13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3283

BUILDING TAGGING CRITERIA BASED ON AFTERSHOCK PSHA

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SUMMARY

The objective of yellow or red-tagging a building after an earthquake is to insure adequate life safety during a period of enhanced seismic activity. A methodology for the life-safety evaluation of an earthquake-damaged building is proposed based on the explicit quantification of the time-varying aftershock ground motion hazard at the site after a major earthquake. The methodology takes into consideration the level of damage sustained by the building due to the mainshock and its residual capacity against collapse due to possible future aftershocks.

The proposed methodology enables us to classify buildings after an earthquake into three groups based on the probability of building collapse due to an aftershock. The fatality risk to an arbitrary occupant is presumed to be proportional to this number. The classification criteria are based on the value of this collapse rate relative to the tolerable value implied by current new building design. The first group of buildings is classified or "tagged" red implying that immediate entry and re-occupancy are not permitted for any personnel. The second group of buildings is tagged yellow; entry by volunteer emergency personnel for repair or retrofit purposes or for continued operation of critical facilities is allowed as long as such personnel are informed of the increased risk they face and are appropriately compensated for it. The third group of buildings is tagged green permitting entry and re-occupancy for all personnel. The proposed methodology also provides for the change of tag color as a function of elapsed time from the mainshock due to the decreasing aftershock hazard at the site.

We also propose a methodology to allow earlier entry into a red-tagged building by introducing the concept of a controlled work force where we limit the total probability of collapse faced by a selected informed and compensated volunteer worker. This can be achieved by limiting the duration these workers may spend in damaged buildings, followed by a required, subsequent rotation to a safer working environment.

INTRODUCTION

After an earthquake buildings might suffer significant damage without collapse. There is a need to "tag" such buildings to decide if it is necessary to evacuate their occupants based on the damage sustained by the buildings. If the occupants of a damaged building are evacuated, it is also necessary to decide if and

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when emergency workers can enter the building for search-and-rescue or temporary shoring missions. Further, there are some critical facilities where it is essential to community recovery to ensure the continuation of their operations after the earthquake. Such facilities include water and power distribution networks etc. For such facilities, it might be extremely important to allow a minimum number of workers to enter the damaged building after the earthquake to perform critical functions. This case requires special consideration.

Such tagging decisions are dependent on the damage state of the building immediately after the first earthquake which we shall refer to as the mainshock. The decision should be based on life-safety considerations in terms of the damaged building's ability to resist aftershocks. Unfortunately, such decisions are complicated by the significantly increased likelihood of aftershocks in the post-mainshock environment. Aftershock rates are also dependent on the elapsed time after the mainshock such that the mean rate of aftershocks is at its maximum immediately after the mainshock and subsequently decreases with time. Also, the mainshock magnitude influences the mean rate of aftershocks in the post-earthquake environment.

Aftershock-based conditions for permissible entry into earthquake-damaged buildings have been addressed in Gallagher [1]. If this reference is followed, for buildings that have been inspected and determined to be unsafe but stable (a red-tagged building), depending on the mainshock magnitude, emergency workers can enter the building for a limited time if they wait for a number of days to pass after the mainshock. For example, if the mainshock magnitude is equal to 6.5 or greater, emergency workers can enter the building for two hours if they wait for one day after the mainshock.

These guidelines are implicitly based on aftershock occurrence rates which are dependent on the mainshock magnitude and elapsed time. The guidelines do not, however, take into consideration the possible aftershock ground motion intensities at the site which are necessary to determine if the damaged building has sufficient residual capacity to resist aftershocks. The damage sustained by the building due to the mainshock also merits quantification.

Here, we introduce a methodology that takes into consideration the increased aftershock ground motion hazard at a site after a mainshock via a procedure referred to as Aftershock Probabilistic Seismic Hazard Analysis or APHSA for short. We also propose a methodology to quantify the life-safety threat in a time-varying environment by representing them as Equivalent Constant Rates, or ECRs. Lastly, we also need to consider the damage states of the building after the mainshock based on the residual capacity of the damaged building to resist aftershock ground motions. This capacity, denoted as Sa_{cap}, is measured in terms of spectral acceleration of the first-mode period of the building.

We describe next each of the three components.

AFTERSHOCK PROBABILISTIC SEISMIC HAZARD ANALYSIS (APSHA)

First, we need to be able to quantify the time-varying post-mainshock hazard in terms of the possible ground motions that can occur at the site due to aftershocks. This process is referred to as Aftershock Probabilistic Seismic Hazard Analysis (APSHA), and interested readers are referred to the detailed manuscript in Yeo [2]. Here, we shall provide a brief summary of APSHA.

Immediately following a mainshock of magnitude m_m, aftershocks occur on a zone typically defined by the extent of the mainshock rupture zone. Aftershocks also occur with a time-varying rate that is at its maximum immediately after the mainshock and decreases with increasing elapsed time from the mainshock. The rate of aftershocks is also dependent on the mainshock magnitude m_m. The time and mainshock-magnitude dependence of aftershock rates is commonly referred to as Omori's Law: a typical California aftershock sequence studied by Reasenberg and Jones has parameters a = -1.67, b = 0.91, p = 1.08 and c = 0.05. See Reasenberg [3] for details. In Equation (1), $\lambda(\tau, m; m_m)$ is defined as the mean instantaneous daily rate of aftershocks with magnitude m or larger at time τ following a mainshock of magnitude m_m.

$$\lambda(\tau, m; m_m) = \frac{10^{a+b(m_m - m)}}{(\tau + c)^p} \tag{1}$$

We truncate the lower and upper bounds of aftershock magnitudes at m_l and m_m. We can then obtain the mean instantaneous daily rate of aftershocks with magnitudes between m_l and m_m at time τ (following a mainshock of magnitude m_m) by evaluating $\lambda(\tau, m_l; m_m) - \lambda(\tau, m_m; m_m)$. We denote this quantity as $\mu(\tau; m_m)$. We can also obtain the truncated exponential probability distribution function of aftershock magnitudes as $f(m; m_m)$ (See Yeo [2] for details). The expressions for $\mu(\tau; m_m)$ and $f(m; m_m)$ are shown in Equation (2) and Equation (3).

$$\mu(\tau; m_m) = \frac{10^{a+b(m_m - m_l)} - 10^a}{(\tau + c)^p} \tag{2}$$

$$f(m; m_m) = \frac{b\log(10)e^{-b\log(10)(m - m_l)}}{1 - e^{-b\log(10)(m_m - m_l)}} \quad \text{for} \quad m_l \le m \le m_m \tag{3}$$

We can then perform a ground motion analysis analogous to conventional PSHA for mainshocks (Kramer [4]) by integrating over all possible locations and magnitudes of the aftershocks. Here, we assume that aftershocks can only occur on the mainshock rupture zone to quantify the probability distribution function of the possible source-to-site distances given aftershock magnitude, f(r|m). By considering a suitable attenuation law, we can then obtain the mean number of aftershocks in the time interval of t and t+T after the mainshock which have first-mode spectral accelerations at the site (Sasite) greater than y. We denote this by μy as shown in Equation (4).

$$\mu_y = \int_t^{t+T} \mu(\tau; m_m)d\tau \left[\int_{m_l}^{m_m} \int_r P(Sa_{site} > y \mid m, r) f(r \mid m) f(m; m_m) dr dm \right] \tag{4}$$

The first integral in Equation (4) captures the temporal aspects and becomes:

$$\int_t^{t+T} \mu(\tau; m_m)d\tau = \left(10^{a+b(m_m - m_l)} - 10^a\right) \left[\frac{(t+c)^{1-p}}{p-1} - \frac{(t+T+c)^{1-p}}{p-1} \right] \tag{5}$$

The second double integral in Equation (4) is "solved" by conventional PSHA computer codes. It represents the probability of Sa_{site} exceeding a level of y given the occurrence of an aftershock. Thus:

$$P(Sa_{site} > y \mid aftershock) = \int_{m_l}^{m_m} \int_{r} P(Sa_{site} > y \mid m, r) f(r \mid m) f(m; m_m) dr dm \qquad (6)$$

The process of quantifying the time-varying aftershock hazard at a site in terms of a suitable ground motion intensity measure (Sa_{site} in this case) is referred to as APSHA.

QUANTIFICATION OF TIME-VARYING RATES AS EQUIVALENT CONSTANT RATES (ECR)

The ability to quantify the time-varying aftershock hazard is the first step towards developing a building-tagging methodology based on the post-mainshock ground motion hazard at a site.

However, as discussed in the previous section, aftershock hazard is time-varying in nature, and it depends on the number of elapsed days after the occurrence of the mainshock. Aftershock hazard is also dependent on the length of the time interval taken into consideration. Such dependence on time is inconsistent with conventional design criteria for buildings. For example, in the United States, design ground motion levels for new buildings are currently set at 0.0004/year (or 2% in 50 years). This frequency is implicitly assumed to be constant and indefinite in time. Life-safety is also normally stated in terms of annual frequency of fatality. For example, the Norwegian Petroleum Directorate (NPD) sets the maximum annual individual fatality risk per worker to 10^{-4} on new platforms for the offshore oil and gas industry (NPD [5]). Again, such criteria implicitly assume time-independent fatality risks that are constant and extend indefinitely into the future. In order to compare or calibrate safety criteria in a time-varying environment (such as aftershocks) to the standard time-invariant situation, some means must be identified to transform the former into the latter.

Such a methodology has been developed in Yeo [6]. There, time-varying rates are changed to "equivalent" constant rates with the desired characteristics by considering an *implied* discounted investment in life-safety technologies for both the constant or homogeneous mainshock case and the time-varying, nonhomgeneous aftershock case on the basis of social equity. Such constant rates which represent the time-varying aftershock rates are referred to as Equivalent Constant Rates, or ECRs. Interested readers are referred to Yeo [6] for further details.

In brief, after a mainshock of magnitude m_m, we can assess the threat due to the time-varying aftershock rates from time t_d for an arbitrarily long duration into the future (i.e. from t_d to infinity when the aftershock rate is negligible) by evaluating $ECR(t_d; m_m)$ based on Equation (7). Here, t_d refers to the date at which a decision is being made about the building; t_d includes day 1 of the mainshock but it also may refer a later date when there might be better information about the damage state of the building (for example, based on better inspection and/or more sophisticated engineering analysis) to facilitate better-informed building-tagging decisions (or revisions of previous building-tagging decisions). These decisions will be based on the assessment of the remaining threat to an occupant in the building. (This will be discussed in more details in later sections.) Here, r refers to the inflation-adjusted discount rate appropriate for discounting societal investments in life-safety technologies in the future.

$$ECR(t_d; m_m) = r \int_{t_d}^{\infty} e^{-r\tau} \mu(\tau; m_m) d\tau \qquad (7)$$

Equation (7) can be approximated as Equation (8) because $\mu(\tau;m_m)$ decreases to zero more rapidly relative to $e^{-r\tau}$ for increasing values of τ.

$$ECR(t_d;m_m) \simeq r\int_{t_d}^{\infty}\mu(\tau;m_m)d\tau \tag{8}$$

Thus, from Equation (8), the ECR(t_d; mm) can be easily estimated by computing the integral in Equation (8). This is simply the expected number of aftershocks in the time interval [t_d, ∞] (which can be computed by evaluating the area under the mean instantaneous daily aftershock rate curve from t_d to ∞) multiplied by the inflation-adjusted discount rate r. A representative value of r is 3.5% per annum (Páte-Cornell [7]).

Thus, as described above, we have transformed the time-varying rate into an equivalent constant rate, ECR(t_d; m_m), based on Equations (7) or (8). Note that ECR(t_d; m_m) is dependent on t_d, which is defined as the time at which the tagging decision (or revision of a previous tagging decision) is made.

QUANTIFICATION OF RESIDUAL CAPACITY OF DAMAGED BUILDINGS TO RESIST AFTERSHOCKS

The procedure briefly discussed below is based on Bazzurro [8]. Interested readers are referred to that manuscript for further details.

The methodology is based on performing a nonlinear static procedure (NSP) on the damaged building to estimate the building's residual capacity to resist aftershocks. The dynamic response is then inferred from the static response by using the SPO2IDA spreadsheet tool (Vamvatsikos [9]) and the median residual dynamic capacity of the building is found in terms of spectral acceleration, Sa_{cap}. This capacity provides an indication of the life-safety threat that the occupants are exposed to. The permitted occupancy status of the building will be determined below based on the median residual capacity to resist aftershocks and the likelihood of an aftershock ground motion exceeding that capacity.

For a damaged building in damage state DS with a random capacity (defined by its median Sa_{cap} (denoted as $\hat{S}a_{cap}$) and dispersion β_{cap} (standard deviation of the logarithm of Sa_{cap})), one can define $ECR_{col}^{DS}(t_d;m_m)$ as the equivalent constant collapse rate corresponding to the expected number of aftershocks (due to a mainshock of magnitude m_m) resulting in collapse of the damaged building from time t_d for an infinite duration. Under certain assumptions, this rate can be found to be numerically equal to Equation (9).

$$ECR_{col}^{DS}(t_d;m_m) = \left[ECR(t_d;m_m)\right]\left[P(Sa_{site} > \hat{S}a_{cap} \mid aftershock)e^{\frac{1}{2}k^2\beta_{cap}^2}\right] \tag{9}$$

ECR(t_d; m_m) has been defined previously. $P(Sa_{site} > \hat{S}a_{cap} \mid aftershock)$ can be evaluated based on Equation (6). The term $e^{\frac{1}{2}k^2\beta_{cap}^2}$ is a factor to account for the dispersion of the Sa_{cap} value, where k is the slope of the linearly-approximated log-log hazard curve. See Cornell [10] for details.

The equivalent constant collapse rate, $ECR_{col}^{DS}(t_d;m_m)$, is assumed to be proportional to the fatality risk to an arbitrary occupant in the damaged building. On the basis of life-safety, given m_m and for a building in damage state DS, we will next compare $ECR_{col}^{DS}(t_d;m_m)$ to existing safety criteria to determine if the safety criteria have been satisfied. This will form the basis of our proposed building-tagging methodology.

PROPOSED BUILDING-TAGGING METHODOLOGY

Using the three components described above, we now propose a building-tagging methodology based on $ECR_{col}^{DS}(t_d;m_m)$.

Given the mainshock magnitude, m_m, the location of the building, the mainshock rupture zone and the degree of damage of the building in terms of $\hat{S}a_{cap}$ and β_{cap}, we have above quantified the $ECR_{col}^{DS}(t_d;m_m)$ of the damaged building as a function of t_d. An occupant in a damaged building will be exposed to a time-varying collapse rate, and thus, a time-varying fatality risk. On the basis of life-safety, we propose to compare $ECR_{col}^{DS}(t_d;m_m)$ to a specified acceptable collapse rate to determine the appropriate tag for the damaged building. Depending on when the tagging decision is to be made, the appropriate tag for the building may improve with an increase in the elapsed time from the mainshock. The possibility of considering changes of building tags arises because of the reduction of the aftershock hazard with increasing elapsed time from the mainshock.

As discussed earlier, the degree of damage of the building will be evaluated to different degrees of "accuracy" at different times. For example, shortly after the mainshock, quick visual inspection provides us with information about the damage state with high degrees of uncertainty as indicated by large β_{cap} values. Better inspection (for example, inspection of the connections in a SMRF building) and engineering analysis (for example, nonlinear time history analysis) provides us with more information about the damage state of the building with different $\hat{S}a_{cap}$ and smaller β_{cap} values. This would provide us with an opportunity to re-assess the remaining threat to an occupant in the damaged building and to re-make our building-tagging decision based on more accurate information about the damage sustained by the building.

We propose three possible tags for buildings after the earthquake, similar to Gallagher [1]. When a building is green-tagged, all occupants may enter the building. When a building is yellow-tagged, only emergency workers may enter the building for search-and-rescue missions, or to restore operations in critical facilities such power production and distribution facilities. Such emergency workers need to be informed of the increased risk that they face when they volunteer to perform their tasks in damaged buildings, and they also need to be appropriately compensated for the increased risk that they face. When a building is red-tagged, neither normal occupants nor emergency workers may be in the damaged building for extended periods of time. These tagging designations are analogous but not equivalent to FEMA [11].

Acceptable Collapse Rate for each Building Tag

First, we need to establish the range of acceptable collapse rates for each of the three building tags.

It is proposed to specify the acceptable (or tolerable) collapse rates for the various tagging states in terms of P_0, the acceptable collapse rate for new, intact buildings designed for mainshocks. This number is important for operations to continue uninterrupted. We propose a comparatively high level of α_1 for such facilities. For non-safety-critical commercial and office buildings, the level of α_1 is set to be lower than that of critical facilities. For residential buildings, the level of α_1 is set to be between that of critical facilities and commercial buildings.

We also need to set a maximum acceptable collapse rate of $\alpha_2 P_0$ beyond which entry by all personnel (including normal occupants and emergency workers) is not allowed on the basis of life-safety. For collapse rates between $\alpha_1 P_0$ and $\alpha_2 P_0$, the building will be yellow-tagged. Entry is permitted for informed, compensated and voluntary emergency workers for the ranges of $ECR_{col}^{DS}(t_d;m_m)$ above. Again, the relative level of α_2 should be set according to the function of the building.. The building tags and their corresponding ranges of collapse rates are shown in Figure 1.

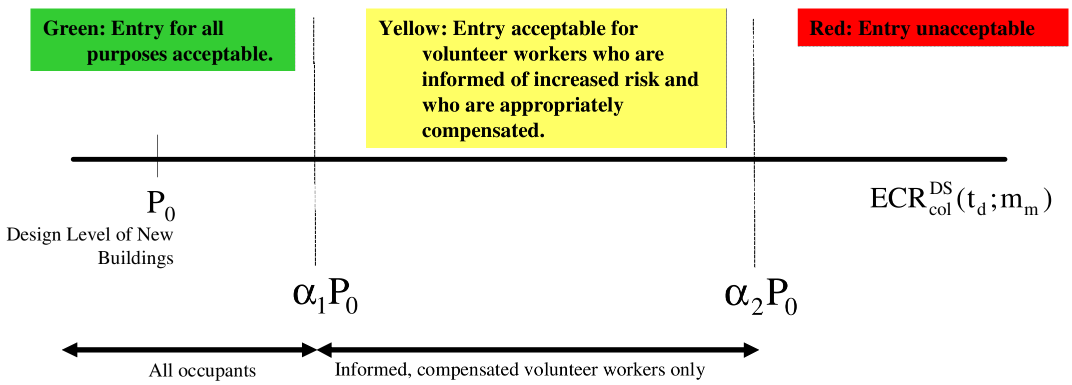

Figure 1: Buildings tags and their corresponding allowable collapse rates

Representative values of α_1 and α_2 might be 5 and 10 for critical community recovery facilities, 3 and 6 for commercial and office buildings and 4 and 8 for residential buildings.

Primary Building-Tagging Basis

We now propose a tagging methodology based on quantifying $ECR_{col}^{DS}(t_d;m_m)$ of the damaged building, first ignoring possible repair or upgrade to the building. We will consider a revised tagging methodology for buildings that might have been repaired or upgraded after the mainshock in a later section.

In order to tag the building, we first evaluate $ECR_{col}^{DS}(t_d;m_m)$ of the building as a function of t_d. Specifically, we represent $ECR_{col}^{DS}(1;m_m)$ (one day after the mainshock) as γP_0. We compare the value of γ to the values of α_1 and α_2 for the building. If γ is less than α_1, then the building is green-tagged one day after the mainshock and the occupants of the building do not need to be evacuated. If γ is less than α_2 but more than α_1, then the building is yellow-tagged and only entry by informed, compensated and voluntary emergency workers is allowed. If γ is greater than α_2, then the building will be red-tagged after the mainshock and complete evacuation of the building is necessary on the basis of life-safety.

If γ is greater than α_2 such that the building is red-tagged after the mainshock (see Figure 2), the tag will remain red until the $ECR_{col}^{DS}(t_d;m_m)$ decreases to a level equal to $\alpha_2 P_0$ on the k^{th} day. This is when the building tag changes to yellow corresponding to an $ECR_{col}^{DS}(t_d;m_m)$ which will be less than $\alpha_2 P_0$ from

α_2 but more than α_1, then the building is yellow-tagged and only entry by informed, compensated and voluntary emergency workers is allowed. If γ is greater than α_2, then the building will be red-tagged after the mainshock and complete evacuation of the building is necessary on the basis of life-safety.

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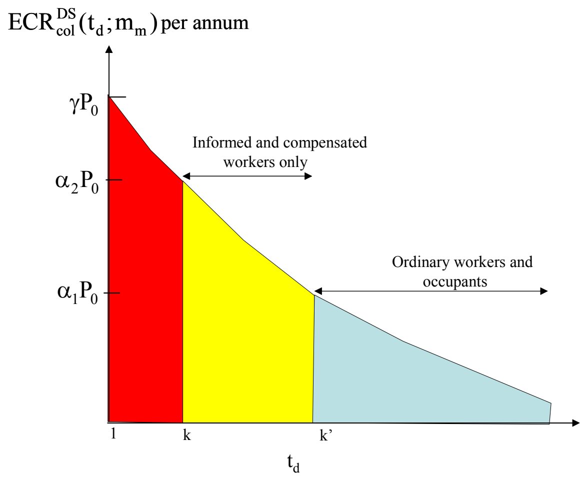

Figure 2: $ECR_{col}^{DS}(t_d;m_m)$ **of a damaged building. The building should be tagged red from day 1 to day k, yellow between days k and k' and green from day k' on.**

Special Tagging Cases: Emergency Workers

There might also be special situations where it is necessary to allow emergency workers to enter a damaged building to perform critical tasks even when the building is red-tagged. For example, it is important to ensure continued operations at power distribution networks in the post-earthquake environment, and hence it might be necessary to allow emergency workers to enter such facilities to perform short-term critical repairs or periodic monitoring or switching. In some other facilities, it might also be necessary to allow emergency workers to enter red-tagged buildings for search-and-rescue missions or collapse-prevention shoring activities.

We propose a revised tagging methodology to allow entry into buildings that have been red-tagged by providing a controlled working environment for emergency workers based on the total life-safety threat that they face by entering such damaged buildings with a high $ECR_{col}^{DS}(t_d;m_m)$. Again, this methodology ignores as yet possible repair or upgrade to the building after the mainshock.

Consider the $ECR_{col}^{DS}(t_d;m_m)$ for a critical facility in damage state DS as shown in Figure 3. The building has been red-tagged immediately after the mainshock because γ is greater than α_2. It is necessary to allow the entry of emergency workers shortly after the mainshock to perform some critical repairs which cannot wait till the k^{th} day when the building tag will change to yellow. To allow such operations, these emergency workers can enter the building earlier at time j if their work schedule and location are properly controlled. This requires both a limited duration, d', in the damaged building and a subsequent rotation after departure to a "safer" environment (SE). The duration d' can be determined for an arbitrary start time j by ensuring that:

$$ECR_{col}^{DS}(j; m_m) - ECR_{col}^{DS}(j + d'; m_m) + ECR_{col}^{SE}(j'; m_m) \leq \alpha_2 P_0 \tag{10}$$

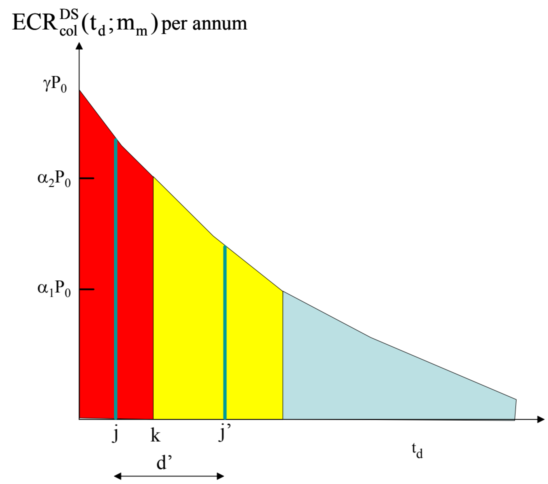

Figure 3: Time-varying $ECR_{col}^{DS}(t_d; m_m)$ of a damaged building. Emergency workers can enter the damaged building on day j for a total duration of d' days if their working environment is properly controlled.

The first two terms reflect the risk associated with the interval in the red-tagged building and the third term reflects the time in the safer environment. The "safer" environment can be achieved by housing and/or employing the workers in a building with demonstrated higher capacity or by moving the workers to a location which is further away from the aftershock zone where the aftershock hazard is lower, or a combination of both. The $ECR_{col}^{DS}(t_d; m_m)$ of the "safer" environment needs to be evaluated based on the median assessed Sa_{cap} of the new building that they are relocated to, and/or on a revised Aftershock Probabilistic Seismic Hazard Analysis (APSHA) which takes into consideration the location of the new building with respect to the mainshock rupture zone. If further occupancy is needed in the mainshock-damaged building, a new group of controlled workers can be engaged to begin on day j'. This new group of workers should have been controlled – in a "safer" environment – since day j.

This tagging proposal is, in effect, a limited cumulative risk concept where we evaluate the cumulative threat to a person due to occupancy in a damaged building and in a "safer" environment. See Cornell [12] for more details.

Tagging Basis with Repair

We next propose a building tagging criterion where we allow possible upgrade or repair to the building after the mainshock. We show in Figure 4 the $ECR_{col}^{DS}(t_d; m_m)$ curves for the damaged building (damage state DS), a new intact building, and the repaired building (repaired state is denoted as R). Note that the $ECR_{col}^{R}(t_d; m_m)$ curve for the repaired building could be either above or below that of the curve for the new intact building.

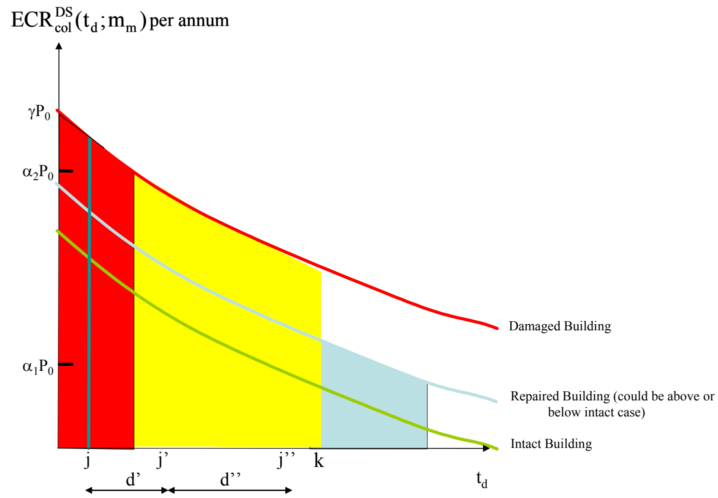

Figure 4: Tagging of a damaged building with possible repair or upgrade to the building

Again, based on the concept of the controlled working environment, emergency repair workers can enter the building from time j for d' days when the building is red-tagged, where the duration d' can be determined based on Equation (10). If building is not completely repaired to code-standard in d' days and assuming that it has been repaired to an intermediate level R', a second group of workers can work for d'' days by ensuring that:

$$ECR_{col}^{R'}(j';m_m) - ECR_{col}^{R'}(j'+d'';m_m) + ECR_{col}^{SE}(j'';m_m) \leq \alpha_2 P_0 \tag{11}$$

If repair is completed on day k (after which one should consider the $ECR_{col}^{R}(t_d;m_m)$ curve for the repaired building), normal occupants can enter the building only if

$$ECR_{col}^{R}(k;m_m) \leq \alpha_1 P_0 \tag{12}$$

If not, normal occupants can enter the repaired building only after the $ECR_{col}^{R}(t_d;m_m)$ for the repaired building has decreased to $\alpha_1 P_0$.

The proposed methodology allows us to take advantage of our knowledge of the time-varying aftershock hazard at the site and the damage state of the building to provide an appropriate tag for the mainshock-damaged building based on life-safety considerations.

WORKED EXAMPLE

To illustrate our proposed-methodology, we consider a three-story steel moment-resisting frame (SMRF) building located at the Stanford, California site. The building has a structural period equal to 0.73s. We assume that a mainshock of magnitude 7.0 has occurred on the San Andreas Fault which has ruptured the neighboring Mid Peninsula Segment. Details can be found in Yeo [2]. We assume that aftershocks can occur anywhere on the mainshock rupture zone with equal likelihood. A schematic layout of the site with respect to the mainshock rupture zone is shown in Figure 5.

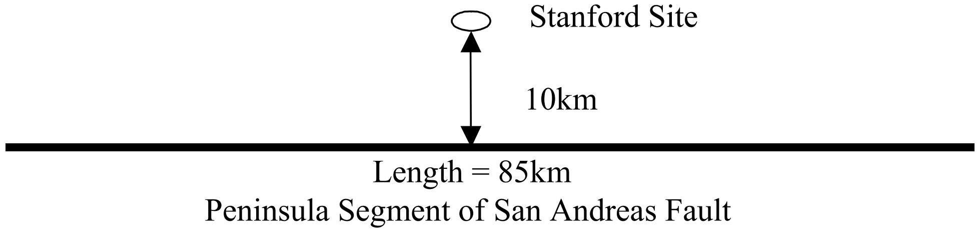

Figure 5 : Location of site with respect to mainshock rupture zone

The instantaneous daily aftershock rates are shown in Figure 6 as a function of elapsed time from the mainshock. Here, we consider aftershocks with magnitudes between 5.0 and 7.0, the mainshock magnitude. Note that, for example, the expected total number of aftershocks starting 10 days after the mainshock over a time interval of infinite length is equal to seven, i.e. the shaded area shown below in Figure 6.

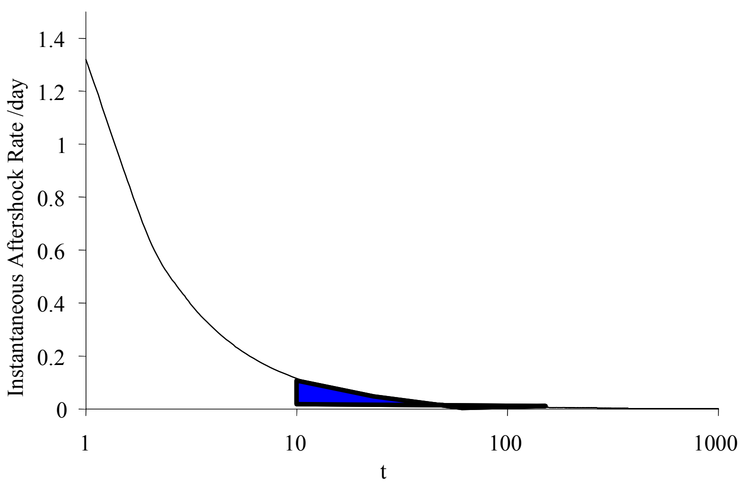

Figure 6: Instantaneous time-varying daily aftershock rate as a function of elapsed time from the mainshock of magnitude 7.0

Next, we convert the instantaneous daily aftershock rates to $ECR(t_d; m_m)$ on an annual basis by using Equation (8). In this case, we assume an inflation-adjusted discount rate of 5% per year. We plot the $ECR(t_d; m_m)$ as a function of t_d in Figure 7. In particular, the $ECR(t_d; m_m)$ 10 days after the mainshock over a time interval of infinite length is equal to 0.35 events/year, approximately equal to the product of five percent and seven.

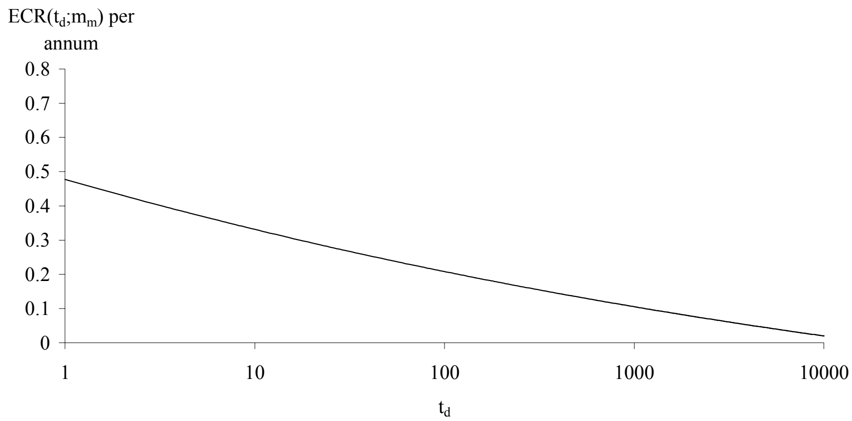

Figure 7: ECR(t_d; m_m) as a function of t_d for a mainshock of magnitude 7.0, assuming an inflation-adjusted discount rate of 5% per year

We then perform an APSHA. We are interested in evaluating the probability of exceeding any particular site Sa given an aftershock, i.e. Equation (6). The APSHA is performed for Sa with T = 0.75s, close to the structural period of our three-story SMRF building of 0.73s. The results are shown in Figure 8. Note that this function times the aftershock rate in Figure 6 gives Equation (4).

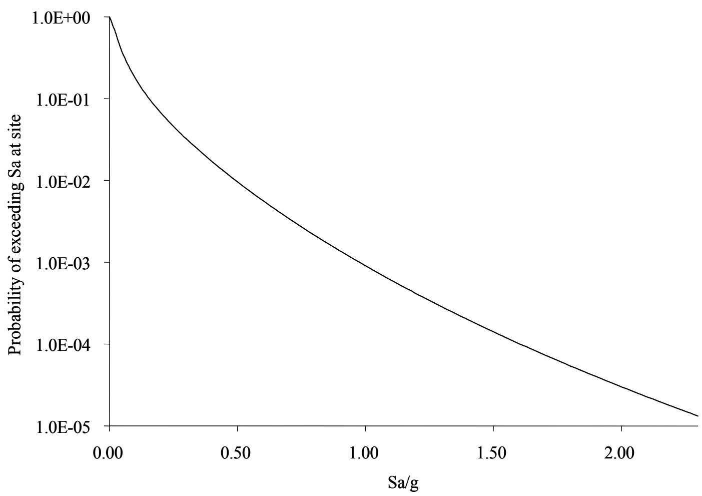

Figure 8: Probability of exceeding site Sa (with T = 0.75s) given an aftershock of random magnitude at a random location relative to the site.

We next evaluate the $ECR_{col}^{DS}(t_d;m_m)$ of the building given different initial post-mainshock damage states. Again, we note here that $ECR_{col}^{DS}(t_d;m_m)$ for a building in a particular damage state corresponds to characterizing the equivalent collapse rate of a building as a function of t_d. We consider three damage states for the building. Damage state 1, or DS1, corresponds to onset of nonlinear behavior in the building, and the median assessed Sa_{cap} to bring a building in DS1 to collapse in an aftershock is 1.4g. The median Sa_{cap} for a building in DS1 is the same as that for an intact building. Damage state 2, or DS2, corresponds to fracture of exterior beam-column connections of the first floor in the building, and the median assessed Sa_{cap} to bring a building in DS2 to collapse in an aftershock is 1.2g. Damage state 3, or DS3, corresponds to fracture of interior connections of the frame (in addition to exterior connections), and the median assessed Sa_{cap} to bring a building in DS3 to collapse in an aftershock is 1.1g. Details of the characteristics of the building can found in Bazzurro [8]. The median Sa_{cap} values are obtained by Dr. Joe Maffei of Rutherford and Chekene (Maffei [13]). The resulting annual $ECR_{col}^{DS}(t_d;m_m)$ for the three damage states are shown in Figure 9.

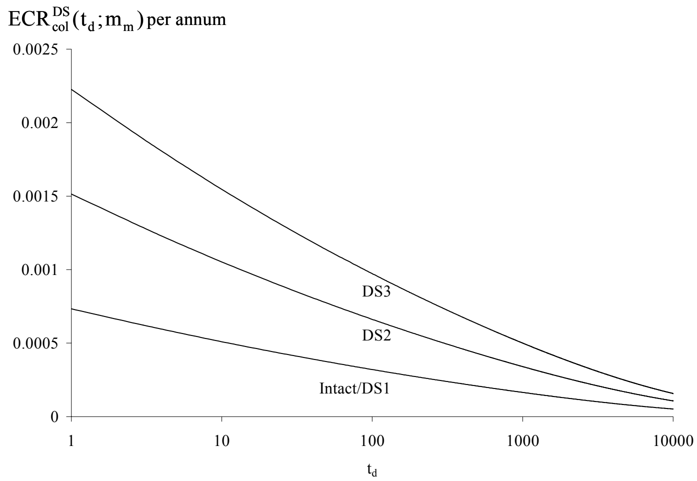

Figure 9: $ECR_{col}^{DS}(t_d;m_m)$ **for three-story SMRF progressing to collapse given different post-mainshock damage states**

We assume that the three-story SMRF building is a residential building with α_1 = 3 and α_2 = 5. Consider the case when the building is in DS3 after the mainshock. We apply our proposed building-tagging methodology to this damaged building. For P_0 = 0.0004/year (corresponding to 2% in 50 years) and assuming no repair or upgrade to the building, we can compute γ ($ECR_{col}^{DS}(1;m_m)$ normalized by P_0) to be equal to 5.56. This is greater than the α_2 value of 5. Thus, the building is red-tagged immediately after the mainshock. We need to wait for three days before the value of $ECR_{col}^{DS}(t_d;m_m)$ reduces to $\alpha_2 P_0$ and the building becomes yellow-tagged. The building only becomes green-tagged 40 days after the mainshock. See Figure 10.

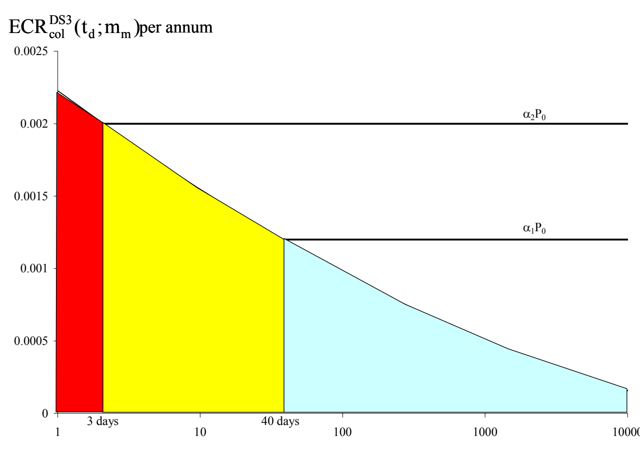

Figure 10: Tagging of damaged building in DS3 assuming no repair or upgrade

We next consider a case where we provide a controlled working environment for volunteer emergency workers so that they can enter the damaged building when it is red-tagged. We assume that the emergency workers will be relocated to a new intact building at the same site with $ECR_{col}^{Intact}(t_d; m_m)$ as shown in Figure 9 after completion of repair. We also assume for illustration that the building repair will be completed in two days. In this case, we compute $ECR_{col}^{DS3}(1; m_m) - ECR_{col}^{DS3}(3; m_m)$ and $ECR_{col}^{Intact}(3; m_m)$. The sum of the two values above is equal to 0.0009/year, less than $\alpha_2 P_0$ which has a value equal to 0.002/year. Hence, the emergency workers can enter the damaged building on day one when the building is red-tagged to complete the repair.

The longest allowable duration d^* for repair can be evaluated by trial and error by ensuring that $ECR_{col}^{DS3}(1; m_m) - ECR_{col}^{DS3}(1 + d^*; m_m) + ECR_{col}^{Intact}(1 + d^*; m_m)$ is less than $\alpha_2 P_0$.

Also, when we evaluate $ECR_{col}^{Intact}(3; m_m)$, we notice that the value of $ECR_{col}^{Intact}(3; m_m)$ is less than $\alpha_1 P_0$. This means that the building will be green-tagged three days after the mainshock if the emergency workers are able to repair the building to its intact capacity in two days.

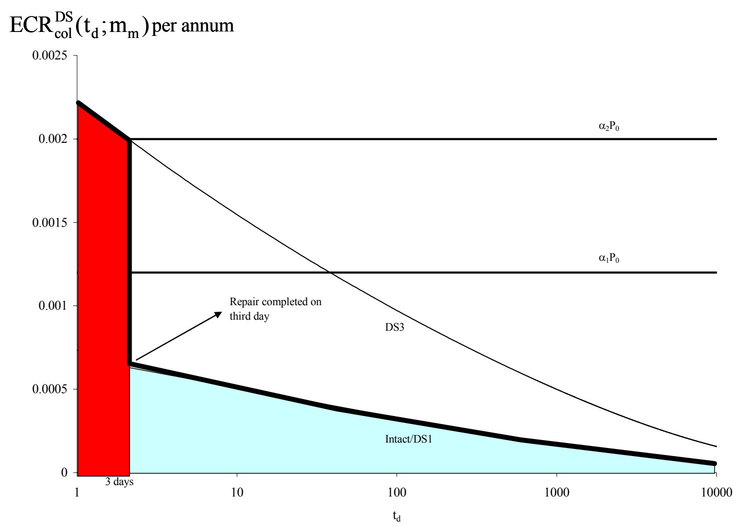

Figure 11: Tagging of damaged building in DS3 with repair

CONCLUSION

We propose a tagging methodology for damaged buildings after the mainshock based on life-safety considerations. We consider the aftershock hazard at the site in terms of possible future aftershock ground motions. The damage state of the building after the mainshock is also taken into account. The proposed methodology allows for entry into a red-tagged building after the mainshock by introducing the concept of a controlled working environment for emergency workers. Possible repair or upgrade to the damaged building can also be introduced in the proposed methodology. It is our hope that such a methodology will allow better tagging decisions to be made after the mainshock. The proposed procedure for given mainshock magnitude and damage state of the building is also used in Bazzurro [8] to assess *pre*-mainshock likelihoods of each of the potential future tagging states of the building.

ACKNOWLEDGEMENTS

This work was supported in part by the Pacific Earthquake Engineering Research Center (PEER Contract SA421) through the Earthquake Engineering Research Centers Program of the National Science Foundation under Award number EEC-9701568. The authors would like to thank Dr. Paolo Bazzurro and Dr. Nicholas Luco for their helpful comments and suggestions.

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