Estimation of Seismic Economic Loss and Downtime of Precast Concrete Frames with “Dry” Connections

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Abstract. The seismic loss of buildings comes not only from the damaged structural components. Much more loss may be induced by non-structural components, the demolition loss and social impacts associated with excessive downtime. One of the main characteristics of a resilient city is that the buildings in the city should be able to recover to their pre-earthquake functionalities with minimized economic loss and downtime. For this purpose, a comparative study regarding seismic economic loss and downtime is conducted between the conventional cast-in-situ reinforced concrete frames (RCFs) and precast concrete frames (PCFs) with "dry" connections. The results show that the PCFs with prestressed tendons (PTs) can effectively reduce demolition loss given their extraordinary self-centering capacity provided by PTs. By adding web friction devices at the beam ends, the economic loss of structural components and drift-sensitive non-structural components can be effectively reduced. The downtime of PCFs is reduced at given hazard levels compared with RCF given their rapid repair speed and easy assemblage. In view of the rapid post-earthquake repair and lower earthquake loss, the PCFs are worth further investigation and application to develop resilient cities.

1. Introduction

Earthquake may induce adverse and long-lasting impacts on economic loss associated with downtime (collectively called seismic consequence later). Stakeholders and government agents are interested in the potential seismic consequence to facilitate more efficient decision making and to construct a more resilient community. Therefore, the Pacific Earthquake Engineering Research center systematically proposed the seismic consequence estimation methodology [1, 2] and later developed by Yang et al. [3], Ramirez and Miranda [4] among others. The PEER seismic consequence estimation methodology (abbreviated as PEER methodology later on) has become one of the most commonly used seismic consequence estimation tools for both pre-earthquake risk analysis and post-earthquake decision making, which has been used for various types of structural and infrastructural systems, such as reinforced concrete frames [4], steel structures [5], masonry structures [6], and bridge-foundation systems [7]. The ultimate outputs of the PBEE procedure are some decision variables, such as the mean economics, downtime and casualty loss associated with their variances. These metrics can facilitate a better communication between professional engineers and stakeholders in some extend.

Precast concrete frames (PCFs) have been widely adopted in engineering practices in China with the advantages of construction simplicity, easy assemblage and fewer in-site labours. As for the PCFs with “dry” connections, the precast components are usually connected through prestressed tendons (PTs),
where no cast-in-situ concrete is needed during the process of on-site construction. Accounting for their reduced lateral deformation demands and satisfactory seismic behaviours, “dry” connected precast structures can be served as a typical kind of earthquake resilient structure, which can not only ensure structural safety under earthquake excitation, but have the potential of restoring structural functionality and mitigating loss after earthquake.

For this purpose, this article conducts an in-depth seismic consequence estimation to compare the performance between the PCFs with “dry” connections and conventional reinforced concrete frame (RCF). The analytical models, building layouts, design information, associated with fragility data of the whole buildings are extended on a relevant article conducted by the authors investigating the fragility and risk analyses of the structures mentioned above [8]. A PEER-compatible seismic consequence estimation methodology is utilized to predict the mean consequence associated with its variance. A comprehensive component fragility database is collected based on the actual engineering practice in China. The seismic consequence metrics are computed and presented in multiple formations, to conduct a comprehensive comparison on how the mechanical properties, damage mechanisms, assemblage and construction characters indicate the advantages of PCFs with “dry” connections.

2. Methodology of PEER-compatible seismic consequence estimation
The most notable characteristic of the PEER methodology is to convolute over four important analysis process (i.e., the seismic hazard analysis, response analysis, damage analysis and loss analysis) using total probability theorem, to generate some expected decision variables associated with their variances. In current study we focus on comparing the economic loss and downtime between RCFs and PCFs, thus these two decision variables (collectively referred as seismic loss) are put emphasis on.

The post-earthquake events of the buildings are disaggregated into three mutual exclusive and collectively exhaustive events: collapse occurs and the building is to be rebuilt (C); collapse does not occur but the building has to be demolished and rebuilt due to unacceptable residual displacement, (NC∩De) and collapse does not occur and the building damage is to be repaired, (NC∩Re) [4]. The three events will be abbreviated as collapse, demolition and repair events later. The seismic loss metrics will be weighed by the probability of occurrences of these three events respectively.

The ultimate output results of seismic loss evaluation including the expected loss conditional on IM levels of interest (which is also known as vulnerability curve), the expected loss over a specific period of time (usually take 1 year as time period, at this moment the expected loss is known as expected annual loss, or EAL), the probability of loss exceeding designated values in specified timeframes (also known as loss hazard), and loss disaggregation, both at component level, at floor level, or at event level. The variance of these metrics should be concerned, because each stage indicates varying degrees of variability, either from epistemic or aleatory uncertainty. Thus, the ultimate output results may indicate strong variance caused by uncertainty propagation [9].

2.1 Total seismic consequence conditional on IM
The total seismic consequence given intensity measure im, $E[L_T|IM]$ represents the mean value of the total loss $L_T$, associated with its variance. The relationship between the expected loss and IM is known as a vulnerability curve. The mean total seismic loss associated with its variance can be expressed as follow

$$E[L_T|IM] = E[L_T|C,IM] \cdot P[C|IM] + E[L_T|De \cap NC,IM] \cdot P[De \cap NC|IM] + E[L_T|Re \cap NC,IM] \cdot P[Re \cap NC|IM]$$

(1)

$$Var[L_T|IM] = \{P(C|IM) \cdot Var(L_T|IM,C) + P(C|IM) \cdot [E(L_T|IM,C) - E(L_T|IM)]^2\} + \{P(De \cap NC|IM) \cdot Var(L_T|IM,De) + P(De \cap NC|IM) \cdot [E(L_T|IM,De) - E(L_T|IM)]^2\} + \{P(Re \cap NC|IM) \cdot Var(L_T|IM,Re) + P(Re \cap NC|IM) \cdot [E(L_T|IM,Re) - E(L_T|IM)]^2\}$$

(2)
where $P[C|IM]$, $P[De \cap NC|IM]$ and $P[Re \cap NC|IM]$ represent the probability that the building collapse, the building will not collapse but has to be demolished and the building will not collapse and can be repaired, conditional on IM values, respectively. The first term can be derived from collapse fragility curve, the second term can be derived through the convolution of empirical demolition fragility based on professional judgement and the conditional CCDF of exceeding a certain level of residual displacement ratio (RDR) [4]. Once the second term is obtained, the last term is trivial because they are mutual exhaustive.

$E[L_T|C, IM]$, $E[L_T|De \cap NC, IM]$ and $E[L_T|Re \cap NC, IM]$ are the total expected loss conditional on collapse, demolition and repair events, and at certain IM values, respectively. The first two terms are generated from the real construction information (e.g., the construction time and cost) multiplied by an amplification factor [10] to account for additional impacts of, for example, debris removal. While for the third term, a component-by-component methodology proposed by Aslani and Miranda [11] is used to account for the loss of all the components existing in the building. Therefore, a comprehensive component fragility database should be defined at first (i.e., the EDP-DS relationship of each component associated with its loss function), then loop over each floor to compute the corresponding loss of each component, based on the maximum EDP data (e.g., the maximum inter-story drift, MIDR or peak floor acceleration, PFA) obtained from nonlinear time history analyses. The specific calculation procedures will be introduced in the next section to account for differences between the evaluation procedures of repair economic and downtime loss.

2.2 Repair loss estimation

The first step of computing the total repair loss is to generate the Loss-IM relationship for individual components at each floor, based on the component fragility information combined with the story response data:

$$E[L_j|Re \cap NC, IM] = \int_{edp} E[L_j|EDP_j] \, dP(EDP_j|Re \cap NC, IM)$$

where $E[L_j|IM, Re \cap NC]$ is the expected loss of the $j$-th component conditional on repair events and IM values. $P(EDP_j|Re \cap NC, IM)$ is the complementary CDF of exceeding $edp_j$ conditional on repair event and IM values, which can be determined from nonlinear history analysis. $E[L_j|EDP_j]$ is the expected value of loss of the $j$-th component conditional on its controlled $EDP_j$, which can be generated through summating the component fragility and its loss function at each damage state:

$$E[L_j|EDP_j] = \sum_{i=1}^{N_{DS}} E[L_j|DS = d_{s,i}] \cdot P(DS = d_{s,i}|EDP_j)$$

where $N_{DS}$ is the total number of damage states of the $j$-th component, $E[L_j|DS = d_{s,i}]$ is the expected value of loss $j$-th component conditional on the $i$-th damage state and $P(DS = d_{s,i}|EDP_j)$ is the probability that the component attain the $i$-th damage state conditional on $EDP_j$. The latter two items can be generated through a prescribed component fragility database.

Especially note the differences of assembling the loss of component into the whole building between the total economic repair loss and total downtime repair loss. As for the total economic repair loss, it can be simply computed by summating of the losses due to each component at each floor, which can be expressed as
\[ E[L_T | Re \cap NC, IM] = E \left[ \frac{\sum_{j=1}^{N_C} T_{i,j} | Re \cap NC, IM]}{wr \cdot cn} \right] \]

where \( E[L_T | Re \cap NC, IM] \) is the mean value of the total economic loss conditional on the repair event and IM value; \( N_C \) is the total number of components located in the building.

Unlike the evaluation process of economic loss, due to the parallelism of repair process, it is unreasonable to sum up all the repair time of individual component, because the repair process cannot be processed one-by-one for each component and is strongly depend on repair scheme. It is difficult to accurately describe the repair order of structural members for post-earthquake repair. In current study, two idealized repair schemes and defined here: the fast-track scheme (i.e., components at each floor are required in parallel) and slow track scheme (i.e., components at each floor are required in series), at each floor each component should be repaired at a series manner. It should be noted that neither of the two schemes can reflect the actual repair actions, but the two idealized schemes can be served as upper and lower bounds of repair time \[12\]. The expected repair time loss required in the \(i\)-th floor can be expressed as

\[ T_i | Re \cap NC, IM = \frac{\sum_{j=1}^{N_C} E[T_{i,j} | Re \cap NC, IM]}{wr \cdot cn} \]

where \( wr \) is the workday ratio of calendar days, \( cn \) is the number of crews available for repair actions. It is assumed that the normative workday hours for each worker is 8 hours, the number of workers \( cn \) is 10 per floor for each of the repair scheme, and the workday ratio \( wr \) is 5:7. As for the slow track scheme, the formation of total repair time loss has the same form as Eq. 5. While for the fast track scheme, the total repair time is defined as the largest value of repair time of all the five floors, which can be expressed as

\[ T | NC \cap Re, IM = \max_{i=1:5} [T_i | Re \cap NC, IM] \]

Considering the formation of Eq. 7, it is not possible to derive its analytical solution of statistical moments (mean and variance), thus Monte Carlo simulations should be used to estimate the distribution of repair time at fast track scheme.

There are many portions contributing to the total downtime of the damaged building, including the time needed to repair the damage of the components located in the building, to determine the financial allocation, and to organize many other regulatory activities. The latter portions, which are denoted as irrational components of downtime in Mitrani-Reiser \[13\], are more difficult to quantify because they are highly dependent on political, economic and societal factors, and were demonstrated by Mitrani-Reiser \[13\] to be a small portion of total downtime in a concrete building compared with building repair time. Therefore, only the time loss result from recovering all the components located in the building to their original performances are considered in current study to serve as the building downtime.

2.3 Expected annual loss

The expected annual loss (EAL) is the mean annual loss within one year, which is a commonly used metric which is interesting to insurance companies and investors, since through this metric they can price reasonable insurance premiums. This metric can be obtained through convoluting the vulnerability curve with mean annual frequency of all the potential earthquake at designated site (i.e., \( \lambda(IM) \), usually called the hazard curve), which can be expressed as \[14\]

\[ \lambda_{L_T} = E[AL] = E[L_T] = \int_{IM} E[L_T | IM]d\lambda(IM) \]

where \( \lambda_{L_T} \) is the mean value of annual loss.
2.4 Loss hazard

The probability of loss exceeding a designated value conditional on IM values, \( P(L_T > l_T | IM = im) \), is helpful for judging whether the probability of exceedance of a critical value is acceptable within a prescribed timeframe. Convoluted with the hazard curve, then the probability of loss exceeding a critical value, \( P(L_T > l_T) \) can be generated. It is also known as loss hazard. This metric can be used to obtain a probability of exceedance of a specified value of loss at given timeframes. The annual probability of exceeding \( l_T \) can be expressed as [6]

\[
\lambda(L_T > l_T) = \int_{im} P[L_T > l_T | IM = im] d\lambda(IM) \tag{9}
\]

\( \lambda(L_T > l_T) \) describes the mean annual rate (or frequency) of exceeding a predesignated loss value \( l_T \). It is always assumed that the occurrence of earthquake conforms to Poisson process, thus the probability of exceeding a total loss value of \( l_T \) over \( n \) years can be expressed as follows

\[
P(L_T > l_T \text{ in } n \text{ years}) = 1 - \exp (-\lambda(L_T > l_T) \cdot n) \tag{10}
\]

3. Seismic hazard

Two typical PCF with “dry” connections (i.e., the PCF-I with PTs only and PCF-II with PTs and web friction devices) combined with a conventional RCF designed with equivalent and comparable seismic performance designed by the author [8] are utilized here to conduct a comparative study. These three structural systems are assumed to locate in urban Beijing (116.4°E, 39.9°N), which is a typical seismic fortification zone with a seismic cautionary intensity of eight (PGA=0.2g). The design site is stiff soil type, class II site category with a design characteristic period of 0.35s is specified, which can be regarded to straddle the boundaries of NEHRP C and D site class [15]. The three structures indicate similar foundation periods with 0.9s. The site-specific hazard curve is generated through a start-of-art probabilistic seismic hazard analysis (PSHA) model for mainland China [16] due to the lack of officially released hazard data in China. A tapered Gutenberg-Richer distribution is utilized to model the seismic activity rate, while residual analysis is used to select ground motion models associated with their logical weights. A \( V_{s30} = 360 \text{ m/s} \) is used here to represent the stiff soil site condition. The seismic hazard curve of the construction site is depicted in Figure 1, where later will be used to generate the mean annual loss values.

![Figure 1. Seismic hazard curve of construction site.](image)

4. Building information and input data

Estimating the total reconstruction cost and time (associated with their variances) provides basic database for calculating the loss at collapse and demolition events. In this study, the reconstruction cost of RCF is estimated as 245$/m^2 \text{ (with an exchange rate of 1$=6.53RMB)} \text{ through a market research (including the construction stages of foundation, superstructure, decoration, MEP associated with personnel salaries). This estimated value is a mean construction cost for a typical Chinese multi-story commercial building. For PCF-I with the same volume, the cost of superstructure increases by 44%}
while the cost of decoration decreases by 10%, through professional estimators. Although the precast frames can reduce the use of formworks, scaffolding and personnel investment at the construction site, the cost in factory prefabrication and in-situ lifting is obviously higher than that of RCF. The mean cost of a web friction device located at the panel zone of PCF-II is estimated as 115$. As for the reconstruction time, considering that the work of erecting formworks and scaffolding is effectively reduced for PCF during construction stage, the estimated construction time is 313.8 and 401 workdays for PCFs and RCF respectively [17]. An increase of 25 percent is included in replacement cost and time, to account for the additional time and costs, including site improvements, debris removal, premium material, and other potential projects included by demolition or replacement [10].

As for calculation of building repair loss, the buildings are discretized into local components, including structural, non-structural components and contents. These statistical data associated with their fragility parameters (the median and dispersion corresponding to EDP), loss functions (the expected repair cost and time, associated with their deviations) for each damage state are collected from a variety of literature [10, 17, 18], as well as expert consultation.

5. Seismic loss estimation

5.1 Vulnerability curves and EAL
The vulnerability curves play a dominant role in performance-based seismic assessment because they not only depict the full distribution of seismic loss under predesignated seismic hazard levels of interest, but also serve as a basis parameter for the following calculations. The vulnerability curves with economic loss and downtime loss (take fast-track scheme as example) of the three structural systems are shown in Figure 2 and Figure 3. The vulnerability disaggregated at the three mutual exhaustive events are also depicted herein. It should be noted that the variances of these total loss value are also significance due to the uncertainty propagation from the database, but only the expected values are depicted here for brevity.

The total economic and downtime losses of the three structural systems are dominated by the repair events, while the contributions of the other two events are almost negligible at the range of $S_a(T_1)$ less than 0.5g, approximately. This is because both three structures are designed to meet the requirements of Chinese seismic code, in which the structure should be repairable at DBE hazard level ($S_a(T_1)=0.19g$ in current study) while collapse should be prevented at MCE hazard level ($S_a(T_1)=0.38g$ in current study). Some safety reserves were considered at the design phase.

The PCFs with PTs show significantly reduced economic and time loss at demolition event at higher IM values. For instant, the demolition economic loss ratio of RCF contributes 14% of the total economic loss, while for PCFs this part of loss is negligible. The PCFs have extraordinary self-centering capacities through configuration PTs through the beam sections, which can drag the structures back to their original positions. Thus, the residual deformation of PCFs is significantly reduced compared with RCF even after severe earthquakes. However, the demolition loss of PCFs does not show a soften segment like RCF at extremely intense IMs, because the PCFs will undergo rapid increase of deformation after the yield of PTs, but the probability that such levels of earthquake occur at the construction site is extremely small (Figure 1).

Correspondingly, the EAL can be computed through Eq. 7. For current case study, it is found that the mean economic annual loss is 887.4$, 778.3$, and 608.1$, while the mean downtime is 0.42, 0.18, and 0.09 workdays for RCF, PCF-I and PCF-II respectively. The PCF equipped with web friction devices has the lowest mean annul loss. This is because the earthquake damage is concentrated on these hysteresis devices while the beam column elements are still in their elastic stage at relatively not that intense earthquake events, thus only by repairing or replacing the replaceable devices can ensure the structure to recover to its original stage. This damage controllable mechanism further speeds up the characteristic of easy-assemble of PCFs, and can effectively reduce the economic loss.
Figure 4 depicts the comparisons of vulnerability curves of mean, repair time for the three structural systems, associated with their variances. An obvious difference can be observed between the two schemes defined above. For example, the repair time of slow track scheme at $S_a(T_1) = 0.6g$ is approximately 4.5 times higher than that of short track scheme. Again, the two schemes considered for repair actions are the upper and lower boundaries for actual situations when acknowledging the complexities of actual repair actions. The repair time of PCF-I is almost no less than that of RCF, even the reduction of repair time of precast components is considered. This is due to the larger lateral deformation responses under severe earthquake events of PCF-I compared with RCF, and additional configurations of hysteresis devices can effectively solve this problem (Figure 4(c)). The repair time is significantly reduced at very intense IM values as expected because at this case the post-earthquake events are dominated by collapse or demolition.

![Figure 2. Total economic loss vulnerability curve and its disaggregation at three events classes for (a) RCF, (b) PCF-I, and (c) PCF-II.](image1)

![Figure 3. Total downtime loss vulnerability curve with fast track and its disaggregation at three events classes for (a) RCF, (b) PCF-I, and (c) PCF-II.](image2)

![Figure 4. Repair time vulnerability curve conditional on non-collapse and repair event for (a) RCF, (b) PCF-I and (c) PCF-II. (The dotted lines refer to mean +/- one standard deviation) events classes for (a) RCF, (b) PCF-I, and (c) PCF-II.](image3)
5.2 Loss disaggregation on component types

It is meaningful to detect the most critical contributors to the total loss at some hazard levels of interest. Through vulnerability curves one can simply get to know which event contribute to the most of the total loss, however, one cannot have an insight into which types of components located in the building are the most damageable component at repair event. Meanwhile, a great portion of loss is originated from the repair event at relatively not that intense hazard levels (Figure 2 and Figure 3). Thus, in the case of repair event, further insight should be generated by disaggregation of the repair loss at component type levels. Three critical hazard levels (i.e., DBE, MCE and ERE levels) defined in Chinese seismic codes are utilized for representation. Figure 5 and Figure 6 depict the disaggregation of repair economic loss associated with downtime on component type at the three prescribed hazard levels, respectively.

The IDR-sensitive non-structural components contribute most to both repair economic loss and repair time loss. This is because the infill walls and wall finishes are most damageable components existing in the whole building, which agree with the deductions by Aslani and Miranda [11], Mitrani-Reiser [13] among others. Meanwhile, the contributions of contents and acceleration-sensitive non-structural components are almost negligible for repair loss at DBE and MCE hazard levels, considering their prescribed high fragility parameters. The structural components in PCF-I contribute higher than the other two structural systems, while for PCF-II the structural components the least. This is due to the damage controllable mechanism of PCF-II that only the replaceable web friction devices need to be repaired or replaced at the first two DSs, which can significantly reduce the repair costs and time for structural components of PCF-II.

Figure 5. Repair economic loss disaggregation on component types at three critical hazard levels for (a) RCF, (b) PCF-I, and (c) PCF-II. (The data provided in parenthesis are relative contribution of each component type to the total loss. Abbreviation: SC = structural components; NSC-IDR = inter story drift-sensitive non-structural components and NSC-ACC = acceleration-sensitive non-structural components)

Figure 6. Repair time loss disaggregation with slow track on component types at three critical hazard levels for (a) RCF, (b) PCF-I, and (c) PCF-II.
5.3 Loss hazard curves at multiple timeframes
The results of seismic economic and downtime loss hazard can be computed through Eq. 9 and Eq. 10. This metric may be interesting for stakeholders because they can estimate the potential degree of loss conditional on certain timeframes, for example, the design life cycles of their buildings. Figure 7 and Figure 8 show the loss hazard curve of total economic loss and total downtime loss (with slow track) at some critical timeframes, combined with the values having 30% and 10% probabilities of exceedance in 50 years. The expected economic and downtime loss with 10% of exceedance in 50 years is 77.06k$ and 31.26 workdays for PCF-II, which is the lowest among the others.

As expected, the results indicate that the PCFs with combination of PTs and additional hysteresis dampers can provide the structure with damage-controlled mechanism and reduced seismic loss. This observation is consistent with the post-earthquake reconnaissance in the 2011 Christchurch earthquake that the seismic performance of PRESSS frames is desirable, providing undamaged and immediate occupancy performances under this intense earthquake event.

6. Conclusion
This article conducts a comparative study of seismic consequence assessment between PCFs and RCFs, which can be served as a companion of another relevant article investigating the fragility and risk analyses of PCFs and RCFs conducted by the authors. The seismic economic loss associated with downtime loss are estimated through a comprehensive PEER-compatible seismic consequence estimation methodology. The results reveal that compared with RCF, the precast frames with "dry" connections have shorter downtime and reduced economic loss.

As for the PCFs with "dry connections", their extraordinary self-centering capacities are generated through configuring PTs through beam sections, thus they can recover to their original positions even after severe earthquake events. Thus, the probability of being demolished due to unacceptable residual
deformations are effectively reduced, and in turn the demolition economic loss associated with downtime can also be decreased.

However, there is almost no differences between downtime loss at repair events between RCF and PCF with PTs only. This is due to the larger lateral deformation compared with an equivalent cast-in-situ counterpart. The seismic response combined with downtime loss can be further reduced by installing hysteresis devices.

Considering the properties of construction simplicity, rapid repair speed and easy assemblage for PCFs with "dry" connections, the PCFs demonstrated to show lower expected annual economic and downtime loss. As for the PCF with additional replaceable web friction devices, the earthquake damage is concentrated at the devices while the precast components are still at their elastic stages after earthquake events. This characteristic facilitates a shorter repair time associated reduced economic loss. It should be noted that the conclusions derived are applicable to the specific structural layout and design information used in this case study, further studies would be extended to PCFs with higher story levels and more spans.

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