Limits of stress-test based bank regulation: Cues from the Covid-19 crisis*

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Abstract

Stress-tests can enhance welfare by providing complementary information about banks' risk exposures to regulators, which allows them to use capital surcharges to better align baseline regulation to individual banks. This paper provides suggestive evidence of inaccuracies in stress-testing using the Covid-19 crisis, and develops a model to study the attendant welfare consequences. We show that inaccuracies reduce welfare by causing excessive (insufficient) regulation of a less (more) risky bank, and by hampering banks' ex-ante incentives. Accuracy and the optimal surcharge have a non-linear relationship, and exhibit a phase shift – for accuracy below a threshold, the optimal surcharge is zero.

JEL Codes: G21, G28, C61

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1 Introduction

Stress-tests have become an important policy tool for regulators globally after the Great Financial Crisis (GFC) [Baudino et al., 2018]. They complement financial reporting and disclosures in revealing private information about banks' risk exposures to regulators [Morgan et al., 2014].[1] This enables regulators to better align baseline capital requirements to individual banks' risk profiles. In both the U.S. and the Euro Area, for instance, stress-test results are used to determine bank-specific quantitative and/or qualitative regulatory requirements.[2]

There are, however, limits to the accuracy of stress-tests, which means that regulation based on test results can be misdirected. For one, models used in the stress-test may not fully capture banks' risk exposures or their response to the crisis, and may lead to assessments that turn out to be inaccurate ex-post [Acharya et al., 2014; Philippon et al., 2017]. Relatedly, reliance on historical data to define stress scenarios may miss unprecedented events [Breuer et al., 2018]. In addition, bank-level inputs to stress-test models may be noisy or not comparable across banks [Ong et al., 2010]. Moreover, technical and computational glitches can lead to faulty results.[3] As such, stress-tests may exhibit Type-I and Type-II errors, as a result of which a less (more) risky bank may fail (pass) the test and face excessive (insufficient) regulation.

In this paper, we use the Covid-19 crisis to provide suggestive evidence of potential inaccuracies in stress-tests, and develop and estimate a model to study the attendant welfare and policy implications. To the best of our knowledge, this is the first paper on

[1] Indeed, the GFC underscored that banks, especially the large and more complex ones, can be very opaque [Gorton, 2008], and that this can give rise to information asymmetries *viz-a-viz* the regulators.

[2] In the U.S., capital surcharges (among other requirements) are determined on the basis of stress-test results. See https://www.govinfo.gov/content/pkg/FR-2020-03-18/pdf/2020-04838.pdf for more details. In the Euro Area, stress-tests conducted by the European Banking Authority (EBA) are a crucial input into the Supervisory Review and Evaluation Process (SREP) which entails capital planning, reporting, and governance requirements tailored to individual banks. See https://eba.europa.eu/eba-launches-2020-eu-wide-stress-test-exercise for more details.

[3] For example, in September 2020, the U.S. Federal Reserve Bank published corrections to its previously issued stress-test results [Fed, 2020b].

both fronts.

Several factors make the Covid-19 crisis a useful natural experiment to obtain cues about the accuracy of the 2020 US stress-test. For one, the Covid-19 crisis was unexpected, like stress-test scenarios also are. Second, the crisis featured an economic scenario that, in many ways, is similar to the ones that stress-tests typically feature. Third, the 2020 US stress test happened just before the crisis, which means that banks did not have time to adjust to the test results before the crisis hit. As such, a comparison of banks' performances – in terms of the decline in capital ratios – in the test viz-a-viz the crisis can provide cues about potential inaccuracies in stress-testing. Granted that stress-tests may not strive to forecast stressed capital ratios. Yet, broad concordance in the performance of banks in the test and in an economic crisis is to be expected because test results underpin bank regulation and thus have a material impact on the financial system.

We find that banks have fared very differently in both relative and absolute terms during the crisis as compared to the stress-test. Many banks that saw a decline in their CET1 ratios in the test were able to increase their ratios in Q2 2020. Noted that the full effect of the crisis on CET1 ratios may only be felt over a longer horizon (say once non-performing assets are recognised). Yet, that loan-loss provisions are forward looking and already rose substantially for most banks in Q2 in anticipation of future losses, the Q2 CET1 ratios ideally already reflects banks' overall performance in the Covid-19 crisis. As such, the discordance between test and actual performance points to potential Type-I/II errors. It further implies that the 2020 U.S. stress-test may have led to inefficiently harsh or liberal regulation for some banks.[4]

To assess the welfare and policy implications of potential inaccuracies in stress-testing, we build a tractable three-period model of stress-test based bank capital regulation under information asymmetry. The bank is a financial intermediary that takes deposits from the

[4]This is via the imposition of Stressed Capital Buffers (SCBs) that depend on how poorly a bank did in the test. See [Fed, 2020a] for details.

household and invests in a risky project. The return on the project can be high or low, depending on the bank's *type*, which in turn depends on the effort it exerts ex-ante. On the back of a mis-priced deposit insurance, the bank over-borrows relative to the social optimal.[5] Over-borrowing increases the probability of failure (which can be costly) and poses an externality. A minimum capital-ratio requirement can mitigate this externality.[6] However, the regulator cannot observe the bank's type, which means it cannot impose the correspondingly optimal requirement, and must adopt a *baseline* requirement that is independent of banks' types.

We introduce stress-tests in the model as a regulatory (supervisory) tool that provides a potentially inaccurate signal about the bank's type, based on which the regulator imposes a capital surcharge on top of the baseline requirement. However, the regulator faces a trade-off. Stress-tests help overcome (some) information frictions and align regulation to individual banks' risk profiles. This improves welfare. Yet, inaccuracies can lead to inefficiently low or high requirements for some banks. Inaccuracies also hamper banks' ex-ante incentives to improve their risk profile.[7] This lowers welfare. We use the model to assess this trade-off formally and characterise the optimal surcharge.

Our main contribution is to analytically derive the relationship between optimal surcharge and stress-test accuracy, as jointly measured by the Type-I and Type-II error rates. We show that this relationship is non-linear, and that it exhibits a phase-shift. When test accuracy is below a threshold, we prove that the optimal surcharge is zero. This is because lower accuracy implies that a high-type bank can fail the test more often and face an inefficiently high requirement. This not only reduces welfare *ceteris paribus* because the

[5] Typical reasons for a mis-priced deposit insurance include the inability of the insurer to observe banks' risk profiles or impose risk-sensitive premium payments. See Flannery et al. [2017] for elaboration.

[6] A large literature provides several rationales for capital-ratio requirements, such as fire-sale externalities [Kara and Ozsoy, 2016], moral hazard issues [Christiano and Ikeda, 2016], implicit guarantees [Nguyen, 2015], and household preference for safe and liquid assets [Begenau, 2019]. The approach in this paper is related to that of Kareken and Wallace [1978], Santos [2001], and Van den Heuvel [2008] who show that over-borrowing, led by mis-priced deposit insurance or otherwise, justifies capital regulation.

[7] In a similar vein, Prescott [2004] shows that poorly executed supervisory audits can create adverse incentives ex-ante.

opportunity cost of a tighter constraint is greater for a high-type bank, it also diminishes the ex-ante incentives of the bank to exert effort towards becoming a high-type. For intermediate levels of accuracy, we show that the optimal surcharge increases with accuracy, but is still smaller than what the full information benchmark would imply. In case of a perfectly accurate stress-test, any surcharge has a strong disciplining effect in terms of eliciting greater ex-ante effort from banks, and accordingly the optimal surcharge is the highest.[8]

When bank failure is costly, the regulator faces a more complex trade-off. We show that in this case, not only is the optimal baseline capital requirement stricter, the optimal surcharge for a given level of accuracy is also higher.

To illustrate our qualitative findings, and to draw quantitative implications, we calibrate the model to U.S. data. We find that the optimal baseline capital requirement lies in the range of 11% to 12%, and is higher for a low-type bank or when failure cost is large. The optimal capital surcharge varies between 0 - 0.6% depending on the exogenously given level of accuracy. In an extension of the model, we endogenise the accuracy to study the following trade-off: while a more accurate stress-test can identify banks more precisely, implementing such a test can be prohibitively costly for regulators and banks. We show that as the unit cost of accuracy decreases, the regulator optimally increases both the accuracy of the test as well as the surcharge for banks that fail the test.

Our paper belongs to a growing literature on bank stress-tests in the post-GFC period. Most studies in this literature have focused on the trade-offs associated with transparency and disclosure policy in stress-testing. For instance, greater disclosure can help enhance market discipline but also hamper ex-ante risk-sharing [Goldstein and Sapra, 2013; Goldstein and Leitner, 2018]. Relatedly, secrecy of stress-test models can prevent gaming but

[8]Our paper formalises the intuition James Bullard (President of the Federal Reserve Bank of St. Louis) had in the context of quantitative easing: *while state-contingent policies are generally desirable, they work well when the states on which the policy is contingent are known.* See this article for a coverage of his remark. Relatedly, our paper supports the remarks made by Mark Zelmer (Deputy Superintendent, OSFI Canada) in 2013 in the context of risk-sensitivity of capital requirements.

may discourage productive investment[Leitner and Williams, 2020].[9] These studies typically assume that stress-tests reveal the true risk profiles of banks.

A smaller strand of the stress-testing literature provides evidence of potential errors in stress-testing. Acharya et al. [2014] find that the stress-test based assessments of banks' capital adequacy are not in line either with market-data based assessments, nor with banks' actual performance during the European Sovereign Debt crisis in 2011. For the 2014 stress-test conducted by the European Banking Authority, Philippon et al. [2017] find that while model-based losses are good predictors of realized losses around announcements of macroeconomic news, banks headquartered in countries with weak banking system have higher realized losses compared with their losses predicted by the 2014 stress test. Frame et al. [2015] show that stress-tests conducted by the U.S. Office of Federal Housing Enterprise Oversight in the pre-GFC period failed to detect risks on the balance sheets of Fannie Mae and Freddie Mac. Covas et al. [2014] show that stress-test assessments can be more informative and less prone to gaming if they are based on density (instead of linear-model based point) forecasts.

Despite evidence on potential limitations of stress-tests, the literature has not formally assessed the attendant welfare and policy implications. Our paper fills this gap, and develops a parsimonious framework to study stress-test based bank regulation in the presence of information frictions.[10] We derive analytical characterisations of the optimal capital surcharge when stress-tests are inaccurate, and calibrate the model to provide quantitative illustrations. In addition, our paper provides complementary suggestive evidence on potential inaccuracies in stress-tests based on the Covid-19 crisis.

[9]Other studies in this literature include Corona et al. [2017] who assess how bailout regime and disclosure policy interact, Orlov et al. [2018] who characterise the optimal disclosure policy for high- and low-risk banks, and Bouvard et al. [2015] who show that the optimal disclosure policy must vary along the business cycle.

[10]Parlatore and Philippon [2018] also model stress-tests, but focus on the optimal design of stress scenarios that enable efficient information acquisition by the regulator. More generally, Morrison and White [2005] study the the effectiveness of capital regulation in avoiding crisis as public confidence in the regulator's ability to screen banks varies. Our paper, in contrast, focuses on how capital regulation must be optimally adjusted as stress-test accuracy changes.

More broadly, our paper contributes to the literature on bank-specific regulation. For instance, Marshall and Prescott [2001] show that state-contingent fines on banks can increase welfare, but assume that the states are observable. Lohmann [1992] shows that when future states are not fully known, it is sub-optimal to commit to a state-contingent policy. In contrast, we model stress-tests as a tool to learn about future states (banks' types). More recently, Ahnert et al. [2020] show that sensitivity of regulation to banks' types must depend on the precision of the attendant signal, like in our paper. Yet, while they show that starting from high precision, lower precision implies greater sensitivity of regulation to risk, we show that such a strategy can decrease welfare by creating adverse incentives ex-ante. This difference stems from the fact that we allow banks to affect the probability that they face a capital surcharge, due to which regulation can affect ex-ante incentives.

2 The Covid-19 crisis: A test of stress-tests

In this section, we review supervisory stress-tests in the U.S., and use the Covid-19 crisis to shed light on potential inaccuracies in stress-test assessments.

2.1 Institutional Background

The Dodd-Frank Wall Street Reform and Consumer Protection Act (Dodd-Frank Act) was enacted in response to the Great Financial Crisis (GFC). It requires the U.S. Federal Reserve Bank (Fed) to conduct an annual stress-test – known as the Dodd Frank Act Stress Test (DFAST) – of large bank holding companies (BHCs).[11] The goal is to evaluate whether the tested entities have sufficient capital to absorb losses resulting from adverse economic conditions. The first DFAST was conducted in 2013, and has evolved quite a bit

[11]Non-bank financial companies designated by the Financial Stability Oversight Council (FSOC) for Fed supervision are also included in the exercise.

since. We focus on the 2020 DFAST in our analysis [DFAST, 2020].

The DFAST considers a hypothetical severely adverse scenario – one in which the U.S. economy experiences a significant recession and financial market stress while other major economies also experience contraction in economic activity – and projects the revenues, expenses, losses, and, crucially, the capital ratios of the participating banks. The projections are generated using inputs provided by the tested banks and forecasting models developed or selected by the Fed. The projections use a standard set of capital action assumptions that entail zero common stock dividend distribution, and no issuance or repurchase of common or preferred stock.[12]

The Federal Reserve imposes a capital surcharge on banks based on their performance in the test, as measured by the projected decline in their Common Equity Tier 1 (CET1) capital ratios in the severely adverse scenario.[13] Banks that perform poorly face a higher Stressed Capital Buffer (SCB) – a surcharge on top of the baseline capital requirements and any other surcharges (such as the G-SIB surcharge) – among other qualitative and quantitative requirements.

2.2 The 2020 Stress-Test

The severely adverse scenario in the 2020 DFAST comprised of a peak unemployment rate of 10 percent, a decline in real GDP of 8.5 percent, and a drop in equity prices of 50 percent through the end of 2020, among other macroeconomic developments.[14] Thirty-three entities participated in the test and the results were published in June 2020, which included projections for the decline in the CET1 ratio relative to the end-2019 value (see

[12]Scheduled dividend, interest, or principal payments that qualify as additional tier 1 capital or tier 2 capital are assumed to be paid, but repurchases of these instruments is assumed to be zero.

[13]The results also contain other capital ratios, namely the tier 1 and total capital ratios, and the tier 1 and supplementary leverage ratios. We focus our attention on the CET1 ratio since it is a core measure of capital adequacy, and also because capital surcharge is expressed in these terms.

[14]The severely adverse scenario was designed in late 2019 and was published in February 2020. While the 2020 DFAST did not adapt the severely stress scenario to incorporate the Covid-19 crisis, it disclosed additional information about predicted aggregate losses in the banking sector based on a sensitivity analysis viz-a-viz the Covid-19 crisis. Bank-level results from this exercise were not disclosed.

Figure 1: Decline in the CET1 ratio in the 2020 DFAST. Unit of the x-axis is percentage points.

Figure 1). The average decline was 2.7 percentage points, with Deutsche Bank USA and the Goldman Sachs Group being the worst performers, and Northern Trust and American Express being the best performers.

Performance in the stress-test and the attendant capital surcharge have a strong and positive relationship.[15] Beyond the minimum SCB of 2.5%, the two go hand-in-hand to a large extent (see Figure 2). In fact, for some banks (eg DB USA, MUFG, HSBC, RBC) the SCB is equal to decline in CET1 ratio in the stress-test. This observation confirms that a bank's performance – especially poor performance – in the test is tightly linked to the capital requirement it faces.

[15]This is despite other considerations that go into calibrating the SCB.

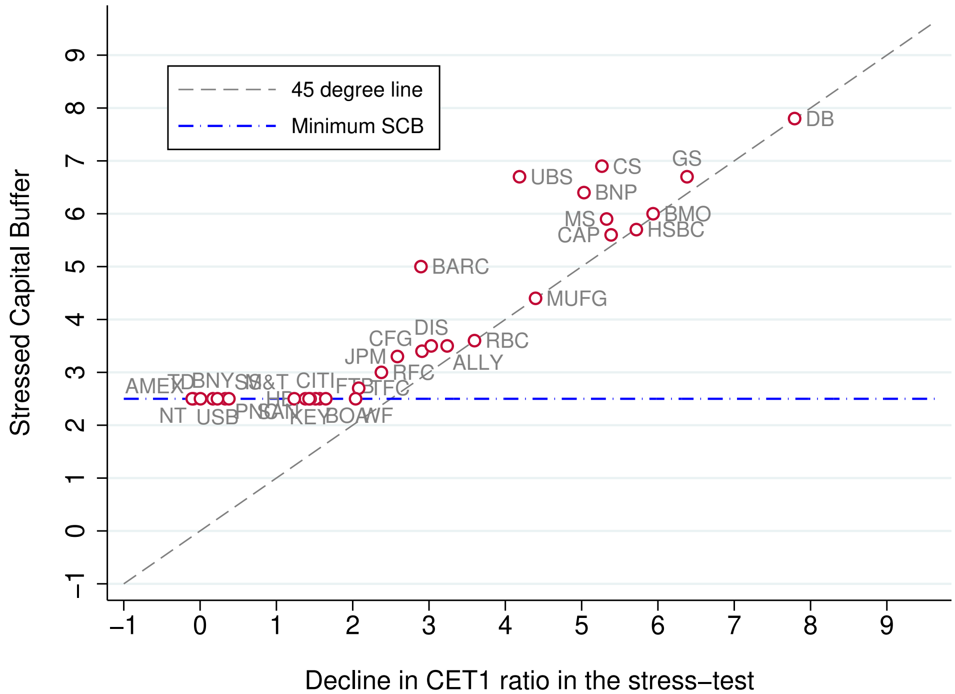

Figure 2: A comparison of the decline in CET1 ratio in the 2020 DFAST and the Stressed Capital Buffer (SCB) imposed on banks. Unit of both axes is percentage points.

2.3 Bank performance during the Covid-19 crisis

Several factors make the Covid-19 crisis a useful natural experiment to appraise the 2020 US stress-test. For one, the Covid-19 pandemic has led to an extremely severe shock to economic activity. At least qualitatively, this is what a typical stress-test scenario emulates. And even though the observed decline in macroeconomic indicators (such as GDP growth rate and employment) is not necessarily *equal* to the one in the 2020 DFAST scenario, they are broadly consistent.[16] In addition, the Covid-19 shock was completely unexpected, like in the case of stress-tests where the hypothetical scenarios are not known to banks in advance. Moreover, the timing of the 2020 DFAST is also ideal for our analysis. The test results were announced on 25th June, which means that it is unlikely that banks were able to anticipate the attendant capital surcharges (i.e. the SCBs) and adjust/raise capital in

[16]The U.S. economy contracted by close to 30% (YoY) in Q2 2020; the peak unemployment rate was 15%; and the Dow Jones Index plunged by close to 30% in March 2020.

time for their second-quarter (i.e., end-June) earnings reports. These factors imply that endogeneity issues associated with the Q2 2020 CET1 ratios can be ruled out.[17]

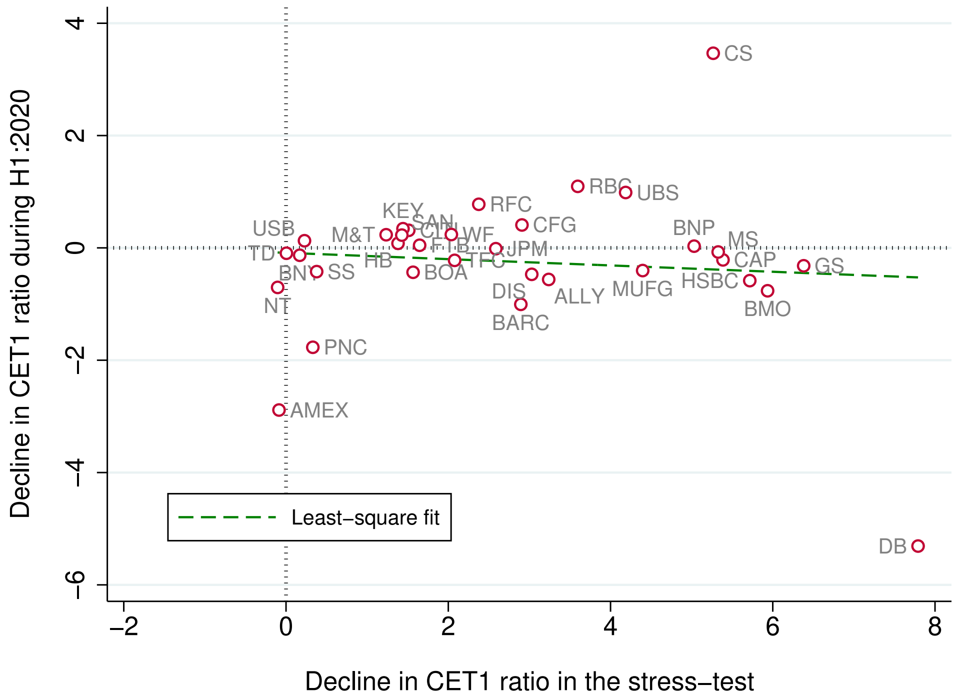

Figure 3: A comparison of the decline in CET1 ratio in the stress-test and the actual decline observed between Q4:2019 and Q2:2020. Unit of both axes is percentage points.

A comparison of the decline in CET1 ratios of banks in the test with the decline observed during the first half of 2020 reveals that the actual and projected declines in CET1 ratios do not line-up (see Figure 3).[18] In fact, while the ratios declined for almost all banks in the test, it rose for many in reality. In the case of Deutsche Bank USA, for instance, the CET1 ratio declined by 8 percentage points (pp) in the test, while during H1 2020, the same ratio rose by 5 pp. A similar although less stark narrative applies to most other banks, and points to potentials Type-I/II errors in stress-test based assessments.[19]

Even in terms of *relative* (cross-sectional) performance of banks in the test as compared

[17]Potential endogeneity issues also suggest that the 2019 DFAST or the 2018 European Banking Authority (EBA) stress-tests cannot be appraised against banks' actual performances in the Covid-19 crisis as banks are likely to act on the test results and evolve materially in the meantime. Note that the 2020 EBA stress-test was postponed to give banks operational relief.

[18]Bank data for end-2019 and Q1 2020 are sourced from Fitch, while Q2 2020 data are sourced from

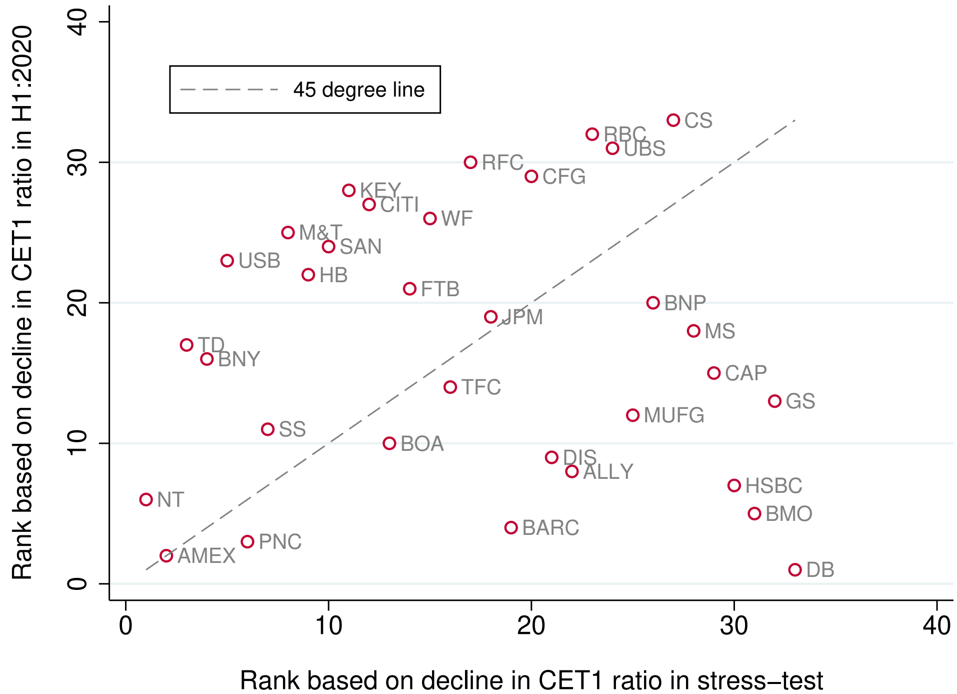

Figure 4: A comparison of the rank based on decline in CET1 ratio in the stress-test and rank based on the actual decline observed between Q4:2019 and Q2:2020. A lower rank (number) indicates a smaller decline in the ratio.

to reality, we notice a high degree of discordance. A comparison of the rank based on the projected and actual declines in the CET1 ratio uncovers large deviations from the 45-degree line that marks the same rank in the test and in reality (see Figure 4).[20] Large deviations above (below) the 45 degree line are once again underscore that several banks did better (worse) in reality as compared to the test.

There are caveats in our approach to identifying Type-I and Type-II errors in stress-tests. First, the CET1 ratio of banks may not have bottomed out yet – and thus the Q2 estimates may not be comparable to the projected declines.[21] However, the fact that risk-weighted assets and loan loss provisions (LLPs) are forward looking, and that banks

the Y9-C reports.

[19]Note that for most banks, the primary driver of change in the CET1 ratio is risk-weighted assets as opposed to the level of CET1 capital. This is consistent with the capital action assumption in DFAST which does not allow for new issuance of CET1 capital.

[20]A lower rank corresponds to a smaller decline in the CET1 ratio and indicates better performance.

[21]The DFAST results only report the minimum and the end-of period ratios.

front-loaded by increasing LLPs substantially in Q2, means that the Q2 capital ratios ideally reflect banks' overall performance in the crisis. Second, differences in some aspects of the severely adverse scenario and the Covid-19 crisis (eg decline in house price index) may render a comparison of the decline in capital ratios in the two cases less meaningful. Relatedly, some banks may be less/more well-positioned to handle specific aspects of the Covid-19 shock, so that *actual* and *test* performances may not be at par. More generally, stress-tests may not be designed to predict future crises or bank's capital ratios therein. Nonetheless, broad concordance in banks' performances in the test and in a crisis, at least in a relative sense, is desirable, not least because stress-test results inform bank regulation and have a material impact on the financial system. More importantly, as we show below, such discordance can create adverse ex-ante incentives and diminish the welfare gains from regulation.

3 Model

Our goal is to analyse the welfare and policy implications of stress-test based capital requirements when stress-tests are potentially inaccurate. To this end, we develop a model with the following main elements. First is a general equilibrium setup that enables us to capture the welfare effect of regulation on the (representative) household's utility. Second is a dynamic setup that allows us to assess the effect of future stress-test and regulation on banks' ex-ante behavior. Third is a rationale for capital-regulation – specifically, an externality that warrants regulatory intervention. Fourth is information frictions – i.e., the unobservability of a bank's type by the regulator – that justify the use of stress-tests. Accordingly, we consider an economy that lasts three periods (0, 1 and 2), and consists of a representative household, a bank that poses an externality and whose type is stochastic, a regulator that cannot (fully) observe the bank's type, and the government.

Household The household is representative, and receives an unconditional income endowment $\bar{Y}$ on dates 1 and 2. On date-1, it decides how much to consume, c_1, and how much to deposit, d, in the bank.[22] Deposits are risk-free, and pay a gross return of R on date-2. The household is also the owner of the bank and receives dividends n on date-2. It pays a lump-sum tax T.

Bank The bank has a capital endowment of k on date-1, and issues deposits d to raise additional funding. It invests $k + d$ in a risky project that pays $\psi g(k + d)$ on date-2, where $g(.)$ is a decreasing returns to scale (DRS) return function. ψ is an investment shock whose density f_s depends on the bank's type s on date-1, which can be high (H) or low (L). Specifically, we assume that while both types face the same standard deviation of ψ, namely σ, the high-type bank has a higher expected return, $\mu_H > \mu_L$, or equivalently, higher *risk-adjusted return*.[23] The probability p with which the bank is of high-type depends on the effort e it exerts on date-0. The cost of exerting effort is $\zeta(e)$.

The bank's deposit liabilities on date-2 equal Rd, and thus the net cash flow equals $\psi g(k + d) - Rd$. When ψ is sufficiently high and the bank is solvent, it transfers the entire cash-flow as dividends n to the household. However, when ψ is low enough so that the cash-flow is negative, the bank fails and shareholders receive null. We assume that shareholders have limited liability, so that they cannot be asked for additional capital to rescue a failing bank. Instead, the government takes the bank into receivership.

Government The government runs the deposit insurance scheme and ensures that depositors are fully protected against bank failure. When a bank fails, the government takes its assets into custody, liquidates the same, and covers any shortfall in the failed bank's

[22] A time subscript is used only for those quantities that are relevant on multiple dates. For instance, since d is only chosen once, on date-1, a time subscript is omitted.

[23] The exact connotation of high and low types is not critical as long as the high-type bank is better from a social welfare point of view. For instance, equivalent connotations of being a high-type bank may stem from having the same mean but lower standard deviation of ψ, or a lower cost of funding.

liabilities via a tax T on the bank's owner, i.e. the household.[24] We assume that the tax is lump-sum. This assumption entails that the insurance scheme is mis-priced, and, as we prove later, leads to an externality.[25] The government runs a balanced budget.

Regulator The regulator is benevolent, i.e. it strives to maximise the welfare of the household. On date-0, it announces the minimum capital-ratio requirement χ that the bank must satisfy on date-1. However, we assume that the regulator cannot *observe* bank's type on date-1. In the baseline economy, as such, it must announce a requirement that does not depend on banks' types, i.e. applies universally to both types of banks on date-1. In the economy with stress-tests, the regulator is able to obtain a noisy signal about the bank, and classify it as a high- or low-type depending on whether it passes or fails the test. The regulator then announces a surcharge x for failing the stress-test, effectively imposing a bank-type specific requirement $\chi_s, s \in \{H, L\}$.

Recursive formulation We now formally setup the problem statements of the agents in the economy. The household chooses d on date-1 to maximize its expected utility over dates 1 and 2:

$$U = \max_{d} \quad c_1 + \beta \mathbb{E} c_2 \quad s.t. \quad c_1 = \bar{Y} - d \quad and \quad c_2 = \bar{Y} + Rd + n - T. \tag{1}$$

The bank chooses e on date-0 which determines the probability of being an H-type on date-1:

$$[Date - 0]: \quad \max_{e} \quad -\zeta(e) + \beta \Big(p(e) V_H(\chi_H) + (1 - p(e)) V_L(\chi_L) \Big). \tag{2}$$

[24]Alternatively, and equivalently, we can treat T as a deposit-insurance premium imposed on the bank.

[25]The reason for introducing an externality in our model is to rationalise capital requirements. A mis-priced deposit insurance is not the only way to do so, but it is a relatively simple method that helps keep our model tractable. Another paper to have taken this route is Van den Heuvel [2008]. A moral hazard between banks and its creditors [Gertler and Kiyotaki, 2010], or implicit government guarantees [Nguyen, 2015] are among the several other ways in which capital requirements can be justified.

where $V_s(\chi_s)$ is defined in Equation (3). Subsequently, the bank of type $s \in \{H, L\}$ chooses d on date-1 to maximize the expected dividend it pays on date-2:

$$[Date-1]: \quad V_s(\chi_s) = \max_d \quad \beta \int_{\frac{Rd}{g(k+d)}}^{\infty} \underbrace{\Big(\psi g(k+d) - Rd\Big)}_{n} f_s(\psi) d\psi \quad s.t. \quad \frac{k}{\chi_s} \geq d. \tag{3}$$

The lower limit on the integral is the ψ cut-off – call it ψ_c – below which the bank fails (and dividends n equal zero). χ_s are the bank-type specific minimum capital-ratio requirements (although the requirements will be the same in the absence of stress tests). The government's budget constraint is as follows:

$$T = \begin{cases} Rd - \psi g(k+d) & \text{If the bank fails i.e. } \psi \leq \frac{Rd}{g(k+d)} \\ 0 & \text{Otherwise} \end{cases} \tag{4}$$

4 Qualitative Analysis

We begin by assessing the equilibrium conditions in the baseline economy. We then characterise – as a benchmark – the optimal regulation in the absence of stress tests. Finally, we analyse the optimal capital surcharge based on stress-test results, including when bank failure is socially costly.

4.1 The competitive equilibrium

The first-order condition (FOC) of the bank's problem on date-0 shows that the effort the bank exerts depends on the *wedge*, say ω, between the value of being a high- as opposed to low-type on date-1:

$$-\zeta'(e) + \beta p'(e) \underbrace{\Big(V_H(\chi_H) - V_L(\chi_L)\Big)}_{\omega} = 0 \tag{5}$$

To see how the effort changes as the wedge increases, we take the total derivative of the Equation 5 with respect to ω, from where it is straightforward to note Lemma 1:

$$- \zeta''(e)\frac{de}{d\omega} + \beta p''(e)\omega\frac{de}{d\omega} + \beta p'(e) = 0 \tag{6}$$

Lemma 1. *If $\zeta(.)$ is increasing and convex, and $p(.)$ is increasing and concave, then the bank exerts more effort when the difference in the value of being a high type compared to a low type increases, i.e. $de/d\omega > 0$.*

The pre-conditions for Lemma 1 to hold are sufficient but not necessary. For instance, the result still holds if $\zeta(.)$ is increasing and linear. Nonetheless, that becoming a high-type bank is increasingly difficult is a realistic assumption to have.

Lemma 1 underscores an important insight. The minimum requirements (χ_H, χ_L) announced on date-0 affect the wedge ω by impacting the value of the bank on date-1. As such, the minimum requirements are a key factor in bank's effort choice on date-0.[26]

As regards the date-1 FOCs, we have the following:

$$\text{Bank:} \qquad \beta \int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g'(k+d) - R\Big) f_s(\psi) d\psi - \Lambda_s = 0 \tag{7}$$

$$\text{Household:} \qquad R = 1/\beta \tag{8}$$

Note in the bank's FOC that Λ_s is the Lagrange multiplier on the regulatory constraint, and that two of the three terms which arise from a routine application of the Leibniz rule are equal to zero. The system of FOCs (5), (7), (8) and the government's budget constraint (4) together characterise the competitive equilibrium of the model economy for a given set of minimum capital-ratio requirements (χ_H, χ_L).

[26]Lemma 1 is related to a similar result proven in Christiano and Ikeda [2016], except for the channel through which regulation has an impact on the bank's effort.

4.2 Optimal ex-post regulation

We now assess the efficiency of the competitive equilibrium, and discuss the role that regulation could play in improving welfare. In this section, we focus on the date-1 economy, and turn to the date-0 economy (and the discussion of stress tests) in the next subsection.

Inefficiency of the competitive equilibrium We compare allocations in an unregulated date-1 economy with a benevolent social planner's allocations. Without loss of generality, we focus on the case of an s-type bank, where s could be high or low.

We consider a constrained social planner that maximizes household welfare, chooses the level of deposit-based funding on behalf of the bank, but takes as given the household's first order condition:

$$\max_d \quad c_1 + \beta \mathbb{E} c_2 \quad s.t. \quad R = 1/\beta; \quad c_1 = \bar{Y} - d; \quad c_2 = \bar{Y} + Rd + n - T$$

Since the planner internalises the effect of choosing d on n and T, we can solve for c_2 using expressions for n and T from equations (3) and (4) respectively:

$$c_2 = \bar{Y} + \psi g(k+d) \tag{9}$$

Next, we rewrite the planner's objective after plugging in the expressions for c_1, c_2, rearranging terms using the household's FOC, and segregating the expectation (i.e. the integral on c_2) at the ψ cutoff for failure of the bank:

$$\max_d \quad (1+\beta)\bar{Y} + \underbrace{\beta \int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g(k+d) - Rd\Big) f_s(\psi) d\psi}_{\text{Bank's date-1 objective}} + \beta \int_0^{\frac{Rd}{g(k+d)}} \Big(\psi g(k+d) - Rd\Big) f_s(\psi) d\psi. \tag{10}$$

By segregating the integral into two parts, the first part matches the bank's objective function, and thus facilitates a comparison of bank's and planner's FOCs, as shown below:

$$\beta \int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g'(k+d) - R\Big) f_s(\psi) d\psi + \underbrace{\beta \int_{0}^{\frac{Rd}{g(k+d)}} \Big(\psi g'(k+d) - R\Big) f_s(\psi) d\psi}_{\text{Bank-failure externality}} = 0. \qquad (11)$$

Equation (11) uncovers a wedge between the planner's FOC and the bank's FOC in the unregulated economy (i.e. equation (7) with $\Lambda_s = 0$). This wedge stems from limited liability and a mis-priced deposit insurance. Basically the bank does not internalise the left tail of the distribution of ψ – the part that corresponds to bank failure. The planner, on the contrary, chooses the level of deposits taking into account the entire distribution of ψ. We refer to this wedge as the bank-failure externality, which the following lemma characterises.[27]

Lemma 2. *The bank's capital ratio, defined as k/d, is smaller in the competitive equilibrium as compared to that in the constrained planner's problem, i.e. second best.*

Proof. Assume that the externality term is positive. Then, $\beta \int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g'(k+d) - R\Big) f_s(\psi) d\psi$ must also be positive. But this is a contradiction since the overall expression for the planner's FOC must equal zero. As such, the externality term must be negative. In turn, this implies that $\beta \int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g'(k+d) - R\Big) f_s(\psi) d\psi > 0$. We know that d^{CE} (the level of deposits in the competitive equilibrium) satisfies $\beta \int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g'(k+d) - R\Big) f_s(\psi) d\psi = 0$. But since $g(.)$ is concave, it must be that $d^{CE} > d^*$ where d^* solves the constrained planner's problem. ■

Implementability of the constrained efficient allocation That the competitive equilibrium exhibits an externality implies that $W^{CE} \leq W^*$ where W^{CE} is the welfare in the competitive equilibrium and W^* is the second-best welfare. The question that

[27] The finding that the bank takes more leverage than what is socially optimal is not unique to this paper, nor is it our main contribution. Several other studies have related findings, such as Van den Heuvel [2008] and Christiano and Ikeda [2016], for instance. Our approach is to develop a relatively parsimonious model that has the mechanisms needed to study the welfare effects of stress-test based capital requirements.

follows is whether a regulatory intervention can help implement or approach the second best.

To this end, we consider a benevolent regulator that sets a minimum capital-ratio requirement $k/d \geq \chi_s$ on the bank in order to maximize welfare. In choosing χ_s, the regulator faces the following trade-off. A higher χ_s forces the bank to reduce deposit-based funding and accordingly its failure probability, which has a welfare improving effect due to a smaller bank-failure externality. Yet, a higher χ_s depresses expected output, which has a welfare reducing effect.

In effect, the regulator's decision problem is very similar to that of a constrained planner. This is because choosing deposits on behalf of the bank to maximise welfare is equivalent to imposing a minimum capital-ratio requirement with the same objective when capital is fixed and the requirement is binding. This is formally seen by comparing equations (7) and (11). Indeed, the first terms are identical. And to the extent the Lagrange multiplier Λ_s on (i.e. the shadow cost of) the regulatory constraint in (7) is equal to the absolute value of the bank-failure externality term in (11), the solution to the two equations must be identical. We note this result in the lemma below, and denote the optimal regulation for an s-type bank by χ_s^o.

Lemma 3. *The solution to the constrained planner's problem can be implemented via a minimum capital-ratio requirement.*[28]

Before turning to the date-0 problem, we document a result that will be useful later. It compares the optimal date-1 regulation for high- and low-type banks.

Lemma 4. *The regulator optimally sets stricter ex-post regulation on the low-type bank as compared to a high-type bank, i.e.* $\chi_L^o > \chi_H^o$.

[28] A capital-ratio requirement is not the only regulatory tool that can implement the second best. A tax (or a deposit insurance premium) that is a function of the balance sheet choice of the bank can achieve the same outcome.

Proof. Consider the non dis-aggregated version of the planner's date-1 FOC – i.e. equation (11) – for both high- and low-type banks. This characterises the optimal level of deposits in each case.

$$0 = \int_0^\infty \Big(\psi g'(k+d) - R\Big) f_s(\psi) d\psi = \mu_s g'(k+d) - R \quad s \in \{H, L\} \tag{12}$$

The total derivative of d with respect μ_s implies:

$$g'(k+d) + \mu_s g''(k+d)\frac{\partial d}{\partial \mu_s} = 0 \implies \frac{\partial d}{\partial \mu_s} > 0 \quad s \in \{H, L\} \tag{13}$$

This immediately implies that the optimal d is higher, or equivalently, the optimal χ^o is lower for a high-type bank. ■

Intuitively, *ceteris paribus*, a low-type bank not only poses a lower expected output, but is also more likely to fail. It thus poses a greater externality which rationalises stricter regulation.

4.3 Optimal ex-ante regulation

The bank forms expectations and chooses its date-0 decisions based on date-1 requirements announced by the regulator on date-0.[29] However, because the bank's type on date-1 is its private information, the regulator cannot announce a type-specific requirement (such as χ_L^o and χ_H^o for low- and high-type banks respectively).[30] As a result, the regulator must adopt a bank-type independent capital requirement – say χ – which is applicable on date-1 irrespective of the bank's type. To characterize the optimal χ, we begin with the following result.

[29] We abstract away from time-inconsistency issues, and assume that regulatory announcements are credible.

[30] In reality, regulators do have some knowledge about banks' characteristics (such as via regulatory filings). We assume that the observable characteristics are embedded in the return function $g(.)$ of the bank while *type* simply summarizes the unobservable characteristics. Furthermore, we assume that the bank cannot credibly communicate its type to the regulator, except via its performance in a stress-test.

Lemma 5. *Assume that regulation χ binds for both bank types on date-1. Then the effort the bank exerts on date-0 decreases as χ rises.*

Proof. As shown in Lemma 1, the bank's date-0 effort e depends on $\omega = V_H(\chi) - V_L(\chi)$, i.e. the wedge between the value of being a high- versus low-type on date-1. The key then to proving this lemma is to characterise how regulation impacts ω.

$$\omega = \beta \int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g(k+d) - Rd\Big) f_H(\psi) d\psi - \beta \int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g(k+d) - Rd\Big) f_L(\psi) d\psi$$

where $d = k/\chi$. The derivative of ω with respect to χ gives:

$$\frac{\partial \omega}{\partial \chi} = -\frac{k\beta}{\chi^2} \left(\underbrace{\int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g'(k+d) - R\Big) f_H(\psi) d\psi}_{\Lambda_H} - \underbrace{\int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g'(k+d) - R\Big) f_L(\psi) d\psi}_{\Lambda_L} \right) \quad (14)$$

where Λ_s is the Lagrange multiplier on the regulatory constraint in the bank's problem.

To sign this expression, we proceed as follows. First note that since the regulatory requirement is the same for both types of banks, their deposit choices and thus the failure cutoffs ψ_c are also the same. Then let $\hat{F}_H$ and $\hat{F}_L$ be the distribution functions of ψ for high- and low-type banks, truncated below at ψ_c. Since $\mu_H > \mu_L$, $\hat{F}_H$ *FOSD* $\hat{F}_L$, that is $\hat{F}_H(\psi) \leq \hat{F}_L(\psi)\ \forall\ \psi$. Finally, since $(\psi g'(k+d) - R)$ is an increasing function of ψ, it follows that:

$$\int \Big(\psi g'(k+d) - R\Big) d\hat{F}_H(\psi) - \int \Big(\psi g'(k+d) - R\Big) d\hat{F}_L(\psi) = \Lambda_H - \Lambda_L > 0.$$ [31]

[31] To prove this formally, consider continuous distribution functions G and H such that $\forall x, H(x) \leq G(x)$, and define $y(x) = H^{-1}(G(x))$. Then for any increasing function $w(x)$, $\int w(y(x))dH(y(x)) = \int w(y(x))dG(x)$. Next, note that $y(x) = H^{-1}(G(x)) \implies y(x) \geq x$ since $\forall x, H(x) \leq G(x)$. In turn, since $w(.)$ is an increasing function, $w(y(x)) \geq w(x)$. Thus, $\int w(y(x))dG(x) \geq \int w(x)dG(x)$. Indeed, intuitively, the *shadow cost* of the minimum capital-ratio constraint should be greater for a bank whose assets are *ceteris paribus* more profitable.

In turn, this implies that $\frac{\partial \omega}{\partial \chi} < 0$. Then from Lemma 1 we know that $\frac{\partial e}{\partial \omega} > 0$, which completes the proof since:

$$\frac{\partial e}{\partial \chi} = \frac{\partial e}{\partial \omega}\frac{\partial \omega}{\partial \chi} < 0.$$

■

Lemma 5 points to an important trade-off the regulator faces while setting χ. Compared to no regulation ($\chi = 0$), a higher χ can improve welfare *ex-post* by mitigating some of the externality the bank poses, especially in case of a low-type bank. Yet, a higher χ can reduce welfare due to its adverse impact on effort exerted *ex-ante*. Moreover, as the following proposition shows, a high χ can be inefficient ex-post, especially in case of a high-type bank.

Proposition 1. *The optimal ex-ante requirement χ^o in the case where the regulator cannot observe the bank's type, is saddled by the optimal ex-post requirement for low- and high-type banks, ie $\chi^o_L > \chi^o > \chi^o_H$.*

Proof. The optimal ex-ante requirement, χ^o, solves the following problem:

$$\max_{\chi} \quad \beta p(e)U_H(\chi) + \beta(1 - p(e))U_L(\chi).$$

Here U_s is the household's expected lifetime utility over dates 1 and 2 when the bank turns out to be of type s. Also, both e and U_s depend on χ. The planner's problem can be re-written equivalently as follows.

$$\equiv p(e)\Big(\bar{Y}(1+\beta) - d + \beta\mu_H g(k+d)\Big) + (1-p(e))\Big(\bar{Y}(1+\beta) - d + \beta\mu_L g(k+d)\Big)$$

$$\equiv \bar{Y}(1+\beta) - d + \beta g(k+d)\underbrace{\Big(p(e)(\mu_H - \mu_L) + \mu_L\Big)}_{\mu_{avg}}$$

Here μ_{avg} is the expected efficiency of the bank, which has the following properties: (i)

$\mu_{ex} = \mu_H$ when $p(e) \equiv 1$; (ii) $\mu_{ex} = \mu_L$ when $p(e) \equiv 0$; (iii) $\mu_L \leq \mu_{ex} \leq \mu_H$. We know from the proof of Lemma 4 that as μ increases, the regulator chooses a smaller $\mathcal{X}$ (ie loosens the requirement). This immediately leads to the current proposition. ■

Intuitively, this proposition shows that when there is information asymmetry, the regulator chooses a *middle-ground* relative to ex-post optimal levels of bank-type specific requirements.

4.4 Mitigating information frictions via stress-tests

Stress test allows the regulator to gather information about banks' types. It thus helps mitigate some information frictions and allows capital requirements to be better aligned to the banks' types. This is desirable as it can improve welfare.

In this subsection, we incorporate stress tests in our model. We assume that the test delivers a noisy signal η to the regulator about the bank's type. The signal distribution Q_H of high-type banks dominates (in the first order stochastic (FOSD) sense) the signal distribution Q_L of low-type banks. Depending on it's preferences for true- and false-positive and negative rates, the supervisor uses a signal cutoff η^c above (below) which the bank is considered pass (fail) and is deemed to be of the high- (low-) type. Thus the probability that a high-type bank passes the test is given as $q_H = 1 - Q_H(\eta^c)$, and the same for an L type bank is given as $q_L = 1 - Q_L(\eta^c)$. Moreover, $Q_H \succcurlyeq_{FOSD} Q_L \implies q_H > q_L$.[32]

The accuracy of the stress-test is fully captured by the tuple (q_H, q_L). Any test can thus be represented by a point in the set $[0,1] \times [0,1]$, as shown in Figure 6. In this format, $(1 - q_H)$ denotes the 'false positive' or Type-I error rate (high-type bank fails the test), while q_L is the 'false negative' or Type-II error rate (low-type bank passes the test). A convenient benchmark, which is equivalent to the full-information case, is when $q_H = 1$ and $q_L = 0$, i.e. a *perfect* stress-test that exactly identifies the type of the bank. In all other

[32] For sake of brevity, we do not model the signal distributions or the regulator's preferences that underpin the signal cutoff η^c. Instead, we directly work with pass probabilities.

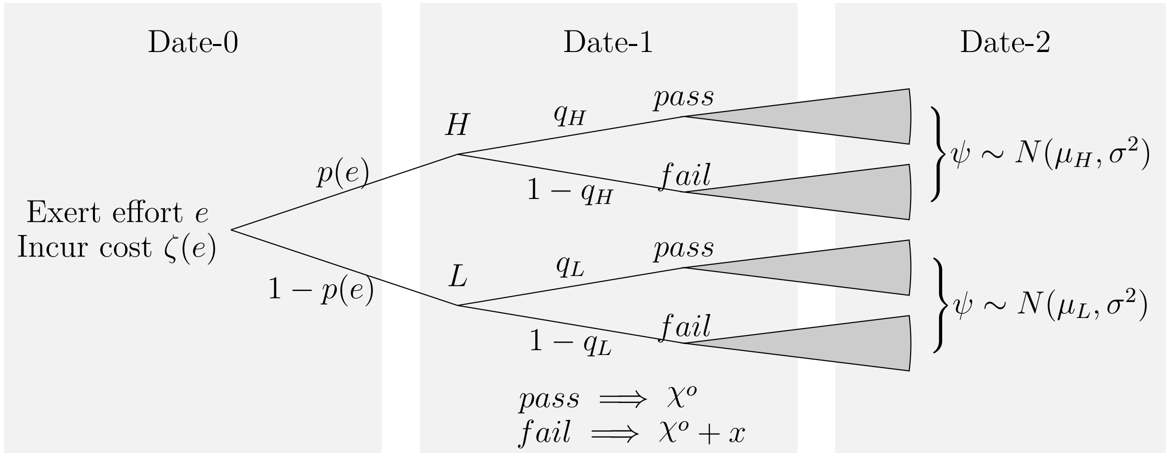

Figure 5: The timeline of events when there is information asymmetry about the bank's type, and stress tests serves as a tool to (partially) mitigate information frictions.

cases, we refer to the test as *imperfect* because an H type bank can fail the test ($q_H < 1$) or an L type bank can pass the test ($q_L > 0$).

The regulator uses the outcome of the stress-test to adjust the baseline capital requirement χ^o. We assume that a bank that passes the stress test is deemed high-type and is allowed to operate at χ^o. A failed bank is deemed to be of the low-type, and is penalized and its capital-ratio requirement in increased by a surcharge $x \geq 0$ (see Figure 5 for the timeline).[33]

The core question of interest then is as follows: what is the welfare maximising level of surcharge x that the regulator must announce on date-0. The choice of x is non-trivial, and must balance a three-way trade-off.

1. In case of the low-type bank, the surcharge (upon failing the test) **increases** welfare *ceteris paribus* as long as $x < \chi_L^o - \chi^o$. This is because the surcharge brings the ex-ante requirement ($\chi^o + x$) closer to the ex-post optimal (χ_L^o).

2. In case of the high-type bank, the surcharge (upon failing the test) **decreases** welfare

[33] This is not the only way in which capital requirements may be imposed following the result of a stress-test. For instance, a regulator may choose to relax the requirement for a bank that passes the test. However, in practice, this is not typical. In the US, for instance, banks that do well in the test also have to satisfy a minimum stress-capital buffer of 2.5%, while those that do poorly face additional requirements (recall Figure 2). Our specification follows this spirit.

ceteris paribus. This is because $\chi^o + x > \chi^o > \chi^o_H$, as a result of which the surcharge takes the ex-ante requirement away from the ex-post optimal.

3. The surcharge affects the wedge between the expected value of being high- versus low-type on date-1, and thus impacts the bank's behaviour on date-0. Depending on the accuracy of the stress test, this can lead to an increase or decrease in the bank's effort. We prove this result in Lemma 6 below. Accordingly, *ceteris paribus*, a higher surcharge can **increase or decrease** in welfare through its effect on effort.

Lemma 6. *The bank's effort may increase or decrease with a surcharge, depending on the accuracy of the stress test.*

Proof. The date-0 problem of the bank is:

$$\max_e \quad -\zeta(e) + \beta p(e) \underbrace{\left(q_H V_H(\chi^o) + (1-q_H)V_H(\chi^o + x)\right)}_{\mathbb{E}V_H} + \beta(1-p(e)) \underbrace{\left(q_L V(\chi^o) + (1-q_L)V_L(\chi^o + x)\right)}_{\mathbb{E}V_L} \tag{15}$$

We begin by noting that similar to the case without stress testing, the effort the bank exerts increases with the *expected* value function wedge $\omega = \mathbb{E}V_H - \mathbb{E}V_L$. Taking the derivative of ω with respect to x at $x = 0$ gives:

$$\left.\frac{\partial \omega}{\partial x}\right|_{x=0} = (1-q_H)V'_H(\chi^o) - (1-q_L)V'_L(\chi^o)$$

where V' indicates the derivative of the value function. To determine the sign of this expression, divide everything by $V'_L(\chi^o)$:

$$sgn\left(\left.\frac{\partial \omega}{\partial x}\right|_{x=0}\right) = sgn\left((1-q_L) - (1-q_H)\underbrace{\frac{V'_H(\chi^o)}{V'_L(\chi^o)}}_{\nu}\right)$$

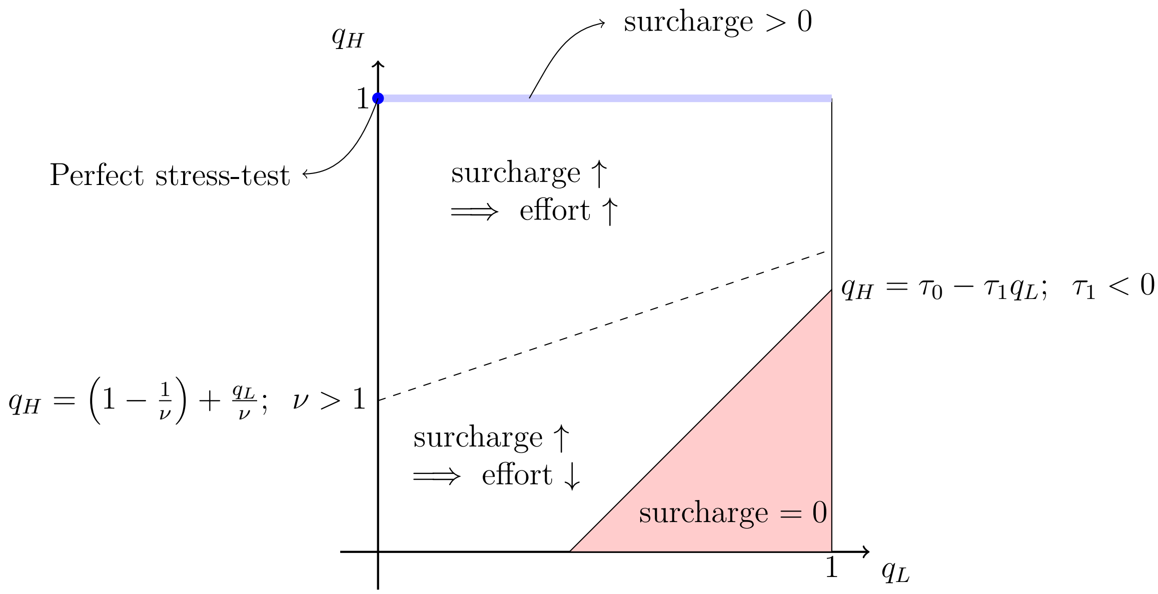

Figure 6: Stress-test accuracy, effect on ex-ante effort, and optimal penalties

Next, recall from the proof of Lemma (5) that $V_H'(\chi^o) - V_L'(\chi^o) < 0$, which implies that $\nu > 1$. Thus, the effect of surcharge on the bank's effort choice depends on the accuracy of the test as follows:

$$(1 - q_L) - (1 - q_H)\nu \begin{cases} > 0 & \implies \quad \text{efforts increases with surcharge} \\ = 0 & \implies \quad \text{efforts does not change with surcharge} \\ < 0 & \implies \quad \text{effort decreases with surcharge} \end{cases}$$

■

Intuitively, ν captures the relative shadow cost of tightening regulation for the high- and low-type banks. *Ceteris paribus*, a higher ν makes imposing a surcharge less desirable by making it more likely that the bank reduces effort. Relatedly, it is clear from Lemma 6 that with a perfect stress test, i.e. when $(q_H = 1, q_L = 0)$, effort increases with surcharge. And that with an imperfect stress test, such as when $q_H = q_L = 0.5$, effort decreases with surcharge. We indicate these insights qualitatively (i.e., not to scale) in Figure 6.

Next we assess the relationship between accuracy of the stress-test and the optimal surcharge.

Proposition 2. *No surcharge must be imposed if the accuracy of stress testing as measured by a (well-defined) linear combination of the Type-1 and Type-II error rates is higher than a cutoff.*

Proof. Welfare as a function of the surcharge x can be written based on the planner's problem as follows (note that e also depends on x in this expression):

$$\max_x \quad W(x) = \beta p(e)\Big(q_H U_H(\chi^o) + (1-q_H)U_H(\chi^o + x)\Big) +$$

$$\beta(1-p(e))\Big(q_L U_L(\chi^o) + (1-q_L)U_L(\chi^o + x)\Big)$$

Our goal is to identify 'a' non-trivial set of (q_H, q_L) where $W(0) > W(x)\ \forall\ x > 0$, i.e. a zero surcharge is optimal.[34] A sufficient condition for this to be the case is $W'(x) < 0\ \forall\ x > 0$. To this end, we consider the first-order condition of the planner's problem:

$$\frac{dW}{dx} = p'(e)e'(x)\Big(q_H U_H(\chi^o) + (1-q_H)U_H(\chi^o + x)\Big) + p(e)(1-q_H)U'_H(\chi^o + x) -$$

$$p'(e)e'(x)\Big(q_L U_L(\chi^o) + (1-q_L)U_L(\chi^o + x)\Big) + (1-p(e))(1-q_L)U'_L(\chi^o + x)$$

To characterise the sign of this expression, we make a few assumptions, again with the goal to find *sufficient* conditions under which the optimal surcharge is zero.

- First we assume that $x \in [0, \chi^o_L - \chi^o]$. The upper bound corresponds to a surcharge amount that results in a requirement for the low-type banks that is equal to the ex-post optimal requirement χ^o_L. In principle the optimal surcharge could be higher (due to its effect on improving ex-ante effort), but that would entail a welfare decreasing effect in case of both high- and low-type banks.

[34] Our goal is to not fully characterise the set of (q_H, q_L) for which the optimal surcharge is zero. We only wish to show that with low-enough accuracy, imposing a surcharge is sub-optimal.

– Second, we assume that (q_H, q_L) are such that the effort exerted by the bank decreases as surcharge increases (as per Lemma 6).

Next, since $U_s(\mathcal{X}^o + x), s \in \{L, H\}$ is a concave function of x, $\mathcal{X}^o_L > \mathcal{X}^o > \mathcal{X}^o_H$ implies the following: (i) $U_H(\mathcal{X}^o) > U_H(\mathcal{X}^o + x)$; (ii) $U'_H(\mathcal{X}^o + x) < 0$; (iii) $U_L(\mathcal{X}^o) < U_L(\mathcal{X}^o + x)$; and (iv) $U'_L(\mathcal{X}^o + x) > 0$; $\forall\, x \in [0, \mathcal{X}^o_L - \mathcal{X}^o]$. It then follows that:

$$\frac{dW}{dx} < p'(e)e'(x)U_H(\mathcal{X}^o) + p(e)(1-q_H)U'_H(\mathcal{X}^o) - p'(e)e'(x)U_L(\mathcal{X}^o) + (1-p(e))(1-q_L)U'_L(\mathcal{X}^o)$$

Finally, we re-arrange and set the right-hand-side expression to zero:

$$p(e)U'_H(\mathcal{X}^o) + (1-p(e))U'_L(\mathcal{X}^o) - p(e)q_H U'_H(\mathcal{X}^o) - (1-p(e))q_L U'_L(\mathcal{X}^o) +$$

$$\underbrace{p'(e)e'(x)\Big(U_H(\mathcal{X}^o) - U_L(\mathcal{X}^o)\Big)}_{A<0} = 0$$

$$\implies \underbrace{\frac{A}{p(e)U'_H(\mathcal{X}^o)} + 1 + \frac{(1-p(e))U'_L(\mathcal{X}^o)}{p(e)U'_H(\mathcal{X}^o)}}_{\tau_0<>0} - q_L \underbrace{\frac{(1-p(e))U'_L(\mathcal{X}^o)}{p(e)U'_H(\mathcal{X}^o)}}_{\tau_1<0} = q_H$$

$$\implies q_H = \tau_0 - \tau_1 q_L \tag{16}$$

In equation (16), while the slope is positive, the intercept can be positive or negative, depending on the underlying parameters. Also, when $q_L = 1$, $q_H < 1$. The equation implies that when $q_H < \tau_0 - \tau_1 q_L$ the surcharge should be zero, as also indicated in Figure 6. ■

Intuitively, the proposition shows that when q_H is low and/or q_L is high – both of which reflect a relatively less accurate stress-test – the surcharge must be zero. The next proposition identifies the conditions under which the optimal surcharge is strictly positive.

Proposition 3. *If the stress-test is accurate in identifying high-type banks $q_H = 1$, but is possibly inaccurate in identifying low-type banks $1 > q_L \geq 0$, then a surcharge can improve* *welfare.*

Proof. First note that a higher x does not affect $\mathbb{E}V_H$, but decreases $\mathbb{E}V_L$ (recall equation (15)). As a result, the bank increases effort as surcharge increases. Second, consider the planner's problem:

$$\max_x \quad \beta p(e)U_H(\mathcal{X}^o) + \beta(1-p(e))\Big(q_L U_L(\mathcal{X}^o) + (1-q_L)U_L(\mathcal{X}^o + x)\Big)$$

Note that since the high-type bank never fails, it is never penalised. A low-type bank can be penalised upon failure, and this increases welfare as long as $x \leq \mathcal{X}^o_L - \mathcal{X}^o$. Beyond this threshold, the effective regulation on the low-type bank is higher than $\mathcal{X}^o_L$, which is sub-optimal (recall Proposition 4).

Combining the effect of a surcharge on effort e and $U_L(\mathcal{X}^o + x)$, both of which increase as x increases, and given that $U_H(\mathcal{X}^o) > U_L(\mathcal{X}^o)$, it is clear that welfare must increase as x rises above zero. ■

Together, Propositions 2 and 3 capture the key result of this paper, which is that there is a phase shift in the relation between optimal surcharge and stress-test accuracy, with the optimal surcharge being zero (positive) if the level of accuracy of the stress tests is sufficiently low (high). While we do not analytically map the optimal surcharge for every level of accuracy (q_H, q_L), in part because that is unlikely to yield additional insights, we compute the full mapping in the qualitative analysis section (see Figure 10).

4.5 Failure costs

Failure of a bank can impose a social cost. This cost can stem from, for instance, forced sale of a failed bank's assets, as well as due to resolution related expenses. It can be a major cost in the case of large banks (due to contagion/knock-on effects), when the resolution framework is not well functioning, or during a crisis when many banks are in insolvency at the same time.

Failure costs pose an additional trade-off for regulators. A higher surcharge (compared to the case without failure costs) may be justified on the grounds that it lowers the expected failure rate and attendant social costs. Yet, to the extent the stress test is not sufficiently accurate, a higher surcharge would not only lower welfare in the case of a high type bank, but also would lower the ex-ante effort exerted by the bank. As such, it is not obvious as to whether the surcharge must be adjusted upwards or downwards as failure costs increase.

To formally assess the effect of failure cost on optimal regulation, we adapt the model as follows. We assume that once a bank fails, the recovery value of its assets is less that a hundred percent. This cost – denoted Δ – is borne by the deposit insurance and is funded via taxes:

$$T(\psi) = \begin{cases} Rd - \psi g(k+d)(1-\Delta) & \text{If the bank fails i.e. } \psi \leq \frac{Rd}{g(k+d)} \\ 0 & \text{Otherwise} \end{cases}$$

In what follows, we prove that the failure cost exacerbates the externality banks pose, and rationalises a higher ex-post requirement χ^o and also a higher ex-ante surcharge x associated with failing the stress test.

We begin by assessing the ex-post requirement, while abstracting away from bank-type as before. Household consumption on date-2 in this case is given as:

$$c_2 = \bar{Y} + \psi g(k+d) - \Delta \psi g(k+d) \mathbb{1}\left(\psi \leq \frac{Rd}{g(k+d)}\right).$$

Accordingly, the planner's problem is:

$$\max_{d} \quad (1+\beta)\bar{Y} + \beta \int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g(k+d) - Rd\Big) df(\psi) + \beta \int_{0}^{\frac{Rd}{g(k+d)}} \Big(\psi g(k+d) - Rd - \Delta\psi g(k+d)\Big) df(\psi),$$

while the attendant first-order-condition is:

$$\begin{aligned} 0 \;=\; & \beta \int_{\frac{Rd}{g(k+d)}}^{\infty} \Big(\psi g'(k+d) - R\Big) f(\psi) d\psi \;+ \\ & \underbrace{\beta \int_0^{\frac{Rd}{g(k+d)}} \Big(\psi g'(k+d)(1-\Delta) - R\Big) f(\psi) d\psi - \beta \Delta \psi g(k+d) \frac{\partial \frac{Rd}{g(k+d)}}{\partial d} f\left(\frac{Rd}{g(k+d)}\right)}_{\text{Bank-failure externality}} \end{aligned} \tag{17}$$

We know from the discussion of equation (11) that the externality term in that equation, namely $\beta \int_0^{\frac{Rd}{g(k+d)}} \Big(\psi g'(k+d) - R\Big) f(\psi) d\psi$, is negative. This means that the left term in the second row of equation (17) is also negative, and even lower in value. At the same time, since $g(.)$ is concave:

$$\frac{\partial \frac{Rd}{g(k+d)}}{\partial d} = \frac{R\Big(g(k+d) - dg'(k+d)\Big)}{g(k+d)^2} > 0.$$

As such, the externality term in equation (17) is negative and larger in magnitude relative to the externality term in equation (11). Thus failure cost amplifies the bank-failure externality. In turn, as shown in Lemma 3, greater externality rationalises a higher minimum capital-ratio requirement. We note this result in Lemma 7.

Lemma 7. *The regulator must optimally impose a higher ex-post minimum capital-ratio requirement on a bank that, all else equal, exhibits a higher failure cost.*

Next we examine how the optimal surcharge must change as failure cost increases. Unfortunately, it is not possible to characterise the change generally. However, it is possible to make progress if we assume that the probability of being a high-type (or equivalently low-type) bank is given and that there is no effort choice involved. The planner's problem in that case is given as follows:

$$\max_{x} \quad W(x) = \beta p\Big(q_H U_H(\chi^o, \Delta) + (1-q_H) U_H(\chi^o + x, \Delta)\Big) +$$

$$\beta(1-p)\Big(q_L U_L(\chi^o, \Delta) + (1-q_L)U_L(\chi^o + x, \Delta)\Big) +$$

Here Δ in the utility function formally expresses the dependence of welfare on failure costs. The attendant first-order condition is as follows, where the D_i operator indicates the derivative with respect to the i^{th} argument of U:

$$p(1-q_H)D_1U_H(\chi^o + x, \Delta) + (1-p)(1-q_L)D_1U_L(\chi^o + x, \Delta) = 0$$

Next, we take the total derivative of this expression with respect to Δ:

$$p(1-q_H)\Big(D_{11}U_H(\chi^o + x, \Delta)\frac{dx}{d\Delta} + D_{12}U_H(\chi^o + x, \Delta)\Big) +$$

$$(1-p)(1-q_L)\Big(D_{11}U_L(\chi^o + x, \Delta)\frac{dx}{d\Delta} + D_{12}U_L(\chi^o + x, \Delta)\Big) = 0$$

$$\implies -\underbrace{\Big(p(1-q_H)D_{11}U_H(\chi^o + x, \Delta) + (1-p)(1-q_L)D_{11}U_L(\chi^o + x, \Delta)\Big)}_{A}\frac{dx}{d\Delta} =$$

$$p(1-q_H)D_{12}U_H(\chi^o + x, \Delta) + (1-p)(1-q_L)D_{12}U_L(\chi^o + x, \Delta)$$

Since both U_H and U_L are concave functions of x, $A < 0$. To sign the RHS, consider $U_s, s = \{H, L\}$:

$$U_s(\chi^o + x, \Delta) = \bar{Y} - d + \beta g(k+d)(\mu_s - \Delta\int_0^{\frac{Rd}{g(k+d)}} \psi f_s(\psi)d\psi) \quad where \quad d = \frac{k}{\chi^o + x}$$

$$\implies D_2U_s(\chi^o + x, \Delta) = -\beta g(k+d)\int_0^{\frac{Rd}{g(k+d)}} \psi f_s(\psi)d\psi)$$

$$\implies D_{21}U_s(\chi^o + x, \Delta) = -\beta\Bigg(g'(k+d)\frac{dd}{dx}\int_0^{\frac{Rd}{g(k+d)}} \psi f_s(\psi)d\psi +$$

$$g(k+d)\frac{d}{dd}\left[\frac{Rd}{g(k+d)}\right]\frac{Rd}{g(k+d)}f_s\left(\frac{Rd}{g(k+d)}\right)\frac{dd}{dx}\Bigg)$$

As x increases, d decreases i.e. $\frac{dd}{dx} < 0$. Also, as d increases, the upper limit on the integral is increases (recall $g(.)$ is concave), which means that by application of Leibniz rule, $D_{21}U_s(\mathcal{X}^o + x, \Delta) > 0$. Since U is a continuous function in both its arguments, $D_{21}U_s(\mathcal{X}^o + x, \Delta) = D_{12}U_s(\mathcal{X}^o + x, \Delta) > 0$ for both $s = H, L$. This immediately leads to the following Proposition.

Proposition 4. *Assuming $p(e) \equiv p$, the optimal surcharge must increase as Δ increases.*

Relaxing the assumption that $p(e) = p$ does not lead to a general result, that is, $\frac{dx}{d\Delta}$ cannot be signed unless the specific values of the parameters of the model are known. As such, we pursue this more general case in the quantitative analysis. Nonetheless, the above proposition suggests that if the stress test is sufficiently accurate so that effort e and thus the probability of being a high-type bank increase as the surcharge increases, then it is likely that the surcharge must be optimally adjusted upwards as the failure cost increases.

5 Quantitative analysis

To illustrate the empirical relevance of our findings, we calibrate the model using data on large US banks that typically participate in the Comprehensive Capital Analysis and Review (CCAR) exercise. For the calibration, we focus on the post-GFC to pre-Covid period – i.e. 2010-2019 – to abstract away from any crisis led large movements in the data. We estimate the model parameters jointly using method of moments i.e. we set the parameters such that model generated moments are equal to the corresponding data moments (see Table 1).

We consider the following moments as targets. First is the pooled mean of return on risk-weighted assets, while taking into account interest as well as non-interest income. Dividing by risk-weighted assets (instead of just assets) helps align the moment condition with the interpretation of high- and low-type bank in our model (recall that high- and low-type banks have the same standard deviation of return on assets, and vary only in terms of the mean return on assets). Second is the pooled mean of equity capital to assets

Parameter	Description	Value	Target moments	Value
α	Payoff exponent: $(k+d)^{\alpha}$	0.914	Gross Return on risk-adjusted assets	10.19%
μ	Mean of ψ	1.336	Equity capital to assets ratio	10.38%
σ	Standard-deviation of ψ	0.102	Value-at-risk threshold	1%
$\bar{Y}$	Household income	117.8	Household savings rate	7.32%
β	Discount factor	0.99	Deposit interest-rate	1%
Δ	Failure cost	0.22	US bank failure losses	22%

Table 1: Parameter values and target moments. Bank micro-data are sourced from Fitch, US household savings rate from FRED, and bank failure losses from FDIC. Note that the last two parameters and target moments have a one-to-one mapping (i.e. they need not be estimated jointly), and that without loss of generality k is normalised to unity. The value of the moments in data are exactly match with those implied by the mode.

ratio. Third is a typical regulatory or bank-management imposed value-at-risk threshold of 1%. Fourth is the household savings rate, defined as the average savings of US households out of their personal disposable income during 2010-2019. Next, we set the interest rate to 1% – a standard value in the literature. Finally, Δ is set in line with the losses associated with bank failures in the US during 2010-2019. According to the Federal Deposit Insurance Commission (FDIC), there have been 367 bank failures during this period, and the median estimated loss is about 21% of the failed bank's assets, while the attendant inter-quartile range is 13% to 30%. Our target moment is the mean, which is 22%.

As regards the functional forms, we assume the cost of exerting effort by the bank on date-0 as $\zeta(e) = e^2/2$, and the attendant probability of the bank becoming a high-type on date-1 as $p(e) = 1 - 1/(1 + e)$. The exact functional form does not matter for our qualitative results as long as $\zeta(.)$ is (weakly) convex and $p(.)$ is concave. As regards μ_H and μ_L, we assume a symmetric perturbation of 50 basis points around μ. Finally, we treat q_H and q_L as free parameters that we conduct comparative statics with respect to.

Optimal ex-post regulation We begin by analyzing the impact of a minimum capital-ratio requirement on the bank's behavior and overall welfare on date-1. Without loss of generality, we consider a high-type bank. Starting from the unregulated economy, a higher minimum capital-ratio requirement forces the bank to deleverage (first panel in Figure 7).

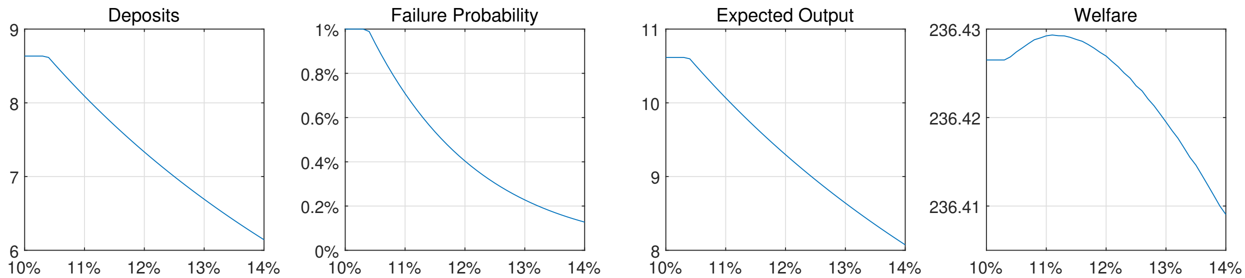

Figure 7: The effect of minimum capital-ratio requirement (x-axis) on the high-type bank and on overall welfare.

This reduces the failure probability (second panel), but also lowers expected output (third panel). The overall effect – one that weighs welfare gains from lower bank failure against the welfare loss from lower expected output – is an inverted U-shaped welfare profile as a function of X. This finding is consistent with Lemmas 2 and 3 where we showed that the unregulated equilibrium is sub-optimal and that a minimum capital-ratio requirement can improve welfare, and also with the broader literature (eg Begenau [2019], Christiano and Ikeda [2016]).

Relatedly, as bank failure costs increases, not only is the optimal requirement higher (as proven in Lemma 7), the welfare gain from regulation is also higher (see left-hand panel in Figure 8).

Finally, we compare the optimal ex-post requirement for low- and high-type banks. Consistent with Lemma 4, we find that the requirement is higher for the low-type bank (see right-hand panel of Figure 8, dotted lines).

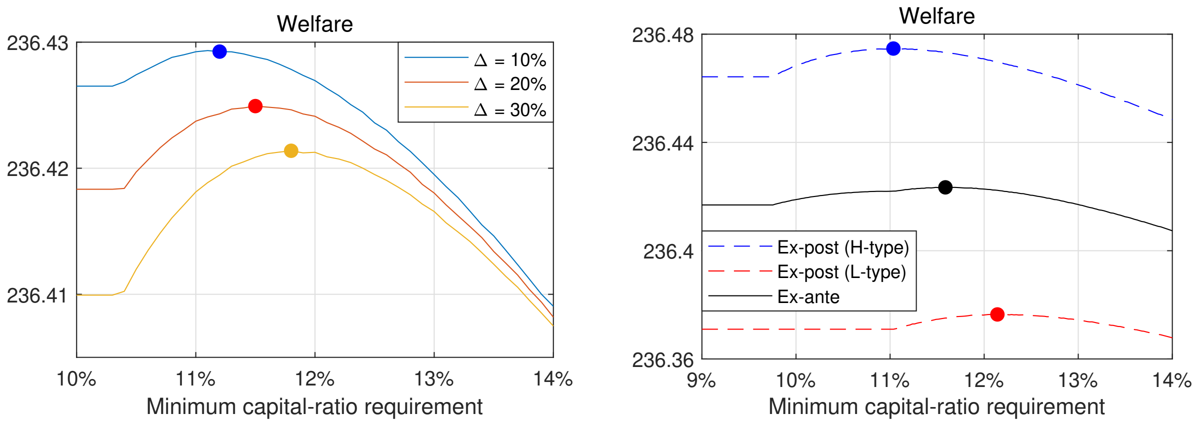

Figure 8: *Left-hand panel*: The welfare maximizing regulation for varying levels of bank failure costs. *Right-hand panel*: Optimal ex-post requirement depending on bank type, and the optimal ex-ante requirement in the absence of stress tests.

Optimal ex-ante regulation When the regulator cannot observe banks' types ex-post, the optimal ex-ante requirement announced on date-0 cannot be bank-type specific. Consistent with Proposition 1, we find that it is saddled by the ex-post optimal requirements (see solid line in the right-hand panel of Figure 8).

Next we assess how a stress-test led surcharge affects bank's behavior. A higher surcharge decreases the value of both high- and low-type banks (left-hand panel of Figure 9). This means that as long as the stress test is not perfect, both $\mathbb{E}V_H$ and $\mathbb{E}V_L$ decrease as x increases. The decrease, however, is starker for a high-type bank – indeed the opportunity cost of not being able to use its balance sheet capacity is higher for a bank whose assets have a higher return. This regularity has important implications for how a surcharge should be imposed.

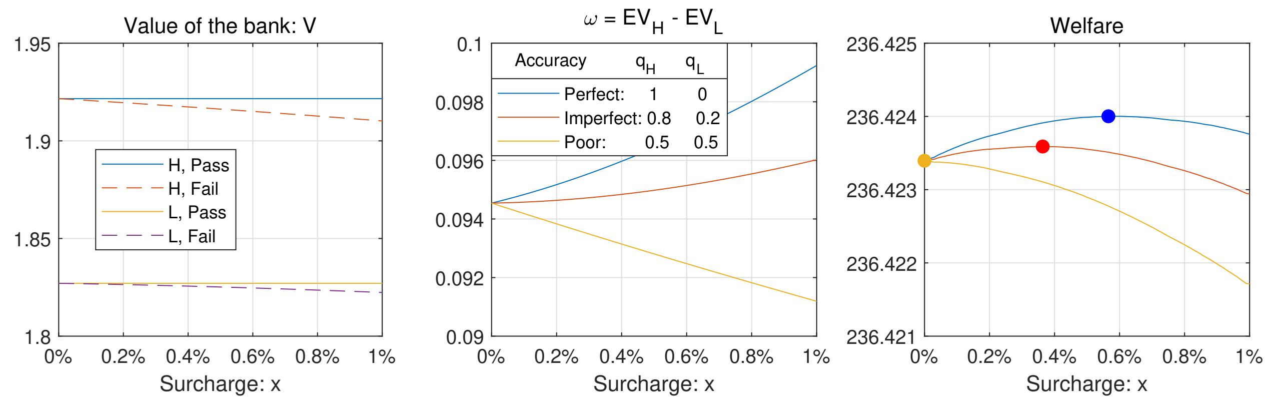

Figure 9: *Left-hand panel:* The value V of the bank in various cases as a function of the surcharge. *Centre panel:* The expected value wedge changes in response to the surcharge for different levels of accuracy of the stress test. *Right-hand panel:* Optimal surcharge.

Relatedly, as we showed in Lemma 6, the difference between $\mathbb{E}V_H$ and $\mathbb{E}V_L$ – namely ω – can increase or decrease depending on the accuracy of the test (see centre panel of Figure 9). This immediately means that the effort banks exert can also increase or decrease as the surcharge is raised (recall that e depends on ω; see the proof of Lemma 5). This is a key insight of the paper – a higher surcharge may not necessarily act as a disciplining device if the basis on which the surcharge is imposed is uncertain.

Overall, the optimal surcharge depends on the following trade-off. Penalizing banks that fail the stress tests can improve welfare to the extent a low-type bank is penalised. As such, a sufficiently inaccurate test may not increase expected welfare. Moreover, in this case, banks may reduce the effort they exert. We confirm this insight quantitatively. For very low level of accuracy, consistent with proposition 2, the optimal surcharge is zero (right-hand panel of Figure 9). For higher levels of accuracy, including the case of a perfect stress test, the optimal surcharge is higher (recall Proposition 3).

We illustrate the optimal surcharge for each accuracy level of the stress-test in the left-hand panel of Figure 10, thus confirming the broad indications sketched in Figure 6. Indeed, a phase shift is evident: for sufficiently low levels of accuracy, the optimal surcharge is zero. Moving closer to a perfect stress test ($q_H = 1, q_L = 0$) increases the size of the

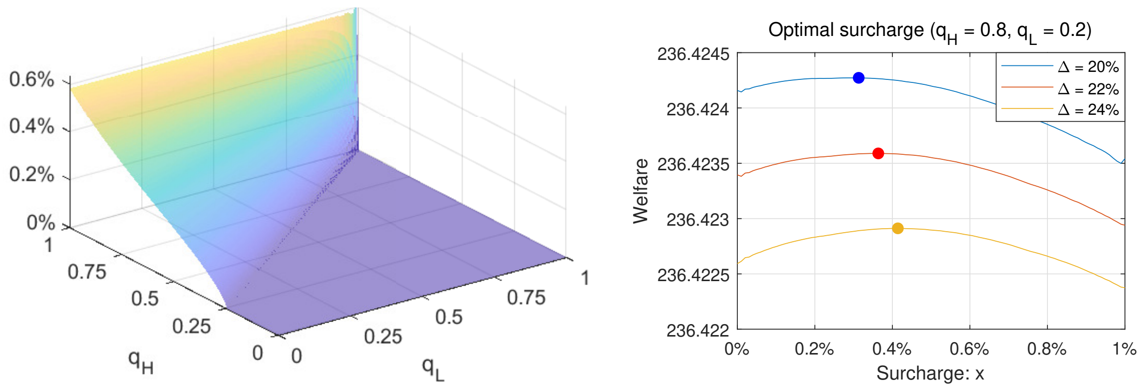

Figure 10: *Left-hand panel*: Optimal surcharge as a function of the accuracy of the stress-test. *Right-hand panel*: Change in optimal surcharge as the cost of failure increases.

optimal surcharge.

Finally, we elaborate upon the result proven in Proposition 4, and show that as the failure cost increases, the optimal surcharge also increases (see the right-hand panel of Figure 10).

Endogenous accuracy Thus far, we consider the accuracy of the stress test – as summarised by (q_H, q_L) – to be given exogenously. In reality, regulators may be able to choose this accuracy, and may prefer to set it at a high level given the welfare gains it entails. Yet, there may be constraints in choosing a high level of accuracy.

For one, by subjecting banks to a much harder test – one that entails a more severe crisis scenario – the regulator may be able to lower the false negative rate, and yet, the false positive rate may surge. Then, in order to reduce the false positive rate, the test may have to become more comprehensive and intrusive, which is likely to be very costly not just for the regulator, but also for the banks. Indeed, a more extensive asset quality review would not only require additional supervisory force, but also more bank employees dedicated to satisfying regulation and attending to supervision. Moreover, there may be fundamental constraints to designing a more accurate stress-test – each crisis or stress scenario is different, and designing one scenario that is all en-compassing may not be possible.

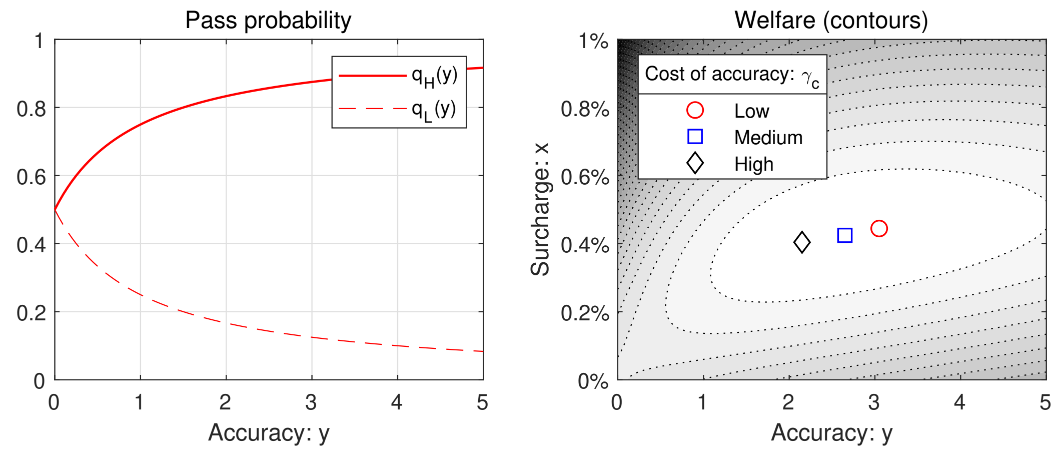

Figure 11: *Left-hand panel:* Pass probabilities for high and low-type banks as a function of accuracy. *Right-hand panel:* The jointly optimal accuracy and surcharge for different levels of cost of accuracy γ_c. Welfare contours correspond to the average γ_c.

To reflect on such issues, we consider the problem of a regulator who chooses the jointly optimal surcharge x and accuracy $y \geq 0$. For brevity, we assume that greater accuracy entails a welfare cost $C(y) = \gamma_c y$ that stems from the supervisory burden on both regulators as well as banks. Accuracy maps to the pass probabilities of high- and low-type banks as follows: $q_H(y) = 1 - \gamma_q/(1+y) \uparrow 1$ as $y \to \infty$, and $q_L(y) = 1 - q_H(y) \downarrow 0$ as $y \to \infty$ (see left-hand panel of Figure 11 for an example). We find that as the cost of accuracy increases, the regulator must optimally work with less accurate stress tests, and at the same time, revise downwards the surcharge it imposes on failings banks (see right-hand panel of Figure 11)

6 Conclusion

Stress tests have become an important tool for regulators in the post-GFC era. They have helped regulators in gauging banks' riskiness and in bolstering financial stability. They continue to evolve and improve based on lessons learnt over the years. Despite these enhancements, stress-tests may not be perfect yet, not least due to fundamental difficulties inherent in prediction. We provide suggestive evidence in favor of this hypothesis by using the Covid-19 crisis as a natural experiment to assess stress-testing. We show that banks' performances in the 2020 U.S. stress-test and during the crisis are highly discordant, both in absolute and relative (cross-sectional) terms. In particular, some of the worst performers in the test actually raised their CET1 ratios during the crisis.

Given that stress-test results underpin banks' capital requirements, inaccurate results can have a large impact on banks' capital costs, on their operations, and on overall economic welfare. A healthy and less-risky bank may unfairly fail the test and face inefficiently strict regulation (and vice-versa). To assess the implications, we build a model of stress-testing, and show that inaccuracies not only reduce welfare directly, but also by creating adverse ex-ante incentives. As such, stress-test based regulatory actions must be less strenuous when accuracy is lower, or when increasing accuracy is fundamentally challenging or prohibitively costly. We illustrate the quantitative implications of our theoretical findings based on U.S. data.

Our model is parsimonious and tractable, and is amenable to extensions that allow studying related questions of interest. For instance, some regulators have discussed maintaining a surprise element in stress-tests on the grounds that it can help avoid pre-positioning or complacency by banks.[35] The welfare effects of surprise or extraneous noise in stress tests is not obvious because while it can limit the scope for gaming by banks, higher regulatory uncertainty can weaken the link between the effort banks exert and their performance in the stress-test. This can make banks exert less effort towards improving their risk-return profile. Our model can be used to study this trade-off by making regulation a discretionary function of the signal received from the test.

[35]See, for instance, the remarks by Mr Jerome H Powell, Chair of US Federal Reserve System, at the research conference titled "Stress Testing: A Discussion and Review" on 9 July 2019. In fact, the continuous evolution of the stress-test regime may be motivated by this pursuit.

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