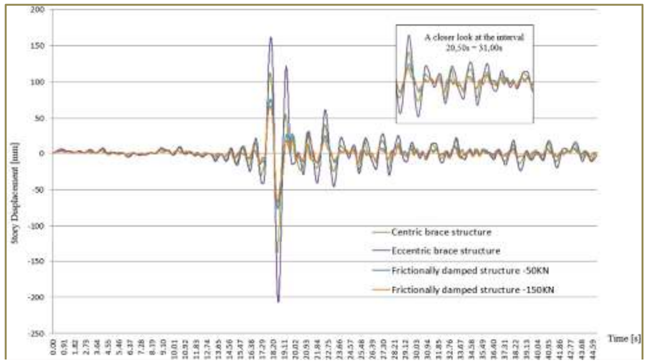


Figure 5.2.8 **Absolute displacements at the top of the structure *(1977 Vranceaaccelerogram N-S INCERC)***

During the seismic action (Vrancea 1977 NS INCERC), the shock absorber with a capacity of 50KN from the first level flows several times during the seismic action compared to the shock absorber with a capacity of 150KN of the other structure (Figure 5.2.9 and Figure 5.2.10).

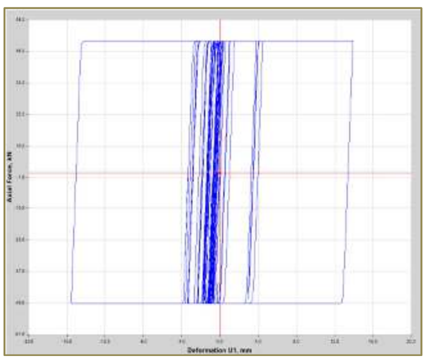


Figure 5.2.9 **Hysteretic curve of the first level shock absorber, with a capacity of 50 KN**

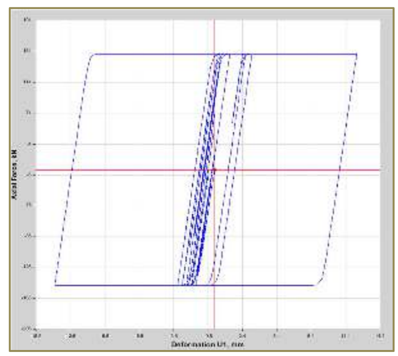


Figure 5.2.10 **Hysteretic curve of the first level shock absorber, with a capacity of 150 KN**

5.2.3 Conclusion

Within the case study, a series of nonlinear dynamic analyses were performed on four types of structures. Following these analyses, the improvement of the seismic response of the structures by equipping them with friction dampers was highlighted.

The analysis showed that the structure equipped with shock absorbers with a capacity of 150 KN has higher acceleration values at the last level than the structure whose shock absorbers have a capacity of 50 KN. At the same time, dampers with lower flow capacity will flow more times during the seismic event than dampers with higher capacity.

Given the relative independence from the environmental conditions of friction dampers, they are a viable alternative for increasing the energy dissipation capacity of structures.

5.3 Case study 2 - Study of the seismic response of metal frames by varying the number and position of friction dampers in the frame structures

5.3.1 Description of the considered structures

In the second case study, the effects of the number and position of friction dampers in four structural configurations were analysed. These four structures with six levels were subjected to nonlinear dynamic analyses, each one based on the accelerometer Vrancea 1977 N-S, INCERC, scaled for the conditions of the Bucharest location, for the peak value of the ground acceleration a g = 0.30g.

5.3.2 Comparative analyses of the obtained results

In figure 5.3.1 it can be seen that the maximum displacement at the top of structure 1 has the highest value, while in the case of structure 4 its value is the lowest. The absolute maximum displacements at the peak in the case of structures 2 and 3 are close to around 60 mm.

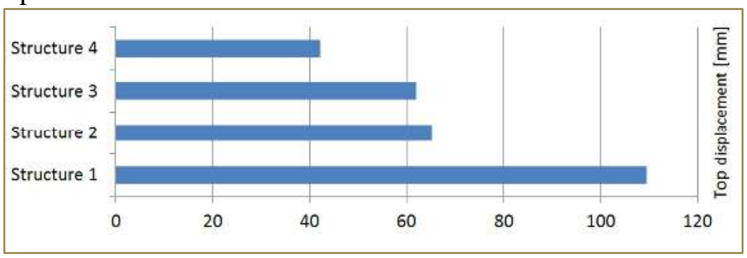


Figure 5.3.1 **Absolute maximum displacements at the top of the structure**

In the case of the maximum basic seismic force, it can be observed that the highest value is also recorded in the case of structure 1, structures 2, 3, and 4 registering values close to approximately 3400 KN.

5.3.3 Conclusion

In the case study, a series of nonlinear dynamic analyses were performed on four types of structures equipped with a different number of dampers with different friction and position within the level. Following these analyses, it was highlighted that the seismic response of the structures is dependent on the positioning of the friction dampers.
The structure with the highest number of dampers (Structure 4) on each level has the most favorable response in terms of maximum absolute displacements at the top of the structure but structure 3 is optimal in terms of dissipated energy. This indicates that a large number of shock absorbers placed in the structure is not always the best solution in terms of dissipated energy.

5.4 Case study 3 - Seismic response of metal structures

5.4.1 Description of the considered structures

In this case study, sets of analyses are performed to compare the seismic response of structures stiffened by large sections (Fig. 5.4.1) with that of centrally braced structures (Fig. 5.4.2) and structures equipped with friction dampers with a capacity of 50 KN and 100 KN respectively (Fig. 5.4.3).
The analysed structures have the following geometric characteristics: 5 openings of 6m, the ground floor has a height of 4.5m and the rest of the levels have a height of 3.5m.

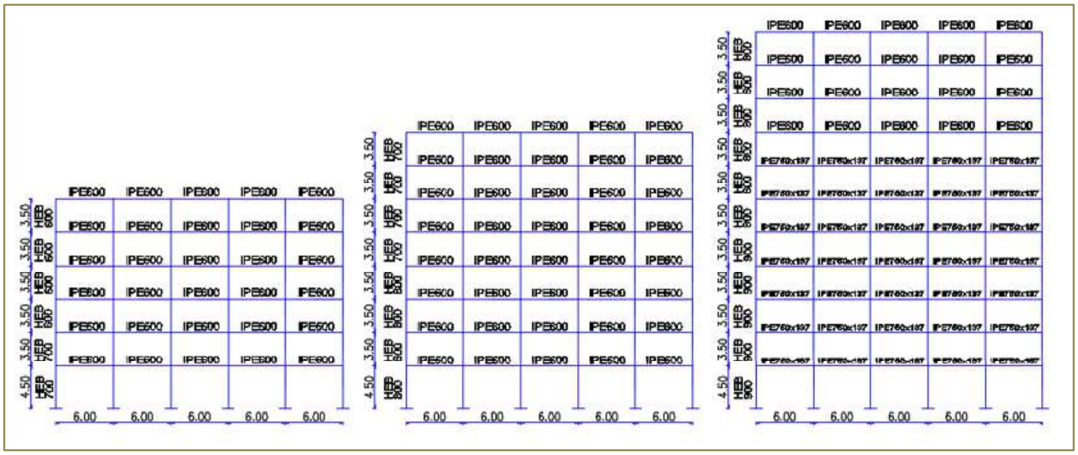


Figure 5.4.1 **Structures with 6, 8 and 11 stiffened levels** ***(Str. rig.)***

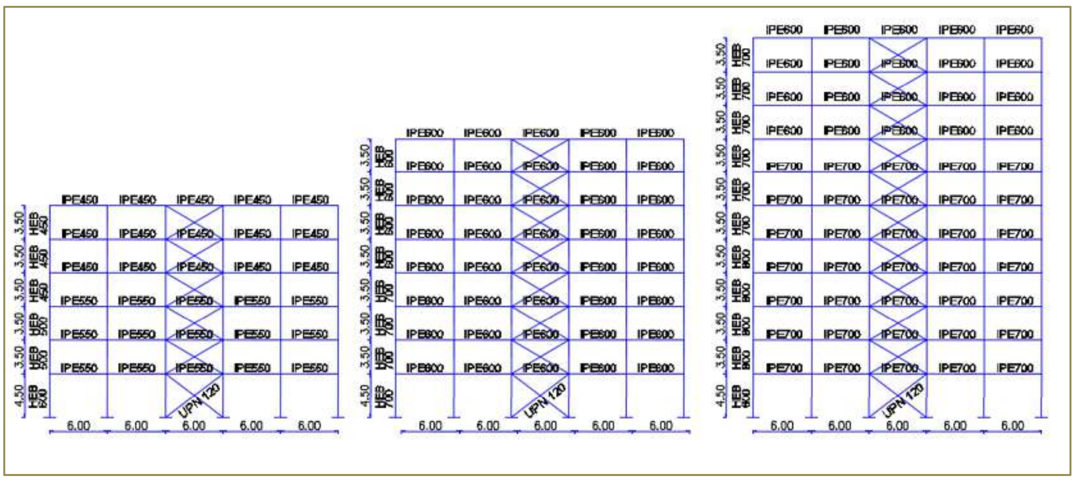


Figure 5.4.2 **Structures with 6, 8 and 11 levels centrally braced** ***(Str. cv.)***

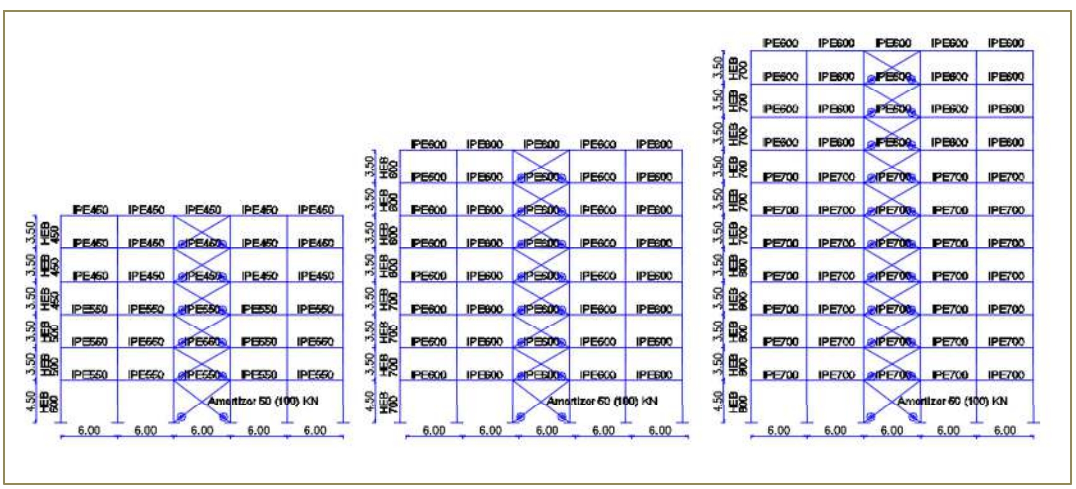


Figure 5.4.3 **Structures with 6, 8 and 11 levels equipped with friction dampers with a capacity of 50KN / 100KN** ***(Str. am. 50KN/100KN)***

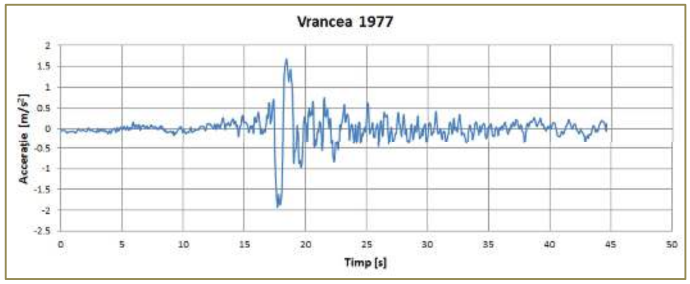


Figure 5.4.4Vranceaaccelerogram **4 March 1977**

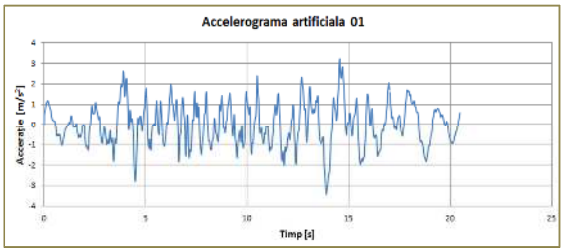


Figure 5.4.5 **Artificial accelerogram** *artif.acc. 01*

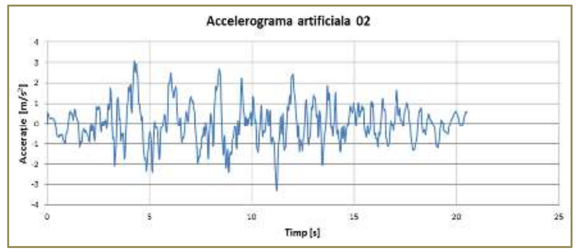
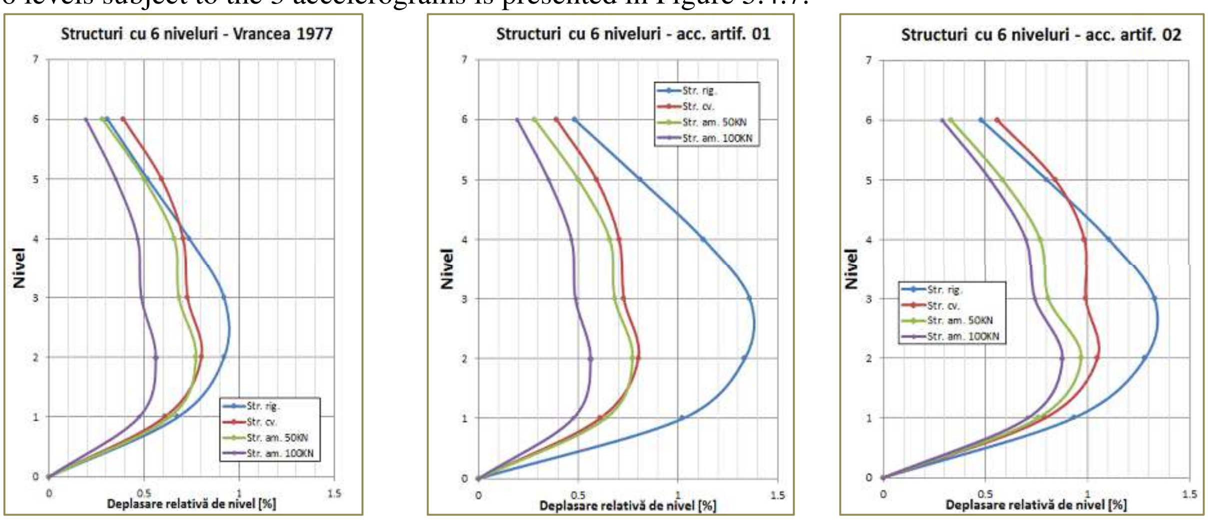


Figure 5.4.6 **Artificial accelerogram** *artif.acc . 02*

5.4.2 Comparative analysis of the obtained results

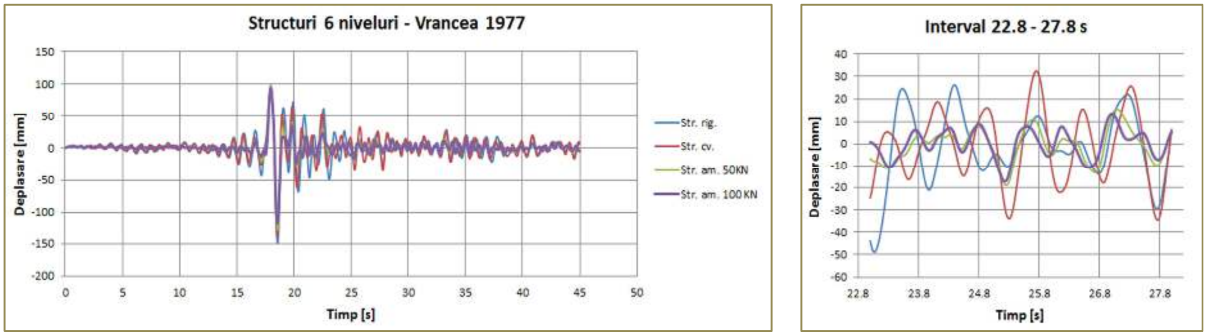
An important parameter that reveals the seismic response of the structures is the relative level displacements. The percentage of relative level displacements being the main criterion that must be met in the seismic design of the structures. The relative level displacements of the 4 structures with 6 levels subject to the 3 accelerograms is presented in Figure 5.4.7.



a) b) c)

Figure 5.4.7 Relative level displacements - 6-level structures for accelerograms:
a)Vrancea 1977, b) Artificial 01, c) Artificial 02

It can be observed that the stiffening brought by braces but also the equipment of the structures with added damping leads to the reduction of the level displacements for the 3 accelerograms (fig.5.4.7). The biggest reduction in terms of relative level shift is found between the frame structure (str. Rig.) And the braced structure.

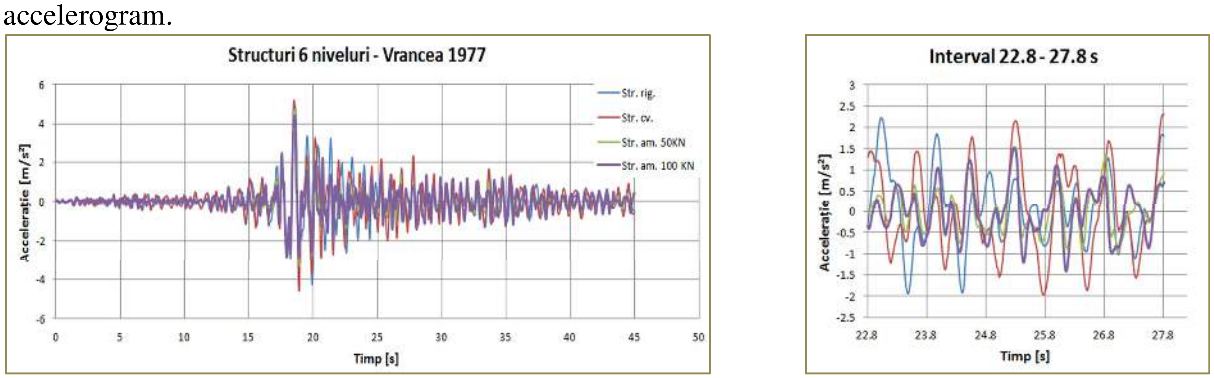


a)

Figure 5.4.8 **Variation of maximum displacements at the top - structures with 6 levels for the 1977 Vranceaaccelerogram**

Figure 5.4.8 shows the variation of the maximum displacements at the peak in the case of the 4 structures with six levels, for the three accelerograms. For the structures provided with friction dampers with a capacity of 50 KN and 100 KN (str. Am 50KN and str. Am. 100KN), there is a phase shift of the maximum displacements from the frame structure and the centrally braced structure.

Lateral level accelerations are a relevant indication in the study of the seismic response of structures located in regions with high seismicity. Figure 5.4.9 shows the variations of the lateral acceleration from the last level of the four structures analysed by applying the 1977 Vrancea accelerogram.



a)

Figure 5.4.9 **Variation of lateral acceleration at the last level - structures with 6 levels for the *Vranceaaccelerogram 1977***

The time response for the seismically operated structures in the case of the three accelerograms is presented in two adjacent images, the first representing the variation of acceleration at the last level over the entire duration of the accelerogram, and the second has an interval of five seconds.

For the 1977 Vrancea accelerogram, the maximum value of the lateral acceleration at the last level is recorded by the centrally braced structure (str.cv) and is 5.20 m / s 2, and the value minimum is registered in the case of the structure with shock absorbers with a capacity of 100 KN (str. am. 100KN) and is 4.41 m / s 2. There is practically a reduction of up to 15.20% of the value of the maximum acceleration at the last level.

Following the study on the response in terms of maximum accelerations at the last level, there is a fairly high variability for the three accelerograms. The reduction of the seismic response is in the range of 15.20% -40.80%.

The variation of the maximum basic seismic force in parallel with the maximum value of the maximum displacement level is shown in Figure 5.4.10.

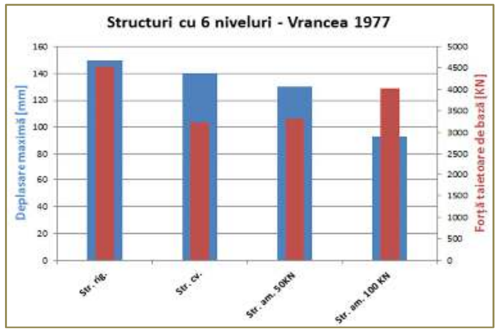
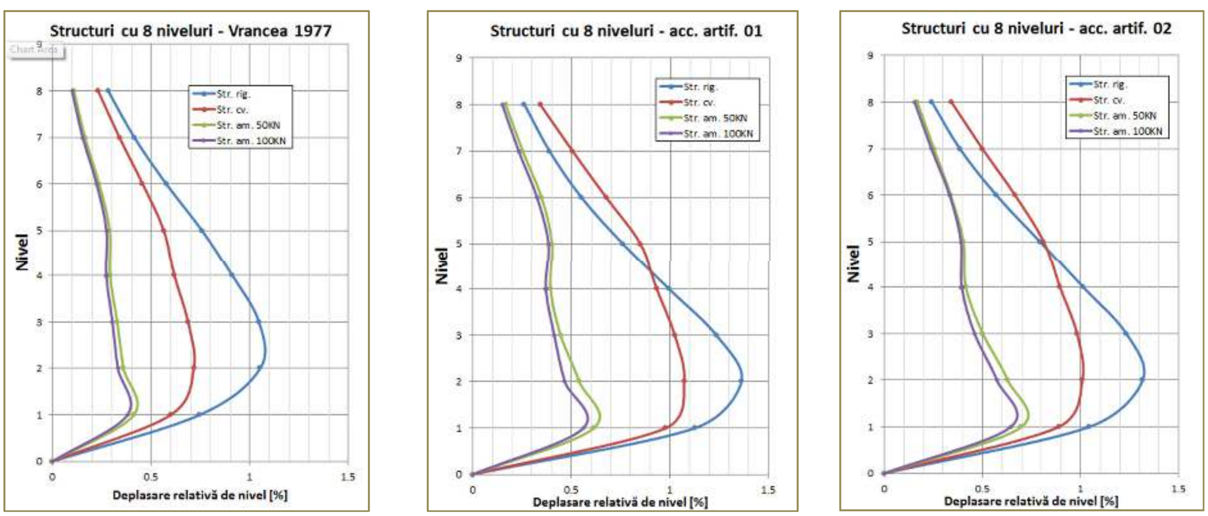


Figure 5.4.10 **Variation of the maximum basic seismic shear force depending on the lateral rigidity –** ***Vrancea1977***

In the case of the structures triggered by the 1977 Vrancea earthquake, it is found that the basic seismic force with the highest value is recorded in the case of the frame structure. The structure equipped with 100KN friction dampers (str. Am. 100KN), although it registers the lowest displacement at the top, „benefits" from a basic shear force 19.55% higher than the braced structure and 17.49% higher than the structure provided with 50KN shock absorbers (str. Am. 50KN) (Fig.5.4.10).

The study of the rigidity of the structures in parallel with the maximum value of the maximum basic seismic force for the structures with 6 levels analysed shows us that there is no direct correlation between these two important parameters addressed in the classical design of structures.

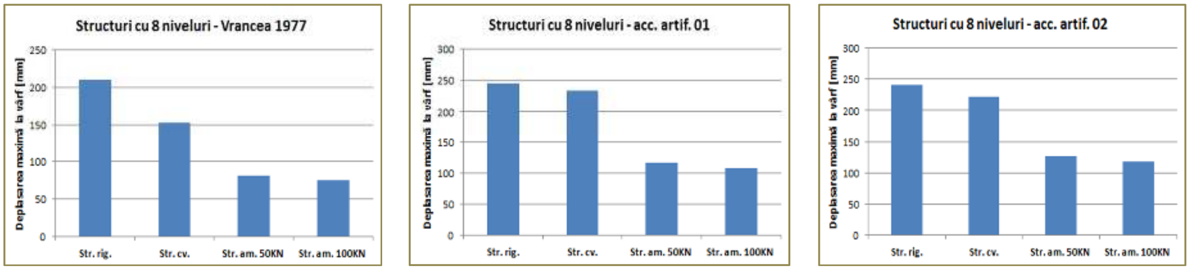
The relative level displacements of the 4 structures with 8 levels subject to the 3 accelerograms for presented in Figure 5.4.11.



a) b) c)

Figure 5.4.11 **Relative level displacements - structures with 8 levels for accelerograms:** ***a)Vrancea 1977, b) Artificial 01, c) Artificial 02***

It can be observed that the stiffening brought by braces but also the equipment of the structures with added damping leads to the reduction of the level displacements for the 3 accelerograms (Fig.5.4.11). In this case, the largest reduction in terms of relative level displacement is found between the braced structure (str. Cv.) and the structure equipped with shock absorbers with a capacity of 50 KN.

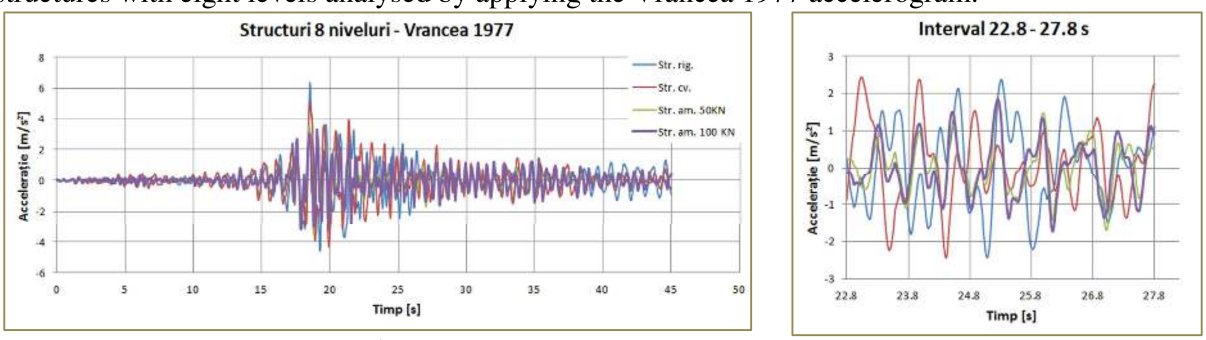


a) b) c)

Figure 5.4.12 **Maximum displacements at the top - structures with 8 levels for accelerograms:** ***a)Vrancea 1977, b) Artificial 01, c) Artificial 02***

The maximum displacement at the peak for the three accelerograms (Fig. 5.4.18) occurs in the case of the frame structure. The minimum value of this parameter is registered within the structure provided with shock absorbers with a capacity of 100 KN (Str. Am 100KN), with up to 56.28% compared to the structure in frames (str. Rig.) for the artificial accelerogram 01.

Figure 5.4.13 shows the variations of the lateral acceleration from the last level of the four structures with eight levels analysed by applying the Vrancea 1977 accelerogram.



a)

Figure 5.4.13 **Lateral acceleration variation at the last level - 8-level structures for the** ***Vranceaaccelerogram1977***

The time response for the seismically operated eight-level structures in the case of the three accelerograms is presented in two adjacent images, the first representing the variation of acceleration at the last level over the entire duration of the accelerogram, and the second has an interval of five seconds.

Following the study on the response in terms of maximum accelerations at the last level for the structures with eight levels, there is a rather high variability for the three accelerograms.

The reduction of the seismic response is in the range of 19.68% - 48.34%.

The variation of the maximum basic seismic force in parallel with the maximum value of the maximum level displacement is shown in Figure 5.2.14.

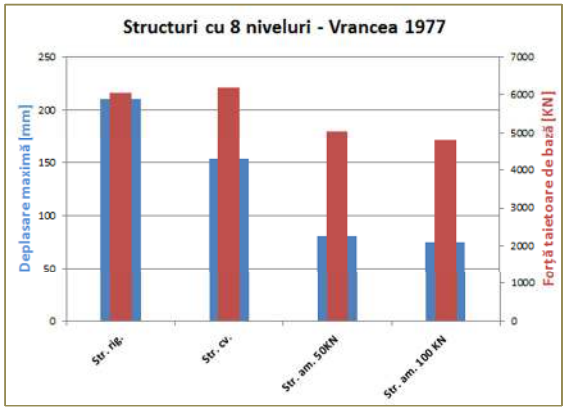


Figure 5.4.14 **Variation of the maximum basic seismic shear force depending on the lateral rigidity - 8-level structures - Vrancea 1977**

In the case of the structures operated by the 1977 Vrancea earthquake, it is found that the basic seismic force with the highest value is registered in the case of the braced structure. The structure equipped with 100KN friction dampers (str. Am. 100KN) registers the lowest displacement at the top and the lowest basic shear force by 22.58% lower than the braced structure and by 5.10% lower than the structure provided with shock absorbers of 50KN (str. am. 50KN) (Fig.5.4.14).
Basically, in the case of structures with 8 levels, there is a direct correlation between the level of the basic seismic shear force and the displacement at the top of the structure for three of the four structures analysed respectively: the frame structure and the structures provided with friction dampers with 50KN and 100KN capacity.
An important parameter that reveals the seismic response of the structures is the relative level displacements. The percentage of relative level displacements being the main criterion that must be met in the seismic design of the structures. The relative level displacements of the 4 structures with 11 levels subject to the 3 accelerograms are presented in Figure 5.4.15.

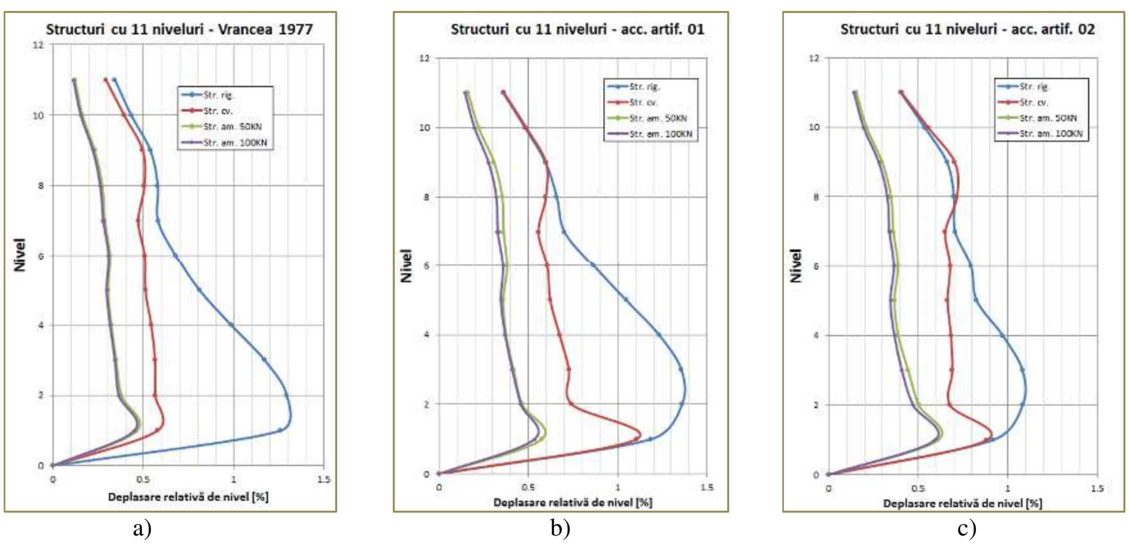
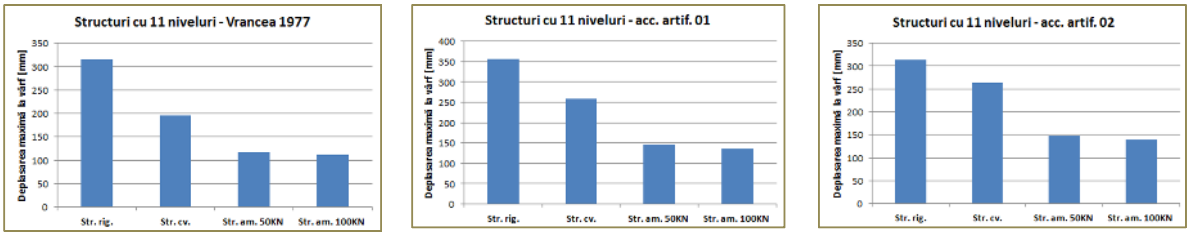


Figure 5.4.15 **Relative level displacements - structures with 11 levels for accelerograms: *a)Vrancea 1977, b) Artificial 01, c) Artificial 02***

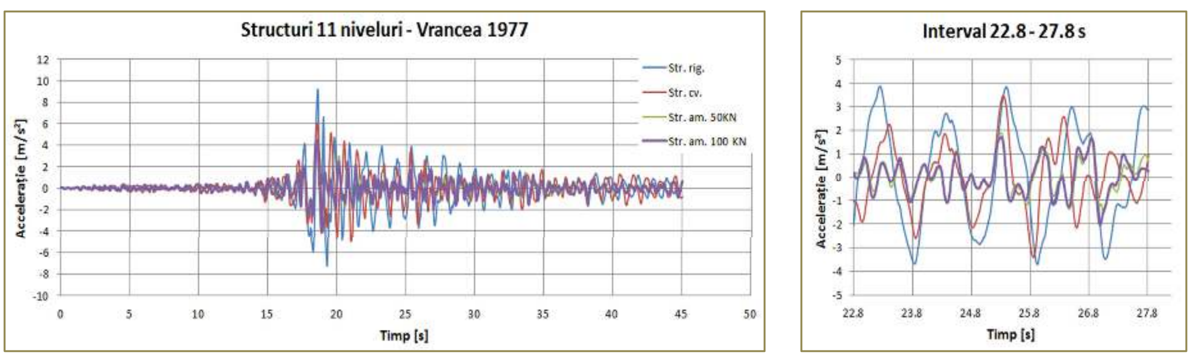
It is observed that the stiffening brought by braces but also the equipment of the structures with added damping leads to the reduction of the level displacements for the 3 accelerograms (fig.5.4.15).
In this case, the biggest reduction in terms of relative level shift is found between the unbroken structure and the centrally braced structure.



a) b) c)

***Figure 5.4.16* Maximum displacements at the peak - structures with 11 levels for accelerograms:**
a)Vrancea 1977, b) Artificial 01, c) Artificial 02

The maximum displacement at the peak for the three accelerograms (Fig. 5.4.16) occurs in the case of the frame structure (str.rig.). The minimum value of this parameter is recorded in the structure provided with shock absorbers with a capacity of 100 KN (Str. am 100KN), by up to 61.80% compared to the frame structure (str. rig.) in the case of the artificial accelerogram 01.
Figure 5.4.17 shows the variations of the lateral acceleration from the last level of the four structures with 11 levels analysed, by applying the 1977 Vrancea accelerogram.



a)

***Figure 5.4.17* Variation of lateral acceleration at the last level - structures with 11 levels for the 1977 Vranceaaccelerogram**

The time response for the 11-level seismically operated structures in the case of the three accelerograms is shown in two adjacent images in Figure 5.4.17, the first of which represents the variation of acceleration at the last level over the entire duration of the accelerogram, and the second has an interval of five seconds.
For the 1977 Vrancea accelerogram, the maximum value of the lateral acceleration at the last level is recorded by the frame structure (str. Rig.) and is 9.22 m / s 2, and the minimum value is recorded in the case of the structure with shock absorbers with a capacity of 100 KN (str. am. 100KN) and is 4.54 m / s 2. There is practically a reduction of up to 50.75% of the value of the maximum acceleration at the last level.
Following the study on the response in terms of maximum accelerations at the last level for the structures with eight levels, there is a rather high variability for the three accelerograms.
The reduction of the seismic response is in the range of 38.28% - 50.75%.

The variation of the maximum basic seismic force in parallel with the maximum value of the maximum level displacement for the structures with 11 levels is presented in Figure 5.4.18.

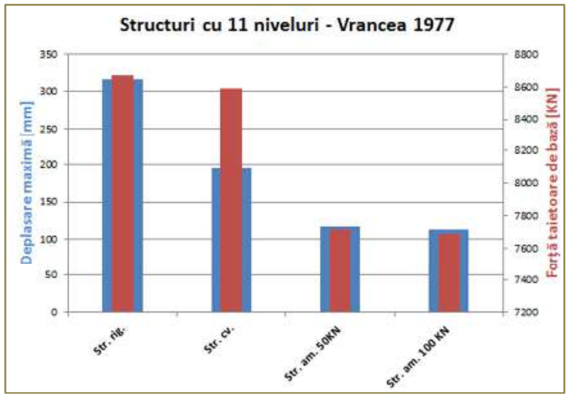


Figure 5.4.18 **Variation of the maximum basic seismic shear force depending on the lateral rigidity - 11-level structures - Vrancea 1977**

In the case of the structures triggered by the 1977 Vrancea earthquake, it is found that the basic seismic force with the highest value is registered in the case of the structure in unbroken frames (str.rig.). The structure equipped with 100KN friction dampers (str. Am. 100KN) registers the lowest displacement at the top and the lowest basic shear force by 11.29% lower than the unbroken structure and only 0.33% lower than the structure provided with 50KN shock absorbers (50KN str.) (Fig.5.4.18).

The energetic approach of the problem of rigidity versus added damping can highlight certain aspects that may be overlooked the designer in the classic design based on the study of kinematic states (lateral displacements) and static states (basic seismic shear forces).

5.4.3 Comparative analyses of energy components. The energy approach.

The energetic approach to the design of structures has its beginnings in 1956 (Housner, 1956) when Housner proposed to ensure a necessary capacity to absorb the energy induced in the structure, by means of design.

The energy balance equation (5.4.1) involves the energy components of the seismic response:

- E_i - Seismic input energy;
- E_k - kinetic energy developed by the motion of masses;
- $E_{s,e}$ - elastic deformation energy (by elastic deformations of the elements);
- E_D - energy dissipated by inherent damping of the structure;
- $E_{S,h}$ - energy dissipated by plastic deformations (plastic joints);
- E_{AD} - energy dissipated by seismic protection devices.

$$E_i = E_K + E_{S,e} + E_D + E_{S,h} + E_{AD} \quad (5.4.1)$$

The energy absorption capacity, E_{ABS}, of a seismically driven structure is given by; the inherent damping of the structure; by the plastic deformations produced by the structural and non-structural elements; and by the seismic protection equipment with which the structure is equipped (Popescu, 2014).

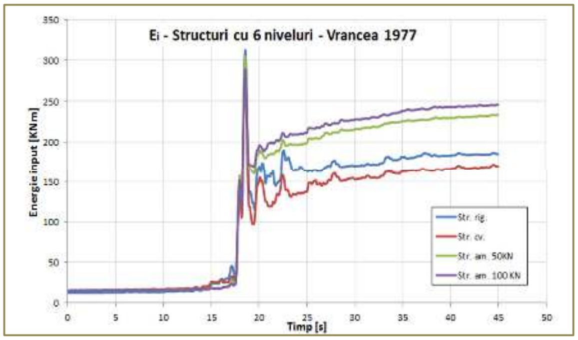


Figure 5.4.19 **Input seismic energy - Vrancea 1977**

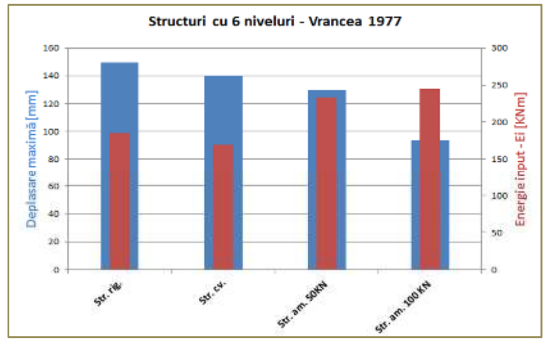


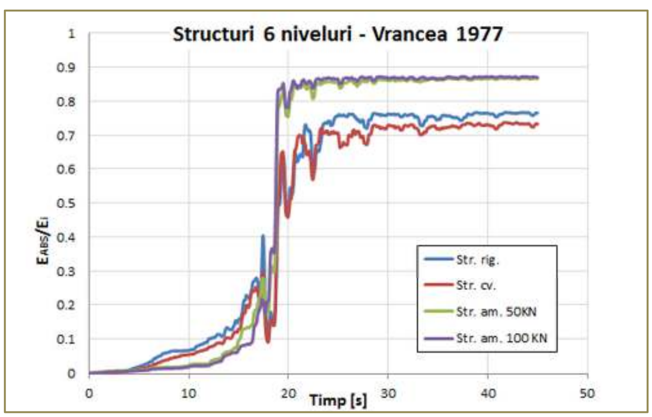
Figure 5.4.20 **The variation of the maximum displacement of the structures versus the input seismic energy - Vrancea 1977**

In the case of the 1977 Vrancea seismic action applied to the structures with six levels, a variation of the seismic input quantity is observed as follows (fig. 5.4.19):

- Centrally braced structure (with high lateral rigidity) absorbs the smallest amount of input energy: 169.59 KNm;
- The structure equipped with shock absorbers with a capacity of 100 KN (lower lateral rigidity compared to the centrally braced structure) absorbs an input energy of 245.47 KNm, 44.74% more than the centrally braced structure (Figure 5.4.20).

For 6-level structures equipped with friction dampers subject to accelerogram. Vrancea 1977 there is an increase in the energy absorbed (E_{ABS}) by the structure by up to 10.43% compared to the unbroken 6-level structure.

The energetic state of the structure is directly dependent on the seismic action and the characteristics structure, the variation of the ratio (E_{ABS}/E_i) provide useful conclusions regarding the energy state of a structure.



a)

Figure 5.4.21 **E_{ABS}/E_i report - 6 levels structures - Vrancea 1977**

Figure 5.4.21 shows that the highest value of the E_{ABS}/E_i ratio is recorded in the case of structures equipped with friction dampers, followed by the structure in unbroken frames and the lowest value is recorded by the centrally braced structure.

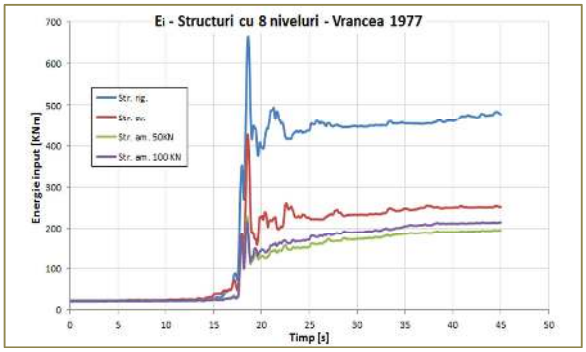


Figure5.4.22 **Input seismic energy.**

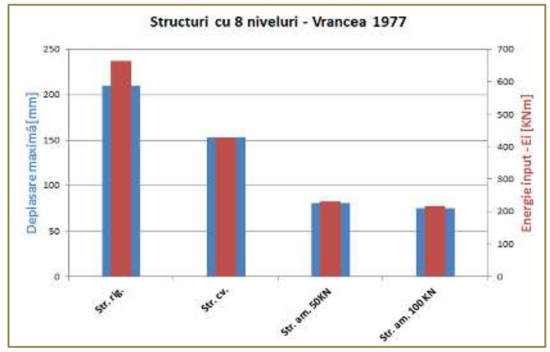


*Figure 5.4.23***Variation of the maximum Vrancea 1977 displacement of the structures versus the seismic input energy Vrancea 1977**

In the case of the 1977 Vrancea seismic action applied to the eight-level structures, a variation of the seismic input quantity is observed as follows (fig. 5.4.22):
- The structure equipped with shock absorbers with a capacity of 100 KN absorbs the lowest input energy: 216.55 KNm;
- Unbroken frame structure (low lateral rigidity) absorbs input energy of 664.50 KNm, by 306.87% more than the unbroken frame structure (Figure 5.4.23);
- In this case, there is a correlation between the maximum displacement level and the seismic input energy.

For the structures with eight levels subjected to the Vrancea 1977 accelerogram, a value of the energy absorbed (E_{ABS}) by the structure is found to be approximately 90% of the seismic input energy (E_i). At the same time, a decrease in seismic input energy can be observed in the case of structures equipped with added damping.

Figure 5.4.24 shows that the highest value of the E_{ABS}/E_i ratio, for the structures with eight levels subjected to the seismic action Vrancea 1977 is registered in the case of the structure in non-braced frames, followed by the frame structure braced centrally and the lowest value is registered by the structure equipped with shock absorbers with a capacity of 50KN. Compared to the case of the six-level structures, the values of the E_{ABS}/E_i ratio for the four analysed structures are much closer to each other, around 0.9.

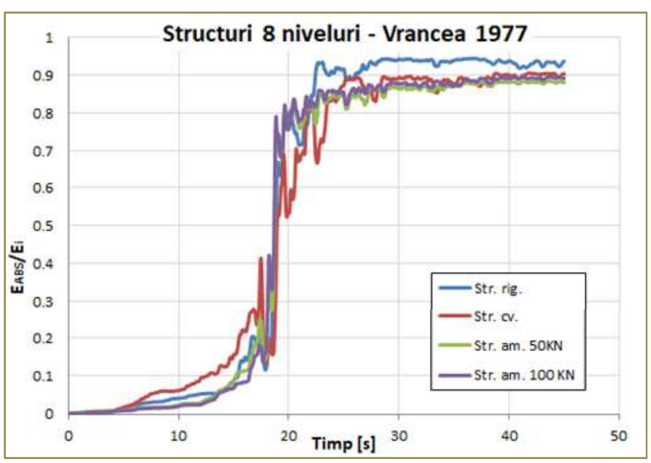


Figure 5.4.24 **E_{ABS} / E_i report - 8-level structures - Vrancea 1977**

For 8-level structures equipped with friction dampers, the input energy (E_i) is up to 12% lower than the structure in unbroken frames.
In the case of the 1977 Vrancea seismic action applied to the structures with 11 levels, a variation of the seismic input quantity is observed as follows (fig. 5.4.25):
- Unbroken frame structure (with low lateral rigidity) absorbs the largest amount of input energy: 1819.37 KNm;
- The structure equipped with shock absorbers with a capacity of 100 KN absorbs an input energy of 471.81 KNm, 3.85 times less than the structure in unbroken frames (Figure 5.4.26);
- The displacements in the case of the structure equipped with shock absorbers with a capacity of 100 KN are 2.80 times smaller than the structure in unbroken frames (Figure 5.4.59).

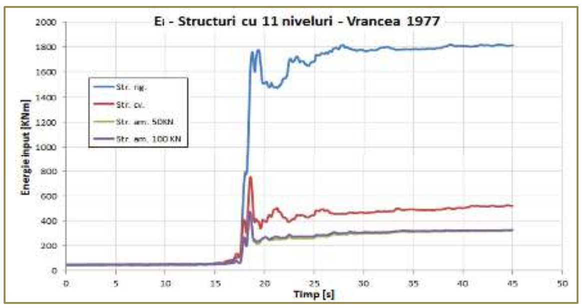


Figure 5.4.25 **Input seismic energy Vrancea 1977**

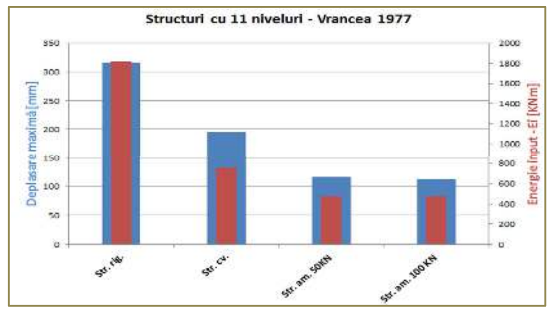


Figure 5.4.26 **The variation of the maximum displacement of the structures versus the input seismic energy - Vrancea 1977**

Figure 5.4.27 shows that the lowest value of the E_{ABS}/E_i ratio is recorded in the case of structures equipped with friction dampers, followed by the centrally braced structure and the lowest value is recorded by the braced frame structure.

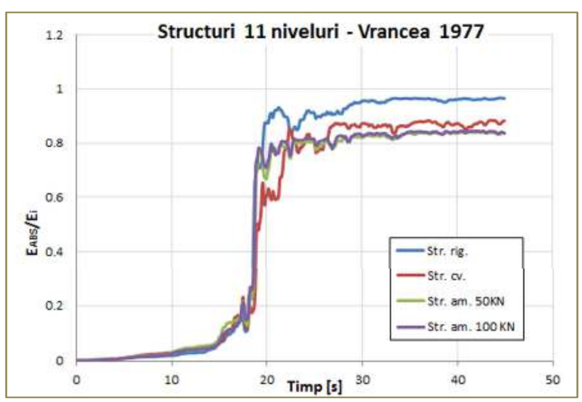


Figure 5.4.27 **E_{ABS}/E_i report - structures 11 levels - Vrancea 1977**

Among the parameters of the energetic response are also listed as the kinetic energy (E_k) and the potential energy (E_p). These two parameters are studied in Annex A of the thesis.

5.4.4 Conclusion

Within the case study, a series of nonlinear dynamic analyses were performed on four types of structures with 6, 8, and 11 levels, respectively. Following these analyses; the seismic response of

the structures was highlighted both in classical terms such as relative level displacement; basic shear force; or acceleration level at the last level and in energy terms: the ratio of absorbed seismic energy to input energy. Following the analyses performed in this study, the following can be observed:
- For the structures with 6 levels analysed, the maximum basic shear force is registered in the case of the rigid structure (str. Rig.);
- In the case of structures with 8 levels analysed, the maximum basic shear force is registered in the case of the braced structure;
- The reduction of accelerations to the last level of the structures provided with friction dampers increases with the increase of the height regime of these structures;
- The largest reduction of maximum accelerations at the top of the structure is recorded in the case of the structure with 11 levels equipped with shock absorbers with a capacity of 100KN, 50.75% lower than the level of maximum acceleration recorded in the case of rigid structure (str.rig);
- It can be seen that in the case of structures equipped with friction dampers, they not only dissipate a large part of the seismic input energy but also the level of seismic input is lower than that of structures in non-braced and centrally braced frames;

6. Chapter 6. Conclusions, personal contributions, and future research directions

6.1 Conclusions

The main objective of the thesis „**Seismic response of structures in braced frames equipped with rotating friction dampers**" was the study of the seismic response of structures in metal frames equipped with rotating friction dampers for seismic conditions in Romania. This study followed both the response of traditional components (displacements, accelerations, shear forces, etc.) and energy components. These shock absorbers can be embedded in the traditional bracing system, resulting in a system with improved seismic action.
Chapter 2 presented general notions of dynamic structures as well as a case study on the effect of added depreciation on a metal frame structure.
Chapter 3 presents the main devices used for seismic protection of structures and examples of their application as well as studies in the literature on the seismic response in energy terms of structures equipped with added damping. A more extensive presentation is made for friction damping devices. In this chapter the energetic approach of design is also presented, both for structures with a degree of dynamic freedom and for structures with several degrees of dynamic freedom.
Chapter 4 includes the experimental studies performed by the author to determine the hysteresis curves in the case of two friction dampers. In order to carry out these experiments, it was necessary to build a universal test machine.
The studies in Chapter 5 showed the improvement of the seismic response of structures using friction dampers. By equipping the structures with such dampers it is possible to increase the lateral rigidity without significantly increasing their mass, also these systems sometimes lead to substantial material savings.

6.2 Personal contributions

In order to fulfill the objectives of the thesis, we obtained a series of results that can be considered personal contributions to the development of the studied field:
- Carrying out the experimental evaluation (chap. 4, subchapters 4.2 and 4.3) of the hysteresis loops for two friction dampers. To carry out this experiment, the author of the thesis designed and built a universal testing apparatus (Chapter 4, Subchapter 4.1);
- Comparative studies on energy absorption capacity (Chapter 5, Subchapter 5.2) resulting from stiffening and, respectively, equipping with friction dampers for a set of 6-level structures. In addition to the traditional seismic response expressed in terms of
displacements and accelerations at the top of the structure, we studied the energy components of the energy response of the structure. The hysteretic curve was studied for with shock absorber located at the first level of the structures, with a capacity of 50 KN and 150 KN respectively;

- Comparative studies on the influence of the number and position of friction dampers in 6-level metal structures (Chapter 5, Subchapter 5.3). The maximum displacements at the peak, the basic shear force, the seismic input energy, the dissipated energy of the system, and the variation in time of the Input energy / dissipated energy ratio were studied;
- Comparative studies on the seismic response (chapter 5, subchapter 5.4) of metal structures with 6, 8, and 11 levels stiffened by large sections, centrally braced and, respectively, equipped with friction dampers of different capacities. For these studies, 30 non-linear dynamic time-history analyses were performed. These analyses resulted in a series of conclusions regarding the influence of the stiffening of the respective structures, of the added damping on the components of the seismic response: maximum accelerations at the peak, relative level displacements, seismic input energy, basic shear forces, absorbed energy and ratio Input energy / absorbed energy.

6.3 Future directions of research

In the process of fulfilling the objectives of the doctoral thesis, the author considers of interest in new research directions in the studied field:
- Studies on the efficiency of equipping existing structures that require seismic upgrading with friction dampers;
- Studies on the seismic response of structures in multi-story space frames equipped with friction dampers. The spatial model increases the accuracy of numerical studies;
- Economic analysis: Comparative costs regarding the possibility of equipping new and existing structures with friction dampers compared to the variant of their stiffening by enlarged sections or bracing.

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