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Engineering the finance of earthquake risk

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ABSTRACT: The insurance industry has traditionally provided the method of hedging losses from earthquakes plus other natural and human-induced catastrophes. But in the wake of recent catastrophes the insurance industry has demonstrated that it has a limited capacity to absorb large financial losses. Thus, instead of utilising reinsurance, the global capital markets have been used in conjunction with Alternative Risk Transfer (ART) products which provide immediate access to capital for prompt recovery action. However, the pricing of these products has been mostly associated with the hazard frequency and intensity; little recognition is made of the riskiness of the structure to be indemnified. This study proposes a valuation methodology for catastrophe-linked ART products based on a four-step engineering loss model. The approach provides a more transparent method in which the risks and value can be directly linked to the characteristics of the insured portfolio of large constructed facilities. The results show a highly nonlinear relationship between the structural (strength and deformation) parameters and financial parameters.

1 INTRODUCTION

An increasingly risk-prone yet risk-averse world has necessitated the need for concerted mitigation efforts to minimize death, damage and downtime. Though life-safety remains the primary goal of the civil engineering community, it has become increasingly important to implement suitable methodologies that ensure an optimum allocation of resources to minimize the degree of loss. Moreover, when a large earthquake occurs, it is important that recovery is as rapid as possible. This is commonly impeded by a lack of immediate financial resources.

Since the 1990's, the financial consequences of natural catastrophes reached new record levels. Hurricane Andrew (1992) and the Northridge Earthquake (1994) alone respectively caused insured losses respectively amounting to some \$23 billion and \$17 billion (Mayer et al. 2009). And the recent Darfield Earthquake (2010) in Canterbury has led to losses in excess of \$4 billion which is a considerable sum for the small nation of New Zealand.

A repeat of a similar earthquake that destroyed Tokyo in 1923 may cause financial damages at the level of \$900 billion to \$1.4 trillion (Valery 1995). Such dark scenarios, although unlikely, are still feasible. These numbers are even more concerning given the fact that the balance sheets of the U.S. property liability insurers have a cumulative operating surplus of approximately \$300 billion (Cummins et al. 2002). This limited capacity to absorb large financial losses has led financiers and economists to develop alternative risk transfer products (ARTs). The two important ARTs used in post loss financing are:

1. Catastrophe bond (CAT bond), an insurance-linked security, designed to finance insurance-related losses with a transfer of the underlying insurance risks from the insurer to capital market investors,
2. Catastrophe Equity Put (CatEPut), a contingent financing instrument designed to pre-finance insurance-related losses but without a transfer of the underlying insurance risks from insurer to capital market investors.

Catastrophe (CAT)-linked ART products (such as CAT bonds and CatEPuts) can effectively be used to reduce the total cost of financing of infrastructure projects in emerging as well as in developed economies by providing an immediate inflow of cash immediately after a catastrophe when the repair and reconstruction funds are most needed. Moreover, there is a further attraction for investors: catastrophe risk tends to be uncorrelated to the typical capital market risks of interest rate and currency fluctuations. Portfolio theory holds that the addition of uncorrelated risks to an investment portfolio enhances the risk-return characteristic of that portfolio.

The occurrence of catastrophes is largely unpredictable. Thus, the valuation of ART products represents a challenge. Most current pricing models use a "black box" approach in which the losses and the claims are estimated using complex simulation models based on assumed statistical distributions and limited historical data. None of the previous studies (Loubergé et al. 1999; Lee and Yu 2002; Gründl and Schmeiser 2002; Vaugirard 2003; Cox et al. 2004; Jaimungal and Wang 2006; Chang and Hung 2009) have considered the damage potential of the underlying constructed facilities (the assets) in the valuation process. In fact, this disconnect represents a significant problem since large constructed facilities such as toll roads, power plants, railroads, and bridges create the major portion of the bill of financial losses in case of a catastrophe. These constructed facilities are uniquely built structures and their performance (and hence loss exposure) can only be captured with engineering analysis. Using only the hazard model (seismic demand) without considering the design characteristics (seismic capacity) does not realistically capture the loss potential. Therefore, more accurate "asset specific" models are needed for fair pricing of CAT-linked ART products.

The objective of this study is to propose a valuation methodology for CAT-linked ART products based on a simplified four-step engineering loss model proposed by Mander and Sircar (2009). The engineering loss model provides a solution for computation of the potential financial losses of engineered structures exposed to seismic risks; this information is then used to valuate CAT bonds and CatEPuts. This approach provides a more transparent method in which the risks and value can be directly linked to the characteristics of the insured portfolio of large constructed facilities.

2 MODELING STRUCTURAL LOSS

A four-step engineering approach can be used to estimate financial losses to the engineering structures resulting from a natural catastrophe (Mander and Sircar 2009). The four-step approach involves the following sequential tasks: (i) hazard analysis; (ii) structural analysis; (iii) damage and repair-cost analysis; and (iv) loss estimation. Each graph in Figure 1 is plotted on a log-log scale and represents the above mentioned four-step process.

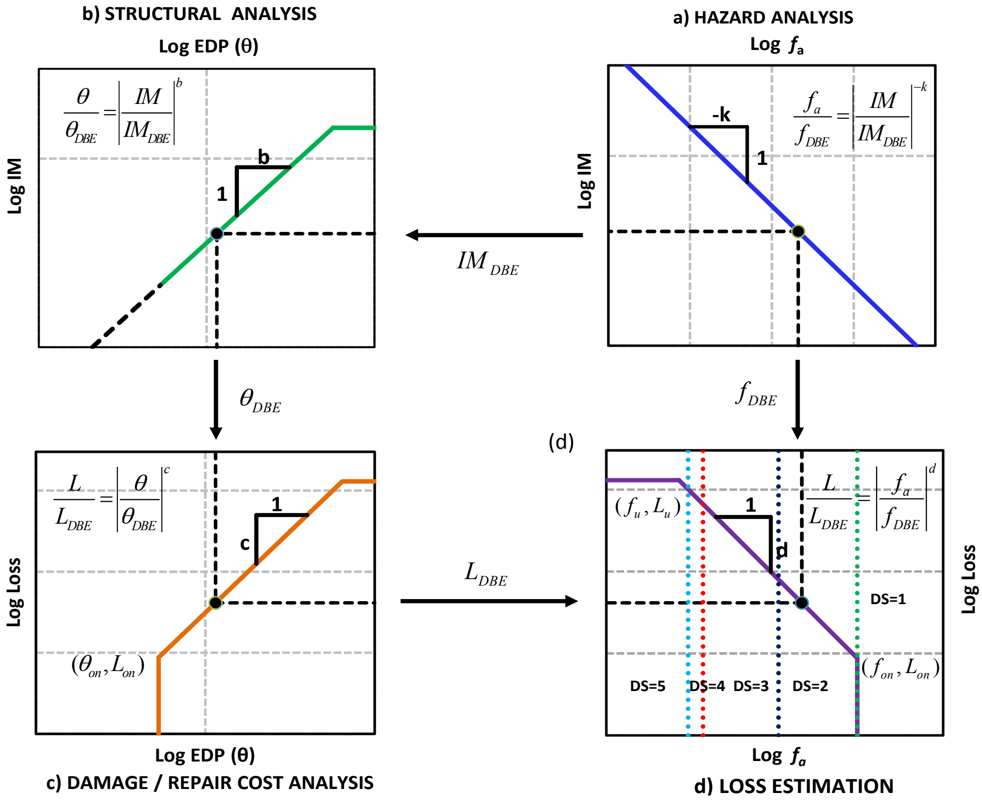

Figure 1: Four step loss estimation procedure

The four graphs are inter-related because the neighbouring two graphs (one beside and one either below or above) use axes that have the same scales. Following the arrows in Figure 1, hazard is mapped into response (a to b); response into damage and hence loss (b to c); and the loss is related back to the hazard (c to d). Each task is referenced to the design basis earthquake (DBE) and each curve plotted in the graph is a median. The damage states (DS) are defined in accordance with the well-known HAZUS descriptors as: (1) none, (2) slight, (3) moderate, (4) heavy, and (5) complete (collapse). HAZUS (1997) was the first edition of risk assessment software package built on GIS technology, used for mapping and displaying hazard data and the results of damage and economic loss estimates for building and infrastructure. Mander and Basoz (1999) developed fragility and loss models for HAZUS99. The seismic fragility curves for highway bridges used rapid analysis procedures based on the fundamentals of mechanics and dynamics with data obtained from the US National Bridge Inventory.

Structural capacities are characterized in terms of column or interstorey drifts and related to damage states (quantified in terms of loss ratios) of the structure. The expected annual loss (EAL) is given by the area under the mean loss curve derived from Figure 1d.

The mathematical expression governing the four-step model which gives mutual relation between the four graphs in figure 1 is:

$$\frac{L}{L_{DBE}} = \left|\frac{\theta}{\theta_{DBE}}\right|^{c} = \left|\frac{IM}{IM_{DBE}}\right|^{bc} = \left|\frac{f_a}{f_{DBE}}\right|^{d} \tag{1}$$

in which, L = loss (which could be either in absolute dollar terms or as a loss ratio which is the ratio of repair cost to replacement cost); θ = interstrory drift, (an engineering demand parameter, EDP, equal to the column deflection with respect to the story height); IM = intensity measure (e.g. PGA for earthquakes); f_a = annual frequency of an event, and the parameters k, b, c are exponents defined by the slopes of the curves in the respective Figures 1a,b,c, such that $d = bc/(-k)$.

Note that $L_{on} < L < L_u$ in which, L_{on} = loss ratio at onset of damage state 2; L_u = loss ratio at complete damage or toppling of structure. There is an assumed upper bound loss of L_u = 1.3 where, $L_u \geq 1$ accounts for expected price surge following a catastrophic event where contractors have to compete heavily for labour and materials. For the entire list of parameters used to develop the structural loss model, see Damnjanovic et al. (2008).

Using the four-step process, it is now possible to assess loss ratios (L) for various hazard scenarios; or to obtain a composite loss measure through calculating expected annual losses (EAL). This information is used in the following section to develop valuation methodologies for CAT bonds and CatEPuts.

3 PRICING THE RISK

3.1 CAT bond valuation model

The CAT bond is a unique class of insurance-linked securities. The structure of a CAT bond typically involves a ceding party (e.g. cedant), who seeks to transfer the risk, and investors who accept the risk for a premium. The cedant can be insurer, reinsurer, or the owner of a facility. The transfer of the risk to the capital markets is achieved by creating a special purpose vehicle (SPV) that provides coverage to the cedant and issues the securities for the investors. The cedant pays a premium in exchange for the coverage against a pre-specified event, while the SPV sells bonds to investors and collects the capital. Raised capital plus any associated insurance premiums are deposited in a trust account that receives a risk-free interest (Damnjanovic et al. 2010).

CAT bonds are typically structured as coupon paying bonds with a default linked to the occurrence of the trigger event (e.g. when losses after a devastating earthquake exceed a pre-specified level). If the trigger event does not occur during the term of the CAT bond, the investors receive their promised coupons and the principal on maturity. However, if a catastrophic event occurs and triggers defined default parameter(s) then, the raised capital residing at SPV accounts is transferred to the ceding company as promised in the bond contract (Cummins 2008).

The coupon of a bond is defined by a risk premium (spread) added to risk free rate. Spread is defined as an interest that compensates the investors for taking on additional risk (investing in a potentially defaulting entity). Therefore, the key factor in determining the value of CAT bonds is finding the spread value for the underlying risk (Damnjanovic et.al).

In the absence of systematic risk, the spread corresponds to the market implied value of the expected losses (Wang 2004). Based on this approach, well known proportional hazard (P-H) transforms are used to calculate the spread values of CAT bonds. The essential point here is that the expected losses to be transformed for considered catastrophes are obtained from the proposed structural loss model. By doing so, a direct link between the structural design parameters and the risk premium is created.

The expected losses from catastrophic events are represented by the loss exceedance (survival) curves. For a loss variable X, the survival function $S(x)$ is given by: $S(x) = P\{X > x\} = 1 - F(x)$. For non-negative random variables, the mean value of the loss variable X, $E(X)$, is obtained by integration of the survival curve over the range from zero to infinity. However, the expectation of losses does not accentuate the very nature of catastrophes, their likelihood and consequences. To account for this Wang (2004) defined the P-H risk adjusted premium (spread) of such CAT-linked contracts with potential losses as the mean of the transformed distribution:

$$\prod_{\lambda}(X) = E\left[\prod_{\lambda}(X)\right] = \int_0^{\infty} S^*(x)dx = \int_0^{\infty} Q\left(\Phi^{-1}\left(S(x)\right) + \lambda\right) dx \qquad (2)$$

The mapping $\prod : S(x) \rightarrow S(x)^*$ referred to as the P-H transform; $\prod_{\lambda}(X)$ is the risk adjusted premium where, Φ is the standard normal cumulative distribution; Q is Student's-t distribution with degree-of-freedom υ; and λ = (E[R]-r) / σ[R]) is the Sharpe ratio.

Once the transformation parameters are set, it is critical to select the survival function that gives the most accurate potential loss information for a specific type of asset. It is possible to use the developed frequency-loss curve shown in Figure 1d as the survival function for computing the spread values of CAT bond contracts. The survival function of a CAT bond can be defined as:

$$S(L) = f_L = f_{DBE}\left|\frac{L}{L_{DBE}}\right|^{1/d} \qquad (3)$$

The fair spread value of CAT bonds where the losses are tied to a particular type of structural asset can be calculated as:

$$\prod_{\lambda}(L) = E\left[\prod_{\lambda}(L)\right] = \int_0^{\infty} Q\left(\Phi^{-1}\left(f_{DBE}\left|\frac{L}{L_{DBE}}\right|^{1/d}\right) + \lambda\right) dL \qquad (4)$$

Full details of these methods have been published by the authors elsewhere (Damnjanovic et al. 2010).

3.2 **CatEPut valuation model**

The CatEPut is a modified put option contract which gives the right to the option buyer to sell a given number of his shares to the option writer at a predetermined fixed price when a specific catastrophe threshold is exceeded. The option can only be exercised after the occurrence of a qualifying catastrophe. Investors in the CatEPut option provide their capital only after a loss event, where in the case of CAT bonds the capital is made available by investors before the loss event.

For better understanding of how a CatEPut option can be used for risk management practices, consider a self-insured company with all the underlying physical assets located in a seismically active area. Further, assume that the operations of those assets create the major, if not the only source of the company revenue (e.g. toll road companies\commissions). Under these settings, a catastrophic event (e.g. earthquake) is likely to result in severe interruption in business operations and thus, a decline in equity value. For such a disaster scenario, an "asset-specific" CatEPut option could be used to provide access to additional capital for immediate repair actions in order to allow prompt recovery of the business operations, as well as to protect the equity value of the company. This scenario is not far from reality especially for industries such as energy and transportation where the major part of the revenue is generated by underlying physical assets (e.g. oil rigs, power plants, toll roads, high speed rails, etc.), and self-insurance is a common form of post-loss financing method.

The CatEPut option payoff is conditional upon two trigger events. The first trigger occurs if the market price of the equity at maturity falls below the exercise price. The second trigger relates to a specific type of catastrophe defined in the option contract that has to occur during the term of the option. Thus, the payoff of the CatEPut option at maturity can be expressed as:

$$Payoff = \mathrm{I}_{\{IM \geq IM_{tr}\}} \left(K - S_T \right)_+ = \begin{cases} K - S_T & \text{if} \quad S_T < K \quad \text{and} \quad IM \geq IM_{tr} \\ 0 & \text{if} \quad S_T \geq K \quad \text{or} \quad IM < IM_{tr} \end{cases} \tag{5}$$

in which $S_T =$ the equity price at maturity; $IM_{tr} =$ the specified level of ground shaking at site (PGA) above which the option becomes in-the-money; $\mathrm{I}_{\{.\}} =$ the indicator function where, $\mathrm{I}_{\{IM \geq IM_{tr}\}} = 1$ if $IM \geq IM_{tr}$, and $\mathrm{I}_{\{IM \geq IM_{tr}\}} = 0$ if $IM < IM_{tr}$, and K = the exercise price.

The proposed model for valuing the CatEPut assumes that the price of the option buyer's equity, *S*, is driven by a Geometric Brownian Motion (GBM) model and the loss process due to earthquakes is driven by the proposed structural loss model. The price per share of the buyer's equity while considering the drops due to a catastrophe occurrence is defined by the following stochastic equation:

$$S_t = S_0 \exp\left(-ZL_t + \sigma W_t + \left[\mu_S - \frac{1}{2}\sigma_S^{\ 2} \right] t \right) \tag{6}$$

where S_0 = the initial equity price; S_t = the equity price at time t; σ_S = volatility; μ = drift; $\{W_t : t \geq 0\}$ = a standard Brownian Motion; L_t = the loss process of the option buyer's underlying asset driven by the loss model during (0, t); and $Z \geq 0$ = the impact factor which weighs the influence of the catastrophe over the market price of the option buyer's equity.

The impact factor, Z, is left as a user-defined parameter because there are measures other than earthquake frequency and intensity that may influence the equity price. For example, the option buyer may have more than one structural asset to which the option contract is tied. In such cases the cumulative impact over the equity price differs from the impact caused by having a single asset exposed to earthquake risk. Alternatively, consider a single asset such as a bridge that connects two other toll roads. Potential damage to this bridge will disable the operations of both toll roads as well. Clearly, the bridge is vital for the continuation of the adjoining businesses and their operations. The option writer must weigh this knowledge accordingly while pricing the CatEPut.

The change in the buyer's equity price can be calculated for any potential earthquake scenarios by using the proposed loss model. Thus, the price of the CatEput option can be written for $IM_u \geq j \geq IM_{tr}$ by the Black-Scholes formula as:

$$\mathrm{E}_t^Q\left[e^{-rT}(K - S_T)_+ \right] = \sum_j (Ke^{-rT}\Phi(dj) - S_0 e^{-ZL_{DBE}\left|\frac{j}{IM_{DBE}}\right|^{-kd}} \Phi(dj - \sigma\sqrt{T})) f_{DBE} \left| \frac{j}{IM_{DBE}} \right|^{-k} \tag{7}$$

$$dj = \frac{\log(K / S_0) - rT + ZL_{DBE}\left| \frac{j}{IM_{DBE}} \right|^{bc}}{\sigma\sqrt{T}} + \frac{1}{2}\sigma\sqrt{T} \tag{8}$$

$$IM_u = IM_{DBE} \left| \frac{f_{DBE}}{f_u} \right|^{1/k} \tag{9}$$

where $j =$ PGA of the exposed earthquake; r = interest rate; and f_u = the annual frequency of the earthquake that leads to collapse.

4 INSURED FACILITY EXAMPLE WITH MANAGERIAL IMPLICATIONS

Consider, for example, self-insured Company X which owns a toll bridge located in California. Further, assume that the operations of the toll bridge create the major, if not the only source of the company revenue. Under these settings, a potential earthquake is likely to result in severe interruption in business operations and thus, a decline in equity value.

The first option that Company X considers is issuing a CAT bond to raise the necessary funds to allow for prompt repair and continuation of its businesses after the potential earthquake. In return, Company X needs to pay a fair risk premium (spread) to the investors of the CAT bond.

A Sensitivity analysis is conducted to evaluate how the engineering design parameters influence the CAT bond spread and results are presented in Figure 2. This analysis highlights an aspect of the engineering implications on financial practice. Six considered parameters showed changes markedly higher than the 5% variation, namely: IM_{DBE}, b, k, c, θ_{DBE}, and θ_c. It is possible to group these parameters to represent: the seismic hazard demand (IM_{DBE}, k); the provided structural strength capacity (b, θ_{DBE}); and the structural deformation capacity which leads to damage potential (c, θ_c).

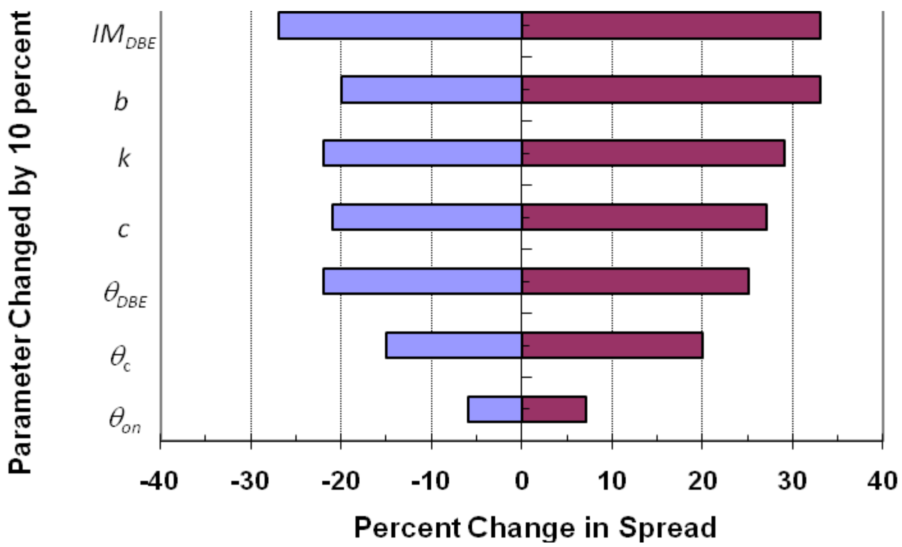

Figure 2: Sensitivity Analysis

The results depict the importance of having dependable local hazard data and specific structure behavioural models to accurately predict the expected losses and the subsequent change in risk premium. Further, the results show that specific design types and structural material characteristics may have a significant influence on reducing the cost of mitigating structural losses due to earthquakes and hence lower the CAT bond spread. In fact, the impact of structural response and damage potential parameters (θ_c, θ_{DBE}, b, and c) are essentially as important as the hazard parameter (IM_{DBE}). This is an important implication for the financial analysts that should pay special attention when evaluating CAT bond contracts tied to a specific constructed facility.

The second option for Company X is to enter a CatEPut contract. The CatEPut option has a downside of diluting the ownership in contrast to the CAT bond scenario, but has an upside of protecting the share value. The Monte Carlo Simulation method is used to predict potential equity price paths for the Company X under earthquake risk. The following market parameters are used in the simulations: $S_0 = \$100$, $r = 0.05$, $\sigma_S = 0.05$, $\mu = 0.05$. Figure 3 presents the results for 10,000 realizations; the blue lines plot the equity prices when the earthquakes do not occur, while the green lines plot the equity prices when earthquakes occur during the term of the option.

Figure 3 shows that the proposed valuation model captures the dynamic relationship between the incurred losses and the equity value process. The magnitude of the drop in equity prices varies based on the intensity of the exposed earthquake. Large (but rare) earthquakes lead to greater damage and hence losses (i.e. the drop in the equity value is correspondingly greater for these severe events).

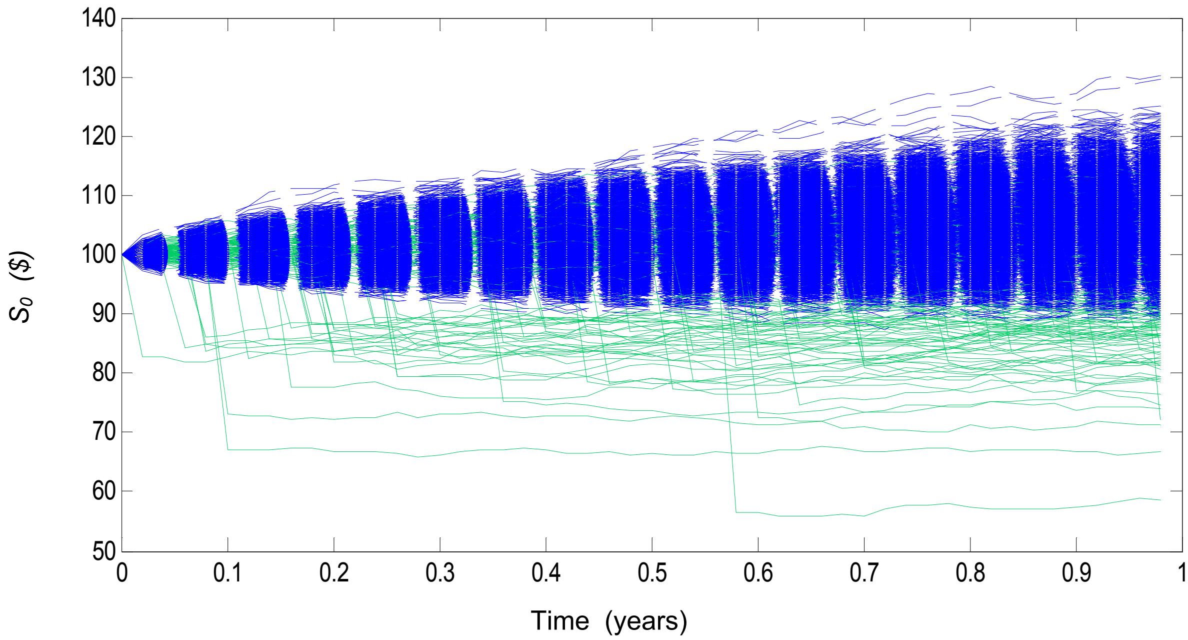

Figure 3: Dynamic relationship between the incurred losses and the equity value

Figure 4 on the other hand, emphasizes the impact of vulnerability of the underlying asset over the value of owner's equity. Here, the vulnerability is considered as the susceptibility of the bridge structures to the potential impact of earthquake hazard. The cumulative distribution function (cdf) of Company X's equity value for two cases where the underlying assets are conventionally (non-seismically) designed bridge structures, and seismically-designed bridge structures, are plotted along with the cdf of the Company X's equity value where no earthquakes occur. As it can be seen from the figure, the median drop in the option buyer's equity value for seismically-designed structures in one year due to earthquakes is at the level of 3% whereas it is at the level of 15% for a non-seismically designed structure. This is an important finding that both option buyer and option writer need to consider.

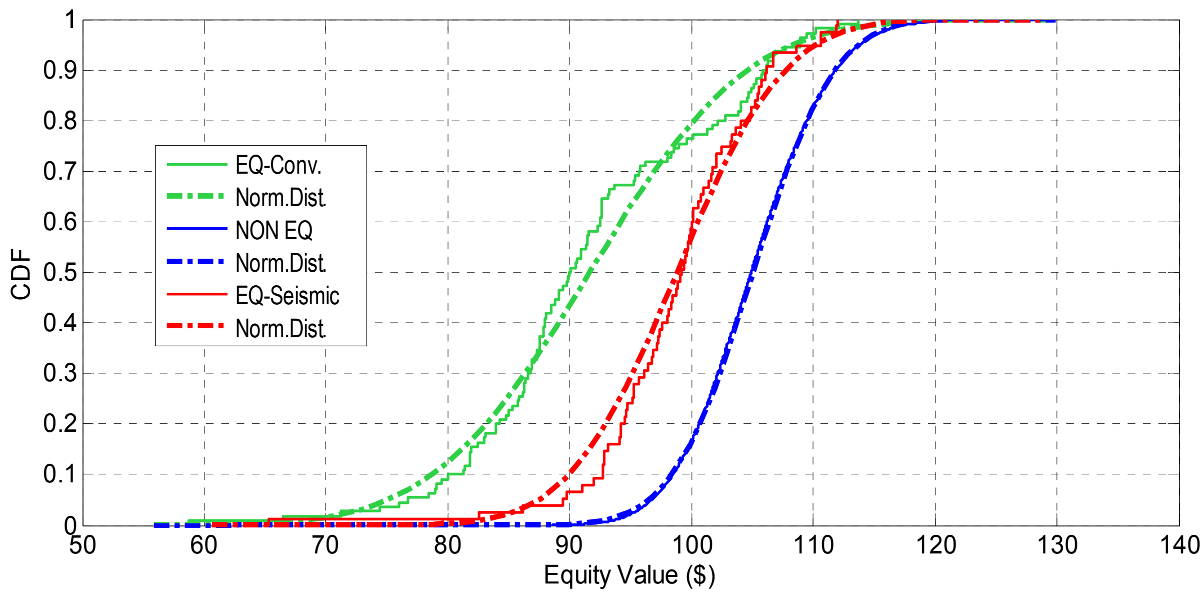

Figure 4: CDF of Company X's equity value for different structural design characteristics

5 CONCLUSIONS

This study integrates different approaches (financial, actuarial, and engineering) into one pricing framework to capture the potential losses and resulting financial consequences as accurately as possible. The proposed model suggests that engineering parameters need to be considered along with the financial and actuarial parameters when pricing structured catastrophe derivatives. The results show a highly nonlinear relationship between the structural and financial parameters and depict that specific design types and structural material characteristics may have a significant influence on reducing the cost of mitigating financial losses due to earthquakes. Further, being able to determine the value of CAT-linked ART products tied to a single constructed facility (asset) or to a portfolio consisting of particular class of structures ensures life-cycle considerations and more effective management practices for the underlying assets. This study will be further investigated and extended to account for broader types of hazards, structures, and losses (e.g. death and downtime) but at present it represents a key step forward in introducing engineering analysis for the pricing of catastrophe linked ART products.

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