Application of Endurance Time Method in Seismic Assessment of Steel Frames with Friction Damper Devices

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ABSTRACT

This work presents a study on the seismic assessment of steel frames with Friction Damper Devices (FDDs). The devices were used to dissipate seismic input energy and protect buildings from structural and nonstructural damage during moderate and severe earthquakes. In the Endurance Time (ET) method, structures are subjected to a specially designed intensifying ground acceleration function and their performance is judged based on their response at various excitation levels. In this paper, steel moment frames equipped with FDDs is investigated under Nonlinear Time History (NTH) and ET analyses. According to the NTH and ET results, it is concluded that by adding FDDs, the reduction percentage of roof displacement of frames will be decreased by increasing the number of stories. ET results show that FDDs have a vital role in energy dissipation because their hysteresis loop is rectangular.

Keywords:
Friction damper device;
Endurance time method;
Roof displacement;
Energy dissipation;
Hysteresis cycle

1. Introduction

Passive control devices have been successfully employed to decrease the response of structures subjected to earthquakes or severe wind gusts. Friction devices have been employed as a component of these dampers since they are easy to install and maintain. They also present high energy dissipation potential at a low cost [1]. A new friction damper device (FDD) was employed for the first time by Mualla [2]. Full-scale tests for three-story structures equipped with FDDs on vibration table was carried out in Taiwan [3]. Komachi et al. [4] used FDD to retrofit Ressalat jacket platform. In Endurance Time (ET) method, structures are subjected to gradually intensifying acceleration functions and their performance is evaluated based on the maximum time duration in which they can meet the predefined endurance criteria [5]. Three steel moment frames with 3, 7 and 12 stories equipped by FDDs are investigated under Nonlinear Time History (NTH) and ET analyses in present study. The influence of FDDs on seismic performance of frames is studied by comparing the parameters such as base shear, roof displacement and energy dissipation. The energy dissipated by FDD and its behavior are investigated. In this paper, the comparison is made between the results of NTH and ET analyses to validation of ET method.

2. Friction Damper Device (FDD)

The FDD consists of three steel plates, and between these plates, there are two circular friction pad discs in order to ensure stable friction force and decrease noise of the movement. The FDD main parts consist of a central plate and two side plates [6], as shown in Figure (1).

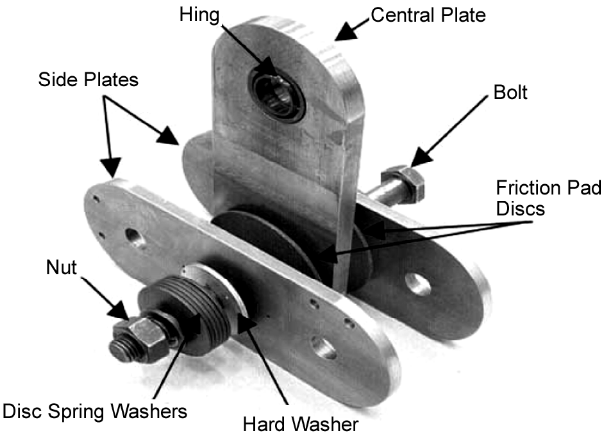

Figure 1. FDD [7].

Figure (2) explains the mechanism of the damper device under an excitation force in different directions. As it is shown, the damper is very simple in its components, which make it easy to assemble and very flexible in arrangement. It can be arranged in many configurations of bracing system as well as in many types of bracing system. The simplicity of the damper design allows constructing a device with multi units, based on the requirements of the designed friction force and the space limitations. Besides, the time required to install the device within a building is relatively short [2].

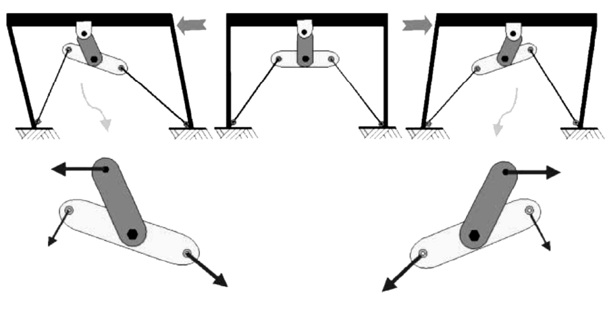

Figure 2. Mechanism of FDD [7].

3. Verification of Model

The response of basic frame obtained by Mualla is shown in Figure (3a) and the response obtained in the present study is given in Figure (3b). Therefore, it can be said that the results are well-matched for Mualla model and that of the present study.

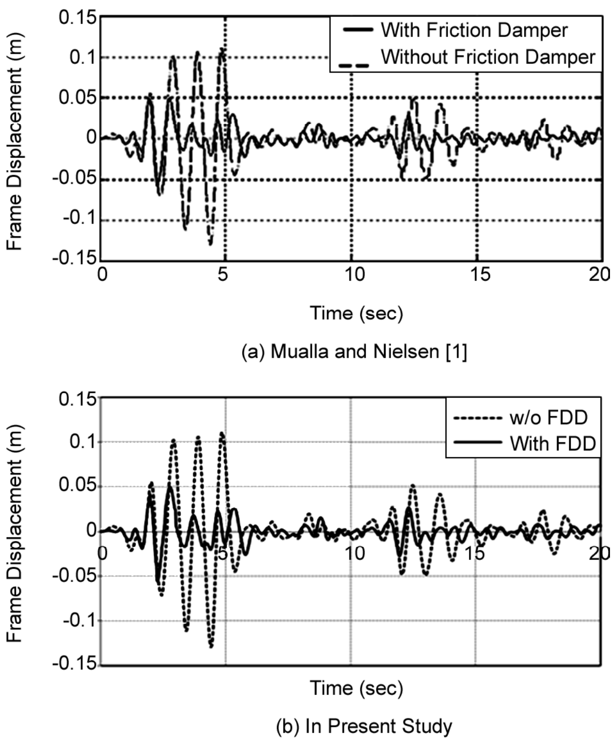

Figure 3. Basic frame response with and without FDD, El Centro earthquake motion.

4. Design of Steel Frames

Steel moment frames with 3, 7 and 12 stories are considered in this research. All frames have three bays. These frames are designed based on Iranian National Building Code (INBC) Section 10 [7], which is close to AISC ASD [8] design code. The studied soil is type C of Standard ASCE/SEI 41-06 [9]. The length of each bay and height of each story in all frames are 5 m and 3.2 m, respectively. FDDs are installed in middle bay and total stories of frames. Prefixes "FR" and "DFR" represent frames without and with FDDs, respectively. For example, "FR12st" represents moment frame with 12 stories. The specifications of the frames of the present study and the period of free vibration of frames with and without FDDs are presented in Tables (1) and (2), respectively.

Table 1. Specifications of the frames.

Frames	Number of Stories	Weight (KN)	Design Base Shear (KN)
FR3st	3	1458.06	182.27
FR7st	7	3491.58	312.84
FR12st	12	6065.42	414.86

Table 2. Period of free vibration of frames with and without FDDs.

Frames	Period of Free Vibration (s)
FR3st	0.945
DFR3st	0.477
FR7st	1.422
RM7st	0.953
FR12st	2.018
DFR12st	1.539

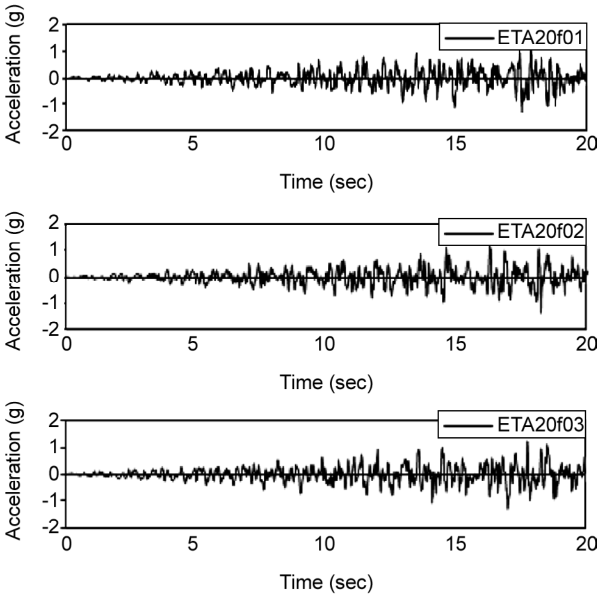

Figure 4. Acceleration functions of ETA20f set used in the present study.

5. The Concept of the Endurance Time Method

In the Endurance Time (ET) method, structures are subjected to a calibrated intensifying accelerograms, and their performance is evaluated based on their response at various equivalent intensity levels [10]. ET acceleration function intensity will be increased along with time [11]. If the main specifications of the ground motions assembled by ET acceleration function, the real response of structures will be evaluated properly according to Performance Based Engineering (PBE) [12]. The validation of ET method by a comparison between the results of this method and nonlinear time-history analysis is one of the goals in the present study. Therefore, the three acceleration function used in the present study (ETA20f01-3) presented in Figure (4), are created in this way; as their response spectra remain proportional to that of the average of seven real records spectra [13]. These records are selected from FEMA440 [14] for soil of type C [11, 15, 16]. The average response spectrum is smoothed and employed for production of the ETA20f set. The characteristics of this set of records are presented in Table (3). The response spectrum of any window of the ETA20f set of acceleration functions from $t_0 = 0$ to $t_1 = t$, in which t resembles the average response spectrum of the seven ground motions with a scale factor that is proportional with time (t) [12]. This scale factor is equal to 1.0 for $t_{Target} = 10$ s in the present study. The comparison between the average of acceleration response spectra of ETA20f set in $t = 10$ s and the average of response spectra of seven scaled records is displayed in Figure (5). It should be noted that in $t = 10$ s, response spectra of ET are remained consistent with the spectra average of seven scaled records [17].

Table 3. Seven records used in this study [16]

Date	Earthquake Name	Magnitude (Ms)	Station Number	Component (deg)	PGA (g)	Abbreviation
06/28/92	Landers	7.5	12 149	0	0.171	LADSP000
10/17/89	Loma Prieta	7.1	58 065	0	0.512	LPSTG000
10/17/89	Loma Prieta	7.1	47 006	67	0.357	LPGIL067
10/17/89	Loma Prieta	7.1	58 135	360	0.450	LPLOB000
10/17/89	Loma Prieta	7.1	1 652	270	0.244	LPAND270
04/24/84	Morgan Hill	6.1	57 383	90	0.292	MHG06090
01/17/94	Northridge	6.8	24 278	360	0.514	NRORR360

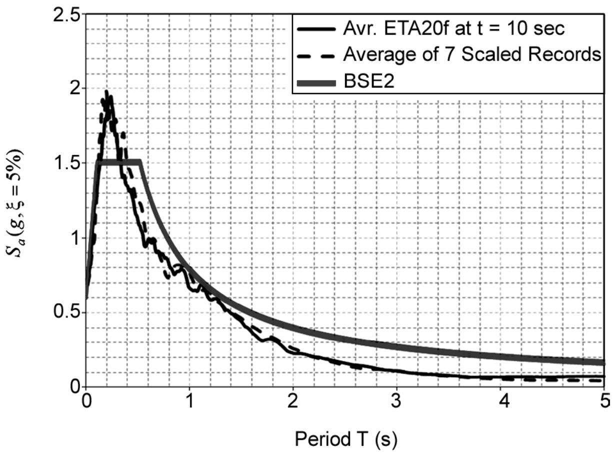

Figure 5. Comparison between the average of acceleration response spectra of ETA20f set in t = 10 s and the average of response spectra of seven scaled records.

The seven records are scaled in such a manner that the average of the ordinates of the 5% damped linear response spectra does not fall under the design spectrum for the period range $0.2T_i$ - $1.5T_i$, where T_i is the fundamental period of vibration of each frame. The records are scaled individually rather than scaling them as pairs, because the studied structures are two-dimensional [11, 17]. The scale factors of frames with and without FDDs for nonlinear time-history analysis are shown in Table (4).

To obtain the equivalent time in ET analysis, the average response spectrum of the scale accelerograms is calculated. The value of this average response spectrum is found at T_i of each frame ($S_{a,Ave}$). Furthermore, the value of the target response spectrum used for the generation of ET acceleration functions at T_i is calculated ($S_{a,ET}$). Finally, the equivalent time is obtained by Eq. (1) [11].

The equivalent times of different frames vary between 10.9 and 14.2 s.

$$t_{eq} = \frac{S_{a,Ave}}{S_{a,ET}} \times 10 \qquad (1)$$

6. NTH and ET Analyses Results

The frames are subjected to NTH and ET analyses. A comparison is made between base shear of FR12st and DFR12st frames under LPGIL06 record, Figure (6). According to the base shear history of mentioned frames, it is observed that by adding FDDs to FR12st frame, the maximum base shear will be decreased by 38.42%. This amount is 23.66% for ETA20f03, Figure (7).

A comparison of the roof displacement is made between FR7st and DFR7st frames under LPSTG000 record, Figure (8). According to the roof

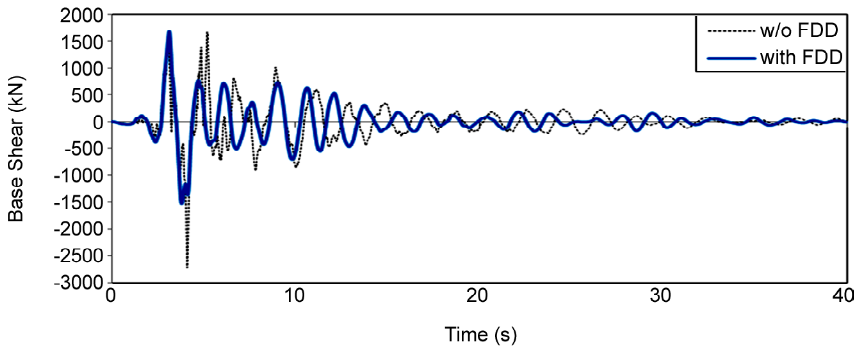

Figure 6. Comparison between base shear of FR12st and DFR12st frames under LPGIL06.

Table 4. Scale factors of seven ground motions for frames with (DFR) and without FDDs (FR).

Frames	LADSP 000	LPAND 270	MHG 6090	LPGIL 067	LPLOB 000	LPSTG 000	NRORR 360
FR3st	3.98	2.98	1.75	2.62	2.73	1.85	1.09
DFR3st	3.87	2.49	2.22	2.14	2.11	2.02	1.32
FR7st	4.20	3.13	2.05	2.83	3.74	1.66	1.13
DFR7st	3.98	2.99	1.75	2.62	2.74	1.84	1.09
FR12st	4.78	3.65	2.78	3.47	5.46	1.71	1.31
DFR12st	4.33	3.27	2.20	2.94	4.08	1.65	1.15

displacement history of mentioned frames, it is determined that by adding FDDs to FR7st frame, the maximum roof displacement will be decreased by 34.69%. This amount is 59.66% for ETA20f02, Figure (9).

The diagram of energy dissipated by FDD in DFR3st frame under LPLOB000 record is presented in Figure (10). According to the diagram by adding FDDs to FR3st frame, 51.55% of input energy will be dissipated. This amount is 53.95% for ETA20f01, Figure (11).

The hysteresis cycle for the FDD in second story of DFR7st frame under record ETA20f03 is presented in Figure (12). As it is obvious, there is an appropriate correspondence between the hysteresis cycle and the real behavior of FDD. Therefore, it can be said that the rectangular hysteretic behavior of FDD represents that its performance in energy dissipation is suitable. Time - rotation diagram for the FDD in second story of DFR7st frame under ETA20f03 is presented in Figure (13), in which the maximum absolute of rotation at 18.78 s equals to 17.37%. After calculating the results mean of NTH and ET analyses, comparisons of parameters such as base shear, roof displacement and energy are made among frames with and without FDDs in

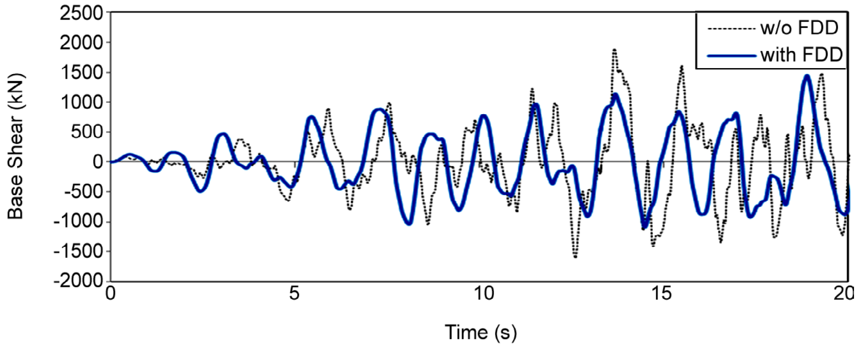

Figure 7. Comparison between base shear of FR12st and DFR12st frames under ETA20f03.

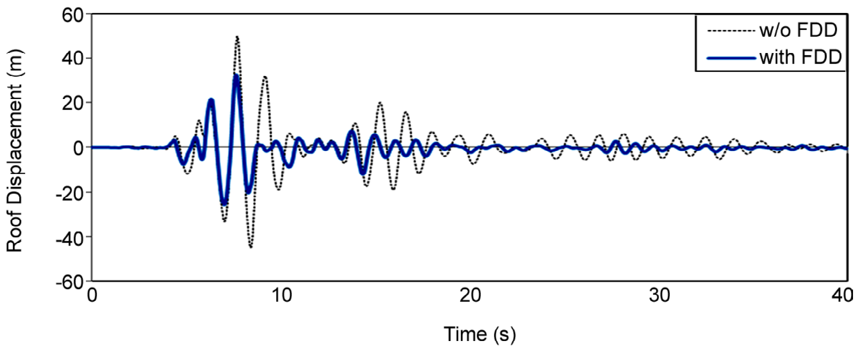

Figure 8. Comparison between roof displacement of FR7st and DFR7st frames under LPSTG000.

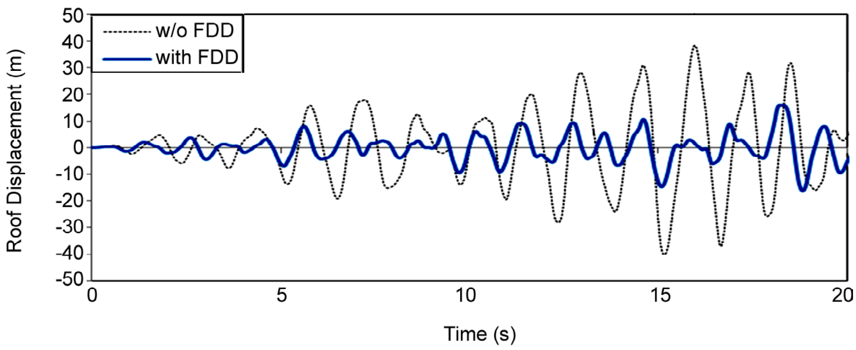

Figure 9. Comparison between roof displacement of FR7st and DFR7st frames under ETA20f02.

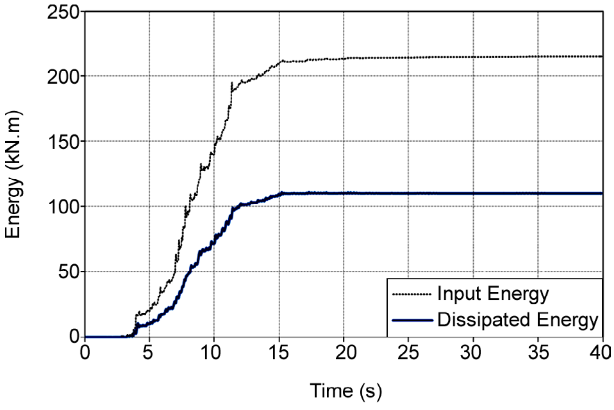

Figure 10. Energy dissipated by FDD in DFR3st frame under LPLOB000.

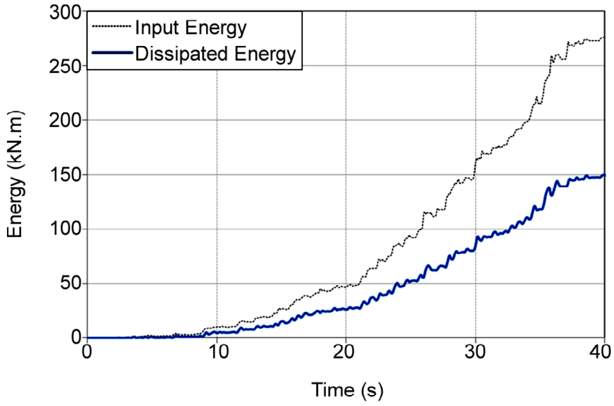

Figure 11. Energy dissipated by FDD in DFR3st frame under ETA20f01.

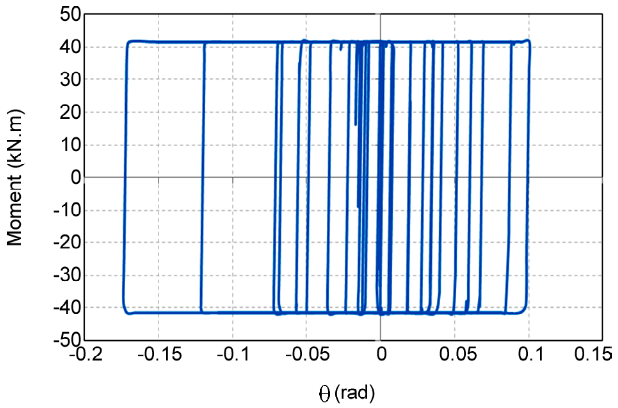

Figure 12. Hysteresis cycle for the FDD in second story of DFR7st frame under ETA20f03.

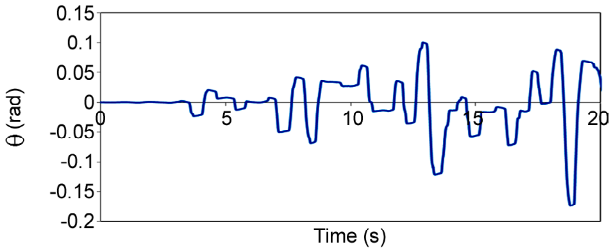

Figure 13. Time rotation diagram for the FDD in second story of DFR7st frame under ETA20f03.

Figures (14), (15) and (16), respectively. Reduction percentage of parameters like base shear and roof displacement of frames by adding FDDs and energy dissipated by FDDs are determined. These items are shown in Table (5).

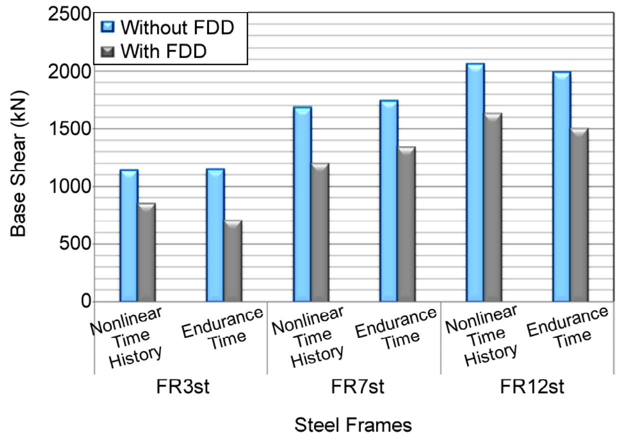

Figure 14. Comparison of base shear among frames with and without FDDs, NTH and ET.

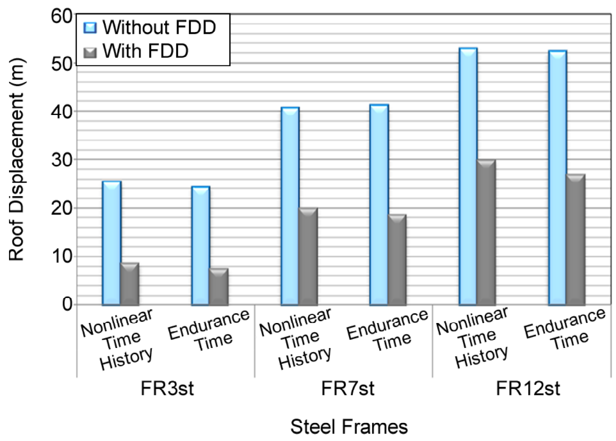

Figure 15. Comparison of roof displacement among frames with and without FDDs, NTH and ET.

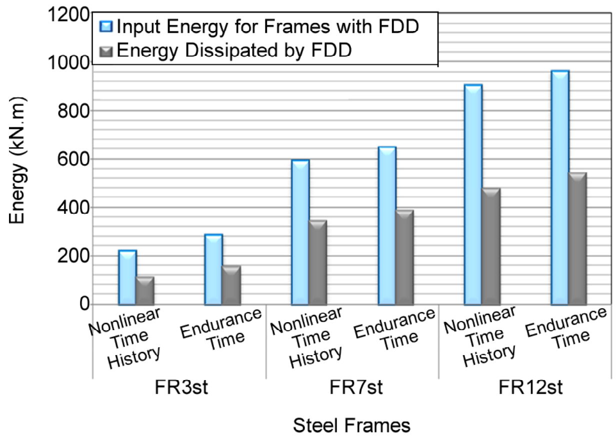

Figure 16. Comparison of energy for frames with FDDs, NTH and ET.

Table 5. Percentage of parameters by adding FDDs to frames.

Frame	Analysis	Reduction of Base Shear (%)	Reduction of Roof Displacement (%)	Dissipated Energy (%)
FR3st	NTH	25.94	66.29	50.93
	ET	39.04	69.72	54.04
FR7st	NTH	28.82	50.96	57.93
	ET	23.28	55.13	59.72
FR12st	NTH	20.87	43.58	53.02
	ET	24.71	48.87	56.30

By comparing the Figures (14), (15) and (16), it is concluded that RFDs improve the performance of steel frames under ground motions and ET acceleration functions. There is almost negligible difference between the NTH and ET results mean. It can be said that the ET method has a valid result. According to Table (5), it is concluded that FDDs have a good performance in reducing the roof displacement and base shear in steel moment frames. FDDs have a considerable role in energy dissipation. The NTH and ET analyses results show that by increasing the number of stories and increasing the free vibration period of structure, the reduction percentage of roof displacement will be decreased by installing the FDDs in the structure. The energy dissipated by FDDs in DFR7st frame is more than other frames.

7. Conclusions

Endurance time (ET) method is a new dynamic analysis procedure that aims at estimating seismic performance of structures by subjecting them to predesigned intensifying acceleration functions. These functions are used as input functions for nonlinear time-history analysis of structures, and performance of structures is judged based on the maximum time duration that they can satisfy the specified performance objectives. In this paper, application of the ET method in seismic analysis of steel moment frames with FDDs has been investigated. According to the NTH and ET results, it is obvious that, by increasing the number of stories and free vibration period of structure, reduction percentage of roof displacement will be decreased by adding FDDs to the structure. The NTH and ET analyses results show that the energy dissipated by FDDs in seven stories frame is more than other frames. It can be said that FDDs have a considerable role in reducing the roof displacement and base shear of frames. According to the present study, FDDs have a vital role in energy dissipation because their hysteresis loop is rectangular.

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