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Structural Damage Control with Interval Type-2 Fuzzy Logic Controler

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ABSTRACT: In this study, with designing of an Interval Type-2 Fuzzy Logic Controller (IT2FLC), the ability of this system to control the uncertainties governing the structure has been investigated. One of the main shortcomings of fuzzy systems is to consider the uncertainties in the fuzzy rule base. IT2FLS, which is in fact a development of fuzzy systems, has the ability to handle this problem and reducing the uncertainties surrounding it. In order to evaluate the performance of the proposed controller, building with the Magneto-rheological (MR) dampers have been used as benchmark. The results of the analysis of the structures in the proposed controller, with the uncontrolled structure, the controlled structures equipped with the type-1 fuzzy controller (FLC Type-1), as well as the controlled structures under the Genetic algorithm-Fuzzy Logic Controller (GA-FLC), have been compared and analyzed.

Numerical results showed that IT2FLC is more effective in reducing the uncertainties governing the structure compared to other controllers, and the structural response will be optimized in different loading conditions. Using the proposed controller will reduce damage in the structure by 5 to 15 percent more than other controllers. In addition, the use of IT2FLC has reduced the displacement and acceleration time history responses of the structure compared with FLC-Type-1. The proposed controller has been able to reduce the maximum response of the different floors of structure by 10 to 30 percent compared to other controllers. Dynamic analysis of IDA method shows that at different load levels, the performance of IT2FLC will be more optimal than FLC-Type-1.

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1- Introduction

Different studies of researchers on the behavior of structures against earthquakes and the more familiarity with the nature of earthquakes has led to the fact that in the last two decades, the discussion of the control of structures is of great interest to researchers. Reducing structural responses to enhance safety and providing conditions for serviceability and maintenance is one of the goals of the researchers. Control tools are very effective in achieving these goals. Structural control methods are classified into several categories including passive, active, semi-active, and hybrid systems. In this research, reducing the damages to the structures against earthquakes by semi-active control method using MR damper and using the results of Incremental incremental Analysis analysis of structures has been studied. Spencer, Dyke et al. studied the MR damper and presented a model for its dynamic behavior. They compared their proposed dynamic model with existing idealized models as well as laboratory samples and showed that proposed models are suitable for analyzing and designing structures equipped with MR damper [1-3]. Carlson, Spencer, Yang et al. studied the dampers in real dimensions of the structures. They examined dampers in real dimensions and they evaluated dynamic models of MR dampers [4-6]. Different algorithms are proposed for controlling structures against earthquake with MR damper. Jansen et al. formulated four different classical control algorithms including the Lyapunov controller, decentralized bang-bang controller, modulated homogeneous friction algorithm, and a clipped optimal controller for use with the MR damper algorithm. In their study, a 6-story frame that had been equipped with this damper was controlled for the El Centro earthquake and the benefits of each of these algorithms were discussed [7]. In addition to classical methods, intelligent methods are also used to control the structures with this damper. Some of these algorithms, such as optimal control, pole positioning, H2, $H\infty$, etc., are based on mathematical methods, and some others such as fuzzy and neural algorithms, are intelligent algorithms. Neural control algorithms and fuzzy control are intelligent control methods that, in contrast to classical control methods, have capabilities such as the ability to handle non-linear and complex problem, learnability, adaptability and robustness to errors and uncertainties. In recent years, extensive research has been done on the use of this tool to control the behavior of structures. Karamodin et al. used a genetic-fuzzy control method in order to control the benchmark structure. Relying on the capabilities of fuzzy controllers like, the ability to handle non-linear and complex problems, training capability, adaptability, and error-tolerance, they controlled the behavior of the benchmark structures. The comparison between their

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proposed controller and other controllers shows a significant decrease in the structure response in comparison with other controllers [8]. Baghban et al. controlled the behavior of a benchmark structure by means of a genetic-fuzzy controller. They compare their proposed controller performance with Linear Quadratic Gaussian (LQG) active controller and Self-Organizing Fuzzy Logic Controllers (SOFLC) with active actuators. They showed that the hybrid genetic-fuzzy controller has been quite effective in overall damage reduction for a wide range of motions, compared with the SOFLC and LQG controllers [9].

Research studies showed that most of the fuzzy systems used in controllers are of type-1. The performance of Type-1 fuzzy systems in the face of varying loading conditions or changes in the dynamic characteristics of the structure and, generally, the uncertainties governing the structure is weak. Zadeh introduced a type-2 fuzzy system in 1975 as a development of fuzzy systems [10]. Type-2 fuzzy systems can replace the type-1 fuzzy system by reducing the uncertainties of the type-1 fuzzy systems and covering their weaknesses. Research on type-2 fuzzy systems suggests that these systems can reduce uncertainty in the system, reduce membership functions and rules, and increase the fuzzy system interpretation.

By 1990, most research in fuzzy systems focused on type-1 fuzzy, and the number of papers on type-2 fuzzy sets was very small. Gradually, research on fuzzy type-2 systems was developed; as Mendel et al. developed the basic concepts of type-2 fuzzy sets [11-16]. Mendel and Liang proposed an effective computational method for calculating operators of type-2 fuzzy sets using the concept of upper and lower membership functions [14]. Mendel developed the advanced concepts of type-2 fuzzy sets in 2007 [17] .Schwartz et al. for the first time introduced an interval approach in fuzzy sets, called the Interval Type-2 Fuzzy Set. They showed the advantages of mathematical and computational simplification of these sets [18].

In recent years, type-2 fuzzy systems have been used effectively in many engineering issues [19-23]. However, despite the ability of this method to deal with issues of high uncertainty, research on the use of these systems in the field of control of structures has been very limited. Shariatmadar et al. studied the seismic control of structures using active tuned mass dampers with an interval type-2 fuzzy controller. In their research, they showed that, despite the fact that an active tuned mass damper with a type-1 fuzzy controller functions is more effective than a passive damper, however, it is not able to manage uncertainty in the fuzzy rule base which does not lead to the desired reduction in responses under different types of earthquake excitations. Also, an interval type-2 fuzzy controller significantly reduces the structural response compared with type-1 fuzzy controller [24].

In this research, an interval type-2 fuzzy system was used to reduce damage in a structure equipped with MR dampers. In this study, first a type 2 fuzzy system is studied and the designed. In the following, a comparison was made between the results of the proposed control system analysis and other control systems. The results showed that the type 2 fuzzy controller, with consideration and management of the uncertainty in the structure, has reduced the response of structure compared with the other controllers. IDA analyzes have been used to evaluate the controller's performance. Using these methods will allow us to examine the strengths and weaknesses of controllers based on a wider range of earthquakes with different maximum acceleration.

The analysis of structures using the IDA method is one of the new methods of non-linear analysis of structures. It involves subjecting a structural model to one (or more) ground motion record(s), each scaled to multiple levels of intensity, thus producing one (or more) curve(s) of response parameterized versus intensity level [25]. In the past, this method was generally used to study the behavior of structures. In this study, the attempts have been made to use the benefits and capabilities of non-linear incremental analyzes s
in the control of structures such as structural science.

2- Structural model

In this paper, the 9-story structure, designed by Ohtori et al., has been used as benchmark structure [26]. Specifications of the structure are presented by Ohtori et al, in detail.

The dimensions of this structure are 45.75 m by 45.73 m in plan and 37.19 m in elevation. The bays are 9.15 m on center, in both directions, with five bays each in the north-south (N-S) and east-west (E-W) directions. The building's lateral load-resisting system is comprised of steel perimeter moment-resisting frames (MRFs) with simple framing on the furthest south E-W frame. The interior bays of the structure contain simple framing with composite floors. The columns are 345 MPa steel. The columns of the MRF are wide-flange. The levels of the 9-story building are numbered with respect to the ground level. The ninth level is the roof. Typical floor-to-floor heights (for analysis purposes measured from center-of-beam to center-of-beam) are 3.96. The floor to-floor height of the basement level is 3.65 m and for the first floor is 5.49 m. The column bases are modeled as pinned and secured to the ground. The seismic mass of the structure is due to various components of the structure, including the steel framing, floor slabs, ceiling/flooring, mechanical/electrical, partitions, roofing and a penthouse located on the roof. The seismic mass of the ground level is $9.65\times x10^5$ kg, for the first level is $1.01\times x10^6$ kg, for the second through eighth levels is $9.89\times x10^5$ kg and for the ninth level is $1.07\times x10^6$ kg. The seismic mass of the above ground levels of the entire structure is $9\times x10^6$ kg. The first five natural frequencies of the 9-story benchmark evaluation model are: 0.443, 1.18, 2.05, 3.09, and 4.27 Hz. The details of this structure are shown in Figure .1.

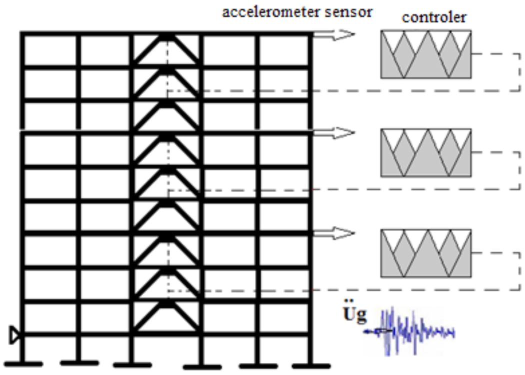


Figure .1. Position of dampers, accelerometer sensors and controllers in benchmark structures

3- Magneto-Rheological Dampers (MR-Dampers)

One of the tools used in the semi-active control method is the Magneto-Rheological (MR) Damper. In analytical and laboratory studies, this damper has been very effective in controlling structures and it has been taken into considerations by many researchers. In this paper, the MR damper is used to control the structural behavior. This damper is usually composed of a cylinder, in which a liquid containing magnetized field with polarized particles is formed. Liquid MR behaviorbehavior is controlled by the magnetic field. In the absence of a magnetic field, the liquid flows through the fluid. But when it is under the influence of the magnetic field, it becomes a semi-solid in a few milliseconds. In this study, the damper parameters are selected to have a maximum capacity of 1000 kN when Vmax is 10 v. In the case of ignorance of the dynamic effect of the tool, the force F_d on the structure is calculated from Eq. (1)uation 1 [8].

$$F_d=C_d\,|\dot{u}_b|^n\,\mathrm{sgn}(\dot{u}_b) \qquad (1)$$

In Eq.(1)uation 1, C_d is the damping coefficient. This coefficient is time dependent and varies from $C_{d,min}$ to $C_{d,max}$. $\dot{u}_b$ is the relative velocity of the damper and n is the coefficient between 0.2 and 2.

4- Magneto-Rheological Dampers (MR-Dampers)

According to The the fuzzy control theory, which was presented by Zadeh on the theory of fuzzy systems, has attracted the attention of many researchers in controlling structures [10]. The remarkable features of this method have been greatly appreciated. This method solves the need for precise mathematical modeling of the structure by applying a series of innovational rules. Other features of this control algorithm can be its robustness against the uncertainties and errors in the various parts of the control system such as data, loads, structure model, measurements, etc. Another important feature of this method is the ability to use it in non-linear systems. Due to the nature of non-linear behavior of structures, this method can be used to control structures. Using human knowledge and experience in controller design and the possibility of adapting the control system can be considered as the other advantages of this method than in comparison with other control methods. In this paper, the type-2 fuzzy systems, which are in fact a development of type-1 fuzzy systems, are applied. In the following, the equations and components of the type-2 fuzzy system are briefly described. The type-2 fuzzy set is represented by Eq. (2) and Eq. (3)uations 2 and 3.

$$\tilde{A}=\int_{x\in X}\frac{\mu_{\tilde{A}}(x)}{x}=\int_{x\in X}\frac{\int_{u\in J_x}\frac{f_x(u)}{(u)}}{x} \qquad (2)$$

$$\mu_{\tilde{A}}(x)=\int_{u\in J_x}\frac{f_x(u)}{(u)},J_x\subseteq[0,1] \qquad (3)$$

In the above equations, X, x, $\mu_{\tilde{A}}$ (x), $J_x\subseteq[0,1]$, u, and $f_x(u)\in[0,1]$ are respectively the reference set, the initial variable or the main variable, the secondary membership function, domain of secondary membership function, the fuzzy set in [0,1] ,and secondary grade.

When all degrees of secondary membership in the type-2 fuzzy set are equal to one, they are referred to as the "Interval Type-2 Fuzzy Set". Otherwise, it is called "General Type-2 Fuzzy Set". The mathematical and computational simplicity of this fuzzy set is one of the advantages of using it. The type-2 fuzzy set causes less complexity and reduces the volume of computations and thus reduces the cost of computations. Simplicity in the mathematical and computational operations of the interval type-2 fuzzy set has led researchers to use these sets. Equations for the interval type-2 fuzzy set are shown in Equation 4.(4).

$$\tilde{A}=\int_{x\in X}\frac{\mu_{\tilde{A}}(x)}{x}=\int_{x\in X}\frac{\int_{u\in J_x}\frac{1}{(u)}}{x},J_x\subseteq[0,1] \qquad (4)$$

The general view of the membership function of the type-2 fuzzy set is shown in Figure 2. Since type-2 fuzzy systems use membership functions that are fuzzy, therefore, the membership function of the type-2 fuzzy set is three-dimensional. Drawing the three-dimensional shape of the type-2 membership function is not simple; therefore, to have an image of it, pulling the two-dimensional domain of the function, which is called the "Footprint of Uncertainty (FOU)" of the type-2 membership function, is useful. The footprint of uncertainty is the key concept in the type-2 fuzzy system, which simulates the uncertainty in the shape and position of the type-1 fuzzy systems. In Figure 2, FOU is represented by two upper and lower membership functions.

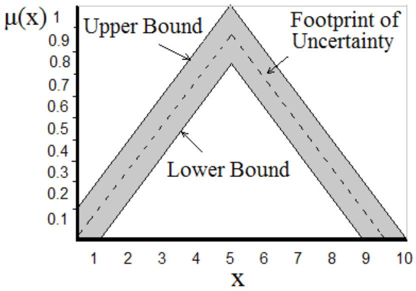


Figure 2. Triangular Type-2 Fuzzy Membership Function

In Figure 3, the overall structure of the fuzzy type-2 system is shown. The type 2 fuzzy system consists of four phases: Fuzzification, Rule base, Inference, and De-fuzzification. In fact, the fuzzy mapping system is between a non-fuzzy input and a non-fuzzy output. In the type-2 fuzzy system, the output process consists of two steps. The first step is to map a type-2 fuzzy set to a type-1 fuzzy set, which is referred to as this type of degradation or reduction of the order. The second stage, the stage of de-fuzzification, is a reduced-order reduction. Reduction methods in type-2 fuzzy systems are in fact the same as developed de-fuzzification methods in type-1 fuzzy systems. In the following, each section of the type-2 fuzzy system is briefly described [24].

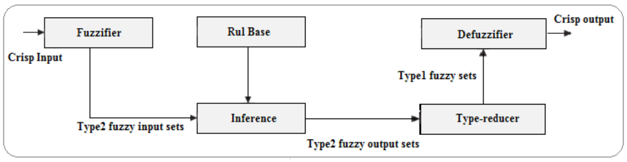


Figure 3. Interval type-2 fuzzy Structure

Fuzzification: Fuzzifier maps the measured inputs into fuzzy linguistic values with the help of fuzzy reasoning mechanism. In the present study, singleton fuzzifier was used which its output is a single point of a unity membership grade.

Rule base: In this part which is a set of IF-THEN rules, the knowledge of experts or tools such as genetic algorithms will be placed. Each law consists of two parts: Antecedence and Consequence. By entering any value such as x into the rule, the Inference mechanism determines the fuzzy output value. J_{th} rule in IT2FLS can be written as:

$$R_j : IF\ x_1\ is\ \tilde{F}_1^{\,j}\ \ and\ x_2\ is\ \tilde{F}_2^{\,j}\ \ and \ldots x_n\ is\ \tilde{F}_n^{\,j}\ \ THEN\ y\ is\ \tilde{G}^{\,j} \quad (5)$$

Where x_i (i=1,2,…,n) and y are IT2FLS input and output, respectively and also show the type-1 or type-2 antecedent and consequent sets, respectively.

Inference: In IT2FLS, the inference engine combines the rules and represents a mapping from input to output IT2FLS. Using input and antecedent operations, the firing set is obtained as:

$$F^j(x) = \prod_{i=1}^{n} \mu_{\tilde{F}_i j}(x_j) \tag{6}$$

Since the present study discusses IT2FLS, the firing input sets are defined based on the upper and lower membership functions as:

$$F^j(x) = (\underline{f}^j(x), \overline{f^j}(x)) \tag{7}$$

Where $(\underline{f}^{j})(x)$ and $(\overline{f}^{j})(x)$ are the J_{th} upper and lower membership functions, which are defined as follows:

$$\begin{aligned} \underline{f}^j(x) &= \underline{\mu}_{\tilde{F}_1 j} * \underline{\mu}_{\tilde{F}_2 j} * \ldots * \underline{\mu}_{\tilde{F}_n j} \\ \bar{f}^j(x) &= \bar{\mu}_{\tilde{F}_1 j} * \bar{\mu}_{\tilde{F}_2 j} * \ldots * \bar{\mu}_{\tilde{F}_n j} \end{aligned} \tag{8}$$

Type-reduction and de-fuzzification: Since the output of the inference engine is an IT2FS, a type reducer is needed before de-fuzzification to convert IT2FS into type-1 fuzzy set. Type reducer was first proposed by Karnik & Mendel [27], [16, 27]. They proposed five different methods of reducing ordering. Among these methods, center of sets (COS) has been extensively used due to easy calculation with the help of Karnik & Mendel's iterative algorithm [27]. The COS type reducer is an interval set which is determined by left-end point Y_l and right-end point Y_r and can be written as:

$$Y_{COS}[Y_l, Y_r] = \int_{\theta^L} \cdots \int_{\theta^M} \int_{f^L} \cdots \int_{f^M} \left(1 \Big/ \left(\left(\sum_{j=1}^{M} f^j . \theta^j\right) \Big/ \left(\sum_{j=1}^{M} f^j\right)\right)\right) \tag{9}$$

Where $f_j F^j\ (x)=((f^j)(x),(\overline{f}^{j})(x))$ and θ^j is the centroid of J_{th} consequent set. In general, there is no closed-form formula for calculating Y_l and Y_r. However, Karnik and Mendel have proposed two algorithms for calculating end-points which are known as KM iterative algorithms. In case of using singleton fuzzifier, product inference engine and COS type reducer, Y_l and Y_r can be written as [28] :

$$Y_l = \left(\left(\sum_{j=1}^{M} f^j{}_l . \theta^j{}_l\right) \Big/ \left(\sum_{j=1}^{M} f^j{}_l\right)\right) \tag{10}$$

$$Y_r = \left(\left(\sum_{j=1}^{M} f^j{}_r . \theta^j{}_r\right) \Big/ \left(\sum_{j=r}^{M} f^j{}_r\right)\right) \tag{11}$$

Where θ^j_l qand θ^j_r are related to left-end point and right-end point of Jth consequent set, respectively. Finally, the obtained set from type reducer can be de-fuzzified by using the average of Y_l and Y_r, as below:

$$y = \left[\frac{Y_l + Y_r}{2}\right] \tag{12}$$

5- Incremental Dynamic Analysis

Incremental Dynamic Analysis (IDA) is a parametric analysis method that is used to evaluate the performance of structures under the earthquake loads and has attracted the attention of the researchers. As shown in Figure 3, in this method, a structure is under the influence of various earthquakes of varying intensity, and the results of the analysis are presented as a curve. The curves are the response of each structure to earthquakes with different seismicity. In these graphs, indicators such as displacement, velocity, storey drift, acceleration of the structure, etc. can be considered as a response of the structure. By studying the obtained diagrams, a comprehensive assessment of the structure's behavior can be made, under the influence of far field and near field earthquakes with different intensities. Thus, knowing the behavior of the structure, it is possible to think about some ways in order to control its behavior. The specific information of IDA curves can justify using this method, despite its time-consuming process and its difficulty. Bertero [29], for the first time in his research, referred to the concept of incremental analysis. Then, many researchers have used this method in their research; some of these researchers are Luco, Nassar, Psycharis, Mehanny, Matteis et al. [30-34]. Vamvatsikos has also carried out extensive research on the IDA method, and has been evaluating the capacity and reliability of structures under various earthquakes. Their research is a complete reference to the method of production, summarization and interpretation of IDA graphs [35]. The FEMA 2000 report also uses this method as a method for determining the final failure capacity of the structure [36].

6- Design of Interval Type-2 Fuzzy Logic System

To design a fuzzy system, input, output, membership functions, and fuzzy rules must be determined. These parameters can be optimized by the knowledge of an expert or by conventional methods. In this research, the general structure of the system, including input and output variables, the number and type of membership functions and fuzzy rules, is determined based on the research of Karamodin et al. [8]. The input values correspond to the acceleration and displacement of the structure and the output values related to the amount of force applied to the structure. Figure 4 shows the general structure of the proposed controller algorithm. As shown in Table 1, for each variable, five values are used.

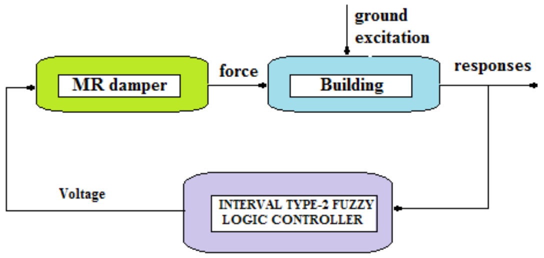


Figure 4. General structure of the proposed controller algorithm

Table 1. Fuzzy variables

Membership function	Input	NL	Negative Large
		NS	Negative Small
		ZE	Zero
		PS	Positive Small
		PL	Positive Large
	output	ZE	Zero
		S	Small
		M	Medium
		L	Large
		VL	Very Large

The values of the input variables are: large negative (NL), small negative (NS), zero (ZE), small positive (PS) and large positive (PL). Similarly, output variable values include zero (ZE), small (S), medium (M), large (L) and very large (VL).

For each input value, two upper and lower triangular membership functions are assigned in [-10, 10]. For the output values, which is the same input voltage as the MR damper, five interval membership functions are used in the [0, 10]. Each of the input variables has five fuzzy values, which divide the input space into twenty five regions. Therefore, the fuzzy rule base will consist of twenty five laws. These rules are shown in Table 2. Specifications of IT2FLC used in this study have been given in Table 3.

Table 2. Inference rules for IT2FLC

		Displacement				
		NL	NS	ZE	PS	PL
Acceleration	NL	M	VL	VL	NUL	NUL
	NS	S	VL	L	VL	L
	ZE	M	NUL	M	VL	ZE
	PS	NUL	NUL	VL	NUL	ZE
	PL	NUL	VL	NUL	VL	L

Table 3. Specifications of IT2FLC

Maximum	Aggregation
Minimum	Implication
Sugeno	Fuzzy Inference
KM	De-fuzzification and Type reducer

7- -Numerical study

In order to evaluate the effectiveness of the proposed control system in managing the uncertainties governing the structure, the benchmark structure equipped with the MR damper was analyzed by the IDA method. The specification of the benchmark structure is presented in Section 2. In each floor, a number of MR dampers with a capacity of 1000 kN are installed in order to control the structure. The number of these dampers in the first to third floor is 3, 2 and 2, respectively, and the number of dampers in the 4th to 9th floor is 1. Accelerometer sensors are installed to measure the response of the structure at the level of the roof of the third, sixth and ninth floors. A controller is considered for dampers of the first to third floor, the 4th to the 6th floor and the 7th to the 9th floor. The details of dampers and controllers and their position are shown in Figure 1.

The input of each controller is acceleration and the relative displacement of the floors is between the two sensors. The design of control parameters of the first three floors is based on minimizing the overall damage to these three floors. This damage is obtained from the weighted average of the damages of the respective floors. The weight of this average is the energy absorbed in each floor. For the second three floors and the third three floors, the same controller of the first three floors has been used.

In accordance with the recommendations of the International Association for Structural Control (IASC) for evaluating the proposed controller, four accelograms have been used in Incremental Dynamic Analysis on a structure equipped with a control system. These ground accelerations are El-Centro and Hachinohe as far-field and Northridge and Kobe as near-field earthquakes. In order to match the selected accelograms, the intensity of two far-field earthquakes has increased 1.5 times. The features and the coefficients of the selected accelograms scale are given in Table 4. In the IDA analysis, the scaled accelerations of Table 4 are assumed to be base accelerations and have been scaled up to more than 1 value while performing dynamic analyzes.

The results of structural analysis in the proposed controller, with the uncontrolled structure response, controlled structures equipped with Type-1 fuzzy controller, as well as controlled structures under the Type-1 genetic-fuzzy controller, have been investigated. After non-linear analysis of the structures, the damages of structures are calculated and compared. The magnitude of damage to each structure in controlled and uncontrolled conditions for various earthquakes is shown in Table 5. The Park and Ang Damage Index has been used to measure damage.

Table 4. Specifications of IT2FLC

Record No.	Earthquake name	Year	Magnitude (Richter scale)	PGA	Scale Factor
1	El Centro	1940	7.2	0.3417g	1.5
2	Hachinohe	1989	7.5	0.2250g	1.5
3	Northridge	1968	6.7	0.8267g	1
4	Kobe	1995	7.3	0.8178g	1

Table 5. Damage Index of structure for different control systems

	Hachinohe		
	FLC-type1	GA-FLC	FLC-type2
Controlled	0.1571	0.1326	0.1472
Uncontrolled	0.2328	0.2328	0.2328
Percent	32.52%	43.04%	36.77%

	El Centro		
	FLC-type1	GA-FLC	FLC-type2
Controlled	0.1873	0.1538	0.169
Uncontrolled	0.256	0.256	0.256
Percent	26.84%	39.92%	33.98%

	Kobe		
	FLC-type1	GA-FLC	FLC-type2
Controlled	0.2849	0.2939	0.2642
Uncontrolled	0.359	0.359	0.359
Percent	20.64%	18.13%	26.41%

	Northridge		
	FLC-type1	GA-FLC	FLC-type2
Controlled	0.3362	0.2969	0.3285
Uncontrolled	0.35	0.35	0.35
Percent	3.94%	6.60%	6.14%

As shown in Table 5, IT2FLC reduces the Damage Index of structure about 3% and 8% more that of the damage of structure controlled by FLC Type-1; therefore, it has a better performance than FLC Type-1. Accurately, as the results of Table 5 shows, it can be seen that the proposed controller could well reduce the damage caused by both far-field and near-field ground accelerations, while FLC Type-1 shows poorer performance in the face of the near field earthquakes in comparison with far-field earthquakes. As the results of Table 5 indicates, it can be seen that the proposed controller has obtained acceptable results in comparison with the GA-FLC. GA-FLC by using the genetic algorithm, optimizing the parameters related to membership functions, the number and type of fuzzy rules, to a large extent, can reduce the FLC Type-1 uncertainties; and the results showed that the results of GA-FLC and IT2FLC are related to each other. However, the uncertainties caused by other factors will still affect the structure controlled by FLC Type-1. For example, one of the uncertainties that the optimized controller have, is related to how the controller is trained. As can be seen in Table 5, GA-FLC (that is trained in the training process under the El-Centro earthquake record) has not shown a proper performance in the face of the Kobe earthquake. However, IT2FLC is able to reduce the damage index of the structure in the Kobe earthquake.

The results of IDA analysis of the building are compared in different cases including: uncontrolled, controlled with FLC-type1, Ga-FLC-type1 and IT2FLC control systems and different earthquake records. In Figure 5 the IDA analysis graphs show the behavior of the structure in a wide range of earthquakes with different maximum acceleration. By comparing the results of the analysis on the structures in Figure 5 and Figure 6, it can be seen that IT2FLC at different loading levels also has reduced the damage of structure more than FLC Type-1. This means that IT2FLC has been able to better control the behavior of the structure by managing uncertainties, at different levels of risk, and in various earthquakes, however, as the intensity of the earthquake increases, the efficiency of IT2FLC is reduced.

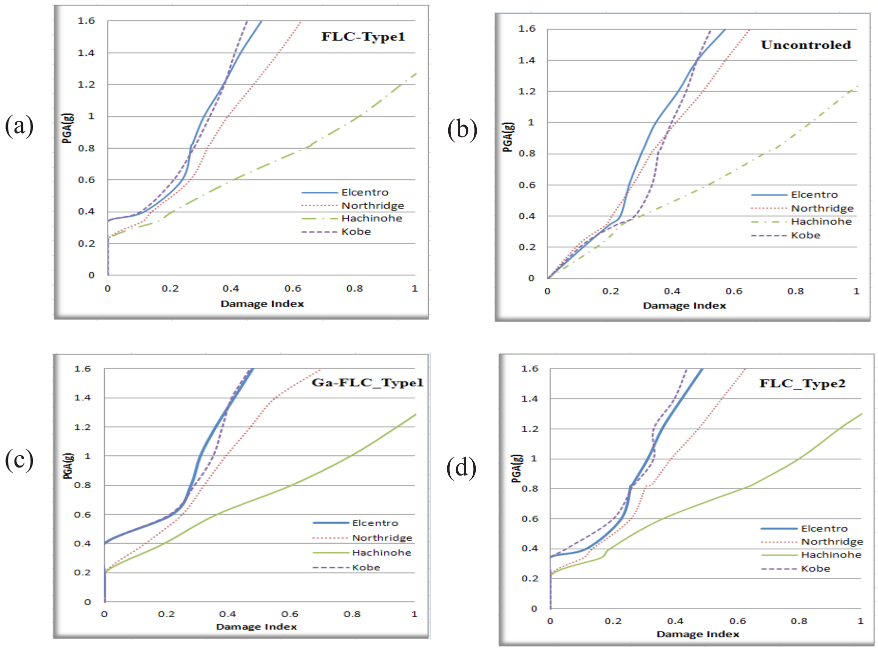


Figure 5. The results of IDA analysis of the building for different control systems

The results of the analysis on the structure with the proposed controller and other structures, it can be seen in Figure 6 that, the Ga-FLC-type1 controller has reduced the damage of structure more than proposed controller when the maximum acceleration is lower than 0.6 g. But, as the intensity of the earthquake increases, the efficiency of Ga-FLC-type1 is reduced because, training of controller in the Ga-FLC-type1 controller is effective only at the particular range of acceleration of earthquakes.

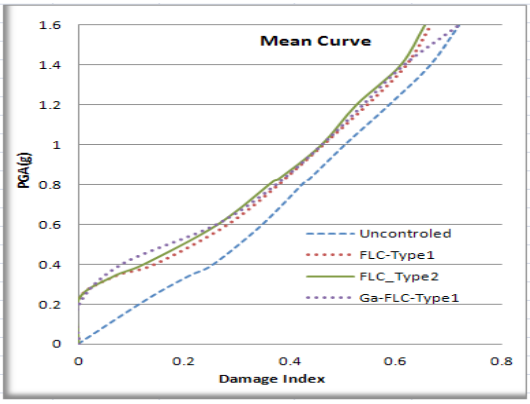
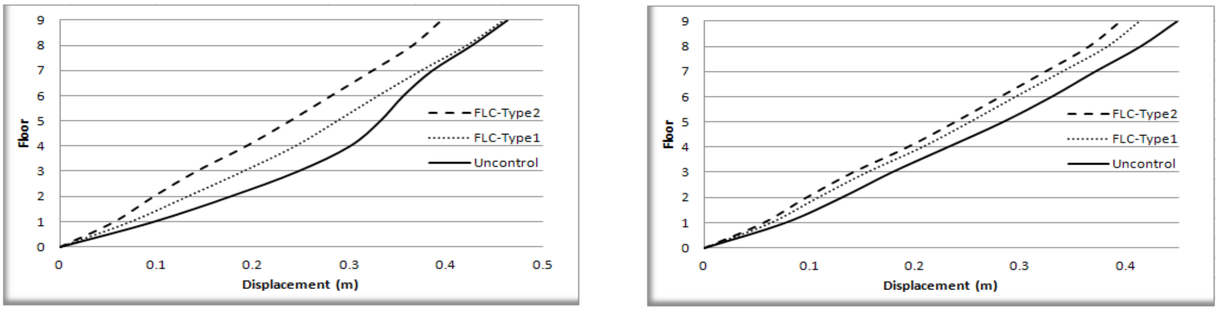


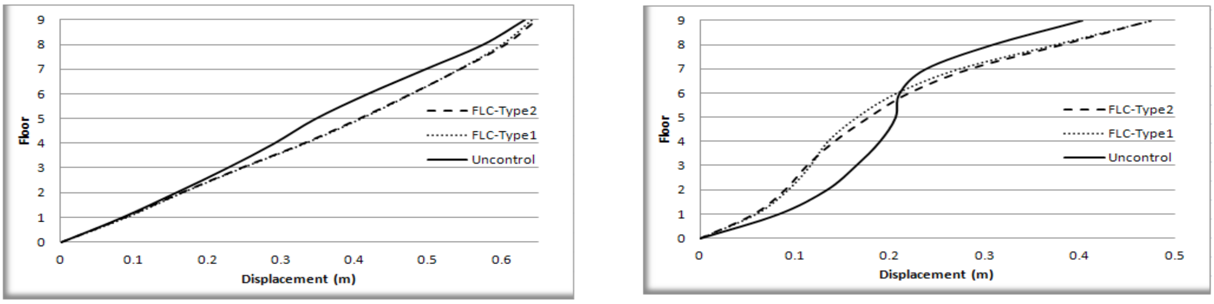
Figure 6. Comparison of the mean of structural responses for different control systems

Graphs in Figure 7 show the displacement response in different floors of uncontrolled structures and structures with fuzzy controllers. The comparison between the graphs shows that IT2FLC, by reducing the uncertainties of the control system, also improves the performance of the fuzzy controllers in reducing the structural displacement response, so that IT2FLC reduces the uncontrolled peak displacement response of stories about 10% to 30% more than the displacement response of the structure with FLC Type-1. While, the graphs indicates that none of IT2FLC and FLC Type-1 couldn’t reduce the peak displacement response of stories rather than uncontrolled structure, under the influence of the acceleration of Kobe and Northridge (as near-field). It is because of this fact that, sometimes, for multi-storey buildings, a stronger ground motion may lead to earlier yielding of one floor which in turn acts as a fuse to relieve another (usually higher) floor, Especially in uncontrolled structure. Therefore, peak displacement response of stories of uncontrolled structure maybe less than structure with IT2FLC and FLC Type-1.

In the following, the performance of IT2FLC is investigated on displacement and acceleration time history responses of structure. Graphs in Figure 8 represent comparison of displacement time history responses of third-floor of structure for different control systems compared to uncontrolled response when subjected to the earthquakes. It is observed carefully in the graphs of Figure 8 that IT2FLC has been able to optimally reduce the displacement time history responses in comparison with FLC Type-1, when the structure subjected to the El-Centro earthquake. Also, the proposed controller reduces acceptably response of the structural displacement history, under the influence of the acceleration of the Kobe (as near-field) earthquake, relative to FLC Type-1.



(a) Elcentro (b) Hachinohe



(c) Northridge (d) Kobe

Figure 7. Comparison of maximum displacement of stories in case of using IT2FLC and FLC Type-1

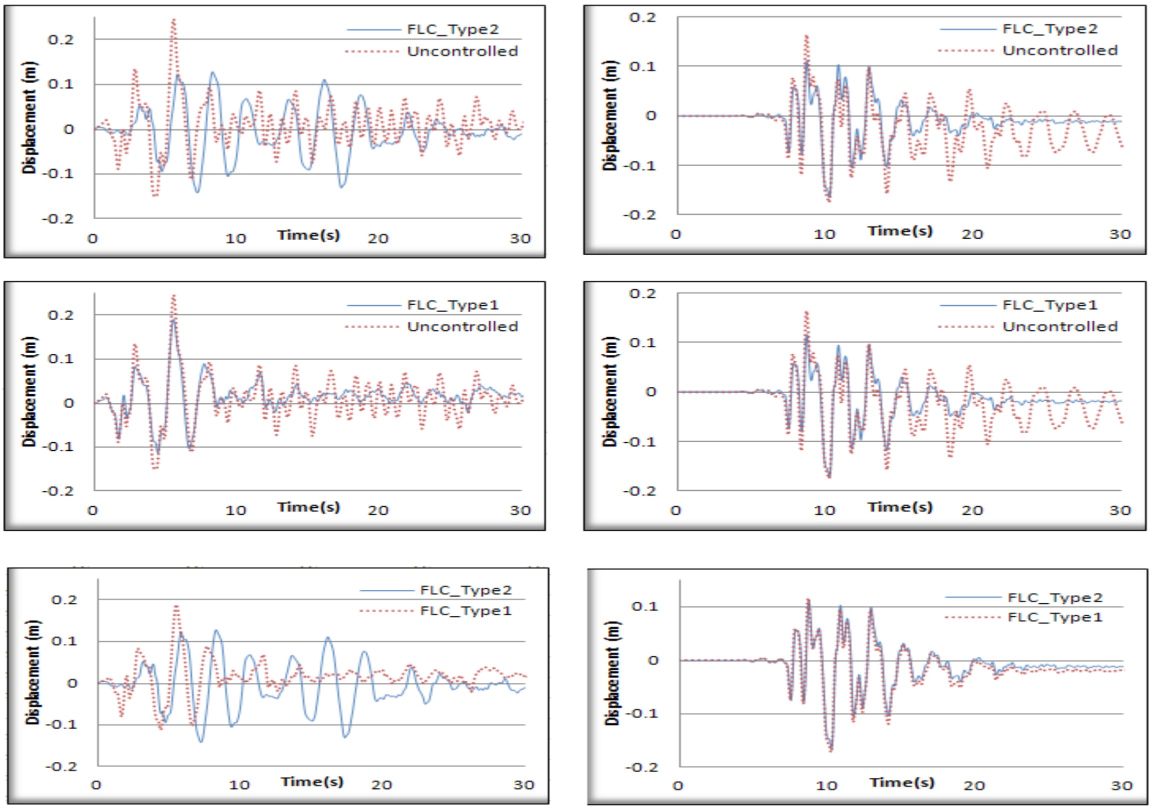


Figure 8. Comparison of displacement time history responses of the third-storey for different control systems

Figure 9 show the acceleration time history responses of structure subjected to two near-field and near-field earthquakes. Structures are analyzed in uncontrolled conditions, equipped with FLC Type-1 and IT2FLC. As can be seen from the Figure 9, although IT2FLC has reduced acceptably the acceleration response of the structure, this decrease in response did not make a significant difference compared to FLC Type-1 in both the near-field and far-field earthquake. In fact, the performance of IT2FLC is slightly better than the performance of the FLC Type-1. It is observed carefully in the results that the proposed controller has been more effective in reducing the response of the structure that subjected to the far-field earthquake in comparison with the near-field earthquake.

By evaluating the graphs of Figures 8 and 9, it can be concluded that IT2FLC, by decreasing the uncertainties and covering the faults of FLC Type-1, has been able to reduce the response of the acceleration and displacement of the structure more, and improve the performance of fuzzy controllers.

8- Conclusions

The results has shown that the performance of type-1 fuzzy systems is weak in the face of structural uncertainties, such as uncertainties arising from different loading conditions, changes in the structural characteristics of the building, or the exact determination of the structure of the fuzzy systems. IT2FLC have been developed in order to covering the weaknesses of FLC Type-1 and reducing the uncertainties surrounding it. In this research, by designing a IT2FLC, the ability of these systems to reduce the uncertainties governing the structures, was studied.

To evaluate the performance of this controller, the 9-storey building, equipped with the MR damper, was used as benchmark. Comparing the performance of the proposed controller with other controllers was investigated by performing the dynamic analysis of IDA on structures controlled with IT2FLC and other controllers. By analyzing the results, the following results can be concluded:

1. The results of the study indicate that using IT2FLC will reduce the damage index in the structure by 3 to 7 percent compared to the controlled structure equipped with FLC Type-1. Therefore, its performance will be more appropriate compared to FLC Type-1.
2. The results of IDA demonstrate that, at different levels of load, IT2FLC also reduced the damage of the structure more effectively than other controllers. In fact, IT2FLC has been able to better control the damage of the structure in various earthquakes at different accelerations, while with the increase in the intensity of the earthquake, the efficiency of FLC Type-1 is reduced.
3. The comparison between diagrams of responses of the structures in different floors is shown the proposed controller has been able to reduce the structure displacement responses by 10 to 30 percent compared to structures with FLC Type-1, by reducing the uncertainties surrounding the control system and improving the performance of FLC Type-1.
4. The results show that the performance of IT2FLC and GA-FLC are very close in reducing damage. The GA-FLC has been able to reduce FLC Type-1 uncertainties,

by optimizing the membership functions, the number and type of fuzzy rules, and obtains similar results with IT2FLC. Since, unlike GA-FLC, the structure of IT2FLC is not optimized, accordingly, the similar results of these two controllers are emphasized on the ability of the proposed controller to manage the uncertainties governing the structure.

The results show that IT2FLC has been more effective in reducing the time history responses of displacement and acceleration of the structure subjected to far field and near field earthquakes compared to FLC Type-1 by decreasing the uncertainties of the control system.

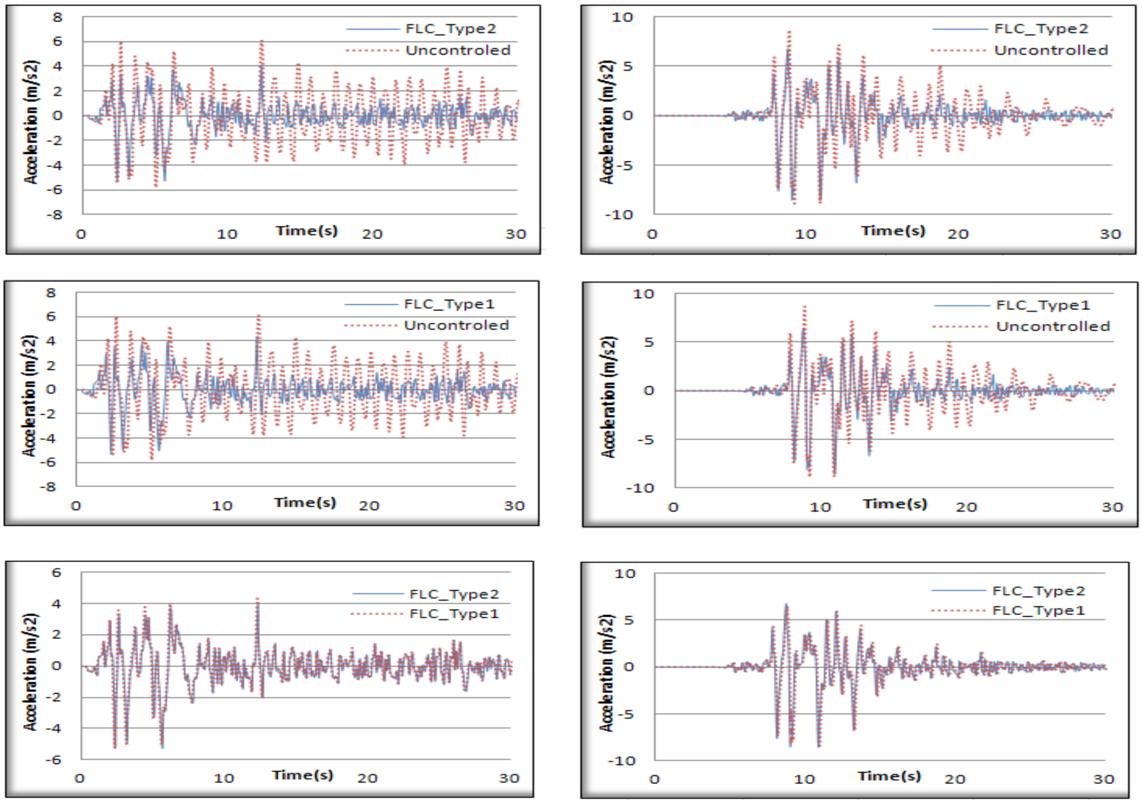


Figure 9. Comparison of acceleration time history responses of the top storey for different control systems

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