Damage Assessment Approach for 1-Story Precast Industrial Buildings

Abstract

Precast industrial buildings have utmost contribution in economic development of countries due to allows to carry out production activities in wide areas and providing employment opportunity to wide audience. Rapid construction with very high quality standards is another advantage of these buildings. However, recent earthquakes occurred in several regions of the world emphasize the excessive damages occurred in precast buildings and hence performance of these buildings should carefully be checked. On the other hand, seismic performance evaluation of structures requires high amount of data such as geometry and features of structural elements, characterization of acting loads and etc. to analyze and decide rehabilitation is needed or not. Practising of such study to numerous buildings involves high computational efforts and loses its practicability. In these cases, assessment approaches which allows screening damage state of the building become essential to fulfill requirements. In the study, deformation demand ratio is used as damage index and damage assessment model is introduced by using equal displacement approach. Introduced model is applied one of the existing precast building and compatibility of approach is investigated. Results indicated that introduced model seems promising for determination of structural damages in 1-story precast industrial facilities.

Keywords: precast buildings; non-linear behavior; performance screening; damage assessment.

1. Introduction

Manufacturing and production activities have very important contribution in economic development of countries. In order to fulfill such activities, wide openings and working area are required and industrial facilities ideally suited for such conditions. Precast structures are also very beneficial as they can be constructed quickly with very high quality standards. However, it was observed that excessive damages occurred in precast buildings (Posada and Wood 2002, Sezen and Whittaker 2006, Parisi et al. 2012) from the recent earthquakes occurred in several regions of the world and this situation emphasize that performance of these buildings should be checked.

In recent years, some studies are performed to investigate the effect of structural characteristics of buildings (Senel and Kayhan 2010, Palanci et al. 2017, Babič and Dolšek 2014) and to determine seismic performance of buildings (Senel ve Palanci 2013) in analytical and probabilistic manner. Senel and Palanci 2013 also studied the structural characteristics of existing 1-story precast industrial buildings located in Aegean part of Turkey and investigated the performance of these buildings under different site conditions and seismic demand estimation methods. Although probabilistic approaches are useful for rapid screening of buildings, they are based on the ground parameter used and related building features which may not be appropriate for seismic characteristics of considered region and building characteristics. Seismic evaluation of structures in analytical methods, on the other hand, requires high amount of data (structural geometry and features of structural elements, characterization of acting loads and etc.) and it consumes time and efforts for modelling and analysis.

Recently, Palanci and Senel 2013 have proposed rapid seismic performance assessment method for 1-story hinge connected precast industrial facilities. By proposed equations of the previous study, structural period ($T_s$), lateral strength capacity ($V_s$), yield ($\Delta_y$) and ultimate displacement capacity ($\Delta_u$) of building could be determined. Method proposed by previous authors is very efficient to visualize complete attributes (both in strength and deformation) of the building and eliminates the modelling issues, but still requires determining the longitudinal and transverse reinforcement features of precast columns and some computational efforts. Instead of finding of all features of structure, direct use of deformation demand ratios may be more robust by using some assumptions and simplifications.

For this purpose, plastic deformation demand ratio ($Dl_{pl}$) is used as a damage indicator and model is established on equal displacement approach in this study. By using the equal displacement approach and doing some mathematical operations, plastic deformation demand ratio is described in terms of strength reduction coefficient ($R_s$) and ductility capacity ($\mu$). Intermidiate Performance limits of precast buildings is not considered in this study as the comparison were performed in terms of plastic deformation demands. Nevertheless, it can be said that “Life Safety” performance can be considered as targeted performance level on the decision of rehabilitation of
precast industrial buildings. In approximate manner, this performance level can be considered as appropriate percentage (e.g. 67%) of the plastic displacement capacity of the building.

Detailed information about the method is given in further sections. Introduced model is applied one of the existing precast building (section 3) and outcomes of the method have shown that model seems promising for determination of structural damages and on the decision of rehabilitation purposes.

2. Establishment of the Method

Primary parameter to obtain structural damages of precast buildings in this study is plastic deformation demand ratio. This ratio is based on the plastic deformation capacity of building \((S_{dy} \text{ and } S_{du})\) and inelastic displacement demand \((S_{dil})\) calculated by appropriate demand scenario. In Eq. 1, calculation of plastic deformation demand ratio \((DI_{dp})\) which used as damage index is given. In the equation “S” is used to donate spectral quantities.

\[
DI_{dp} = \frac{(S_{dy} - S_{du})}{(S_{du} - S_{dy})}
\]  

In order to calculate deformation demand ratio, displacement demand of structure should be obtained. Actual displacement demand can be calculated by performing nonlinear dynamic analysis, but it requires high computational efforts. Instead of dynamic analysis, approximate code based seismic demand estimation can be used. In various regions of the world, several seismic codes and regulations (ATC-40, EC-8, TEC-2007) are available to estimate seismic demands. In some of these codes (TEC-2007, EC-8), equal displacement approach is used when the natural period of the structure \((T_1)\) is higher than is the upper limit of the period of the constant spectral acceleration branch \((T_c)\) of the demand spectrum. Estimation of displacement demand by equal displacement approach is illustrated in Fig. 1.

\[
S_{dil} = S_{ae}(T_1)\left(\frac{T_1}{2\pi}\right)^2
\]  

It is also possible to obtain mathematical relation between spectral displacement and accelerations considering the similarity of triangles illustrated in the Fig. 1. Mathematical expression of this relation is given in Eq.3. It can be seen that right side of equilibrium is quite known parameter and it can be simply regarded as strength reduction coefficient \((R_y)\).

\[
\frac{S_{dil}}{S_{dy}} = \frac{S_{ae}(T_1)}{S_{dy}}
\]  

Considering this fact, equation 3 can be re-written as follows;
\[ S_{di} = R_y S_{dy} \]  

(4)

Ductility capacity (\( \mu \)) of the building, on the other hand, is the ratio of ultimate and yield displacement capacity of the building. So, Eq. 5 can be used as mathematical expression between yield and ultimate displacement of building.

\[ S_{di} = \mu S_{dy} \]  

(5)

If the equations of 4 and 5 are placed in Eq. 1 and some mathematical operations are performed then Eq. 1 can be re-determined as follows;

\[ DI_{dp} = \frac{(R_y - 1)/\mu - 1}{\mu - 1} \]  

(6)

It can be seen from the Eq. 6 that plastic deformation demand ratio is highly reduced to a simpler expression. According to this equation, if the strength reduction coefficient and ductility capacity of the building is determined then plastic deformation demand and hence performance assessment of building can be performed. For this reason, both parameters should be determined separately and combined in Eq. 6.

2.1. Determination of Strength Reduction Coefficient (\( R_y \))

It is worth to remind that \( R_y \) is the ratio of elastic spectral acceleration that corresponds to natural period of the building and yield acceleration capacity of the SDOF system. This situation implies that base shear capacity \( (V_t) \) and natural period \( (T_1) \) of the structure should be obtained. For this purpose, typical capacity curve of 1-story precast building shown in Fig. 2 is investigated. It can be seen from the figure that elastic slope of capacity curve, in other words, stiffness of the building rely on lateral strength and yield displacement capacity of the building (see Eq. 7).

![Figure 2. Typical capacity curve of precast building](image)

\[ K = \frac{V_t}{A_y} \]  

(7)

Eq. 7 clearly shows that if the stiffness of the precast frame and yield capacity of the building is obtained base shear capacity of the building can be determined. Precast columns are hinge connected at roof level and as a consequence of this situation columns behave as cantilever beam. Using the advantage of cantilever behavior, stiffness of each precast columns in the frame can be obtained by Eq. 8 and if the individual columns stiffness are summed then total stiffness of the frame can be determined. Stiffness of individual member depends on young modulus of concrete used \((E)\), height of column or can be represented as building elevation \((L)\) and effective moment of inertia of precast column \((I_{eff})\).

\[ k_i = 3EI_{eff}/L^3 \quad K = \Sigma k_i \]  

(8)

Effective moment of inertia of member \((I_{eff})\) can be expressed by multiplication of constant coefficient \((\eta)\) and gross moment of inertia \((I)\). In this study, effective moment of inertia is calculated as 20% of gross moment of inertia \((I)\) (i.e. \(I_{eff}=0.20I\)) (Panagiotakos and Fardis 2001, Mirza 1990). Gross moment of inertia \((I_{eff}=bh^3/12)\) can be simply calculated by determination of column dimensions \((b\) and \(h)\) but careful attention should be made for section dimension \((h)\) parallel to seismic excitation as power of height is equal to three. After determination of structural stiffness, yield capacity of the building is required. Palanci and Senel have provided simple equation for determination of yield capacity of precast columns and hence the building. According to previous study, yield capacity of the building \((A_y)\) can be taken equal to minimum of individual yield displacement of the member \((\delta_y)\).

Yield displacement capacity of individual precast columns can also be calculated by Eq. 9. In the equation, \( n \) represents number of columns existing in the precast frame.

\[ A_y = \frac{n \delta y}{n} \]  

(9)
\[
\delta_{yi} = 1.95(c_i L_i^2/3h_i) \& \Delta_2 = \min(\delta_{y1}, \delta_{y2}, ..., \delta_{yn}) \tag{9}
\]

It can be understood from the Eq. 9 that if the length of all columns in the frame are equal (i.e. building elevation), yield capacity of the building can be taken equal to yield capacity of member which have the highest dimension parallel to seismic excitation. In this case, it is now possible to determine base shear capacity of building \((V_i)\) by combining the Eqs. 8 and 9 into Eq. 7. Furthermore, yield acceleration of the building \((S_e)\) can be obtained by determination of total Mass\((M)\) or Weight\((W)\) of the building. Building mass \((M=W/g)\) can easily be determined by performing vertical load (dead and live loads) analysis.

Secondly, natural period of the building \((T_i)\) is examined and stiffness of the building \((K)\) determined in previous steps is used for the calculation of this parameter. Natural period of the structure can be typically determined by Eq. 10 using mass and stiffness. As described earlier building mass can be determined vertical load analysis and for considered building type (i.e. 1-story precast industrial building), stiffness of the building is given in Eq. 7 and related parameters for determination of stiffness is given.

\[
T_i = 2\pi(M/K)^{0.5} \tag{10}
\]

If the related parameters are placed in to Eq. 10, natural period can be re-determined as follows;

\[
T_i = 2\pi(MA/V_i)^{0.5} \tag{11}
\]

2.2. Determination of Ductility (\(\mu\))

In previous section, determination of building yield capacity \((\Delta_y)\) is defined. For this reason, the other parameter, ultimate displacement capacity of the building \((\Delta_u)\), should be investigated. In order to determine ultimate displacement capacity of any RC member, moment-curvature \((m-\phi)\) relations is required and such response can be defined by performing moment-curvature analysis. However, this analysis may increase the calculation efforts. Instead of determining sectional responses, it may be more useful to use approximate methods. For this aim, rapid assessment method proposed by Palanci and Senel 2013 can be very helpful as provided equations are directly based on precast column characteristics. In addition, there are several studies (Palanci 2017, Colajanni et al. 2013, Panagiotakos and Fardis 2001) to determine flexural response of RC members in literature. So, ductility of the building can be determined by selecting the any of the options mentioned earlier.

In this study, one another option is preferred. In this option, no calculation effort is needed and ductility capacity of the building is handled directly by semi initiative approach. Semi initiative is called as it depends on outcomes of some analytical studies (Senel and Palanci 2013; Senel et al. 2013, Palanci et al. 2017) and use of knowledge. Senel and Palanci 2013 have examined the numerous existing precast industrial facilities and they have demonstrated that ductility of precast building commonly range between 1.5 and 3.0. Outcomes of this study can be clearly used for defining upper and lower limits of ductility capacities. Senel et. al 2013 also examined the effect of structural characteristics of precast buildings on fragility curves of one-story precast industrial facilities and they expressed that value of 2.5 can be as threshold value for discretization of high ductile and low ductile precast industrial facilities. More recently, Palanci et al. 2017 have shown that precast industrial buildings can be categorized to three subclasses in terms of their structural characteristics based on the fragility curves. In the previous study, high and low ductile buildings are separated according to their design code (TEC-1998 or newer and TEC-1975) and ductility capacity of high and low ductility of precast building are provided as 2.90 and 2.10 in average, respectively. When the consequences of pre-mentioned studies are considered, it can be said that ductility of the precast building can approximately be attained by judgement approach. By this way, ductility and hence performance of the building can be visualized by approximate manner.

3. Application of the Method

In this section, introduced method is applied to one of the existing industrial building located in Denizli Organized Industrial Zone (DOIZ) in Aegean part of Turkey. In order to compare efficiency of the introduced method, sample building assessed by also Palanci and Senel 2013 is used. In the previous study, a seismic assessment result of the sample building is also provided. Detailed information about the building features and results of rapid methods are given and can be found in related work.

In Fig. 3, precast building frame of the sample building in X direction is given schematically. As the precast building are mostly constructed by repetition of identical frames, a sample frame taken from within the precast building can be used the represent seismic performance of the structure.
In the sample building all columns have square dimensions and two different dimensions (400mm and 450mm) were used for precast columns. As the building elevation is identical, then yield displacement capacity of the building can be taken equal to yield displacement capacity of the precast column with dimension of 450mm, so yield displacement capacity was calculated as \( \Delta_y = 194.13 \text{mm} \) or 2.43\% in terms of drift ratio \( (\Delta_y/L) \). Palanci and Senel also specified that confinement level of precast columns in average considering the volumetric transverse reinforcement ratio of precast columns. As the ductility of precast industrial structures is strictly related to ductility of components of bearing elements, it can be assumed that building ductility will possibly be between 2.1 and 2.5 if the outcomes of the some analytical studies are considered (Senel and Palanci 2013, Palanci et al. 2017). Thus, study of Palanci and Senel demonstrated that ductility capacity of considered building was 2.28 and according to their rapid assessment method (REM) ductility was determined as 2.17 (see Table 1). As the previous authors do not provide the construction year of the sample building, ductility of the building can be assumed by using previous findings.

Considering the previous discussions, then ductility capacity of sample building may be taken equal to 2.3 as a result of average of minimum (2.1) and maximum (2.5) values provided by Palanci et al. 2017. Dimensions of precast columns and building height is known so, stiffness of precast frame shown in Fig. 3 can easily be calculated \( (541.05 \text{ N/mm}) \) using Eq. 8. In accordance with yield capacity of the building and stiffness then base shear capacity of the building can be found \((105.04 \text{ kN})\) by Eq. 7. Since the yield displacement capacity and base shear capacity of the building is acquired, natural period \( (T_1) \) of the building can be calculated by Eq. 11. In Eq. 11, mass of building is needed and this parameter is calculated approximately 90.2 kNs\(^2/\text{m}\) according to study of Palanci and Senel 2013. Finally, natural period of the building \( (T_1) \) and spectral yield acceleration of the building \( (S_{ay}) \) is determined as 2.56s and 0.119g respectively. Consequently, strength reduction coefficient \( (R_y) \) will be set, but elastic spectral acceleration \( S_{ae}(T_1) \) of first (natural) mode should be calculated.

According to equal displacement approach, elastic spectral acceleration of first (natural) mode can be calculated by Eq. 12. As the seismic assessment of sample building will be compared with study of Palanci and Senel 2013, parameters of Eq. 12 should be compatible with previous study to make reliable comparison. For this reason, \( S_{ae,max} \) is taken equal to 1g and \( T_C \) was taken 0.46s and 0.69s respectively. Different \( T_C \) values were used to account different site conditions in the previous study.\[ S_{ae}(T_1) = S_{ae,max}(T_C/T_1) \] (12)

When the Eq. 12 is applied for different \( T_C \) values, \( S_{ae}(T_1) \) is determined as 0.179g and 0.269g respectively. Then for different site conditions, \( R_y \) will be calculated as 1.51 and 2.27 by proportion of \( S_{ae}(T_1) \) and \( S_{ay} \), respectively. Consequently, capacity related parameters in Table 1 and plastic deformation demand ratio of the sample building is shown in Table 2 respectively.

### Table 1. Comparison of capacity related parameters

<table>
<thead>
<tr>
<th>Assessment Method</th>
<th>Base Shear ((V_t))</th>
<th>( \Delta_y/L )</th>
<th>( \Delta_{IO}/L )</th>
<th>( \Delta_{LS}/L )</th>
<th>( \Delta_{CP}/L )</th>
<th>( \mu (\Delta_{CP}/\Delta_y) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>REM*</td>
<td>120.27</td>
<td>2.43%</td>
<td>2.71%</td>
<td>4.32%</td>
<td>5.27%</td>
<td>2.17</td>
</tr>
<tr>
<td>Analysis*</td>
<td>115.67</td>
<td>2.39%</td>
<td>2.74%</td>
<td>4.40%</td>
<td>5.45%</td>
<td>2.28</td>
</tr>
<tr>
<td>This study</td>
<td>105.04</td>
<td>2.43%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>2.30</td>
</tr>
</tbody>
</table>

*Results are provided by Palanci and Senel (2013).
Table 2. Comparison of deformation demand ratios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Assessment Method</th>
<th>$T_1$ (s)</th>
<th>$S_{dd}/L$</th>
<th>$DI_{yp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_c=0.46$ s</td>
<td>REM*</td>
<td>2.40</td>
<td>3.42%</td>
<td>35.12%</td>
</tr>
<tr>
<td></td>
<td>Analysis*</td>
<td>2.43</td>
<td>3.47%</td>
<td>35.14%</td>
</tr>
<tr>
<td></td>
<td>This study</td>
<td>2.56</td>
<td>N/A</td>
<td>39.25%</td>
</tr>
<tr>
<td>$T_c=0.69$ s</td>
<td>REM*</td>
<td>2.40</td>
<td>5.14%</td>
<td>95.38%</td>
</tr>
<tr>
<td></td>
<td>Analysis*</td>
<td>2.43</td>
<td>5.20%</td>
<td>91.79%</td>
</tr>
<tr>
<td></td>
<td>This study</td>
<td>2.56</td>
<td>N/A</td>
<td>97.34%</td>
</tr>
</tbody>
</table>

*Results are provided by Palanci and Senel (2013).

It can be seen from the tables that some parameters are provided from the damage assessment approach presented here in the study. This situation is another advantage of the presented assessment approach that reduces the computational efforts to minimum level. On the other hand, when the results of REM, analysis and this study compared, it can be said that presented approach is slightly overestimate the damage ratios but it is still very promising to visualize the damage potential of the precast building.

4. Summary and Conclusions

In this study, damage assessment approximation based on the equal displacement approach is presented. Plastic deformation demand ratio ($DI_{yp}$) which uses the deformation capacity of the building at yield and ultimate and inelastic displacement demand ($S_{dd}$) is used as damage index and efficiency of the presented method is checked in terms of this quantity. In order to establish the background of the presented method some mathematical operations were made on the Acceleration Demand Response Spectrum (ADRS) for both Capacity and Demand curves. Ultimately, it was determined that considered damage index can also be represented by strength reduction coefficient ($R_y$) and ductility capacity of the building ($\mu$). Ductility, among the aforementioned parameters, were especially provided from the various studies conducted for one-story precast industrial buildings and by this way computational efforts were substantially reduced. Using the same similar point of view, determination of strength reduction coefficient was simplified by only taking account of the precast column height and section dimensions which can be obtained with very simple measures.

In order to validate and check the performance of the presented method, a sample existing 1-story precast industrial building located in one of the important organized industrial zone of west part of Turkey is considered. Validity of the method is investigated under two different demand scenario according to distinct local soil conditions. Comparisons have shown that damage estimates of the presented model is very similar to outcomes of analytical analysis and also compatible with rapid assessment method proposed for one-story precast buildings. Consequences of the comparisons have indicated that introduced model seems promising for determination of structural damages in 1-story precast industrial facilities.

References


