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# EFFECT OF VARIOUS HYSTERETIC MODELS ON SEISMIC FRAGILITIES OF PRECAST INDUSTRIAL BUILDINGS

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## ABSTRACT

One story precast buildings constitutes the majority of industrial building stock of Turkey. Therefore this study interested in the seismic performance of existing precast industrial buildings. For this purpose, Denizli Organized industrial zone, which is among the important industrial regions of western Turkey, was selected. Structural properties of more than a hundred precast buildings were determined by means of project and site investigations and capacity curves of buildings were obtained by using non-linear analysis method.

Seismic performance assessment of precast buildings revealed that lateral strength and ductility capacities and vibration periods of buildings range between 10%-30%, 1.3-3.5 and 1-2.8 seconds respectively. In order to assess the seismic performance of buildings, fragility curves were used and lateral drift demands, which control the fragilities of precast buildings, were calculated by using non-linear time history analyses. More than 300 records, which classified according to their peak ground velocities (to represent low, moderate and severe earthquakes), were selected.

Fragility response of precast buildings under different behavior models were examined by using four different hysteretic models. Damage probabilities of buildings were calculated by using each of these models and compared. Comparisons were made by considering different intensity levels and various damage states which are expressed in Turkish Earthquake Code-2007. Buildings were classified into sub groups considering lateral strength and ductility capacities. By this way precast industrial buildings was represented under four different strength and ductility classes. Consequently, the effect of both structural properties of buildings (expressed in terms of lateral strength and ductility) and various hysteric models were considered. Preliminary results have shown that different hysteric models have not significant effect on seismic fragilities of precast industrial buildings.

## INTRODUCTION

In Turkey, majority of industrialized zones are located in high seismic regions. Thus, one story precast buildings constitutes the majority of industrial building stock of Turkey. The amount of damage to these buildings took the attention and this situation led to question seismic safety of precast industrial buildings after devastating earthquakes occurred in 1998 and 1999. In order to better understand seismic behavior of these buildings, seismic performance of existing precast industrial buildings is investigated. For this purpose, Denizli Organized industrial zone (DOIZ), which is among the important industrial regions of western Turkey, was selected. Structural properties of existing precast buildings were determined by means of project and site investigations and capacity curves of buildings

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were obtained by using non-linear analysis method. Analysis results have shown that lateral strength and ductility capacities and vibration periods of buildings range between 10%-30%, 1.3-3.5 and 1-2.8 seconds respectively.

In recent years, probabilistic methods are widely used in many engineering fields and this situation shows that these methods can also be applied for precast buildings. One of the important methods which give opportunity to assess seismic performance of buildings is the calculation of seismic fragility curves of buildings. In order to assess the seismic performance of buildings, fragility curves were used and lateral drift demands, which control the fragilities of precast buildings, were calculated by using non-linear time history (NLTH) analyses. Lateral drift demands were calculated by selecting more than 300 records according to their peak ground velocities (to represent low, moderate and severe earthquakes). Seismic behavior of precast buildings is represented by four different hysteretic models (elastoplastic (EP), elastoplastic with %5 hardening (EP5%), Modified Clough stiffness degrading model (Mod. Clough) and bilinear slip (Bil. Slip)) were used.

Damage probabilities of buildings were calculated for hysteretic models and compared by considering different intensity levels and various damage states. Buildings were classified into sub groups and precast industrial buildings were represented under four different strength and ductility classes. By his way, the effect of both structural properties of buildings (expressed in terms of lateral strength and ductility) and various hysteric models on seismic fragilities of precast industrial buildings was investigated.

## CAPACITY CURVE AND DAMAGE LEVELS OF PRECAST BUILDINGS

Structural models of each building in the building stock were created and axial load ratio of each member was determined. Properties of each member (column) were determined by site and project investigations. By combining each data, strength and ductility capacities of individual member (column) were determined by moment-curvature analyses. During the moment-curvature analysis, concrete behavior model was represented by Modified Kent-Park (Park et al., 1982) model and each member sectional damage levels "Immediate Occupancy(IO), Life Safety(LS), Collapse Prevention(CP)" was obtained by considering concrete and steel strain limits given in Turkish Earthquake Code-2007 (TEC-2007, 2007). Strain limits of each damage level given in TEC-2007 are shown in Table 1. During the moment curvature analyses, both concrete and steel strain based limits were checked and curvature capacity of member damages was determined which limit was satisfied first. Yield curvature and moment capacity of members was calculated by considering Priestley et al. (2007) approach.

Table 1. Strain based sectional member damage definitions

| Member damage level | Concrete | Steel |
| --- | --- | --- |
| Immediate Occupancy (IO) | $(\varepsilon_c)_{IO} = 0.0035$ | $(\varepsilon_s)_{IO} = 0.01$ |
| Life Safety (LS) | $(\varepsilon_{cc})_{LS} = 0.0035 + 0.01\left(\dfrac{\rho_s}{\rho_{sm}}\right) \le 0.0135$ | $(\varepsilon_s)_{LS} = 0.04$ |
| Collapse Prevention (CP) | $(\varepsilon_{cc})_{CP} = 0.004 + 0.014\left(\dfrac{\rho_s}{\rho_{sm}}\right) \le 0.018$ | $(\varepsilon_s)_{CP} = 0.06$ |

One story precast industrial buildings can simply be shown in Fig.1. Majority of these buildings are constructed as hinged upper connections. For this reason, each member's behavior can be represented as cantilever column and as seen from the figure that plastic hinge regions are located at the bottom of each column. This type of behavior makes simple to calculate capacity curve of buildings. For this reason, individual response of each member is calculated and then they are combined. Construction of capacity curve of precast industrial buildings can be found in the study performed by Senel and Palanci (2013).

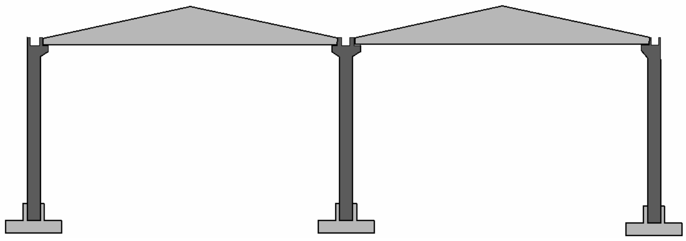

Figure 1. Typical representation of one storey existing precast buildings

In Fig.2, response of cantilever type member is shown. By using moment-area theorem, displacement capacity of individual members can be calculated by Eqs.(1-3). It should be noted that one of the key factor on displacement capacity of member is the length of plastic hinge. In this study, plastic hinge length is taken the half of column height as suggested in TEC-2007. Strength capacity of is calculated by Eq.(3).

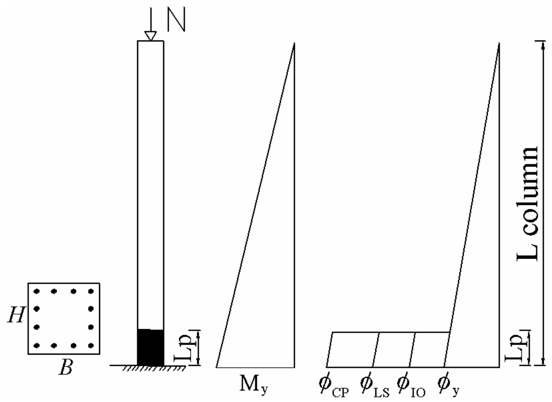


Figure 2. Response of cantilever column

$$\delta_{y_i} = \frac{\phi_{y_i} \cdot L_i^2}{3} \tag{1}$$

$$\delta_{DS_i} = \delta_{y_i} + (\phi_{DS_i} - \phi_{y_i}) L_{p_i} \left( L_i - \frac{L_{p_i}}{2} \right) \tag{2}$$

$$v_{t_i} = \frac{M_{y_i}}{L_i} \tag{3}$$

Capacity curve of buildings were determined by lateral strength capacity and displacement capacity, respectively. During the calculation of capacity curves, it was considered that all columns have same drift ratios at roof level. By using this assumption, lateral strength capacity of buildings was calculated by summing of individual strength capacity of columns. Each damage state of buildings (Slight damage, moderate damage, extensive damage and collapse) was also determined by considering minimum displacement of each member damage level. It is worth to state that similar properties of columns (column dimensions, transverse/longitudinal ratios) cause similar damage levels of each individual column. Because of this reason, individual member damage drift ratios of columns (Immediate Occupancy, Life Safety, and Collapse Prevention) are not widely distributed.

Aforementioned process was carried out for each DOIZ buildings and capacity curves were determined. Vibration period of buildings which is related with stiffness of the building was calculated from elastic slope of capacity curves. In Fig.3, lateral strength ratio ($V_t$/W) according to vibration period (Fig.3a) and distribution of ductility capacity of buildings (Fig.3b) are illustrated. High vibration periods, emphasize the problems of inadequate lateral stiffness of precast buildings observed in past earthquakes, is also valid for DOIZ buildings.

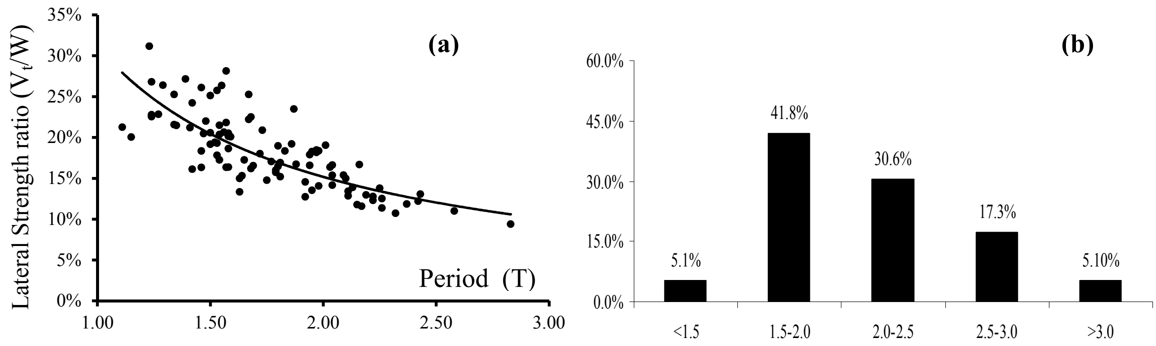


Figure 3. Capacity related parameters of industrial precast buildings

## DETERMINATION OF SEISMIC DISPLACEMENT DEMANDS

Seismic capacity of all buildings was determined in the earlier chapter, and lateral strength ratios ($V_t$/W) are obtained. In order to determine seismic performance of the buildings seismic demands should be calculated. In this study, seismic demands are calculated using nonlinear-time history analyses. For this reason, 364 records were selected (292 unscaled and 72 scaled records). Records were scaled (maximum scale factor: 1.52) to represent moderate to severe earthquakes in terms of higher peak ground velocities (PGV). In literature, some studies (Akkar and Ozen 2005, Akkar and Kucukdogan 2008) pointed out the high correlations between seismic demand of single degree of freedom systems (sdof) and PGV values. Thus, PGV was considered as earthquake parameter during the calculation of fragility curves of precast buildings and PGV value of records were selected between 20 and 80 cm/s. In Table 2, number of selected records corresponding to each PGV bin is given. As it can be seen from the tables that 12 PGV intervals was generated and almost equal number of records were selected to obtain uniform PGV distribution. After selection of records, each building was analyzed using its own lateral strength ratio and vibration period by Bispec (Hachem, Bispec) program. During the analyses seismic behavior of precast buildings is represented by four different hysteretic models “elastoplastic (EP), elastoplastic with %5 hardening (EP5%), Modified Clough stiffness degrading model (Mod. Clough) and bilinear slip (Bil. Slip)”.

Table 2. Strain based sectional member damage definitions

| PGV bin name | Lower-Upper limits (cm/s) | No. of records | Mean PGV (cm/s) | Std.dev |
|---|---|---|---|---|
| PGV1A | <25.0 | 29 | 21.69 | 1.21 |
| PGV1B | 25.0-30.0 | 31 | 27.31 | 1.50 |
| PGV1C | 30.0-35.0 | 34 | 32.05 | 1.48 |
| PGV1D | 35.0-40.0 | 30 | 37.35 | 1.9 |
| PGV2A | 40.0-45.0 | 30 | 41.77 | 1.28 |
| PGV2B | 45.0-50.0 | 30 | 47.15 | 1.54 |
| PGV2C | 50.0-55.0 | 30 | 52.16 | 1.47 |
| PGV2D | 55.0-60.0 | 30 | 57.18 | 1.32 |
| PGV3A | 60.0-65.0 | 30 | 62.07 | 1.14 |
| PGV3B | 65.0-70.0 | 30 | 67.52 | 0.97 |
| PGV3C | 70.0-75.0 | 30 | 72.55 | 0.75 |
| PGV3D | >75.0 | 30 | 77.31 | 1.09 |

## ANALYTICAL FRAGILITY CURVES OF PRECAST BUILDINGS

As a result of nonlinear dynamic analyses, 142688 maximum seismic demands are calculated for all hysteric models. Exceeding numbers and ratios of each group and each damage level was obtained by comparing each displacement demand and damage levels. Analytical fragility curves of precast buildings were then drawn by assuming two-parameter lognormal distribution using these exceedance ratios. Lognormal distribution parameters; mean (λ) and standard deviation (σ) were estimated by least squares method. Eq.(4) can be used to express cumulative probability of interested exceeding damage level.

$$\mathrm{Pr} = \Phi\left[\frac{(\ln \mathrm{PGV} - \lambda)}{\sigma}\right] \quad (4)$$

In equation, Φ is represented as standard cumulative normal distribution function and as mentioned earlier PGV is ground motion parameter selected for this study. In Fig.4, probability of extensive damage fragility curves is drawn for each hysteric model and all buildings. Mean fragility curve of each hysteric model is also illustrated with thick lines. Fig.4 clearly indicates the variability of fragility curves of buildings and hysteric models. In order to investigate the effect of hysteric models and structural parameters, mean fragility curve of each strength and ductility classes is obtained and compared.

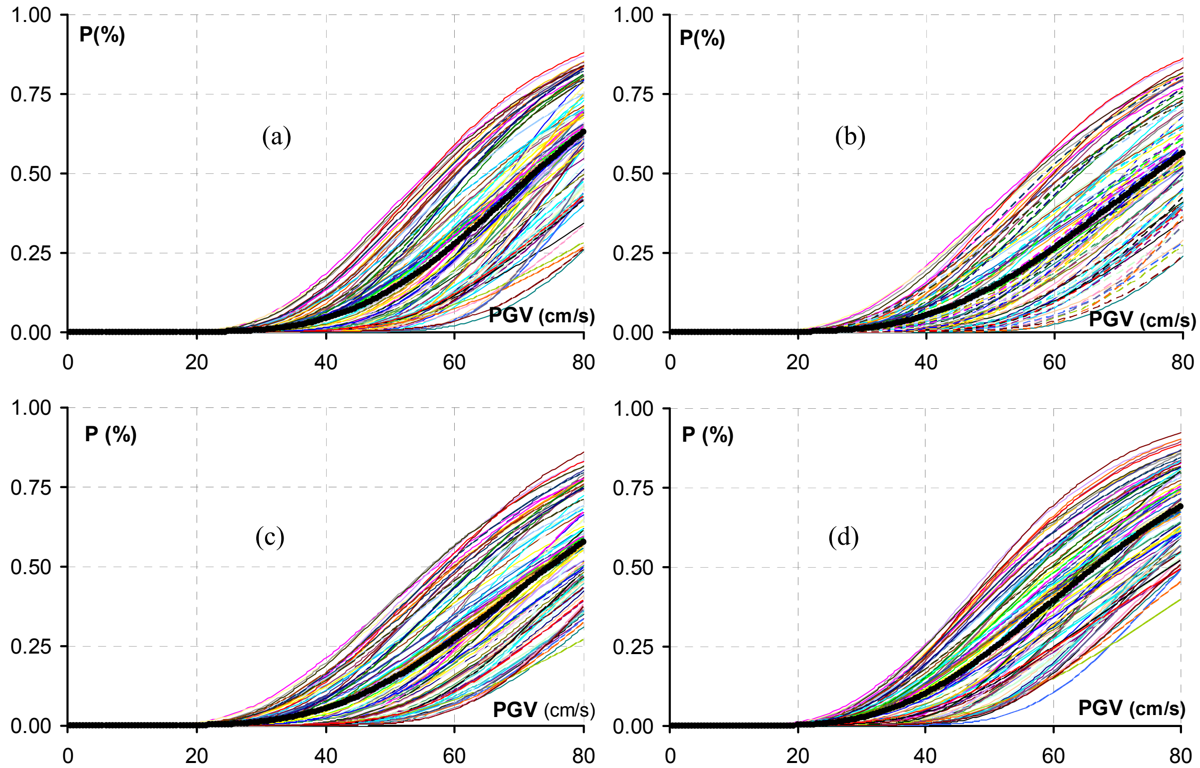


Figure 4. Probability of extensive damage (a: EP, b: EP (%5), c: Mod. Clough, d: Bil. Slip)

## EFFECT OF STRUCTURAL PARAMETERS AND HYSTERIC MODELS ON FRAGILITY CURVES

Senel et al. (2013) is investigated the effect of stiffness which is related with vibration period, lateral strength ratio and ductility parameters on seismic performance of precast buildings. According to study, lateral strength ratio and ductility capacity parameters have highest priority on seismic performance of precast buildings especially at higher damage levels. Accordingly, structural parameters (lateral strength ratio and ductility capacity) are willingly selected to investigate the effect of hysteric models on seismic performance (fragility) of precast buildings. Selected structural parameters are clustered into four groups and given as follows:

Low strength – low ductility cap.  : Vt/W < 18%  & μ< 2.5
High strength – low ductility cap. : Vt/W ≥ 18%  & μ< 2.5
Low strength – high ductility cap. : Vt/W < 18%  & μ≥ 2.5
High strength – high ductility cap.: Vt/W ≥ 18%  & μ≥ 2.5

After separation of groups the effectiveness of damage states on hysteric models was first checked. Observations indicated similar probability of slight and moderate damage states for all hysteric models in each group. Fig.5 presents seismic fragilities of slight and moderate damage states of distinct low strength& low ductility and high strength& high ductility buildings groups. In the figures it is hard to distinguish seismic fragilities of hysteric models. Similar observations were made for rest of groups. For this reason, the effect of structural parameters and hysteric models are investigated for extensive damage and collapse states in the rest of paper.

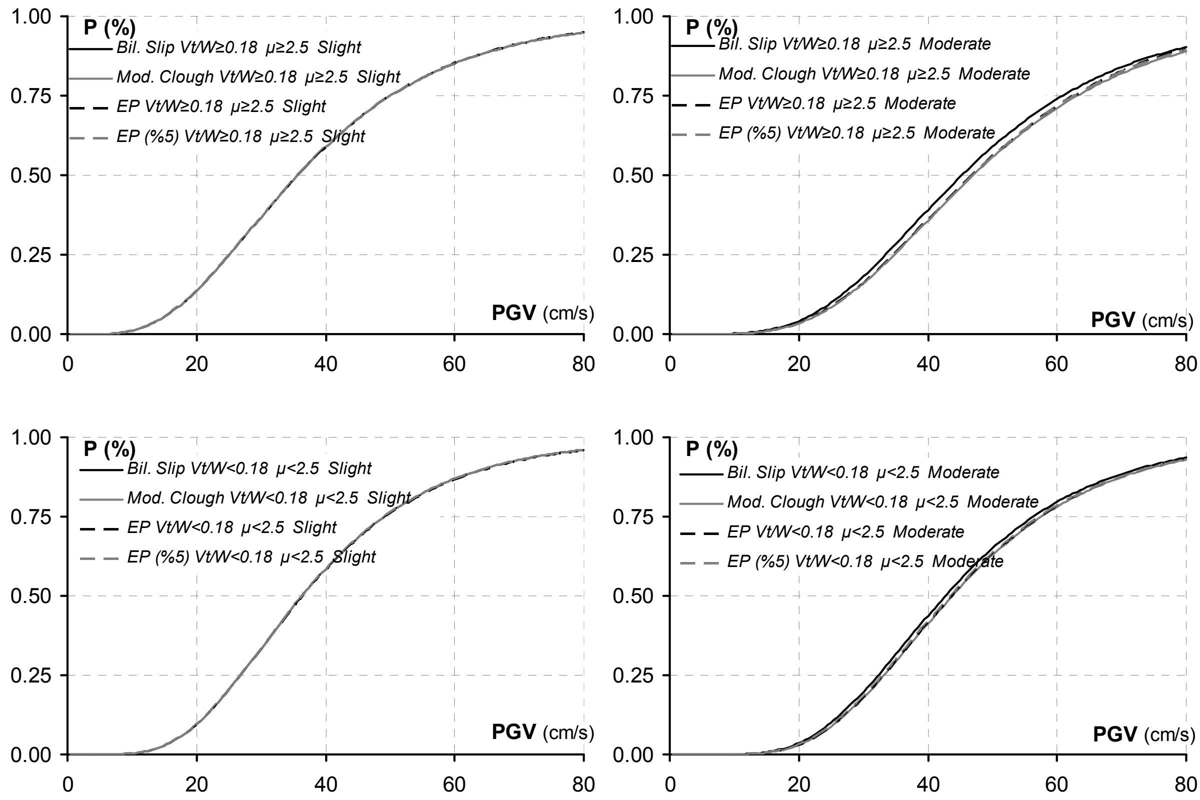


Figure 5. Comparison of different hysteric model fragilities in terms of slight and moderate damages

After first observations, the effectiveness of parameters is followed in two cases. In the first case, the effects of structural parameters are evaluated for each hysteric model. Fig.6 presents the comparison of seismic fragilities of two damage states for all building groups and hysteric models. As expected, high probabilities are observed in low strength& low ductility groups and low probabilities are observed in high strength& high ductility groups. If the ductility capacity or lateral strength ratio is kept constant, it will be seen that the probability of damages decreases with an increasing ductility capacity and/or lateral strength ratio.

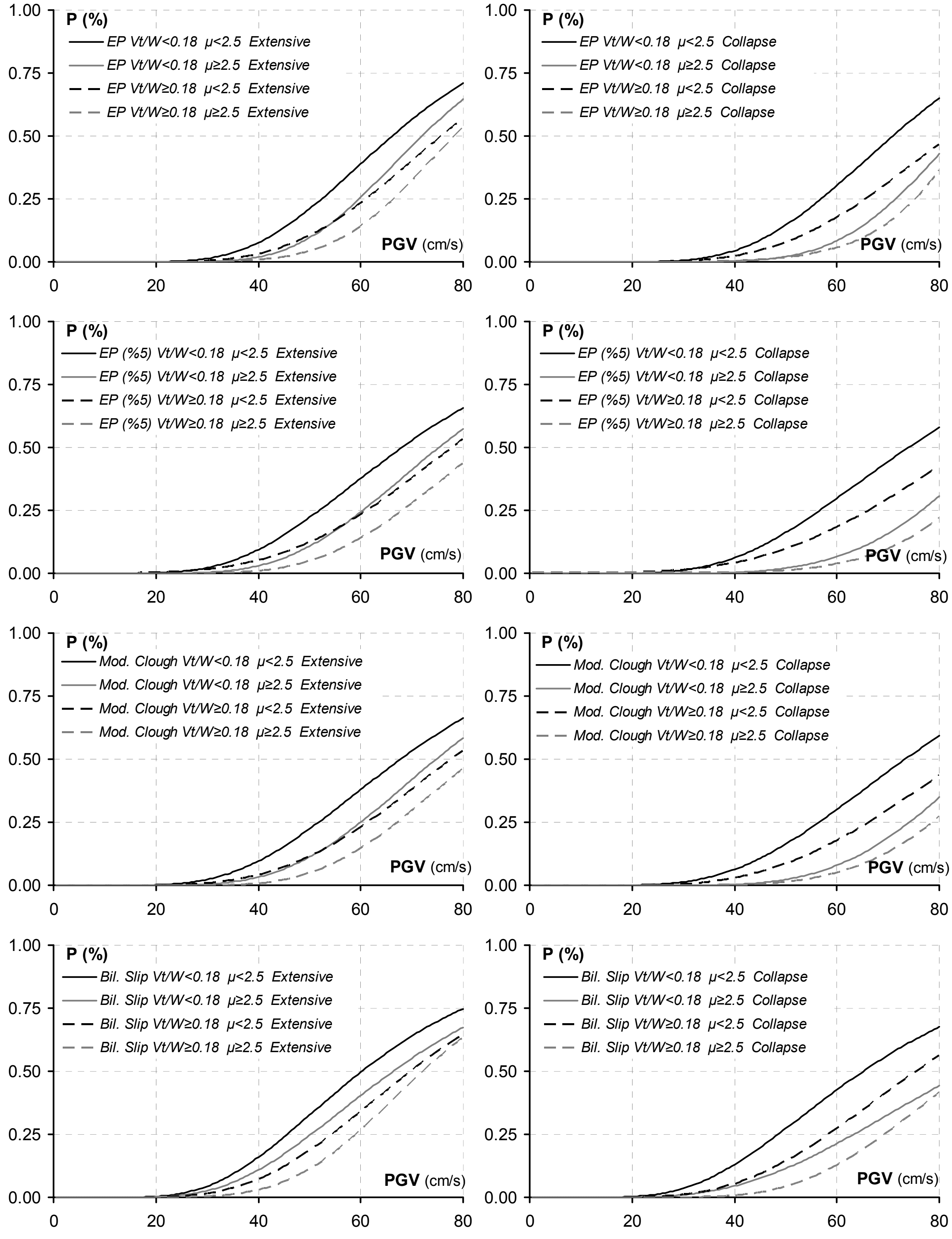


Figure 6. Effect of structural parameters on seismic fragilities of precast industrial buildings

In second case, each building group is evaluated separately and effect of hysteric models on seismic fragilities of precast buildings is investigated. It can be seen from the Fig.7 that in all building groups and in each damage case Bil. Slip hysteric model results give the highest probabilities. Furthermore, EP %5 hysteric model results give the lowest probabilities in each group. Except the minor changes, similar probabilities are observed in EP and Modified Clough hysteric models.

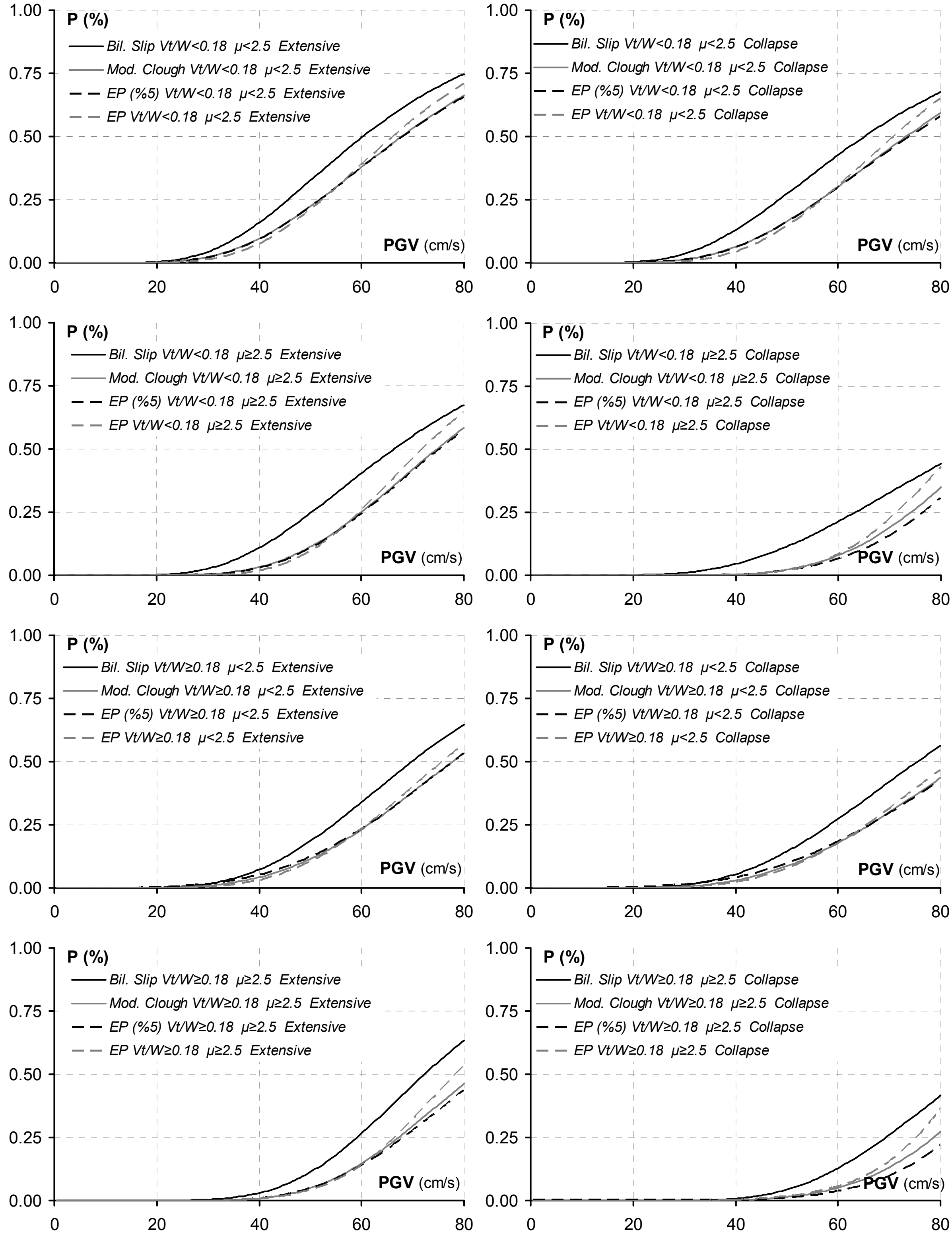


Figure 7. Effect of hysteric models on seismic fragilities of precast industrial buildings

Even though behavior of EP and Modified Clough hysteric models are quite different, fragilities of these models are similar. In the study, Modified Clough model was used to reflect strength and stiffness degrading characteristics but as mentioned in earlier, precast industrial buildings have lower lateral stiffness capacity. So, the effect of stiffness degrading behavior cannot clearly be seen on fragility curve of precast industrial buildings. In conclusion, results have shown that different hysteric models have not significant effect on seismic fragilities of precast industrial buildings.

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## CONCLUSIONS

Structural properties of numerous precast industrial buildings were determined in DOIZ by using design projects of precast buildings and then buildings were inspected by site investigations. Non-linear analysis models of DOIZ buildings were prepared and capacity curve of buildings were constructed. Using obtained capacity curves, buildings were divided into 4 groups according to their lateral strength ratio and ductility capacity. Previous studies and experiences have shown that selected groups can be used to represent inventory buildings and existing building stock of Turkey. Thus, groups can be used to evaluate the relation of damage states and capacity related parameters of precast industrial buildings. For this purpose, probabilistic approach was used and fragility curve of precast buildings for various earthquake intensities was calculated. While fragility curves of precast industrial buildings were prepared, different hysteric models were also used for corresponding groups. By this way the effect of various hysteric models on seismic fragilities of precast buildings were investigated. Obtained fragility curves were evaluated and following conclusions are made:

- Ductility parameter becomes more effective on seismic fragilities of precast buildings especially at higher damage levels.
- Lateral strength ratio is found as the most effective parameter on seismic fragilities of precast buildings.
- Observations has clearly that lateral strength ratios may be used to represent slight and moderate damage levels, but this situation is not valid for extensive and collapse damage states. So, both ductility and lateral strength ratio parameters should be used together to represent higher damage ratios.
- Extensive and collapse fragility curves are relatively close together in buildings which have lower ductility ($\mu$<2.5).
- Hysteric models on slight and moderate damage fragilities have lower effects (See Fig.4).. This situation is valid for all building groups
- Higher probabilities are observed in low strength& low ductility groups and low probabilities are observed in high strength& high ductility groups as expected and this situation is valid for all hysteric models.
- It is found that bilinear slip hysteric model gives the highest probabilities for all building groups among the other hysteric models. Elastoplastic with 5% hardening model gives the lowest probabilities.
- It is observed that modified Clough and elastoplastic with no hardening hysteric models have similar probabilities.
- When all seismic fragilities are evaluated, it is seen that different hysteric models have not significant effect on seismic fragilities of precast industrial buildings.

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