SEMI-ACTIVE FUZZY CONTROL FOR VARIABLE DAMPING DEVICES FOR SEISMIC PROTECTION

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Abstract

Dynamic actions, in general, and earthquakes, in particular, can transmit very high forces to structures. Protection control systems have been developed to reduce the damaging effect of those actions. Semi-active control devices may generally be referred to as controllable passive devices. The semi-active control approach consists of the indirect application of variable control forces whose energy derives directly from the motion of structures and is obtained by instantaneous change of the parameters and dynamic characteristics according to a predetermined control criterion. No mechanical energy is inputted directly into the structure, making the entire system intrinsically dynamically stable. The efficiency of the protection will depend on the efficiency of the control algorithm.

Fuzzy control has been widely implemented in many fields due to its efficiency, while having simple and straightforward rules. In structural control, fuzzy logic has an interesting potential for mitigating earthquake vibrations. The reaction of a fuzzy control system can suitably adapt to the high randomness of seismic accelerations, so algorithms of this type of control should be developed, analyzed and studied for structural application.

An algorithm using fuzzy control has been developed for application in a semi-active variable damping device for controlling seismic actions in structures. Input membership functions were selected using ground acceleration feedforward control and displacement and velocity feedback control. The output pertinence functions set the damping value to be selected for the device using the centroid method. All membership functions were defined using a triangular function. In this paper, the proposed algorithm is presented, described and tested with numerical simulations. The tests were performed using artificial accelerograms representative of the Portuguese Seismic Action in a one degree of freedom and two degrees of freedom models. The results are then compared with traditional passive protection using a viscous damper, allowing to compare the efficiency of the proposed original fuzzy control algorithm.

Keywords: Structural control; Fuzzy logic; Control Algorithm; Seismic Protection; Semi-Active devices

1. Introduction

1.1 Seismic Protection Systems

Dynamic actions on structures can lead to high vibration levels and consequently significant structural damage. Situations may exist without structural safety being endangered but with unacceptable vibrations from the standpoint of human comfort or economic damage. Structural protection for these types of actions may not be achieved (or undesirable to be achieved) by increasing the strength or stiffness of its elements due to its own limitations, either due to lack of resilient foundation capacity, cost associated with increased strength or even for aesthetic reasons. Additionally, in certain situations such as seismic action, increased stiffness may intensify the effects of vibrations, which is precisely what is intended to be prevented. In addition, it should be noted that traditional structural design methods consider the inelastic deformation capacity, allowing for significant damage to the structure. This issue may be critical in structures such as hospitals, communications centers, historic heritage buildings or vital transport infrastructures, i.e. structures or routes that should remain operational or with sensitive equipment that must remain operational during and especially after high magnitude earthquakes. In such cases the use of alternative seismic protection methods may be the appropriate solution.

The techniques used in seismic protection of structures do not strengthen the structure, but rather reduce the forces absorbed by the structure due to the input action, consequently reducing the structural response. These systems have been applied both to new constructions and to the reinforcement of existent structures, particularly historic buildings that correspond to an important heritage [1].

Control and protection systems have been used to solve problems related to damaging dynamic actions, such as earthquakes, wind, pedestrian traffic, etc. These systems improve the dynamic structural behavior by modifying the dynamic characteristics of the structure or influencing the way in which the action is transmitted to the structure. The different performance patterns result in the classification of different types of dynamic protection.

Seismic protection systems can be designated as passive or active depending on the energy requirement for their operation. The use of passive devices such as viscous dampers does not input power into the system, but it increases the dissipation capacity of the global system. A passive device does not have the ability to adapt itself to the input action and once installed it changes the dynamic properties of the structure for whatever type of action. On the other hand, active systems allow to adjust the response of the structure considering the input action or its intensity. In addition to active and passive protection systems, there are also hybrid and semi-active systems.

The use of semi-active, hybrid or active systems implies the application of some level of structural control with a decision algorithm. The basic principle of control protection systems is the online prediction of the structure's dynamic response. A control unit processes the information obtained from sensors placed in carefully selected places in the structure and that allow the measurement of the parameters necessary to satisfy the control criterion.

Active systems use energy to produce and apply forces to the structure, in order to correct inappropriate structural behaviors [2]. This involves a high amount of energy, which, in cases of power cuts, such as those that commonly occur during earthquakes of high magnitude, may compromise the entire functioning of the system. Semi-active systems use energy to modify the dynamic characteristics of the device, subsequently affecting the entire structure. The energy required is much less, ensuring stability to the system [3]. Hybrid systems combine two or more different types of devices, bringing together advantages and eliminating the inconveniences of isolated devices.

1.2 Semi-Active Systems

Semi-active control devices can be described as passive devices with modifiable properties during dynamic actions, according to a predefined control algorithm [4]. The semi-active control approach consists of the indirect application of variable control forces into the system by changing the dynamic characteristics and, thus, improving the dynamic behavior. There is no direct input of mechanical energy directly into the structure, making the entire system intrinsically stable from a dynamic point of view [5]. In addition, semi-active systems do not require power supplies with a high energy capacity like active systems. Many of the semi-active devices operate on simple batteries, with clear advantages in the case of seismic action. In addition, in the rare case of a power failure, passive components still offer some protection. One of the other advantages is the fact that they require much less installation space than active systems [6].

The most relevant drawback of this type of systems is that the control capacity is restricted by the mechanical part of the device [7]. Semi-active devices are as reliable as passive devices, while at the same time having the advantage of adjustable parametric characteristics such as active control. With an appropriate algorithm, the results obtained may be equal to or greater than those obtained through active control [3].

There are basically two types of semi-active devices: those that use a mechanical system to change their dynamic parameters and those that have special fluids with controllable characteristics. Examples of the first type include devices with variable damping or variable stiffness, where a valve allows adjusting the damping or stiffness of the device. For the second type of semi-active devices mentioned, there are electro-rheological or magneto-rheological devices, in which the application of an electric or magnetic field allows to modify the mechanical properties of the fluid and, consequently, the control force in the device.

Like passive viscous dampers, the energy of the excitation is dissipated by the heat generated by the movement of the two extremes of the device. This movement is a consequence of the forced passage of a viscous fluid through a small opening. In semi-active devices where the response is changed through a mechanical system, the size of the orifice through which the fluid passes may be adjusted based on a control algorithm. The corresponding damping is adjusted by the opening rate of the flow control valve inside the damper. The damping coefficient is modified to appropriately reduce the acceleration response during severe disturbances. For minor disturbances the system works as a viscous passive damper.

Alternatively, semi-active controllable fluid dampers consist of devices that allow the reversible modification of a free flow of a viscous fluid to a semi-solid flow with a controllable resistance. This happens because the fluid inside the device has peculiar characteristics, being constituted by non-colloidal micro-particles, magnetically or electrically polarized, dispersed in mineral or silicone oil. When the fluid is exposed to an electric or magnetic field, the change takes place in milliseconds [3]. They are called magneto-rheological fluids or electro-rheological fluids, as they react to a magnetic or electric field, respectively.

When a magnetic or electric field is applied, chains of particles are formed, giving a sudden change in the rheological behavior of the fluid and it becomes semi-solid, exhibiting viscoelastic behavior [3]. The intensity of the magnetic or electric field can be controlled by an appropriate algorithm, producing the damping forces necessary to improve the dynamic behavior of the system.

Magneto-rheological fluids have shown advantages over electro-rheological fluids, such as faster response and the ability to reach higher values, having been used more frequently. In addition, they have proven to be very fast in their response and, therefore, particularly suitable for semi-active applications of seismic engineering [5].

2. Fuzzy Control

In a semi-active system, there are one or more devices connected to the structure capable of modifying some of its own characteristics. This modification is done according to a set of rules, called a control algorithm, in order to improve the structural response. The algorithm is responsible for deciding the action to be taken depending on the information obtained by the sensors, so its choice and correct definition is fundamental.

Fuzzy algorithms can also be used for different purposes and must obey a set of rules. Fuzzy Logic was originally identified by Lotfi Zadeh in [8] and is based on the human logic used when solving a problem. Human beings have the ability to absorb and evaluate all kinds of information about the physical world in which they find themselves. They are then able to mentally analyze, summarize and condense all the information to select an optimal course of action to take. Much of this information is not very precisely characterized in detail and much of its processing is not easily possible to define. Fuzzy control (sometimes called fuzzy logic) tries to replicate these procedures. There are occurrences that cannot be precisely classified as “true” or “false” (1 or 0) and rather correspond to a transition between two states. The diffuse logic allows treating this information and obtaining a result that is then applicable in solving a specific issue. The diffusion of initial information is measured by the degree of its imprecision.

This type of logic can be applied in the most diverse fields such as engineering, economics, psychology, marketing, weather, biology, politics, etc. It does not require an exact model of the system, which is the main reason why it is so widely used. With fuzzy logic methodology, some time-consuming steps in the development phase can be eliminated, especially when it is intended to evaluate non-quantifiable concepts. However, it may be needed long time to define and fine tune the algorithm. This type of control requires simulations and experimental tests in order to measure its efficiency since it is impossible to identify the optimal solution just by mathematical manipulation.

The fuzzy logic consists of the application of rules that correlate data with results according to three basic steps: fuzzification, application of rules and defuzzification.

In the fuzzification step, the initial information is acquired and transformed into diffuse information through membership functions that define the degree of belonging in each of the categories. The limits of these categories are not precise but rather diffuse, which allows for a gradual variation avoiding discontinuities. The form of the membership functions can take different aspects. The most common shape is triangular, but trapezoids and 1st degree curves are also used. The number of curves and their location are more important than their shape. Narrow triangles allow for tighter control, and are used in the central area, while wider triangles tend to be at the ends. Three to seven curves are generally suitable to cover the range of values in the input data [9]. Then, the rules that define the fuzzy algorithm. This relates the input membership functions with the output membership ones. In the defuzzification process, the fuzzy values of the results are converted into precise and quantifiable values using a previously chosen method, such as the centroid or weighted average method, among others [10].

3. Models Description

Two models were considered: a single degree of freedom (SDOF) system, and a two degrees of freedom system, defined in Fig.1. These models represent typical frames of a regular building.

a) b)

Fig. 1 – Models used in this study: a) Model A; b) Model B

The general mathematical formulation for SDOF and MDOF (Multi-Degree Of Freedom) are shown in Eq. (1) and (2), respectively. Table 1 shows the characteristics considered for both models.

$$m\ddot{x}(t) + c(t)\dot{x}(t) + kx(t) = -m\ddot{x}_g(t) \tag{1}$$

$$[M]\{\ddot{x}(t)\} + [C(t)]\{\dot{x}(t)\} + [K]\{x(t)\} = -[M][1|]\ddot{x}_g(t) \tag{2}$$

Where,

$x(t)$ - Relative displacement (and where the point(s) indicates differentiation from time)
m - Mass of the structural system ([M] is the mass matrix)
c(t) - Damping of the structural system (consists of the building damping and additional damping from the device)
k- Stiffness of the structural system
$\ddot{x}_g(t)$ - ground acceleration

Table 1 – Model Features

	SDOF	MDOF
Characteristic	Value	Value
Mass	m=20 ton	$[M] = \begin{bmatrix} 20 & 0 \\ 0 & 25 \end{bmatrix}$
Stiffness	k=15000 kN/m	$[K] = \begin{bmatrix} 30000 & -15000 \\ -15000 & 15000 \end{bmatrix}$
Structural Damping	5%	5%
Device Damping	Between 0 e 20%	Between 0 e 20%

4. Fuzzy Control Algorithm

In this article, the objective of the control is to minimize the displacements of the system's mass by controlling the displacements and velocities. Considering the SDOF system described above, when subjected to a dynamic action, the first story will oscillate around its equilibrium position. The elastic force is continually pushing the force to its equilibrium position. However, the damping force sometimes has the same sign as the elastic force and sometimes doesn't. This means that sometimes the system itself naturally returns to its equilibrium position while at other times it moves away.

The membership functions were defined for the input data and the results, as shown in Fig. 2 and 3. Regarding the input data, displacement and velocity, 5 levels were defined: negative high, negative low, zero, positive low and positive high. The membership functions for the results, which relate to the damping value of the semi-active device, consider 4 levels: zero, low, medium and high. The limits of the different membership functions are presented in Tables 2 and 3.

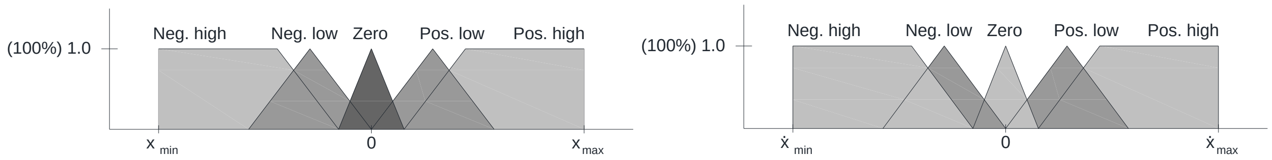


Fig. 2 – Input membership functions

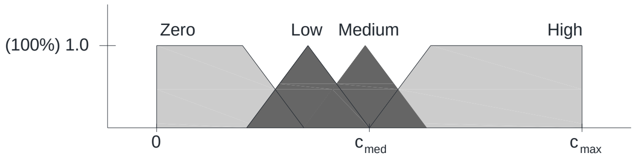


Fig. 3 – Output membership functions

The limits of the different membership functions are presented in Tables 2 and 3. The velocity membership functions limits are identical to those displayed in Table 2, replacing the reference to displacement by velocity.

Table 2 – Definition of the fuzzy sets of the input membership functions

Level	Value	Height h
Negative high	x_{min}	1
	$x_{min}/2$	1
	$x_{min}/6$	0
Negative low	$3/5*x_{min}$	0
	$3/10*x_{min}$	1
	0	0
Zero	$x_{min}/6$	0
	0	1
	$x_{max}/6$	0
Positive low	0	0
	$3/10*x_{max}$	1
	$3/5*x_{max}$	0
Positive high	$x_{max}/6$	0
	$x_{max}/2$	1
	x_{max}	1

Table 3 – Definition of the fuzzy sets of the output membership functions

Level	Value	Height h
Zero	0	1
	$c_{max}/4$	1
	$3/8*c_{max}$	0
Low	$c_{max}/4$	0
	$3/8*c_{max}$	1
	$c_{max}/2$	0
Medium	$3/8*c_{max}$	0
	$c_{max}/2$	1
	$5/8*c_{max}$	0
Alto	$c_{max}/2$	0
	$5/8*c_{max}$	1
	c_{max}	1

Table 4 present the fuzzy algorithm rules, which take into account the issues described previously, changing the damping value of the semi-active device to maximum when the system moves out of balance and to zero when approaching, taking advantage of the energy of the system.

Table 4 - Fuzzy algorithm rules

	General Rule: **AND**	**Velocity** Negative high	Negative low	Zero	Positive low	Positive high
Displacement	Negative high	High	High	High	High	High
	Negative low	High	Medium	Low	Medium	High
	Zero	Medium	Low	Zero	Low	Medium
	Positive low	High	Medium	Low	Medium	High
	Positive high	High	High	High	High	High

The results are obtained by combining the input data defined in the table in percentages. For example, let's consider the system registers a displacement d_a and a velocity v_a. The percentages associated with each of the membership functions are determined by the heights of the intersections between the various categories, represented by the heights h_1, h_2, h_3 and h_4, as shown in Fig. 4.

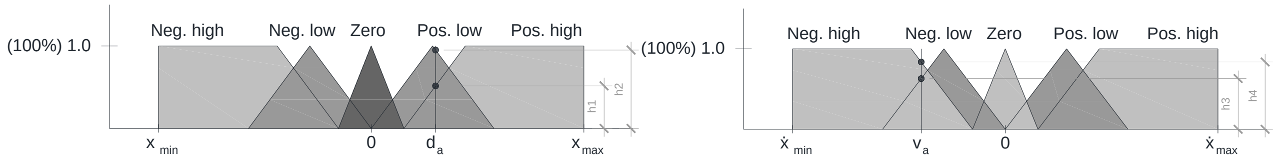


Fig. 4 – Percentages of input membership functions

The percentages of the output membership functions are then determined based on the rules of the algorithm. Thus, the displacement d_a crosses the positive high level with the percentage h_1 and the velocity v_a intersects the negative low level with the percentage h_3. Since all the rules in Table 4 were established with the operation "AND", the minimum criterion is adopted. According to the fuzzy rules, *positive high displacement* **AND** *negative low velocity* leads to a high damping value. As $h_1 < h_3$, the percentage h_1 is considered for the high damping in this combination. The remaining combinations are determined similarly and are shown in Fig. 5.

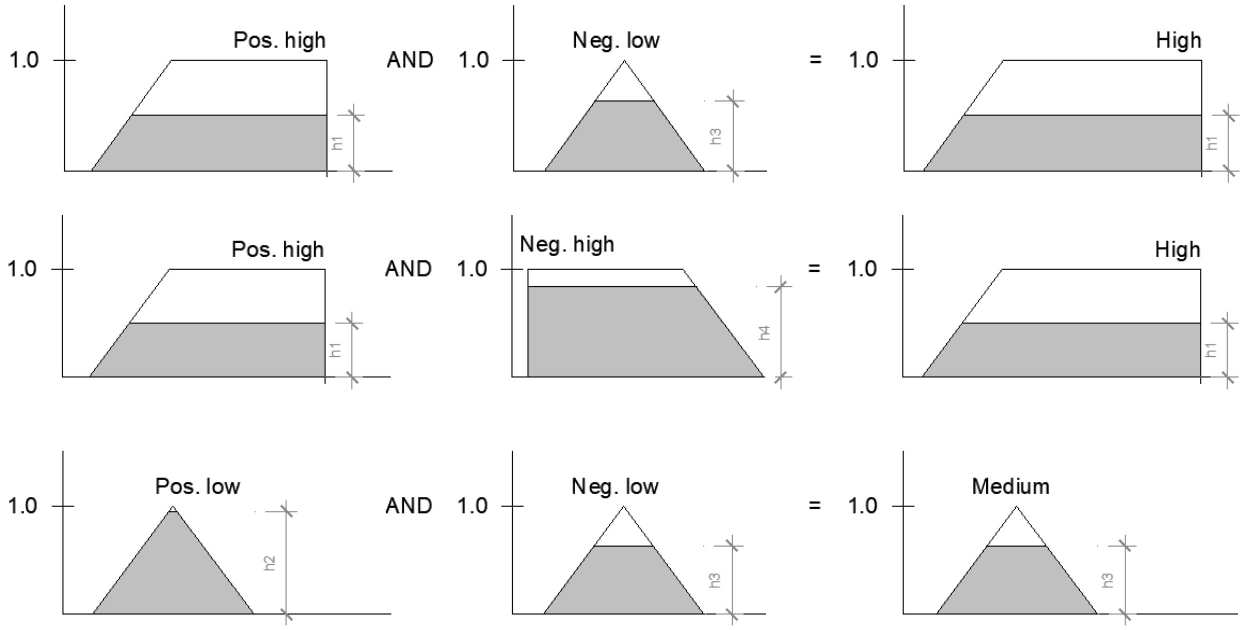


Fig. 5 – Percentages of output membership functions

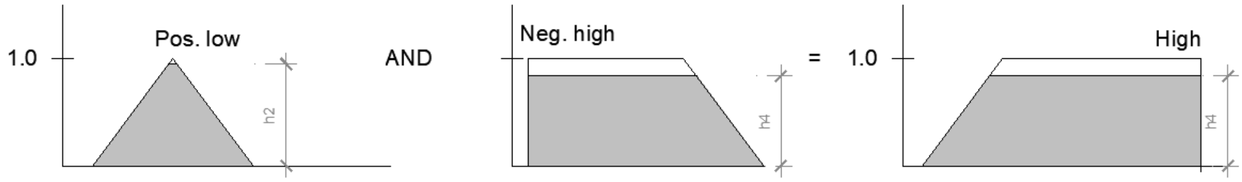


Fig. 5 – Percentages of output membership functions (continuation)

The four results obtained are then superimposed, and point C is determined using the Centroid Method, thus obtaining the final value for the damping of the device, as shown in Fig. 6.

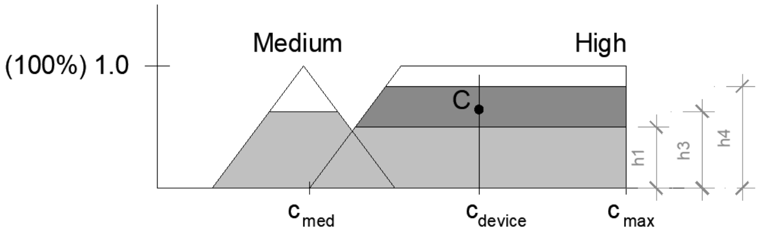


Fig. 6 – Percentages of output membership functions - Results

As fuzzy logic there is no sudden change between states, but rather a variation in the value in the membership function. When it loses value in one membership function, it gains in another.

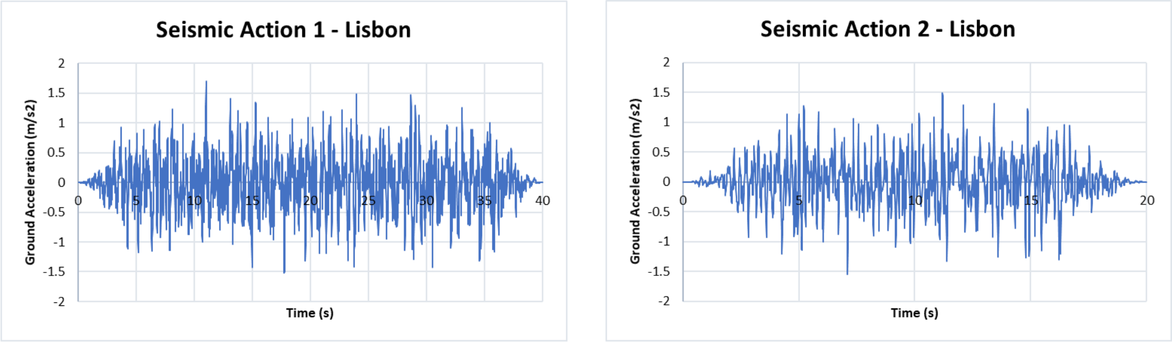
For the MDOF model, the input data considered was the displacement and the velocity of the 2nd story, using the same fuzzy rules and membership functions described for the SDOF system.

5. Seismic Actions

The two models were tested under 20 artificial accelerograms for each of the Portuguese seismic actions defined for soil A, accordingly to Eurocode 8, for Lisbon. A sample for each type of the actions is shown in Fig. 7.

6. Results

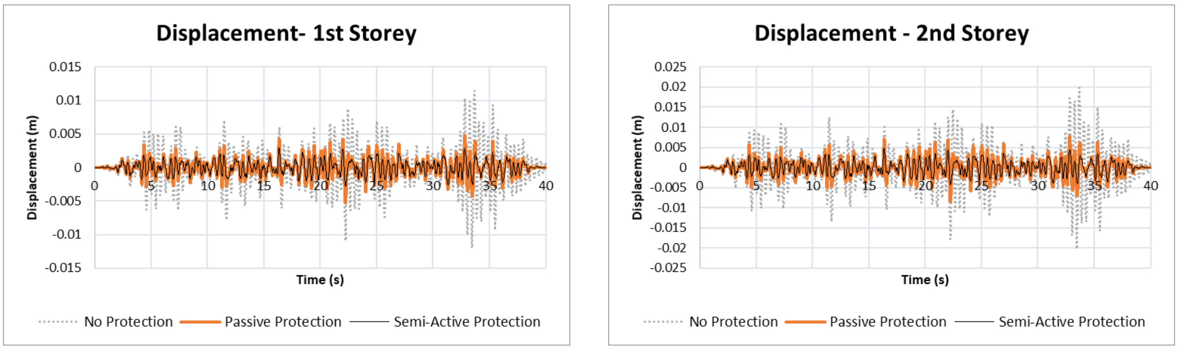
Three situations were considered: no protection, passive protection and semi-active protection. In the first case, only the building damping is considered. The passive protection adopted was the one corresponding to a damping coefficient of 20%. In order to establish a comparison with the passive protection, the maximum damping coefficient of the fuzzy algorithm for the semi-active system was assumed to be 20%.



a) b)

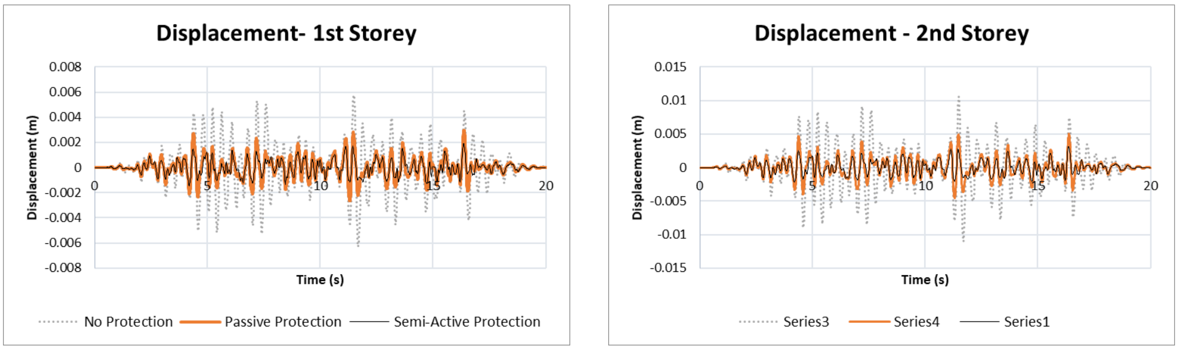
Fig. 7 – Portuguese Seismic Action: a) Type 1; b) Type 2

In Fig. 8, 9, 10 and 11, the results obtained by the MDOF model described are compared, in terms of displacement history and force-displacement graph, under one of the artificial accelerograms for the type of seismic action referred in the figure.



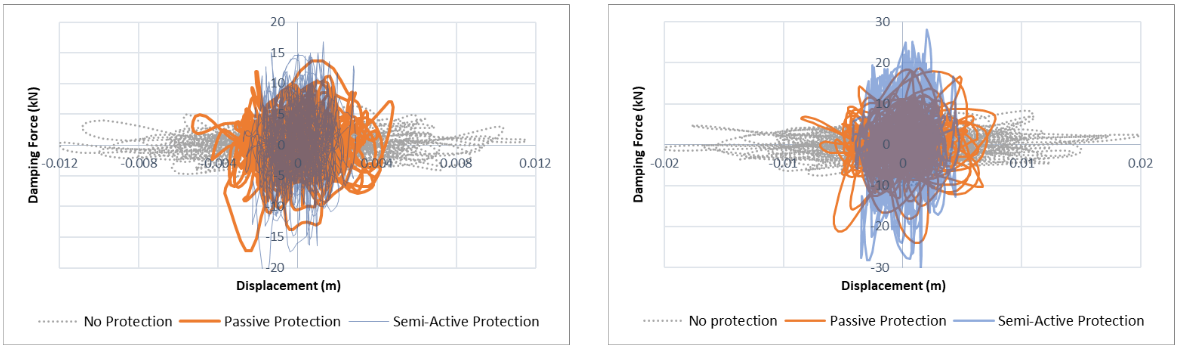
a) b)

Fig. 8 – Displacement History under Seismic Action Type 1: a) First storey; b) Second storey



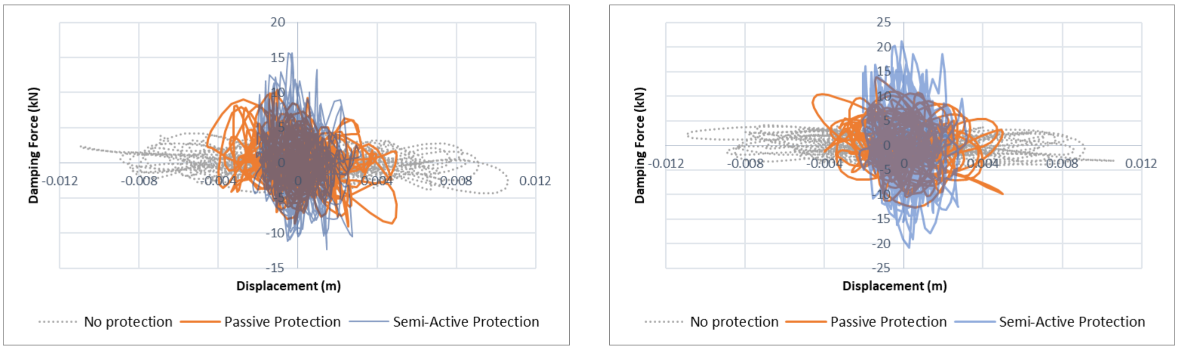
a) b)

Fig. 9 – Displacement History under Seismic Action Type 2: a) First storey; b) Second storey



a) b)

Fig. 10 – Force-Displacement Graph under seismic action Type 1: a) Storey 1; b) Storey 2



a) b)

Fig. 11 – Force-Displacement Graph under seismic action Type 2: a) Storey 1; b) Storey 2

Table 5 shows the numerical results obtained, for the average of the 20 artificial accelerograms for the SDOF model. Table 6 shows equivalent numerical results obtained for the MDOF model. Regarding the SDOF model, differences between passive and semi-active protection are small, but for the MDOF model, there are considerable enhancements. As it possible to see in the Figures 8 to 11 and Table 6, the semi-active protection allows a higher reduction on velocities and displacements than the passive protection. In fact, while passive protection a 53% reduction is obtained for displacements and velocities in comparison with the no protection case, semi-active protection allows a 65% and 90% reduction on displacements and velocities, respectively, for either storey and either seismic action.

Table 5 - Numerical results for SDOF

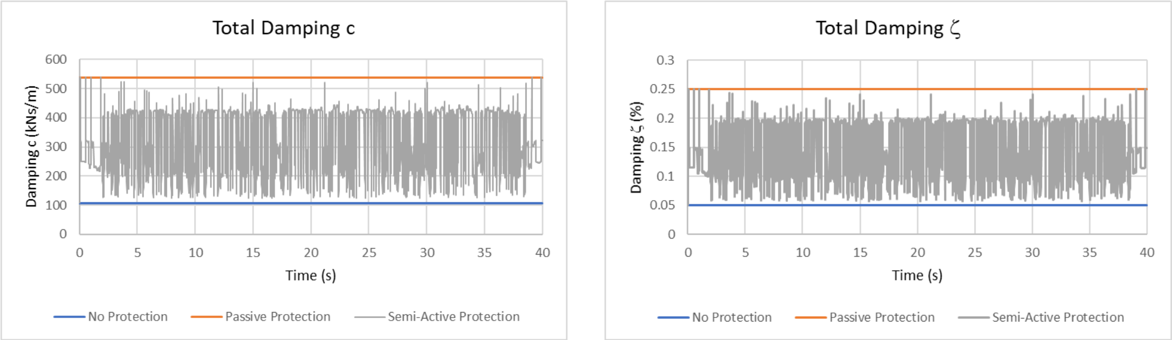
Parameter	Seismic Action 1			Seismic Action 2		
	No Protection	Passive Protection	Semi-Active Protection	No Protection	Passive Protection	Semi-Active Protection
d_{max}	0.00528	0.00261	0.00256	0.00546	0.00246	0.006321
v_{max}	0.13242	0.05631	0.05685	0.14415	0.00242	0.006324

Table 6 - Numerical results for MDOF

Parameter	Storey	Seismic Action 1			Seismic Action 2		
		No Protection	Passive Protection	Semi-Active Protection	No Protection	Passive Protection	Semi-Active Protection
d_{max}	1	0.01073	0.00530	0.00378	0.00742	0.00351	0.00255
	2	0.01784	0.00860	0.00605	0.01267	0.00583	0.00415
v_{max}	1	0.53671	0.26510	0.05416	0.37088	0.17555	0.04619
	2	0.89184	0.42992	0.08592	0.63358	0.29127	0.06996

Figure 12 shows the total damping ***c*** in the structural system in each instant of time for an accelerogram of Seismic Action Type 1, for the first mode. In the no protection case, there is only 5% of damping. With the passive protection, 20% of damping is added to the structural one. In these two last cases, the damping is constant through time. For the semi-active protection, the damping varies accordingly to the algorithm explained. This can be clearly seen in Figure 12, as the value of c is constantly varying in value, having the minimum value corresponding to 5% of damping (only structural damping) and maximum value corresponding to 25% of damping (structural damping plus a comparable passive protection of 20%).

Differences with passive protection exist and are significant, with improvements of 12% for the displacements and 37% for the velocities. Further studies are required in order to completely assess the efficiency of the algorithm with other types of rules or limits for belonging functions that are defined in a more elaborate way and using more in-depth programming techniques.



a) b)

Fig. 12 – Evolution of Damping: a) Damping c value; b) Damping coefficient value

7. Concluding Remarks

Fuzzy control has been widely implemented in the most diverse fields due to its efficiency, while having simple and direct rules. In structural control, fuzzy logic has an interesting potential in terms of mitigating vibrations caused by earthquakes. The reaction of a fuzzy control system can adapt itself conveniently to the high randomness of the seismic accelerations, in a stable and appropriate way.

A simple and original algorithm using fuzzy control was developed for application in a semi-active device with variable damping to control structures under seismic action. The input membership functions were selected using displacement and velocity control. The output membership functions of the results establish the damping value to be selected for the device using the centroid method. All membership functions were defined using triangular or trapezoidal functions.

The proposed algorithm was tested with numerical simulations, using 20 artificial accelerograms representative of the two types of seismic action, soil A, for the Portuguese seismic action defined in Eurocode 8, for Lisbon. Two models were studied: one story frame and two stories frame. The results are then compared to traditional passive protection using a viscous damper with 20% damping.

The use of semi-active systems allows significant improvements in the displacement and velocity responses, with important reductions for the MDOF model. This is obtained by adjusting the damping coefficient ***c*** of a variable viscous damping device accordingly to the rules of the presented algorithm.

The presented algorithm is extremely simple and basic, demonstrating that there is room for improvement with other types of rules or limits for belonging functions that are defined in a more sophisticated way, so algorithms of this type of control must be developed, analyzed and studied for application in structures.

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