Probabilistic Characteristics of older PR Frames in the Mid-America Earthquake Region

Do-Hwan Kim and Roberto Leon

***Abstract*—**Probabilistic characteristics of seismic responses of the Partially Restrained connection rotation (PRCR) and panel zone deformation (PZD) installed in older steel moment frames were investigated in accordance with statistical inference in decision-making process. The 4, 6 and 8 story older steel moment frames with clip angle and T-stub connections were designed and analyzed using 2%/50yrs ground motions in four cities of the Mid-America earthquake region. The probability density function and cumulative distribution function of PRCR and PZD were determined by the goodness-of-fit tests based on probabilistic parameters measured from the results of the nonlinear time-history analyses. The obtained probabilistic parameters and distributions can be used to find out what performance level mainly PR connections and panel zones satisfy and how many PR connections and panel zones experience a serious damage under the Mid-America ground motions.

***Keywords*—**Mid-America earthquake, Panel zone, PR connection, Probabilistic characteristics, seismic performance

I. Introduction

THE role of probability is quite pervasive in engineering. It ranges from the description of information to the development of bases for design and decision making. Most of all, the significant role of probability concepts is in the utilization of this information in the formulation of proper bases for decision making and design [1].

The techniques of deriving probabilistic information and of estimating parameter values from observed data are embodied in the methods of "statistical inference", in which information obtained from sampled data is used to make generalizations about the populations from which the samples were obtained. Inferential methods of statistics, therefore, provide a link between the real world and the idealized probability models assumed or prescribed in a probabilistic analysis. The role of statistical inference in the decision-making process is schematically shown in Fig. 1.

Once the distribution function of a random variable and the values of its parameters are known, the probability associated with events defined by values of the random variable can be computed. The calculated probability is clearly a function of the values of the parameters, as well as of the assumed form of distribution.

Do-Hwan Kim is with the Research Institute of Industrial Science and Technology (RIST), Incheon, 406-840 South Korea (phone: +82-32-200-2434; fax: +82-32-200-2449; e-mail: dohwan.kim@rist.re.kr).

Roberto Leon is with the Civil and Environmental Engineering Department, Georgia Institute of Technology, Atlanta, GA 30332 USA (phone:+1-404-894-2220; e-mail: roberto.leon@ce.gatech.edu).

In general, to evaluate seismic performance of a building, only the maximum response demands of the primary indices such as inter-story drift, connection rotation, plastic hinge rotation, panel zone deformation, etc are considered from the results of the nonlinear time history analyses. However, these maximum demands consider only one element ignoring other demands in a frame. In other words, it is questionnaire what response demands were observed and how severely other members were damaged in a building.

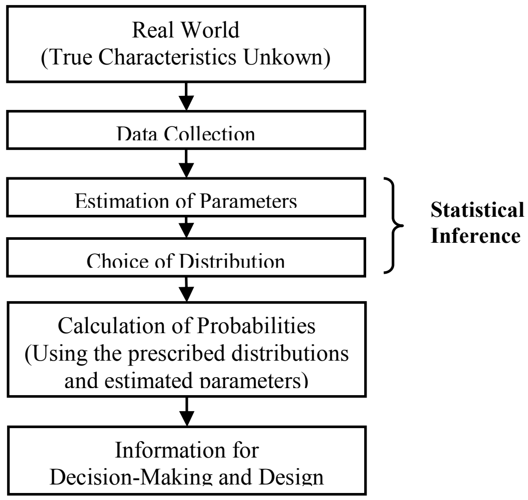


Fig. 1 Statistical inference in decision-making process

To address these issues, this study estimates the probabilistic characteristics of seismic response demands of the local connection elements in a steel moment frame using probabilistic approaches shown in Fig. 1. Partially restrained connection rotations (PRCR) and panel zone deformations (PZD) in older steel moment frame built in 1950-60s are selected as response indices because their responses vary dependent on many factors such as their installed locations, adjacent beam depth, column size, etc. Uncertainties and randomness in the connection behavior also exist due to the variability in the material properties, tightening of bolts, fit-up of parts, and even analytical models. Since it is impossible to gather these data in real world, the nonlinear time-history (NTH) analysis results obtained in Kim and Leon [2] were utilized.

II. Frame Modeling and Ground Motions

A. Target Frame

The 4, 6, and 8-story older steel frames designed in this study have 3 bays by 3 bays. Bay lengths are 20ft-10ft-20ft

(6.1m-3.05m-6.1m) in the North-South (NS) direction and three 20ft (6.1m) in the East-West (EW) direction. All connections of the older frames were designed as PR connections. Therefore, this building consists of moment-resisting frames in the NS direction and braced frame in the EW direction. There are no leaner columns in this configuration. Figs.2 and 3 show the typical floor framing plan and 6-story elevation of the older frame. In Fig. 2, the thick lines in the building plan represent the moment-resisting frames. The building elevation shown in Fig. 3 represents the target frames 1 and 2 boxed in building plan which will be designed and analyzed using the SAP2000 and DRAIN-2DX programs, respectively. Frames 1 and 2 are linked by rigid element with hinge connection to enforce a rigid

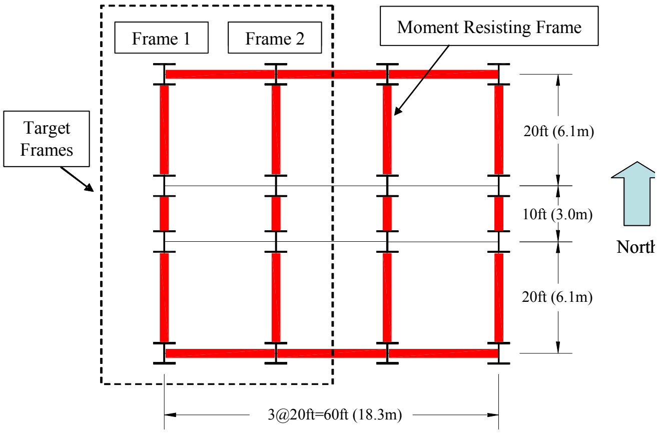


Fig. 2 Typical building plan

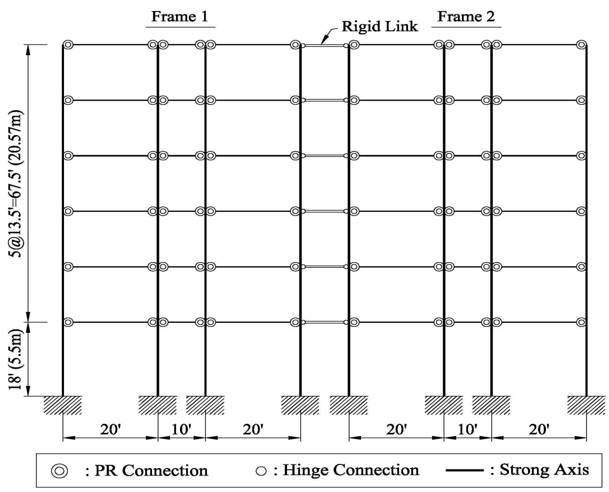
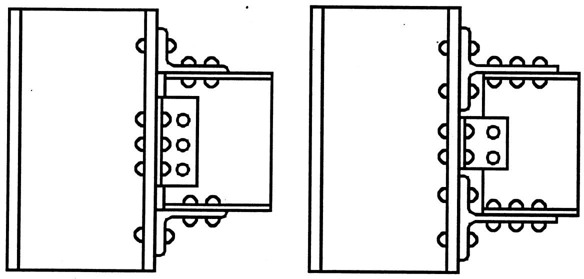


Fig. 3 Elevation of the 6-story older frame

diaphragm constraint. There are no weak axis columns in this frame configuration. This frame was designed in accordance with the 1952 AISC Steel Design Specification [3] for gravity and the 1948 Joint Committee Recommendations of San Francisco [4] for lateral load.

B. PR Connections

Typical connections used in older structures are clip angle (CA) or T-stub (T) connections as shown in Fig. 4. The former is typically used in low-rise structures and the latter is used in taller structures. In this study, both connections were selected for the older frame and modeled by curve fitting the test results of Roeder et al. [5] and Forcier [6] for CA and T connections, respectively, which resulting connection response was very pinched and resembled more the behavior of non-seismic concrete construction than what is customarily expected of steel construction. As a result, the yield rotation, θ_y, of CA and T connection models was 0.0075 rad and 0.003 rad, respectively. Also, initial rotational stiffness, k_θ, of T models was approximately 2.5 times stiffer than that of CA models.



(a) Clip angle connection (b) T-stub connection

Fig. 4 Typical older PR connections

C. Ground Motions

The Mid-America earthquake (MAE) region is defined as the region of the central and southeastern U.S. comprising those states that have expected ground motions greater than 0.1g for the 10% probability of exceeding in 50 years. The causes and effects of earthquakes in the western U.S. are reasonable well understood because many earthquake events are associated with surface faulting. In contrast to the western U.S., the causes of earthquakes in the MAE region are beginning to be understood for about 10 years ago. USGS and CERI scientists estimate that there is a 25-40% chance of a magnitude 6.0 or greater

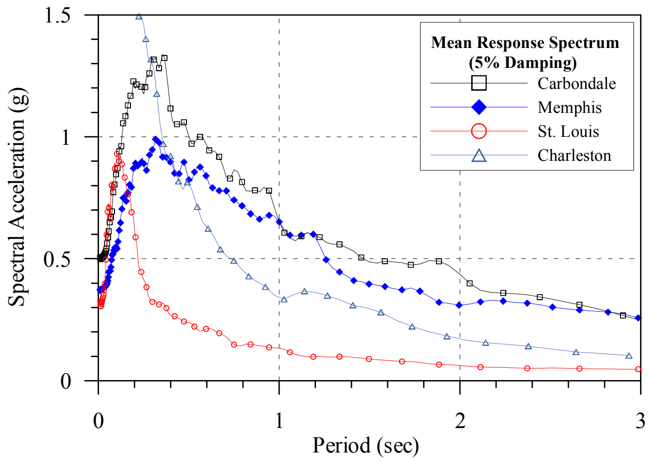


Fig. 5 Mean response spectrum of 2%/50yrs ground motions

earthquake occurring in the next 50 years [7].

The synthetic ground motions having 2% probability of exceeding in 50 years (2%/50yrs) seismic hazard level are selected for nonlinear analyses for the cities of Carbondale, Illinois, St. Louis, Missouri and Memphis, Tennessee developed by Wen and Wu [8] and Charleston, South Carolina developed by Papageorgiou et al. [9]. There are 10 ground motions per each city. Therefore, total 40 NTH analyses were conducted in each frame. Fig. 5 shows the mean response spectra of 10 ground motions at each city with 5% damping.

III. Estimates of Probabilistic Parameters

A. Introduction

The probabilistic characteristics of random variables - the PRCR and PZD - can be described completely if the form of the distribution function (or equivalently its probability density or mass function) and the associated parameters are specified. However, since the form of the distribution function is unknown, an approximate description of a random variable is often necessary.

The probabilistic characteristics of a random variable can be described approximately in terms of its main descriptors [1]. The most importance of these is the central value and a measure of the dispersion of its values. A skewness measure is also important and useful when the underlying distribution is known to be asymmetric. In this study, the mean, median, and mode are used as the central values of the PRCR and PZD data. The standard deviation (STD) and coefficient of variation (COV) are considered as the measure of dispersion. The skewness and 95% confidence intervals are also computed. Based on these histograms, the probability distributions are estimated.

B. Data Collection

The probabilistic characteristics of the PRCR and PZD were estimated for the CA and T connection models. The NTH results for the four cities - Memphis, Carbondale, St. Louis, and Charleston - were combined as one because this research focused on estimating probabilistic characteristics in the MAE region. It is obvious that the response demands vary per the locations installed in a frame such as floor level, column locations, etc. Therefore, the connections and panel zones were classified largely with 4 different locations per their installed locations in a frame (inside or outside of columns and roof or typical floors) to collect the response demands. Table I shows the acronym of PRCR and PZD locations and Fig. 6 shows the schematic view of collecting zones. Probabilistic characteristics of PRCR and PZD were estimated based on these 4 locations.

TABLE I
Acronym of Response Demand Collecting Locations

Level	Column	PRCR	PZD
Floor	Interior	L1PR	L1PZ
	Exterior	L2PR	L2PZ
Roof	Interior	L3PR	L3PZ
	Exterior	L4PR	L4PZ

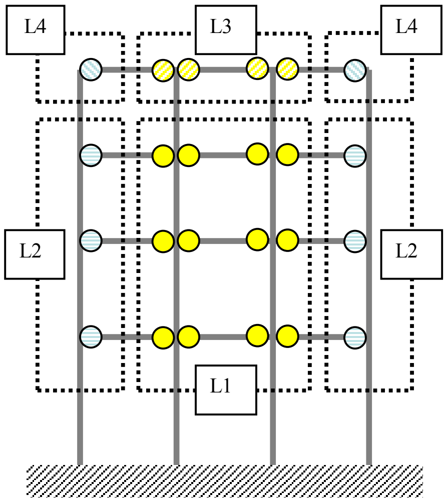


Fig. 6 Schematic view of four collecting locations

C. Parameter Estimates of PRCR and PZD

Tables II to IV present the measures of the main descriptors of the 4, 6 and 8 story older frames, respectively. The units for all estimators except COV and skewness are a milli-radian (mrad). The COV and skewness are unitless. From Table III, the mean of the T connection rotations in the L1PR is 7.04 and the 95% CI is 0.23. This implies that the mean value of the L1PR lies between 7.04±0.23 mrad with a probability of 95%. From these data tables, the following observations can be made: the demands at roof level such as the L4PR, L3PZ, and L4PZ for both the CA and T models were negligible since rotational demands of most connections were in elastic range or slightly over the yield limits; the demands of the L1PR and L1PZ were larger than the other locations; the PRCR of the T connections were approximately 40%-50% lower than those of the CA connections at each model; the median demands of the L1PZ for both connection models decreased markedly as the number of stories increased. This is due to the fact that panel zone strengths depend on column size; that is, Story↑ ⇒ Column size↑ ⇒ Panel zone (PZ) Strength↑.

Based on the estimated measures, the probability density function (PDF) and cumulative distribution functions (CDF) for each case were estimated.

IV. Probability Distributions of PRCR and PZD

A. Choice of Distribution

There are two main types of probability distributions available: discrete distributions and continuous distributions. For discrete distributions, there are Bernoulli, binomial, geometric, Poisson, uniform distributions, etc. A continuous distribution is one that can take on any value in some interval, such as [0 to infinity] (non-negative real numbers) or any value [a to b]. An unbounded distribution is one that can take on any real number and, thus, has a range of (-infinity, infinity). A bounded distribution is one that can take on any value in a finite

TABLE II
PROBABILISTIC PARAMETERS OF 4 STORY OLDER FRAME

Loc'n	N[a]	Mean[b]	Median[c]	Mode[d]	STD	COV	Skewness	95% CI[e]
CA connection (θ_y=7.5 mrad)								
L1PR	720	9.43	9.09	10.59	3.90	0.41	0.35	0.28
L2PR	360	8.66	7.26	13.01	3.82	0.44	0.34	0.39
L3PR	240	6.91	5.55	10.34	3.09	0.45	0.46	0.39
L4PR	120	4.31	4.73	4.90	1.25	0.29	-0.49	0.22
L1PZ	360	9.60	9.70	16.92	6.75	0.70	0.36	0.70
L2PZ	360	6.80	6.23	7.72	4.79	0.70	0.55	0.49
L3PZ	120	3.04	2.39	4.76	2.29	0.75	1.17	0.41
L4PZ	120	1.82	1.60	1.71	1.31	0.72	2.34	0.23
T connection (θ_y=3 mrad)								
L1PR	720	4.59	2.74	2.04	2.95	0.64	0.71	0.22
L2PR	360	2.24	2.30	2.00	0.51	0.23	-0.52	0.05
L3PR	240	3.17	2.25	6.30	1.96	0.62	0.58	0.25
L4PR	120	1.33	1.46	1.63	0.34	0.26	-0.53	0.06
L1PZ	360	10.67	10.59	12.35	7.56	0.71	0.60	0.78
L2PZ	360	9.75	9.14	12.98	7.05	0.72	0.76	0.73
L3PZ	120	2.37	2.05	4.55	1.49	0.63	1.83	0.27
L4PZ	120	1.60	1.62	1.67	0.87	0.54	4.00	0.16

[a]Sample size
[b]Average value
[c]Value of a random variable at which values above and below it are equally probable (Probability at the median = 50%)
[d]The most probable value of a random variable (the value of the random variable with the largest probability or the highest probability density.
[e] 95% confidence interval of a mean value.

TABLE III
PROBABILISTIC PARAMETERS OF 6 STORY OLDER FRAME

Loc'n	N	Mean	Median	Mode	STD	COV	Skewness	95% CI
CA connection (θ_y=7.5 mrad)								
L1PR	1200	12.47	10.52	11.67	7.19	0.58	0.76	0.41
L2PR	600	12.13	10.05	6.18	7.44	0.61	0.66	0.60
L3PR	240	6.84	5.63	3.33	3.13	0.46	0.48	0.40
L4PR	120	4.23	4.34	5.66	1.27	0.30	-0.29	0.23
L1PZ	600	6.94	4.76	11.29	6.51	0.94	1.19	0.52
L2PZ	600	4.38	1.91	1.54	4.11	0.94	1.35	0.33
L3PZ	120	2.75	1.85	1.86	2.03	0.74	1.00	0.36
L4PZ	120	1.79	1.47	0.68	1.62	0.91	5.95	0.29
T connection (θ_y=3 mrad)								
L1PR	1600	7.04	6.60	2.04	4.76	0.68	0.63	0.23
L2PR	800	5.55	2.74	11.79	5.14	0.93	1.25	0.36
L3PR	320	3.62	2.31	1.64	2.40	0.66	0.53	0.26
L4PR	150	1.45	1.56	1.79	0.35	0.24	-0.56	0.06
L1PZ	800	9.91	8.90	13.17	6.88	0.69	0.61	0.48
L2PZ	800	7.92	5.94	10.45	6.28	0.79	0.98	0.44
L3PZ	160	3.60	2.96	1.23	2.61	0.72	1.40	0.40
L4PZ	160	2.34	1.72	1.85	1.79	0.77	2.32	0.28

TABLE IV
PROBABILISTIC PARAMETERS OF 8 STORY OLDER FRAME

Loc'n	N	Mean	Median	Mode	STD	COV	Skewness	95% CI
CA connection (θ_y=7.5 mrad)								
L1PR	1680	10.37	9.24	11.71	5.81	0.56	0.88	0.28
L2PR	840	11.19	9.06	10.22	6.98	0.62	0.79	0.47
L3PR	240	6.68	5.66	4.94	2.95	0.44	0.47	0.37
L4PR	120	4.19	4.52	5.78	1.21	0.29	-0.33	0.22
L1PZ	840	6.21	2.93	12.51	5.89	0.95	0.96	0.40
L2PZ	840	3.41	1.67	1.23	3.39	0.99	1.72	0.23
L3PZ	120	2.48	1.83	1.86	2.03	0.82	2.15	0.36
L4PZ	120	1.61	1.52	1.65	1.12	0.70	4.20	0.20
T connection (θ_y=3 mrad)								
L1PR	1680	5.65	3.58	1.82	4.66	0.82	1.43	0.22
L2PR	840	6.06	2.53	2.49	5.70	0.94	1.08	0.39
L3PR	240	3.00	2.23	1.64	1.81	0.60	0.59	0.23
L4PR	120	1.29	1.33	1.47	0.30	0.23	-0.25	0.05
L1PZ	840	7.87	5.03	10.96	7.04	0.89	1.01	0.48
L2PZ	840	5.33	2.85	1.61	4.94	0.93	1.38	0.33
L3PZ	120	1.83	1.67	1.73	0.90	0.49	0.98	0.16
L4PZ	120	1.42	1.45	1.44	0.35	0.25	-0.02	0.06

interval (a, b). Typical examples of continuous distributions are as followings and basic information for these probability distributions can be obtained in Ang and Tang [1]:

- Non-negative distributions [0 to infinity]: Erlang, exponential, gamma, log-logistic, lognormal, Rayleigh, Weibull
- Unbounded distribution (-infinity, infinity): exponential power, extreme value type A, extreme value type B, Johnson SU, logistic, normal.
- Bounded distribution (a, b): beta, Johnson SB, uniform

Based on the PRCR and PZD data set collected in the previous section, the probability distributions were estimated using the ExpertFit program [10]. It determines automatically and accurately which probability distribution best represents a data set. The determination is made by the goodness-of-fit test which estimates a null hypothesis (the Anderson-Darling (A-D) test, the Kolmogorov-Smirnov (K-S) test, and the chi-square test). Table V shows an example of the estimated goodness-of-fit test results by the ExpertFit. The lower the statistics value for each test is the better result is. The 2nd column in this table shows top 3 distribution models among various probability distributions obtained from the goodness-of-fit tests. From this table, the weibull and normal distribution is fitted well in PRCR and PZD, respectively.

TABLE V
THE GOODNESS-OF-FIT TEST RESULTS (4-STORY, CA MODEL)

Index	Distribution model	A-D test		K-S test		Chi-Square test	
		Stat.[a]	Rank	Stat.[a]	Rank	Stat.[a]	Rank
L1PR	Weibull	5.46	1	0.065	1	330.00	1
	Ext. Value B[b]	6.71	2	0.081	3	343.44	3
	Gamma	8.72	3	0.080	2	331.78	2
L2PR	Weibull	6.72	2	0.101	1	232.00	2
	Ext. Value B	5.65	1	0.110	2	222.67	1
	Normal	8.35	3	0.173	3	244.89	3
L1PZ	Normal	5.05	1	0.110	3	261.56	1
	Ext. Value B	7.40	3	0.102	1	262.00	2
	Logistic	5.37	2	0.107	2	352.67	3
L2PZ	Normal	5.78	2	0.106	1	348.67	3
	Logistic	5.72	1	0.113	3	275.78	2
	Ext. Value B	6.18	3	0.108	2	211.56	1

[a]Statistics
[b]Extreme Value B

Fig. 7 shows a typical example of estimating probability distribution to measured data set. From the PDF curve, x-axis represents the rotation demands for the PRCR and PZD and y-axis represents the fraction (0 to 1) of total observations obtained from dividing the number of observations at each interval by total observations. From the CDF curve, x-axis is the same as that for the PDF curve and y-axis represents the probability of non-exceedance of the value x (0 to 1). From this figure, the distribution is close to those of an unbounded distribution such as normal or Johnson SU.

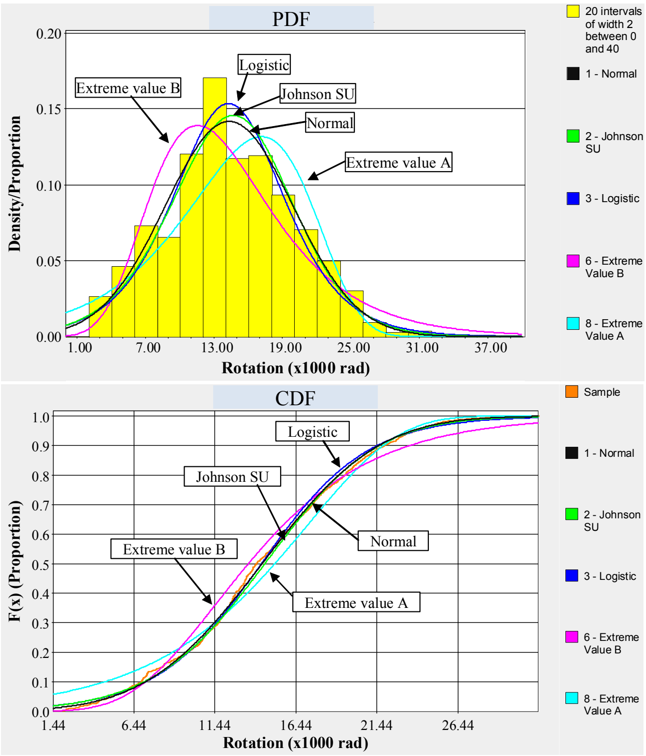


Fig. 7 Example of estimated PDF & CDF

B. Estimate Results

Tables VI and VII provide the estimated probability distributions of the CA and T models at L1 and L2 locations, respectively. For CA model, the weibull distribution (non-negative distribution) was fitted to empirical curve in most cases. On the other hand, in T model, there is no typical distribution but non-negative distributions were governed.

It is much clearer to compare each case using PDF and CDF graphs. Figs. 9 to 12 show the PDF and CDF of L1PR and L1PZ fitted to empirical curves for CA and T models. Other cases were omitted due to limit of paper length. From these figures, most distributions followed non-negative distribution with positive skewness. This implies that most PRCR and PZD concentrated on low demand level, approximately less than 10 mrad. Also, the fitted CDF curves are getting closer to empirical curves as story goes up because number of samples increased as story is higher.

TABLE VI
PROBABILISTIC DISTRIBUTIONS OF CA MODEL

	4 story	6 story	8 story
L1PR	Weibull	Weibull	Weibull
L2PR	Weibull	Weibull	Weibull
L1PZ	Normal	Gamma	Gamma
L2PZ	Normal	Weibull	Weibull

TABLE VII
PROBABILISTIC DISTRIBUTIONS OF T MODEL

	4 story	6 story	8 story
L1PR	Lognormal	Gamma	Weibull
L2PR	Extreme Value A	Lognormal	Lognormal
L1PZ	Logistic	Extreme Value B	Gamma
L2PZ	Normal	Gamma	Weibull

V. PROBABILITY OF PERFORMANCE LEVEL

FEMA 273/356 [11][12] consider four building Performance Levels: Operational (OP), Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). The levels are discrete points on a continuous scale describing the building's expected performance, or alternatively, how much damage, economic loss, and disruption may occur. Fig. 8 shows the building performance levels and ranges with an expected post-earthquake damage state.

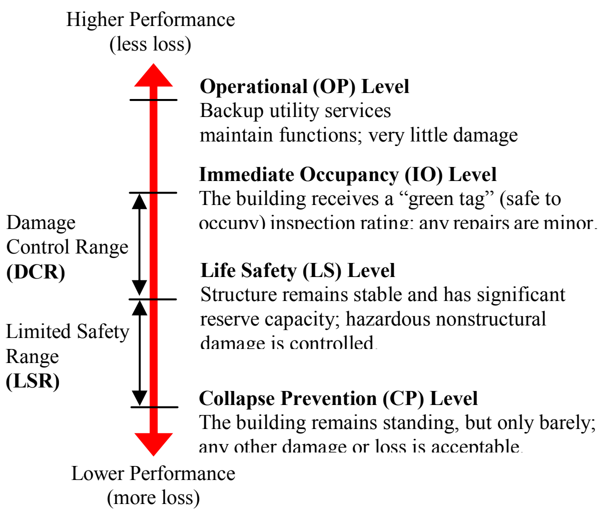
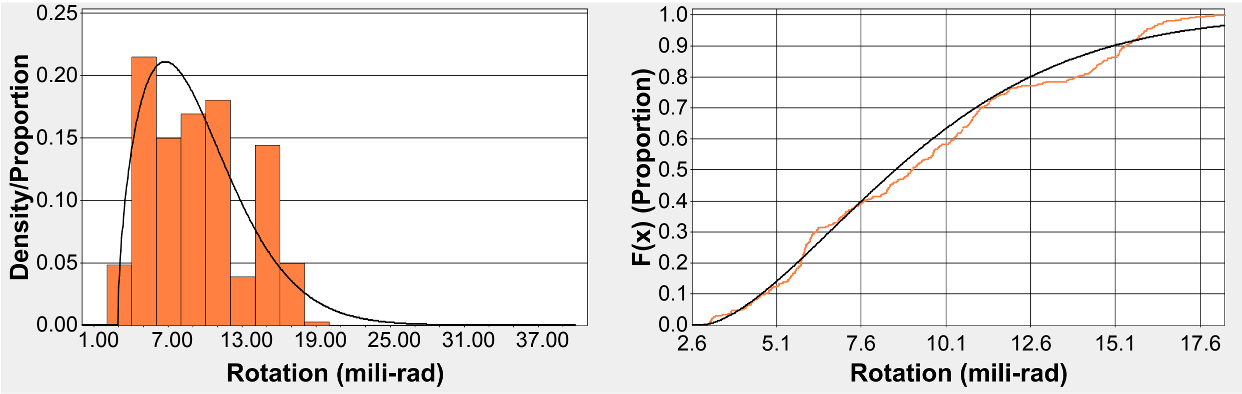


Fig. 8 Building performance levels and ranges [12]

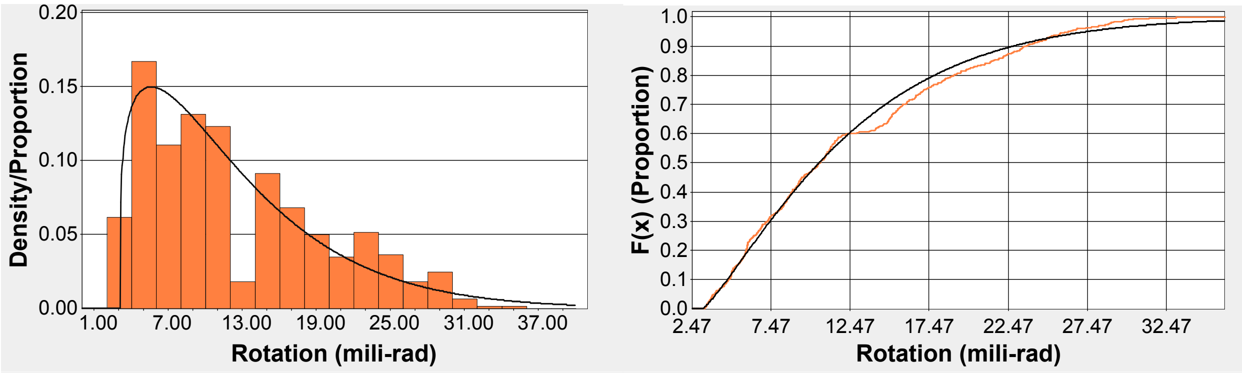
According to FEMA 273/356 criteria, the PRCR and PZD were chosen as the local performance criteria and their limits are 10 mrad for IO level, 25 mrad for LS level, and 35 mrad for CP level. The detail probability about how many PR connections and panel zones satisfy each performance level can be obtained from the CDF curve. For example, in Fig. 9(c), approximately 58% of PRCR of CA model in L1 location was less than 10 mrad and satisfied the IO level. On the other hand, in Fig. 10(c), approximately 86% of PRCR of T model in the same location was less than 10 mrad and satisfied IO level. Therefore, it can be conclude that T-stub connection has approximately 50% better performance than clip angle connection in 8 story older frame. Similarly, the damage severity (or limit state) of overall connection rotations and panel zone deformations can be evaluated in a building using these curves.

VI. CONCLUSION

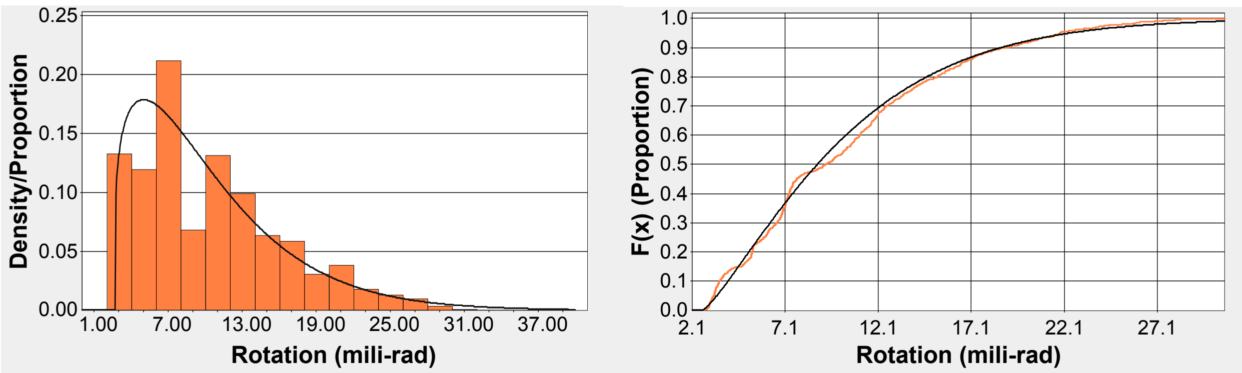
This probabilistic approach was useful to estimate probabilistic characteristics and distributions of PRCR and PZD and evaluate damage severity in accordance with performance limit states. The data generated in this study can be also used in many different ways to understand the overall seismic responses of PR connections and panel zones. However, it was the subjective judgment of the research team that these issues represented two interesting opportunities to analyze the data and provide meaningful contributions to the understanding of PR frame behavior.



(a) 4 story older frame

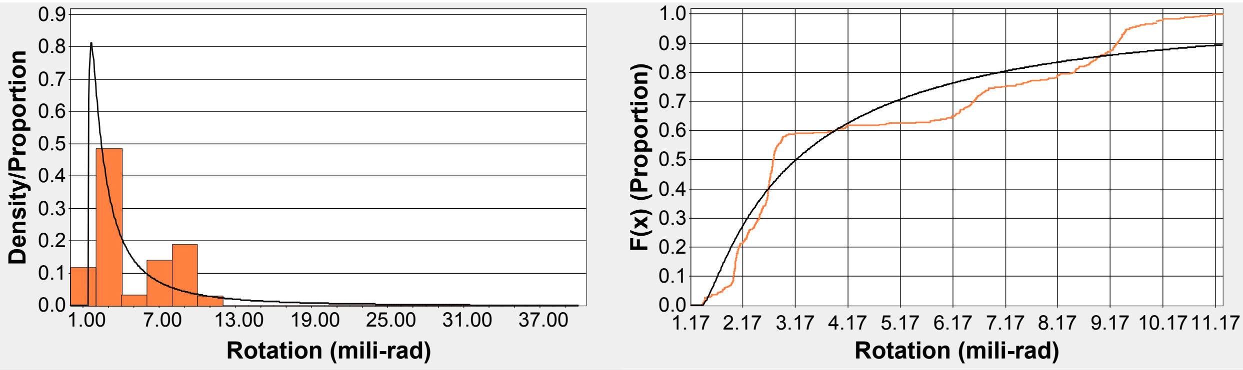


(b) 6 story older frame

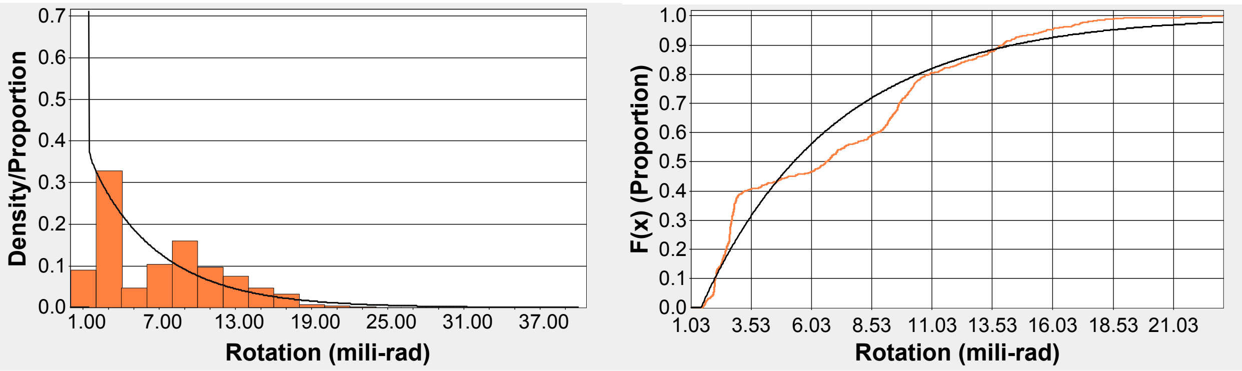


(c) 8 story older frame

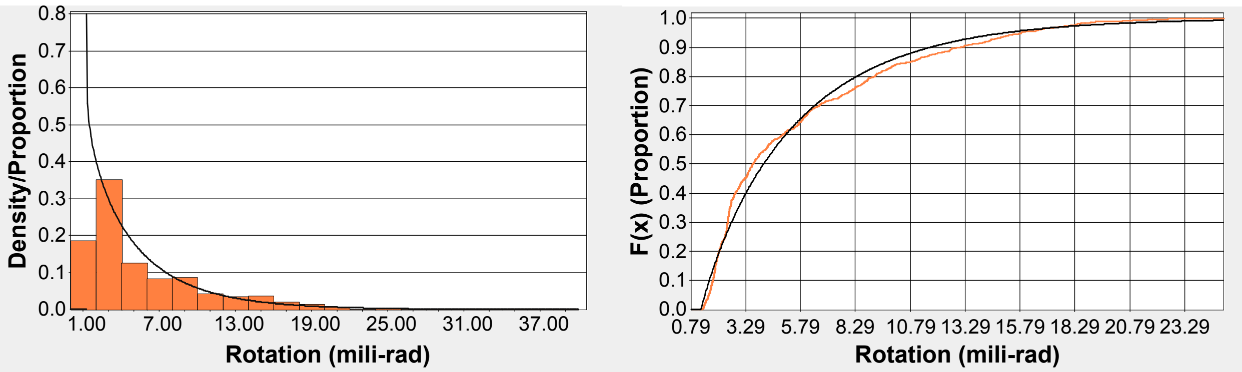
Fig. 9 PDF & CDF of L1PR for the CA model



(a) 4 story older frame

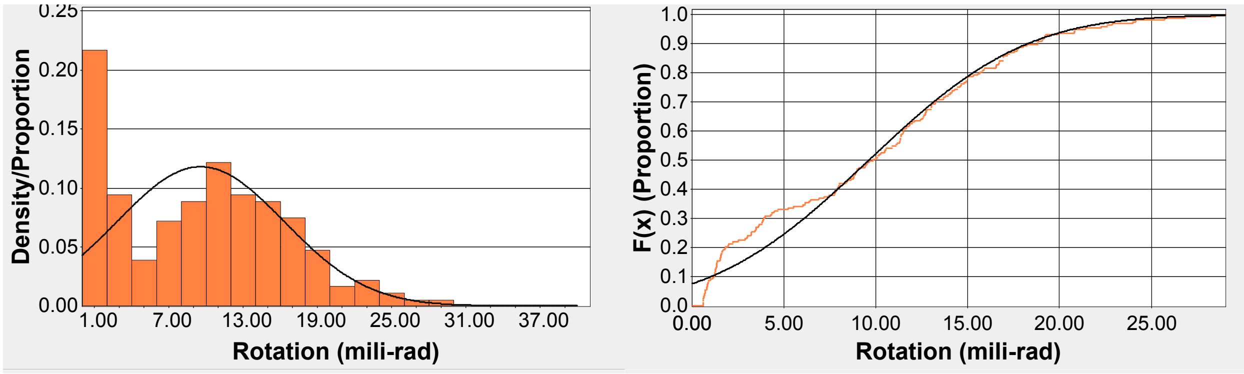


(b) 6 story older frame

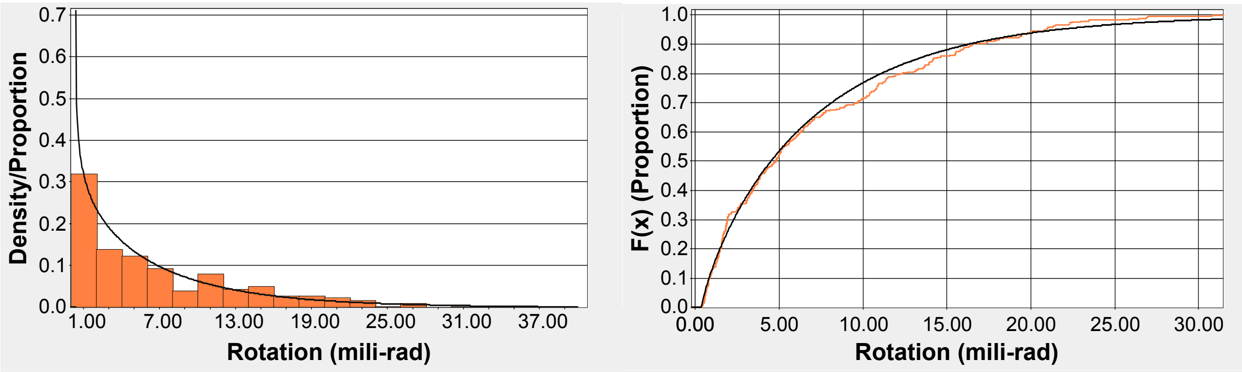


(c) 8 story older frame

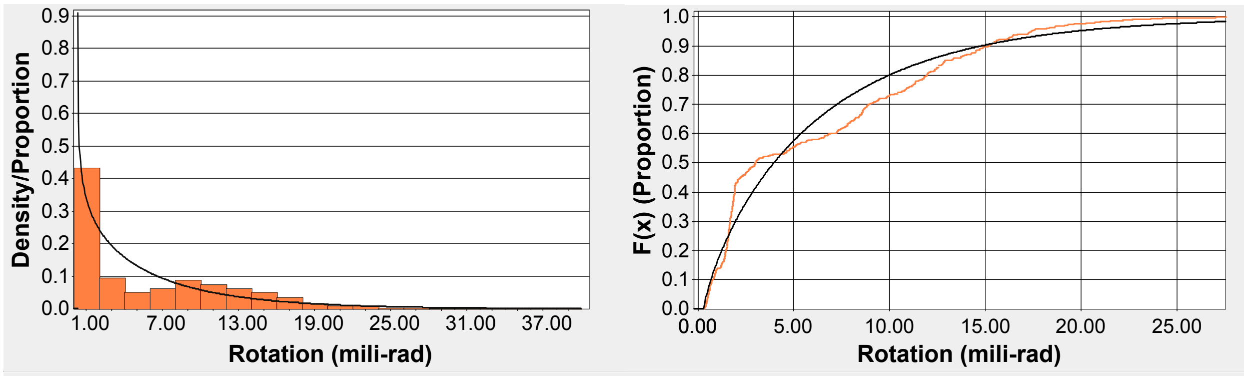
Fig. 10 PDF & CDF of L1PR for the T model



(a) 4 story older frame

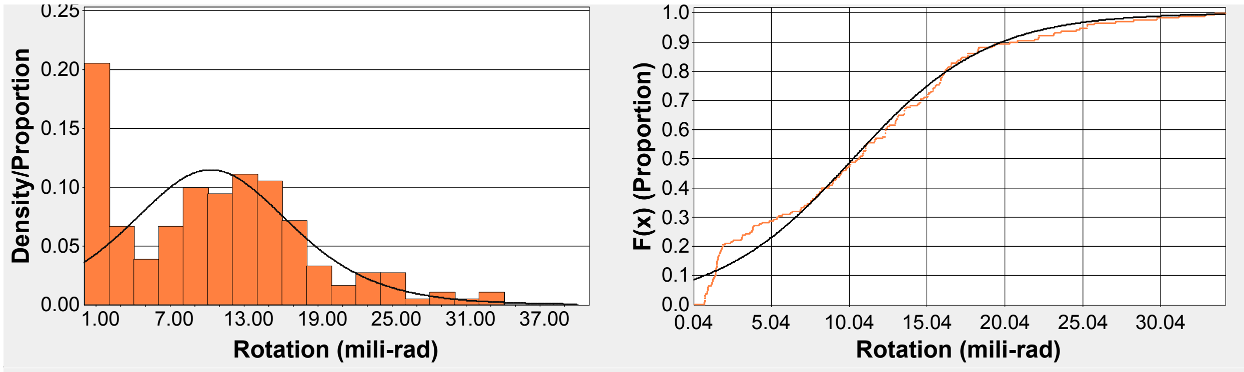


(b) 6 story older frame

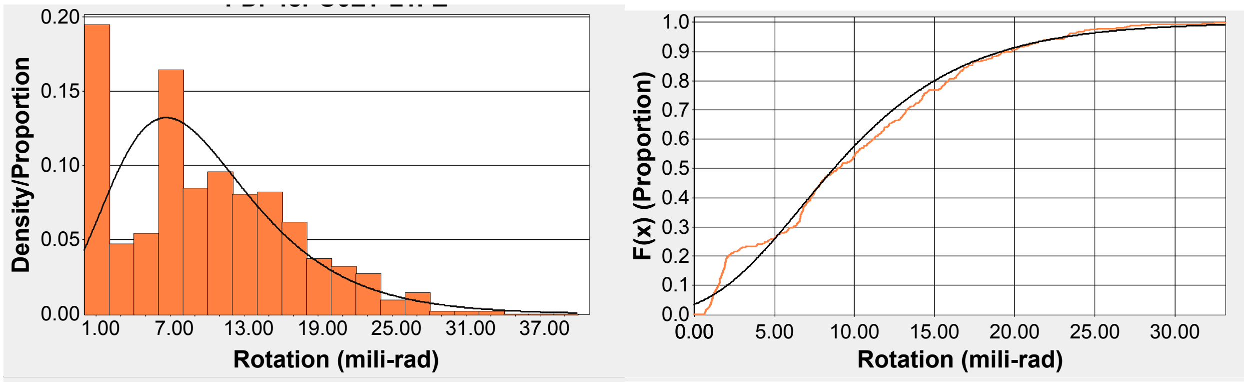


(c) 8 story older frame

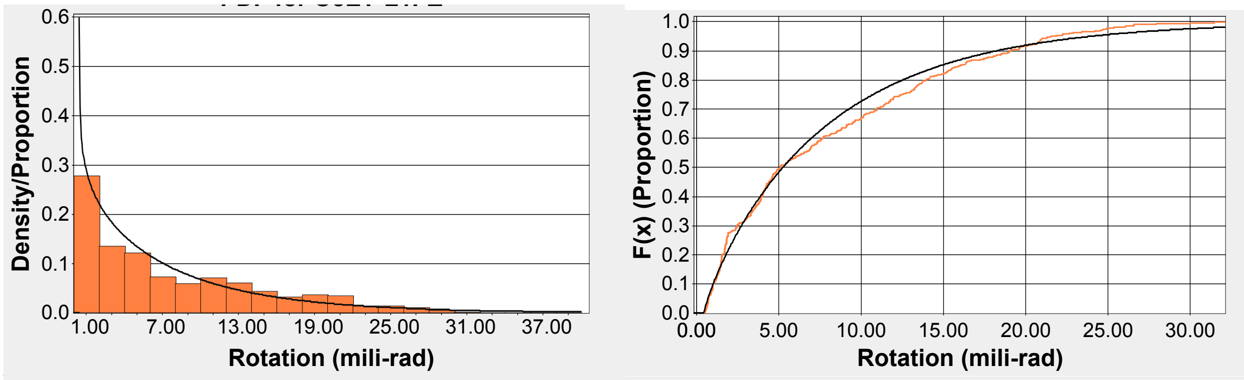
Fig. 11 PDF & CDF of L1PZ for the CA model



(a) 4 story older frame



(b) 6 story older frame



(c) 8 story older frame

Fig. 12 PDF & CDF of L1PZ for the T model

REFERENCES

[1] A. Ang and W. H. Tang, Probability Concepts in Engineering Planning and Design. 2nd ed. vol I & II, John Wiley & Sons, Inc., 2006.
[2] D. H. Kim and R. T. Leon, "Seismic performance of PR frames in frames in the Mid-America Earthquake Region," ASCE J. of Structural Engineering, vol. 133, no. 12, pp. 1808-1820, 2007.
[3] AISC, Steel Construction Manual. 5th ed., American Institute of Steel Construction, 1952.
[4] Anderson, Blume, Degenkolb, Hammill, Knapik, Marchand, Powers, Rinne, Sedgwick, and Sjoberg, "Lateral Forces of Earthquake and Wind," Transactions, ASCE, vol. 117, p. 716, 1952.
[5] C. W. Roeder, R. T. Leon, and F. R. Preece, Strength, Stiffness and Ductility of Older Steel Structures under Seismic Loading. Report SGEM 94-4, Department of Civil Engineering, University of Washington, Seattle, 1994.
[6] G. P. Forcier, Seismic Performance of Older Steel Frames. Ph.D. dissertation, Department of Civil and Environmental Engineering, University of Minnesota, Minneapolis, MN, June 1994.
[7] CERI, Center for Earthquake Research and Information. University of Memphis, http://www.ceri.memphis.edu/public/, 2001.
[8] Y. K. Wen and C. L. Wu, "Generation of Ground Motions for Mid-America Cities," University of Illinois at Urbana-Champaign, December 2000.
[9] Papageorgiou et al., Engineering Seismology Laboratory (ESL) at the State University of New York at Buffalo, 2002.
[10] A. M. Law and W. D. Kelton, Simulation Modeling and Analysis. 4th ed., McGraw Hill, 2007.
[11] FEMA, NEHRP Guidelines for the Seismic Rehabilitation of Buildings. Report FEMA-273, Federal Emergency Management Agency, Washington, D.C., 1997.
[12] FEMA, Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Report FEMA-356, Federal Emergency Management Agency, Washington, D.C., November 2000.