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A CLOSED-FORM APPROXIMATION TO ADAPTIVE STRUCTURAL FRAGILTIY TO AFTERSHOCKS

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ABSTRACT

Structural vulnerability assessment to aftershocks is particularly challenging due to the cumulative damage induced in the structure. In an adaptive approach to aftershock vulnerability assessment, the structural model can be updated in a daily manner so that the damage caused by the previous aftershocks is taken into account. In such a context, the forecasting or prediction interval reduces to 24 hours. The daily aftershock fragility curves may be defined as conditional first-excursion probabilities given seismic intensity for prescribed structural limit states. Exploiting the basic probability theory rules, the structural fragility to aftershocks is derived, taking into account sequence of events that may occur during the prediction interval. Herein, a closed-form approximation to the sequence-based daily aftershock fragility is derived. As a numerical example, daily aftershock vulnerability and risk is calculated for a typical RC infilled frame subjected to the L'Aquila 2009 aftershock sequence (central Italy), for two distinct limit states. The approximate closed-form fragility curves reveal remarkable agreement with the complete sequence-dependent fragility curves. Furthermore, the adaptive daily risk prediction, obtained based on the approximate closed-form formulation, manages to properly predict the first-excursion of prescribed limit states during the days elapsed after the main-shock.

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A Closed-form Approximation To Adaptive Structural Fragility To Aftershocks

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ABSTRACT

Structural vulnerability assessment to aftershocks is particularly challenging, due to the cumulative damage induced in the structure. In an adaptive approach to aftershock vulnerability assessment, the structural model can be updated in a daily manner so that the damage caused by the previous aftershocks is taken into account. In such a context, the forecasting or prediction interval reduces to 24 hours. The daily aftershock fragility curves may be defined as conditional first-excursion probabilities given seismic intensity for prescribed structural limit states. Exploiting the basic probability theory rules, the structural fragility to aftershocks is derived, taking into account the sequence of events that may occur during the prediction interval. Herein, a closed-form approximation to the sequence-based daily aftershock fragility is derived. As a numerical example, daily aftershock vulnerability and risk is calculated for a typical RC infilled frame subjected to the L'Aquila 2009 aftershock sequence (central Italy), for two distinct limit states. The approximate closed-form fragility curves reveal remarkable agreement with the complete sequence-dependent fragility curves. Furthermore, the adaptive daily risk prediction, obtained based on the approximate closed-form formulation, manages to properly predict the first-excursion of prescribed limit states during the days elapsed after the main-shock.

Introduction

The first days, elapsed after the occurrence of an earthquake, are crucial in terms of emergency decision-making. Such decision-making is rendered more complicated by the occurrence of aftershock events in the ongoing seismic sequence. Therefore, it is logical to adapt the interval of predictions to the short-term nature of the problem. A 24-hour time interval seems a suitable choice for the prediction or the forecasting interval, also consistent with the operational earthquake forecasting framework [1]. Hence, the adaptive aftershock vulnerability assessment can be performed for a structure that is subjected to the aftershock events occurred before the beginning of the 24-hour prediction interval. In a previous work, the authors have derived a formulation for time-dependent aftershock vulnerability by applying basic probability theory rules [2]. In a recent work, the authors have modified the original methodology so that it can be implemented in an adaptive aftershock vulnerability assessment framework [3-5]. Based on the proposed methodology, adaptive daily fragility curves can be calculated as a weighted sum of

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fragility curves derived on the condition that a specific number of aftershock events has occurred. The weights are calculated as the probability that a specific number of aftershocks have taken place in the prediction interval of interest. A non-linear dynamic analysis procedure coined as the "sequential cloud analysis" [3, 5] is adopted in order to calculate the sequence aftershock fragility curves. This method relies on a set of ground motion sequences constructed by selecting aftershocks already registered during the ongoing aftershock sequence; that is, before the beginning of the forecasting interval.

In this work, based on a simplifying approximation, a simple analytic close-form solution to the adaptive daily aftershock fragility curve is derived. This simple expression is a function of the expected number of aftershock events of interest in the forecasting interval (i.e. a desired day after the main event for which the predictions are going to be performed) as well as the fragility curve associated with the state of the structure at the start of the day. As a numerical example, adaptive daily vulnerability and risk predictions for two ultimate limit states are provided for a typical RC frame building with infill panels subjected to the L'Aquila aftershock sequence (2009, central Italy).

General Definitions for Adaptive Vulnerability Assessment

As mentioned before, in the adaptive vulnerability assessment procedure discussed herein, 24-hour predictions of seismic fragility curves (given a desired limit state) are provided. In a more general sense, the adaptive fragility curves correspond to the *j*th day elapsed after the main-shock and the forecasting (prediction) time-interval $[T_{start}, T_{end}]$. This prediction is based upon: (1) the registered sequence of aftershock wave-forms with magnitudes greater than a lower level, $M \geq M_l$, in the time elapsed between the main-shock until T_{start}, denoted as **seq**; and (2) various plausible aftershock sequences in the forecasting interval, namely $\mathbf{seq}_{\mathrm{gen}}$. The maximum number of aftershock events taking place in the prediction time interval, i.e. the number of events within $\mathbf{seq}_{\mathrm{gen}}$, is denoted as N_{as}.

Methodology

Time-dependent Performance Variable

In this study, the same structural performance variable, which has been used by the authors in their previous works (see [3, 5]), is implemented. This adaptive time-dependent performance variable is defined as the ratio of maximum demand increment due to the *n*th event within the sequence to the residual demand capacity right after the sequence of (*n*-1) events:

$$Y_{LS}^{(n)} = \frac{D_{\mathrm{max}}^{(n)} - D_{\mathrm{r}}^{(n-1)}}{C_{LS} - D_{\mathrm{r}}^{(n-1)}} \tag{1}$$

where D_{max} is the maximum demand associated with the sequence of n events, D_{r} is the residual demand corresponding to the sequence of (n-1) events, and finally C_{LS} is the limit state capacity. The term in the denominator of Eq. 1 can be viewed as the structural residual demand capacity right after the sequence of (n-1) events. At the onset of the limit state *LS*, the performance variable Y_{LS} is equal to unity.

Formulation of Time-dependent Risk

The daily rate of exceeding the limit state λ_{LS} can be calculated based on the total probability theorem and the assumption of a filtered Poisson process:

$$\lambda_{LS} = \lambda\left(Y_{LS} \geq 1 \mid \mathbf{I}_j\right) = \int_x P\left(Y_{LS} \geq 1 \mid x, \mathbf{I}_j\right) \left| d\lambda(x \mid \mathbf{I}_j) \right| \tag{2}$$

where $\mathbf{I}_j$ denotes the background information indicating the **seq** of aftershock events with $M \geq M_l$ corresponding to the jth day; $\lambda(x|\mathbf{I}_j)$ is the mean daily rate that the spectral acceleration at a desired period *T,* denoted by $Sa(T)$, exceeds a given value x (also referred to as daily aftershock hazard [6]); and $P(Y_{LS} \geq 1|x,\mathbf{I}_j)$ is the conditional probability of exceeding the limit state given a specified value x. This quantity, which is referred to hereafter as the adaptive daily fragility curve for a given limit state, can be expanded by using the total probability theorem:

$$P\left(Y_{LS} \geq 1 \mid x, \mathbf{I}_j\right) = \sum_{n=1}^{N_{as}} P\left(Y_{LS} \geq 1 \mid x, n, \mathbf{I}_j\right) P\left(n \mid \mathbf{I}_j\right) \tag{3}$$

where $P(Y_{LS} \geq 1|x,n,\mathbf{I}_j)$ is the probability of exceeding the limit state given a specific value of spectral acceleration x and that exactly n aftershock events take place; and $P(n|\mathbf{I}_j)$ is the probability that exactly n events take place in the prescribed time interval. Strictly speaking, this term should be conditioned on x; we have dropped this term assuming that the number of events with $M \geq M_l$ does not depend on the spectral acceleration level x.

The fragility term $P(Y_{LS} \geq 1|x,n,\mathbf{I}_j)$ in Eq. 3 is called herein the *event-dependent* fragility (see [3, 5]). It can be shown that the event-dependent fragility term can be derived from the following expression [2, 3, 5, 7]:

$$P\left(Y_{LS} \geq 1 \mid x, n, \mathbf{I}_j\right) = \sum_{k=1}^{n} \left(\pi_k \cdot \prod_{i=1}^{k-1} \left(1 - \pi_i\right) \right) \tag{4}$$

where π_k denotes the probability that the first limit state excursion takes place after the occurrence of the kth event, given that it has not exceeded the desired limit state after none of the previous (k-1)th event. The sequence of fragility terms $\{\pi_k(x)|k=1{:}n\}$ is estimated herein by implementing the Cloud Method [8, 9].

With reference to Eq. 3, the probability term $P(n|\mathbf{I}_j)$ can be estimated by a non-homogenous Poisson probability density function (PDF) with the time-decaying rate based on the MO model. This rate, which is denoted as $\lambda_{\mathrm{MO}}(t,M_l|\mathbf{I}_j)$, is the daily rate of having aftershock events with $M \geq M_l$. The parameters of this model are estimated in an adaptive manner, using the Bayesian updating, based on the aftershock events within the **seq** (see [6] for extensive discussions on the aftershock model adopted). Furthermore, a best-estimate for the maximum number of aftershock events of interest N_{as} is taken as the expected value plus two standard deviations for the Poisson distribution $P(n|\mathbf{I}_j)$ provided by the MO model.

Derivation of a Closed-form Approximation

Let us assume that the sequence of fragility terms $\{\pi_n(x)|n=1:N_{as}\}$ are identical and equal to the time- and sequence- invariant function $\pi(x)$. Thus, Eq. 4 becomes a geometric series as follows:

$$P\left(Y_{LS} \geq 1 \mid x, n, \mathbf{I}_j\right) = \sum_{k=1}^{n}\left[\pi(x)\left(1-\pi(x)\right)^{k-1}\right] = \pi(x)\left[\frac{1-\left(1-\pi(x)\right)^n}{\pi(x)}\right] = 1-\left(1-\pi(x)\right)^n \tag{5}$$

Accordingly, Eq. 3 can be re-written as:

$$P\left(Y_{LS} \geq 1 \mid x, \mathbf{I}_j\right) = \sum_{n=1}^{N_{as}}\left[1-\left(1-\pi(x)\right)^n\right]\frac{\left(\int_{T_{start}}^{T_{end}} \lambda_{\mathrm{MO}}\left(t, M_l \middle| \mathbf{I}_j\right) dt\right)^n e^{-\int_{T_{start}}^{T_{end}} \lambda_{\mathrm{MO}}\left(t, M_l \middle| \mathbf{I}_j\right) dt}}{n!} \tag{6}$$

The integral of the MO rate in Eq. 6 is in fact equal to the average number of aftershock events, $N_{\mathrm{MO}}(M>M_l|\mathbf{I}_j)$ or more briefly N_{MO}, which take place in the forecasting time interval:

$$N_{MO} = N_{\mathrm{MO}}\left(M > M_l \middle| \mathbf{I}_j\right) = \int_{T_{start}}^{T_{end}} \lambda_{\mathrm{MO}}\left(t, M_l \middle| \mathbf{I}_j\right) dt \tag{7}$$

Thus, Eq. 6 can be re-written as:

$$P\left(Y_{LS} \geq 1 \mid x, \mathbf{I}_j\right) = 1-\sum_{n=0}^{\infty}\left(1-\pi(x)\right)^n \frac{\left[N_{\mathrm{MO}}\left(M > M_l \middle| \mathbf{I}_j\right)\right]^n e^{-N_{\mathrm{MO}}\left(M>M_l \middle| \mathbf{I}_j\right)}}{n!} \tag{8}$$

Note that we have set the sum's index to start from zero (as the expression inside the sum in Eq. 6 is equal to zero at n=0). Eq. 8 can be further simplified as:

$$P\left(Y_{LS} \geq 1 \mid x, \mathbf{I}_j\right) = 1-\left(e^{-\pi(x)N_{\mathrm{MO}}}\right)\sum_{n=0}^{\infty}\frac{\left[\left(1-\pi(x)\right)N_{\mathrm{MO}}\right]^n e^{-(1-\pi(x))N_{\mathrm{MO}}}}{n!} = 1-e^{-\pi(x)N_{\mathrm{MO}}} \tag{9}$$

where sum is in Eq. 9 is equal to unity, since it is equal to the sum of a filtered Poisson probability mass function over all its possible values. According to this closed-form expression, for approximating the daily aftershock fragility, it is only required to estimate the average number of events in the jth day with $M>M_l$ and the time-invariant fragility term $\pi(x)$.

Estimating $\pi_n(x)$ by performing a sequential Cloud Analysis

In order to estimate $\{\pi_n(x)|n=1:N_{as}\}$, as required in Eq. 4, a sequence of cloud analyses will be performed in the following steps:

(1) A number of N_{seq} ground motion sequences, denoted by $\mathbf{seq}_{\mathrm{gen}}$, are generated (the methodology for generating $\mathbf{seq}_{\mathrm{gen}}$ will be described later). Each generated sequence is comprised of N_{as} events.

(2) Each of the generated $\mathbf{seq}_{\text{gen}}$ are applied to the structure that departs probably from a damaged state due to the sequence of events, **seq**, preceding the forecasting time window.
(3) Within N_{seq} generated sequences, the pairs of cloud data ($Sa^{(n)}$, $Y_{\text{LS}}^{(n)}$) are obtained. Each pair consists of the first-mode spectral acceleration at a prescribed period and performance variable, both corresponding to event n, n=1:N_{as}.
(4) Exclude the pairs associated with sequences in which limit state excursion has already taken place in their previous events.
(5) Assuming that the conditional distribution of the structural performance variable $Y_{\text{LS}}^{(n)}$ given level of $Sa(T)=x$ is described by a lognormal distribution, the fragility term $\pi_n(x)$ can be expressed as:

$$\pi_n(x) = P\left(Y_{LS}^{(n)} \geq 1 \,|\, x, \mathbf{I}_j, \text{no LS exursion in prev. } n\text{-1 events}\right) = 1 - \Phi\left(\frac{-\ln \eta_{Y_{LS}|Sa}^{(n)}(x)}{\beta_{Y_{LS}|Sa}^{(n)}}\right) \quad (10)$$

where $\Phi(\cdot)$ is the standardized Gaussian CDF; η and β are conditional median and standard deviation (dispersion) of the natural logarithm of $Y_{\text{LS}}^{(n)}$ given spectral acceleration, directly obtained by performing a logarithmic linear regression on the cloud data (see [2, 3, 5, 8, 9] for more details).
(6) By repeating the above steps, the sequence of fragilities $\{\pi_n(x)|n=1:N_{as}\}$ can be obtained for the desired time interval.

The authors have adopted both *Sa* at the period of the intact structure as well as *Sa* at the post main-shock period in the above-mentioned sequential cloud procedure [5]. It has been observed that *Sa* at the post main-shock period is a more sufficient intensity measure compared to that at the natural period of the intact structure. However, since the results at the risk level were not so different, *Sa* at the period of the intact structure is adopted herein.

Estimation of π(x)

We have adopted two different estimators for the time-invariant fragility function $\pi(x)$ in the derived closed-form: (a) the fragility term $\pi_1(x)$; this term can be calculated from Eq. 10, by performing a standard Cloud Analysis on the structural state, updated based on the aftershock events occurred prior to the prediction interval; (b) the fragility term $\pi(x)=\pi_{N\text{MO}}(x)$; this term can be calculated through the sequential Cloud procedure described above only once for the value $n=N_{\text{MO}}$. We expect option (b) to provide upper-bound estimates for the aftershock fragility.

Numerical Example

General Description

Adaptive daily aftershock vulnerability and risk assessment are performed for a typical RC building with infill panels subjected to the L'Aquila 2009 aftershock sequence (central Italy in the Abruzzo region). Both complete (Eq. 3) and closed-form (Eq. 9) formulations are implemented for calculating the daily fragility curves associated with the specified limit states. For estimating the risk based on Eq. 2, results of a previous work by the authors [6] are exploited in order to obtain the daily aftershock hazard rates $\lambda(x|\mathbf{I}_j)$. The sequence of aftershock events, denoted as **seq**, consists of the aftershock wave-forms with $M>M_l$ registered in the above-mentioned catalog after the main-shock up to 6:00 a.m. UTC (i.e., T_{start}) of the upcoming day (i.e. jth day). The lower magnitude M_l is taken to be 3.3.

The case-study structure is a simple nonlinear representation (shear building model) of a two-dimensional 3-story infilled RC frame with the geometric configuration shown in Fig. 1a. The column dimensions along the building height are (30×30) cm^2. The one-bay infill panel is uniformly distributed with a thickness equal to 20 cm. The small-amplitude first-mode period of the building is equal to 0.27 sec. More information on the building structure as well as the nonlinear behavior attributed to column elements and infill panel are described extensively in [5]. The expected failure mechanism is considered to be the formation of a local soft story at the first-story level. Hence, the nonlinear behavior is attributed only to those elements, and the elements in the upper stories are considered to remain elastic. The parameter D in Eq. 1 is taken as the displacement of the first story.

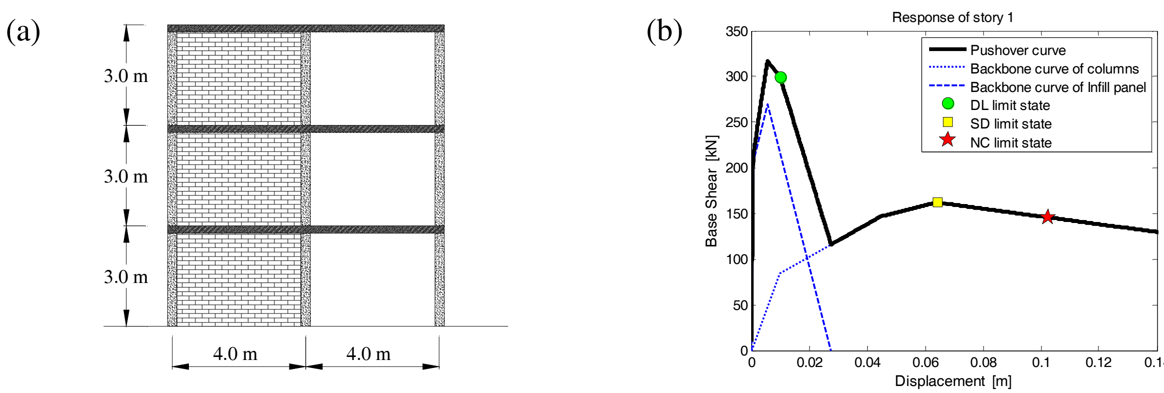

Figure 1. (a) General configuration of the case study infilled RC frame, (b) Pushover curve of the frame showing base shear versus displacement of the first story, as well as the points corresponding to the DL, SD and NC limit states

The Limit States

Discrete limit states of Damage Limitation (DL), Significant Damage (SD) and Near Collapse (NC) are defined as the performance objectives for post-earthquake assessment. It is assumed that the DL limit state is the displacement corresponding to the attainment of 20% drop in the ultimate strength of the first-story infill panel. The SD limit state is defined by the maximum displacement associated with the achievement of either the maximum strength in the columns or the complete collapse of the infill panel in the first story. Finally, the NC limit state threshold is conservatively set herein to 10% drop in ultimate strength of the columns (i.e., instead of 20% as denoted in EC8 [10]). This has been done to take into account unknown sources which may accelerate the deterioration of columns. Fig. 1b shows the onset of the above-mentioned limit states marked on the pushover curve of the structure.

Due to L'Aquila 2009 main-shock, the maximum displacement demand exceeds the limit state of DL. Therefore, the daily fragility curves are obtained for SD and NC limit states.

Complete and Closed-form Solutions for Daily Fragility Curves

In this section, the adaptive daily aftershock fragilities are calculated based on the complete and closed-form approximation obtained from Eq. 3 and Eq. 9. As mentioned above, $\pi(x)$ is estimated by following the two options (a) $\pi(x)=\pi_1(x)$, and (b) $\pi(x)=\pi_{N\mathrm{MO}}(x)$, described before. The suite of ground motion sequences $\mathbf{seq}_{\mathrm{gen}}$ for the Cloud Analysis is generated by permutation (with replacement) of the registered events within the **seq**. It has been observed that permutation of records (instead of repeating the same record over and over again) leads to more accurate estimates for daily aftershock fragilities [3, 5].

Evaluating $P(n|\mathbf{I}_j)$ and N_{MO}

The probability distribution for the number of events, $P(n|\mathbf{I}_j)$, is calculated based on a non-homogeneous Poisson probability model, and the expected number of events N_{MO} is obtained from Eq. 7 (see [6]). The first column of Fig. 2 illustrates the probability mass function for this distribution as well as N_{MO} for the first four days after the main event.

The adaptive daily fragility curves

The daily fragility curves for two limit states, namely NC (2nd column) and SD (3rd column) are illustrated in Fig. 2. The fragility curves plotted in various shades of grey are the so-called event-dependent fragility curves calculated from Eq. 4. Note that the first curve (plotted in thick black dashed line) is the $\pi_1(x)$. It can be observed that the closed-form results with $\pi(x)=\pi_1(x)$ (plotted in thick red line) lead to interestingly close agreement with the curves obtained from the complete formulation (plotted in thick blue line). It is important to recall that $\pi_1(x)$ is obtained by performing a Cloud Analysis on the structure already subjected to the sequence of records **seq**.

Moreover, the closed-form results with $\pi(x)=\pi_{N\mathrm{MO}}(x)$ (plotted in dashed red line) leads to consistently upper-bound estimates for the daily fragility curve, with respect to the complete formulation. However, recall that $\pi_{N\mathrm{MO}}(x)$ is estimated by performing a Sequential Cloud Analysis.

As a benchmark for the predicted fragility curves, the aftershock events that lead to first-excursion of the SD and NC limit states are marked with stars at probability level equal to unity in Fig. 2 (right-hand column). Accordingly, the aftershock events preceding the first-excursion are illustrated as stars at zero probability. Note that these points are obtained by considering the actual registrations during the prediction time interval. It can be observed that the first excursion of the SD limit state takes place in the 2nd day elapsed after the main-shock (by a record with local magnitude of 5.4). The NC first excursion occurs in 4th day elapsed after the main event (by a record with local magnitude of 5.0). The predicted fragility curves (both closed-form and complete) "predict" these events successfully with exceedance probabilities superior to 80%.

Adaptive Daily Aftershock Risk Prediction

Predictions of aftershock risk, expressed in terms of the mean daily rate of exceeding a prescribed limit state, can be directly provided by substituting daily fragility and hazard predictions (not reported herein, see [6]) in Eq. 2.

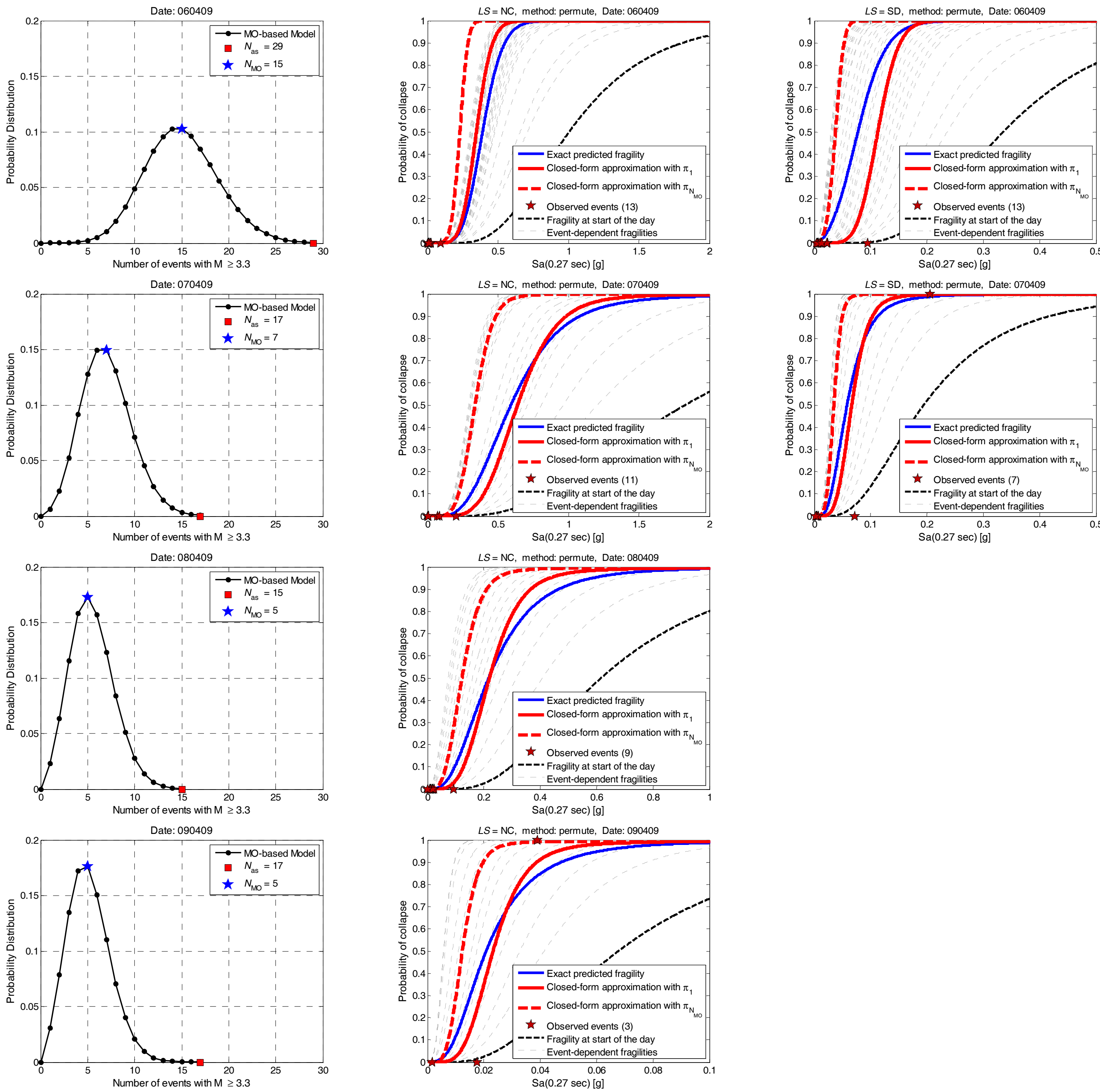

Figure 2. The probability distribution of the number of events and the predicted fragility curves for SD and NC limit states from 6 April 2009 up to 9 April 2009

Fig. 3 illustrates adaptive daily risk predictions for two limit states SD and NC obtained based on both closed-form and complete fragilities. The risk predictions obtained by adopting the complete formulation are plotted as black circles with solid line and those calculated by adopting the closed-form fragilities with $\pi(x)=\pi_1(x)$ are plotted as red squares with dashed line. The first-excursion of SD and NC are reported as stars corresponding to a daily risk equal to unity.

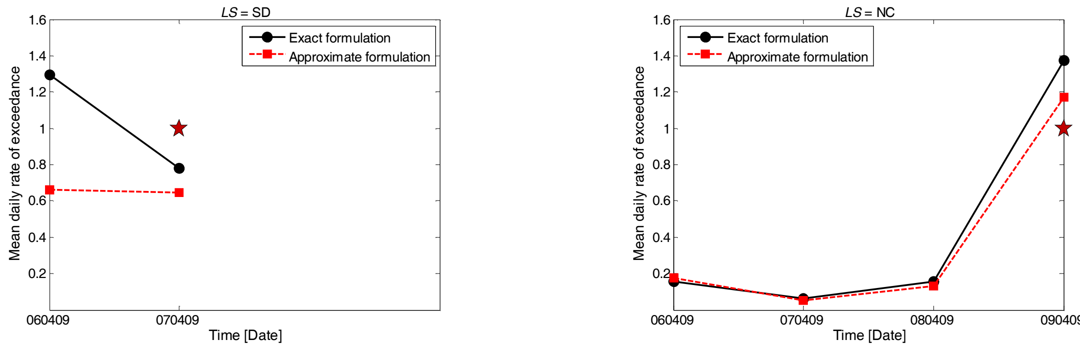

Figure 3. Daily risk prediction for SD (left) and NC (right) limit states for the first four days from 6 April 2009 to 9 April 2009

It can be observed that the complete fragility formulation leads to a "premature" prediction of the SD limit state excursion. In the second day, the limit state excursion is predicted by the complete and closed-form solutions with rates of exceedance equal to 80%, 65%, respectively. On the other hand, the first-excursion of NC limit state in the fourth day is accurately predicted, i.e., with exceedance rates 120% and 140% from closed-form and complete solutions, respectively.

Conclusions

This paper presents an approximate close-form solution for the adaptive daily aftershock fragility curves. The daily fragility curves are defined as conditional first-excursion probabilities, for severe damage and near collapse limit states, given spectral acceleration at the first-mode period of the intact structure. This closed-form solution, which enjoys a remarkably simple formulation, is derived from an existing time-dependent fragility assessment methodology, proposed previously by the authors [3, 5]. Its calculation requires only the estimation of the average number of events expected to happen during the prediction interval and a standard non-linear dynamic analysis procedure (e.g., Cloud Method) applied to the structure, whose state is updated at the beginning of the prediction interval. The closed-form solution can also be implemented by performing a sequential Cloud Analysis, having a number of records equal to the expect number of events of interest. This solution is expected to lead to upper-bound estimates of the daily fragility curves. Having adopted an adaptive strategy for aftershock fragility prediction, it is assumed that the sequence catalog and wave-forms are available up to the beginning of the prediction interval. It should be noted that the availability of the sequence catalog is perfectly consistent with the requirements for an operative earthquake forecasting framework.

The case-study application for the L'Aquila 2009 seismic sequence demonstrates that the closed-form solution leads to a good estimation of the adaptive daily fragility curves. Benchmarking the results with respect to the actual sequence (i.e., assuming that the events actually occurred during the prediction interval are known), reveals that the closed-form solution can provide sufficient (but not perfectly accurate) warnings for the first-excursion of the considered limit states. It should be kept in mind, however, that the Cloud Method used for demand estimation for both the complete and closed-form solutions, is quiet sensitive to the selection the suite of records/sequences. This issue needs to be further investigated. Furthermore, the accuracy of the risk predictions (provided by both approaches) significantly depends on the accuracy of the daily hazard predictions.

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