Evaluating Probable Bending of Frames for Near-Field and Far-Field Records

Majid Saaly, Shahriar Tavousi Tafreshi, Mehdi Nazari Afshar

***Abstract*—**Most reinforced concrete structures are designed only under heavy loads have large transverse reinforcement spacing values, and therefore suffer severe failure after intense ground movements. The main goal of this paper is to compare the shear- and axial failure of concrete bending frames available in Tehran using Incremental Dynamic Analysis (IDA) under near- and far-field records. For this purpose, IDA of 5, 10, and 15-story concrete structures were done under seven far-fault records and five near-faults records. The results show that in two-dimensional models of short-rise, mid-rise and high-rise reinforced concrete frames located on Type-3 soil, increasing the distance of the transverse reinforcement can increase the maximum inter-story drift ratio values up to 37%. According to the existing results on 5, 10, and 15-story reinforced concrete models located on Type-3 soil, records with characteristics such as fling-step and directivity create maximum drift values between floors more than far-fault earthquakes. The results indicated that in the case of seismic excitation modes under earthquake encompassing directivity or fling-step, the probability values of failure and failure possibility increasing rate values are much smaller than the corresponding values of far-fault earthquakes. However, in near-fault frame records, the probability of exceedance occurs at lower seismic intensities compared to far-fault records.

***Keywords*—**Directivity, fling-step, fragility curve, IDA, inter story drift ratio.

I. Introduction

THE new generation codes are moving towards performance-based design (PBD) concept and exact displacement criteria estimation to assess structural failure. The amount of damage caused by earthquakes depends on many factors such as rupture mechanisms, fault distance to the site, soil type, earthquake record properties, including frequency content, duration, amplitude, and dynamic properties of the structure. Since 1960, earthquakes have been divided into two categories of near-field and far-field according to the distance of site to the fault location. It is generally assumed that ground motion reporting by the station at less than 20 km from the fault is a near-fault record. The characteristics of near-fault ground motions are directly related to the seismic source mechanism, the direction of fault rupture relative to the site, and the permanent ground deformations due to tectonic fault movements. After the Parkfield, California earthquakes of 1966 and the Pacquimao, San Fernando earthquake of 1971, the term near-fault earthquake was coined by Bolt [1], [2]. Although close effects of the fault were known in the past, the significance of this issue in the design of structures was not well understood until the devastating earthquakes such as the 1992 Landers earthquake, the 1994 Northridge earthquake, the 1995 Japan Kobe earthquake, and the 1999 Chi-Chi, Nantou County earthquake in Taiwan, in which the effects of near-fault earthquakes were studied [3], [4]. In the Northridge earthquake, many code-based designed structures were damaged.

In 2000 [7], "A Parametric Study of the Response of Steel Moment Frames under the Near-Fault Records with funding from the US Federal Emergency Management Agency (FEMA)" was published. Based on the results of this study, it was found that inelastic stress is generally created in the beams, but a significant amount of yield occurs in the columns [5]-[7]. So, the seismic codes design forces for near-fault earthquakes must increase to consider the effects of near-fault records. The near-fault earthquakes have velocity pulses and apply a large amount of energy to the structure during an earthquake. The velocity pulses of near-fault ground motions are much higher than far-fault ones. It means that the near-fault earthquakes transmit large velocity pulses with long-period to structures. The researchers have suggested different distances between 10 and 60 km as the near-fault areas [1], [8]. The UBC-97 code states that stations with distances of fewer than 15 km toward their sources would be supposed near-fault earthquakes. But today, it is commonly assumed a distance of 20 km for the near-fault zone. Chopra [2] studied 15 earthquakes which were scaled according to the UBC 97 code's design response spectrum. They showed that the effects of directivity increase the response spectrum at periods greater than 0.6s. Some conclusion reveals efforts to identify the characteristics of near-fault earthquakes showed that these earthquakes had large pulses in directivity of the Earth's velocity mapping. Some conclusions indicate that near-fault records had very high-frequency content and had visible deformations due to the occurrence of Fling-step in areas adjacent to faults [3], [10]. If the propagation velocity of a fault to a site is close to the shear wave velocity in the soil of that site (approximately 80% of the shear wave velocity), then earth motion velocity mapping has a pulse species component. This pulse-type component in velocity mapping has a significant amount of cumulative energy that is released in a short time and imposed on the structures [2]. Another destructive feature of the near-fault records is the occurrence of permanent deformations, which increases the demand for displacement in structures. However, the permanent deformations of the region have a limited effect,

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and their seismic importance is less than the directivity [3]. The main factor in the production of permanent deformations is the unilateral pulses resulting from directivity. That is why some researchers are using mathematical models to approximate the pulse type of velocity mapping, to find the elastic and non-human responses of the resulting structures. Instead, some researchers prefer to separate and examine the effects of directivity and the effects of permanent deformations through methods of processing non-resident signals [2], [3].

Past studies [2], [3] showed that long transverse reinforcement spacing of reinforced concrete columns leads to a sharp decrease in the bearing capacity of axial loads. So, the distribution of gravity loads has an important role in this type of destruction in reinforced concrete frames. In 2003 [3], shake table tests have been performed to discover the exact sequence of shear and axial fractures of reinforced concrete columns, as well as the effects of these failures on the stability of concrete frames. However, there are still so many ambiguities in this regard. Therefore, it is obvious that minimizing the loss of life, economy, society, etc. losses require the development and dissemination of analytical perspectives on the vibrations of nearby earthquakes [5].

In this article, the exact effects of cross-sectional reinforcement column spacing on shear-axial failure in reinforced concrete frames of 5, 10, and 15-story have been studied. Also, a comparison of seismic requirements of frames with suitable stirrup spacing (15 cm) under near-fault and far-fault was conducted. Investigating the relationship between the total height of the structure and the probability of structure failure (short-rise to high-rise), and the effects of directivity and Fling-step phenomena on shape and rate of increase in the exceedance probability curves have been carried out.

II. Literature Review

A. Shear And Axial Rupture of Concrete Columns

Many parameters affect the capacity of reinforced concrete moment frames, and so far many numerical and experimental studies have been performed to find the exact evaluation of these parameters. The results of studies on shear and axial loads of reinforced concrete columns showed that the ratio of transverse reinforcement of columns and their initial axial load have the most significant roles in the ductility of existing structures [5]. In 2003, Elwood et al. [6] evaluated shear axial columns failure under high axial loads. They found that a sample with a lower axial load had a greater suffering capacity under secondary axial loads. In 2011, Marzban et al. [5], after conducting seismic tests on reinforced concrete frames with three 1-story openings and comparing the results with dynamic simulation, found that axial springs should be used to identify the overall destruction of the structure. In 2010, Wu et al. [8] performed shake table tests and numerical studies to find out axial failure modes of reinforced concrete columns based on ASCE-SEI 41-06 codes. The results of their numerical simulations were very consistent with the experimental tests. They found that frames with high transverse reinforcement spacing experienced shear and axial failures. However, short transverse reinforcement spacings are more flexible and experience bending fractures. Cornell et al. [10] conducted a study to calculate the exact location of a critical shear crack event. They considered the critical shear cracks as the final limit of collapse and general failure. They found that in flexible columns, the exact location of the plastic region is equal to the distance of the transverse reinforcement.

B. Fragility Curves

Increasing IDA analysis [3] is one of the new methods in earthquake engineering based on performance, which expresses the behavior of the structure in a wide range of different seismic intensities. The basis of the IDA method is to control the desired structures, being analyzed for several or single earthquake acceleration records to obtain several points. By drawing and connecting these points to each other, a continuous image of the spectrum of structural behavior in all elastic stages to yield and finally failure of the structure is obtained and then a good view of the behavior is shown.

Seismic Vulnerability Assessment is defined as a function of reaching the level of damage at a given intensity of motion and can be represented as a possible failure matrix, a graph between the average failure ratio and the intensity of the earth's motion, or as a fragility curve. Determining the seismic vulnerability of buildings in the technical literature is common by using conventional fragility curves. In these curves, the degree of vulnerability is expressed as a probable outcome and in the form of a function of parameters such as earthquake intensity and probability of occurrence. Statistical data are used to draw these curves. Data are obtained in a variety of ways, depending on how the uncertainties are calculated. Uncertainties may result from field experience, laboratory studies, or numerical simulation. Fragility curves show the probability of structural damage as a function of the severity of seismic stimulation. Seismic excitation can also be the maximum ground acceleration, spectral acceleration corresponding to the first mode of the Sa structure (T1, 5%), spectral displacement (Sd), and so on.

Today, fragility curves express the probability that structural damage will pass from a certain level of damage to several levels of danger from seismic movements. In fact, the fragility curves reflect the uncertainties in the capacity and demand of the structure to determine the performance of the reflected structure. In a point-by-point analysis, the collision of two capacitance and demand curves will provide the expected level of performance of the building, and the performance of the structure will be at a certain point. However, due to the uncertainties in the capacity and demand of the structure, there will be a wide range of possible functions and also no clear point and definite answer [2]-[5].

C. Review of Literature on Near-Field Earthquakes

In areas close to the fault, the movement of the ground is strongly affected by the mechanism of failure, the direction of its fault is relative to the structure, and the permanent displacement of the ground is due to the static slip of the fault. Regulation UBC-97 considers a distance of less than fifteen kilometers (15 km) from the center as a close area. However, researchers have suggested different distances of 10 to 60 km as a close range [2]. Today, it is commonly assumed that the movements recorded less than 20 km from the fault site and the epicenter are near-fault mappings. The near-field movements have unique characteristics. These include the effect of rupture directivity, permanent deformation of the earth and high frequency content [1], [2]. When fault rupture extends to the site and fault direction is the same, a forward directivity occurs, and a large pulse is generated at the beginning of the record and in the direction perpendicular to the fault. If the site is in a position where the rupture propagation causes the fault to move away from the site, earthquake waves will slowly and proportionally reach the site over time, called reverse directivity. The sites outside the edge of the rupture plane and rupture that is not moved away from the site are called neutral directivity. The directivity occurs in both strike-slip faults and dip-slip faults. There is a big difference between near-fault record components in the directions of perpendicular and parallel to the site [12]. Therefore, when considering the distance close to the source, one should also consider its fault expansion direction. In near-fault earthquakes, Fling-steps were observed due to the constant deformation of the ground. Fling-step occurs in a few seconds during fault rupture. Fling-step is in the direction of fault slip (perpendicular to the rupture directivity). One of the salient features of the velocity record in the near-fault (forward directivity) is the existence of outstanding pulse (with large amplitudes and short duration time). In 2004 Bolt BA indicated that the dominant period changes from 0.35 to 1.2 seconds at near-fault distances. They proved that the pulse of forward-directivity is significant due to the creation of velocity and large movement on the ground. They also asserted that forward-directivity of a strike-slip fault, in high intensity increases the response spectrum in the normal-horizontal component. Bolt BA [1] showed that directivity effects increase the response spectrum at periods greater than 0.6 seconds. in 2001, Chopra et al. [2] found that being near the fault had significant effects on the quadrilateral response spectrum. In a way, it reduces sensitive areas quickly and increases areas sensitive to displacement and acceleration. The following conclusions were drawn from the study carried out by Chopra et al. [2]:

- The dominant period at intervals close to the fault jumps from 0.35 to 1.20 seconds.
- Pulse due to progressive directivity is important due to the production of speed and large displacements in the Earth.
- The effect of progressive directivity in strong ground motions increases the response spectrum in the normal-horizontal component in the slip line.
- The velocity pulses of near-field earthquakes are about 0.5 to 2 m/s.
- In near-field earthquakes, displacement pulses and long periods are about 1 to 3 seconds.

Near-field earthquakes have characteristics such as high vertical acceleration, lack of energy dissipation of earthquake waves, short duration of an earthquake, and differences in components.

In 2001 Chopra et al [2]. found that near-fault records significantly affect the quadrilateral response spectrum, reducing speed-sensitive areas, and increasing displacement/acceleration-sensitive areas. They also pointed out that the dominant period of near-fault zone changes from 0.35 to 1.2 seconds, and pulses caused by forward-directivity create high velocities and large ground displacements. In 2001, Chopra and Pakdee [2] found that for the same structures, near-fault earthquakes had much greater demand values, rather than far-fault ones. Researching near-fault earthquakes at Arzinkan station in Turkey, Kobe and Takatori stations in Japan, Lucerne station in Landers, and Los Gatos station in Loma Prieta, Pinchera et al. found that the acceleration and displacement spectra of Kobe, Taktori, and Los Gatos earthquakes were significantly higher than the spectral acceleration and displacement of the NEHRP 1997 code [20]. In 2006 [21], Kitada et al. studied the structural behavior of nuclear facilities under near-fault earthquakes with some special characteristics, including short time, strong directional effects, and low-frequency shock vibrations in the velocity component. Mavroeidis et al. [23] investigated the separation of pulses from the ground motions time history to provide an equivalent pulse and calculate the response of structures to this pulse. Via a detailed study of the behavior of moment frames under near-fault earthquake motions, Elwood, Moehle et al. found that the seismic responses of structures are dependent on spectral accelerations, the ratios of PGA and PGV, and Pulse Period of Near-Fault Ground Motions [3]-[6].

III. Characteristics of Near-Field Earthquakes

A. Directivity of Failure

When the fault failure is in the direction of the construction site and the fault directivity is in the same direction, the progressive permeability mode occurs. In this case, the failure spreads away from the epicenter to the construction site. Due to the proximity of the fault failure rate to the shear wave velocity (lower failure rate), the waves released in successive slips in the front of the failure path accumulate in the fault and technically energy accumulates in front of the failure and enters the structure as a strong shock. This shock forms a large pulse at the beginning of the record and in the perpendicular direction to the fault line. If the construction site is in a position where the failure spread causes the fault to be removed from the structure, the earthquake waves will reach the construction site slowly and proportionally over time; these conditions are called regenerative directivity. Locations that are outside the edge of the failure plate and the failure is not considered or removed from the affected area are called points with neutral directivity [2]-[6].

B. Permanent Location Change of Earth

In near-fault earthquakes, there are permanent displacements due to the change in the constant shape of the earthquake field, which is called the permanent fling-step. The permanent displacement of the earth occurs at separate intervals of a few seconds during the slip of the fault. Directivity change is in the direction of the fault slip (perpendicular to the fracture orientation). Therefore, they are not mainly combined with dynamic displacements due to the effects of failure directivity. In landslide faults, the pulse is due to the forward directivity in the direction perpendicular to the fault slip and then the change of the permanent displacement of the ground in the direction parallel to the fault slip occurs. In faults, the slope of the slip component of the pulse occurs perpendicular to the slip of the fault, and the change of the permanent displacement of the earth in parallel with the slip of the fault happens. The permanent location change occurs within a few seconds of the fault slip and due to the pulse of the one-way velocity, and the change of location is seen as a leap step in the time history [2], [3].

C. Pulse-Like Movement in Near-Fault Records

Studies of a large number of near-field earthquakes [3], [4], [6], such as the North Ridge earthquake, the Kobe earthquake, and the Taiwan and Turkey earthquakes show that in near-fault earthquakes, two significant factors that affect the earthquake are (i) the effect of forward-directivity or backward-directivity, which depends on the failure mechanism and the expansion of the fault and (ii) permanent change due to a slip in the fault. One of the prominent features of the speed record in the near-field (for the forward direction) is the existence of a strong pulse (with a large amplitude) with a considerable period length and short durability of time compared to the total durability of time of earthquakes. Pulse-type earthquakes may cause significant damage to buildings with moderate to high eruptions. Because the response ranges in near-fault earthquakes in the long-range period are different from the corresponding quantities in far-fault earthquakes. This pulse can appear in the history of acceleration, velocity, and reversal of many near-field records. The number of important pulses can be defined as the number of semicircular velocity pulses that have a value equal to at least 50% of the earth's maximum velocity. To calculate the number of important velocity pulses, only the perpendicular component to the fault is considered. Knowing more about the pulse-like motion, which is a clear feature of near-fault records, is essential to be aware of the actual behavior of structures under near-fault records [2], [3].

D. Close Effects of Faults in Vertical Earthquake Components

The vertical vibration of the earth is due to pressure waves (i.e. P waves) and S shear waves (i.e. S waves). If the fault shift is purely horizontal, the shear waves generated are of the horizontal shear type, and if the fault shift is only vertical, the shear waves generated are of the vertical shear wave. Since fault displacement is a combination of horizontal and vertical displacement, there are always horizontal and vertical shear waves. Research has shown that [2], [3] the majority of vertical earth vibrations belong to P waves, unless the seismic station is very close to the fault and the fault is normal or reverse, in which case the vertical vibration belongs to the vertical shear wave. This component decreases faster than the horizontal component of the earthquake as it moves away from the source of the earthquake. Based on analyzes of the vertical vibration of 5 earthquakes in California, it was found that volumetric waves or waves in less than 0.1 second P range and in the range of periods greater than 0.1 seconds, shear waves or S waves affect the vertical component of the earthquake. The vertical component on the earth's surface has a frequency content at high frequencies [2], [3].

IV. Simulation in OpenSees Software

A. Study Models

To evaluate and compare the maximum responses of 5, 10 and 15-story existing reinforced concrete frames with a distance of 15, 20, and 25 cm transverse reinforcement, two-dimensional models were evaluated under the effects of directivity and fling-step. The structures are assumed to be located in Tehran an area with a very high relative risk (according to the earthquake zoning map of Iran 2800) [12]. The important factor of I = 1, seismic zone factor of A = 0.35, soil type III, and the ultimate response modification factor of R = 7.0 have been considered within the frames design procedure. Frames have three five-meter spans and four symmetrical columns. The three-span 5, 10 and 15-story frames were designed by Sap2000 software. The story heights of the models were considered 4.0 and 3.2 m, respectively, in the case of the first and the other floors, and the length of the frame openings is 5 meters. Models have been loaded according to Section 6 of the National Iranian Building Code [13] and the analysis and design criteria following Section 9 of the National Iranian Building Code [13], [14], Code 2800 [12] and with the taken requirements of FEMA P-695 [15]. The bending, shear, and axial springs were set by a zero-length at both ends of the columns. Also, to model the rotation and deformation of longitudinal rebar in beams, bending springs were considered at both ends of beams. The stiffness of all springs was assumed to be following the reference formulas [11]-[16]. The purpose of simultaneously applying bending, shear, and axial springs in column elements is to investigate the simultaneous interaction of three modes of deformation in close to real-life conditions [9], [17]. All simulations were performed using OpenSees software [18]. To model the beams and columns, a non-linear beam-column element [6] with a wide distribution of plasticity along the element and fiber section [6], [8] was used. In the models, the effect of frame skeleton weight was ignored. The compressive strength of concrete is 20 MPa and 20,594 MPa of the modulus of elasticity. The yield strength of concrete is 0.002 and the final yield is 0.0052. The strain of concrete after the occurrence of flaking is considered to be 0.006. The longitudinal bars have a yield stress of 399 MPa and a modulus of elasticity of 200,000. The yield stress of transverse reinforcement is also equal to 300 MPa. The concrete cover of all the elements was considered to be five centimeters. Table I shows the details of the beams and columns of the 5, 10 and 15-story frames studied in this article, and Fig. 1 shows a schematic example of sectional behavior, elements, and springs used in this study. The connections of the nodes are considered to be rigid and their effect on the structure was ignored [10]-[13]. Elwood showed that shear and axial springs are only valid for columns with bending-shear modulus [15]. In this case, the column first experiences bending failure and then shear failure during demolition and if it has not yet entered into an unstable state, it will experience decentralization and instability as the drift and force increase [5]. In this dissertation, two-dimensional nonlinear dynamic analyzes that are required for IDA were performed in Opensees software [18]. All nonlinear time history analyzes were performed in two dimensions, with seven far-fault records and five near-fault records, taken from the Pacific Earthquake Engineering Research Center. All records are of earthquakes with a magnitude greater than 6.5 Richter and related to Type III soils following Standard no. 2800 (Fourth Edition) (similar to the assumed Earth material for the model of the studied frames). In far-fault records, the effects of the area near the fault were ignored, given that the distance between the recording stations and the fault was more than 10 km. In the process of performing IDA for 5,10 and 15-story models, damage measure [2], [3] is equal to the maximum drift between floors and the seismic intensity measure [3] was considered equal to the spectral acceleration corresponding to the first structural mode Sa (T1, 5%). All drawing of the fragility curves in this article were done using the concepts of the normal logo distribution function [5].

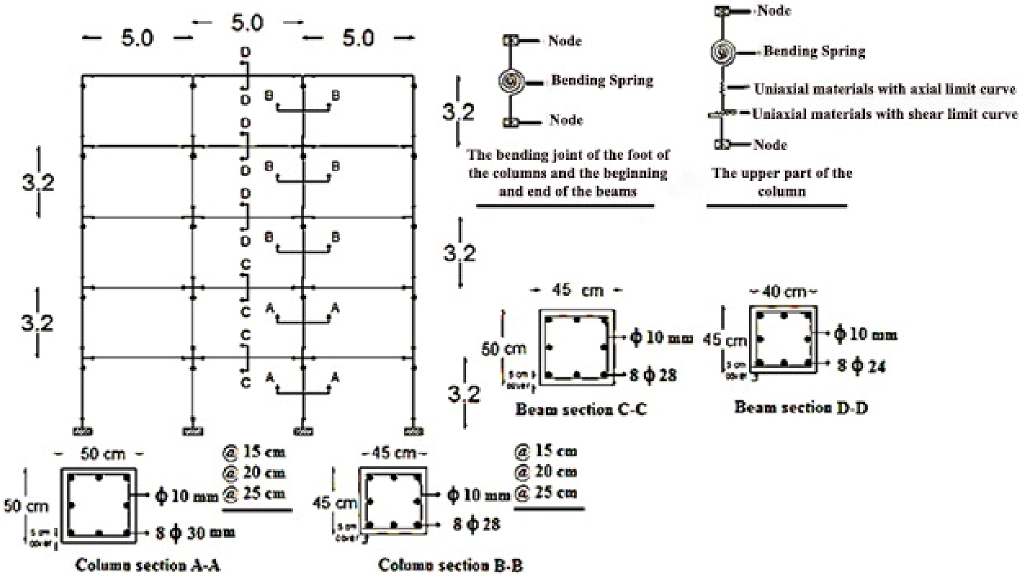

Fig. 1 Schematic examples of the behavior of the sections, elements and springs used in this research [16]

B. Studied Earthquakes

To study the models in this assessment precisely, five seismic far-fault records related to type III soil, and five seismic near-fault records were extracted from the Pacific Earthquake Engineering Research Center [19]. All records are of magnitudes greater than 0.6 Richter. In far-fault records, since the distances between the recording stations and the faults are more than 10 km, the effects of the near-fault area are more accurate. Tables II and III, respectively, show characteristics of far-fault and near-fault records related to type III soil, including the maximum ground acceleration (PGA), the earthquake magnitude and the shortest distance of the record station from the fault (d), and Figs. 2 and 3 show the charts of the acceleration response spectra of the records listed in Tables II and III, along with their mean values. In this article, as the analysis was not two sided, in all incremental time history analyzes, horizontal components specific to the stronger direction (with a larger PGA value) were used. Since the selection of acceleration record plays a very important role in the results of time history analyzes, in selecting the near-fault records in this article, the results of studies conducted by Kalkan and Kunnath [3] on changing permanent ground locations and forward orientation in near-fault records were used.

TABLE I
DETAILS OF THE BEAMS AND COLUMNS OF 5, 10 AND 15-STORY FRAMES

Model	Story	Columns	Beams
5 story	1,2	50 × 50 Cm 30 Φ 8	45 × 50 Cm 14 Φ 8 Top 14 Φ 8 Bottom
	3,4,5	45 × 45 Cm 28 Φ 8	45 × 50 Cm 14 Φ 8 Top 14 Φ 8 Bottom
10 story	1,2,3	55 × 55 Cm 32 Φ 8	50 × 55 Cm 15 Φ 8 Top 15 Φ 8 Bottom
	4,5,6	50 × 50 Cm 30 Φ 8	45 × 50 Cm 14 Φ 8 Top 14 Φ 8 Bottom
	7,8,9,10	45 × 45 Cm 28 Φ 8	40 × 45 Cm 12 Φ 8 Top 12 Φ 8 Bottom
15 story	1,2,3	60 × 60 Cm 36 Φ 8	55 × 60 Cm 15 Φ 10 Top 15 Φ 10 Bottom
	4, 5, 6, 7	55 × 55 Cm 32 Φ 8	50 × 55 Cm 15 Φ 8 Top 15 Φ 8 Bottom
	8, 9, 10, 11	50 × 50 Cm 30 Φ 8	45 × 50 Cm 14 Φ 8 Top 14 Φ 8 Bottom
	12, 13, 14, 15	45 × 45 Cm 28 Φ 8	40 × 45 Cm 14 Φ 8 Top 14 Φ 8 Bottom

TABLE II
SPECIFICATIONS OF FAR-FAULT RECORDS RELATED TO TYPE III SOIL [19]

	Earthquake Name	Year	Station	Mw	D (km)	PGA (g)
1	Chuetsu-Oki	2007	Kashiwazaki NPP, Unit 1	6.8	11.0	0.909
2	El Mayor-Cucapah	2010	Riito	7.2	13.71	0.39
3	El Mayor-Cucapah	2010	Cerro Prieto Geothermal	7.2	11.0	0.288
4	El Mayor-Cucapah	2010	Michoacan De Ocampo	7.2	16.0	0.538
5	Loma Prieta	1989	Gilroy Array #4	6.93	14.34	0.419
6	Morgan Hill	1984	Gilroy Array #4	6.19	11.54	0.349
7	Northwest China-03	1997	Jiashi	6.1	17.73	0.3

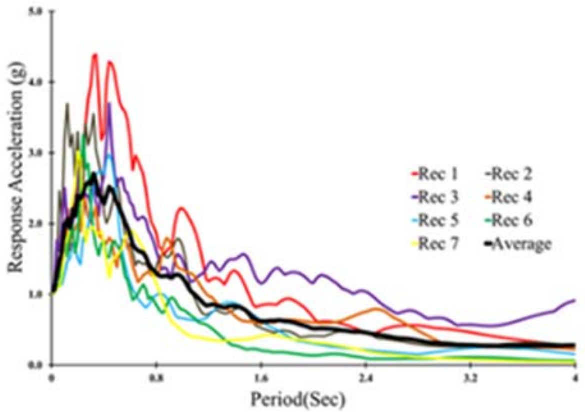

Fig. 2 Acceleration response spectrum of far-fault records specific to type III soil and their mean

TABLE III
SPECIFICATIONS OF NEAR-FAULT RECORDS RELATED TO TYPE III SOIL [19]

	Earthquake Name	Year	Station	Mw	D (km)	PGA(g)
1	Loma Prieta	1989	LGPC	6.93	3.88	0.57
2	Kocaeli_ Turkey	1999	Yarimca (YPT)	7.51	7.51	0.83
3	Chi-Chi, Taiwan	1999	TCU052	7.62	0.66	0.36
4	Chi-Chi, Taiwan	1999	TCU068	7.62	0.32	0.512
5	Chi-Chi, Taiwan	1999	TCU074	7.62	0.2	0.596

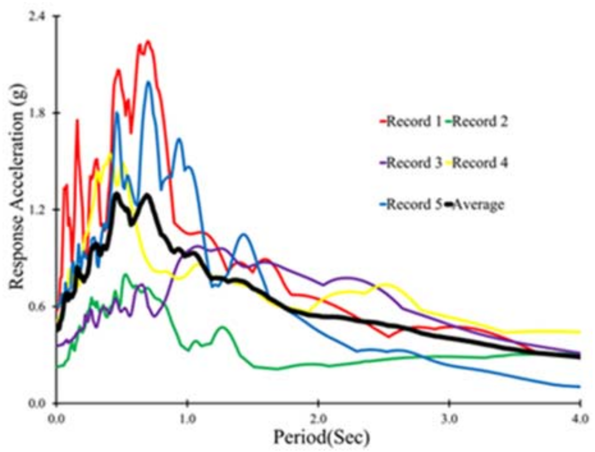

Fig. 3 Acceleration response spectrum of near-fault records specific to type III soil and their mean

C. Used Performance Levels

Table IV presents the values of drift modes between the authorized limit floors specified in the Hazus-MH MR-5 code [19] for different types of building types and different failure modes.

TABLE IV
DRIFT MODE VALUES BETWEEN THE AUTHORIZED LIMIT FLOORS SPECIFIED IN HAZUS-MH MR-5 REGULATIONS

	Inter-Story Drift Ration Value (%)			
Type	Sligh	Moderate	Extensive	Complete
C1M	0.0033	0.0067	0.02	0.0533
C1H	0.0025	0.005	0.015	0.04

V. SIMULATION IN OPENSEES SOFTWARE

A. Results of IDA Analysis

After performing IDA analysis under several different earthquake records, a set of IDA curves is obtained. In an IDA curve, each curve represents the specific behavior of the structure under a particular earthquake record and therefore does not indicate the overall seismic performance of the structure. To achieve an overview of structural behavior and reduce information dispersion, IDA curves can be summarized. Figs. 4 and 5 show IDA curve summary of 5, 10 and 15-story frames with a stirrup spacing of 15, 20, and 25 cm, under seven far-fault and five near-faults records, respectively. As shown in Figs. 3 and 4, IDA curves cover a wide range of seismic demands (such as a spherical ball) under near- and far-fault records. This indicates that the selection of near and far earthquakes has been made intelligently. According to Figs. 3 and 4 in the IDA curves of two-dimensional 5, 10 and 15-story frames with a stirrup spacing of 15, 20, and 25 cm, near-fault records can increase the maximum amount of inter-story drift up to 60% for 5, 10-story frames, and up to 234% for 15-story frames (compared to far-fault records). This indicates that the directivity and fling-step that are destructive characteristics of near-fault records cause extensive damage and large amounts of seismic demands. According to Figs. 3 and 4, in short-rise, mid-rise, and high-rise models of reinforced concrete located on Type III soil, with a distance of 15, 20, 25 cm transverse reinforcement located on Type III soil, increasing the distance between transverse reinforcement can maximize drift between floors up to a maximum of 37%. So, in all frames with 20 cm and 25 cm transverse reinforcement spacing, the maximum values of drift between floors are respectively reduced by 23 and 37%. Therefore, it is necessary to consider the distance of suitable transverse reinforcement (15 cm) in reinforced concrete structures located on type III soils and if it is not considered, there will be some probable hazards. In all short-rise, mid-rise, and high-rise models with a transverse reinforcement spacing of 15 cm for constant seismic intensity values, the maximum drift values between the lower floors are obtained compared to stirrup spacings of 20 and 25 cm. In addition, when using transverse reinforcement at distances of 15 cm, maximum fixed drift values between floors occurred at higher seismic intensities. Therefore, choosing the appropriate distances for the stirrups in the columns has significant effects on reducing the dynamic response of short, medium, and high-order structural models. According to the results, frames with suitable transverse reinforcement spacings (15 cm) have a better seismic performance from the points of view of reducing the maximum values of floor drift, and energy loss, and reducing dynamic responses in various short, medium, and high order models.

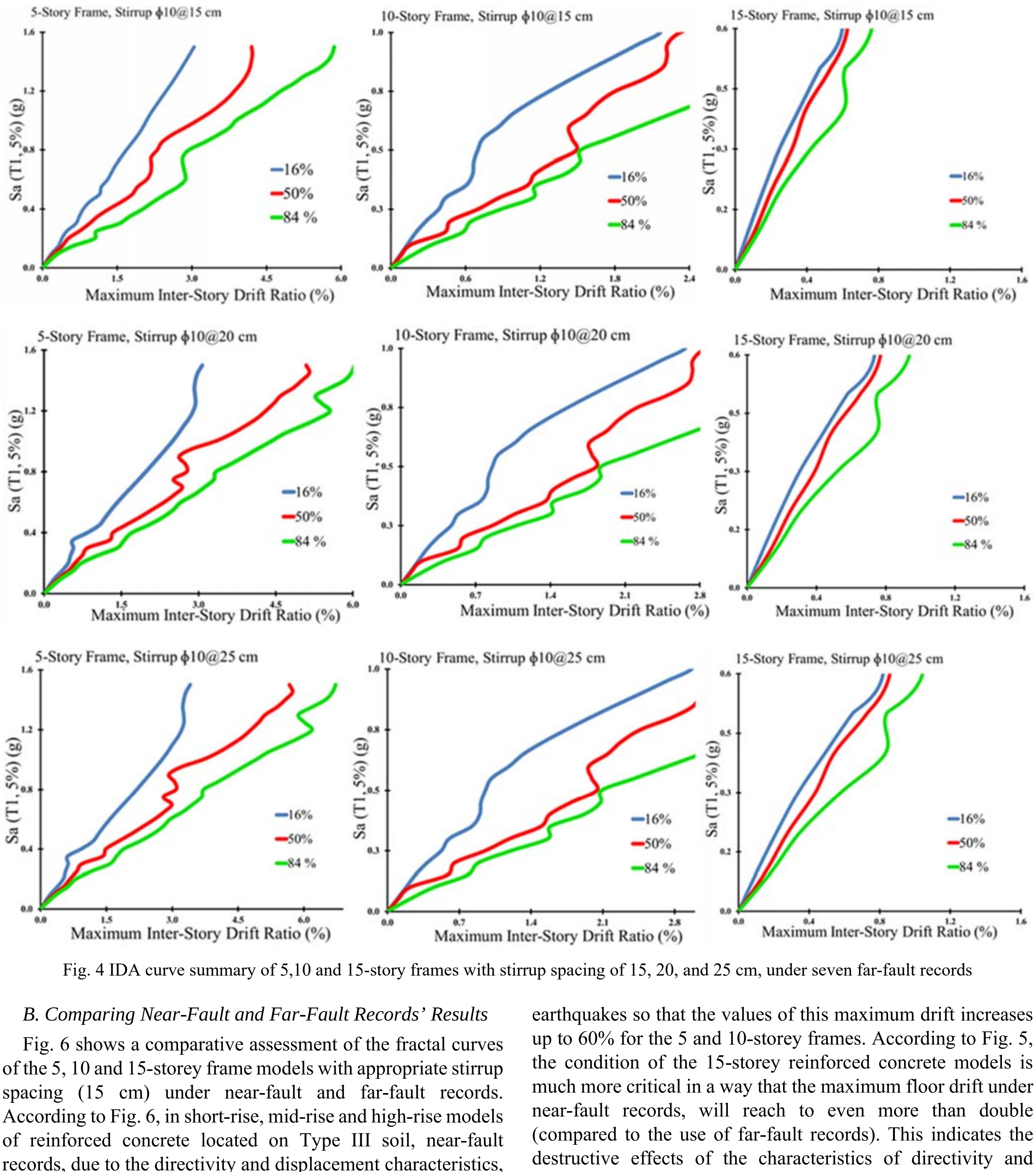

Fig. 4 IDA curve summary of 5,10 and 15-story frames with stirrup spacing of 15, 20, and 25 cm, under seven far-fault records

B. Comparing Near-Fault and Far-Fault Records' Results

Fig. 6 shows a comparative assessment of the fractal curves of the 5, 10 and 15-storey frame models with appropriate stirrup spacing (15 cm) under near-fault and far-fault records. According to Fig. 6, in short-rise, mid-rise and high-rise models of reinforced concrete located on Type III soil, near-fault records, due to the directivity and displacement characteristics, creates maximum drift between floors comparing to far-fault earthquakes so that the values of this maximum drift increases up to 60% for the 5 and 10-storey frames. According to Fig. 5, the condition of the 15-storey reinforced concrete models is much more critical in a way that the maximum floor drift under near-fault records, will reach to even more than double (compared to the use of far-fault records). This indicates the destructive effects of the characteristics of directivity and permanent displacement.

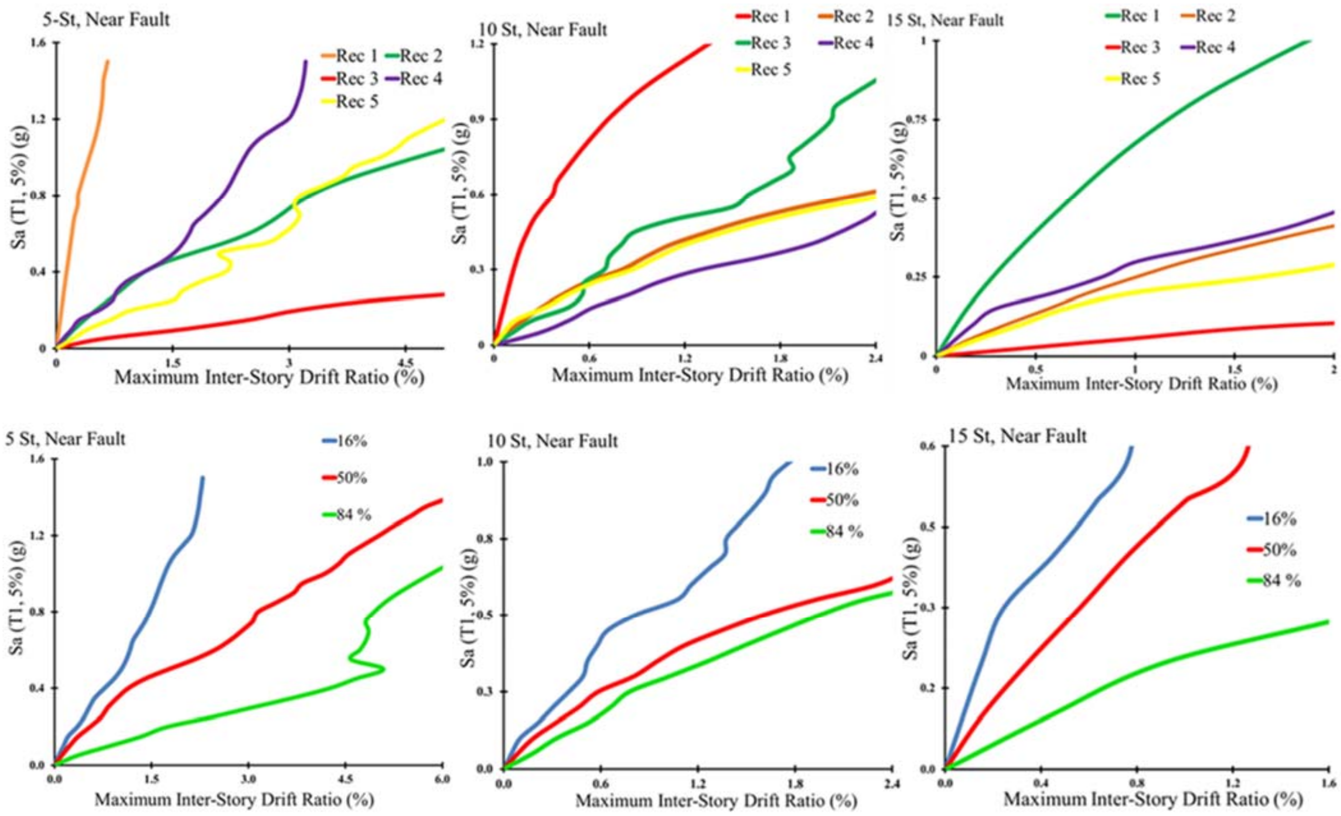

Fig. 5 IDA curve summary (and IDA Curves) of 5,10 and 15 story frames, under five near-fault records

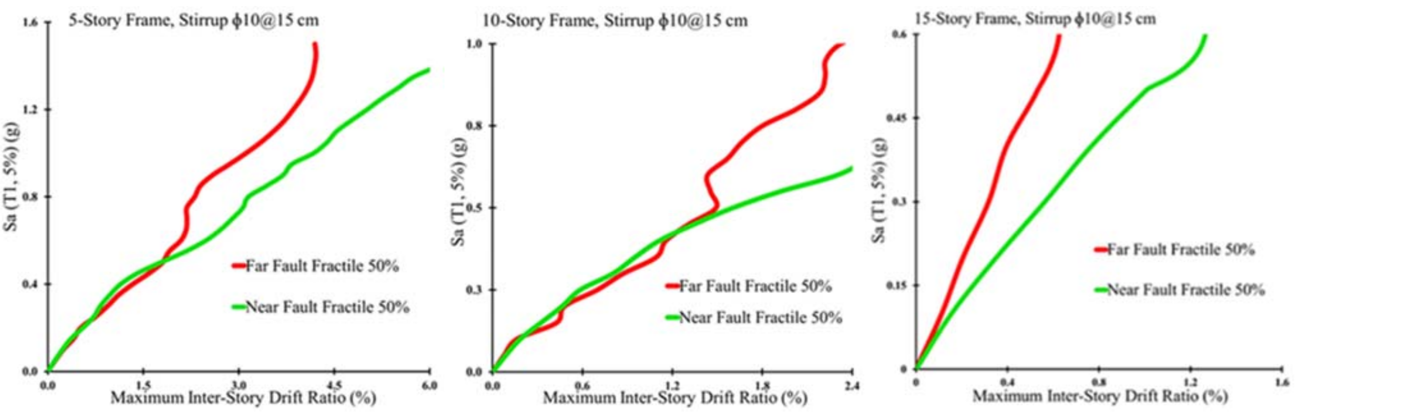

Fig. 6 Comparison of fractal curves of 5, 10 and 15-storey frame models under near-fault and far-fault records

C. Fragility Curve of Models

Figs. 7-9 show a comparison of the fragility curves of different models of 5, 10 and 15-storey frames with suitable stirrup spacing (15 cm) under near-fault and far-fault records.

As can be seen in the figures, in all 5, 10 and 15-storey models under near-fault and far-fault records, the probability of structural failure exceeding a certain level increases with increasing Sa (T1, 5%). In addition, a comparison of the fragility curves of near-fault and far-fault earthquakes shows that with increasing altitude, the vulnerability of structures at the four levels of failure is slightly increased. The results show that in all short-rise, mid-rise and high-rise frames, in case of seismic excitation modes under far-fault records, the values of the rate of probable failure or the rates of increasing of failure (the slopes of the fragility curves) are much higher than the corresponding values under near-fault records and this fact is extended to all levels of functions such as slight, moderate, extensive and complete. Although in general, it can be concluded that in all frames under near-fault records, the values of the probable failure rate at much lower seismic intensities are obtained comparing to far-fault records. This indicates that the phenomena of kicking and directivity play a destructive role on the structural behavior of short-rise, mid-rise and high-rise frames.

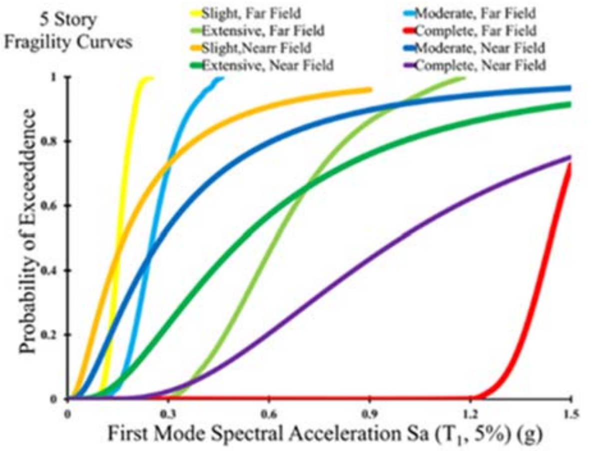

Fig. 7 Comparison of fragility curves of 5-storey model under near-fault and far-fault records

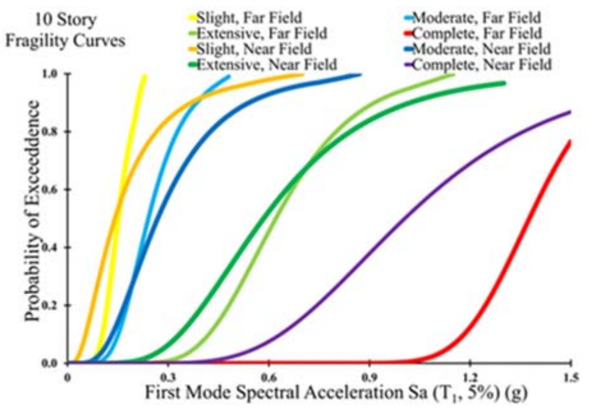

Fig. 8 Comparison of fragility curves of 10-storey model under near-fault and far-fault records

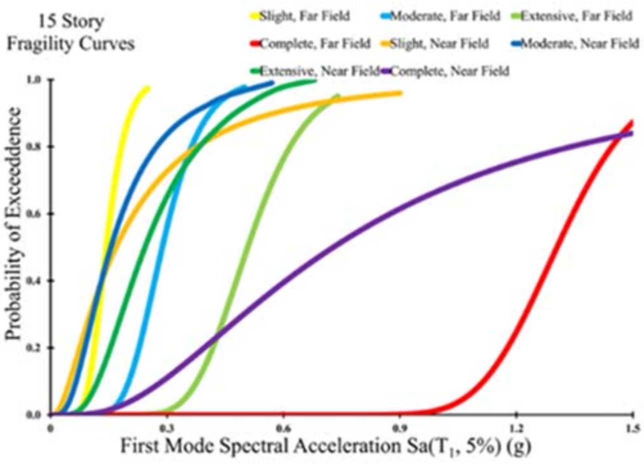

Fig. 9 Comparison of fragility curves of 15-storey model under near-fault and far-fault records

VI. Conclusion

The results of the IDA curves for the maximum ratio of relative displacement within the two-dimensional models of the existing 5, 10 and 15-storey reinforced concrete frames signifies that:

1. In two-dimensional models of short-rise, mid-rise and high-rise frames of reinforced concrete located on type III soil, increasing transverse reinforcement spacings can increase the maximum drift between the floors by up to 37%. Therefore, it is necessary to consider suitable transverse reinforcement spacings (15 cm) in reinforced concrete structures located on type III soil, and there may be unrealistic results and possible risks if it is not considered.
2. In all models with a transverse reinforcement spacings of 15 cm per constant seismic intensity values, the maximum drift between the lower floors is obtained compared to the modes of using stirrup spacings of 20 and 25 cm. In addition, when using the transverse reinforcement spacings of 15 cm, the maximum drift between the floors occurred at higher seismic intensities. Consequently short-rise, mid-rise and high-rise frame models with 15 cm stirrup spacings have better seismic performance from the reducing maximum floor drift, energy loss, and dynamic response.
3. In models with 15, 20 and 25 cm stirrup spacings, failure modes are of bending-shear and axial ones and increasing the stirrup spacings has a significant effect on reducing the shear strengths of different models of short-rise, mid-rise and high-rise.
4. The results of IDA analyses for short-rise, mid-rise and high-rise models of reinforced concrete available on Type III soil indicate that near-field records, due to the characteristics of directivity and permanent displacement, have maximum drift between floors comparing to far-fault earthquakes in way that the values of this maximum drift increase are up to 60% for 5, 10-storey frames, and up to 234% for 15-storey frames.
5. In all short-rise, mid-rise and high-rise frames, in the case of seismic excitation modes under far-fault records, the values of probability of failure or the rate of increasing the possibility of failure are much higher than the corresponding values of near-fault records.

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