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Abstract:
Stress testing has recently become a critical risk management and capital planning tool for large financial institutions and their supervisors around the world. However, the one prior U.S. experience tying stress test results to capital requirements was a spectacular failure: The office of Federal Housing Enterprise Oversight's (OFHEO's) risk-based capital stress test for Fannie Mae and Freddie Mac. We study a key component of OFHEO's model—the performance of 30-year fixed-rate mortgages—and find two key problems. First, OFHEO left the model specification and associated parameters static for the entire time the rule was in force. Second, the house prices stress scenario was insufficiently dire. We show how each problem resulted in a significant underprediction of mortgage credit losses and associated capital needs at Fannie Mae and Freddie Mac during the housing bust.

JEL Classifications: G21, G23, G28
Keywords: bank supervision, stress test, model risk, residential mortgages, government-sponsored enterprises

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1 Introduction

In the aftermath of the global financial crisis, policymakers in the United States and elsewhere have adopted stress testing as a central tool for supervising large, complex financial institutions and promoting financial stability (Bank for International Settlements, 2009, 2010).[1] This trend started in February 2009, when then U.S. Treasury Secretary Timothy Geithner unveiled the Supervisory Capital Assessment Program (SCAP), which was principally based on a stress test of the 19 largest U.S. banking organizations with more than $100 billion in total assets, in an effort to restore confidence in the U.S. financial sector. The SCAP was widely viewed as credible and as having reduced uncertainty about the financial strength of covered institutions (Bernanke (2010); Tarullo (2010); Peristiani, Morgan, and Savino (2014)).[2] Based on this success, the Federal Reserve institutionalized the use of supervisory stress tests for establishing minimum capital standards in 2010 through its now annual Comprehensive Capital Assessment and Review (CCAR) for the same large banking organizations.[3] Shortly thereafter, the Dodd-Frank Act mandated stress testing of all banking organizations with more than $50 billion in total assets, as well as "systemically important nonbank financial institutions" designated by a newly established Financial Stability Oversight Council.

The introduction of supervisory stress testing requirements may confer substantial benefits, such as enhanced risk measurement and management at covered financial institutions as well as supervisory learning about the firms and system-wide vulnerabilities. But such tests are vulnerable to model risk, arising from: stress scenario design, data, empirical model specification, estimation frequency, forecast horizon, and treatment of future business. Indeed, the one pre-crisis attempt by U.S. supervisory authorities to use stress testing to

[1] Despite its recent surge in popularity, stress testing is not a new risk management practice, as large banks in the United States and Europe have reported conducting such tests for many years for individual business lines (Committee on the Global Financial System, 2001). The International Monetary Fund also conducts financial system-wide stress tests for individual countries as part of its Financial Sector Assessment Program. For details, see: http://www.imf.org/external/NP/fsap/fsap.aspx.

[2] Critical to the perceived credibility and success of SCAP was the fact that financial institutions that were found to have capital shortfalls and were unable to raise the required capital in private markets were eligible to receive such funding from the U.S. Treasury through the Capital Assistance Program (part of the Troubled Asset Relief Program, or TARP).

[3] In the CCAR, covered banking organizations must be projected to maintain a ratio of Tier 1 common equity to total assets of at least 5 percent throughout a nine-quarter stress horizon. This requirement is in addition to satisfying the three standard capital adequacy targets post-stress: (1) a Tier 1 capital ratio of 4 percent; (2) a total capital ratio of 8 percent; and (3) a Tier 1 leverage ratio of (generally) 4 percent.

measure capital adequacy was, by all accounts, a spectacular failure. We are referring here to the risk-based capital stress test for Fannie Mae and Freddie Mac—the two government-sponsored enterprises (GSEs) that are central to the U.S. housing finance system.[4]

The Federal Housing Enterprise Safety and Soundness Act of 1992 created the U.S. Office of Federal Housing Enterprise Oversight (OFHEO) as the supervisor of Fannie Mae and Freddie Mac, and charged the new agency with developing a risk-based capital regulation based on a stress test.[5] OFHEO took almost a decade to develop the underlying modelling framework and finalize the regulation. But when operationalized in 2002, the OFHEO stress test was hailed as "state of the art," and prominent economists concluded that if Fannie Mae and Freddie Mac could meet the standard, their risk of insolvency was "effectively zero" (Stiglitz, Orszag, and Orszag (2002)).

Fannie Mae and Freddie Mac both maintained capital well in excess of the risk-based supervisory standard for the 24 quarters that the rule was in force (through June 30, 2008). Unfortunately, as we demonstrate below, OFHEO's stress test failed to detect the growing risk and ultimate financial distress at Fannie Mae and Freddie Mac, as mortgage market conditions deteriorated in 2007 and 2008. On September 6, 2008, Fannie Mae and Freddie Mac were both deemed insolvent and placed in federal conservatorship; the two GSEs ultimately received $187.5 billion from the U.S. Treasury (see Frame et al. (forthcoming), for a detailed discussion).[6]

In this paper, we study the sources of failure with OFHEO's risk-based capital stress test of Fannie Mae and Freddie Mac. We focus on a key component of the stress test: estimates of the performance of single-family, 30-year fixed-rate mortgages. We choose this area of focus because these mortgage contracts represented about 75 percent of the combined book-of-business at Fannie Mae and Freddie Mac and accounted for most of the losses at the two GSEs during the housing bust. Furthermore, large, loan-level datasets are available to

[4]As of June 30, 2008, Fannie Mae and Freddie Mac collectively held or guaranteed about $5.2 trillion of U.S. home mortgage debt. By law, Fannie Mae and Freddie Mac operate exclusively in the secondary mortgage market by: (1) issuing credit guarantees on mortgage pools (securitization), and (2) engaging in leveraged investment in mortgage loans and mortgage-backed securities.

[5]The 1992 legislation also subjected Fannie Mae and Freddie Mac to minimum leverage capital requirements of 2.50 percent for on-balance sheet assets and 0.45 percent for off-balance sheet credit guarantees.

[6]For many years, market participants, policymakers, and academics recognized that Fannie Mae and Freddie Mac benefitted from a market perception of a federal guarantee of their so-called Agency debt and Agency mortgage-backed securities that, in turn, markedly lowered their funding costs. Several studies seek to measure such GSE benefits, including: Congressional Budget Office (2001); Ambrose and Warga (2002); Nothaft, Pearce, and Stevanovic (2002); Passmore (2005); and Lucas and McDonald (2006).

estimate mortgage performance and a well-developed research methodology exists for model specification.

Our analysis uncovers two key problems with the implementation of the OFHEO stress test. The first pertains to model estimation frequency and specification. During the seven years that OFHEO's risk-based capital stress test was in force, the supervisor neither re-estimated the mortgage default and prepayment forecasting model nor introduced new variables, despite well-documented changes in mortgage underwriting practices during this time. The parameters of the model were estimated using data on mortgages originated between 1979 and 1997, and were then applied to mortgage performance data between 2002:Q3 and 2008:Q2. One potential reason for this static approach was that OFHEO was required by law to fully disclose the stress test model and went so far as to publish all stress scenarios, empirical specifications, and parameter estimates in the Federal Register. Hence, it would have been administratively cumbersome to make any material changes to the underlying models.

As a starting point, we use the published model specification and parameters of OFHEOs 30-year fixed-rate default and prepayment forecasting model, provided in the risk-based capital regulation, to construct a quarterly time-series of default forecasts over the period 2000–2010. We then compare these forecasts to realized outcomes over the same period and find that OFHEO's model did a very poor job of predicting mortgage defaults. Indeed, realized defaults during the crisis period were approximately 4–5 times those predicted by OFHEO's model.

To establish what would have happened if OFHEO had updated their model, we engage in some reverse engineering. During the relevant period, Fannie Mae and Freddie Mac did not provide loan-level data on the mortgages they purchased or guaranteed. Hence, we use a large, commercially available dataset that identifies loans acquired by the two institutions and is representative of their overall book of business. We then re-estimate the OFHEO model parameters on a quarterly basis, using a rolling sample, and compare the associated mortgage default forecasts with those produced by the original OFHEO model. We show that simply updating the model dramatically improves the default forecasts. Unlike the static OFHEO model, the updated model generates a substantial increase in expected defaults, starting in 2005. We then augment the OFHEO model specification with variables understood in the literature to affect mortgage performance, such as credit scores and loan documentation, and re-estimate at a quarterly frequency. This further improves forecast accuracy.

With these three sets of forecasts, we implement OFHEO's 10-year stress test in order to determine how the GSEs' risk-based capital requirements for the credit risk associated with 30-year fixed-rate mortgages would have evolved. OFHEO's static model implied that the statutory minimum capital requirement for GSE credit guarantees (45 basis points) would have been adequate through 2008:Q2—precisely when the federal government declared Fannie Mae and Freddie Mac insolvent. By contrast, a continually updated model with additional covariates would have identified capital deficiencies a year earlier.

The second problem pertains to the choice of house price stress scenario. OFHEO's adverse house price scenario (a peak-to-trough decline of 11 percent) was significantly less stressful than what actually transpired during the recent housing bust (a peak-to-trough decline of 18 percent). Perhaps more concerning is that OFHEO's adverse house price scenario assumed that housing values would actually *increase* over the first 10 quarters of the stress test—a period when new mortgages are at an increasing risk of default (for example, Deng, Quigley, and Order (2000); Danis and Pennington-Cross (2008)). We find that if OFHEO had, counterfactually, used the actual post-2006 U.S. experience as a house price stress and the updated 30-year fixed-rate mortgage performance model with additional covariates, it would have been apparent at the end of 2006, almost two years before the conservatorships occurred, that Fannie Mae and Freddie Mac were insufficiently capitalized for this risk.

Importantly, the fact that the actual house price scenario was worse than the stress scenario does not necessarily imply that the stress test was flawed. If one were to choose a sufficiently extreme scenario such that Fannie Mae and Freddie Mac could never fail, the ex post benefits of financial stability might well fall short of the costs. Therefore, the fact that the stress scenario was "not bad enough" should be interpreted as an explanation for why the two GSEs failed despite the existence of the test, and not as an indictment of the test itself.

Finally, our analysis highlights a potential problem with one of the key structural assumptions of the OFHEO stress test: "no new business." This meant that stress test was only applied to mortgages held by Fannie Mae or Freddie Mac at the time the test was run—and did not account for loans expected to be made in the future. This assumption clearly limited the usefulness of the stress test as a barometer of the GSEs' future health under adverse economic conditions. As our analysis shows, the stress test indicated that Fannie Mae and Freddie Mac had sufficient capital to withstand a major decline in house prices until just prior to their failure. This was clearly wrong—because the GSEs were principally sunk by mortgages originated in 2007 and 2008. Nevertheless, adding new business to the stress test is not a trivial task because it requires critical assumptions about the amount, composition, and risk characteristics of the new mortgages. Policymakers debated whether or not to do so when developing the OFHEO model in the 1990s and concluded that the costs outweighed the benefits.

The remainder of the paper is structured as follows. Section 2 provides background information about the OFHEO risk-based capital stress test, including the 30-year fixed-rate mortgage default and prepayment models. Section 3 discusses the data and general empirical framework. Section 4 conducts an evaluation of the forecasting performance of the original OFHEO mortgage model and then shows how parameter updating and the addition of key underwriting variables would have improved mortgage default forecasts. In Section 5, we evaluate the effect that these changes to the model would have had on the risk-based capital requirements for Fannie Mae and Freddie Mac. Here, we also point out some shortcomings with OFHEO's treatment of house price stress. Section 6 discusses constraints faced by OFHEO that may have limited their ability to update their stress test. Section 7 offers concluding remarks.

2 Background: The OFHEO Risk-Based Capital Stress Test

The Federal Housing Enterprise Financial Safety and Soundness Act of 1992 (the 1992 GSE Act) created a two-part regulatory structure for Fannie Mae and Freddie Mac. Mission regulation was to be conducted by the U.S. Department of Housing and Urban Development (HUD), while safety-and-soundness regulation was to be conducted by a new regulatory agency within HUD called the Office of Federal Housing Enterprise Oversight (OFHEO).

The 1992 GSE Act subjected Fannie Mae and Freddie Mac to two separate capital requirements to be enforced by OFHEO: a minimum capital requirement set by statute and a risk-based capital requirement based on the outcome of a stress test. The statutory minimum capital requirement was set at 2.5 percent of on-balance sheet assets plus 0.45 percent for off-balance sheet credit guarantees. The risk-based capital requirement was to be based on a stress test constructed by OFHEO, but subject to certain statutory requirements. According to the law, OFHEO was to ensure (on a quarterly basis) that Fannie Mae and Freddie Mac could maintain positive capital throughout a 10-year period of stressful credit and interest rate conditions plus an additional 30 percent for management and operations risk. The law further dictated two important parameters of the risk-based capital stress test related to interest rate and credit risks.

In terms of interest rate risk, the 1992 Act specified two stress scenarios for the 10-year U.S. Treasury constant maturity rate (CMT). The first scenario involves the 10-year CMT rate falling by the lesser of 600 basis points (bps) below the average yield during the nine months preceding the stress period, or 60 percent of the average yield during the three years preceding the stress period, but in no case to a yield less than 50 percent of the average yield during the preceding nine months. The second scenario has the 10-year CMT rate rising by the greater of 600 bps above the average yield during the nine months preceding the stress period, or 160 percent of the average yield during the three years preceding the stress period, but in no case to a yield greater than 175 percent of the average yield during the preceding nine months.[7]

In terms of mortgage credit risk, OFHEO was to identify a "benchmark loss experience" based on the worst cumulative credit losses experienced by loans originated during a period of at least two consecutive years in contiguous states comprising at least 5 percent of the U.S. population. Loans originated in Arkansas, Louisiana, Mississippi, and Oklahoma (ALMO) in 1983 and 1984 were identified by OFHEO. The mortgage credit risk element of the stress test was to then be "reasonably related" to the benchmark loss experience. This was done through adjustments to mortgage performance models as well as through the assumed path of house prices during the 10-year stress test horizon.

[7] OFHEO implemented the prescribed interest rate stress in the following way. For the 10-year stress period, OFHEO assumed that in both interest rate scenarios the 10-year CMT changes in 12 equal monthly increments from the starting point (the average of the daily 10-year CMT yields for the month before the stress period) and stays at the new level for the remaining nine years of the stress period. OFHEO also established the relevant U.S. Treasury yield curve for the stress period in relation to the prescribed movements in the 10-year CMT. In the down-rate scenario the yield curve was assumed to be upward sloping during the last nine years of the stress period, while in the up-rate scenario the yield curve was flat during the last nine years of the stress period. All other interest rates were set as the ratio of their average relative to the comparable CMT for the two years prior to the stress period.

The general approach of the OFHEO stress test with respect to mortgage performance (and hence mortgage credit risk) involved four principal steps. The first was the specification and estimation of statistical models of mortgage default and prepayment for different products. Second, adjustments were made to the statistical models to assure a reasonable relationship to the benchmark loss experience.[8] Third, for the risk-based capital calculation in any particular quarter, contemporaneous mortgage data were run through the fitted and adjusted models to construct 10-year quarterly forecasts of expected default and prepayment probabilities, assuming that house prices followed the path of the West South Central Census Region between 1984 and 1993.[9] This was done twice, once for the "up-rate" interest rate scenario and once for the "down-rate" interest rate scenario. Finally, 10 years of quarterly conditional cash flows were projected, with the fraction of the pool's unpaid principal balance estimated to be current, prepaid, and defaulted, in each period. Estimated losses were then calculated for those loans that defaulted. Importantly, the OFHEO risk-based capital stress test assumed no new business, so only mortgages that were held or guaranteed by the GSEs at the time of the stress test were considered. As we show below, this "no-new-business" assumption had important implications for the risk-based capital requirements and the usefulness of the stress test as an early warning signal of GSE financial distress.

OFHEO promulgated its risk-based capital rule for Fannie Mae and Freddie Mac in three steps. There was a First Notice of Proposed Rulemaking (June 1996), which addressed the methodology for identifying the benchmark loss experience and specified the use of OFHEO's Census Division house price indices (HPI) to update original loan-to-value (LTV) ratios for loans held by Fannie Mae and Freddie Mac.[10] A Second Notice of Proposed Rulemaking (April 1999) outlined the remaining specifications of the stress test.[11] The final risk-based capital rule, which included several changes from the proposals, was issued in 2001 and

[8]The adjustments were made to the estimated loan-to-value parameters and are discussed in further detail in the online appendix.

[9]For computational simplicity, before estimating the model, OFHEO aggregated the loan-level data into groups of loans having similar characteristics, such as: product type, interest rate, original LTV, age, loan size, Census Division, etc. Hence, the default and prepayment models calculate the proportions of outstanding principal balances of loan groups. This was done to speed up computational time, as computers were significantly slower at that time. We implement the estimation below using a random sample of the loan-level data rather than aggregating in the manner done by OFHEO.

[10]See Federal Register 61(113): 29592–29621.

[11]See Federal Register 64(70): 18084–18131.

became effective in 2002:Q3.[12]

As shown in Figure 1, for each of the 24 quarters that both capital requirements were in force, reported levels of capital for both Fannie Mae (upper panel) and Freddie Mac (lower panel) were above the statutory minimum requirements and widely exceeded the risk-based requirement.[13] For example, Freddie Mac's estimated risk-based capital requirement remained below 2.0 percent throughout the entire 2003-to-2007 period, whereas its minimum capital requirement ranged between 3.0 percent and 4.5 percent. Both capital requirements were suspended with the imposition of the conservatorships at Fannie Mae and Freddie Mac in September 2008.

At the end of the first quarter of 2008, when the decline in U.S. housing prices was well underway, OFHEO's stress test was reporting that Fannie Mae and Freddie Mac had substantially more capital than necessary to weather a 10-year period of housing market stress. Furthermore, both GSEs were holding more capital than was required by statute. However, only a few months later, Fannie Mae and Freddie Mac would find themselves deemed insolvent, relying on U.S. taxpayer support for continued operations. Frame et al. (forthcoming) provide a detailed discussion of the GSEs' financial distress and the imposition of federal conservatorships in 2008.

In the remainder of the paper, we focus our attention entirely on the GSEs' combined portfolio of single-family 30-year fixed-rate mortgages. This is the most popular U.S. mortgage contract and accounts for about 75 percent of the GSEs' book-of-business. Moreover, mortgage credit losses accounted for the lion's share of the GSEs' total losses between 2008 to 2010.[14] Furthermore, large, loan-level datasets are available to estimate mortgage performance, and a well-developed research methodology exists for model specification.

To measure the projected losses on 30-year fixed-rate mortgages held or guaranteed by Fannie Mae and Freddie Mac, OFHEO derived estimates of expected loan performance from statistical models of default and prepayment, which were treated as competing risks and

[12]See Federal Register 66(178): 47730–47875. OFHEO also issued a set of technical amendments to the rule in December 2006. See Federal Register 71(240): 75085–75106.

[13]In 2005, OFHEO forced Fannie Mae to remedy accounting irregularities. According to the revised accounts, Fannie Mae's capital actually fell short of the minimum requirement in 2002 and 2003 and was almost exactly equal to the risk-based requirement in 2003.

[14]Table A.1 in the Internet Appendix documents the sources of each GSE's capital erosion, using data from the Federal Housing Finance Agency. The table shows that losses on the single-family credit guarantee business accounted for $181 billion of the total capital erosion of $232 billion that occurred between 2008 and 2010.

estimated jointly using a multinomial logit specification. OFHEO defined default as having occurred when a mortgage terminated with a loss. In such cases, default was then recorded as having occurred as of the last mortgage payment. Prepayment was defined as an instance in which the borrower voluntarily paid off the entire outstanding balance of the mortgage. The independent variables in the default and prepayment specifications were: loan age, original loan-to-value ratio, probability of negative equity, burnout, investor, relative spread, yield curve slope, and relative loan size. Each variable was represented categorically—indicating that a loan has a particular characteristic.

Patterns of mortgage default and prepayment rates have characteristic age profiles, increasing during the first years after origination and then declining. OFHEO accounted for such loan seasoning by including a series of nine indicator variables for mortgage age (AGE) in both the default and prepayment models: six that correspond to each of the first six years of a loan's life and then categories for loans aged seven to nine years, 10–12 years, and older than 12 years.

The original loan-to-value ratio is an indicator of the borrower's financial resources, and loans with higher LTVs are more likely to default and less likely to prepay. OFHEO included six original LTV categories in their model: LTV = (LTV $\leq$60, 60<LTV$\leq$70, 70<LTV$\leq$75, 75<LTV$\leq$80, 80<LTV$\leq$90, 90<LTV). Virtually all mortgages will have origination LTVs below 100 percent, meaning that the borrower has positive equity and little incentive to default at that time. However, over time, changes in area home prices can affect this equity position (positively or negatively) and hence the borrower's propensity to default or prepay. To capture this, the OFHEO model also includes a measure of the probability that a borrower is currently in a position of negative equity (PNEQ), which is defined as the cumulative normal density for the ratio of the natural logarithm of the *current* LTV ratio to the contemporaneous housing price index (HPI) dispersion parameter (historical volatility) for the relevant Census Division.[15] The numerator of the current LTV is the current balance, while the denominator is the current estimated property value (based on the relevant U.S. Census Division HPI series). PNEQ is then assigned to categories: PNEQ = (0<PNEQ$\leq$0.05, 0.05<PNEQ $\leq$0.1, 0.10<PNEQ$\leq$0.15, 0.15<PNEQ$\leq$0.20, 0.20<PNEQ$\leq$0.25, 0.25<PNEQ$\leq$0.30, 0.30<PNEQ$\leq$0.35, 0.35<PNEQ).

[15]The probability of negative equity is included in the model—as opposed to the direct estimate of a borrower's equity position—in order to account for the measurement error that comes from using an aggregated house price index to estimate the values of individual properties.

Borrowers who passed up previous opportunities to refinance when market rates were significantly below their current coupon rate are generally viewed as being either financially unsophisticated or experiencing financial difficulties. Such borrowers are subsequently more likely to default and less likely to prepay, holding other things constant. The indicator variable BURNOUT equals one if the market rate is 200 basis points below the loan's coupon rate in any two quarters out of the first eight quarters of a loan's life. Once detected, the burnout effect is phased in over the first eight quarters: no effect during the first two quarters of a loan's life, 25 percent effect during quarters three and four, a 50 percent effect during quarters five and six, and a 75 percent effect during quarters seven and eight.

For a given level of property (negative) equity, it is understood that investors are more likely to default than owner-occupiers. This occurs because the investors do not realize the personal consumption value of the home as shelter. Investors also tend to be more financially sophisticated and less credit constrained on average, and hence more likely to exercise their prepayment option. The variable INVESTOR indicates mortgages made to investors (including second homes and all 2–4-family properties).[16]

The multinomial logit model was estimated using a 10 percent random sample of mortgage loans that Fannie Mae and Freddie Mac had securitized or retained between 1979 and 1999 (with origination years from 1979 to 1997).[17] Importantly, after the initial estimation of the parameters, the model was never subsequently re-estimated using updated data. As we show below, this had a profound effect on the forecasting ability of the model and, in turn, on the required risk-based capital levels derived from the stress test.

[16]Three additional variables were included in the prepayment model, but omitted from the default model: 1) The relative spread between the interest rate on the mortgage and the current rate (RS), which is a proxy for the "mortgage premium value," or value to a borrower of the refinance option; 2) the slope of the yield curve (YCS), which was measured as the difference between the 10-year CMT and 1-year CMT (the shape of the yield curve reflects expectations of the future levels of interest rates and will therefore affect borrowers' mortgage prepayment decisions); and finally, 3) the size of a particular loan relative to its state average (RLS), which may be related to prepayment behavior insofar as refinancing costs are proportionately higher for lower-balance loans.

[17]OFHEO used the CATMOD procedure in SAS to obtain estimated parameters for all values of the categorical variables. We also use CATMOD in our analysis below. Additionally, while the same set of covariates was included in the empirical specification for both the default and the prepayment hazards, certain parameters of the default hazard were constrained to be zero in the estimation routine (that is, those associated with relative spread, yield curve slope, and relative loan size)

3 Data

OFHEO used proprietary data on residential mortgages held or guaranteed by Fannie Mae and Freddie Mac to estimate their single-family mortgage performance models for the risk-based capital stress test. Since this dataset is not available to us, we use commercially available loan-level mortgage data from Lender Processing Services (LPS) for 1993–2009 to re-estimate the OFHEO model specification and to conduct three principal empirical exercises (described below).[18]

The LPS dataset, the main dataset we use, is collected from several of the largest U.S. mortgage servicers, covers a large fraction of active loans, and includes a great many standard mortgage underwriting fields.[19] Loan-level attributes include borrower characteristics (for example, origination credit score (FICO), occupancy status, and documentation level), collateral characteristics (for example, property type, original loan-to-value ratio, and zip code), and loan characteristics (for example, loan balance, lien holder type, and loan status). The monthly history of each loan appears in the data, including its current payment/performance status. One issue with the LPS data is that not all servicers populate all fields, although this was primarily an issue before the mid-2000s and the affected fields were generally not those used in the OFHEO risk-based capital model (investor status excepted). We come back to this issue below.

The LPS field "lien holder type" allows us to identify those loans held or guaranteed by Fannie Mae and Freddie Mac. These comprise our loan sample. To check the representativeness of our sample, we compare the annual sample means for certain key variables (origination loan-to-value ratio, unpaid principal balance at origination, and interest rate at origination) with those provided to us by staff at the Federal Housing Finance Agency (FHFA) for the population of Fannie Mae and Freddie Mac loans held or guaranteed each year between 1995 and 2005. The comparisons are provided in Table 1. There are minor differences between the two datasets in any given year, but the broad patterns are very consistent and suggest that the LPS data are quite representative.

For each quarter under study (1993:Q1 through 2009:Q4), we pare down the number of

[18]Fannie Mae and Freddie Mac have recently publicly released a limited sample of their historical loan-level data. We do not use data from this release, as the sample is limited and also does not include granular property location information.

[19]The LPS loan-level dataset covers approximately 40 million active first-lien mortgages and 8 million active second-lien mortgages. See Foote et al. (2010) for a more detailed discussion of the LPS dataset.

loans, using the following selection criteria. First, we only include loans that LPS indicates as being held by Fannie Mae or Freddie Mac. By law, these loans must have original balances below the "conforming loan limit" for the year and location that the loan was made.[20] Second, we consider loans in only the 48 contiguous U.S. states, consistent with OFHEO's sample restrictions. We further restrict the sample to loans that finance a single-family residence, first lien mortgages, and fully amortizing 30-year fixed-rate loans.

Due to the large size of the LPS dataset, we work with random samples of the data. The coverage of the LPS data relative to the population of outstanding mortgages varies over time. LPS added mortgage servicers to their database over time, thereby increasing their coverage of the U.S. mortgage market. In order to maintain an approximately constant number of loans in our estimation sample, we decrease the proportions of the random samples over time. For loans originated before the end of 1998:Q4, we take a 30 percent random sample of loans meeting our selection criteria. Then, for loans originated during 1999:Q1 through 2004:Q4 and meeting our selection criteria, we use a 21 percent random sample, and for loans thereafter we take a 17 percent random sample. These samples are used to estimate the various models over different time horizons. Also, when comparing forecasts generated by the various mortgage performance models to realized outcomes, we utilize 5 percent random samples for the outcomes.

The analysis also requires information about house prices and interest rates. In order to replicate OFHEO's 30-year fixed-rate mortgage performance model, we collect quarterly Census Division house price indices and associated price volatility series from the Federal Housing Finance Agency. In some additional analysis, we also utilize county-level house price series available from CoreLogic. We collect monthly series for 30-year mortgage interest rates, as well as 1-year and 10-year Treasury rates from the Federal Reserve Board website.

4 Model Estimation

We conduct three exercises aimed at understanding how the OFHEO 30-year fixed-rate mortgage default and prepayment models performed in the years leading up to the mortgage bust and subsequent financial crisis. Section 4.1 analyzes the ability of the published version of the OFHEO model (which we refer to as the "static" OFHEO model due to the lack of

[20] See Federal Housing Finance Agency (2013) for historical data about the conforming loan limits.

parameter updating) to predict default and prepayment rates, by comparing one-quarter and two-year-ahead out-of-sample forecasts with realized values, assuming perfect foresight about quarterly house prices and interest rates. Section 4.2 then determines whether re-estimating the OFHEO model specification on a quarterly basis would have improved its out-of-sample forecasting ability (we refer to this re-estimated model as the OFHEO "updated" model). Section 4.3 then adds underwriting variables, like credit scores and documentation levels, to the OFHEO updated model (we refer to this as the "additional covariate" model) and examines out-of-sample forecast performance.

4.1 Static OFHEO Model

Our first exercise explores how well OFHEO's 30-year fixed-rate mortgage performance model would have predicted quarterly default and prepayment propensities, assuming the supervisor had perfect foresight about house prices and interest rates. The perfect foresight assumption is made in order to obtain a clear determination of how well OFHEO's model can predict defaults and prepayments. We construct one-quarter-ahead as well as two-year-ahead default and prepayment probability forecasts using the public OFHEO parameter estimates and compare these with realized default rates in the LPS data.[21]

Since the LPS data do not include information about mortgage losses, we define default as occurring when a foreclosure is completed, and we date the default back to the last observed payment.[22] We define prepayment in the same manner as OFHEO. Table 2 compares the default and prepayment parameter estimates for 30-year fixed-rate mortgages published by OFHEO (based on proprietary Fannie Mae and Freddie Mac loan data between 1979 and 1999) with our estimates, using the LPS data between 1994 and 2000. For brevity, we display the parameters associated with the LTV and probability of negative equity (PNEQ) variables. The parameter estimates are surprisingly consistent, given the fact that the OFHEO and LPS estimation samples have very little overlap (only six years). The signs of the parameter estimates are almost identical across all categories, and the magnitudes are

[21] We do not construct out-of-sample forecasts longer than two years in this section because our LPS data on mortgage performance end in December 2010. Due to this sample restriction, we are not able to construct longer forecasts through 2008 and still maintain our perfect foresight assumption.

[22] A foreclosure auction marks the completion of foreclosure proceedings. The auction either results in the lender assuming ownership of the property, in which case we see the mortgage status transition from foreclosure to bank-owned real estate (REO) in the LPS dataset, or it results in a new homeowner, in which case we see the mortgage status transition from foreclosure to terminated.

very similar.

Figure 2 presents the actual and predicted default rates for each quarter from January 2000 through December 2008.[23] The top panel displays actual and predicted default rates over a one-quarter horizon, while the bottom panel displays results over two years. The solid black line in each panel (labeled "Actual") corresponds to actual default rates, while the predicted rates from the static OFHEO model are represented by the dashed blue lines (labeled "OFHEO Model"). At both horizons, the static OFHEO model consistently underpredicts default rates. The forecast errors were relatively small between 2002 and 2006. However, with the onset of the housing bust in late 2006, the errors increased dramatically. At the end of 2007, actual 2-year cumulative default rates associated with the GSEs' holdings of 30-year fixed-rate mortgages were approximately 2.0 percent, and increased to 2.5 percent in 2008. The static OFHEO model predicts that the 2-year default rate hovers around 0.5 percent for both years.

4.2 Updated Model

The second exercise extends the analysis by simply updating the parameters of the OFHEO 30-year fixed-rate mortgage performance model on a quarterly basis. This allows us to explore whether default forecasts could have been improved by using data available to the supervisor in real-time. Specifically, we re-estimate the OFHEO model using the LPS data based on a seven-year rolling window and then again compare these updated default forecasts with realized default rates, assuming perfect foresight about future house prices and interest rates. The first estimation window spans 1993:Q1 to 2000:Q1 and is then updated quarterly through 2008.

The lines labeled "Updated Model" in Figure 2 (dashed red lines) show the default predictions from this model, which can be compared with realized default rates and prior forecasts generated by the static OFHEO model. (Again, each forecast is predicated on the supervisors having had perfect foresight about the future path of house prices and interest rates). It is quite clear for both horizons that simply re-estimating the OFHEO model each quarter dramatically reduces the forecast error. The updated model no longer systematically

[23]We focus exclusively on default rates, which were the primary driver of the GSEs' losses during the crisis period. However, we do show how the OFHEO model performed in forecasting prepayment rates, in the online appendix.

underpredicts default rates prior to 2006 and (unlike the static model) generates a sharp increase in expected defaults as we move into the housing bust (albeit with a lag). Simply updating the model parameters decreases the forecast errors by about 50 percent in the post-2006 housing bust period.

To dig a little deeper into the source of this significant improvement in predictability, we investigated the evolution of the parameter estimates. We found that, over time, the coefficients associated with the LTV indicators and the PNEQ variables changed fairly dramatically. Figure 3 shows how the parameters associated with mortgages in various LTV ranges changed relative to the parameter associated with low-LTV mortgages over the sample period (LTV $<$ 60 percent). Based on data from before 2000, a loan with an origination LTV of over 90 percent (black dashed line in the figure) was about four times as likely to default as a loan with an origination LTV of under 60 percent. However, by the end of 2008, the updated parameter estimate, based on data from 2001 to 2008, implies that the ratio of default probabilities for loans in those two respective LTV bins had soared to 16. This helps to illustrate why OFHEO's static default model forecasts deteriorated so dramatically over the sample.

4.3 Additional Covariate Model

The OFHEO 30-year fixed-rate mortgage performance model specification lacks several covariates that have been shown to have predictive power in forecasting mortgage defaults. For example, FICO scores were not widely used for mortgage underwriting until the early 2000s, and, in fact, the FICO field was rarely populated in the LPS data until 2002. Our third exercise explores whether adding additional relevant predictors to the updated OFHEO model improves the default forecasts. We specifically focus on FICO scores, loan documentation, and local unemployment rates.[24]

First, for credit scores, we include a series of categorical variables in 40-point increments.[25] The specific categories are: $\text{FICO}\leq 620$, $620<\text{FICO}\leq 660$, $660<\text{FICO}\leq 700$, $700 <$

[24] We also tried expanding the set of original LTV indicator variables. First, we redefined $\text{LTV}>90$ as a series of indicator variables: $90<\text{LTV}\leq 95$, and $\text{LTV}>95$, to account for the dramatic rise in high-leverage mortgages originated during the boom. Second, we tried including an indicator for loans with loan-to-value ratios exactly equal to 80 percent (LTV=80) to account for the fact that some of these loans had unobserved subordinate liens. However, neither of these changes substantially affected the model forecasts.

[25] The first FICO score was made available to the three major U.S. credit bureau agencies in 1991. However FICO scores were not introduced into mainstream mortgage models until the mid-1990s (for more details

FICO $\leq$ 740, 740<FICO$\leq$780, 780<FICO$\leq$820, and FICO$\geq$820.

Second, the lack of loan documentation has been previously identified as a risk factor, as well as a contributor to the recent housing bust. Moreover, the GSEs became significant purchasers of low-documentation mortgages during the housing boom, as the share of such loans in the marketplace increased.[26] Hence, we add variables indicating whether the loan was a "no-doc" or "low-doc" mortgage.

Figure 4 displays statistics summarizing how the distribution of FICO scores and the fraction of low- and no-documentation mortgages in our sample of conforming 30-year fixed-rate mortgages evolved over time. The top left panel shows that the distribution of FICO scores for *newly originated* loans declined slightly over time. (The 10th percentile loan, for example, had a 650 FICO score in 1999, but by 2007 it had fallen to 625.) The result is that the distribution of credit scores fell very modestly over the sample for the stock of active loans at a point in time (displayed in the top right panel). The bottom left panel shows that the share of low-documentation loans reported in the data was essentially zero until 2002 and then shot up to 10 percent of new originations in 2003. It is unclear whether this pattern reflects the failure of originators to report documentation status until the early 2000s, or a real change in the fraction of low-documentation loans being acquired by the GSEs. The share of reduced documentation mortgages held or guaranteed by the GSEs was around 10 percent in early 2005 and grew modestly over the course of the housing boom.

Finally, we also add county-level unemployment rates from the Bureau of Labor Statistics, as job loss is likely to be an important factor in a borrower's decision to stop making mortgage payments.[27] We add both the level of the unemployment rate and the cumulative

we direct the reader to http://www.fico.com/en/Company/Pages/history.aspx). Thus, FICO scores were unavailable to OFHEO when it estimated the risk-based capital model.

[26]Low-documentation mortgages did not become popular until the 1990s, and thus were likely not prevalent in the sample of mortgages used by OFHEO to estimate the model. See Foote, Gerardi, and Willen (2012) for more detail on the history of low-documentation loans. At the peak of the housing boom in 2006, almost 40 percent of newly originated subprime mortgages had less than full-documentation of income and assets (Gerardi et al. (2008)). Low-documentation mortgages were even more common in the Alt-A segment of the market, reaching a peak of 78 percent of originations in early 2007 (Sengupta (2010)).

[27]Previous empirical default studies have not found a strong correlation between the incidence of mortgage default and unemployment rates at the state or county level. However, Gyourko and Tracy (2013) show that a weak correlation between aggregate unemployment rates and default could be consistent with a strong correlation between household-level unemployment shocks and default, due to a large attenuation bias that occurs by using aggregate unemployment rates to proxy for individual unemployment shocks. Gerardi et al. (2013) confirms this attenuation bias directly by using direct information on unemployment spells and default rates in the Panel Study of Income Dynamics. Since we do not have individual data, we use aggregate rates in our analysis.

change in the unemployment rate since the quarter of origination. The first variable likely captures persistent differences in unemployment across geographic areas, while the second variable captures differences in the evolution of unemployment rates across geographic areas during the life of the mortgage.[28]

The OFHEO 30-year fixed-rate mortgage default model included a variable, PNEQ, intended to capture the probability that a given mortgage is in a negative equity position—"under water"—based on updated property values and amortization. As noted above, property values were updated using the OFHEO/FHFA house price index (and index dispersion measure) for the Census Region where the property was located. While it is a reasonable attempt to capture the effect of changes over time in home equity positions, the use of regional house price indices may significantly reduce the usefulness of this variable, as the correlation between changes in individual property values and changes in such an aggregated index is likely very weak. We attempt to address this issue at least partially by reconstructing the PNEQ variable using a more disaggregated house price index at the county level from CoreLogic.

The lines labeled "Updated Model, with Covariates" in Figure 2 (dashed green lines) show the default rate predictions from a model that includes all these additional variables as predictors. At the one-quarter horizon, the model with additional covariates predicts the dramatic rise in default rates that occurred in 2006 and 2007, and actually overpredicts default rates in the 2008–2010 period. A similar pattern can be seen for the two-year horizon.[29]

5 Risk-Based Capital Implications

Recall that Figure 1 showed that the risk-based capital requirement was never binding for either Fannie Mae or Freddie Mac, even in the midst of the foreclosure crisis in 2007 and 2008. In this section, we begin by exploring whether the model updating explored in Section 4 would have materially increased the GSEs' risk-based capital requirements and alerted

[28]We also experimented with shorter-term changes in unemployment rates, such as the change in unemployment over the previous four quarters, but found no significant differences in the forecasting results.

[29]In the online appendix we illustrate the effects of adding the additional covariates sequentially, in order to shed some light on which variables have the largest impact on the default forecasts. Adding the unemployment variables and measuring PNEQ using county-level house prices makes the most difference, while adding the FICO score and documentation level does not have a significant effect on the out-of-sample forecasts.

supervisors to their vulnerability to mortgage credit losses well before the imposition of the conservatorships. To that end, we use OFHEO's house price and interest rate stress scenarios to calculate quarterly, risk-based capital requirements for Fannie Mae and Freddie Mac between 2000 and 2009. We then compare the OFHEO house price stress scenario with the actual path of house prices during the recent housing bust and recompute the risk-based capital requirements.

It is important to stress that we are unable to fully replicate the risk-based capital requirements displayed in Figure 1. Those capital requirements were calculated using the GSEs' entire balance sheets and all off-balance sheet exposures. Our calculations below are based solely on the credit risk associated with the GSEs' portfolio of 30-year fixed-rate mortgages and are compared with the 45 basis point minimum standard. As noted previously, 30-year fixed-rate mortgage guarantees comprised the vast majority of the GSEs' credit guarantee business and generated the bulk of their credit losses during the crisis.

5.1 Calculation of 10-Year Cumulative Default Forecasts

The first step in replicating the OFHEO stress test involves calculating, for every quarter in our sample period, 10-year cumulative default and prepayment forecasts, using each of the three models presented above (the static OFHEO model, the updated model, and the additional covariates model) along with the supervisors' assumed house price and interest rate stress scenarios and an assumption of no new business (that is, portfolio run-off) as in the regulation.

Figure 5 displays the 10-year cumulative default forecasts for both the static OFHEO model and the updated OFHEO model for each quarter through 2008.[30] To be clear, each data point in the figure corresponds to a 10-year cumulative default rate forecast computed on the GSEs' portfolio of active 30-year fixed-rate mortgages in that quarter. Figure 5 clearly shows that the updated model generates significantly higher 10-year cumulative default forecasts throughout the entire 2000–2008 period compared with the static model. The differences range between 1 and 3 percentage points through 2006 and then rise substantially beginning in 2007. By the end of 2008, the difference in default forecasts between the two models is approximately 6 percentage points.

[30]The default forecasts from the additional covariate model look very similar to the forecasts from the updated model and thus are omitted from the figure for clarity.

5.2 Calculation of 10-Year Expected Losses

Armed with the cumulative default (and prepayment) forecasts, the next step in replicating the stress test involves estimating the net income associated with bearing this mortgage credit risk for each of the 40 quarters over the stress horizon and then discounting the net income stream back to construct a single present value.

Quarterly net income is computed in the following way. First, loans that are "current" in a given quarter produce principal and interest payments. Part of these interest payments reflect the guarantee fee paid by originators, which is the income accruing to the GSEs for bearing mortgage credit risk. We assume this guarantee fee to be 20 basis points per year, which is consistent with each GSE's long-run average fee during this time. Second, loans that prepay in a given quarter return all principal and interest due at that point in time. Third, loans that are delinquent in a particular quarter (that is, those that did not make a payment, but have not yet been deemed to have defaulted) produce no income or loss. Finally, loans that are ascribed default status produce a loss that we attempt to estimate by applying OFHEO's prescribed method.

OFHEO assumed three distinct sources of loss associated with defaulted mortgages. The first component is a foreclosure discount, which takes into account the well-known tendency of a foreclosed property to sell at a substantially lower price than an equivalent nondistressed property.[31] The second component consists of expenses that occur during the foreclosure process itself, as well as during the REO period in which the lender attempts to sell the property. The final component consists of the amount of unpaid interest that the GSEs are obligated to forward to mortgage-backed securities investors during the delinquency/foreclosure period. The losses are calculated as a percentage of the unpaid principal balance at the time of the first missed mortgage payment, with an appropriate adjustment for the existence of private mortgage insurance (PMI). The details regarding the calculation of each loss component and the PMI adjustment are provided in the online appendix.

For a given quarter, the difference between the defaulted unpaid principal balance and recoveries from sale of the property and PMI represent credit losses. These losses are then netted against guarantee fee income derived from performing loans and any prepaid principal. These projections of quarterly net income are then discounted to the present (that

[31] For example, Campbell, Giglio, and Pathak (2011) find a 27 percent foreclosure discount using a sample of single-family properties in Massachusetts. See Frame (2010) for a review of this literature.

is, the start of the stress test) using the six-month enterprise cost of funds (ECOF), which is the discount factor used in the regulation.[32] This discounted stream of cash flows represents an estimate of the required risk-based capital for credit risk. Below, we express these cash flow gains/losses as a percentage of the total unpaid principal balance of the GSEs' holdings of 30-year fixed-rate mortgages in any given quarter. For comparison purposes, the GSEs' statutory minimum capital for mortgage credit risk (credit guarantees) is 45 basis points.

5.3 Risk-Based Capital Requirements Using Different Models

The top panel of Figure 6 displays our quarterly estimates of the GSEs' risk-based capital requirements for the 30-year fixed-rate mortgages, conditional on OFHEO's stress scenarios for house prices and interest rates. We do this for the static OFHEO model (dashed blue line), the updated model (dashed red line), and the updated model with additional covariates (dashed green line).

Before discussing the results in the figure, we draw the reader's attention to two key points. First, if the GSEs' actual capital ratio had exceeded the estimate in a given quarter, then Fannie Mae and Freddie Mac would have been expected to be able to successfully absorb all losses through the 10-year stress test. Second, the risk-based capital requirement was sometimes actually *negative*, indicating that expected income from guarantee fees under the stress scenario exceeded expected credit losses.

According to the blue line in the top panel of the figure, estimated mortgage credit losses from the stress test using the static OFHEO model do not appear until the beginning of 2008, and do not surpass the 45 basis point statutory minimum capital requirement for mortgage credit risk until the third quarter of 2008. This implies that the GSEs could have weathered a significant housing market downturn up until that point. However, as we know in hindsight, this was precisely when regulators placed the GSEs into federal conservatorship on the grounds that they were insolvent—even without the stress scenario actually having occurred! Estimated losses continue to rise through the rest of the sample period, peaking at 110 basis points as of year-end 2009.

Turning to the updated model (dashed red line), estimated losses now first appear in the first quarter of 2007 and rise above the statutory minimum in the fourth quarter of

[32] The ECOF is a proportional spread over the six-month constant maturity Treasury index (CMT). We direct the reader to the online appendix for a more detailed explanation of the discount factor.

2007, three quarters before they appear in the static OFHEO model. By the time of the conservatorships, the estimated net loss is 170 basis points according to the updated model, compared with only 51 basis points based on the static model. These calculations are consistent with the results displayed in Figure 5, which show a large difference between the default forecasts of the static and updated models that begins to emerge in late 2006.

The updated model with additional covariates (dashed green line) predicts net losses at the very end of 2006, which then breach the statutory minimum near the end of 2007. By the time of the GSE conservatorships, the model with additional covariates estimates expected losses to be approximately 370 basis points: twice as high as the estimates of the updated model and seven times higher than those of the static model. The main take-away from this figure is that simple model updating and enhancement would have likely provided OFHEO with a much earlier warning of the increased credit risk associated with the GSEs' 30-year fixed-rate mortgage portfolio as the housing market turned in late 2006 and early 2007.

In Table 3 we further break down expected losses by loan vintage to determine which vintages were responsible for the rise in credit risk.[33] The table displays estimated losses for the static OFHEO model and the additional covariate model under the OFHEO stress scenario. The table clearly shows that the rise in credit risk in 2006 and 2007 primarily comes from those two loan vintages (and to a lesser extent the 2005 vintage). According to the additional covariate model, in the third quarter of 2008, expected losses from the 2006 and 2007 vintages were almost 600 bps, compared with just over 300 bps and 140 bps for the 2005 and 2004 vintages, respectively. The table also clearly shows that the differences in expected losses generated by the static and additional covariate models are close to an order of magnitude.

It is obvious from the results generated by the updated and additional covariate models that credit risk in the GSEs' 30-year fixed-rate mortgage portfolio increased dramatically in 2006 and 2007, and that the increased risk was driven predominantly by the latest loan vintages. This increase in predicted losses is driven by two factors: (1) a relaxation of underwriting standards and acquisition of riskier loans by the GSEs over the course of the housing boom; and (2) the subsequent decline of U.S. house prices that began in 2007. The

[33]Recall that the stress test was applied to the entire GSE loan portfolio. Thus, estimated losses in each quarter represent an average over all of the mortgage vintages held by the GSEs.

lower right panel of Figure 4 shows that the average mark-to-market LTV ratio of the whole book of GSE loans, including previously originated loans, rose from 55 percent in 2006 to more than 75 percent in 2009. This huge increase in mark-to-market LTV ratios was the direct result of the severe house price decline, and is captured in the OFHEO model by the PNEQ variables. In contrast, the relaxation in underwriting standards is much more modest. As Figure 4 shows, the origination LTVs of *new* loans rose only slightly between 2006 and 2007, and the distribution of credit scores did not change dramatically over the sample period.[34]

5.4 Treatment of House Price Stress

Now that we have seen the implications of model updating on long-term default forecasts and credit loss estimates, we turn our attention to the role of the house price stress scenario. Figure 7 compares the house price path used by OFHEO in the risk-based capital stress test with the realized path of U.S. house prices, measured using FHFA's national house price index, since the beginning of the housing bust in the fourth quarter of 2006 (what we will refer to as the "2007 scenario").

Recall that the OFHEO house price stress is the realized path of house prices for the West South Central Census Region between 1984 and 1993. To construct the figure we took the quarterly growth rates of house prices in this series and applied them to the level of house prices that prevailed at the beginning of the housing bust at the end of 2006. Since we have have 6.5 years of house price data for the recent period, we assume that between the end of the recent data (2013:Q2) and the end of the 10-year stress horizon, house prices will grow at a 1 percent quarterly rate, the rate that prevailed in the pre-2000 sample period. The figure clearly shows that the house price stress adopted by OFHEO was significantly less dramatic than the recent U.S. experience. The cumulative peak-to-trough decline in house prices assumed in the OFHEO stress scenario is 11 percent, versus the almost 18 percent drop in the national OFHEO index during the recent financial crisis.

While the difference between the scenarios is fairly strking, the national house price decline that occurred during the recent crisis was unprecedented (at least over the period

[34]There is a significant amount of empirical evidence that shows that mortgage underwriting standards in certain segments of the market, like privately securitized mortgages, declined significantly during the housing boom, but there is much less evidence for GSE loans, because detailed loan-level data on the GSEs' credit guarantee business has been largely unavailable to researchers.

in which house price indices have been computed). Furthermore, OFHEO was not alone in failing to predict the possibility of such a large housing bust. Most market participants were caught by surprise, including the credit rating agencies whose responsibilities included determining the extent of mortgage-backed security losses under adverse house price scenarios.

However, we do think it is fair to criticize OFHEO's assumption that house prices would *rise* by 2 percent over the first 10 quarters of the stress test before starting to fall. The assumption of slightly rising prices at the beginning of the stress test likely had significant ramifications for default forecasts and expected credit losses. Evidence from the mortgage finance literature suggests that default hazards peak within the first few years of the life of a loan. Thus, assuming a slightly rising price path during the period in which loans are most prone to default likely contributed to low credit loss estimates from the stress test.

To get an idea of how this difference in house price stress may have impacted estimated credit losses, the bottom panel of Figure 6 displays quarterly estimates of the GSEs' risk-based capital requirements for 30-year fixed-rate mortgages conditional on the 2007 house price scenario rather than OFHEO's house price stress scenario (which is shown in the top panel of the figure). The patterns in the two panels of the Figure 6 look broadly similar, although there are some important differences. Focusing on the static OFHEO model (dashed blue line), expected net losses rise above the statutory minimum of 45 basis points in the fourth quarter of 2007 under the 2007 house price scenario—compared with the third quarter of 2008 under the OFHEO house price scenario. The pattern is similar for the updated and additional covariates models, as in both cases the statutory minimum is breached almost a year earlier under the 2007 scenario. Using the additional covariates model, estimated net losses are 67 basis points in the third quarter of 2006, a full two years before the GSEs were placed in conservatorship.[35]

Thus, it is clear that an alternative house price stress scenario as severe as the actual path of prices during the recent housing bust would have significantly increased the risk-based capital requirements for the GSEs' portfolios of 30-year fixed-rate mortgages. Combined with an updated and enhanced model, this likely would have raised alarm bells long before the conservatorships occurred.

[35] The 10-year cumulative default rates displayed in Figure 5 increase by about 2 percentage points for each quarter in the sample period when the OFHEO stress scenario is swapped for the 2007 house price scenario. This increased default forecast is largely responsible for the increase in the estimated credit losses.

5.5 Assumption of No New Business

The analysis above suggests that if OFHEO had periodically re-estimated their model of mortgage performance and used a more adverse house price scenario in which prices initially fell rather than rose, then the stress test would have predicted that the GSEs were undercapitalized almost two years before the conservatorships took place. If OFHEO had been armed with this information and had enforced their capital standards, the GSEs would have been required to raise large quantities of capital in a very short period of time. However, to do so, OFHEO likely would have had to face some unpalatable choices, including having Fannie Mae and Freddie Mac shrink their business, significantly increase guarantee fees, and/or engage in several large rounds of equity financing. A by-product of these choices would have been a material tightening of mortgage credit supply, which would have potentially exacerbated the financial crisis.

The highly nonlinear pattern of risk-based capital displayed in Figure 6 raises an important question about the OFHEO stress test. Why does the test, even with an improved forecasting model and a more adverse house price scenario, indicate that the GSEs were well capitalized throughout the bulk of the sample period? Put differently, our results imply that the GSEs could have survived the exact same housing market bust that made them insolvent had it happened only two years earlier and with *no* capital. Given the relatively modest change in underwriting standards that we see in our data over the sample period, this does not seem plausible.

The simple reason for this finding is that the stress test only said that the GSEs had enough capital to absorb 10 years of losses on the loans *outstanding* in 2006. But Figure 8 shows that more than half of the GSE mortgages that defaulted in 2008 were made in 2006 and 2007. (Since these loans were made at the peak of the bubble, they also generated much larger losses than earlier vintages when they defaulted.) Under the "no-new-business" assumption, the stress test does not begin to project losses until actual adverse conditions in the housing market start to occur. This limited the usefulness of the stress test as a barometer of the GSEs' future health under adverse economic conditions.

Incorporating new business does present challenges. On one hand, it seems obvious that new loans originated when house prices are falling means that a stress test that does not consider new business will underestimate the risk faced by the institutions. However, allowing for new business requires critical assumptions about the size, composition, and risk characteristics of the new loans. Indeed, the General Accounting Office (2002) concluded that OFHEO should:

> ...not incorporate new business assumptions into its stress test, because determining the assumptions is inherently speculative and including them would introduce more complexity to an already complex model.

We believe that the issue of how to treat new business is something that warrants future research attention, given the important role that stress testing has assumed in macroprudential supervision. Our view is that the highly nonlinear path of estimated credit losses in Figure 6, to the extent that it could have led to a rapidly increasing path of required capital charges, is inherently problematic.

6 Discussion

The analysis in this paper uncovers two implementation issues that led to the ultimate failure of the OFHEO stress test. First, the lack of updating meant that while the OFHEO mortgage model may have reasonably described household default decisions in 1999, it did not do so during the recent housing bust. Second, the house price stress scenario used by OFHEO was significantly less adverse than the recent U.S. experience, but more importantly not adverse at all over the first 10 quarters of the stress test horizon. This section discusses reasons why policymakers made it very difficult for OFHEO to update the model and to consider alternative stress scenarios.

Why did OFHEO choose to not update its mortgage performance models over almost an entire decade in which there were marked improvements in mortgage modeling? We believe that OFHEO faced challenges emanating from statutory model disclosure requirements, as well as statutory limits to the specification of the house price and interest rate stress scenarios. These constraints, coupled with the political power of Fannie Mae and Freddie Mac, made it extremely difficult to introduce meaningful changes to the risk-based capital rule.

The Federal Housing Enterprises Safety and Soundness Act of 1992 required that OFHEO's risk-based capital stress test be: (1) subject to notice and comment rulemaking; (2) sufficiently specific to permit anyone to apply the test given relevant data; and (3) made public

(12 U.S.C. 4611). The first requirement is standard and the third fairly innocuous. However, OFHEO's interpretation of the second requirement may have created a barrier to improving the risk-based capital stress test. Testimony by OFHEO Acting Director Mark Kinsey (Kinsey, 1999) summarized the supervisory policy approach to the stress test:

> "The model can't be a black box. It has to be something that the [GSEs] can use to anticipate what their capital requirements will be. It also has to be transparent so that everybody else can evaluate it, including investors. Our proposed rule is, of necessity, lengthy. Every single equation and parameter in our model that are (sic) needed to reproduce our proposed capital standard are (sic) detailed in the proposal."

This suggests that OFHEO intended that Fannie Mae and Freddie Mac have the ability to use the stress test for business and capital planning purposes. While understandable that a regulated entity would find this helpful, the approach limited OFHEO's ability to incorporate changes and muted their incentives to engage in continual model development. Consequently, the complete micro-disclosure approach effectively turned the risk-based capital stress test into a compliance exercise. This situation—coupled with investors' perceptions of an implied federal guarantee of GSE obligations—also markedly reduced incentives for Fannie Mae and Freddie Mac to invest in risk management systems and would have allowed them to take on risks that were not captured well by the models.

The political clout of Fannie Mae and Freddie Mac during the 1990s and early 2000s is legendary in Washington, DC. Each GSE was a major lobbying force and campaign contributor during this time—to Democrats and Republicans alike.[36] Fannie Mae also established over 50 "partnership offices" around the country in order to maintain Congressional relationships outside the beltway. (Office staff typically included former Capitol Hill aides to key committees or members.) Fannie Mae also maintained a foundation that gave money to various charities, especially in the Washington, DC, area. Several senior Clinton Administration officials, including former Fannie Mae CEO Franklin Raines, also moved between government and executive positions at the GSEs. Discussions of all of these relationships

[36] Based on data available from the Center for Responsible Politics, between 1998 and 2007, Fannie Mae and Freddie Mac together spent $172.4 million on lobbying and provided another $16.5 million in campaign contributions. The campaign contributions consisted of employee donations, as the companies were not allowed to directly contribute themselves.

and the GSEs' use of them to bully critics are ubiquitous; Morgenstern and Rosner (2011) and McDonald (2012) provide several examples.[37]

The GSEs' political prowess comes into play within the context of our analysis. The Federal Housing Enterprises Safety and Soundness Act of 1992 placed some important limitations on OFHEO. Unlike bank supervisors, OFHEO had no ability to set minimum capital standards, lacked the authority to resolve a failed GSE through receivership, and could not even bring a lawsuit on its own behalf. Moreover, the agency's funding required annual Congressional appropriations. OFHEO was chronically underfunded, but keenly aware that if it upset Fannie Mae and Freddie Mac, the GSEs' associates on Capitol Hill would likely have reduced its budget further.[38] Taken together, this suggests that OFHEO's perceived weakness was a feature—and not a flaw—of the supervisor's enabling statute.[39]

With respect to the risk-based capital regulation, OFHEO was subject to the replicability requirement and important limitations on the broad underlying parameters of the stress test (discussed above). Given the political environment, OFHEO staff would have naturally been cautious about the components of the rule and, once the rule had been established, would have been reluctant to make changes that might adversely affect the GSEs.

7 Conclusion

Stress tests have become an increasingly important part of financial institution risk management programs and a critical tool used by supervisory authorities to evaluate the financial health of large banking organizations and financial systems. While stress testing exercises can provide valuable insights, they are vulnerable to model risk.

This paper studies a recent U.S. supervisory experience with a complex and fully disclosed stress test that failed spectacularly: OFHEO's risk-based capital stress test for Fannie Mae and Freddie Mac. The analysis focuses on a key element of OFHEO's stress test: the

[37] Ullmann (1999) claims that: "Fannie Mae plays hardball. It will hire key government critics to buy their silence, and it will intimidate lawyers, consultants, and financiers who go up against it by pressuring clients of the opponents to withdraw their business."

[38] For example, OFHEO's 2005 initial budget authorization included a provision that required that the Director (Armando Falcon) be replaced before monies could be disbursed. This ploy came in response to OFHEO's investigation of Fannie Mae's accounting practices.

[39] A decade later, former U.S. Treasury Secretary John Snow (Snow, 2003) testified that "the supervisory system for the housing GSEs neither has the tools, nor the stature, to effectively deal with the size, complexity, and importance of these Enterprises."

models used to predict default and prepayment of 30-year fixed-rate mortgages. We first demonstrate the poor out-of-sample forecasting performance of OFHEO's mortgage default model, especially during the recent housing bust. The principal cause of this failure appears to have simply been that the supervisor never re-estimated the model and hence left parameters static for almost a decade. We show that this was problematic because certain parameters, like those associated with borrower leverage, were unstable in the pre-crisis period. In addition, we find the exclusion of certain variables that became increasingly common in residential mortgage modeling in the decade prior to the financial crisis, such as credit scores, indicators for documentation levels, and more disaggregated house price indices, also had a negative impact on model performance. Finally, we illustrate how making straightforward model improvements would have affected OFHEO's risk-based capital calculations for the credit risk associated with 30-year fixed-rate mortgages held by the GSEs during the 2000–2008 period. Our conclusion is that an updated model would have provided a more timely signal to OFHEO about deteriorating mortgage quality at Fannie Mae and Freddie Mac well before conservatorships were imposed in September 2008.

We also document that OFHEO's adverse house price scenario (a peak-to-trough decline of 11 percent) was significantly less stressful than what actually transpired during the recent housing bust (a peak-to-trough decline of 18 percent). Perhaps more concerning is that OFHEO's adverse house price scenario assumed that housing values would actually increase over the first 10 quarters of the stress test—a period in which new mortgages are at an increasing risk of default. We then show that if OFHEO had been using the actual post-2006 U.S. experience as a house price stress and the updated 30-year fixed-rate mortgage performance model with additional covariates, the emerging risk at Fannie Mae and Freddie Mac would have been apparent even sooner.[40] Our analysis also uncovers a potential problem with one of the key structural assumptions of the OFHEO stress test: "no new business." This meant that stress test was only applied to mortgages held by Fannie Mae or Freddie Mac at the time the test was run—and did not account for loans expected to be made in the future. We demonstrate how this assumption limited the usefulness of the stress test as a barometer of the GSEs future health under adverse economic conditions.

[40]We are, of course, ignoring the possibility that other relevant stresses, like unemployment, may have been relevant. See Pritsker (2012) for a discussion.

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Table 1: Comparison of OFHEO and LPS Datasets

Panel A: Fannie Mae

Year	Avg. LTV Ratio (%)		Avg. UPB ($)		Avg. Interest Rate (%)	
	OFHEO	LPS	OFHEO	LPS	OFHEO	LPS
1995	80.1	79.5	101,518	101,393	8.1	8.6
1996	79.1	77.3	105,059	107,358	8.0	8.1
1997	78.1	78.5	111,398	115,546	7.8	8.0
1998	76.2	78.0	122,646	129,966	7.1	7.1
1999	77.6	76.8	123,600	128,224	7.4	7.2
2000	78.9	77.9	128,041	137,490	8.2	8.1
2001	76.2	74.9	145,435	148,313	7.1	7.1
2002	74.3	74.2	153,982	155,927	6.7	6.7
2003	72.2	72.4	162,743	160,537	5.9	5.9
2004	74.4	70.8	162,513	161,472	6.0	6.0
2005	73.8	72.4	175,886	164,631	6.0	6.1

Panel B: Freddie Mac

Year	Avg. LTV Ratio (%)		Avg. UPB ($)		Avg. Interest Rate (%)	
	OFHEO	LPS	OFHEO	LPS	OFHEO	LPS
1995	78.8	75.8	103,682	111,936	8.1	7.8
1996	78.2	71.6	106,414	115,373	8.0	7.9
1997	77.6	74.9	112,231	123,512	7.8	7.8
1998	75.5	73.8	122,976	123,961	7.1	7.0
1999	77.2	76.2	123,772	127,018	7.4	7.2
2000	78.4	71.1	128,781	126,022	8.2	8.1
2001	76.1	72.1	145,741	145,714	7.0	7.1
2002	74.5	72.5	153,380	158,182	6.6	6.8
2003	72.5	68.5	159,715	181,222	5.8	5.7
2004	74.3	72.6	164,079	177,177	5.9	5.9
2005	72.7	72.1	178,889	178,042	5.9	5.8

Notes: This table presents annual comparisons between the OFHEO and LPS datasets for three key mortgage contract terms: loan-to-value ratio (LTV), unpaid principal balance (UPB), and interest rate. Sample average values for new originations are provided separately for Fannie Mae (Panel A) and Freddie Mac (Panel B) for each year, 1995 through 2005. The OFHEO data are based on the population of single-family mortgages purchased or guaranteed by each GSE. LPS data reflect loans identified as being held or guaranteed by each GSE.

Table 2: Comparison of Estimates from Default and Prepayment Hazard Models for 30-Year Fixed-Rate Mortgages as Specified in the OFHEO Risk-Based Capital Stress Test

Variable	Default Hazard Estimates		Prepayment Hazard Estimates	
	OFHEO (1979 – 1999)	LPS (1994 – 2000)	OFHEO (1979 – 1999)	LPS (1994 – 2000)
Loan-to-Value (LTV)				
LTV $\leq$ 60	-1.150	-0.983	0.048	-0.035
60 $<$ LTV $\leq$ 70	-0.104	-0.057	-0.031	-0.095
70 $<$ LTV $\leq$ 75	0.597	0.473	-0.099	-0.077
75 $<$ LTV $\leq$ 80	0.224	0.109	-0.041	-0.050
80 $<$ LTV $\leq$ 90	0.200	0.177	-0.005	0.058
90 $<$ LTV	0.233	0.280	0.128	0.199
Probability of Negative Equity (PNEQ)				
0 $<$ PNEQ $\leq$ 0.05	-1.603	-1.260	0.591	0.694
0.05 $<$ PNEQ $\leq$ 0.1	-0.524	-0.371	0.370	0.456
0.1 $<$ PNEQ $\leq$ 0.15	-0.181	-0.053	0.229	0.322
0.15 $<$ PNEQ $\leq$ 0.2	0.080	0.093	-0.020	0.034
0.2 $<$ PNEQ $\leq$ 0.25	0.255	0.240	-0.160	-0.212
0.25 $<$ PNEQ $\leq$ 0.3	0.515	0.459	-0.246	-0.386
0.3 $<$ PNEQ $\leq$ 0.35	0.652	0.426	-0.294	-0.357
0.35 $<$ PNEQ	0.806	0.466	-0.464	-0.551

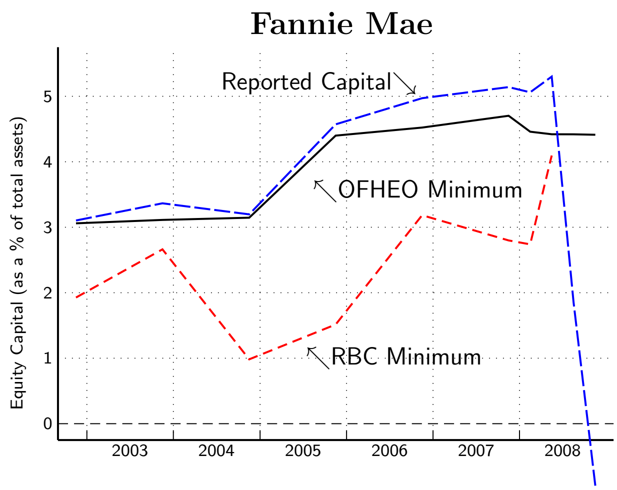
Notes: This table compares parameter estimates associated with discrete measures of the loan-to-value ratio (LTV) and probability of negative equity (PNEQ) produced by OFHEO-defined default and prepayment hazard models for 30-year fixed-rate mortgages. OFHEO estimates reflect those provided in the risk-based capital stress test, which were produced using a sample of loans from Fannie Mae and Freddie Mac between 1979 and 1999. LPS estimates were produced using a sample of loans identified as owned or guaranteed by Fannie Mae or Freddie Mac between 1994 and 2000.

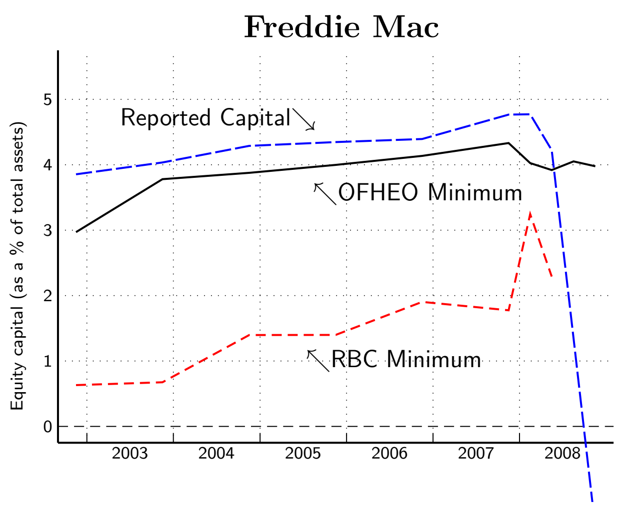
Table 3: 10-Year Expected Losses by Loan Vintage under OFHEO House Price Stress Scenario

	Expected Loss as % of Original UPB (end of quarter)									
	Static Model					Additional Covariate Model				
Stress	Vintage Year					Vintage Year				
Quarter	2003	2004	2005	2006	2007	2003	2004	2005	2006	2007
2004:Q1	-0.11	.	.	.	.	-0.39	.	.	.	.
2004:Q2	-0.20	-0.09	.	.	.	-0.38	-0.30	.	.	.
2004:Q3	-0.25	-0.14	.	.	.	-0.54	-0.50	.	.	.
2004:Q4	-0.27	-0.10	.	.	.	-0.54	-0.47	.	.	.
2005:Q1	-0.28	-0.05	.	.	.	-0.49	-0.18	.	.	.
2005:Q2	-0.30	-0.13	0.02	.	.	-0.44	-0.20	0.03	.	.
2005:Q3	-0.33	-0.17	0.02	.	.	-0.42	-0.12	0.15	.	.
2005:Q4	-0.36	-0.20	0.00	.	.	-0.41	-0.10	0.12	.	.
2006:Q1	-0.39	-0.25	-0.02	.	.	-0.43	-0.14	0.09	.	.
2006:Q2	-0.41	-0.27	-0.07	0.26	.	-0.45	-0.12	0.12	0.44	.
2006:Q3	-0.43	-0.30	-0.12	0.32	.	-0.43	-0.16	0.10	**0.64**	.
2006:Q4	-0.43	-0.30	-0.14	0.33	.	-0.40	-0.11	0.14	**0.76**	.
2007:Q1	-0.44	-0.32	-0.18	0.31	.	-0.36	-0.06	0.20	**0.86**	.
2007:Q2	-0.45	-0.32	-0.15	0.32	0.38	-0.35	-0.03	0.38	**1.12**	**1.01**
2007:Q3	-0.41	-0.30	-0.12	0.42	**0.60**	-0.31	0.00	0.36	**1.02**	**1.09**
2007:Q4	-0.40	-0.30	-0.12	0.44	**0.65**	-0.17	0.21	**0.69**	**1.80**	**2.00**
2008:Q1	-0.33	-0.24	-0.08	**0.49**	**0.68**	0.02	0.46	**1.26**	**2.77**	**2.81**
2008:Q2	-0.37	-0.25	0.00	**0.86**	**1.10**	0.14	0.84	**2.01**	**4.20**	**4.18**
2008:Q3	-0.33	-0.16	0.28	**1.36**	**1.63**	0.31	1.37	**3.03**	**5.58**	**5.61**
2008:Q4	-0.27	-0.11	0.36	**1.60**	**1.84**	**0.63**	**2.09**	**4.63**	**8.47**	**8.55**
2009:Q1	-0.29	-0.15	0.26	**1.39**	**1.65**	**1.04**	**2.92**	**5.56**	**10.18**	**10.45**
2009:Q2	-0.32	-0.12	**0.45**	**1.88**	**2.20**	**1.05**	**3.05**	**5.58**	**10.07**	**10.78**
2009:Q3	-0.29	-0.04	**0.82**	**2.42**	**2.86**	**0.96**	**2.86**	**5.72**	**9.94**	**10.77**
2009:Q4	-0.30	0.00	**0.85**	**2.57**	**3.07**	**0.87**	**2.84**	**5.58**	**9.98**	**10.79**

Notes: This table displays the results of the risk-based capital calculation for the GSEs' portfolio of 30-year fixed-rate mortgages under the OFHEO house price stress scenario and declining interest rate scenario by loan vintage. We refer the reader to the online appendix for details regarding how these numbers were calculated. Numbers in bold font signify expected losses in excess of the statutory minimum capital requirement of 45 bps for off-balance sheet credit guarantees.

Figure 1: GSE Reported, Minimum, and Risk-Based Regulatory Capital Levels

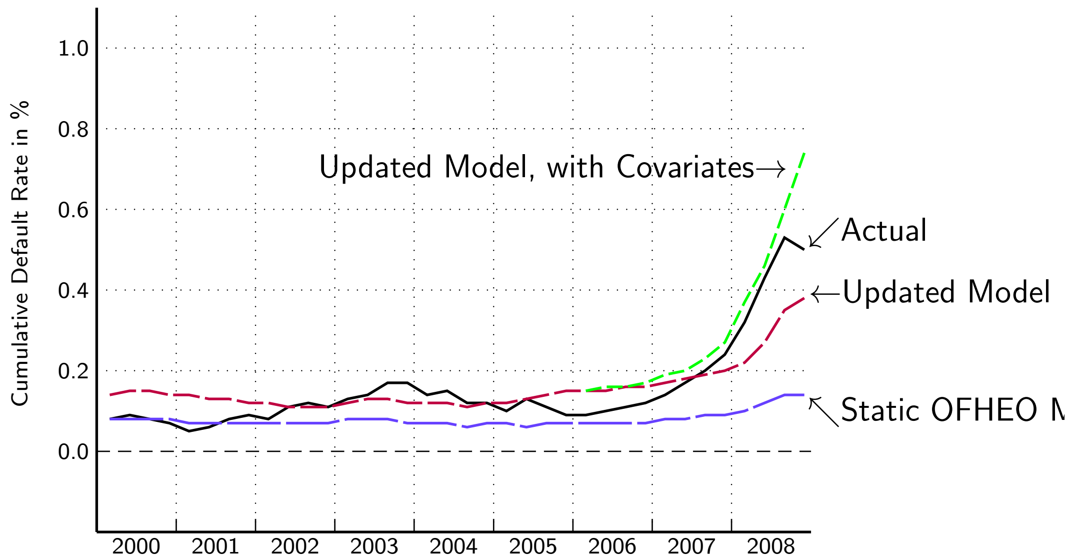




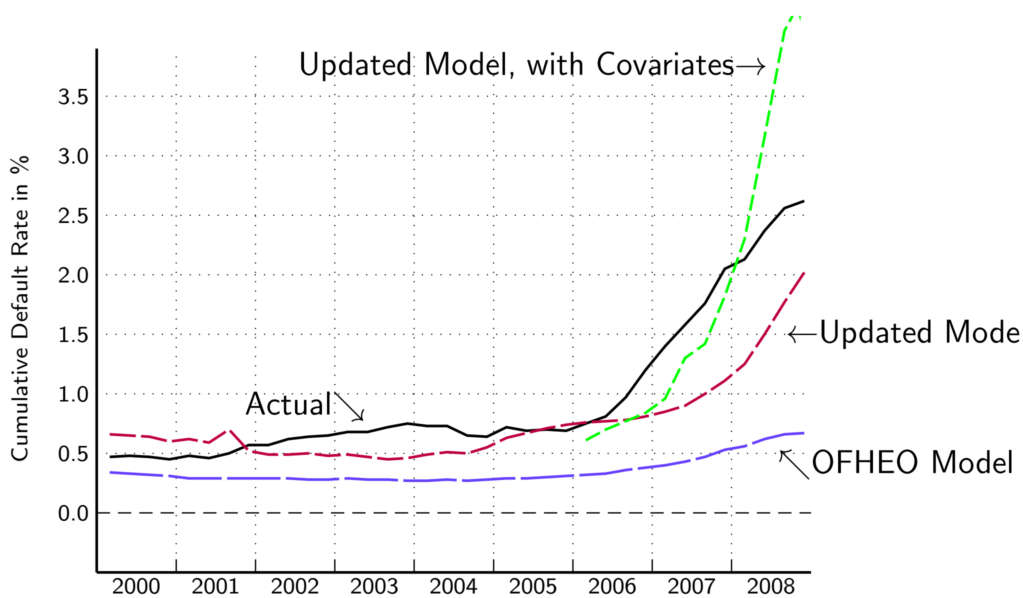
Notes: This figure illustrates the required statutory minimum capital, risk-based capital requirement, and actual capital (as a percentage of total assets) for Fannie Mae (Panel A) and Freddie Mac (Panel B). Minimum capital is simply computed as 2.50 percent of total assets plus 0.45 percent of off-balance sheet guarantees, plus a 30 percent surcharge of this total for management and operations risk. Minimum capital sometimes also included temporary surcharges imposed following accounting difficulties. Freddie Mac faced a 30 percent surcharge between 2003:Q4 and 2007:Q4, which was reduced to 20 percent thereafter. Fannie Mae faced a 30 percent surcharge between 2005:Q3 and 2007:Q4, which was reduced to 20 percent thereafter. Risk-based capital is computed by the stress test and represents the larger of the results produced under the two interest rate scenarios ("up rate" and "down rate"). The data come from the Federal Housing Finance Agency website. http://www.fhfa.gov/SupervisionRegulation/FannieMaeandFreddieMac/Pages/Capital-Requirements.aspx

Figure 2: Forecasting Performance of Various Default Models

1-Quarter Horizon

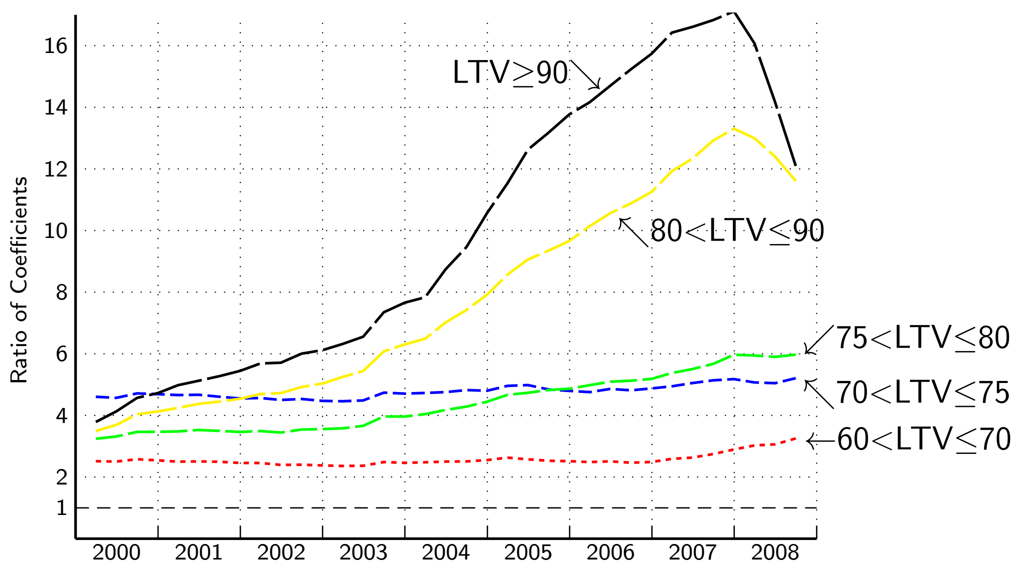


2-Year Horizon



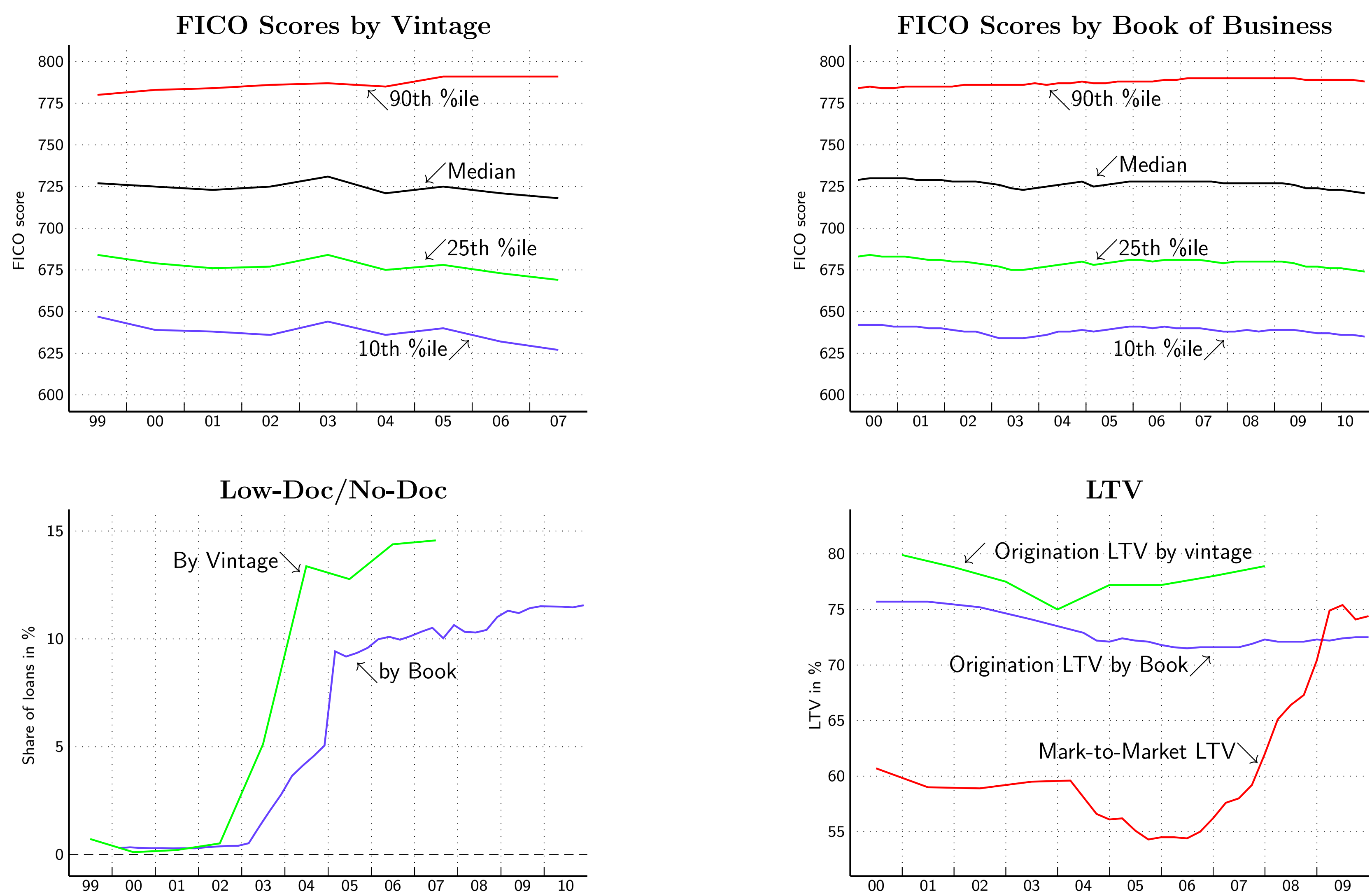
Notes: This figure presents the actual and predicted default rates for 30-year fixed-rate mortgages loans between 2000:Q1 and 2008:Q4 over one-quarter and two-year horizons. Actual default rates are based on mortgages identified as being held by Fannie Mae or Freddie Mac in the LPS data. Predicted default rates use the same LPS data projected through the parameterized default model published as part of the OFHEO risk-based capital stress test or by other models estimated by the authors, as described in the text.

Figure 3: Evolution of LTV Parameter Estimates



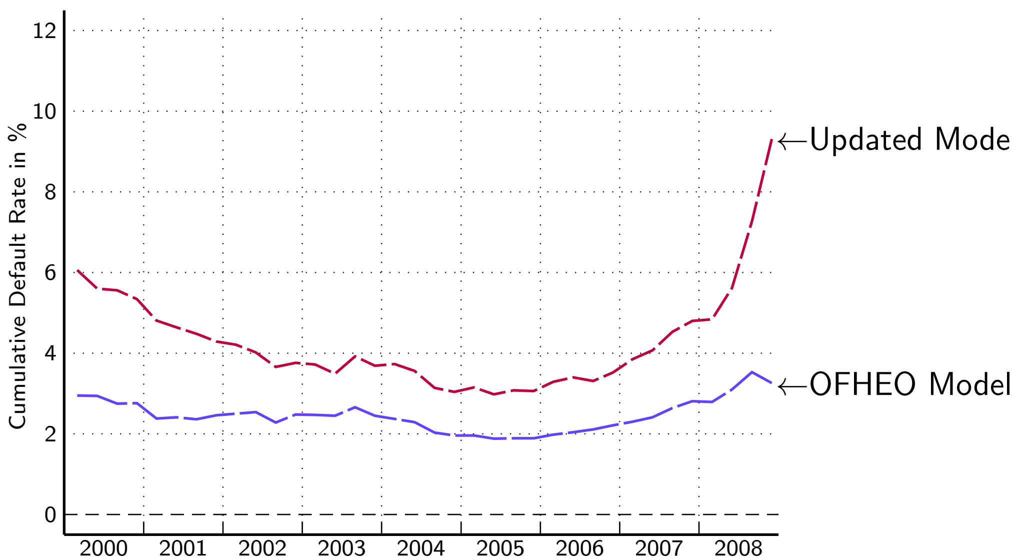
Notes: This figure displays the evolution of multinomial logit coefficient estimates associated with the loan-to-value (LTV) variables in the default hazard for the updated OFHEO model. All LTV variables are expressed as indicator variables in the model.

Figure 4: Evolution of Key Underwriting Characteristics of GSE 30-Year Fixed-Rate Mortgages: 1999–2007



Notes: This figure displays quarterly summary statistics for underwriting characteristics of the GSEs' 30-year fixed-rate mortgage portfolio based on the LPS sample. Updated LTV is calculated using cumulative house price appreciation since the month of origination and assuming a fully amortizing payment schedule. FHFA Census Division house price indices are used to calculate updated LTVs.

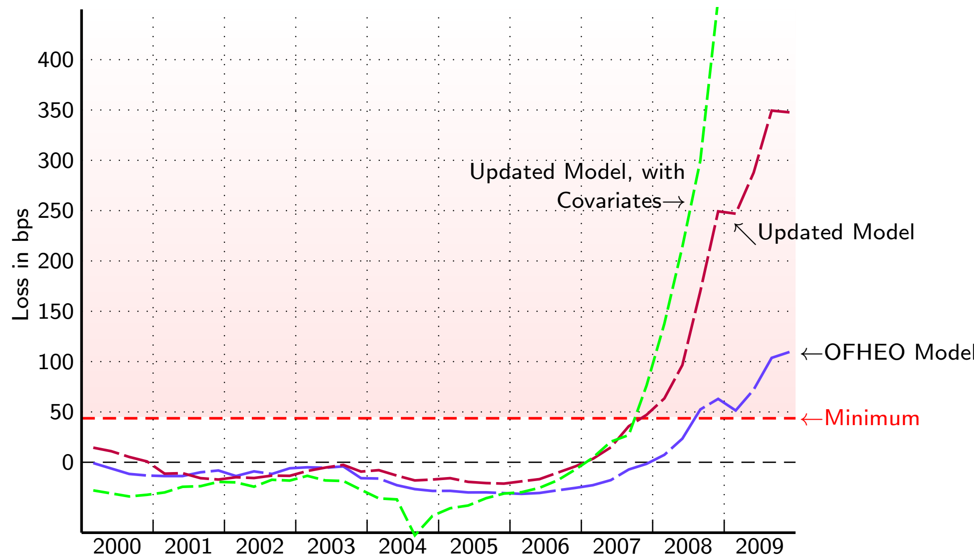
Figure 5: 10-Year Cumulative Default Forecasts Using Different Models



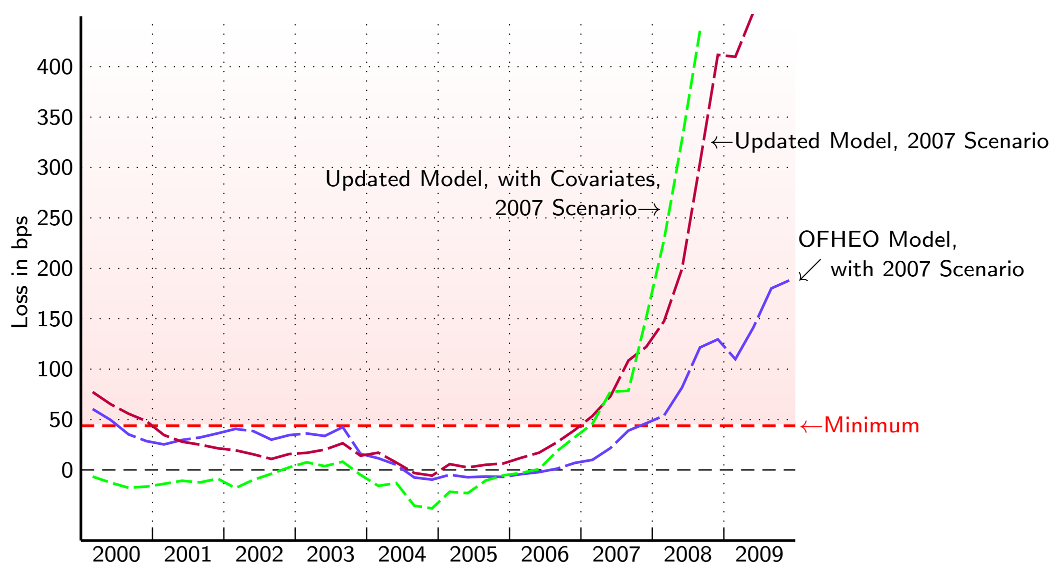
Notes: This figure presents 10-year cumulative default forecasts assuming the OFHEO stress scenario for house prices for both the static OFHEO model and the updated model. Both models are estimated using 30-year fixed-rate mortgages identified in the LPS data as being held by Fannie Mae or Freddie Mac.

Figure 6: Estimated GSE Risk-Based Capital Requirements Using Different Models and House Price Scenarios: 2000–2009

Panel A: OFHEO House Price Scenario

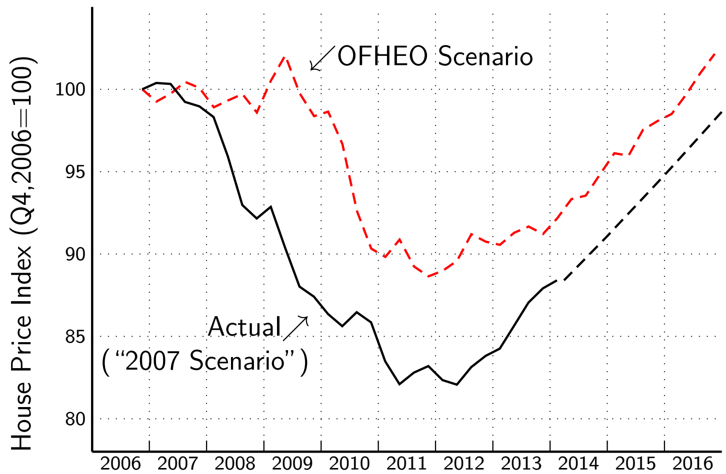


Panel B: 2007 Actual House Price Outcomes



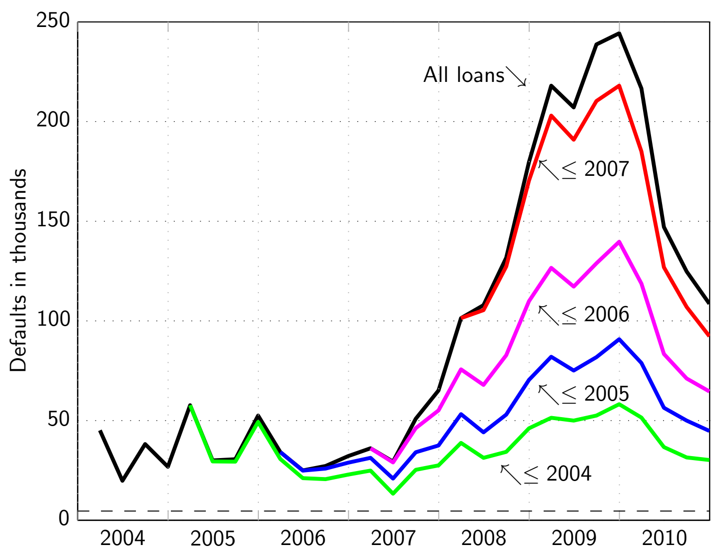
Notes: This figure displays risk-based capital calculations for the GSEs' 30-year fixed rate mortgages using the static OFHEO model, the updated model, and updated model with additional covariates. Results are presented using the OFHEO prescribed house price stress (Panel A) and the realized 2007 scenario (Panel B). We refer the reader to the online appendix for details regarding how these numbers were calculated.

Figure 7: U.S. House Price Stress: The OFHEO Scenario versus 2007 Scenario



Notes: This figure compares OFHEO's house price stress scenario to the actual path of U.S. house prices from the start of the recent housing bust in 2007:Q1 through 2013:Q1, the last quarter of available house price data. OFHEO's house price stress was the path of house prices in the West South Central Census Division between 1984 and 1993. The actual path of U.S. house prices is measured by the FHFA National House Price Index from 2007 through 2012. The dashed black line corresponds to the path of house prices from 2013:Q1–2017:Q1 assuming that prices grow at the average quarterly growth rate in the 1980–2000 period (1%).

Figure 8: Number of GSE 30-Year Fixed Rate Mortgage Defaults by Vintage: 2006–2010



Notes: This figure shows the number of foreclosure starts on 30-year fixed-rate mortgages identified as being held by Fannie Mae and Freddie Mac in the LPS data for different groups of loan vintages.

A Internet Appendix

This appendix supplements "The Failure of Supervisory Stress Testing: Fannie Mae, Freddie Mac, and OFHEO" by Frame, Gerardi, and Willen (2015) and contains the following material:

- Section A.1 presents a table that details the GSEs' overall balance sheets in the 2008–2010 period. In addition, the table breaks down losses over the period between the GSEs' single-family credit guarantee business and their investment portfolio.
- Section A.2 details how OFHEO calculated the risk-based capital charges, which they derived from the stress test and applied to Fannie Mae and Freddie Mac.
- Section A.3 provides further detail on how OFHEO developed its house price stress scenario.
- Section A.4 shows the forecast of the various models.

A.1 GSE Losses: 2008 – 2010

Table A.1: Sources of Capital Erosion at Fannie Mae and Freddie Mac: 2008–2010.

A. Overall Balance Sheet

	Fannie Mae	Freddie Mac	Combined
Beginning Capital	44	27	71
+ Equity Issuance	7	0	7
= Available	51	27	78
−Total Capital Erosion	141	91	232
= Single-Family Guarantee Earnings	118	64	181
+ Investments Contribution 3,4	0	2	3
+ Other	14	15	27
+ Senior Preferred Dividends	10	10	20
= Capital Deficit	-90	-64	-154
Treasury Senior Preferred Draw	90	64	154

B. Details of Single-Family Guarantee Business

	Fannie Mae				Freddie Mac				Combined
	2008	2009	2010	Total	2008	2009	2010	Total	2008-2010
Revenue	$9	$9	$2	$20	$5	$4	$5	$14	$35
− Credit-Related Expenses	30	71	26	127	19	34	21	70	200
= Provision for Credit Losses	26	50	25	100	16	29	19	64	165
+ Foreclosed Property Expenses	2	1	2	4	1	0	1	2	6
+ Losses on Repurchased Loans	2	20	0	23	2	5	0	6	29
− Other Expenses	2	3	2	7	1	1	2	4	11
− Loss on Tax Position	5	-1	0	3	5	-4	-1	-1	4
= **Net Income**	**-27**	**-64**	**-27**	**-118**	**-20**	**-27**	**-16**	**-64**	**-181**

C. Details of Investment Business

	Fannie Mae				Freddie Mac				Combined
	2008	2009	2010	Total	2008	2009	2010	Total	2008 -2010
Revenue	8	13	13	34	3	8	6	17	51
+ Unrealized Gains on AFS	-6	11	4	9	-20	19	14	13	22
− Portfolio Activity	20	1	-4	19	10	-10	-2	3	22
− Impairments	7	7	1	15	17	5	4	26	40
− Other Expenses	1	1	0	2	2	1	-1	1	3
− Loss on Tax Position	9	0	0	9	2	1	0	2	11
= **Investments Contribution**	**-35**	**15**	**20**	**0**	**-48**	**30**	**16**	**-2**	**-3**

Source: FHFA Conservator's Reports.

A.2 Implementation of OFHEO's Risk-Based Capital Calculation

The capital calculations presented in the paper are based on those developed by OFHEO for their risk-based capital stress test for Fannie Mae and Freddie Mac. While OFHEO carried out the capital calculations for each GSE's entire book of business, we focus on one specific component: the credit risk associated with 30-year fixed-rate mortgages. We attempt to replicate the OFHEO methodology as closely as possible, but certain aspects are omitted due to data restrictions.[41]

In each period, a GSE receives income from current mortgages and incurs expenses associated with delinquent and defaulted loans. Net income is then calculated for each quarter over the 10-year stress test horizon and then the cash flow is discounted back to the present (the quarter for which the stress test is being carried out).

As discussed above, the "stress" in OFHEO's stress test manifests itself through the assumed 10-year paths of house prices and interest rates. Based on these inputs, some covariates in the specified default and prepayment equations evolve over the 10-year horizon: the probability of negative equity, relative spread, yield curve slope, and burnout. All covariates are then used in conjunction with estimated model parameters (OFHEO's reported static estimates as well as our updated estimates) to calculate unconditional default and prepayment probabilities for each of the $t = 1, \ldots, 40$ quarters of the stress period, using the multinomial logit likelihood function:

$$\begin{aligned} P(Default_{it}) &= \frac{exp(X_{it})\beta_D}{1 + exp(X_{it})\beta_D + exp(X_{it})\beta_P} \\ P(Prepayment_{it}) &= \frac{exp(X_{it})\beta_P}{1 + exp(X_{it})\beta_D + exp(X_{it})\beta_P} \\ P(Current_{it}) &= 1 - P(Default_{it}) - P(Prepayment_{it}), \end{aligned}$$

where β_D and β_P are the parameter vectors for the default and prepayment hazards, respectively. Based on these probabilities, the performance of each mortgage is simulated in each period, conditional on its status in the previous period. The three performance states are: current, prepayment, or default.

To illustrate, assume that we have a single loan (Loan 1) with the following unconditional

[41] One other difference is that we estimate cash flows on a quarterly rather than a monthly basis.

probabilities for each state (current, default, or prepayment) as of Period 0. The goal of the simulation is to assign the loan to a state (Current, Default, or Prepayment) for each quarter of the stress test, depending on its unconditional transition probabilities in Period t as well as its state in Period $t-1$.

Loan	Period	P(Current)	P(Default)	P(Prepayment)
Loan 1	0	1	0	0
Loan 1	1	0.95	0.01	0.04
Loan 1	2	0.94	0.015	0.045
Loan 1	3	0.9	0.02	0.08

In order to assign Loan 1 to a state in Period 1, we construct the following (3 x 3) probability matrix:

From	To		
	Current	Default	Prepayment
Current	0.95	0.01	0.04
Default	0	1	0
Prepayment	0	0	1

The first row of this matrix is just the unconditional probabilities for Loan 1 in Period 1. Default and prepayment are terminal states and hence their transition probabilities are always equal to one. Pre-multiplying this (3 x 3) matrix with the (1 x 3) state vector for Loan 1 in Period 0 [1,0,0], we get the following (1 x 3) vector of conditional probabilities:

P(Current)	P(Default)	P(Prepayment)
0.95	0.01	0.04

Hence, the conditional and unconditional probabilities are the same for Period 1.

To assign a state in Period 1, we take a random draw from the uniform distribution (0, 1) and compare it to the probability vector above. If the draw Z is less than 0.95, we assign a value of 1 to P(Current) and a value of 0 to both P(Default) and P(Prepayment). If the draw instead is $0.95 < Z < 0.96$, then we assign a value of 0 to P(Current), a value of 1 to P(Default), and a value of 0 to P(Prepayment). Finally, if the draw is greater than 0.96, then P(Prepayment) is equal to 1, while P(Default) and P(Current) are each equal to 0.

Assume that our draw is $Z = 0.951$ (meaning that the loan defaults in our simulation); then data for Loan 1 looks like:

Loan	Period	P(Current)	P(Default)	P(Prepayment)
Loan 1	0	1	0	0
Loan 1	1	0	1	0
Loan 1	2	0.94	0.015	0.045
Loan 1	3	0.9	0.02	0.08

To assign a state to Loan 1 in Period 2, our (1 x 3) state vector becomes [0, 1, 0], and our (3 x 3) probability matrix is:

From	To		
	Current	Default	Prepayment
Current	0.94	0.015	0.045
Default	0	1	0
Prepayment	0	0	1

After multiplying the two, we get the following (1 x 3) vector:

P(Current)	P(Default)	P(Prepayment)
0	1	0

Since the loan defaulted in Period 1, it stays in default in Period 2 (and onwards). We still do the comparison with a draw from the uniform distribution, but when our initial state vector is a terminal state, multiplying by the probability matrix will result in a vector with the same terminal state (due to the construction of the probability matrix). After repeating for all time periods, the time series of assigned states for Loan 1 will look like the following:

Loan	Period	P(Current)	P(Default)	P(Prepayment)
Loan 1	0	1	0	0
Loan 1	1	0	1	0
Loan 1	2	0	1	0
Loan 1	3	0	1	0

Proceeding like this across all loans gives us the output of one simulation. The simulation is conducted multiple times in order to account for the randomness introduced by assigning states based on draws from the uniform distribution. However, because our actual sample size is relatively large, we obtain quite stable results when we vary the number of simulations from 2 to 5 to 10. In Table 4, the numbers reported are based on eight simulations for each quarter that the stress test is carried out.

For each quarter of the stress test, guarantee fee income accrues to the GSEs related to their holdings of 30-year fixed-rate mortgages (whole loans and those in mortgage-backed securities). We assume guarantee fees to be 0.05 percent of performing unpaid principal balance on a quarterly basis (or 0.20 percent on an annualized basis). These figures are consistent with the GSEs' historical performance.

Estimating the losses associated with defaulted loans is a much more complicated process. OFHEO assumed that the timing of the default process evolved in the following way. First, a borrower ceases payments and is delinquent for four months, after which the mortgage enters foreclosure, where it stays for 13 months. Second, upon completion of foreclosure, the mortgage ceases to exist, and the property becomes real estate owned (REO) by the lender. At that time, foreclosure expenses are incurred, and mortgage insurance proceeds (if any) are received and these net cash receipts are discounted back to the month of default, using the 6-month enterprise cost of funds index (defined below). Third, the property is assumed to remain in REO for seven months, after which time the property is sold. At that time, sale proceeds are received, REO expenses are paid, and these net receipts are discounted back to the month of default.

Once a loan is identified as having defaulted, we calculate OFHEO's loss severity rate and apply it to the outstanding unpaid principal balance (UPB) of the mortgage at the time of default. The loss severity rate for a loan is given by the following equation:

$$\begin{aligned} LossSeverityRate_{it} &= \frac{1}{(1+\frac{DR}{2})^{\frac{MDQ}{6}}} \\ &+ \frac{(\frac{MDQ}{12} * (INT_i - GFEE - SFEE)) + F - PMI_{it}}{(1+\frac{DR}{2})^{\frac{MF}{6}}} + \frac{R - RP_{it} - ALCE}{(1+\frac{DR}{2})^{\frac{MF+MR}{6}}} \end{aligned}$$

- DR Discount rate (annualized);
- MDQ Months Delinquent (assumed to be four months);
- INT Interest rate of the loan (fixed);
- GFEE Guarantee fee rate (annualized, assumed to be 20 basis points);

- SFEE Servicing fee rate (annualized, assumed to be 25 basis points);
- F Foreclosure costs (3.7 percent of defaulted UPB);
- PMI Private mortgage insurance (percentage of origination amount);
- MF Months to Foreclosure (assumed to be 13 months);
- R REO expenses (16.3 percent of defaulted UPB);
- RP REO proceeds (61 percent recovery rate divided by the updated LTV of mortgage at time of default);
- MR Months from REO acquisition to REO disposition; and
- ALCE Aggregate limit credit enhancement. (Note that ALCE is not used in our calculations, due to data limitations.)

While most of the components of the loss severity rate are constant across loans, there are a few that depend directly on the characteristics of the loan at the time of default (Interest Rate, PMI, REO Proceeds) and one that depends on the quarter of the stress test (Discount Rate).

Our data do not allow us to observe whether a particular mortgage has private mortgage insurance (PMI) or the amount of coverage. By law, the GSEs cannot purchase or guarantee a mortgage unless it has an original LTV of less than 80 percent or an equivalent credit enhancement (for example, PMI). So we assume that any loans with an original LTV exceeding 80 percent must carry this coverage. In terms of the extent of coverage, we follow what we understand to be standard conventions: (i) If $LTV 95\%$, the GSEs purchase coverage equal to 30 percent of the origination amount of the loan; (ii) If $LTV 90\%$ but $< 95\%$, the GSEs purchase coverage equal to 25 percent of the origination amount; or (iii) If $LTV > 80\% but < 90\%$, the GSEs purchase coverage equal to 12 percent of the origination amount. Moreover, once the updated LTV ratio (based on a given amortization schedule) is less than 78 percent, mortgage insurance is cancelled, as long as payments are current. Hence PMI for loan i is calculated as follows:

$$PMI_{it} = (1 - MIExp_{it}) * \text{Coverage} * (1 + (\frac{MF}{12} * INT_i) + F),$$

where

$$\begin{aligned}\text{Coverage} &\epsilon (0.12, 0.25, 0.30)\\ MIExp_{it} &= 1 \text{ if } LTV_{i,Orig} * \frac{UPB_{it}}{UPB_{i,Orig}} < 0.78,\\ &= 0 \text{ otherwise.}\end{aligned}$$

For example, for a loan with an origination LTV of 92 percent, an interest rate of 6.0 percent, and an updated LTV at time t equal to 80 percent, PMI_it would be 0.2755, or 27.55 percent of the origination amount. OFHEO's calculation for mortgage insurance coverage also includes haircuts based on the credit rating of the counterparty (insurer). We do not have the necessary information to replicate this and hence omit it from our calculation. The discount rate is the 6-month enterprise cost of funds (ECOF), which, during the stress test, is assumed to be constructed using a two-step process. First, recall that OFHEO only provides a path for the 10-year constant maturity Treasury (CMT) rate and then extrapolates to the rest of the CMT term structure. For the stress test, OFHEO set the 6-month CMT = 0.76697*10-year CMT. Second, OFHEO defined the 6-month ECOF as a proportional spread over the 6-month CMT averaged over the two years prior to the stress test: $\frac{1}{24} * \sum_{k=1}^{24} \frac{(\text{6-month } ECOF_{t-k} - \text{6-month } CMT_{t-k})}{\text{6-month } CMT_{t-k}}$. Recall that the 10-year CMT (and hence all other interest rates) evolves over the first year of the stress horizon and then remains constant for the remaining nine years. For simplicity, in all our calculations, we simply use the steady-state value for the ECOF that is, the one in force for years 2–10 of the stress test.

A.2.1 Sample Capital Calculation

Consider a stress test for loans active in the first quarter of 2006 (2006:Q2 will be the first quarter of the stress test). At the beginning of 2006:Q1, there are four active loans with original unpaid balances of $210,000, $170,000, $355,000, and $130,000. The stress test lasts three quarters. Below is the simulated performance of the loans from a single simulation.

Loans	Year-Qtr	Origination Amount	P(Current)	P(Default)	P(Prepay)
Loan 1	2006-Q2	$210,000	1	0	0
Loan 1	2006-Q3	$210,000	0	1	0
Loan 1	2006-Q4	$210,000	0	1	0
Loan 2	2006-Q2	$170,000	1	0	0
Loan 2	2006-Q3	$170,000	1	0	0
Loan 2	2006-Q4	$170,000	1	0	0
Loan 3	2006-Q2	$355,000	0	0	1
Loan 3	2006-Q3	$355,000	0	0	1
Loan 3	2006-Q4	$355,000	0	0	1
Loan 4	2006-Q2	$130,000	1	0	0
Loan 4	2006-Q3	$130,000	1	0	0
Loan 4	2006-Q4	$130,000	0	1	0

Based on the underlying characteristics of each mortgage that defaults, loss severity rates are calculated and applied to the unpaid balance at the time of default. Furthermore, guarantee fee income is calculated for loans that are current.

Loans	Year-Qtr	UPB	Loss Severity Rate	Losses	G-Fee Income
Loan 1	2006-Q1	$90,000	N/A	N/A	N/A
Loan 1	2006-Q2	$89,200	.	.	$45
Loan 1	2006-Q3	$88,400	20%	$17,680	.
Loan 1	2006-Q4	$87,600	.	.	.
Loan 2	2006-Q1	$142,000	N/A	N/A	N/A
Loan 2	2006-Q2	$141,000	.	.	$71
Loan 2	2006-Q3	$140,000	.	.	$70
Loan 2	2006-Q4	$139,000	.	.	$70
Loan 3	2006-Q1	$150,000	N/A	N/A	N/A
Loan 3	2006-Q2	$147,500	.	.	.
Loan 3	2006-Q3	$145,000	.	.	.
Loan 3	2006-Q4	$142,500	.	.	.
Loan 4	2006-Q1	$128,000	N/A	N/A	N/A
Loan 4	2006-Q2	$127,500	.	.	$64
Loan 4	2006-Q3	$127,000	.	.	$64
Loan 4	2006-Q4	$126,500	49%	$61,985	.

Losses and guarantee fee income for each quarter are summed across loans, and net losses or gains are calculated.

Year-Qtr	Total G-Fee Income	Total Losses	Net Loss
2006-Q2	$179	$0	-$179
2006-Q3	$134	$17,680	$17,547
2006-Q4	$70	$61,985	$61,916

Using a quarterly discount rate of 2 percent, calculate the present value in 2006-Q1 for “Net Loss”:

$$PV(Net\ Loss) = \frac{-179}{1.02} + \frac{17,547}{1.02^2} + \frac{61,916}{1.02^3} = \$75,034$$

Calculate the resulting net loss as a percentage of the unpaid balance at the beginning of the stress test:

$$Percent\ Losses = \frac{\$75,034}{\$90,000 + \$142,000 + \$150,000 + \$128,000} = 0.147$$

This exercise is repeated eight times for each stress test quarter and the resulting percent losses are averaged to give us the numbers in Table 4. Exercises are done separately for the two different interest rate scenarios.

A.3 OFHEO's Benchmark Loss Experience and House Price Stress

In order to identify the stressful credit conditions that are the basis for credit losses in the OFHEO risk-based capital stress test, the 1992 Act required the supervisor to identify the worst cumulative credit losses experienced by loans originated during a period of at least two consecutive years in contiguous states comprising at least 5 percent of the U.S. population. OFHEO identified loans originated in the Arkansas, Louisiana, Mississippi, and Oklahoma (ALMO) region during 1983 and 1984, which had an average 10-year cumulative default rate of 14.9 percent, as the "benchmark loss experience."

The benchmark loss experience was incorporated into the risk-based capital stress test in two ways. First, the path of house prices for the stress scenario was chosen to roughly correspond to the house price experience of the ALMO region during the 1984–1993 period . Specifically, OFHEO used the monthly growth rate of the OFHEO house price index (now the FHFA house price index) for the West South Central Census Division.[42] Second, when OFHEO applied its models of default and prepayment to the benchmark loans, the default rates generated by the model were close to the actual default rates experienced by the benchmark loans, but did not match them exactly. Due to this difference, OFHEO decided to introduce what they referred to as calibration factors for each LTV category. The calibration factors were static adjustments to the coefficient estimates associated with each LTV category in the model, which brought the estimated default rates in line with the realized default rates for the benchmark loans from the ALMO region.

Importantly, in our effort to replicate the OFHEO risk-based capital stress test, we chose to omit the calibration factors. The primary reason for this omission is the inability to calculate new calibration factors for our updated models due to data restrictions. If we had the original data used by OFHEO, we could compare the estimated default rates from our updated models with the realized default rates associated with the benchmark ALMO loans and obtain updated calibration factors. Furthermore, we are unable to identify a

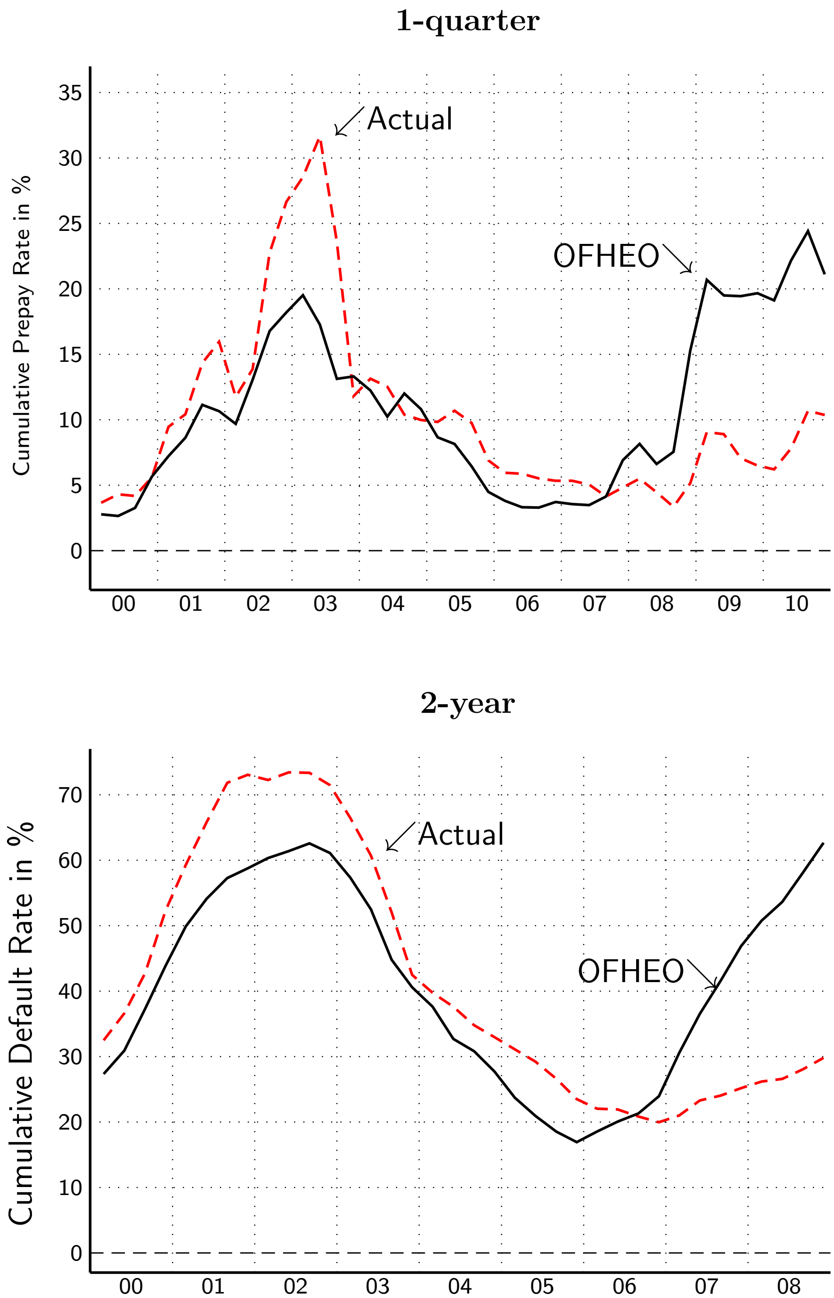
[42] The West South Central Census Division does not exactly correspond to the ALMO region as it includes the states of Arkansas, Louisiana, Oklahoma, and Texas, but does not include Mississippi.

straightforward way to translate OFHEO's reported calibration factors to estimates suitable for our models. Therefore, in order to keep our comparisons across models consistent, we decided to omit calibration factors altogether. We do not think this introduces material bias to our estimates.

A.4 Prepayment Forecasts

Figure A.1 displays actual and predicted one-quarter-ahead (top panel) and two-year-ahead (bottom panel) prepayment rates from 2000 through 2008. The model predicts prepayments relatively accurately from 2000 through 2002 and from 2004 through 2007, but significantly misses in two sub-periods. It underpredicts prepayments during the refinance boom in 2003, and severely overpredicts prepayments during the financial crisis period in 2008 and 2009.

Figure A.1: Prepayment Forecasting Performance of Models



Notes: This figure presents the actual and predicted quarter-end prepayment rate on 30-year fixed-rate mortgage loans between 2000:Q1 and 2008:Q4. Actual prepayment rates are based on mortgages identified as being held by Fannie Mae or Freddie Mac in the LPS data. Predicted prepayment rates represent the prior quarters' one-quarter-ahead forecasts using the same LPS data projected through the parameterized prepayment model published as part of the OFHEO risk-based capital stress testor by various models estimated by the authors as described in the text.