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Abstract

Catastrophe bonds feature full collateralization of the underlying risk transfer and thus abandon the reinsurance principle of economizing on collateral through diversification of risk transfer. Our analysis demonstrates that this feature places limits on catastrophe bond penetration, even if the structure possesses frictional cost advantages over reinsurance. However, we also show that catastrophe bonds have important uses when buyers and reinsurers cannot contract over the division of assets in the event of insolvency and, more generally, cannot write contracts with a full menu of state-contingent payments. In this environment, segregation of collateral—in the form of multiple reinsurance companies, as well as catastrophe bond vehicles—can ameliorate inefficiencies due to reinsurance contracting constraints by improving welfare for those exposed to default risk. Numerical simulation illustrates how catastrophe bonds improve efficiency in market niches with correlated risks, or with uneven exposure of buyers to reinsurer default.

Introduction

The introduction of the catastrophe bond in the 1990s was hailed by many as the vanguard of a revolution in insurance. The optimists held that the catastrophe-linked security would follow in the footsteps of the mortgage-backed security, eventually dominating its market and connecting those desiring protection with deep,

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unexploited pools of risk-bearing capacity in the capital markets. The logic seemed straightforward. If catastrophe risks were small relative to the capital markets and were, as the available evidence suggested, uncorrelated with returns on other securities, then the cost of bearing those risks should be small. Securitization was seen as a savior for a risk-transfer market plagued by dysfunction.[1]

Not all were convinced. Catastrophe bond structures, then as now, relied on full collateralization of the underlying risk transfer and offered protection only to a single client for a limited set of perils. In this sense, the catastrophe bond represented a retreat from the time-tested concept of diversification that allows reinsurers to protect insured value far in excess of the actual assets held as collateral for clients. This seemingly inefficient use of collateral was noted by Doherty (1997, pp. 717–718) and Niehaus (2002, p. 593).

Their indictments were serious. If frictional costs (e.g., due to taxes, regulations, or agency costs) make capital and other collateral costly to hold, the risk transfer market must economize on collateral. A fully collateralized instrument (such as the catastrophe bond) obviously fails to do so. Viewed in this light, the greater puzzle lies in understanding the success the catastrophe bond has had in establishing itself in a niche within the risk transfer market, and the lesser puzzle its failure to live up to the revolutionary expectations of the 1990s.

This leads to a deeper question regarding the generally high degree of collateral segregation within the risk transfer market. From the perspective of economizing on collateral, the most efficient market structure is a single reinsurer holding collateral accessible by all potential claimants. Yet, this is far from the reality of the market, where collateral has been segregated into scores of structures—including both traditional reinsurance companies and "alternative risk transfer" vehicles, such as catastrophe bonds and sidecars. What drives the risk transfer market to segregate collateral? Under what circumstances could this segregation be efficient?

This article examines the issue of segregation by developing a theory of risk-transfer collateralization. Specifically, we study the efficient division of risk-bearing assets into reinsurance companies and catastrophe bond special purpose vehicles. Both serve as warehouses for collateral held to guarantee promises made to consumers. Our environment features two key imperfections: (1) contracting constraints that place limits on the complexity of state-contingent payments in risk-transfer contracts and (2) frictional costs associated with holding risk-bearing assets. In the absence of these imperfections, the theory supports the skeptical intuition outlined earlier. When reinsurance contracts can promise arbitrarily complex menus of state-contingent payments, and when frictional costs are identical for catastrophe bonds and reinsurer assets, the socially optimal risk-transfer mechanism features a single reinsurer. Any form of collateral segregation (whether in the form of catastrophe bonds or additional reinsurance companies) is at best redundant and more often reduces welfare.

Contracting constraints and frictional cost differences, however, can motivate the segregation of collateral. Contracting constraints are evident in the absence of detailed

[1] See Froot (2001) for discussion of the puzzling performance of the catastrophe risk transfer market.

contingencies within reinsurance contracts, especially with respect to the handling of bankruptcy. Instead of contractually specified contingent payouts, the division of assets under bankruptcy is determined by receivership laws, which distribute the assets of failed companies according to legal rules. When insureds are homogeneous and risk exposures binary (loss or no loss), simple receivership rules—e.g., a *pro rata* rule that pays all claimants at the same rate on the dollar in the event of insurer bankruptcy—may be optimal. Under the more general case of consumer heterogeneity, however, *pro rata* rules misallocate assets in the bankruptcy state[2] by failing to direct sufficient indemnification to those who value consumption the most. Some reinsurance buyers may be more exposed to default than others and may desire more security than their peers. A single reinsurer is unable to efficiently address these needs, so opportunities exist for additional vehicles to address unexploited risk transfer opportunities with pools of collateral legally distinct and isolated from the original reinsurer.[3]

Catastrophe bond structures in particular have a role to play in addressing this deficiency, because they are immune to bankruptcy risk by design. As such, they can help to reallocate indemnification in the event of reinsurer default(s). Their value in this role depends upon their frictional cost advantages over reinsurance companies. If none exist, the economic distinction disappears, and a catastrophe bond structure is simply a reinsurance company subject to a constraint of full collateralization. In other words, catastrophe bonds are at best equivalent and more likely inferior to reinsurers, in the absence of frictional cost advantages.

On the other hand, frictional cost advantages, such as those that might arise from differences in agency costs or taxation, create a unique role for catastrophe bond vehicles in the segregation of collateral. Similarly, a role for catastrophe bonds could open up if the supply of traditional reinsurance companies is fixed in the short-run, in which case the need for additional pools of collateral could be met through catastrophe bond structures due to greater ease of formation.

Regardless, the catastrophe bond must ultimately reckon with its failure to economize on collateral. Catastrophe bonds consume more collateral per dollar of coverage than reinsurers, who economize on collateral by diversifying across buyers with imperfectly correlated losses. This forfeiture of diversification opportunities acts as a headwind against catastrophe securitization as currently structured—the greater the diversification opportunities, the greater the frictional cost and bankruptcy advantages required for catastrophe bonds to take the lead in the risk-transfer market.

Numerical simulation reveals that contracting constraints create an opening for catastrophe bonds, when insureds are heterogeneous and *pro rata* rules inefficient. However, the trade-off between frictional costs and diversification opportunities governs

[2] Mahul and Wright (2003) also note the inefficiency of *pro rata* rules in the context of a model with identical consumers but generalized loss distributions.

[3] It is important to note here that although *collateral* is segregated, *consumers* of protection will not necessarily be segregated. It may be optimal for consumers to hold claims on multiple pools of collateral, rather than sorting into a particular pool that has, for example, a particular level of credit quality. Multiple vehicles help diversify risk transfer across consumers to the greatest extent possible, and help consumers hedge default risk.

the extent to which they penetrate the overall market. In particular, modest frictional cost advantages could vault catastrophe securitization into dominance within insurance market segments where diversification opportunities are few. Conversely, however, market segments with substantial diversification opportunities would require extremely large frictional cost advantages, far beyond those seen today, for catastrophe securitization to make any headway. The analysis suggests that catastrophe bond issuance will improve performance in particular niches of the risk transfer market, but widespread securitization of insurance exposures is unlikely absent dramatic reductions in the frictional costs associated with securitization.

The article is laid out as follows. The "Background and Motivation" section provides some background and context on catastrophe bonds. The "A Simple Example" section then develops a concrete two-consumer example to illustrate the intuition behind our results. The "Theory" section develops our results formally in the context of a social planning problem with N consumers. The "Empirical Implications of the Theory" section offers numerical results to illustrate the trade-offs involved. The "Other Risk Transfer Options" section discusses other strategies for protecting consumers against default and interprets them in the context of the model. In particular, it considers how collateralization clauses in reinsurance policies influence the priority of claimants under bankruptcy, and the extent to which such clauses substitute for fully collateralized instruments, such as catastrophe bonds. The "Concluding Remarks" section concludes. Finally, analytic details and derivations are presented in an online appendix, which can be found at http://healthpolicy.usc.edu/catbond101124_appendix.pdf.

BACKGROUND AND MOTIVATION

A catastrophe bond transaction centers on a special purpose reinsurance vehicle (SPV). The SPV sells securities (catastrophe bonds) to investors, and the proceeds from the sale are deposited in trust and invested. The SPV then provides reinsurance to a ceding insurer or reinsurer (i.e., an insurance company seeking to transfer risk, which we will henceforth refer to as a *cedent*), who pays a premium in exchange. The premium, as well as income earned on the trust investments (which are often swapped for either fixed or variable returns provided by a swap counterparty), funds interest payments to investors. If a contractually defined trigger event occurs, part or all of the bond principal is forfeited to the cedent; if no event occurs, the principal is returned to investors.[4] While early catastrophe bonds linked forfeiture of principal to the cedent's actual losses (an *indemnity trigger*), triggers linking forfeiture of principal to industry losses, catastrophe model output, or to specific parameters of the disaster (e.g., the strength of an earthquake centered in a certain geographic region) have grown in popularity. Some deals feature multiple event triggers—requiring two or more major disasters within a short time period to trigger principal forfeiture (see Woo, 2004).

A key institutional detail is that the entire face value of the bond is held in trust and available if the bond is triggered. Take an example \$50m bond issue. At the time of issuance, bond purchasers put up the full \$50m face value, which is held in trust. Until

[4] For more details on the structure of insurance-linked securities, see Cummins and Weiss (2009).

the bond matures, the issuer pays interest on the bond. If the contractual trigger is met, interest payments cease, and the entire \$50m bond value is paid to the issuer. In this sense, the catastrophe bond provides \$50m in coverage through a single insurance policy and is fully collateralized by the funds held in trust. As a contrasting example, consider a reinsurer that holds \$50m in claims-paying assets. This firm sells coverage to multiple cedents, with the aggregate face value of coverage ending up far higher than \$50m. The reinsurer "economizes" on collateral in the sense that its \$50m of collateral assets support a much larger face value of coverage than in the case of the catastrophe bond, where \$50m of collateral assets support exactly \$50m of coverage. This economizing is made possible by diversification—the reinsurer takes advantage of imperfect correlation among its multiple cedents to promise more in coverage than it actually holds in assets. This is the sense in which we say that reinsurance exploits diversification opportunities in coverage provision, while catastrophe bond structures, which promise coverage only to a single cedent and only to the extent of the assets held, do not. But a cedent must consider the different levels of security when choosing between the fully collateralized option of catastrophe bond issuance and the purchase of a reinsurance policy, which is subject to some risk of nonperformance due to insufficient collateral.

Most risk transfer is still in the form of reinsurance, although catastrophe securitization has grown over the past decade. Although issuance fell off in 2008 and 2009 relative to the 2007 record of \$7 billion, it rebounded strongly in the first half of 2010, and outstanding principal by mid-2010 amounted to about \$12 billion.[5] However, catastrophe bond principal is still small in comparison with the assets of the reinsurance industry despite being around for more than 15 years.[6] Thus, the catastrophe securitization market has not come close to replacing the intermediated reinsurance market, but, on the other hand, it does seem to have filled a niche within the risk transfer market.

Our assessment of the present level of catastrophe bond penetration, as well as its future prospects, hinges on two key differences between reinsurance and catastrophe securitization: (1) the different levels of collateralization discussed earlier and (2) frictional cost differences. Although reinsurers economize on collateral relative to catastrophe bond structures, it seems likely that their expenses per dollar of collateral are considerably higher. Perhaps as a result of the complexity of dealing with multiple clients, reinsurers feature much more elaborate infrastructure—in terms of corporate governance and various functions, such as underwriting and claims adjustment—than catastrophe bonds, and they also require more time to become fully operational.

Forecasts of a dominant future for catastrophe securitization inevitably postulate that securitization will be more efficient, presumably because the frictional costs associated with catastrophe bonds will eventually be significantly lower than those associated with reinsurance equity. Our analysis develops the intuition offered by Niehaus (2002)

[5] The sources for this information are the Guy Carpenter reports: *Reinsurance Market Review 2010* and *2010 World Catastrophe Report*. Figures include only publicly disclosed transactions.
[6] Standard & Poor's *Global Reinsurance Highlights, 2010 edition* tallied over \$425 billion in total adjusted shareholder funds for the industry at year-end 2009.

and Doherty (1997) and underscores the incompleteness of this argument. Assets in reinsurers support larger volumes of risk transfer by exploiting diversification opportunities within the risk transfer market. Because these opportunities are abandoned by fully collateralized structures, emerging frictional cost advantages in the latter will not necessarily translate into dominance in all segments of the market. Our numerical results in the "Empirical Implications of the Theory" section suggest that when significant diversification opportunities exist, frictional cost advantages have to be quite large for catastrophe securitization to effectively compete with reinsurance. This is not to say that it is impossible for such advantages to emerge, nor to suggest that diversification opportunities are ever abundant. The point is simply that frictional cost advantages will be offset by diversification disadvantages, and it, thus, seems likely that catastrophe securitization will encounter stronger resistance to penetration than was seen in the case of mortgage securitization.

That said, our analysis also shows that catastrophe bonds can serve an important economic role in *supplementing* the reinsurance market, as opposed to replacing it. Practical limits on reinsurance contract complexity interact with diversity of consumer risks and preferences to open up opportunities for segregation of collateral within the risk transfer market. And catastrophe bonds may serve those opportunities if they enjoy lower frictional costs associated with collateral, or if the reinsurance infrastructure is inflexible in the short run in the sense of the number of reinsurance companies being fixed.

A SIMPLE EXAMPLE

In the context of a simple two-consumer example, we illustrate how a role for catastrophe bonds depends on the presence of (1) nonzero bankruptcy risk for the reinsurer, (2) contracting constraints that prevent the insurer from optimally allocating claims payments in the bankruptcy state, and (3) heterogeneity across consumers, such that one consumer faces greater exposure to insurer bankruptcy risk.

Consider the case of two cedents, named A and B. Cedent A faces a 10 percent chance of losing \$100, while Cedent B faces a 1 percent chance of losing \$100. A reinsurer issues simple contracts to indemnify the cedents, fully or partially, in the event of a loss. In the bankruptcy state (where claims exceed reinsurer assets), claims payments are allocated according to a mechanical rule by dividing assets on a *pro rata* basis, according to the claims made by the cedents.[7]

Suppose we have \$150 in assets. How should we allocate them? Consider first the case where we use all \$150 to fund a reinsurance company, which issues a \$100 limit reinsurance policy to A and a \$100 limit policy to B. Expected claims in this example equal

$$10\% * \$100 + 1\% * \$100 = \$11. \tag{1}$$

The reinsurer is able to pay all claims in full except when both cedents suffer a loss; in that event, the reinsurer pays out all \$150 of its assets but declares bankruptcy.

[7] The exact form of the mechanical rule is less relevant than the presence of contracting constraints in the bankruptcy state.

Therefore, expected claims payments equal

$$10\% * 99\%(\$100) + 1\% * 90\%(\$100) + 10\% * 1\%(\$150) = \$10.95. \tag{2}$$

Overall, the reinsurer pays $\frac{10.95}{11}$, or better than 99 cents, on the dollar. However, Cedent B ends up being much more exposed to bankruptcy risk on a per dollar basis, because it faces a higher relative likelihood of suffering a loss in the state of the world where the other cedent *also* suffers a loss. Specifically, Cedent A expects to lodge \$10 worth of claims and to receive payments of

$$10\% * 99\% * \$100 + 10\% * 1\% * \$75 = \$9.975. \tag{3}$$

On the other hand, Cedent B expects to lodge \$1.00 worth of claims, but receive

$$1\% * 90\% * \$100 + 1\% * 10\% * \$75 = \$0.975. \tag{4}$$

Thus, Cedent A receives 99.975 cents on the dollar, while Cedent B receives only 97.5 cents.

Cedent A has better coverage than Cedent B, and we might consider redistributing coverage from Cedent A to Cedent B. One way of accomplishing this is to redeploy some of our assets in the form of a catastrophe bond tied to Cedent B. Suppose we now use \$100 to fund the reinsurance company, which sells a \$100 limit policy to Cedent A and a \$50 limit policy to Cedent B. We then use the remaining \$50 on a catastrophe bond payable to Cedent B in the event of a loss.

Cedent A still expects to lodge \$10 worth of claims, but now receives payments of

$$10\% * 99\% * \$100 + 10\% * 1\% * \left(\frac{100}{150} * 100\right) = \$9.967. \tag{5}$$

On the other hand, Cedent B now expects to lodge \$0.50 worth of claims with the reinsurance company, but now also is entitled to receive \$50 of catastrophe bond principal in the event of a loss

$$1\% * 90\% * (\$50 + \$50) + 1\% * 10\% * \left(\frac{50}{150} * \$50 + \$50\right) = \$0.983. \tag{6}$$

The recovery differential has narrowed. Cedent A now receives 99.67 cents of relief per dollar of loss, a slightly worse rate than before. With the catastrophe bond in place, Cedent B now receives a bit more—98.3 cents.

In this example, using the catastrophe bond in addition to a reinsurance company effectively transfers coverage from one cedent to the other. The transfer occurs only when the reinsurer defaults. That is, we have sufficient assets to fully indemnify both cedents *except* when both experience a loss, and the catastrophe bond allows us to affect the distribution of indemnification in that maximum-loss state of the world. Of course, the question of whether or not this redistribution is desirable depends on particulars such as preferences—but the general point is that the allocation of assets to cedents in the bankruptcy state may be suboptimal with a single pool of collateral, and the catastrophe bond is one way of securing the interests of one cedent over the other.

The presence of contracting constraints, the risk of bankruptcy, and the presence of cedent heterogeneity all play key roles in driving this result. If the reinsurer is able to write complex contracts that vary indemnification across all states of the world, there is no point in segregating collateral. For instance, in the aforementioned example, we could replicate the payoffs involved under the second (catastrophe bond) approach by capitalizing the reinsurer with \$150 and issuing policies offering full \$100 indemnification, except in the case where both cedents had losses. In this case, Cedent A would receive \$66.67 and Cedent B would receive \$83.33.[8] Contracting constraints that prevent the reinsurer from specifying such complicated priority rules under bankruptcy are necessary to preclude this possibility. Heterogeneity also plays an important role in rendering mechanical bankruptcy rules inefficient. If Cedents A and B were identical, an equal *pro rata* division of resources in the bankruptcy state would be optimal, and neither cedent would be any more exposed to default risk.

This example shows how catastrophe bonds can be used to improve social welfare by redistributing coverage among cedents in "high-loss" states of the world, but it falls short of illustrating other aspects of the general trade-off between catastrophe bonds and reinsurance. Earlier, we emphasized the costliness of fully collateralized catastrophe bonds, relative to less than fully collateralized insurance. Yet in this example, there is no disadvantage to "sequestering" assets in the catastrophe bond structure since we make full use of the collateral assets. In the general characterization of the problem explored below, an important drawback associated with the catastrophe bond is that the assets are dedicated to one cedent and not available to pay losses experienced by others.

THEORY

Our approach borrows from Borch's (1962) analysis of optimal risk sharing among many consumers. Instead of modeling individual behavior, we study the social planning problem. We thus sidestep thorny issues involved with insurance pricing in the presence of heterogeneity (see Phillips, Cummins, and Allen, 1998; Myers and Read, 2001; Zanjani, 2002). We depart from Borch's setup, however, by using a partial equilibrium framework where costly risk-bearing collateral can be provided by outside investors as well as by those engaged in sharing risks. In Borch's model, collateral was not a concern (since contract performance was not an issue), and outside investors were not present to bear risks.

[8] Note that if we allowed policy limits to exceed cedent assets, this would allow cedents to influence the division of resources in the bankruptcy state. However, this is a blunt instrument for resource allocation that cannot generally replicate the payouts of catastrophe bonds. For example, with more than two cedents, reinsurer bankruptcy is not perfectly correlated with the loss experience of any one cedent, because there are many possible loss configurations that trigger bankruptcy. Nevertheless, in the general theory developed in the "Theory" section we place no constraints on the choice of policy limits.

Environment

Consider a world with N cedents, which are insurance companies seeking to transfer risk. Cedent i is endowed with initial wealth W_i and faces the risk of experiencing a loss of fixed size—denoted by L_i. The cedents are risk averse. In the typical case where cedents are insurers or other financial institutions, risk aversion can be motivated by Froot and Stein (1998). There are two risk-transfer technologies available. First, we can use reinsurance companies that issue reinsurance policies to cedents, collateralized in each case by the assets of the reinsurer that issued the policy. Second, we can issue a risk-linked security on behalf of a cedent (i.e., a catastrophe bond) that pays off in the event that the cedent experiences a loss.

We allow as many as K reinsurance companies. We imagine K as being determined by the existing productive infrastructure in the reinsurance market; it may or may not be the socially optimal number. Into reinsurance company k, we deposit assetsA^k. Throughout our discussion, we think of "assets" as all the resources the reinsurer can draw upon to pay claims. Therefore, it includes both capital paid in by investors and premiums paid in by cedents.[9] When assets exceed claims, the residual reverts to investors. If claims exceed assets, the company defaults, and claimants are assumed to be paid according to a *pro rata* rule, with everyone receiving the same rate of recovery per dollar of claim.

We also allow each cedent to issue a catastrophe bond[10] to investors. The principal of the bond is forfeited to the cedent in the event of a loss, but not otherwise. We use B_i to denote the bond issuance of cedent i. Note that the catastrophe bond is really just a reinsurance company with a single client. However, embedded here is the notion that single-client catastrophe bond vehicles can be more easily and quickly set up than multiple-client reinsurance companies, so we do not place an *ex ante* restriction on the number of catastrophe bonds that can be issued.

Notice that this is a stylized notion of a catastrophe bond, simplified for purposes of focusing on the key collateralization issue studied in the article. We simplify matters by assuming *indemnity* triggers—where principal forfeiture is linked directly to the losses suffered by the issuer—and thus avoid the complexities of optimal trigger design (see Doherty and Mahul, 2001) and the problem of basis risk. More generally, we do not directly model costs associated with asymmetric information.[11] Given our single-period setting, we also ignore the issue of contract tenor—which is typically longer for catastrophe bonds than for reinsurance contracts and thus offers issuers more price stability than can be obtained in the reinsurance market—and, similarly, ignore any long-term motives cedents might have for establishing a securitization facility as a channel for accessing the capital markets in the future (see, e.g., Cummins and Trainar, 2009, p. 480). That said, some of these issues are captured (in an indirect

[9] For our purposes, the key issue is whether or not a given dollar is available for claims payment, not how it would be treated by accounting conventions.

[10] We refer to "catastrophe bonds" because of their familiarity, but the following analysis also applies to other fully collateralized instruments used in risk-transfer—such as collateralized reinsurance policies and "sidecars." These and other risk-transfer alternatives will be discussed in the "Other Risk Transfer Options" section.

[11] See Finken and Laux (2009) for a theoretical justification for the catastrophe bond market based on asymmetric information between insurers and reinsurers.

and nonstructural sense) in the frictional costs associated with catastrophe bond principal and reinsurance company assets described later.

What do insurance policies and catastrophe bonds cost? The cost of risk transfer can be decomposed into (1) fair *ex ante* compensation for claims expected to be paid under the risk transfer agreement and (2) frictional costs associated with establishing and maintaining the risk transfer scheme. In the absence of frictional costs, the outcome is well known—all cedents will be fully insured, and it is irrelevant how risk transfer technologies are combined in providing this full insurance. Frictional costs provide a motivation to economize on assets in the process of collateralizing risk transfer.

We start simply with a model where insurance risks are "zero beta" but where frictional capital costs exist. More specifically, we start by assuming that the cost of risk transfer amounts to the expected value of claims plus a frictional cost proportional to the amount of collateral used in the risk transfer scheme (i.e., the amount of assets used in the insurance company, or the amount of catastrophe bond principal used). We then show that these results hold even when insurance risks correlate in some way with capital market returns and thus the cost of risk transfer reflects that correlation.

Frictional costs are imagined here as deriving from agency costs, taxes, liquidity costs, or other market frictions. Each dollar of assets held in the insurance company results in per unit frictional costs of δ_A. Each dollar of catastrophe bond principal raised has the frictional cost δ_B. There are many reasons why we might expect the frictional costs associated with the two risk transfer technologies to differ. Reinsurance company assets are under the discretion of company managers, who may deploy assets suboptimally from the perspective of investors and/or consumers. Catastrophe bond principal, on the other hand, is largely insulated from the discretion of management. Moreover, the distribution of interest and the return of capital takes place at contractually specified dates, making the investment of finite duration with predictable returns. However, the protection of investors is purchased partly at the expense of cedents, who are exposed to basis risk unless indemnity triggers are used. In any case, while the micro-foundations of frictional costs are a potentially interesting topic, it is not our goal to explicitly model them here. Instead, we take as given the proposition that the two technologies have different frictional costs, and we explore the optimal structure of the risk transfer market on the basis of that assumption.

Cedents must pay for all frictional costs and fair compensation for recoveries expected from the risk transfer. We denote the portion of this total risk transfer cost allocated to consumer i as c_i.

We model reinsurance policies as simple promises of indemnification. Reinsurer k promises to pay I_i^k in the event that cedent i experiences a loss. The promised indemnity is positive but may be less than, equal to, or greater than the prospective loss. Reinsurer contracting is significantly constrained, however, in that indemnification promises cannot be made contingent on the loss experiences of other insureds. If the reinsurer is able to pay, it pays in full; if not, it defaults, and all claims are paid at the same rate on the dollar. Later, we present an example suggesting that relaxing this contracting constraint will obviate roles for catastrophe bonds or other fully collateralized instruments. In Section A of the appendix, which is available online,[12] we verify that this is in fact the case: When frictional costs are identical ($\delta_A \equiv \delta_B$), allowing the social planner to arbitrarily vary the indemnification promised in each insurance policy eliminates any potential role for catastrophe bonds.

Moreover, it is evident that this line of reasoning can be extended further. Without contracting constraints, not only is there no need for catastrophe bonds (in the absence of a frictional cost advantage), there is also no need for *any* segregation of collateral in the reinsurance industry. A single reinsurer can deliver the socially optimal outcome.

Mathematical Framework

To characterize the possible states of the world, we define a row vector $\mathbf{x}$ of length N, with the elements all taking a value of zero or one: $\mathbf{x}(i) = 1$ means that cedent i experienced a loss, while $\mathbf{x}(i) = 0$ means that it did not. Let Ω denote the set of all such vectors of length N with the elements taking values of one or zero. Each element of Ω corresponds to a complete description of one possible state of the world. The entire set Ω contains all possible such states. The following set definitions are useful:

$$\Omega^i = \{\mathbf{x} : \mathbf{x}(i) = 1\},$$

the set of all states in which agent i suffers a loss, and

$$\Gamma(\mathbf{x}) = \{i : x(i) = 1\},$$

the set of all agents that suffer a loss in state $\mathbf{x}$.

Thus, using this notation, we may describe the probability of loss faced by cedent i as

$$p_i = \sum_{\mathbf{x}\in\Omega^i} \Pr(\mathbf{x}).$$

We can now define utility for cedent i (according to the usual Von Neumann-Morgenstern assumptions) as

$$EU_i = \sum_{\mathbf{x}\in\Omega^i} \Pr(\mathbf{x})U_i\left(W_i - L_i + \sum_{k=1}^{K} f_{\mathbf{x}}^k I_i^k + B_i - c_i\right) + \sum_{\mathbf{x}\notin\Omega^i} \Pr(\mathbf{x})U_i\left(W_i - c_i\right), \quad (7)$$

where $f_{\mathbf{x}}^k$ represents the proportion of the indemnity payment promised by reinsurer k that is actually paid in state $\mathbf{x}$.

The social planning problem can now be written as

$$\max_{\{A^k\},\{B_i\},\{c_i\},\{I_i^k\},\{f_{\mathbf{x}}^k\}} V = \sum_i EU_i \quad (8)$$

[12] See http://healthpolicy.usc.edu/catbond101124_appendix.pdf.

TABLE 1
Table of Variables Used

Variable	Definition	Concept
c_i	Cedent i's cost share	Allocation of total risk transfer cost
W_i	Cedent i's wealth	Wealth
L_i	Cedent i's size of loss	Loss exposure
B_i	Cedent i's size of catastrophe bond	Bond issue in terms of consumption units
A^k	Reinsurer k's assets	Assets held by reinsurer k
I_i^k	Cedent i's policy limit	Indemnity promise by reinsurer k to cedent i
$f_{\mathbf{x}}^k$	Proportion paid by reinsurer k in state x	Rate at which reinsurer defaults
$\mathbf{x}$	$x(i) = 1$ if cedent suffers loss $x(i) = 0$ if cedent i does not suffer loss	A realization of x summarizes one state of the world
Ω	Set of all possible vectors x	Set of all possible states of the world
Ω^i	$\Omega^i = \{x: x(i) = 1\}$	Set of states where cedent i suffers loss
$\Gamma(\mathbf{x})$	$\Gamma(x) = \{i: x(i) = 1\}$	Set of cedents suffering a loss in state x
p_i	$p_i = \sum_{\mathbf{x}\in\Omega^i} \Pr(\mathbf{x})$	Probability that i suffers loss

subject to

$$[\mu] : \sum c_i \geq \delta_A \sum_{k=1}^{K} A^k + \delta_B \sum_i B_i + \sum_{\mathbf{x}\in\Omega} \Pr(\mathbf{x}) \left(\sum_{i\in\Gamma(\mathbf{x})} \sum_{k=1}^{K} f_{\mathbf{x}}^k I_i^k + \sum_{i\in\Gamma(\mathbf{x})} B_i \right) \tag{9}$$

$$[\lambda_{\mathbf{x}}^k] : f_{\mathbf{x}}^k \sum_{i\in\Gamma(\mathbf{x})} I_i^k \leq A^k, \forall \mathbf{x} \tag{10}$$

$$[\phi_{\mathbf{x}}^k] : f_{\mathbf{x}}^k \leq 1, \forall \mathbf{x} \tag{11}$$

$$[\Lambda_{\mathbf{x}}^k] : (1 - f_{\mathbf{x}}^k) \left(A^k - f_{\mathbf{x}}^k \sum_{i\in\Gamma(\mathbf{x})} I_i^k \right) \leq 0, \forall \mathbf{x} \tag{12}$$

and subject to nonnegativity constraints on catastrophe bond principal, reinsurer assets, and policy limits. Constraint 9 ensures that cedents' total payments for risk-transfer instruments ($\sum c_i$) cover the frictional costs and expected losses. Constraint 10 ensures that the reinsurer k always has enough assets on hand to cover *actual* (as opposed to promised) liabilities. Constraint 11 precludes the reinsurer from ever paying out more than the policy limit. Finally, constraint 12 ensures that each reinsurer always pays claims in full, whenever it remains solvent. Table 1 summarizes all variable definitions given to this point.

The optimality conditions are derived in the online appendix (Section B.1), as is the following marginal condition for catastrophe bond issuance (where we use the notation $U_i^{\mathbf{x}}$ to denote the utility of cedent i in state $\mathbf{x}$)

$$R_i = \sum_{\mathbf{x}\in\Omega^i} \Pr(\mathbf{x})[1 - f_{\mathbf{x}}^k]\left(\frac{\partial U_i^{\mathbf{x}}}{\partial W} - \sum_{j\in\Gamma(\mathbf{x})} w_{\mathbf{x}j}^k \frac{\partial U_j^{\mathbf{x}}}{\partial W}\right) - \sum_{\mathbf{x}\notin\Omega^i} \sigma_{\mathbf{x}}^k + (\delta_A - \delta_B)\mu \leq 0, \tag{13}$$

where $\frac{\partial U_i^{\mathbf{x}}}{\partial W}$ is the marginal utility of wealth for cedent i in state $\mathbf{x}$, and

$$w_{\mathbf{x}j}^k \equiv \frac{I_j^k}{\sum_{j\in\Gamma(\mathbf{x})} I_j^k},$$

$$\sigma_{\mathbf{x}}^k \equiv \lambda_{\mathbf{x}}^k - \left(1 - f_{\mathbf{x}}^k\right)\Lambda_{\mathbf{x}}^k,$$

where $\sigma_{\mathbf{x}}^k$ is the marginal value of reinsurer k's assets in state $\mathbf{x}$. This will be zero in states where the reinsurance company remains solvent.

Note that this condition can be expressed using any reinsurer with strictly positive assets. As shown in the online appendix, the marginal benefit associated with asset holdings is the same across all reinsurance companies (other than those with no assets). Therefore, the marginal condition for catastrophe bond issuance for cedent i can be derived with reference to any reinsurer k where $A^k > 0$ and $I_i^k > 0$ (i.e., cedent i is a client of reinsurer k).

The Social Value of Catastrophe Bonds

R_i is the marginal value of catastrophe bond issuance at the optimum. $R_i < 0$ if and only if catastrophe bonds cannot improve on a reinsurance-only equilibrium. Specifically, if R_i is negative, this means that catastrophe bond issuance was not useful (optimal) for cedent i—or, in other words, that $B_i^* = 0$. Conversely, if R_i is zero, this means that some level of catastrophe bond issuance was optimal for cedent i—i.e., that $B_i^* > 0$ at the optimum.

We start analysis of (13) by considering the case where

$$\delta_A \equiv \delta_B \equiv \delta.$$

Thus, we initially focus on how the nature of preferences and risk affect the optimal mix of the two risk transfer technologies. This reveals three noteworthy results.

First, a catastrophe bond's potential to enhance the welfare of the issuing cedent is intimately linked to the presence of default risk. If cedent i does not face any risk of default (i.e., $f_{\mathbf{x}}^k = 1$ for all $\mathbf{x} \in \Omega^i$), catastrophe bond issuance cannot be useful for that cedent.[13]

[13] This is equivalent to saying that $R_i < 0$, except in solutions where the reinsurance company never defaults on any contract. If the reinsurer never defaults, $R_i = 0$, implying that

Second, assuming cedent i is confronted with default, catastrophe bond issuance on behalf of that cedent may be useful only if her marginal value of consumption exceeds the average value of consumption for her peers, in the states where the company defaults on her claim. In other words, collateral should be dedicated to cedent i only if it is more valuable to her than to other cedents. Mathematically, this implies that

$$\sum_{\mathbf{x}\in\Omega^i} \Pr(\mathbf{x})[1 - f_{\mathbf{x}}^k] \left(\frac{\partial U_i^{\mathbf{x}}}{\partial W} - \sum_{j\in\Gamma(\mathbf{x})} w_{\mathbf{x}j}^k \frac{\partial U_j^{\mathbf{x}}}{\partial W} \right) > 0.$$

Finally, the value of catastrophe bond issuance for cedent i also depends on the extent of diversification possibilities, as captured in

$$\sum_{\mathbf{x}\notin\Omega^i} \sigma_{\mathbf{x}}^k. \tag{14}$$

This term represents the total marginal value of reinsurer k's assets across all states where cedent i does not suffer a loss. It reflects the opportunity cost—in terms of forfeited diversification opportunity—of dedicating collateral to cedent i rather than making it available to other claimants. Recall that the marginal value of reinsurer assets is zero in states where the reinsurer is solvent. Therefore, (14) is positive only if the company defaults in states where cedent i does not suffer a loss. If positive, this term does not preclude the issuance of catastrophe bonds for cedent i, but it acts as a brake on issuance. Any benefits obtained by sequestering collateral on behalf of cedent i (and, thus, shielding the assets from cedents who place lower valuations on additional coverage in those states where cedent i is exposed to default) must be weighed against the forfeited opportunity of allowing cedents exposed to default in other states of the world from accessing that collateral.

If bond principal enjoys frictional cost advantages relative to insurer assets ($\delta_B < \delta_A$), an additional motivation for catastrophe bond issuance arises through the last term in (13). Note, however, that (13) shows unequivocally that this is by no means the only consideration in assessing the potential for catastrophe bond issuance. The extent of heterogeneity across cedents—in terms of preferences and in terms of risk exposures—as well as the presence or absence of diversification opportunities, all of which feed into the other terms in the equation, must be considered.

The importance of differences across cedents is highlighted by the case where cedents are homogenous, or *ex ante* identical. The online appendix explores this in detail, showing that catastrophe bonds will not be useful in this case unless they possess frictional cost advantages. The result (shown in the online appendix, Section B.3) can be understood by noting that, assuming that symmetric solutions apply under

catastrophe bonds could figure in a solution. However, as shown in the online appendix (Section B.2), any such solution would not be unique: Without default, any solution with catastrophe bond principal can be matched by a solution without catastrophe bond principal.

homogeneity, the marginal utilities of cedents who lose will be equivalent in each state. So (13) reduces to

$$R_i = -\sum_{x \notin \Omega^i} \sigma_{\mathbf{x}}^k + (\delta_A - \delta_B)\mu \leq 0.$$

In other words, catastrophe bond issuance will be strictly suboptimal in the absence of frictional cost advantages unless diversification possibilities have been completely exhausted. In mathematical terms, catastrophe bonds are strictly welfare reducing, unless $\sigma_{\mathbf{x}}^k = 0$ for all $x \notin \Omega^i$.[14] This condition can hold only when all cedents enjoy full indemnification except in the state where everyone experiences a loss. Thus, under homogeneity, catastrophe bonds can be used only if the risk of insurer default is confined to the absolute worst-case scenario of N losses.

The N-cedent case under homogeneity exposes the disadvantage of catastrophe bonds with respect to diversification. Even when catastrophe bonds are cheaper than insurance company assets (i.e., if $\delta_B < \delta_A$), they could still be strictly suboptimal if the welfare-maximizing solution involves tolerance of default beyond the absolute worst-case scenario of N losses.

The extent of the role for catastrophe bonds is also potentially affected by the extent of reinsurance infrastructure (i.e., the number of reinsurance companies, or the size of K). As K becomes larger, it is possible to exploit more and more diversification opportunities using reinsurance. If catastrophe bonds do not possess a frictional cost advantage, reinsurance will be the preferred vehicle for exploiting such opportunities. Indeed, if K were set optimally to fully exploit the available diversification opportunities, the use of catastrophe bonds (or, equivalently, fully collateralized reinsurance companies) will be limited to extreme circumstances. If, however, K is set below the optimal level—as it might be if it were hard to adjust the number of functional reinsurers in the short or intermediate run—the use of reinsurers alone will not circumvent the inefficiency wrought by contracting constraints, and there will be additional opportunities for catastrophe bonds to improve welfare in circumstances where diversification opportunities are relatively limited. The latter characterization also describes the direction in which the catastrophe bond's role expands as frictional cost advantages are introduced, regardless of whether K is set optimally.

To this point, we have abstracted from modeling any risk premium that might be demanded by investors. The compensation owed to investors, however, will generally depend on how the insurance risks borne correlate with returns on other capital assets. Our basic findings are robust to this possibility and continue to underscore the importance of frictional costs. To our knowledge, little evidence exists connecting the cost of capital in the insurance industry to the risk characteristics of the underlying policyholder liabilities.[15] Nevertheless, there exists a theoretical connection, which

[14] Consistent with the insurance demand model of Doherty and Schlesinger (1990), the cedent has less than full coverage in the presence of default risk. By reducing the premium paid, partial coverage transfers wealth into states of the world where the company is insolvent.

[15] See Cummins and Harrington (1987) and Cox and Rudd (1991) for studies of the connection between returns on insurance liability portfolios and stock market returns. Hoyt and

we explore by allowing the cost of risk transfer to depend on the relationship between the risk transferred and the risks in the broader capital markets. We start with a state-pricing approach built on the assumption of no arbitrage, as described in the first chapter of Duffie (1992). For insurance markets to be relevant (and not redundant), it must be the case that financial markets are incomplete. Specifically, if it is possible to replicate the payoffs from an insurance policy using existing securities in frictionless markets (and if those securities are priced fairly), there will be no need for insurance policies. Therefore, we work under the assumption that markets are incomplete—or, specifically, that insurance policy payoffs cannot be replicated using other financial instruments. This is similar in flavor to the assumption underlying Mayers and Smith (1983)—tradable portfolio securities are assumed to have well-defined prices that flow from an equilibrium asset pricing model, but insurance risks are denoted as "nontradable" and thus must be dealt with separately (although, as noted by Mayers and Smith, 1983, the decisions are not independent).

A key question not addressed by Mayers and Smith (1983), but crucial for our purpose, is how insurance policies are priced when they are nontradable and cannot be replicated with other financial instruments. The obvious approach is to price insurance policies "as if" they were traded financial securities. That is, their prices are determined by their contingent payoffs, weighted by appropriate state prices—just as with any other security. The only complication is that, by assumption, the contingencies relevant for insurance policy payoffs do not map into the state space that governs the security markets—so the state prices needed to price policies will not follow from the absence of arbitrage among the financial instruments traded in the security markets. With this in mind, we extend state prices derived from the assumption of no arbitrage in the security markets to apply to subsets of events within states, scaled by the objective probability measure. While this extension is not a technical implication of arbitrage pricing theory, it yields a foundation for insurance pricing that is logically consistent with security market pricing, relying on the implicit assumption that the insurance market is small in relation to the broader capital markets.

Section C of the online appendix derives the solution in detail. There are several important lessons, which speak to the continued importance of frictional costs. In the absence of frictional costs, cedents fully insure when the insurance is fairly priced. Moreover, there is no incentive to economize on collateral in this setting—collateral is "free" in the sense that there are no frictional costs. The only "costs" with holding assets in the reinsurer or the SPV are the fair value of expected claims payments to policyholders or catastrophe bond issuers. Since there are no penalties associated with overcollateralization, neither risk transfer instrument holds a natural advantage over the other. However, if frictional costs are present, the earlier results carry through—even after the introduction of security markets and equilibrium risk pricing.

EMPIRICAL IMPLICATIONS OF THE THEORY

Our results flow from a trade-off between reinsurance's inefficiencies due to bankruptcy and its economies of collateral. This trade-off has a variety of specific aspects. To illustrate, we obtain numerical solutions for the case of constant absolute

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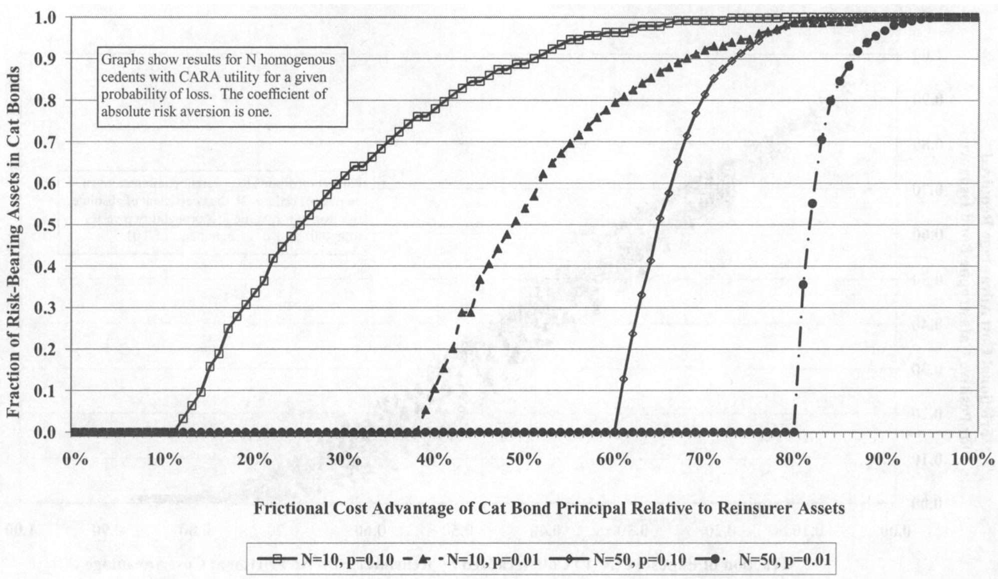
McCullough (1999) and Litzenberger, Beaglehole, and Reynolds (1996) study catastrophe losses in particular, finding them to be uncorrelated with stock market returns.

FIGURE 1
Catastrophe Bond Reinsurance as a Function of Frictional Cost Advantage



risk aversion (CARA) and show how outcomes vary with opportunities for diversification of cedent exposures, bankruptcy risk, and frictional cost differences. The simulations characterize the conditions under which bond issuance improves welfare in scenarios with a single reinsurance company ($K = 1$). We then calibrate the simulations to real-world data on frictional costs and collateralization in today's market to shed light on the prospects for widespread securitization of insurance contracts.

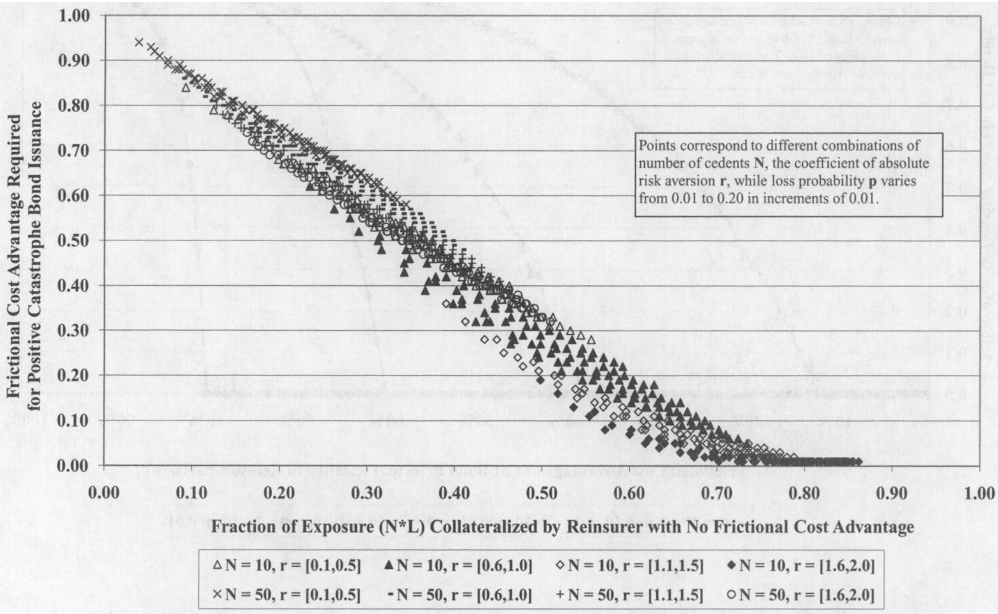
Numerical Simulations

The numerical analysis suggests that, with today's levels of collateralization and frictional cost advantages, securitization is unlikely to supplant traditional reinsurance contracts. However, it also suggests that securitization can substantially improve welfare for particular market segments subject to extraordinarily high degrees of implicit collateralization in the reinsurance market. These include segments with risks that are highly correlated and hard to diversify, along with segments where heterogeneous insureds are unevenly exposed to bankruptcy risk.

We start by studying the costs and benefits of catastrophe bonds along two key axes—frictional costs and the collateralization of reinsurance. When bonds have frictional cost advantages, they are more likely to be issued, but the size of the cost advantage necessary to stimulate issuance depends on the economies of collateral achieved by reinsurers. When frictional cost advantages are modest, catastrophe bonds have value only for segments of the market where reinsurance transfer would be heavily collateralized in the absence of catastrophe bond issuance.

Figures 1 and 2 shed light on the prospects for widespread securitization of insurance exposures. Figure 1 considers the case of homogeneous cedents, and varies

FIGURE 2
Frictional Cost Advantage Required for Catastrophe Bond Issuance as a Function of Collateralization in Reinsurance Market



(1) frictional cost advantages for catastrophe bonds (x-axis), (2) number of cedents (N), and (3) probability of loss (p). The frictional cost advantage on the x-axis represents the percentage cost advantage for catastrophe bonds. For example, a value of 40 percent implies that $\frac{\delta_A - \delta_B}{\delta_A} = 0.4$.

The figure shows that catastrophe bonds are not used in the absence of a frictional cost advantage over reinsurance company assets—as predicted by theory. As the frictional cost advantage increases, however, so does the propensity to use catastrophe bonds. Moreover, if the frictional cost advantage is large enough, catastrophe bond principal can "dominate" by comprising the majority of risk-bearing assets in the risk transfer market.

In Figure 1, the frictional cost advantage required to stimulate catastrophe bond issuance tends to rise with the number of insureds but fall with the probability of loss. For example, the case of 10 insureds and a 10 percent loss probability features catastrophe bond participation starting at a frictional cost advantage of about 10 percent and passing reinsurance when the advantage exceeds 25 percent. With 50 insureds and a 1 percent probability of loss, however, catastrophe bond participation does not even start until the advantage exceeds 80 percent. The differences in catastrophe bond usage across scenarios can be understood largely as deriving from differences in diversification opportunities—which, in turn, lead to differences in the extent of optimal level of collateralization in the reinsurance market when catastrophe bonds are not being used.

The role played by collateralization becomes apparent in Figure 2, which provides a scatter plot relating the frictional cost advantage necessary for catastrophe bond participation (the y-axis) to the extent of collateralization present in an reinsurance-only solution (the x-axis) for various combinations of N (number of cedents), p (probability of loss), and r (coefficient of absolute risk aversion).

On the x-axis is the extent of collateralization present before catastrophe bonds are introduced—i.e., it shows the fraction of total exposure $N * L$ that is covered by assets in the reinsurance company when the optimal level of asset holdings is determined in the absence of a frictional cost advantage for catastrophe bonds. The y-axis gives the frictional cost advantage required for any catastrophe bond issuance to be optimal. The points in the plot correspond to different configurations for the number of insureds (N), the coefficient of absolute risk aversion (r), and loss probabilities. The values for N and r are given in the legend; the loss probabilities range from 0.01 to 0.20.

The figure demonstrates that a high degree of collateralization within the reinsurance market reduces the cost advantage required for catastrophe bond penetration. The intuition can be grasped by imagining the polar case where reinsurance company assets completely cover total exposure, so that the risk transfer is completely collateralized. Since reinsurance has no collateralization advantage in this case, the catastrophe bond requires only an epsilon advantage in frictional costs. In circumstances close to that polar case—where the optimal collateralization level is high—diversification opportunities are limited, so catastrophe bonds do not require much of a frictional cost discount to be deployed. On the other hand, when total exposure exceeds collateral assets by a substantial margin (e.g., the upper left area of Figure 2), diversification opportunities are substantial, and catastrophe bonds are useful only in the presence of substantial frictional cost advantages.

It is important to stress that we are *not* holding the probability of insolvency constant in these simulations. The level of collateralization at the reinsurer before the introduction of catastrophe bonds (i.e., before the introduction of a frictional cost advantage) is determined by the optimization process. A low degree of collateralization indicates that a reinsurer alone was able to satisfy cedent needs with relatively small asset holdings—in the context of homogeneous cedents, this means either that diversification was effective or that cedents are risk tolerant (or both). A high degree of collateralization may mean the reverse, although this outcome could also result in practice from binding legal constraints on the minimum degree of collateralization. For example, in Figure 2, the upper left area (low collateralization in the absence of CAT bonds, high frictional cost advantage required for CAT bond usage) is populated largely by data points corresponding to the case of 50 cedents, while the lower right area (high collateralization, low frictional cost advantage required) is populated by data points corresponding to the case of 10 cedents. Diversification is obviously much less effective in the 10-cedent case, so the higher level of collateralization in the context of 10 cedents may be interpreted as a symptom of the ineffectiveness of diversification rather than an indicator of higher security. And, when diversification is ineffective, CAT bonds face a lower hurdle for usage.

Figure 2 illustrates that the degree of collateralization is a useful summary measure of these factors. Insurance market segments with higher degrees of collateralization can be expected to deploy catastrophe bonds sooner and in larger quantities than their less collateralized counterparts if and when frictional cost advantages materialize.

Model Calibration

So are we headed toward a world where individual homeowners and auto exposures are securitized and traded in the same manner as credit card receivables and auto loans? Figures 1 and 2, when applied to real world data,[16] suggest that such an outcome is highly unlikely. Specifically, we construct empirical estimates of collateralization and frictional costs for catastrophe bonds and reinsurance.

On an aggregate basis, collateralization in the U.S. property and casualty industry is less than 5 percent. AIR Worldwide Corporation has estimated total insured U.S. property exposure at $44 trillion,[17] while the total claims-paying resources of the U.S. insurance and global reinsurance industries is approximately $2 trillion.[18] Even if all these resources were dedicated to U.S. property, this yields a modest rate of collateralization under 5 percent. The actual figure would drop even further when liability and other exposures are added in. According to Figure 2, a homogenous market with this low level of collateralization would require an enormous frictional cost advantage—more than 90 percent—for catastrophe bonds to even be issued. Even our most generous estimates of the actual frictional cost advantage of catastrophe bonds do not approach this level.

As detailed in Section D of the online appendix, we estimate the annual frictional cost associated with catastrophe bond principal to be 600 basis points, while rough estimates of the corresponding frictional costs associated with reinsurance assets and with total domestic insurance industry assets to be about 1,200 and 2,000 basis points, respectively.

We think about frictional costs for catastrophe bonds as expected excess returns plus issuance costs. Excess returns are taken from estimates by Lane Financial, LLC, which estimates the average expected excess return at 535 basis points. Issuance costs are taken from the GAO; average issuance costs are estimated to be approximately 70 basis points.[19]

Frictional costs estimates of insurance and reinsurance are more difficult to construct, and we detail the construction of an estimate for the latter in what follows. The total cost is estimated as having three components. First is the cost of held capital. We derive

[16] The details supporting the empirical estimates used in this section are provided in Section D of the online appendix.

[17] AIR Worldwide Corporation (2006), *The Coastline at Risk: Estimated Insured Value of Coastal Properties*. Boston: AIR Worldwide.

[18] The claims-paying resources estimate is based on Federal Reserve estimates that total assets and capital of the domestic property–casualty industry approach $1.25 trillion and $450 billion, respectively. Offshore firms contribute at most an additional $800bn, according to the International Association of Insurance Supervisors. Details appear in Section D of the online appendix.

[19] United States General Accounting Office (September 2003), "Catastrophe Insurance Risks: Status of Efforts to Securitize Natural Catastrophe and Terrorism Risk," *Report to Congressional Requesters* (GAO-03-1033, p. 21).

this from the estimated cost of capital for property–liability insurers from Cummins and Phillips (2005), which suggests a range of 700 to 1,300 basis points. These costs are applied to estimates of total industry surplus from A.M. Best's *Aggregates and Averages* to arrive at a cost of capital. Second, we add the cost of "contributed capital," which is equal to an estimate of equity underwriting fees (5 percent) multiplied by A.M. Best's figure for contributed capital. Finally, we add reinsurer expenses from A.M. Best. The sum of these three cost components are divided by estimated "assets" for reinsurers. Broadly speaking, assets are estimated as industry capital, plus earnings from asset holdings, plus premiums written, minus dividends paid, and minus expenses.[20] This approach yields a range of frictional cost estimates from 1,050 and 1,530 basis points (the midpoint of which is rounded to 1,200 basis points), and a similar approach for the property–casualty industry as a whole yields a range of estimates from 1,870 to 2,170 basis points.

In spite of generously estimated frictional cost advantages for catastrophe bonds, diversification is so value enhancing within the overall insurance market that a widespread transition to a model where insurers originate and transfer primary exposures to fully collateralized special purpose vehicles—seems far from being cost effective.[21]

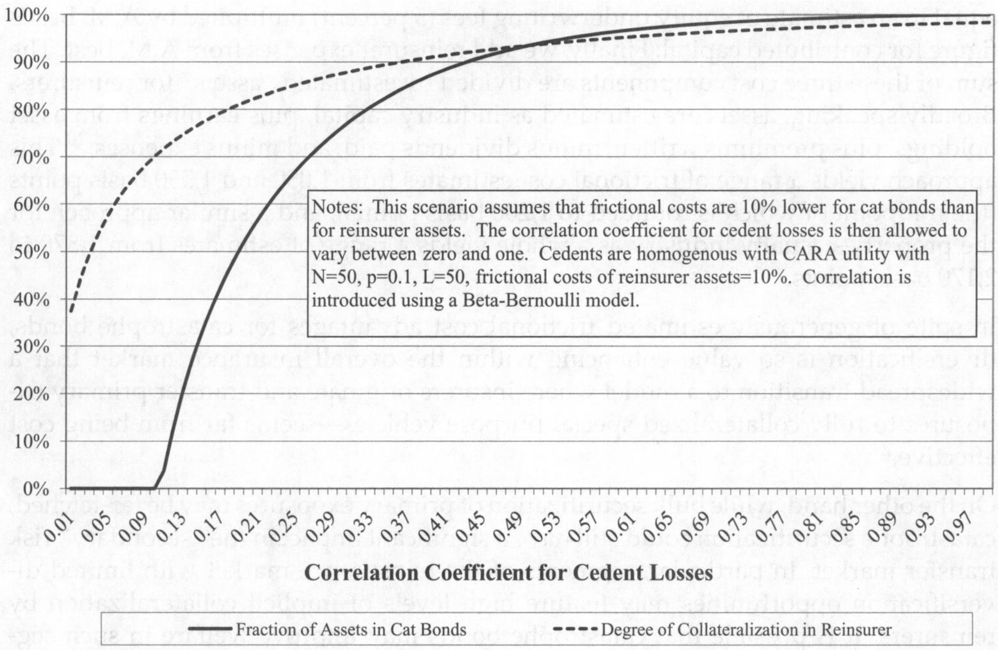
On the other hand, while bulk securitization of primary exposures may be far-fetched, catastrophe securitization could still have a significant impact in the "secondary" risk transfer market. In particular, segments of the reinsurance market with limited diversification opportunities may feature high levels of implicit collateralization by reinsurers. It is possible that catastrophe bonds may improve welfare in such segments. Figure 3 illustrates this point. Figure 3 analyzes the role played by correlated risks, which increase collateral requirements in reinsurance by reducing opportunities for diversification; the relative payoff to securitization increases as a result. We analyzed scenarios with 50 homogenous cedents each facing a 10 percent chance of losing \$50, and with a small (10 percent) frictional cost advantage for catastrophe bonds. The correlation between cedent losses is allowed to vary from zero to one. The solid line in the figure shows the fraction of assets deployed in catastrophe bonds, rather than in the reinsurance company. As the correlation rises, so does the fraction of risk-bearing assets devoted to catastrophe bonds, while the fraction devoted to traditional reinsurance falls. Catastrophe bonds comprise a majority of risk-bearing assets when the correlation approaches 0.2.

The dashed line in the figure illustrates why. This line shows reinsurer assets as a fraction of total loss exposure, in a reinsurance-only solution. It represents the degree to

[20] The online appendix provides a more nuanced and detailed description of our approach. Given the nature of our exercise, we deliberately err on the high side for these estimates. For instance, underwriting expenses for catastrophe lines might be quite a bit lower than our industry-wide average numbers. And one could also argue that our definition of "assets" is too restrictive. Thus, the frictional cost advantages estimated for catastrophe bonds should be thought of as upper bounds.

[21] Diversification opportunities abound even in catastrophe prone areas: The same AIR study estimates \$7.2 trillion of insured property in coastal areas exposed to hurricanes in the United States, a figure also far in excess of the total assets that could plausibly be reckoned to be supporting those exposures.

FIGURE 3
Correlated Losses and CAT Bond Utilization With 10 Percent Frictional Cost Advantage for CAT Bonds

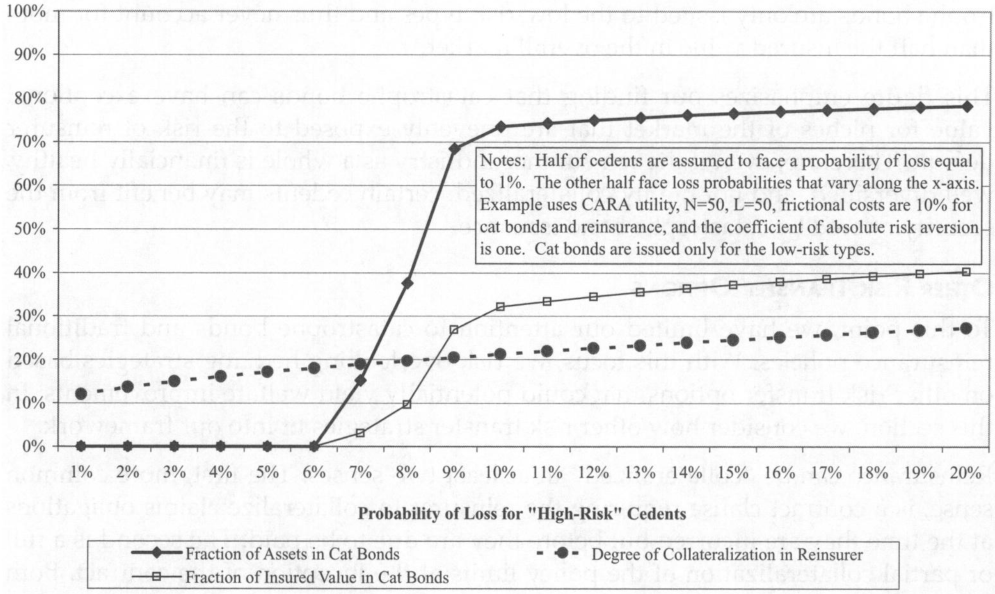


which the reinsurer is able to economize on collateral. As the correlation approaches 0.2, the reinsurer holds assets equal to 80 percent of exposure (a degree of collateralization far higher than what is observed in practice), and thus cannot be gaining much through diversification. In this example, reinsurance holds only a slight edge in collateralization over the catastrophe bond—even at modest levels of correlation. This advantage is overcome by the bond's modest frictional cost advantage.

Suggestive empirical validation of this result is provided by comparing the reinsurance prices paid by regional cedents with those of national cedents. Recent data on the cost of regional reinsurance programs most closely comparable to catastrophe bond deals[22] ranged from 300 basis points per unit of exposure in 2005 (pre-Katrina) to 450 basis points after Katrina. The comparable figures for national programs were 550 basis points and 1,300 basis points. One interpretation of these differences is that the reinsurance industry is able to effectively diversify regional risks and thus assigns (in an internal accounting sense) relatively little collateral per dollar of coverage to support the risks therein. Since little supporting collateral is assigned, the frictional costs of equity do not contribute burdensome margins to the price. National programs, however, are priced as if reinsurers assign much more collateral per dollar of coverage to them—even though they have the same expected loss as their regional

[22] The data are for regional programs (as defined by Guy Carpenter) with a 2 percent rate of expected loss per unit of exposure. Further details are presented in the online appendix.

FIGURE 4
Heterogeneous Loss Probabilities and CAT Bond Utilization



counterparts. Perhaps the national cedents are transferring risks that are no longer easily diversified with other risks—and it is in this area and those beyond it (e.g., property retrocessions) where one can start making a case that catastrophe securitization (with a 600 basis point cost) may prove to be competitive, especially during the hard markets after major disasters.[23]

Figure 4 illustrates another important case where bond issuance may be significant even in the absence of heavy collateralization within reinsurers. If particular subgroups are unevenly exposed to bankruptcy, bonds provide a direct way of securing their interests. For these scenarios, frictional costs are identical for catastrophe bonds and insurer assets. Differential exposure to bankruptcy generates a motive for bond issuance. We divide the set of cedents into two halves—one-half faces a uniform loss probability of 1 percent; for the other half, we allow the loss probability to vary along the x-axis. When loss probabilities are identical, or close to identical, no bonds are issued. However, when the "high-risk" types face loss probabilities over 6 percent, compared to 1 percent for the low-risk types, some bond issuance takes place.

The solid curve marked by diamonds illustrates the fraction of risk-bearing assets deployed in bonds, while the solid curve marked by circles gives the fraction of insured value produced by bonds. Catastrophe bonds represent a majority of risk-bearing assets when the difference in loss probability approaches an order of magnitude. At

[23] Lane and Mahul (2008) note that catastrophe bond pricing varies positively with the reinsurance cycle, although the variation appears to be less than one to one, which suggests that catastrophe bond issuance will become relatively attractive during hard markets.

this point, they also produce a majority of the insured value *for the low-risk types*. However, because they are so much more heavily collateralized than insurance (see the dashed line), they still do not produce most of the aggregate insured value. Catastrophe bonds are only issued to the low-risk types and thus never account for more than half the insured value in the overall market.

This figure emphasizes our finding that catastrophe bonds can have exceptional value for niches of the market that are unevenly exposed to the risk of reinsurer default. Therefore, even if the reinsurance industry as a whole is financially healthy, well diversified, and not highly collateralized, certain cedents may benefit from the security offered by catastrophe bond issuance.

OTHER RISK TRANSFER OPTIONS

To this point, we have limited our attention to catastrophe bonds and traditional reinsurance policies. With this focus, we risk overlooking hedging strategies based on other risk transfer options that could potentially yield welfare improvements. In this section, we consider how other risk transfer strategies fit into our framework.

Reinsurance can be "collateralized" in at least two senses. The first, more common sense, is a contract clause requiring the reinsurer to collateralize claims obligations at the time they are incurred but before they are due to be paid. The second is a full or partial collateralization of the policy limits at the inception of the contract. Both are interesting for our article, because they allow the reinsurer and its customers to influence how assets are divided up in the event of bankruptcy. We discuss each in turn.

Reinsurance contract clauses regarding the collateralization of liabilities arise in transactions between offshore reinsurers and U.S. cedents due to the state regulations governing the latter. Regulations regarding statutory credit for reinsurance typically stipulate that a cedent may take credit for anticipated recoveries from unlicensed reinsurers only if those anticipated recoveries are fully secured. Acceptable forms of security include funds held in trust and clean, irrevocable, and evergreen letters of credit issued by financial institutions deemed acceptable by the cedent's regulator.

To the extent that some cedents have these contract clauses and others do not, the clauses may be interpreted as a means of affecting the distribution of assets in bankruptcy. Secured claimants effectively "step ahead" of unsecured claimants in the liquidation process, though it should be noted that the ability to "step ahead" is by no means absolute and depends on *ex post* actions by the insurer. For example, a transfer of assets to a trust for the benefit of a cedent (or to collateralize a letter of credit issued by a third party for the benefit of a cedent) can be challenged as a voidable preference if bankruptcy follows soon thereafter.[24] Hence, in practice, a cedent cannot count on security being posted when a reinsurer is in or near insolvency, and, even if the reinsurer is willing to post security, the transfer is subject to challenge.

[24] For more details, especially with respect to letters of credit, see Hall (2000) and the NAIC's *Receivers Handbook for Insurance Company Insolvencies*.

It is also possible to provide partial or full collateralization (e.g., a letter of credit) of the policy limits at contract inception. This approach is useful if the underwriter does not have a financial strength rating. Another variation on this theme is the reinsurance "sidecar," where investors capitalize a special purpose company to provide quota share reinsurance to a cedent, with the capital being held in a collateral trust account for the benefit of the cedent.[25] In our framework, these forms of collateralized reinsurance are similar, from the perspective of collateralization, to a catastrophe bond with an indemnity trigger.

For underwriters issuing policies to multiple cedents that differ in the degree of collateralization, the situation is more complicated. Since collateral posted will presumably be released in the event that the underlying policy is not triggered, it will subsequently become available to pay claimants whose policy limits were not fully secured at inception. In our framework, this approach to collateralizing risk transfer offers the potential for welfare improvement relative to catastrophe bonds because of this increase in the availability of assets to pay claims.

In principle, varying the degree of collateralization across policies could be used to affect the allocation of assets during bankruptcy, but it is important to note the theoretical limits. Varying the degree of collateralization associated with policies will generally give the reinsurer only limited control over the allocation of assets in bankruptcy. With multiple cedents, there are multiple possible bankruptcy scenarios, with different cedents making claims in different scenarios. Given a multiplicity of scenarios, it may not be possible in general to achieve an arbitrary schedule of asset allocation within bankruptcy simply by varying *ex ante* collateral levels.

Practical limits also apply, as the effective exposure to default will not be transparent to the cedent. To form an expectation of relative priority in bankruptcy, one must know all the details about the collateralization of other policies. Furthermore, in a world where claims are being submitted in continuous time, the reinsurer will not be able to commit all of its assets to *ex ante* collateralization, since it would have no funds available beyond the collateral supporting any given policy to pay a claim on that policy.

CONCLUDING REMARKS

Our model offers an explanation for the segregation of collateral within the risk transfer market. Contracting constraints prevent reinsurers from allocating assets efficiently in the event of insolvency. Segregation of collateral into legally distinct reinsurance companies and/or catastrophe bond SPVs can mitigate this inefficiency. Numerical simulation illustrates that catastrophe bonds are unlikely to make major inroads into the larger insurance markets, but that they will have important uses in markets with highly correlated risks, and in markets where cedents are unevenly exposed to default risk.

[25] For more details, see Murray, A., 2006, "Reinsurance Side-Cars: Going Along for the Ride," *Special Comment*, Moody's Investor Service. From the perspective of the cedent, the main difference between the sidecar and the catastrophe bond is the capped quota share nature of the sidecar reinsurance contract, in which the sidecar takes a percentage of the both the premiums and losses generated by the ceding insurer (with losses "capped" by the resources of the sidecar's trust account).

Some expect more. The success of asset-backed securitization—especially mortgage securitization—fueled predictions of a similar revolution in catastrophe risk transfer. Though the revolution has yet to materialize, optimists cite the surge in catastrophe securitization after Hurricane Katrina, as well as the gradual development of mortgage securitization[26] in the 1970s, as evidence that revolution may still be in the offing. Is the catastrophe bond the next mortgage-backed security?

Even apart from the recent chaos in the debt markets, our analysis suggests problems with the analogy. If securitization conquers the catastrophe risk transfer market, the conquest will be supported on fundamentals different from those apparent in the mortgage market today. The catastrophe bond's current reliance on full collateralization serves as an impediment to deep market penetration, one that can only be overcome by substantial frictional cost advantages, far beyond those observed in today's marketplace. On the other hand, our analysis suggests that catastrophe bonds will have a role in circumstances where diversification opportunities are relatively limited—especially if reinsurance infrastructure is costly to build or difficult to adjust in the short run.

Our work suggests several areas for future empirical research. First is the empirical prediction that market segments with a high degree of reinsurance collateralization should also be the ones with the greatest catastrophe bond penetration. As a related matter, the availability of catastrophe bonds should boost rates of coverage in such markets. Second is the empirical prediction that catastrophe bond usage is most likely for those cedents with significant exposure to reinsurer default risk. These predictions should be tested in a variety of settings, as this helps identify areas of the market where catastrophe bonds are likely to generate the most social value.

From a theoretical point of view, our research suggests a link between the segregation of assets into multiple reinsurers, and into different kinds of insurance vehicles with different degrees of collateralization. Future work should continue to unify the theory that determines the number of reinsurers, their degree of collateralization, and the number of types of insurance vehicles in the marketplace. An issue that also deserves further attention is investor demand for catastrophe bonds and its determinants. We incorporated this portfolio aspect into our model, but it should continue to be incorporated into a unified theory of how the reinsurance market should be structured into multiple firms and vehicles. Finally, we abstracted from a number of issues relevant to catastrophe bonds, such as optimal trigger design and duration; these also merit integration into a theory of reinsurance structure. Trigger design itself raises other trade-offs that distinguish catastrophe bonds from reinsurance, such as different incentives for underwriting and moral hazard.

Catastrophe bonds clearly have a role to play in the broader market for risk transfer, even if they are unlikely to displace reinsurance. Our study has taken steps toward deepening that understanding, which also provides insight into the socially optimal structure of reinsurance arrangements.

[26] According to the Federal Reserve's *Flow of Funds of the United States*, about 11 percent of single-family residential mortgages (in value terms) had been securitized by the end of 1980. This figure rose above 50 percent in the mid-1990s.

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