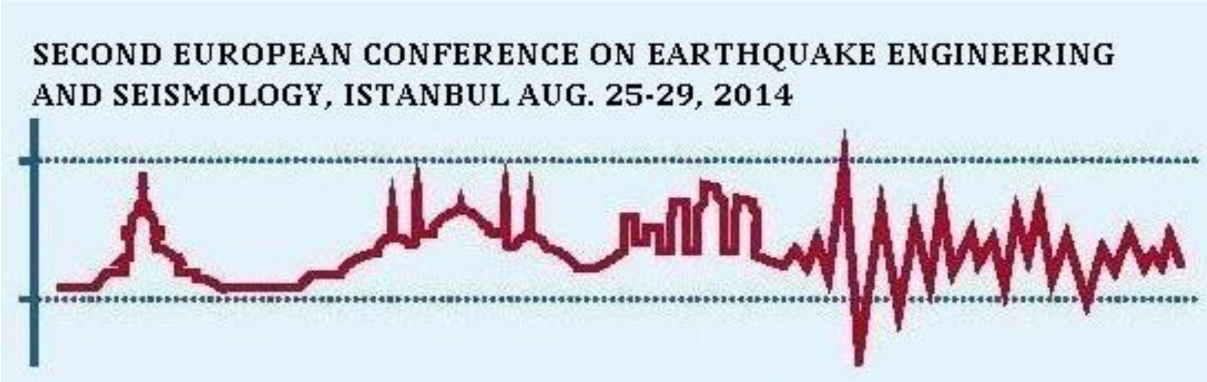

EFFECT OF STRENGTH DEGRADATION ON DRIFT DISTRIBUTION OF STEEL SPECIAL MOMENT FRAMES

Devrim ÖZHENDEKCİ[1]

Post-Northridge (or currently designed) steel special moment frames assumably do not deteriorate considerably unless the interstory drift ratios reach 0.04 radian under earthquake loading owing to the seismically compact structural elements and the use of prequalified beam-to-column connections. This is widely accepted, however do the seismically compactness limits really provide member ductilities lying in the range of 5 to 15 which corresponds to a 3 to 5 global ductility ratio in every case? The answer to this question is: Sometimes. Actually if there is local buckling in the beam, the strength of the plastic hinge will reduce with cycles. The amount of strength loss for each cycle is a function of compactness of the cross section and the reached maximum rotation during previous cycles. An approximate value of 10% degradation is validated via the experiments and analyses conducted during the SAC project. Thus, 10% strength degradation model is used for the behavior of beams in this research. Strength degradation is imposed to the building via the added springs at the ends of beams. Beams are modeled as beam-column elements with DRAIN-2DX software. The rigid end offsets are also added as separate elements to the ends of springs. A 10 story steel special moment frame is designed and analyzed. The whole far-fault records of soil class C of PEER Strong Motion database are studied. Initially, the record with the higher PGA value is chosen for each pair. Subsequently, the records with PGA values smaller than 0.10 are eliminated. Each record is scaled to the spectral acceleration of Maximum Considered Earthquake (MCE) for the model frame's fundamental period. MCE spectrum is determined per SEI/ASCE 7-10 which has approximately 2% probability of exceedance in 50 years. However most of the scale factors obtained are too high, only 9 of them are smaller than 3. Thus, 9 records are used during analyses. The results of the analyses with and without strength degradation are compared. Accordingly, degradation does not result in the increase of the whole story drift ratios, it causes some of these ratios to increase but some of them to decrease along the frame height because of the change of modal contribution in dynamic analyses in effect of the degradation. Most of the increase ratios are below 10%. Generally decrease ratios are higher than the increase ratios in terms of percentage and amplitude. The maximum increase (50 %) in story drift happens for the earthquake with the maximum Arias duration. For one of the chosen records which has the minimum bracketed duration among the set, strength degradation does not yield any difference on the story drifts. Accordingly, there is a relation between strong motion duration and the effects of degradation as expected, however the number of suitable records for the specified earthquake hazard level is not adequate for generalization.

INTRODUCTION

The experience gained during 1994 Northridge Earthquake yielded drastic modifications to the seismic design codes. The research held immediately after this earthquake provided too much additional knowledge next to the gained experience especially in terms of understanding and impeding the probable building damage for future earthquakes. Actually a result of this research, currently designed special moment frames can sustain interstory drift angle of 0.04 rad. without experiencing

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beam-to-column connection damages. This is relieving since once the connection damage occurs, the story integrity will be lost rapidly. The damage is generally confined to the beams via the capacity based design principles and the beam's dynamic stability is assured by choosing seismically compact profiles. However, seismically compactness may not guarantee the strength degradation for large inelastic displacement demands in the case of infrequent seismic events. Strength degradation is a typical behavior for a steel beam with local buckling. As a result the beams of a special moment frame can experience strength degradation even if the developed interstory drift ratios are below 0.04 rad (Fema 355c, Huang and Foutch 2009). The amount of strength loss is a function of $b/2t_f$ and the maximum rotation during previous cycles. (Here b and t_f are the width and thickness of the beam flange, respectively.) However, a constant value of 10% degradation rate can be assumed to represent the behavior of current design of steel special moment frames with compact sections (Huang and Foutch 2009).

In this research the effects of 10% strength degradation of beam plastic hinges are studied especially on the drift amplitude and distribution. To this aim a 10-story special moment frame is designed per ASCE/SEI 7-10, ANSI/AISC 341-10 and ANSI/AISC 360-10. The spectral values used during the design are chosen as lower bounds proposed in ASCE/SEI 7-10 for the deterministic ground motion response spectrum. A finite element model of the frame is constructed in DRAIN-2DX software. Strength degradation is imposed to the building via the added springs at the ends of beams. Beams are modeled as beam-column elements and the rigid end offsets are also added as separate elements to the ends of these springs. Orthogonal and gravity columns are also taken into consideration as leaning columns for P-Delta effects. Special care is given during the record selection for inelastic dynamic analyses in order not to spoil the earthquake hazard level represented by the Maximum Considered Earthquake (MCE). The whole far-fault records of soil class C of PEER Strong Motion database are studied. Initially, the record with the higher PGA value is chosen for each pair. Subsequently, the records with PGA values smaller than 0.10 are eliminated. Each record is scaled to the spectral acceleration of Maximum Considered Earthquake (MCE) for the model frame's fundamental period.

Inelastic analyses are carried out for both non-degrading and 10% strength degrading finite element models for each record. The amplitudes and distribution of story drifts are compared.

MODEL FRAME

Basic geometric properties of the model frame can be found in Fig.1. The span length is chosen as 6.5 m (21.33 ft) based on the findings of a previous work (Özhendekci and Özhendekci 2012) in which similar span length/story height ratios are found to provide optimum solution in both design (economy) and seismic performance aspects for 10 story SMFs. All of the columns and beam sections are chosen as W sections. The structural steel used for the elements with W sections is A992 (Fy = 34.5 kN/cm^2, 50 ksi). The profiles assigned to the cross sections of the model SMF is provided in Table 1. Each column has two splices, so columns consist of three components with different profiles assigned.

Dead load value assigned to the normal stories is 3.83 kN/m^2 (80 psf) including the weight of structural steel elements. Live load applied to the normal stories is 3.11 kN/m^2 (65 psf) including the weight of partition walls. Dead and live load values assigned to the roof used for promenade purposes are 3.11 kN/m^2 (65 psf) and 2.87 kN/m^2 (60 psf), respectively. The site class which the sample building is assumed to be constructed on is C. The mapped maximum considered earthquake spectral response acceleration values at short and 1 second periods are 1.5g and 0.6g, respectively. Seismic design category of the sample building is D. Seismic response modification factor (R) is 8 and deflection amplification factor (C_d) is 5.5.

The detailed information concerning the design procedure, gravity columns and finite element model formation with the use of springs for inelastic dynamic analyses can be found in the principle research paper (Ozhendekci 2014). This study reflects and emphasizes the initial findings that provide required information for the record selection phase of the principal research.

Table 1. Assigned profiles to the cross sections of structural elements of the sample SMF

Element Type	COLUMNS									
Element Title*	**C1**	**C2**	**C3**							
Assigned Profile	W14×311	W14×257	W14×233							
Element Type	GIRDERS									
Element Title*	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**	**G8**	**G9**	**G10**
Assigned Profile	W21×73	W24×84	W24×84	W24×76	W24×76	W21×73	W24×62	W21×50	W18×40	W16×31

*Element titles are addressed in Fig. 1.

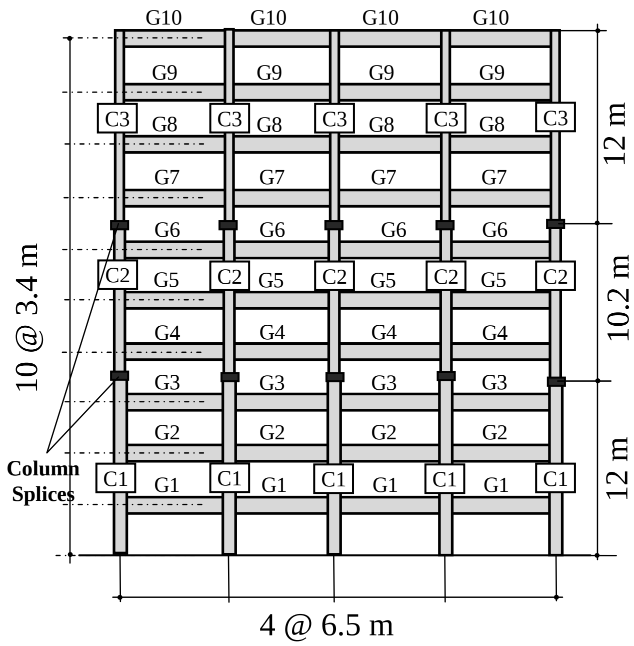

Figure 1. Basic geometric properties and cross section labels of the model frame

EARTHQUAKE RECORD SET

Actually, the initial target was to use many number of records in order to be able to generalize the results of the parametric study. To this aim, the whole far-fault records of soil class C of PEER Strong Motion database are studied. At the beginning, the record with the higher PGA value is chosen for each pair. Subsequently, the records with PGA values smaller than 0.10 are eliminated. Each record is scaled to the spectral acceleration of Maximum Considered Earthquake (MCE) for the model frame's fundamental period (2.183 s). This target ordinate can be obtained as follows per SEI/ASCE 7-10:

$$S_a = \frac{S_{M1}}{T_1} = \frac{F_v \times S_1}{T_1} = \frac{1.3\times 0.6g}{2.183} = 0.357g \quad (1)$$

Here S_1 is the mapped MCE spectral response acceleration at a period of 1 s for site class B, F_v is a coefficient for the correction relevant to the local site class, T_1 is the fundamental period of the model frame, and S_{M1} is the MCE spectral response acceleration at a period of 1 s for site class C. MCE has approximately 2% probability of exceedance in 50 years. Actually, we may call MCE as maximum risk considered earthquake (MCRE) as its current form in the latest specifications (ASCE/SEI 7-10), too since we use the deterministic lower bound. This definition suits with the risk targeted hazard level approach. Most of the obtained scale factors in order to reach the value given in Eq.1 are too high, only 9 of them are smaller than 3. Thus, 9 records are used during analyses. The basic characteristics of these records are given in Table.2 and also the pseudo acceleration response spectra of the chosen record set is given in Fig.2.

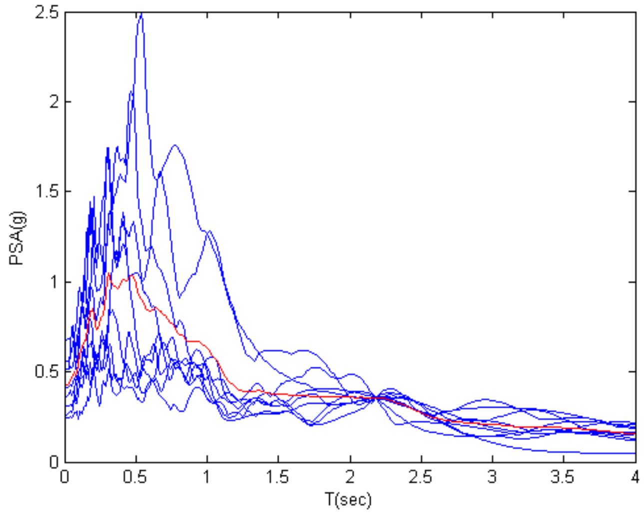

Figure 2. Pseudo Acceleration Spectra of the scaled records and the mean spectrum

It is expected that the effects of the strength degradation will increase with the increasing strong motion duration. So it is necessary to examine the strong motion duration of the utilized records in correlation with the story drifts. Though, there are various definitions of strong motion duration (Bommer and Pereira 2008), in this research two of them: Arias duration and bracketed duration will be used.

The Arias intensity AI (Arias 1970) is defined as:

$$AI = \frac{\pi}{2g}\int_0^{t_r} a^2(t)dt$$

where a(t) is the acceleration time history, t_r is the total duration of the accelogram and g is the acceleration due to velocity. The "significant duration" (or Arias duration) is defined as the interval over which some proportion of the total integral is accumulated. The study of strong motion duration by Trifunac and Brady (1975) used the significant duration concept defined for the integrals of the squares of acceleration. This duration is defined as the interval between the times at which 5% and 95% of the total integral is attained. This definition is directly used in this research.

The bracketed duration is defined as the total time elapsed between the first and last excursions of a specified level of acceleration. This acceleration treshold is chosen as 0.05g in this research.

Table 2. Basic properties of the record set

NGA#	**Direction**	**Event**	**Year**	**Mechanism**	**Mom. Mag.**	**R_{jb} (km)**
776	FP	Loma Prieta	1989	Rev.-Ob.	6.93	27.7
787	FN	Loma Prieta	1989	Rev.-Ob.	6.93	30.6
1236	FP	Chi-Chi, Taiwan	1999	Rev.-Ob.	7.62	37.5
1471	FN	Chi-Chi, Taiwan	1999	Rev.-Ob.	7.62	49.8
1477	FP	Chi-Chi, Taiwan	1999	Rev.-Ob.	7.62	30.2
1479	FN	Chi-Chi, Taiwan	1999	Rev.-Ob.	7.62	35.7
1525	FN	Chi-Chi, Taiwan	1999	Rev.-Ob.	7.62	54.5
3269	FN	Chi-Chi, Tai.-06	1999	Rev	6.3	40.1
3281	FN	Chi-Chi, Tai.-06	1999	Rev	6.3	53.2

Table 2 (cont.). Basic properties of the record set

NGA#	R_{rup} (km)	V_s30 (m/s)	PGA	a/v	T_p (s)
776	27.9	370.8	0.3012	0.7296	none
787	30.9	425.3	0.2532	0.5811	none
1236	37.5	366.2	0.2196	1.0597	none
1471	49.8	426	0.1184	0.3284	none
1477	30.2	489.2	0.1518	0.3276	11
1479	35.7	393.8	0.2309	0.5401	8.6
1525	54.5	421.2	0.1082	0.3459	none
3269	41.4	544.7	0.2518	1.1244	none
3281	54.1	442.1	0.139	1.0278	none

Table 2 (cont.). Basic properties of the record set

NGA#	Scale Factor	Arias In.-unscaled	Arias Dur.	Arias In.-scaled	Bracketed Dur. -unscaled	Bracketed Dur.-scaled
776	*2.2538*	1.26E-04	20.63	6.39E-04	22.21	36.19
787	*2.0219*	8.92E-05	11.235	3.65E-04	14.225	23.595
1236	*2.5346*	9.25E-05	32.615	5.94E-04	36.245	49.72
1471	*2.2179*	3.70E-05	23.91	1.82E-04	31.185	19.965
1477	*2.0442*	4.11E-05	33.685	1.72E-04	16.305	38.96
1479	*1.7856*	7.65E-05	19.29	2.44E-04	20.695	26.9
1525	*2.2509*	2.14E-05	25.72	1.08E-04	17.23	27.115
3269	*2.0455*	2.41E-05	13.645	1.01E-04	7.43	14.11
3281	*2.6213*	1.68E-05	19.445	1.15E-04	8.52	26.14

RESULTS OF THE ANALYSES

Story drift ratios, and mean and median values of them obtained for the model frames with and without strength degradation are provided in Fig.3. All of the story drift ratios are below 0.04 rad. and mean and median values are nearly 0.02 radians (except for the first stories) for both models. Interstory drift ratios are also checked and found out that they are below 0.04 rad., too. This indicates that any kind of additional strength degradation especially because of the connection damage is not expected to happen for the chosen earthquake record set and for both of the models.

As it can be followed from the figure N0776, N1236 and N0787 records cause high story drifts at upper stories in a descending manner from record to record, respectively. These records have the largest Arias Intensity values in the same order. N0776 which causes the largest upper story drift has also the shortest fault distance and the other two records have relatively close distances among the record set. This result yields to the conclusion that the records with high Arias Intensity and short fault distances may cause higher mode effects.

It is also obvious from the figure that the records N3281, N3269, N1525, and N1471, namely the ones with relatively long fault distances cause the formation of maximum story drift ratios at lower stories.

Though the distribution varies too much from record to record, the mean and median values are quite uniform with the value of around 0.02 both for the model with and without strength degradation. Actually, in order to examine the difference between the models with and without strength degradation, it is appropriate to determine the ratios of story drifts obtained via the use of these models (Fig.4). Accordingly, degradation does not result in the increase of the whole story drift ratios, it causes some of these ratios to increase but some of them to decrease along the frame height because of the change of modal contribution in dynamic analyses in effect of the degradation. Most of the increase ratios are below 10%. Generally decrease ratios are higher than the increase ratios in terms of percentage and amplitude. The maximum increase (50 %) in story drift happens for the earthquake with the maximum Arias duration (N1477) for the sixth floor level. For N3269 which has the minimum bracketed duration among the set, strength degradation does not yield any difference on the story drifts. It seems that if the strong motion duration is high, than the effect of the strength degradation is high, too. Accordingly, there is a relation between strong motion duration and the effects of degradation as expected, however the number of suitable records for the specified earthquake hazard level is not adequate for generalization. Furthermore, N1479 also causes a high difference for the third floor nearly 30%, but it has a moderate strong motion. So there should be an additional factor next to the duration. Actually, these two records are pulse-like which means the pulse-like records with high or moderate strong motion durations cause the most drastic story drift increase ratios because of the strength degradation of the beams.

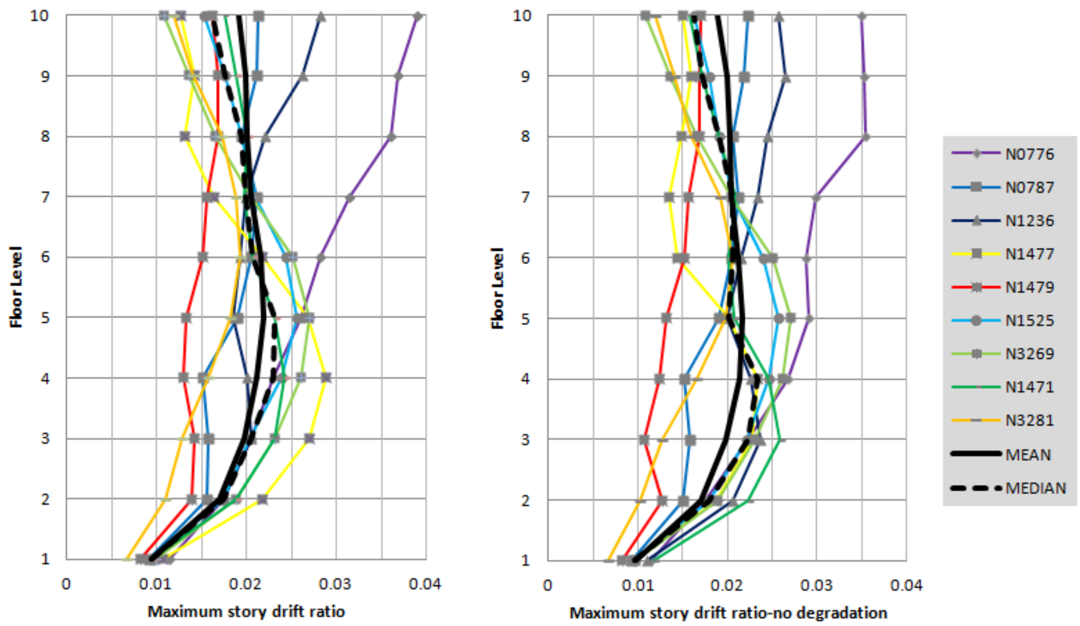

Figure 3. Story drifts, and mean and median values of story drifts obtained for the models with and without strength degradation

Though the median values of the ratios of strength degrading to non-degrading models' story drifts can reach approximately 10% for the third and fifth stories, both median and mean values of these ratios are approximately 2%. It is quite disturbing that even though the mean and median values of the difference are acceptable, the difference for some of the individual records can be as high as 50%. This indicates the need for thoroughly examining this relation with as much as possible number of earthquake records. In current practice, strength or stiffness degradation is generally not taken into consideration and ideal elasto-plastic behavior with 3% strain hardening ratio is mostly used during modeling frames for seismic performance assessment, as long as the interstory drift ratios are below 0.04 rad.

The first point of the sixth floor's moment-rotation history for the degrading model is also provided in Fig.5, in order to demonstrate the effect of strength degradation in terms of hysteretic behavior for the most affected floor level. The question why this record affected the frame most depends on the record properties. N1477 is a pulse-like record. Actually, the records with pulses N1477 and N1479 resulted in the highest increases in the peak story drifts, respectively. These two records are the only pulse like records among the used set. The sharp increase in the earthquake demand causes the sudden strength degradation and the following cycles having too much strength demands cause the plastic deformation to increase further. Moreover, the longer the strong motion duration, the more the strength degradation. As a result both strong motion duration and the existence of pulses increase the effects of strength degradation on story drift ratios.

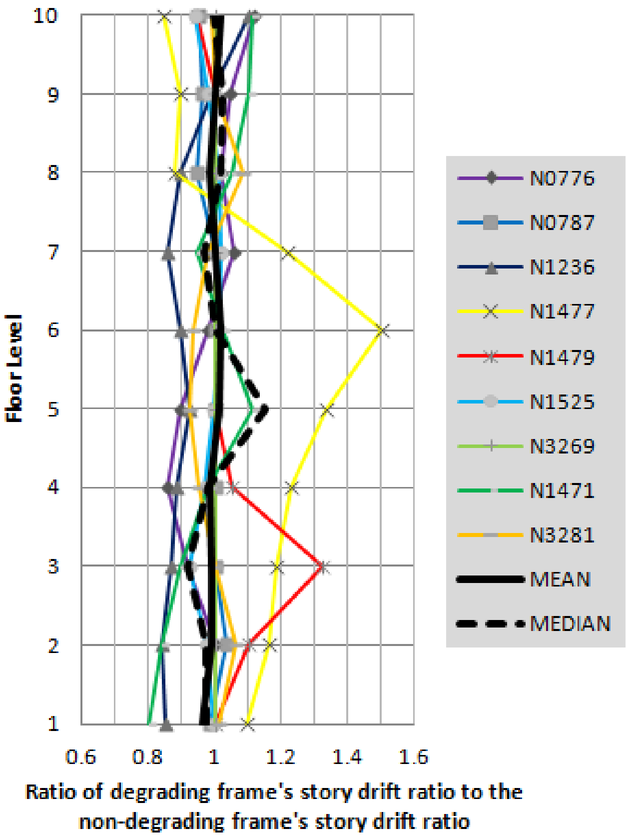

Figure 4. Ratio of degrading frame's story drift ratio to the non-degrading frame's story drift ratio

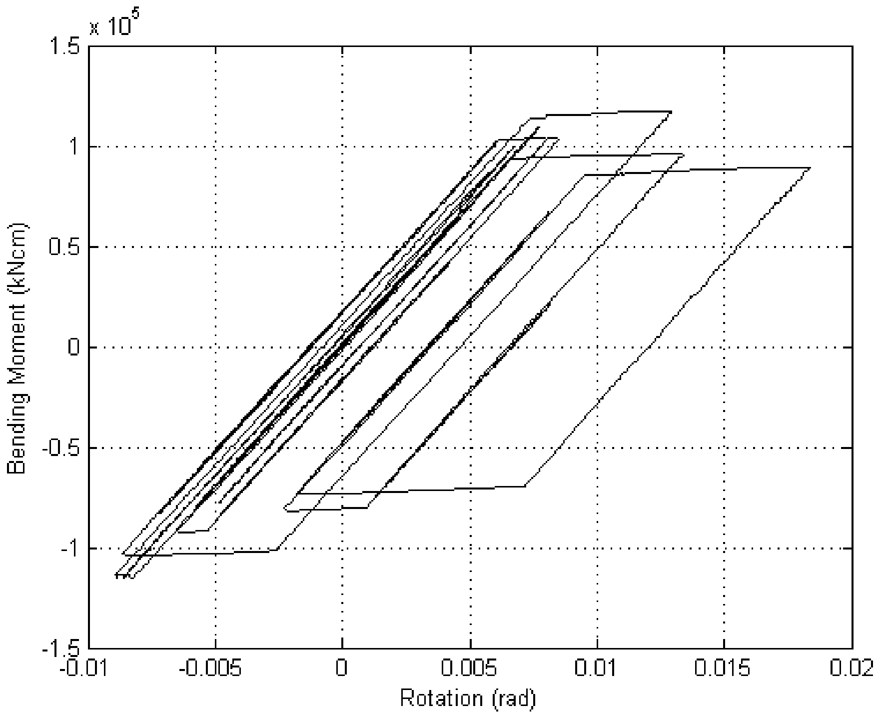

Figure 5. The first joint of the sixth floor's moment-rotation history for the degrading mode

CONCLUSIONS

The results of this study indicates that there is a strong possibility that a systematic relation exists between the strong motion duration and the effects of strength degradation on story drifts. Moreover, the pulse-like records may have considerable effects even if they have moderate strong motion durations. However, since the chosen number of records are quite few in this research (in order not to spoil the earthquake hazard level defined by the code) it is not appropriate to draw certain conclusions, but it seems the effects of degradation increase with the increasing strong motion duration and with the existence of pulses and of course with the combined effect.

The maximum difference between the strength degrading and non-degrading models in terms of story drift ratios can reach to 50%. However, though there are such peak points, the mean and median values of these ratios of are in the order of approximately $\pm$2%. This acceptable mean or median value is not relieving because of the peaks of individual records. This ratio should be investigated more thoroughly with much more earthquake records and model frames.

Based on the findings of this research, the records with high Arias Intensity and short fault distances may cause higher mode effects whereas the relatively far records generally affect the lower stories. However, this case may be attributed to the design procedure followed, the cross sections assigned, the records used, etc. Actually, a thorough parametric study is being carried out to approve these initial findings.

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