International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:10, No:6, 2016

Effects of Damper Locations and Base Isolators on Seismic Response of a Building Frame

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***Abstract*—**Structural vibration means repetitive motion that causes fatigue and reduction of the performance of a structure. An earthquake may release high amount of energy that can have adverse effect on all components of a structure. Therefore, decreasing of vibration or maintaining performance of structures such as bridges, dams, roads and buildings is important for life safety and reducing economic loss. When earthquake or any vibration happens, investigation on parts of a structure which sustain the seismic loads is mandatory to provide a safe condition for the occupants. One of the solutions for reducing the earthquake vibration in a structure is using of vibration control devices such as dampers and base isolators. The objective of this study is to investigate the optimal positions of friction dampers and base isolators for better seismic response of 2D frame. For this purpose, a two bay and six story frame with different distribution formats was modeled and some of their responses to earthquake such as inter-story drift, max joint displacement, max axial force and max bending moment were determined and compared using non-linear dynamic analysis.

***Keywords*—**Fast nonlinear analysis, friction damper, base isolator, seismic vibration control, seismic response.

I. Introduction

THERE are many ways improve the performance of a structure against lateral forces from earthquakes. Existing methods for providing earthquake resistance to a structure include a combination of strength, deformability and energy absorption capacity [1]. Seismic events may lead to un-compensable outcomes such as life and economic loss, and thus response of the structure against earthquake load must be taken into account.

Designing and retrofitting of structures utilizing energy absorption devices are considered many times as these devices enhance the capacity of energy dissipation in structures during earthquake events. Control technology for diminishing seismic response in a structure was first introduced in 1960s [2]. Earthquake applies high amount of energy in the form of kinetic and potential energy to a structure which is dissipated by the structure through inelastic deformation and optionally using of supplemental energy dissipating devices such as base isolators or dampers. These devices can dissipate the earthquake energy with increasing the reliability and safety in the structure. A large volume of existing research in control devices in seismic response show that they are reliable options for increasing seismic safety of structures [3].

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Dampers are the devices used in structures to absorb the earthquake's energy and gradually reduce the amplitude of the seismic vibration. There are different types of dampers used in the structures such as friction dampers, metallic dampers, lead injection dampers, viscous dampers, mass dampers etc. The advantages of using dampers in a structure are their high energy absorbance, easy installation and replacement as well as their interaction with other structural members.

Using dampers in structure is costly. Therefore, their number and optimal locations in a structure, where their performance can be optimal in terms of seismic energy dissipation, is significant to build a cost-effective earthquake resistant structures. Some research has been conducted in terms of the number of dampers and their optimal location in structures which can improve the seismic performance of the building against any vibration. Xu and Igusa [4] investigated that using several dampers instead of one damper with total mass could be more effective in terms of seismic performance during the earthquake event. Optimal placement of control devices has been studied in terms of increasing their effectiveness in improving the mechanical properties of structures [5]. The objective of this study is to investigate the effect of various positions of friction dampers and base isolators in a 2D frame for better seismic response during an earthquake event.

II. Research Methodology

A two bay and six story frames with different formats with varying damper location was studied and modeled in SAP 2000 for this study. The bays width is 5m and story height is 3m. Two friction dampers with several distribution formats and a case with base isolators were considered. The friction damper is of exponential type and the base isolator is triple pendulum type. FNA was used to analyze the structural frame with dampers and isolators to investigate the effect of variable position of dampers, and use of base isolators for controlling the seismic response such as inter-story drift, maximum joint displacement, maximum axial force and maximum bending moment. The aforementioned parameters are compared for each format to see which ones can be the best in terms of each parameter. In terms of FNA, all frames will be subjected to the El Centro earthquake ground motion.

III. Case Study Frame

As mentioned earlier, two bay and six story frame as well as exponential friction dampers and triple pendulum base isolators were considered and modeled in SAP 2000 V17.

Table I shows the properties of damper and base isolator used in this study. The values indicated in Table I are hypothetical.

Different distributions of a pair of dampers as well as one case with base isolators have been studied. Fig. 1 shows different formats of the frame which have been analyzed in this study.

As shown in Fig. 1, Format 0 was considered as the reference format which is without any damper and base isolator. Format 1 to Format 18 are with different distribution of friction dampers and Format 19 is the only format in which base isolators were used.

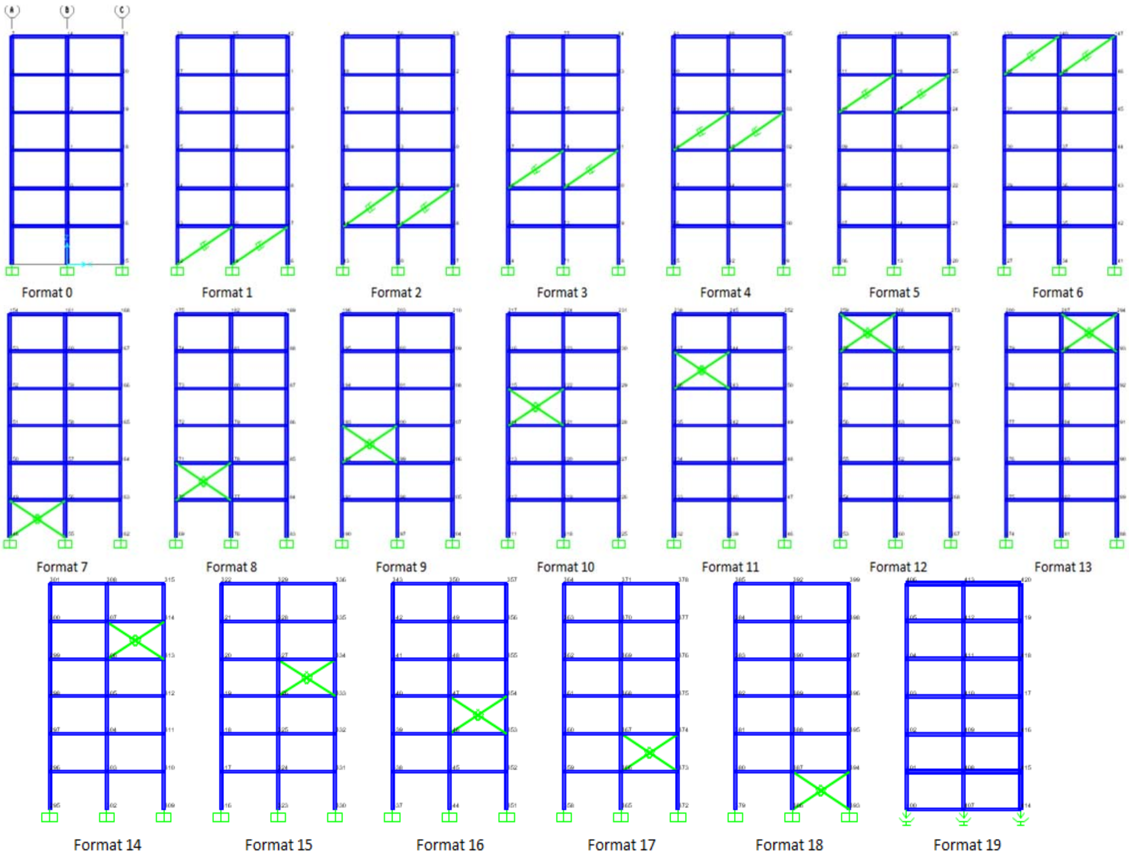

Fig. 1 Various distribution formats of friction dampers and base isolators

IV. Fast Non-Linear Analysis (FNA)

The Fast Non-linear Analysis (FNA) available in SAP 2000 is efficient and fast when dealing with predefined location non-linearity in a frame. The FNA analytical technique is well suited to modern earthquake design practice such as performance based design with the goal to restrict the non-linear behavior to vary specific regions of the structure and an effort to minimize overall damage. FNA is non-linear modal for time history analysis using load dependent Ritz vectors. As mentioned earlier, El Centro earthquake ground motion was used for non-linear analysis of the frames.

El Centro earthquake (or Imperial Valley earthquake) occurred in 1940 in the Imperial Valley in southern California USA which was characterized as a typical moderate-sized destructive event. El Centro earthquake ground motion data was imported to the model from SAP 2000 database to be used for FNA. The number of output time steps used in this study was 5000 and the output time step size was 0.002. Fig. 2 shows time versus acceleration diagram of El Centro earthquake ground motion plotted in SAP 2000.

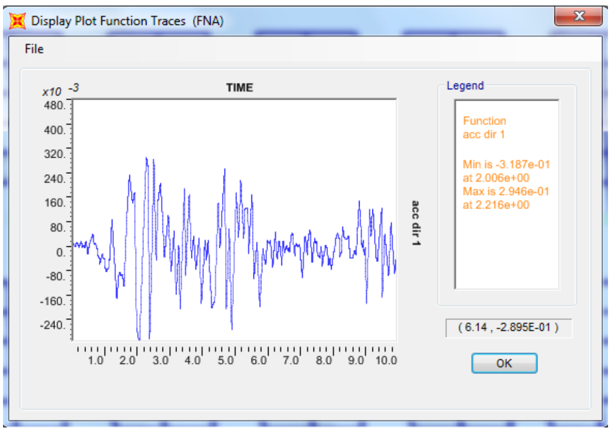

Fig. 2 Ground acceleration diagram of El Centro earthquake ground motion

As indicated in Fig. 2, the maximum positive acceleration is about 0.295g at time step 2.216 s, and the maximum negative acceleration is about 0.319g at time step 2.006 s (g is acceleration due to gravity).

In order to perform FNA, load-dependent Ritz vector must be used. There are two different analyses, Eigen-vector analysis and Ritz-vector analysis. Eigen-vector analysis determined determines the undamped free vibration mode shapes and frequencies of the system which provide an excellent insight into the behavior of the structure.

TABLE I
PROPERTIES OF FRICTION DAMPERS AND BASE ISOLATORS

Exponential friction dampers	Non-linear properties along the damper's axis	Non-linear stiffness	35025.37 KN/m			
		Damping coefficient	1395.53			
		Damping exponent	0.5			
Triple pendulum base isolator	Non-linear vertical properties	Effective linear stiffness	175128.5 KN/m			
		Effective non-linear analysis	175128.5 KN/m			
	Non-linear horizontal properties	Effective linear stiffness	17512.68 KN/m			
			Outer top	Outer bottom	Inner top	Inner bottom
		Non-linear Stiffness	17512.68	17512.68	17512.68	17512.68
		Non-linear friction coefficient, slow & fast	0.1	0.042	0.01	0.01
		Radius of sliding surface	1.3716	1.3716	0.2794	0.2794
		Stop distance	0.2268	0.2268	0.0889	0.0889
	Rotation properties	Effective stiffness	175128.5 KN/m			

TABLE II
INTER-STORY DRIFT OF EACH LEVEL OF THE FRAME FOR EACH FORMAT

Level	Format 0	Format 1	Format 2	Format 3	Format 4	Format 5	Format 6	Format 7	Format 8	Format 9
6	0.0022	0.002	0.0021	0.0013	0.0009	0.0004	0.0003	0.0024	0.002	0.0015
5	0.003	0.0027	0.0026	0.0017	0.0008	0.0004	0.002	0.003	0.0026	0.0018
4	0.0037	0.003	0.0027	0.0014	0.0004	0.002	0.003	0.0036	0.0028	0.0013
3	0.004	0.003	0.002	0.0004	0.002	0.0034	0.004	0.0036	0.002	0.0005
2	0.0037	0.0026	0.0004	0.0016	0.002	0.0034	0.0036	0.0026	0.0006	0.0016
1	0.0018	0.0003	0.0005	0.0012	0.001	0.0017	0.0018	0.0006	0.0006	0.001
Level	Format 10	Format 11	Format 12	Format 13	Format 14	Format 15	Format 16	Format 17	Format 18	Format 19
6	0.001	0.0003	0.0003	0.0003	0.0004	0.0009	0.0015	0.0022	0.0024	0.0007
5	0.0007	0.0005	0.002	0.002	0.0003	0.0008	0.0017	0.0025	0.003	0.001
4	0.0005	0.002	0.003	0.003	0.002	0.001	0.0014	0.003	0.0036	0.001
3	0.002	0.003	0.004	0.004	0.0036	0.0014	0.0004	0.0022	0.0036	0.001
2	0.003	0.003	0.0036	0.0036	0.0036	0.003	0.0017	0.0003	0.0026	0.0016
1	0.0016	0.002	0.002	0.002	0.0015	0.0016	0.0013	0.0007	0.0005	0.002

Ritz-vector analysis determines the modes that are excited by a particular loading which can provide a better result than do Eigen vector when used for response spectrum or time history analyses. Load-dependent Ritz vectors are most suitable for analyses involving vertical ground acceleration, localized machine vibration and the non-linear FNA. They are also efficient and widely used for dynamic analyses involving horizontal ground motion. Their benefit is that, for the same number of modes, Ritz vectors provide a better participation factor, which enables the analysis to run faster with the same level of accuracy.

For analyzing the frame with base isolators, after defining the time history function, a ramp function must also be defined. Ramp function is for applying the dead load. The base isolators are friction pendulum and thus their behavior is controlled by friction forces which mean that isolators must be loaded with the vertical load before an earthquake analysis begins. Therefore, defining the dead load using a time history is needed.

V. RESULTS AND DISCUSSION

Each of frame formats have been analyzed and assessed in SAP 2000. Some of the structural parameters of each frame such as inter-story drift, maximum joint displacement, maximum axial force and maximum bending moment have been determined and compared to identify the formats which can be better in terms of each parameter. The values of the frame's inter-story drift of each level for each format are shown in Table II and compared in Fig. 3.

As indicated in Table II and Fig. 3, it is obvious that for each format, the inter-story drift of the levels in which dampers are installed is the lowest. But in total, according to the values, it can be understood that formats 3, 9 and 16 which the dampers are installed in level 3 can be the best cases in terms of inter-story drift. In terms of base isolators shown in format 19, although joint displacement in each floor is increased, but the inter-story drift of each level in total is reduced which can protect the occupants from major damage or injury.

Table III shows the values of the maximum joint displacement of the frame in x direction for each format and Fig. 4 compares them together to identify which distribution format of dampers can be more effective in reducing the maximum joint displacement in x direction.

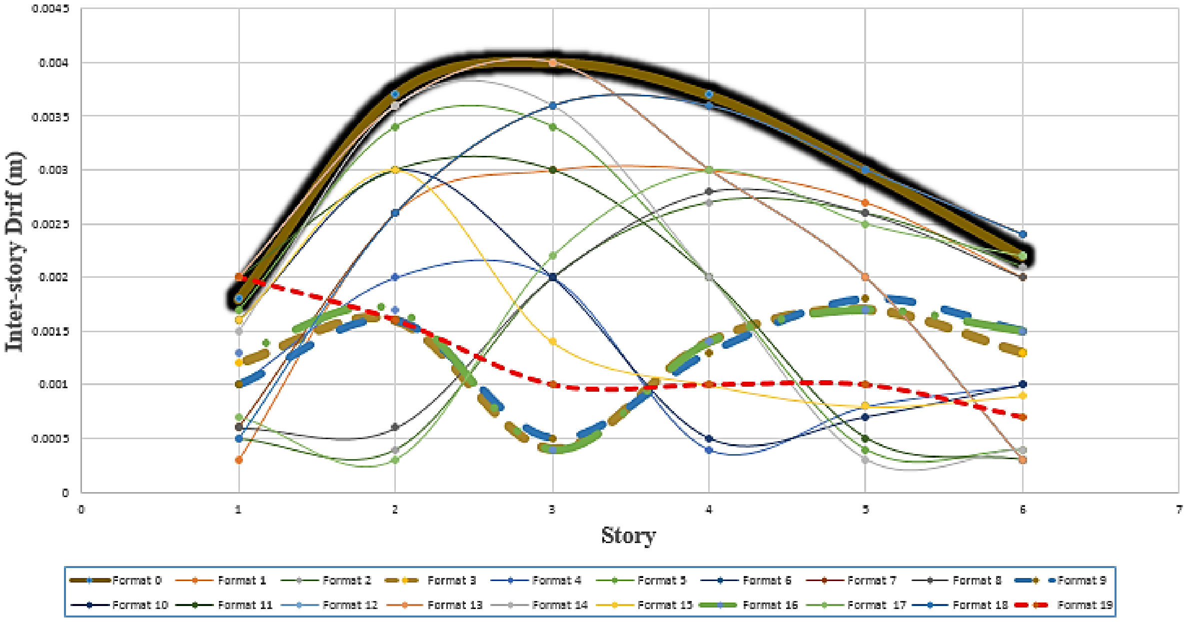

Fig. 3 Comparing the inter-story drift of each story for each format

TABLE III
MAX JOINT DISPLACEMENT IN THE FRAME FOR EACH FORMAT

Format **0**	Format **1**	Format **2**	Format **3**	Format **4**	Format **5**	Format **6**	Format **7**	Format **8**	Format **9**
51.8	40.8	26.5	**20.2**	25.5	34	41.6	41	26.5	**22**
Format **10**	Format **11**	Format **12**	Format **13**	Format **14**	Format **15**	Format **16**	Format **17**	Format **18**	Format **19**
25.8	33.5	41.9	41.8	33.5	25.8	**22**	26.5	41	175

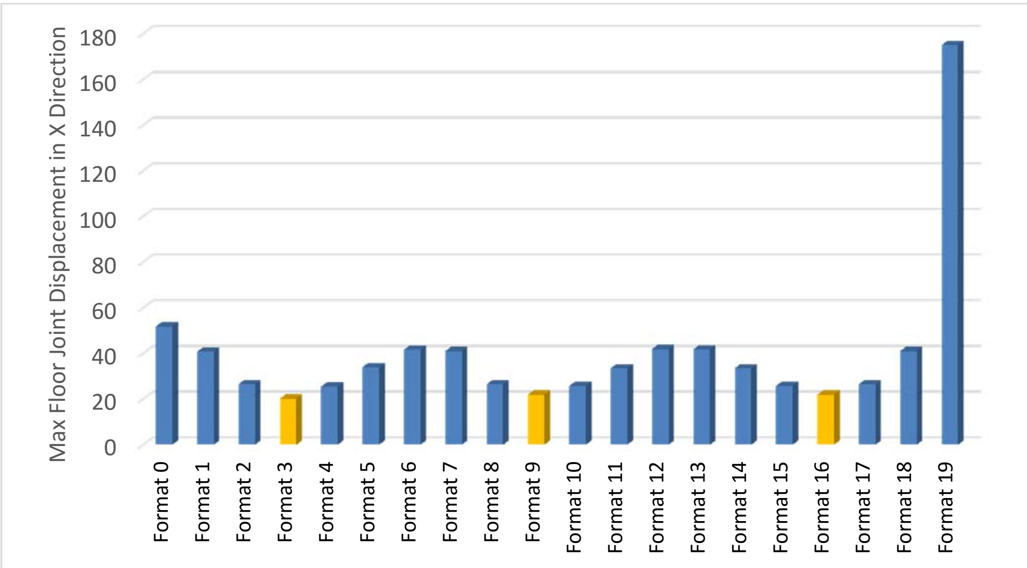

Fig. 4 Comparison of the values shown in Table III

According to Table III and Fig. 4, it is understood that Format 3, Format 9 and Format 16 are location formats in which maximum reduction of joint displacement is observed. Although by using dampers, reduction in maximum joint displacement is inevitable, but location of dampers can be considerable to achieve the desired results. As can be seen, in all formats using dampers except format 19, in which base isolators were used instead of dampers, maximum joint displacement of the frame was reduced compared to the reference format (Format 0) in which no damper was used. But Formats 3, 9 and 16, in which dampers are installed in Level 3, have the best cases with 61%, 57.5% and 57.5% reduction in max joint displacement in x direction respectively. In terms of using base isolators in format 19, joints displacement of the frame are significantly increased as expected. As shown in Table I, the isolators have much lower lateral stiffness that is why most of the displacement occurs across the isolation system. As the fundamental period increases, the spectrum acceleration reduces while displacement increases. Base isolator systems reduce floor joint acceleration and velocities and therefore increase the floor joint displacement. In this case, the floor joint displacement can be decreased by increasing the isolators' damping. Fig. 5 illustrates the deformed shape of the frame format with base isolators (Format 19) obtained by performing FNA. The frame's deformed shape, as shown in Fig. 5, is obtained at time step 2.216 which max positive acceleration occurs. It is obvious that the frame was mostly deformed in lateral direction.

TABLE IV
MAX AXIAL FORCE VALUES OF THE FRAME FOR EACH FORMAT

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
186	276	234	**162**	210	246	252	292	248	336
10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
294	258	228	222	252	288	330	372	282	280

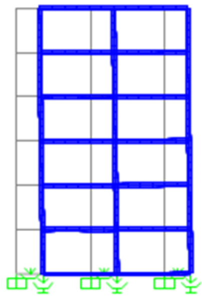

Fig. 5 Deformed shape of the frame with base isolators

Table IV shows the maximum axial force in the frame for each format and Fig. 6 compares them together to identify which distribution format can be more effective in reduction of maximum axial force of the frame.

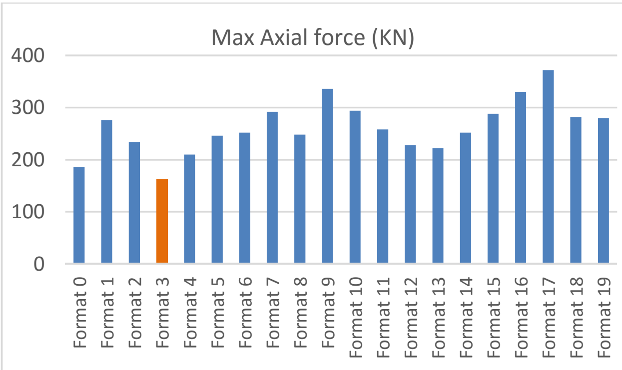

Fig. 6 Comparing the maximum axial load of the frame for each format

TABLE V
MAX BENDING MOMENT OF THE FRAME FOR EACH FORMAT

Format **0**	Format **1**	Format **2**	Format **3**	Format **4**	Format **5**	Format **6**	Format **7**	Format **8**	Format **9**
119.2	80	60.4	66	108.2	115.2	118	85.2	63	70
Format **10**	Format **11**	Format **12**	Format **13**	Format **14**	Format **15**	Format **16**	Format **17**	Format **18**	Format **19**
108.4	115.2	118	118	115.2	108.3	69.6	62.4	82	**50**

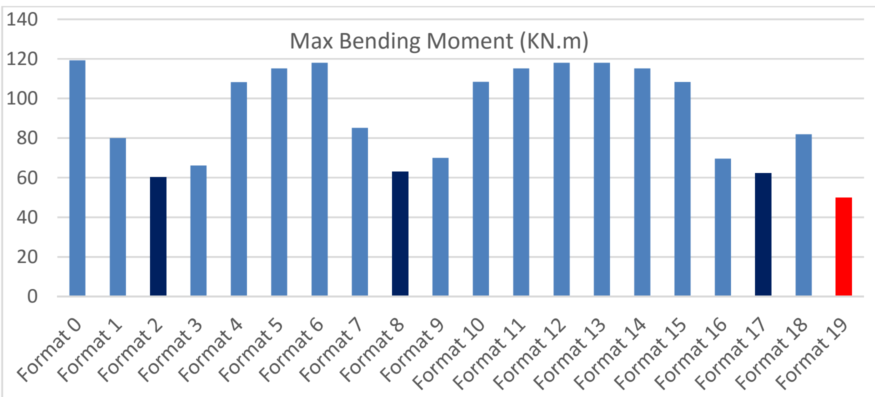

Fig. 7 Comparison of the maximum bending moment of the frame for each format

Damping devices are included in the building's diagonal bracing system. For such a configuration, it has been recognized that due to vertical component of the damper force, the columns would experience additional axial forces during an earthquake. Because of that in almost all formats, axial force in columns was increased. The reduction in axial forces is observed as 13% for only format 3. It shows that the location and number of dampers can effect on axial forces in members.

When format 3, 9 and 16 are compared to each other in which dampers are installed in level 3, it is understood that distributing dampers in different bays of a level is more effective than concentrating dampers in only one bay. In terms of maximum bending moment, Table V and Fig. 7 show and compare the maximum bending moment in the frame for each format.

As shown in Fig. 7, in all formats in which dampers and base isolators were used, maximum bending moment were reduced. Although seismic dampers can reduce the story drift and thus reduce the bending moment, the load paths are also changed [6], and this change in the load paths leads to substantial axial loads in the column as shown in Table IV. According to Table V and Fig. 7, the maximum reduction in bending moment is observed as 49.3%, 47%, 47.6% and 58% for format 2, format 8, format 17, and format 19 respectively, which among them, the frame with base isolators in this study is the best for reducing the bending moment of the frame.

VI. Conclusion

This study investigated the capability of FNA in analyzing a structural 2D frame with dampers and isolators. It has highlighted the use of FNA in identifying the most effective distribution formats of dampers and isolators. In order to achieve the objectives of the study, a six story 2D frame with twenty formats were modeled in SAP 2000. Some of the response parameters of the frame such as inter-story drift, max floor joint displacement, max axial load and max bending moment for each format were determined and compared to each other. Although it was observed that use of dampers reduces the seismic response of the frame, Format 3 in which dampers are installed in both bays of [level 3 was found to be more effective with respect to inter-story drift, maximum floor joint displacement and maximum axial force. Format 2 is also found to be quite effective with respect to reducing the max bending moment of the frame. About base isolators used in Format 19, it was observed that it is very effective in reducing the inter-story drift and max bending moment of the frame.

Acknowledgment

The support of Natural Sciences and Engineering Research Council (NSERC) of Canada is gratefully acknowledged.

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