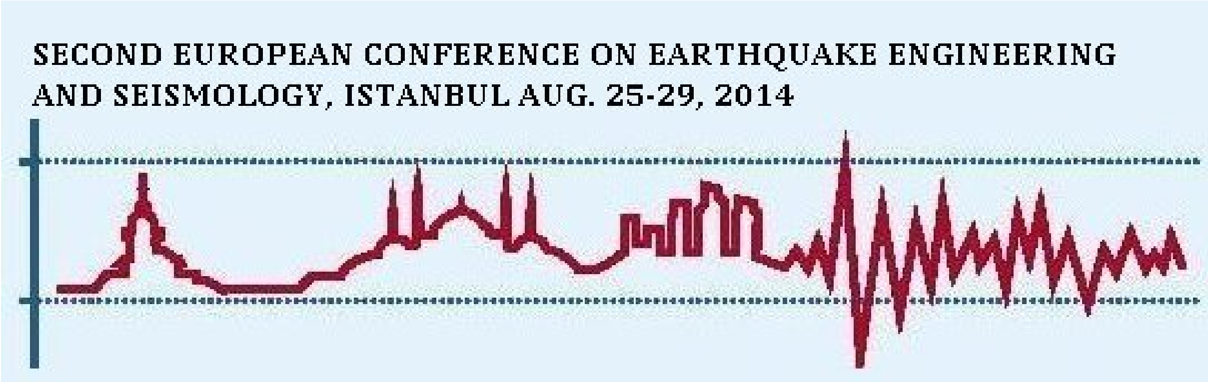

INVESTIGATION OF MEMBER DAMAGE LIMITS AND BUILDING PERFORMANCE STATES IN EXISTING RC BUILDINGS

Şevket Murat ŞENEL[1], Mehmet PALANCİ[2], Ali KALKAN[3], Yasin YILMAZ[4]

ABSTRACT

Seismic performance evaluation of existing buildings has been an important topic in Turkey as well as in other earthquake prone countries. Considerable life and property losses necessitate the seismic performance evaluation of existing buildings. For this reason an additional chapter, which regulates the seismic performance evaluation of existing buildings, was added in to the Turkish earthquake code of 2007. Target performance levels named as Immediate Occupancy, Life Safety, Collapse prevention were described depending on the building type in the code and each performance level was related with the amount of column and beam damages. Damage levels in columns and beams, on the other hand, are explained by using strain based expressions. Threshold strains defining the minimum, safety and collapse limits of sections are explained in terms of compression strains for concrete and tensile strains for steel. However, compatibility of building performance levels and member damage limits is the key point that should be considered. Correlation of member damage limits and building performance states for various structural systems and configurations should be studied.

In literature, some studies indicate that formation of member damages occurs at very scattered drift levels and hence performance levels determined by these scattered values may not reflect the real situation. In order to investigate this problem 10 R/C building were selected and analysed. Five of them represent the former code (1975 code) buildings and the rest of them are selected from the newer (1998 code) buildings..

Structural properties (member dimensions, reinforcement ratios etc) of members were determined by using design projects and 3-D building models were prepared. Sectional damage limits were calculated according to strain based damage definitions of Turkish earthquake code and plastic hinges were assigned to models by using user-defined (moment and shear) hinges. Capacity curve of buildings were obtained by performing nonlinear pushover analyses. Structural drift ratios corresponding to member (beams and columns) damage levels were obtained. Distribution of these drift points were marked on the capacity curves of buildings and the variation of these points was obtained. Cumulative probability of exceeding member damage limits were calculated and compared with the code conformed values. Results indicate that the distribution of drift ratios corresponding to member damage limits in new and old buildings can be considerably different. Furthermore, it is also observed that identical drift ratios may correspond to completely different performance levels.

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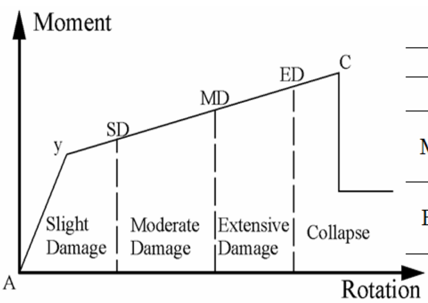
INTRODUCTION

As in earthquake prone countries, seismic performance evaluation of buildings has also been an important topic in Turkey. Considerable losses after devastating earthquakes in Turkey increased the need of new treatments to guides and seismic codes. One of the treatments in seismic code of Turkey (TEC-2007, 2007) is applied by adding of new chapter to evaluate the seismic performance of new and existing buildings. In TEC-2007, performance levels are described and named as Immediate Occupancy, Life Safety and Collapse prevention depending on the building type. In the code, each performance level is related with the amount of column and beam damages and these levels are explained by using strain based expressions. These strain based expressions are explained in terms of compression strains for concrete and tensile strains for steel.

In literature, (Senel 2009, Senel and Palanci 2011, Senel et al., 2013) some studies indicate that formation of member damages occurs at very scattered drift levels and hence performance levels determined by these scattered values may not reflect the real situation. For this reason, compatibility of building performance levels and member damage limits should be should be examined. In addition, member damage limits and building performance states for various structural systems and configurations should be studied in order to assess this problem. In order to investigate this problem, 10 reinforced concrete (R/C) buildings were selected and analysed. Five of them were selected to represent the former code (TEC-1975, 1975) buildings (called as existing buildings in the rest of paper) and the rest of them were selected from the newer (TEC-1998, 1998) buildings (called as new buildings in the rest of paper). Structural configuration of members such as dimensions, reinforcement ratios etc. were determined by design projects of buildings and 3-D building models were prepared. Sectional damage limits were calculated according to strain based damage definitions of Turkish earthquake code and plastic hinges were assigned to models by using user-defined (moment and shear) hinges. Capacity curve of buildings were obtained by performing nonlinear pushover analyses. Structural drift ratios corresponding to member (beams and columns) damage levels were obtained from each step of pushover analysis. Determined drift values were marked on the capacity curves of buildings and the variation of these points was obtained. Cumulative probability of exceeding member damage limits were calculated and compared with the code conformed values.

MODELLING OF R/C BUILDINGS

Structural configurations of member was determined by design projects of buildings and then 3-D models of buildings were created by Sap2000 (Sap2000, CSI). Later, strength and ductility capacity of each members were determined by moment-curvature analyses. During the moment-curvature analysis, concrete behaviour was represented by Modified Kent-Park (Park et al., 1982) model and each member sectional damage levels was obtained by considering concrete and steel strain limits given in TEC-2007 (TEC-2007, 2007). So, concrete and steel limits were checked in the analysis and each damage curvature capacity of member was determined which limit was reached first.



Member damage	Concrete	Steel
Slight Damage (SD)	$(\varepsilon_c)_{SD}=0.0035$	$(\varepsilon_s)_{SD}=0.01$
Moderate Damage (MD)	$(\varepsilon_{cc})_{MD}=0.0035+0.01\left(\frac{\rho_s}{\rho_{sm}}\right)\le 0.0135$	$(\varepsilon_s)_{MD}=0.04$
Extensive Damage (ED)	$(\varepsilon_{cc})_{ED}=0.004+0.014\left(\frac{\rho_s}{\rho_{sm}}\right)\le 0.018$	$(\varepsilon_s)_{ED}=0.06$

Figure 1. Typical representation of member moment-rotation capacity and strain damage limits according to TEC-2007

In Fig.1 typical moment-rotation capacity of member and strain limits according to TEC-2007 is shown. Moment-rotation capacities of members were then assigned to critical sections. Plastic hinge length was taken as a half of section height in corresponding direction as suggested in TEC-2007. Shear capacity of members was also considered and was assigned to centre of member length. Shear capacity was calculated by eq.(1) (TS-500, 2000).

$$Vr = 0.182\sqrt{f_c}\,b_w d\left(1 + 0.07\,N/A_c\right) + A_{sw}/s\; f_y d \qquad (1)$$

In eq.(1), f_c and f_y define existing compressive strength of concrete and tensile strength capacity of transverse reinforcement. Other definitions are b_w, d section width and section height, A_c section area, N axial load, A_{sw} transverse reinforcement area in corresponding direction, and s stirrup space.

In this study, six-storey 5 new and existing (constructed after TEC-1998) buildings are used. Also, all buildings used in this study were designed as residential buildings. Compressive strength and tensile strength capacity of buildings were obtained from design project of buildings. According to design projects, compressive strength capacity of existing and new buildings are C16 and C30 (16-30 N/mm^2) and tensile strength of longitudinal and transverse reinforcement are S220 and S420 (f_y=220-420 N/mm^2) respectively. Seismic weight of buildings was calculated by combination dead and 30% of live loads. During the pushover analysis, the effective stiffness of beams was considered as 0.4EI and effective stiffness of the columns depending axial load ratio recommended in TEC-2007 was used (Eq.(2)). In Eq.(2), N is axial load of column, A_c is column cross-sectional area and f_c is the compressive strength of concrete. Linear interpolation can be applied for axial load ratio between 10% and 40%.

$$If\; N/\left(A_c f_c\right) \le 10\% \Rightarrow (EI)_{cr} = 0.4EI \qquad (2a)$$

$$If\; N/\left(A_c f_c\right) \ge 40\% \Rightarrow (EI)_{cr} = 0.8EI \qquad (2b)$$

3-D models of 10 R/C buildings was created and general properties of new and existing buildings for each direction (vibration period, building height, seismic weight) are determined (Table 1).

Table 1. General properties of selected buildings

Direction	Existing Buildings				New Buildings			
	Build. No	Seismic weight (ton)	Build. Height (H) (m)	Build. Period (s)	Build . No	Seismic weight (ton)	Build. Height (H) (m)	Build. Period (s)
X	1	1011.13	17.50	0.752	6	2582.76	18.55	1.055
Y				0.917				0.808
X	2	794.50	16.80	0.634	7	1813.68	16.80	0.851
Y				0.741				0.693
X	3	1352.93	16.80	0.955	8	1383.04	16.80	0.800
Y				0.846				0.966
X	4	952.91	17.50	0.740	9	897.7	17.50	0.965
Y				0.981				0.865
X	5	964.08	17.50	0.820	10	1234.41	17.75	0.860
Y				0.927				0.964

CODE BASED ASSESSMENT OF R/C BUILDINGS

Capacity curve of buildings were obtained by performing nonlinear static pushover analysis. During the analyses buildings were first subjected to gravity loads and then lateral force distribution was applied. Lateral force distribution was obtained by multiplying each story weight and first modal shape amplitude at each story level. P-Delta effects were considered during the analyses. Capacity curve of buildings were then converted to dimensionless by proportion of base shear force and seismic weight of building (V/W) in y-axis and by proportion of roof displacement capacity and building height in x-axis.

In order to simplify and to understand capacity related parameters in easy way, capacity curve of buildings were converted to bi-linearized. Bi-linearization of capacity curves were made by ATC-40 (ATC-40, 1996) approach. Using same approach, selected multi degree of freedom (MDOF) buildings were converted to equivalent single degree of freedom (sdof) systems. In order to make comparison between new and existing buildings or same group of buildings, common modal and capacity parameters is determined and given in Table 2.

Table 2. Capacity parameters of selected buildings

Build. No	Direction	V_t/W	Δ_y/H (%)	Δ_u/H (%)	K_2/K_1	PF_1	α_1
1	X	0.125	0.165	0.943	1.91	1.324	0.805
	Y	0.072	0.143	1.098	2.60	1.314	0.804
2	X	0.121	0.118	0.905	1.41	1.324	0.805
	Y	0.104	0.136	0.911	4.20	1.316	0.816
3	X	0.080	0.172	0.851	6.09	1.310	0.819
	Y	0.075	0.128	1.042	3.59	1.311	0.815
4	X	0.133	0.165	0.789	3.58	1.308	0.819
	Y	0.089	0.189	0.629	1.40	1.288	0.831
5	X	0.103	0.158	0.783	6.36	1.323	0.822
	Y	0.097	0.191	0.691	5.29	1.307	0.812
6	X	0.146	0.338	1.271	6.89	1.311	0.846
	Y	0.218	0.320	2.055	4.39	1.350	0.803
7	X	0.211	0.370	1.607	6.77	1.320	0.807
	Y	0.284	0.348	1.746	5.36	1.346	0.782
8	X	0.192	0.297	1.696	4.75	1.323	0.809
	Y	0.157	0.338	1.938	7.12	1.274	0.815
9	X	0.178	0.376	2.087	5.52	1.293	0.810
	Y	0.241	0.422	2.540	8.64	1.312	0.796
10	X	0.240	0.396	2.868	7.22	1.297	0.814
	Y	0.192	0.369	2.392	4.88	1.233	0.834

After determination of parameters, selected buildings were assessed by TEC-2007. In the code, target performance levels named as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Each performance level is related with the amount of column and beam damages. Apart from these performance levels, building is assumed collapse if the criteria of CP is not satisfied. The criteria suggested by TEC-2007 for IO, LS and CP performance levels are given in Table 3.

Table 3. Performance levels criteria defined in TEC-2007

Location	Performance levels criteria
Immediate Occupancy (IO)	1. At most 10% of beams in any story exceed “slight damage”. Other beams have “slight damage”. 2. All the columns have “slight damage” performance.
Life Safety (LS)	1. At most 30% of beams in any story exceed “moderate damage”. 2. In any story, the shear force carried by columns which have “extensive damage” must be less than 20% of story shear force. In the top story, this ratio must be less than 40% of story shear force. 3. In any story, the shear force carried by columns at both ends of which exceeds “slight damage” must be less than 30% of story shear force. 4. No beam or column in any story allowed having “collapse”.
Collapse Prevention (CP)	1. At most 20% of beams in any story have “collapse”. 2. In any story, the shear force carried by columns which exceeds “slight damage” at both ends must be less than 30% of story shear force. 3. No column in any story allowed having “collapse”.

It can be seen from the table that, multiple criteria are defined for each performance level. So, multiple values are obtained for each performance level but critical performance level of building is determined by taking the minimum of all corresponding criteria results. In TEC-2007, except CP level, IO and LS performance levels do not covers the brittle damaged structural members if they are strengthened. However, in this study performance level of buildings are determined by considering also brittle damaged members as we try to understand and investigate the member damages and performance levels of buildings. As a result of performance level determination of selected buildings is given in Table 4.

Table 4. Performance levels of selected buildings in terms of drift ratio

Direction	Existing Buildings				New Buildings			
	Build. No	(Δ_{IO}/H) %	(Δ_{LS}/H) %	(Δ_{CP}/H) %	Build. No	(Δ_{IO}/H) %	(Δ_{LS}/H) %	(Δ_{CP}/H) %
X	1	0.24	0.24	0.76	6	0.43	1.14	1.27
Y		0.26	0.40	1.07		0.42	1.63	2.06
X	2	0.09	0.68	0.91	7	0.44	1.35	1.61
Y		0.26	0.85	0.85		0.38	1.55	1.75
X	3	0.09	0.10	0.85	8	0.34	1.17	1.64
Y		0.24	0.91	1.03		0.38	1.41	1.94
X	4	0.27	0.45	0.67	9	0.41	1.27	1.91
Y		0.19	0.20	0.51		0.34	1.25	2.08
X	5	0.14	0.14	0.64	10	0.37	1.60	2.52
Y		0.17	0.18	0.22		0.27	0.29	1.34

In order to assess the effect of each criteria given for corresponding performance levels, analysis of buildings were inspected. Detailed analysis and investigations on performance of existing buildings is investigated in detail in the study made by Senel et al., (2013). To summarize, in the study it was shown that IO and LS levels are dominated by 1st criteria (related to beam criteria), but CP level is mostly controlled by 3th criteria of corresponding performance levels in existing buildings. The observations on performance levels has shown that as same as in existing buildings, IO and LS performance levels are controlled by 1th criteria in new buildings. It is also observed that CP level is controlled by 1st and 3nd (criteria related to column damages) criteria in new buildings. Moreover, it is found that half of capacity curves are controlled by 1st (Build no: 6, 7 and 8-Y direct.) and rest of them by 3nd criteria.

RELATIONSHIP OF MEMBER DAMAE LIMITS AND PERFORMANCE STATES

The performance levels of buildings has shown that similar performance drift ratio may be obtained for different performance levels in existing buildings but this situation is not valid for selected new buildings. This situation has shown that performance levels should be investigated on basis of member damage limits. In order to investigate the relationship between performance levels and member damage limits, pushover analyses were checked. By this way, roof displacements values were obtained when beam or columns exceeds the any member damage limit from step by step pushover analysis results. Obtained roof displacements are marked on bi-linearized pushover curves of selected buildings and shown in Figs.2 and 3, respectively.

It can be seen from the figures that structural members get damage in earlier drift ratios in existing buildings and drift capacity of new buildings is 3~4 times higher than existing buildings. Almost all columns in existing buildings in collapse state around %1.1 drift ratios, but columns in new buildings are still in moderate damage state. Beams in existing buildings suffer from severe damages at earlier drift ratios due to higher shear effects, but bending is more effective in new buildings. Although shear effects the worst beam capacity in 10th building, but still collapse state of beams (%0.30) in new buildings start quite after beams in existing buildings (%0.12) when compared in terms of drift ratios.

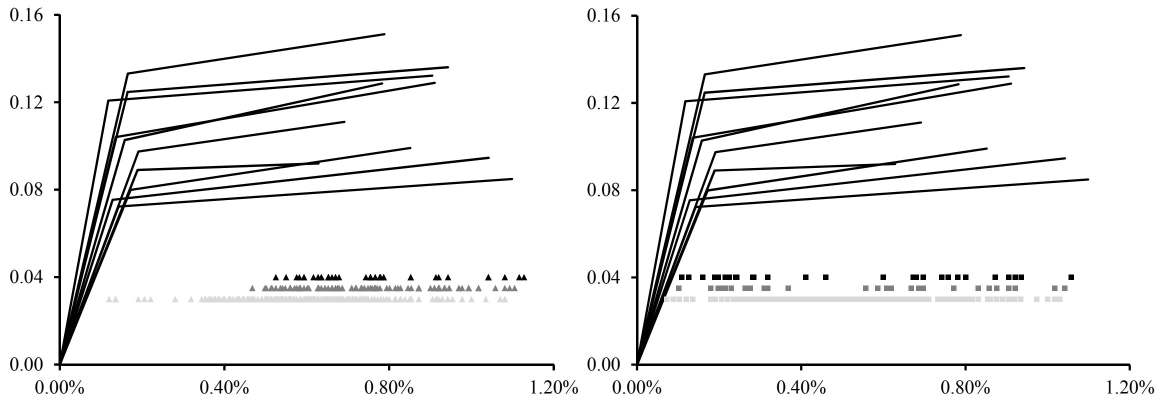


Figure 2. Pushover curve and scatter of damages in existing buildings (left: column, right: beam)

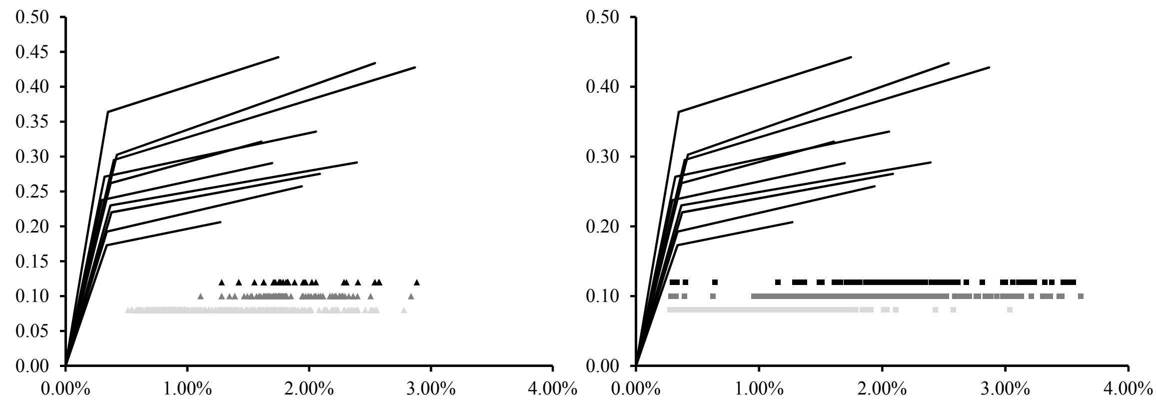


Figure 3. Pushover curve and scatter of damages in new buildings (left: column, right: beam)

The obtained drift ratios has shown that each member damage should be investigated more and by this way relation of member damage limits and performance states of buildings may better be understood. For this reason, cumulative probabilities of damages are calculated for beams and columns respectively. Later, probabilities are investigated in two cases. In the first case, column and beam damage probabilities are compared with each other (Fig.4). It can be clearly said that drift capacity of members in new buildings are quite higher than in existing buildings. When probabilities of moderate damage are compared, it can be said that probabilities of this damage can be separated in both new and existing buildings. However, this situation is not so apparent in extensive and collapse damage states. Also, collapse state probabilities of columns are increasing rapidly with an increasing drift ratio (Senel et al., 2013). Note that damage probabilities of column are higher than beam in Fig.4c. This situation implies that member damage limits and performance state criteria should more carefully be investigated in performance state descriptions.

In second case, column and beam probabilities are investigated separately and probabilities of member damages are compared. The comparison of member damage probabilities in new and existing buildings is shown in Fig.5. Figure implies that probabilities of moderate and extensive damages of both building types (new and existing) can be separated for beams. Moderate and extensive damage probabilities are separated in new buildings, but this situation is not valid for existing buildings. Probabilities of columns have shown similarities in new and existing buildings and they have similar trends in extensive and collapse damage probabilities. While moderate and extensive/collapse damage probabilities appears parallel in existing buildings, probabilities of these damages at lower drift ratios are quite far and at higher drift ratios (after drift ratio of 1.7%) getting closer in new buildings.

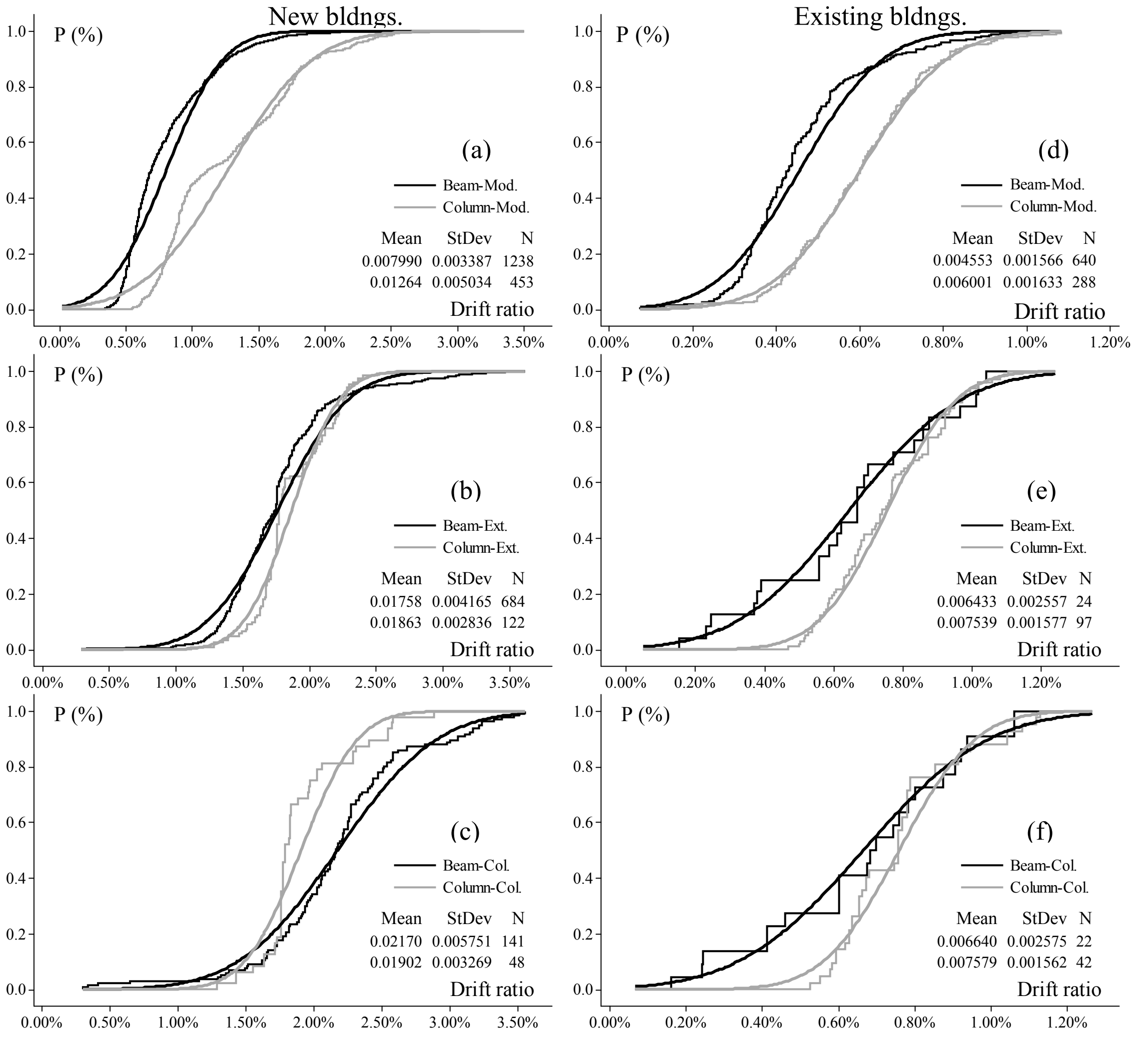


Figure 4. Comparison of beam and column damage cumulative probabilities in selected buildings

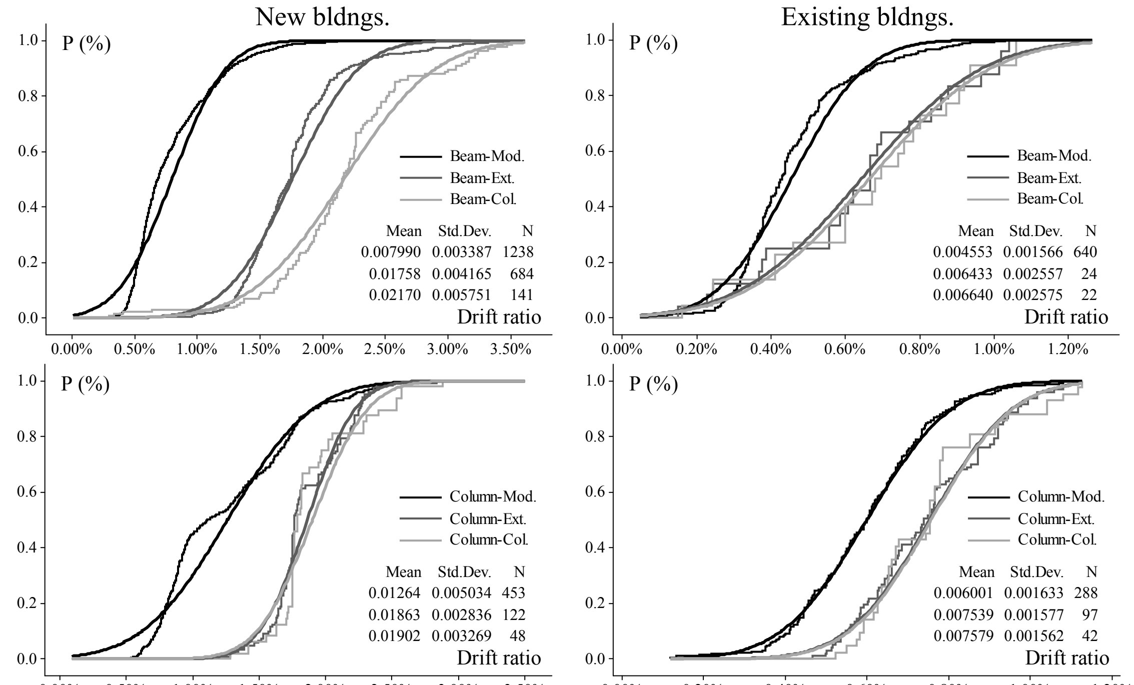


Figure 5. Comparison of cumulative probabilities of beam and column damages in selected buildings

Although beam and column damage probabilities show differences (see Fig.4), similar trends are observed when beam and column probabilities of selected buildings are compared separately. In order to bring more clearance to this situation, pushover analysis of selected buildings were used. Results have shown that shear behavior affects especially the probabilities of beams and causes similar damage probabilities at higher damages. Probabilities of different member damages are quite different in selected new buildings owing to well confinement. On the other hand, bending behavior dominates the damage probabilities in columns and this behavior causes similar trend probabilities in both building types. This situation should also be considered in TEC-2007 performance descriptions. It is worth to remind that numerous new and existing buildings should be evaluated in order to verify the findings in this study.

In table 5, proportion of each performance levels in selected buildings given is given. When the values are checked, it will be seen that performance levels of new buildings are relatively higher than existing buildings. The values also imply different drift ratios for distinct performance levels, but this situation not valid for existing buildings. Same drift ratios are obtained for distinct performance levels of 1^{th}, 2^{nd}, 5^{th} buildings.

Table 5. Proportion of distinct performance levels in selected buildings

Direction	Existing Buildings			New Buildings		
	Build. No	IO/LS	LS/CP	Build. No	IO/LS	LS/CP
X	1	1.00	3.12	6	2.66	1.11
Y		7.72	1.33		3.90	1.26
X	2	3.30	1.00	7	3.09	1.19
Y		1.53	2.68		4.13	1.12
X	3	1.12	8.27	8	3.46	1.40
Y		3.81	1.13		3.68	1.38
X	4	1.68	1.49	9	3.10	1.51
Y		1.06	2.51		3.71	1.66
X	5	1.00	4.59	10	4.33	1.57
Y		1.05	1.20		1.07	4.66

CONCLUSIONS

In the content of this study, 10 R/C existing buildings were selected. Half of selected buildings were constructed in accordance with TEC-1998 (newer) and rest of buildings in accordance with former code. Capacity curve of selected buildings were calculated by pushover analysis and performance levels of building are determined. In TEC-2007, each performance level is related with the amount of column and beam damages. In order to compare and investigate the member damage limits and performance states, pushover analysis results were used and drift ratios of member damage limits was found step by step for all joints of members. Results are given as follows:

- Apparent ductility differences are observed between new and existing buildings.
- Immediate Occupancy and Life Safety performance levels of new and existing buildings are dominated by beam related descriptions.
- Collapse Prevention performance levels of new and existing building are mostly controlled by column related parameters.
- Extensive and collapse damages probabilities of columns are increasing rapidly at higher drift ratios. In addition, collapse state damage probabilities of column are higher than beam in new buildings.
- When column damage probabilities of new and existing buildings are compared, similar trends of extensive and collapse damages are noted.
- Comparison of damage probabilities of beams is shown that extensive and collapse damage state probabilities are almost identical in existing buildings. However, this situation is not valid for new buildings.

- Pushover analysis results and damage probabilities of members have shown that lack of confinement may result more critical situations to beams than columns.
- Performance levels drift ratios of buildings controlled by beams are higher than buildings controlled by columns.
- It is determined that extensive and collapse state damage probabilities of columns are similar in new and existing buildings. Because of this reason, closer or even identical drift ratios can be obtained for different performance levels of buildings. This situation should be considered during determination of performance levels criteria of buildings.

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