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Performance of Mid-rise Buildings with Tubular Structure Under the Effect of Near Field Earthquakes

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Abstract

The aim objective of this study is to investigate the effects of near-field earthquakes on the response of mid-rise buildings with tubular structure. For this purpose, a 20-story building with a square plan of six by six bays, all with 6 m span, and story height of 3.70 m is considered. Axial force of columns, shear lag, and inter-story drift values are used as the main response parameters. Nonlinear time history analyses (NLTHA) of the considered building were conducted by using once the two-component, and once more three-component accelerograms of both far- and near-field selected earthquakes for comparison. Numerical results of NLTHA show that inclusion of a vertical component of ground motion leads to around 17% and 32% increase, in average, in axial forces of side and corner columns respectively in case of far-field earthquakes. These increases were respectively 22% and 37% in case of near-field earthquakes. The vertical ground motion also leads to around 11% and 15% increase, in average, in shear lag of side and corner columns respectively in case of far-field earthquakes, and 13% and 19% increase in case of near-field earthquakes. The amount of increase in inter-story drift values due to the vertical ground motion was observed in range of 24% and 27% for far- and near-field earthquakes respectively.

***Keywords**:* Nonlinear Time History Analysis (NLTHA), Two- and Three-Component Earthquake Accelerograms, Axial Forces of Side and Corner Columns, Shear lag, Inter-Story Drifts

1. Introduction

From the late nineteenth century that the high-rise buildings flourished in the world, up to now, diverse structural systems have been used mid-rise and high-rise buildings. The taller is the high-rise building the more important is its structural system, and subsequently selection of its structural form [1]. Non-structural considerations have also an important impact on the selection of structural form and may also be decisive. The key idea for better understanding of the behavior of the structural system of mid- and high-rise buildings is analogy of the building with a cantilever column; and the lateral forces due to wind or earthquake tend to create shear forces and bending moments in the building structural system, against them the system should withstand preferably in the elastic range of materials' behavior.

One of the structural systems, known as the best for tall buildings, is the tubular system. In this system, which is considered as the enhanced and upgrading traditional moment frame system, it is tried to place most of the columns at the building's perimeter so that the flexural and torsional stiffness of the structural system as well as its moment of inertia reach their maximal values [2-4].

The story drifts in this system is due to cantilever action and shear lag as well as the distortion of panel zone, and by controlling these factors the drifts can be reduced to some acceptable limits. Shear lag is one of the most important factors in the structural performance of the peripheral frame system, which affect not only the axial forces, but also the transverse and shear forces, and therefore this effect should be considered in the design process [5- 8].

Northridge earthquake of 1994, Kobe earthquake of 1995, Izmit earthquake of 1999 as well as Bam earthquake of 2003 showed the necessity of inclusion of near-field earthquakes in design. This is while in the present design codes of tall buildings the effects of near-field earthquakes are not addressed.

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Researchers, conducted on near field earthquakes, have shown that these earthquakes include critical energy pulses [9]. In fact, although near field earthquakes may have small magnitudes, they may have a high potential for destruction [10]. The most important difference between far- and near-field earthquakes is the ratio of maximum vertical acceleration to maximum horizontal acceleration, which is higher in a case of near-field earthquakes [11, 12].

With regard to seismic response of tubular buildings some researches have been conducted since early 2000. Memari and colleagues In a study on seismic evaluation of an existing 32-story reinforced concrete framed tube building based on inelastic dynamic time-history analysis force and deformation response of the structure subjected to three ground motion records has been obtained [13]. In that study details of the modeling based on the DRAIN-2D program, plastic rotation, rotation and curvature ductility demands and capacity evaluation of members have been discussed, and previous recommendations for plastic hinge rotation and plastic hinge length modifications have been discussed and the results of the application of some of these recommendations have been evaluated. Some observations with regard to shear lag effect have been also presented and some of the difficulties in using the direct results of inelastic dynamic time history analysis in seismic assessment for practical applications have been demonstrated.

Jiang, H. J., Fu, B., & Liu, L. E. In another study on Seismic Performance Evaluation of a Steel-Concrete Hybrid Frame-Tube High-Rise Building Structure, mentioning that due to its unique advantages, the steel-concrete hybrid structure has been widely used in tall buildings around the world, and that in mainland China it has been utilized as one of the most popular structural types for super tall buildings, the seismic performance of a code-exceeding tall building with the hybrid frame-tube structure to be constructed in Beijing has been evaluated by numerical analysis [14]. In that study the analytic model of the structure has been established with the aid of PERFORM-3D program, and the nonlinear time history analysis has been performed by inputting four sets of earthquake ground motions. The elastic dynamic characteristics, the global displacement responses, the performance levels and the deformation demand-to-capacity ratios of structural components under different levels of earthquakes have been presented. Numerical analysis results of that study indicate that the hybrid structure has good seismic performance.

Zhong, L., & Deling, Q. According to an actual super high-rise building with the frame-core tube structure, mode analysis of a super high-rise reinforced concrete frame-core tube structure has been discussed by using large-scale finite element software ANSYS, verified through the design software ETABS, and the characteristics of nature vibration have been obtained [15]. Based on the modal analysis, nonlinear seismic analysis of structure has been carried out by the time-history analysis method. Inputting three different seismic waves to structure whose calculated results have been fully analyzed and compared, including floor displacement angle envelope curves, vertex displacement time-history curves, floor displacement curves and time-history curve of roof acceleration. The results of that study show that the maximum damage of concrete exists in the bottom of super high-rise building with the frame-core tube structure, the structure has no obvious weak story and maximal floor displacement angle occurs in the upper floors, and its value is less than 1 /100 of Technical Specification for Concrete Structures of Tall Building and can meet the code requirements for energy dissipation structures.

It is seen that although several studies have been conducted with regard to seismic studies of tubular buildings, the past researches have rarely addressed the effects of near-field earthquakes on this type of buildings. The aim of this study is to investigate the behavior and dynamic response of tubular structures subjected to earthquake loads in near field and comparing them with that of far field earthquakes.

2- Methodology

In this study a 20-story tubular building with a square plan of 36 m dimension of 36 m is considered. The inner bays have 6 m span, while for the outer frames spans of 2 m are considered to create the tubular system. Story height has been assumed to be 3.70 m resulting in an overall height of 74 m for the building. Plan and elevation of the considered building are shown in Figure 1.

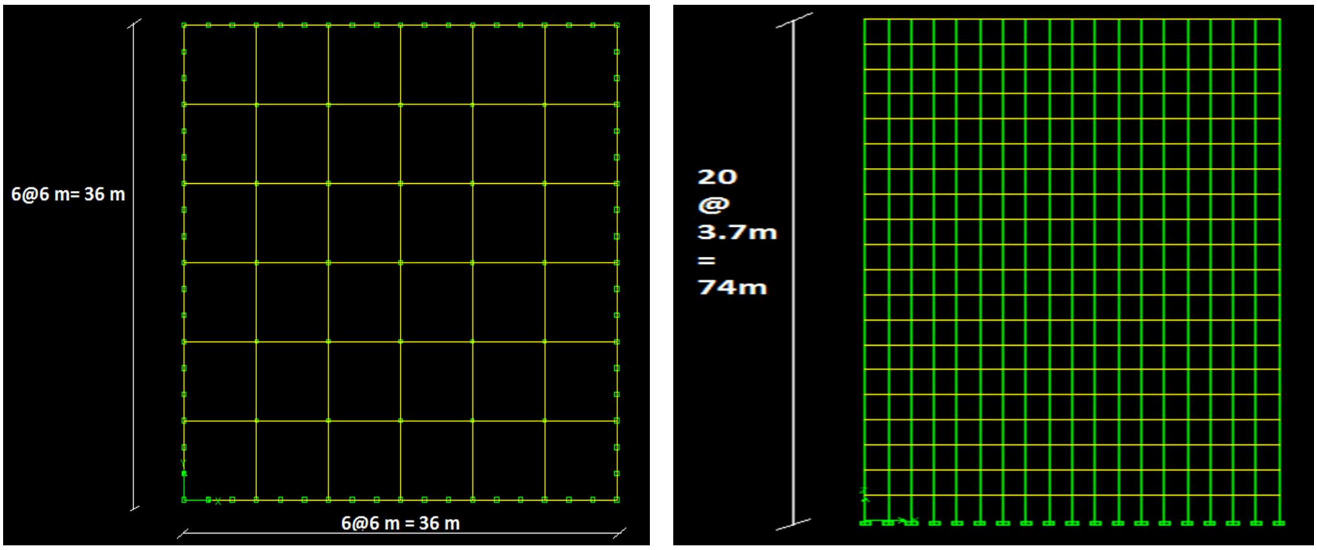

Figure 1. Plan and elevation of the considered tubular building

The considered building was designed based on Iranian Standard No. 2800, assuming soil type III for the building site, and Iranian National Regulations for steel building, considering ST-37 for the structural material. It was tried to keep the over-strength of the building as minimal, by limiting the lower bound of the stress ratios to 0.85 in most of the structural elements. The modal characteristics of the building for its first few modes are given in Table 1.

Table 1- Modal characteristics of the considered tubular building

Mode No.	1	2	3	4	5	6
Period (sec)	2.87	2.15	1.86	1.52	1.14	0.73
Cumulative Mass Participation Factor	72.43	77.27	81.35	84.27	88.18	90.12

For nonlinear time history analysis (NLTHA) of the building seven near-fields as well as seven far-field earthquakes were considered, whose specifications are given in Tables 2 and 3.

Table 2- Specifications of selected near-field earthquakes on soil type III

No.	**The Record Name**	**Date**	**Station**	**Distance (km)**	**PGA (g)**	**Magnitude**
1	Denali, Alaska, USA	2002	PS-10047	0.18	0.419	7.90
2	Kobe, Japan	1995	Takatori, 000	1/46	0.611	6.90
3	Chi-Chi, Taiwan	1999	TCU101	2.13	0.422	7.62
4	Northridge, USA	1994	CDMG Station 24087	3.30	0.476	6.69
5	Imperial Valley, USA	1979	USGS Station 955	4.90	0.485	6.53
6	Cape Mendocino, USA	1992	CDMG Station 89324	7.88	0.549	6.92
7	Duzce, Turkey	1999	LAMONT Station 1062	9.15	0.357	7.14

Table 3- Specifications of far-field selected earthquakes on soil type III

No.	The Record Name	Date	Station	Distance (km)	PGA (g)	Magnitude
1	Coalinga, USA	1983	Parkfield Fault Zone 12	27.96	0.276	6.36
2	Chuetsu, Japan	2007	Joetsu Kita	28.97	0.311	6.80
3	Morgan Hill, USA	1984	Hollister City Hall	30.76	0.314	6.19
4	Kocaeli, Turkey	1999	Goynuk	31.74	0.338	7.51
5	Big Beer, USA	1992	San Bernardino	33.56	0.364	6.46
6	Iwate, Japan	2008	Sake City	35.11	0.233	6.90
7	N. Palm Spring, USA	1986	Sunny Mead	37.66	0.219	6.06

All records were selected from the PEER data base. Magnitude of the selected earthquakes was between 5 to 8 Richter. Focal distance of the selected earthquakes was between zero and 10 km for near-field ones and between 25 and 38 km in case of far-field ones. The acceleration spectra of the scaled accelerograms of the selected earthquakes are presented in Figures 2 and 3.

In both cases of near- and far-field earthquake the NLTHA have been conducted once without considering the vertical component of ground motion, and once more with considering it. Since seven near-field as well as seven far-field records were used for the analyses (conducted by using Perform-3D-V-5-0 software) in the whole 28 cases of NLTHA were performed. The numerical results are presented and discussed in the next section.

3- Numerical Results and Discussion

3-1- Axial force and shear lag of columns

In average the maximum axial forces occurred in corner columns, and then in those side columns which are closer to the corner columns and are in line with the internal columns. Also the minimum axial forces occurred in peripheral middle columns at each side of the building. The locations of these corner and side columns are shown in Figure 4.

With regard to shear lag an index was used, defined as the ratio of the maximum axial force in the column to that of the central side column. To find out the variation of the maximum axial forces as well as shear lags along the building's height the values related to the first, 10th and 16th story were considered. Figures 5 and 6 show the average of maximum axial forces of columns in the first story of the building subjected to far- and near-field earthquakes, respectively for 2-Component and 3-Component excitations, and Figure 7 compares the results related to far-field earthquake with those related to near-field earthquakes all with 3-Component excitations. The same results are shown by Figures 8 to 10 and 11 to 12 respectively for columns in the 10th and 16th story of the building.

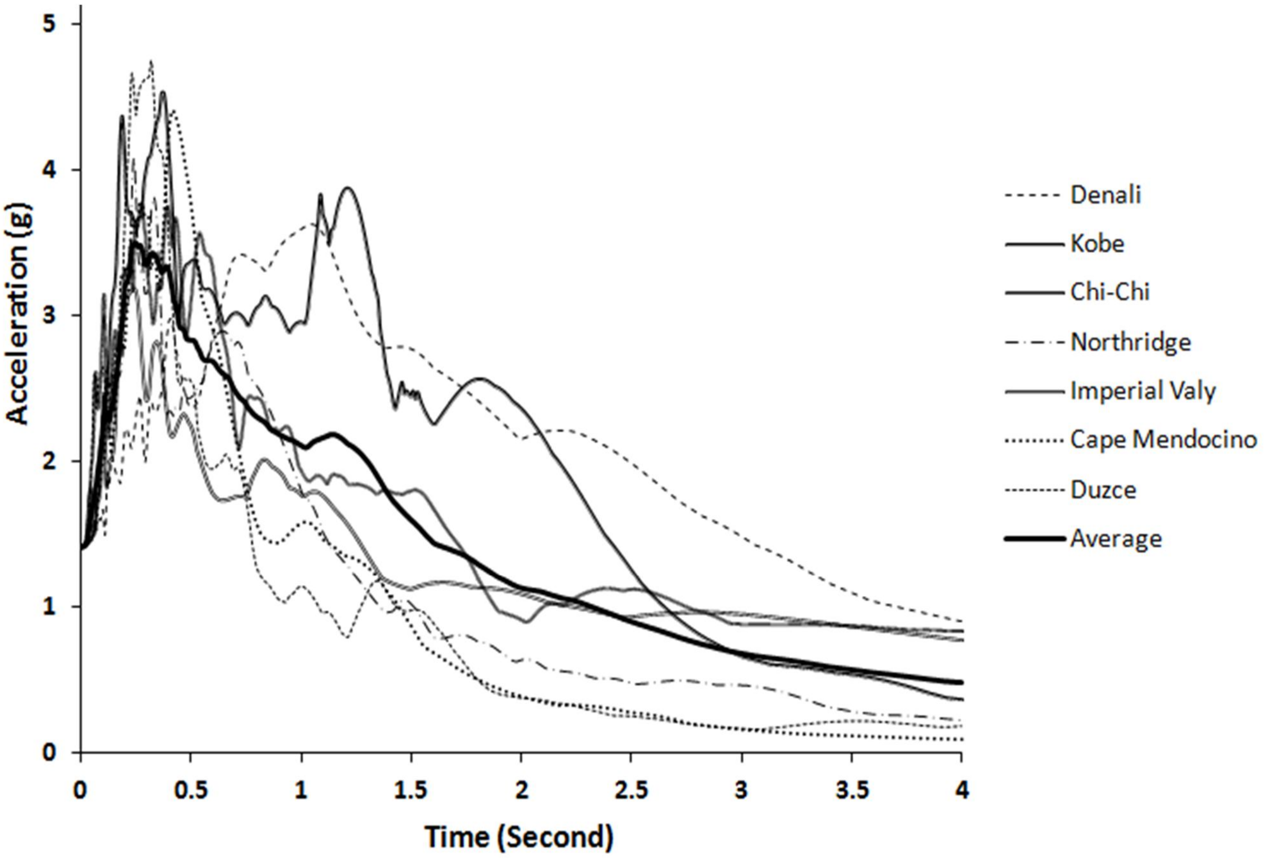

Figure 2. The SRSS combination of acceleration spectra of the two horizontal components of the selected near-field earthquakes normalized to 1.0g

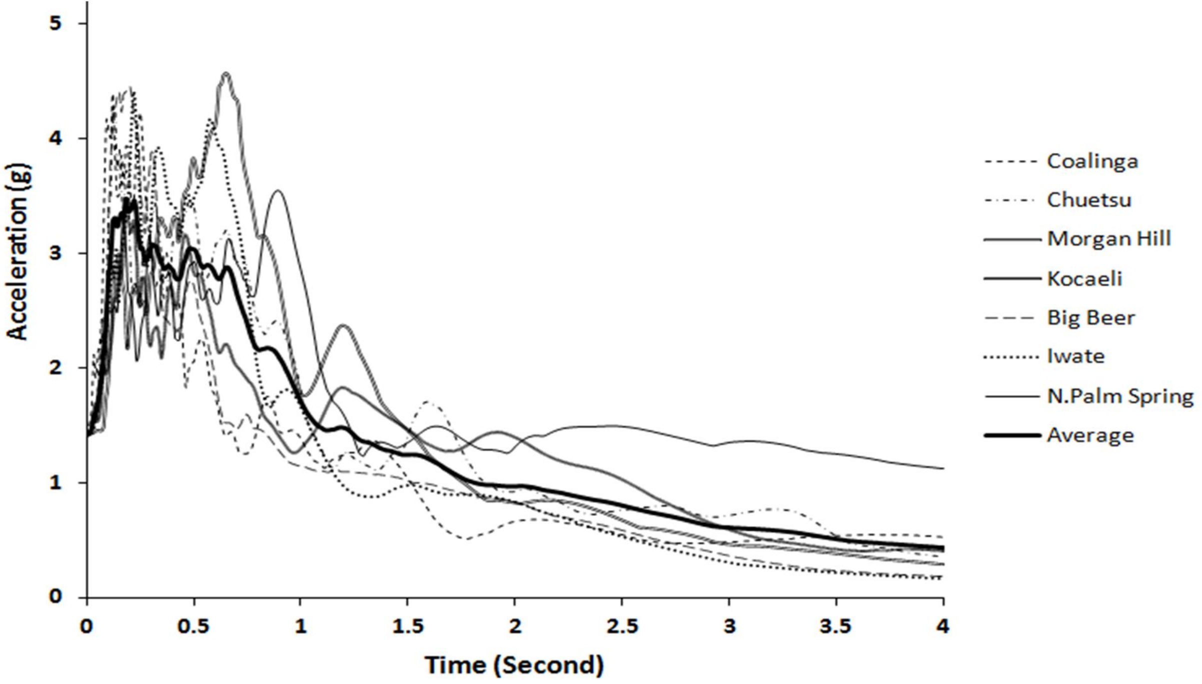

Figure 3. The SRSS combination of acceleration spectra of the two horizontal components of the selected far-field earthquakes normalized to 1.0g

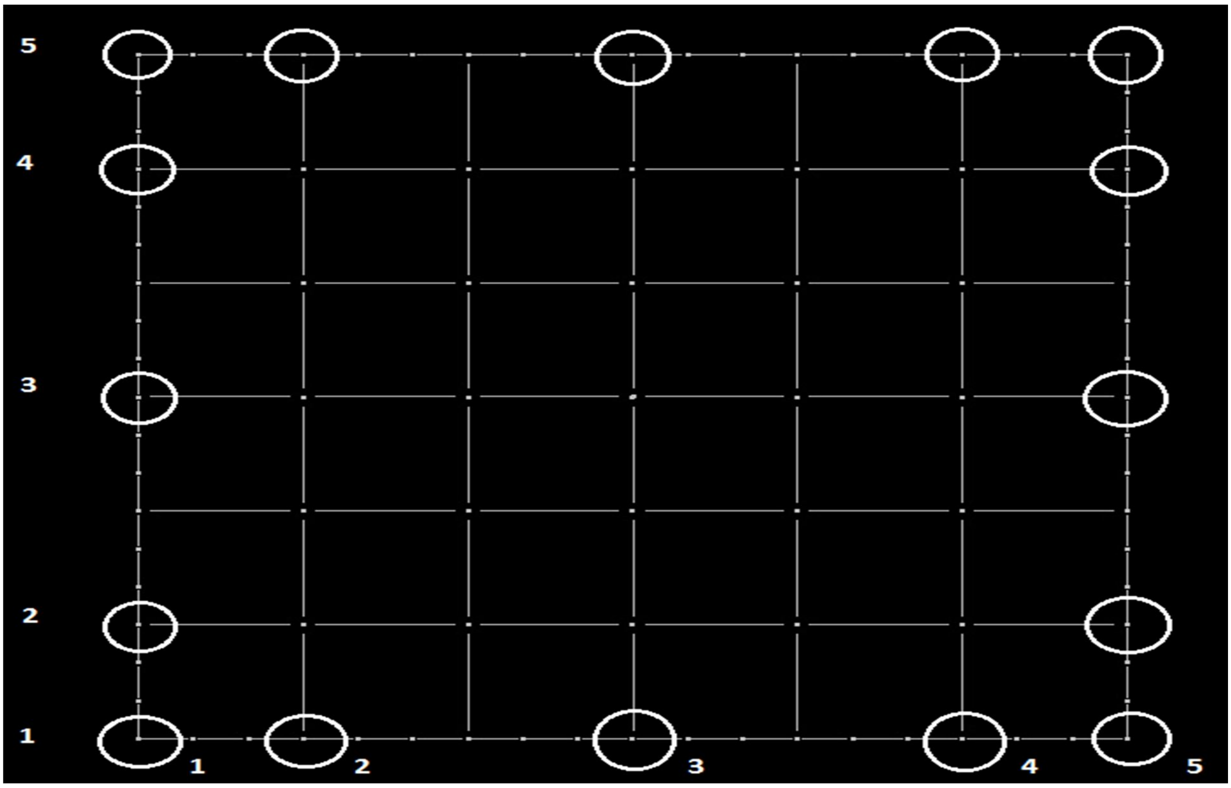

Figure 4- Locations of the peripheral columns for investigation of axial forces and shear lags

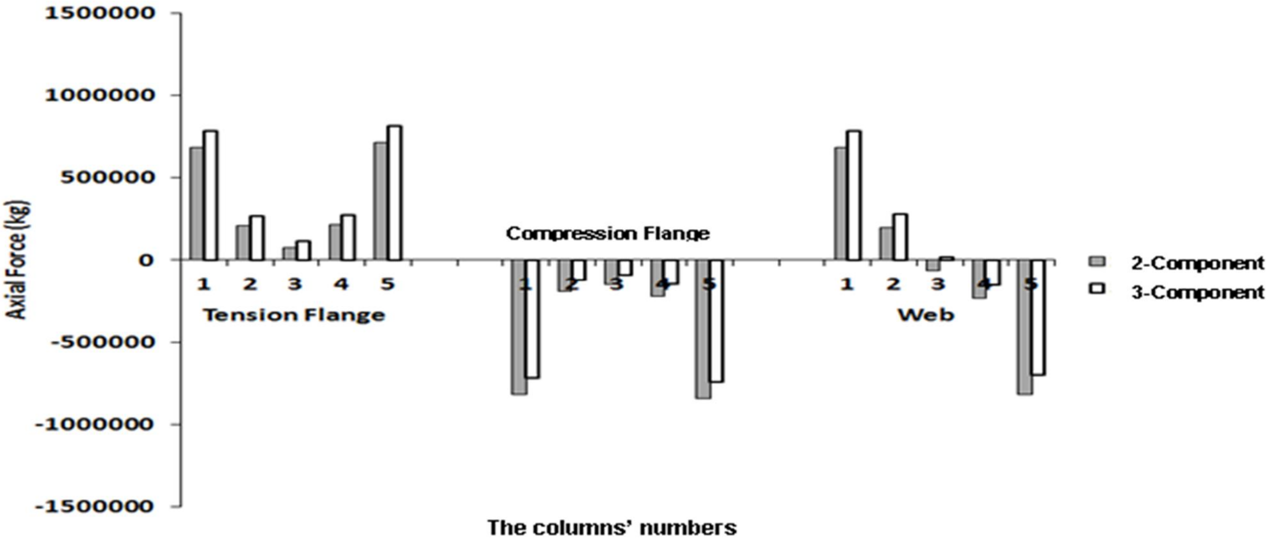

Figure 5- Comparison of average maximum axial forces in columns acting as tension flange, compression flange and web of the tubular structure at the 1st story of the building subjected to the considered far-field earthquakes

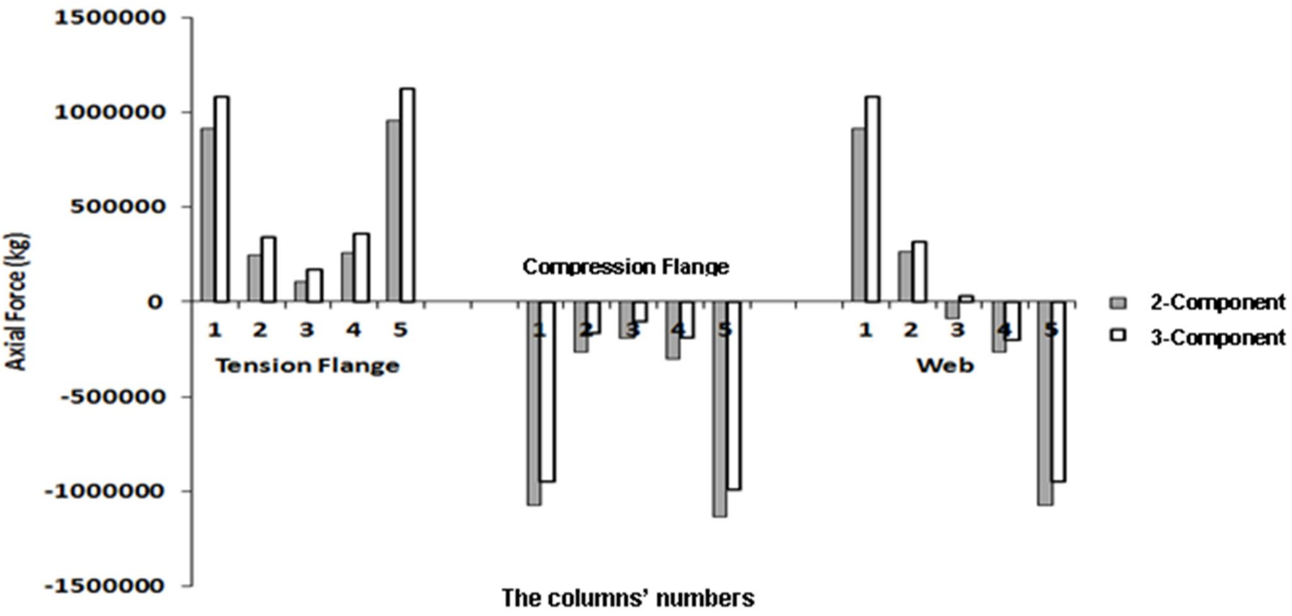

Figure 6- Comparison of average maximum axial forces in columns acting as tension flange, compression flange and web of the tubular structure at the 1st story of the building subjected to the considered near-field earthquakes

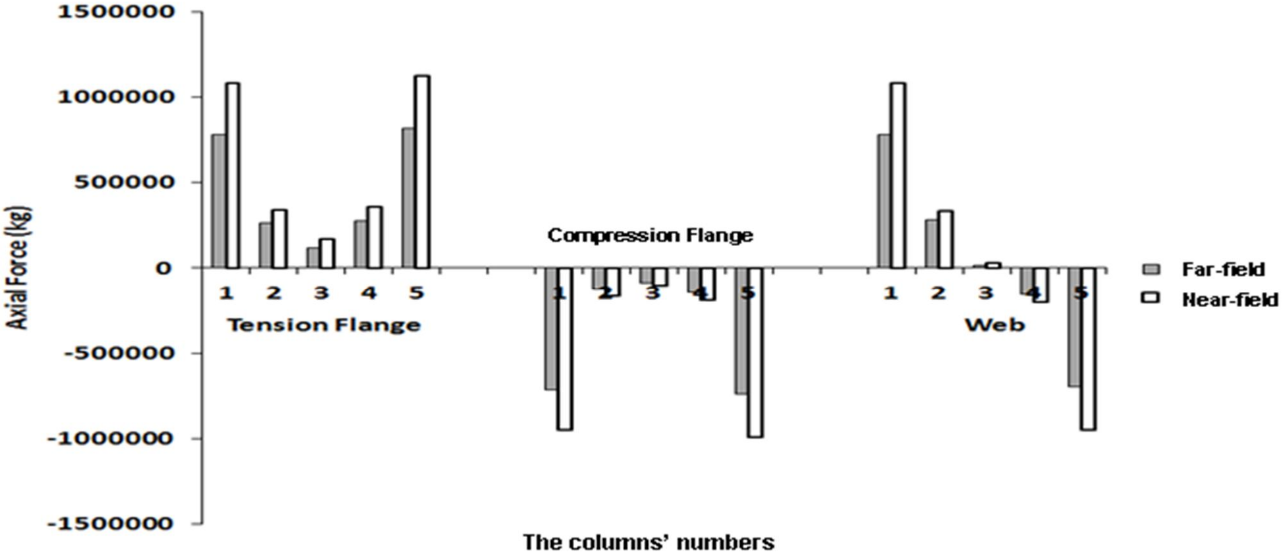

Figure 7- Comparison of average values of the maximum axial forces in columns acting as tension flange, compression flange and web of the tubular structure at the 1st story of the building subjected to the considered far- and near-field earthquakes with 3-Component excitations

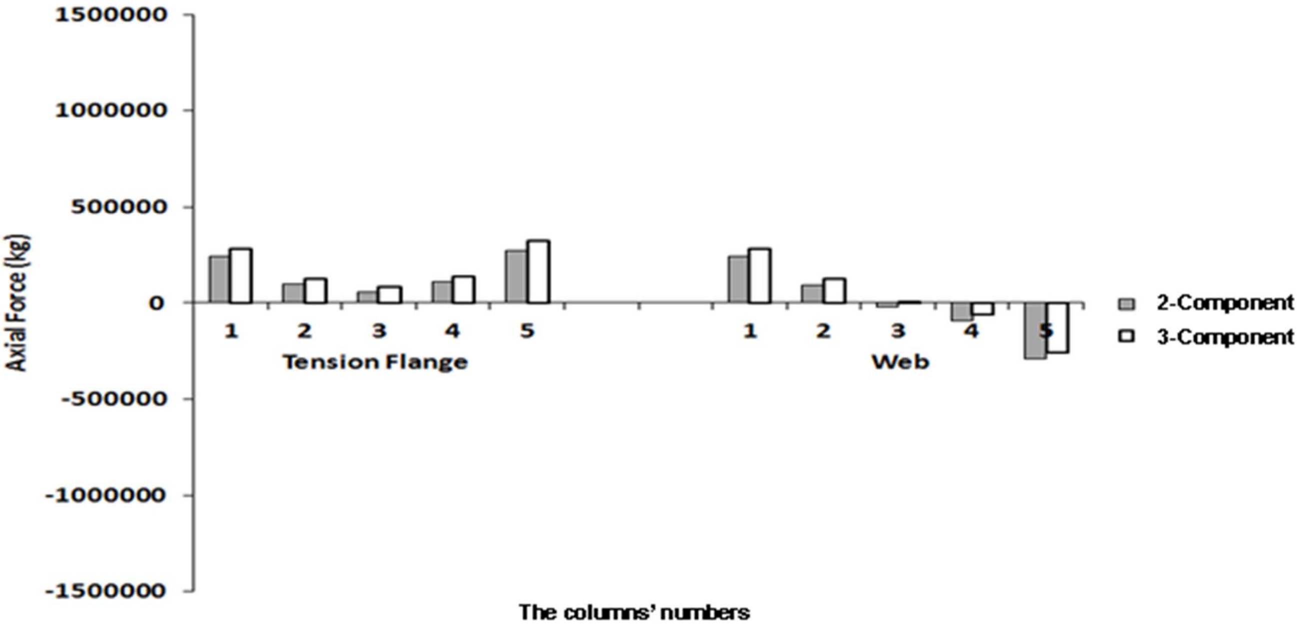

Figure 8- Comparison of average maximum axial forces in columns acting as tension flange and web of the tubular structure at the 10th story of the building subjected to the considered far-field earthquakes

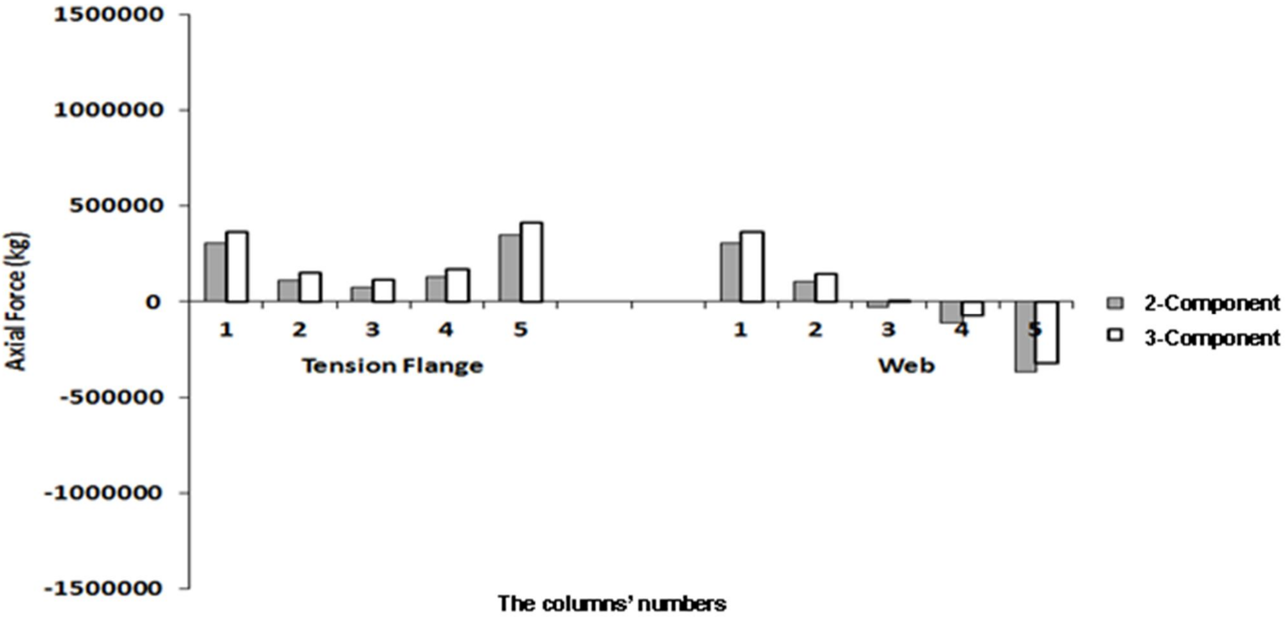

Figure 9- Comparison of average maximum axial forces in columns acting as tension flange and web of the tubular structure at the 10th story of the building subjected to the considered near-field earthquakes

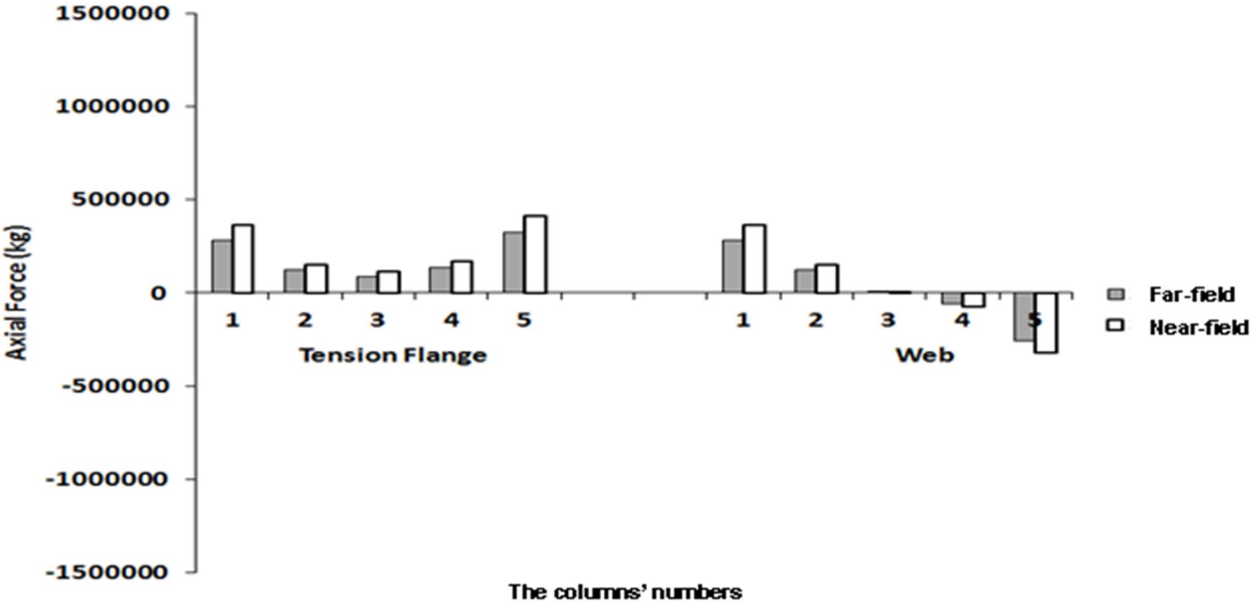

Figure 10- Comparison of average values of the maximum axial forces in columns acting as tension flange and web of the tubular structure at the 10th story of the building subjected to the considered far- and near-field earthquakes with 3-Component excitations

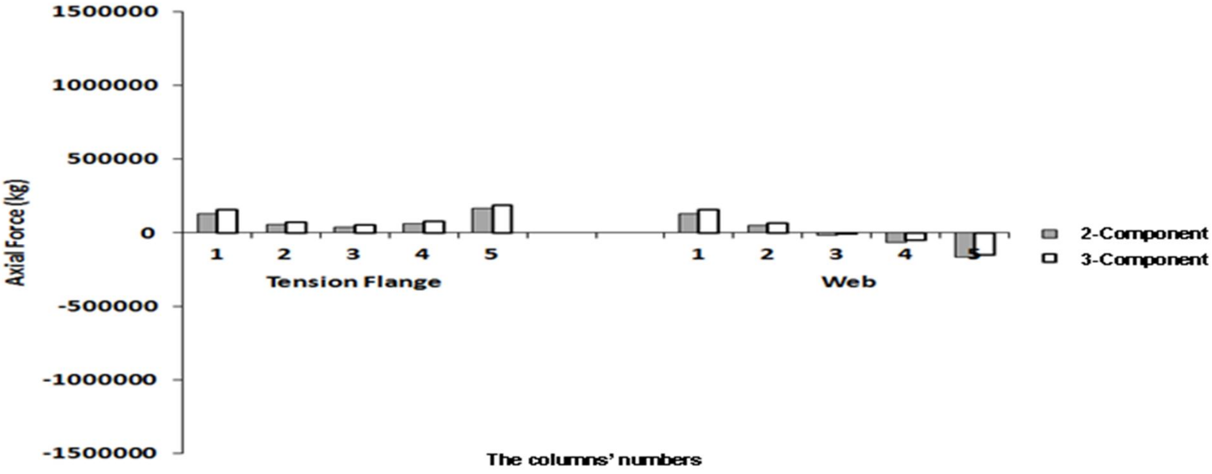

Figure 11- Comparison of average maximum axial forces in columns acting as tension flange and web of the tubular structure at the 16th story of the building subjected to the considered far-field earthquakes

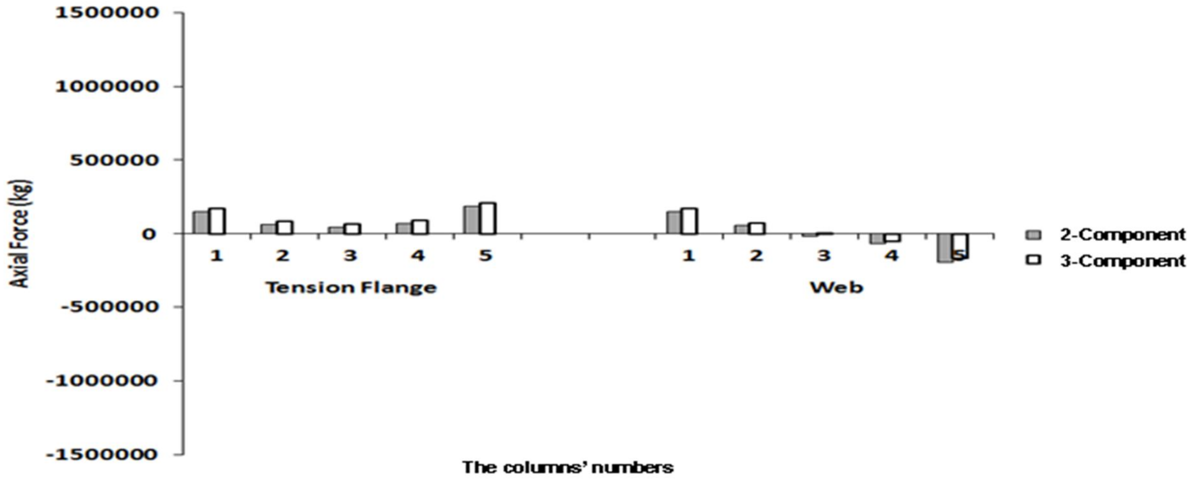

Figure 12- Comparison of average maximum axial forces in columns acting as tension flange and web of the tubular structure at the 16th story of the building subjected to the considered near-field earthquakes

Figure 13- Comparison of average values of the maximum axial forces in columns acting as tension flange and web of the tubular structure at the 16th story of the building subjected to the considered far- and near-field earthquakes with 3-Component excitations

Number of columns acting as tension and compression flanges as well as the web of the tubular structure, mentioned in Figures 5 to 12, have been respectively 7, 7 and 12 (corner columns are shared between flanges and web), of which 5 of tension flange and 5 of compression flange and also 5 of the web zones have been considered for investigating the axial forces and shear lag values. As it can be seen in Figures 5, 8 and 11, which are related to far-field earthquakes, that the tensile axial forces have been increased and compressional axial forces have been decreased due to the application of 3-Component accelerograms rather than 2-Component ones. The same conclusion is true with regard to Figures 6, 9 and 12, which are related to near-field earthquakes. However, the amounts of differences between the results of 2-Component excitations and 3-Component excitations are slightly more, which is due to the effect of higher vertical acceleration in case of near field earthquakes. The closeness of maximum tensile and compressive axial forces in columns, observed in Figures 5 to 13, is due to this fact that the majority of the gravity load in the tubular system is carried out by the inner columns and the maximum forces in the peripheral columns are basically due to the effect of lateral loads. Looking at Figures 7, 10 and 13, which compare the far-field and near-field responses, one can realize that the response values in case of near-field earthquakes are generally higher than those of the far-field.

Based on Figures 5 to 7 the amount of differences between the results of 2-Compomnet and 3-Component far-field excitations for the axial force responses at the first story of the building are in average around 14% and 38% for side and middle columns respectively. These values are respectively 18% and 42% in case of near-field earthquakes. The amount of differences in the shear lag values of side and middle columns due to 2-Compomnet and 3-Component are respectively 20% and 14% for far-field excitations and 25% and 17% for near-field excitations. The amounts of differences in axial force responses due to far- and near-field earthquakes are respectively 35% and 37% for side and middle columns. For shear lag values the amount of differences are respectively 33% and 19% for side and middle columns.

With regard to the axial force responses at the 10th story of the building, based on Figures 8 to 10 the amount of differences between the results of 2-Compomnet and 3-Component far-field excitations are in average around 17% and 32% for side and middle columns respectively. These values are respectively 25% and 35% in case of near-field earthquakes. The amount of differences in the shear lag values of side and middle columns due to 2-Compomnet and 3-Component are respectively 14% and 10% for far-field excitations and 17% and 13% for near-field excitations. The amounts of differences in axial force responses due to far- and near-field earthquakes are respectively 24% and 26% for side and middle columns. For shear lag values the amount of differences are respectively 22% and 16% for side and middle columns. Also based on Figures 11 to 13 the amount of differences between the results of 2-Compomnet and 3-Component far-field excitations for the axial force responses at the 16th story of the building are in average around 18% and 26% for side and middle columns respectively. These values are respectively 22% and 33% in case of near-field earthquakes. The amount of differences in the shear lag values of side and middle columns due to 2-Compomnet and 3-Component are respectively 11% and 7% for far-field excitations and 13% and 9% for near-field excitations. The amounts of differences in axial force responses due to far- and near-field earthquakes are respectively 12% and 17% for side and middle columns. For shear lag values the amount of differences are respectively 16% and 11% for side and middle columns. It is also worth mentioning that in case of far-field earthquakes the maximum axial force in some middle columns of the building in its 10th and 16th stories is compressive, while in case near-field excitations the maximum axial force in the same columns is tensile.

3-2- Inter-story Drift Ratios

The other response value which is of great concern in seismic design is the inter-story drift ratios. Figures 14 and 15 show the average values of maximum inter-story drift ratios based on seven far-field as well as seven near-field earthquakes for comparison.

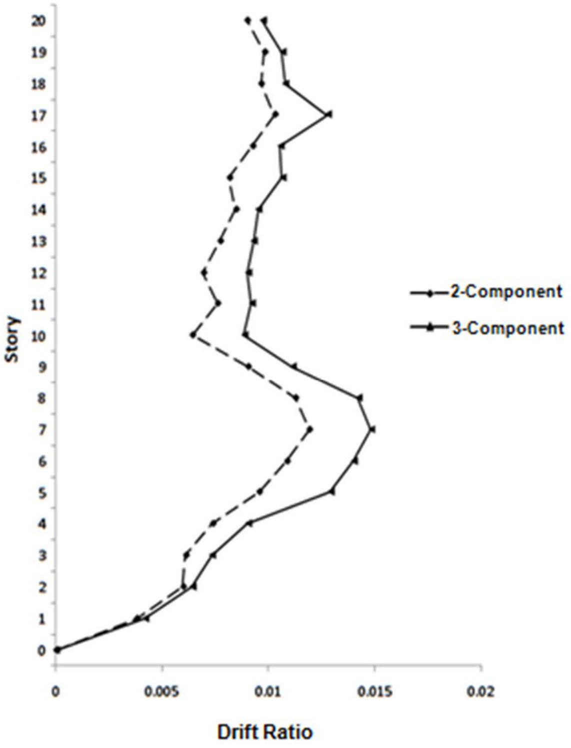

Figure 14- Comparison of the average values of maximum inter-story drift ratios in the building subjected to far-field earthquakes in two cases of 2- and 3-Component excitations

It is seen in these two figures that the average amount of the maximum inter-story drift ratios are generally more in case of 3-Compinent accelerograms than 2-Component ones. Based on Figure 14 the amounts of increase in the average values of maximum inter-story drift ratios for the case of 3-component accelerograms comparing to the case of 2-component accelerograms for far-field earthquakes are 24%, 32% and 14% respectively for the 7th, the 10th and the 16th story of the studied 20-story building. Also Figure 15 shows that the amounts of increase in the average values of maximum inter-story drift ratios for the case of 3-component accelerograms comparing to the case of

2-component accelerograms for near-field earthquakes are 26%, 34% and 21% respectively for the 7th, the 10th and the 16th story of the building.

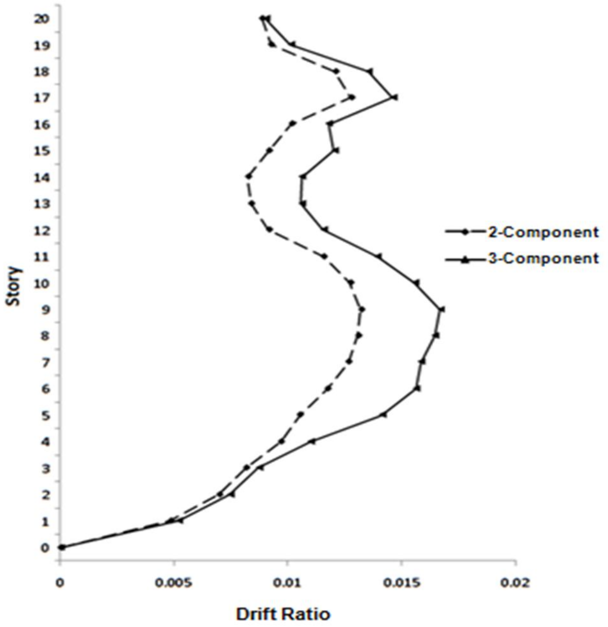

Figure 15- Comparison of the average values of maximum inter-story drift ratios in the building subjected to near-field earthquakes in two cases of 2- and 3-Component excitations

Figures 14 and 15 show that the amount of difference between the average values of the maximum inter-story drift ratios in the intermediate stories of the building is larger than the lower and upper stories for both 2-Component and 3-Component accelerograms.

To make a better comparison between the average values of maximum inter-story drift ratios in the two cases of far- and near-field earthquakes these values are shown in Figure 16. Based on this figure in general the average values of the maximum inter-story drift ratios are higher in case of near-field earthquakes than far-field earthquakes. The amounts of increase in the average values of the maximum inter-story drift ratios for the case of 3-component accelerograms of near-field earthquakes comparing to those of far-field earthquake are 10%, 42% and 15% respectively for the 7th, the 10th and the 16th story of the building.

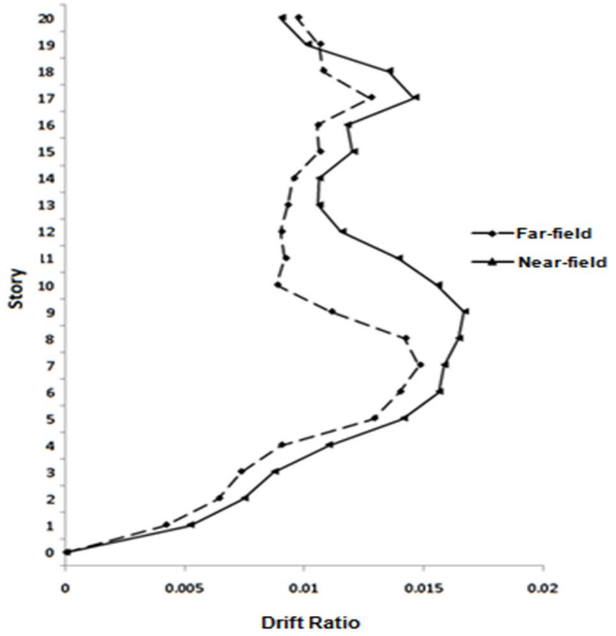

Figure 16- Comparison of the average values of maximum inter-story drift ratios in the building subjected to far- and near-field earthquakes with 3-Component excitations

4- Conclusions

Based on the results of the NLTHA, conducted in this study for a 20-story building with tubular structural system, the following findings can be mentioned:

- Applying 3-Component earthquake accelerograms instead of 2-Component ones causes the increase of axial force in side and middle columns of the tension flange of the tubular system. This is vice versa for the compression flange.
- The amount of increase in axial forces of columns were observed around 17% to 32% for far-field earthquakes and 22% to 37% for far-field ones.
- Due to applying 3-Component accelerograms the amount of shear lag increases around 11% to 15% for far-field earthquakes and around 13% to 19% for near-field ones.
- Applying 3-Component accelerograms causes around 24% and 27% increase in the average values of the maximum inter-story drift ratios, respectively for far- and near-field earthquakes.

Based on the abovementioned findings it can be recommended to consider more appropriate provisions for design of buildings with tubular systems located in near-source areas, particularly for columns and foundations.

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