Strategies to Reduce the Risk of Building Collapse in Developing Countries

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Carnegie Mellon University

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Carnegie Mellon University

CARNEGIE INSTITUTE OF TECHNOLOGY

THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF Doctor of Philosophy

TITLE   Strategies to Reduce the Risk of Building Collapse in Developing Countries

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Strategies to reduce the risk of building collapse in developing countries

Submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in

Engineering and Public Policy

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Abstract

In developing countries, poor quality construction has led to spontaneous building collapse and, during earthquakes, to major disasters. While reliable building codes are widely used in design, builders in developing countries often fail to meet acceptable standards. Structural defects are frequently identified too late, often after catastrophic collapse. In Kenya, more than eighty people have been killed, an over 290 injured, by collapsed buildings, since 2006. However, Kenya is not an exception. Throughout the world, in particular in countries with developing economies and growing populations, thousands of dangerously weak buildings will be built, and millions of people will be exposed to unnecessarily higher risks for generations. This research aims at contributing towards finding solutions to this problem by: 1) demonstrating that, in Kenya, many buildings are approved for occupation based on false material strength data produced by ineffective quality-control methods; 2) engaging the help of experts in Kenyan construction to list and ranked probable causes and plausible solutions to the problem of unsafe construction practices in Kenya; 3) presenting a method and a simulation model to estimate the damages in Nairobi (or other cities in Africa) in case of and earthquake, which can be used by policy makers when evaluating alternative policy interventions; and 4) proposing a strategy that combines the enforcement of quality reporting for construction, the open publication of the reports, the diffusion of non-destructive testing in construction, a risk communication program, and internet forums to help educate and provide guidance to the public in good construction practices.
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Chapter 1: Introduction

Motivation

Improving the structural quality of buildings in poorer parts of the world is an effective way to significantly reduce fatalities when natural disasters occur. Most jurisdictions worldwide have adopted building codes. However, in developing economies these codes have often not been effective. Structural defects are frequently identified too late, often after catastrophic collapse. Researchers attribute most of the 230 thousand deaths in Haiti during the 2010 earthquake to the low quality of Haitian construction (1). But, sadly, Haiti is not an exception. In 2009 Kenyan officials estimated that 65% of Kenya’s buildings fail to meet code standards (2). Between 2006 and 2014, seventeen buildings spontaneously collapsed in Kenya alone, and caused eighty-four deaths and more than 290 injuries (3–7). The catastrophe in Haiti and the accidents in Kenya, followed by a constant stream of sad news of building collapse tragedies in Ghana (8), Tanzania (9), Bangladesh (10), Mumbai (11), Medellin (12), Casablanca (13) and most recently Nigeria (14), demonstrate that this problem is not unique to any one nation or region.

Thousands of dangerously weak buildings will be built, and millions of people in developing countries will likely be exposed to unnecessarily higher risks for generations. The objective of this work is to help reduce building collapse catastrophes in developing countries through better structural reliability diagnostics and the development of a set of policies and incentive structure that will promote the adoption of effective building code enforcement strategies.
Thesis overview

Our research examines the state of the industry with respect to compliance with construction standards, assesses the risks of building damage or collapse associated with shoddy practices, and proposes solutions to reduce risk. Careful implementation of cost-effective sensing, risk communication information technologies and adequate regulation could be effective in improving the safety of built structures in the developing world.

This work is divided into four studies discussed in papers titled:

Comparison of reported and actual strength of concrete used in new and existing Nairobi construction (Chapter 2). This paper explains why thousands of defective buildings may be approved for occupation based on false material strength data produced by ineffective quality-control methods, and the research that let us to that conclusion.

Eliciting experts to assess, diagnose and rank interventions to improve reliability of Kenyan construction (Chapter 3). We elicited the opinions of experts in Kenyan construction. The experts accurately predicted low strength of concrete in Kenyan construction, and listed and ranked probable causes and plausible solutions to the problem of unsafe construction practices in Kenya.

A model to estimate the effects of improved construction quality on reinforced concrete buildings in central Nairobi (Chapter 4). In this paper we describe a model
that uses Monte Carlo simulation to estimates the square meters of buildings in Nairobi that would either collapse or suffer severe damage in case of earthquakes with different spectral accelerations.

**Policy recommendations to improve the structural safety of reinforced concrete buildings in Kenya** (Chapter 5). In this paper we propose a strategy which entails the simultaneous development and implementation of: a) an open-access reporting system modeled after the Toxic Release Inventory program operated by the U.S. Environmental Protection Agency; b) an educational and forum web portal; c) the promotion of non-destructive testing of concrete during construction; and d) a risk communication program.

Chapter 6 contains the summary of the conclusions from the four studies and final remarks.

**References and Notes**


Chapter 2: Comparison of reported and actual strength of concrete used in new and existing Nairobi construction

Abstract

In developing countries, poor quality control in building construction has led to spontaneous building collapse and, in the event of even moderate seismic activity, to major disaster. The resilience of structures is a function of safe design, adequate materials, and competent workmanship. While earthquake-resistant designs, which are accessible to designers everywhere, have greatly improved international building codes, construction in developing countries often fails to meet acceptable standards. This paper examines the state of the industry's compliance with standards for concrete used in reinforced concrete structures in Kenya. This is done in two ways: 1) with a comparison of non-destructive-test data collected at twenty-four construction sites to test results reported by established laboratories in Nairobi from a sample of new construction projects, and 2) through a survey of fifty-one existing buildings in the Metropolitan area of Nairobi. The findings suggest that concrete is frequently weaker than claimed by the laboratory test reports, which indicates fraud; and that the current quality control practices are not effective in ensuring structural reliability of new or existing buildings. Institutions interested in safer cities should give a high priority to developing strategies to enforce prudent quality-control protocols and regulations.
One Sentence Summary

Thousands of defective buildings may be approved for occupation based on false material strength data produced by ineffective quality-control methods.

Introduction

Unsafe buildings are a hidden and growing problem that can put millions at risk

The amount of construction in developing countries is overtaking that in industrialized nations (1, 2). Sadly, many developing countries lack effective regulatory environments and suffer pervasive corruption (3–7). The construction industry has been consistently ranked as the most corrupt worldwide (8). In this environment, international construction codes, even where adopted on paper, have not been adequately protective. When earthquakes occur in developing countries, defective buildings collapse, killing thousands of people (Table 1) (9). Earthquakes with similar characteristics in developed countries fortunately often cause significantly fewer deaths as well as considerably less economic loss.
Table 1. In the last fifty years, all earthquakes that caused twenty thousand deaths or more from collapsed buildings have occurred in places with low incomes and structures not built to resist the seismic activity forecasted for their regions. Earthquakes of comparable magnitude in developed countries have caused a considerably lower number of casualties (between 2 and 4 orders of magnitude). (Source: U.S. Geological Survey) (10)

<table>
<thead>
<tr>
<th>Region</th>
<th>Deaths (1,000)</th>
<th>Year</th>
<th>Magnitude (Richter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangshan (China)</td>
<td>400+</td>
<td>1976</td>
<td>7.5</td>
</tr>
<tr>
<td>Haiti</td>
<td>230</td>
<td>2010</td>
<td>7.0</td>
</tr>
<tr>
<td>East Sichuan (China)</td>
<td>88</td>
<td>2008</td>
<td>7.9</td>
</tr>
<tr>
<td>Kashmir (India)</td>
<td>86</td>
<td>2005</td>
<td>7.6</td>
</tr>
<tr>
<td>Manjil-Rudbar (Iran)</td>
<td>50</td>
<td>1990</td>
<td>7.4</td>
</tr>
<tr>
<td>Bam (Iran)</td>
<td>31</td>
<td>2003</td>
<td>6.6</td>
</tr>
<tr>
<td>Armenia</td>
<td>25</td>
<td>1988</td>
<td>6.8</td>
</tr>
<tr>
<td>Guatemala</td>
<td>23</td>
<td>1976</td>
<td>7.5</td>
</tr>
<tr>
<td>Gujarat (India)</td>
<td>20</td>
<td>2001</td>
<td>7.7</td>
</tr>
</tbody>
</table>

The United Nations Department of Social and Economic Affairs projects that, by 2050, more than 80% of the world’s urban population will be living in the fast-growing cities of developing countries (11). Indicative of this growth, between 2001 and 2010, the number of building permits granted in Nairobi annually climbed from 485 to 3,203 (12), and cement consumption in East Africa tripled (13). Because of poor building practices, the hundreds of millions of people occupying millions of new structures built in the coming years in developing cities worldwide will be at risk to even moderate earthquakes. The more than 300,000 fatalities in the Haitian earthquake of 2010, which registered magnitude 7.0 on the Richter scale (Figure 1), highlight the urgency of improving building reliability in developing countries. (14).
Figure 1. The United Nations Development Program Headquarters (UNDP) in Port-au-Prince collapsed on January 12, 2010. The aerial photo shows the building’s crumbled concrete roof. The Presidential Palace of Haiti also collapsed that day. Hidden structural defects can go unnoticed for years. (Source: UNDP) (15)

Partly because East Africa experiences seismic activity infrequently, earthquake-resistant design and structural quality control receive low priority. As a result, some structurally defective buildings have collapsed, while many others might remain in use for many years before an earthquake reveals their inherent weaknesses.
Some structures are built so poorly that they are at risk of spontaneously collapsing

Between 2006 and 2014, at least seventeen buildings spontaneously collapsed in Kenya, causing eighty-two deaths and 291 injuries (Table 2). Similar accidents, such as the collapse of a six-story building in Accra, Ghana, in November 2012 that killed twelve people and injured seventy-eight more (16); the factory collapse in Bangladesh in 2013 that killed over 1,100 people and injured more than 2,500 (17, 18); the church collapse in Nigeria, where 44 died (19); and others in Tanzania (20) and Casablanca (21) suggest that Kenya is not an exception.

Table 2. Incidence of building collapse in Kenya from 2006 to 2014. Despite the public concern caused by these accidents, new structures continue with the same construction methods. (Sources: CNN, The Daily Nation, Standard-Media, Architectural Association of Kenya, Fox News) (22–26)

<table>
<thead>
<tr>
<th>Municipality</th>
<th>Year</th>
<th>Deaths</th>
<th>Injured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nairobi</td>
<td>2006</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td>Ngala St.</td>
<td>2009</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Kiambu</td>
<td>2009</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>Kisii Town</td>
<td>2009</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Kiambu</td>
<td>2010</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Kiambu</td>
<td>2011</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Embakasi</td>
<td>2011</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Langata</td>
<td>2011</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Ngara</td>
<td>2011</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Mathare</td>
<td>2011</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>Luanda</td>
<td>2011</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>Bungoma</td>
<td>2012</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Kisii</td>
<td>2012</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Mulolongo</td>
<td>2012</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Kisumu</td>
<td>2013</td>
<td>9</td>
<td>35</td>
</tr>
<tr>
<td>Nairobi</td>
<td>2013</td>
<td>11</td>
<td>90</td>
</tr>
<tr>
<td>Thika</td>
<td>2014</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>84</strong></td>
<td><strong>291</strong></td>
</tr>
</tbody>
</table>
New laws enacted and institutions created to improve the quality of construction have emphasized certification of contractors and supervision by certified engineers, but construction practices remain unchanged. The spontaneous collapse of buildings has triggered regulatory review in Kenya. This has focused on zoning, building permits, and licensing (27, 28), because it is commonly understood that defective designs and inadequate standards are to blame for collapse accidents. In 2006, while rescue operations were underway after a building collapsed in Nairobi, Kenyan Army Brigadier G. Kyaka, said, “This is all about building standards” (29), and Kenya’s Vice-president, Moody Awori, stated that, “It is very important that we put in place mechanisms to ensure that only properly designed buildings are built.”

In 2011 the government of Kenya enacted two laws to improve the quality and safety of buildings: the Engineers Act authorizes the Board of Engineers of Kenya, a new statutory body created by the Act, to access and inspect construction sites at will (30), and the National Construction Authority Bill created a National Construction Authority (NCA) with a mandate to regulate and improve the construction industry (27). The NCA Bill expressly states that one of its objectives is to “promote quality assurance in the construction industry” (27). However, these efforts have yet to catalyze dramatic changes in fundamental industry practices, including quality control protocols, partly because, until now, most of the work has focused on tighter regulation and certification of building contractors, while quality control methods remain for the most part as they have been for decades. (Meetings with NCA officials, and consultation with practitioners in Nairobi, in February 2014)
The reinforced concrete building process

Cast-in-place reinforced concrete (RC) is the dominant construction method in Africa (31). To make RC, steel reinforcing bars (rebar) are first cut, bent, and installed inside molds following design specifications (32, 33). Concrete is then mixed and poured into the molds, embedding the rebar. The performance of a well-designed structural element depends on the tensile strength and layout of the rebar, the compressive strength of concrete ($f_c$), and the bond between the rebar and the concrete (34, 35).

In developed countries, most concrete is mixed and delivered by ready-mix suppliers who use automated dispensing stations and drum-mixer trucks with capacities between five and nine cubic meters [$m^3$] (36). However, in Kenya as well as in many developing countries, where low wages favor manual methods, most concrete is mixed manually or with small mixers on construction sites (36, 37). The daily concrete production goal for a medium-sized contractor in East Africa is to pour between twenty and fifty cubic meters of concrete, using portable 125-liter mixers (37). The resulting 160 to 400 mix loads are hauled in wheelbarrows and poured into molds. A standard mix used in Kenya, yielding concrete with $f_c$ of 25 megapascals [MPa], requires 400 kilograms [Kg] of cement (37–39). Therefore, on a typical construction site, builders use between 160 and 400 bags of cement per day, each of which weighs fifty kg. It is challenging to ensure quality when the process is so cumbersome and physically taxing (Figure 2).
Figure 2. Mixing structural concrete in Nairobi. Cement, gravel and sand are measured using metal boxes made for that purpose. Between eight and ten people work each mixer, and between twenty and thirty others transport and pour the mixed concrete. (37)

Compressive strength of concrete as a surrogate for construction quality (CQ)

Engineers and inspectors determine if structures are safe based on the findings of their inspection visits to construction sites, and on the values of the tensile strength of steel and of $f_c$ reported by materials testing laboratories. Real estate developers in Kenya assume that the quality of the concrete used in construction is verified following the sampling and testing processes outlined in relevant codes, mainly ASTM C31 and ACI 318-08, though BS EN 12350-1 and BS EN 12390-1 are more commonly used in Kenya (40). Under these procedures, technicians from the testing laboratories collect samples of
the poured concrete and store them in secure locations. The specimens are crushed in a calibrated hydraulic press at pre-determined ages (7, 14, and 28 days). The design $f_c$ must be achieved in 28 days. It is commonly believed that, as stated by one Kenyan architect and blogger, “If the project is using a registered architect & structural engineer, chances are he is making sure that the batch testing of concrete is being done and he can provide this information to you” (47).

Rebar steel is tested in a similar fashion, following ASTM A370, ASTM A615, ASTM A996, BS 4449, EN 10002-1, and others. However, while steel is typically tested at the beginning of a construction project, the $f_c$ of concrete is verified throughout as new elements of the structure are cast. Therefore, the largest portion of a structural engineer’s quality assurance and control documentation is a collection of test reports for steel (very few) and concrete (dozens per project) from materials laboratories, together with correspondence from the engineer accepting these reports. The $f_c$ is, for most practitioners in Kenya, a proxy for CQ.

**Previous Work**

Global accounting firms have implemented improved project accounting mechanisms to prevent fraud (8). New regulations prescribe better permit issuing, licensing and zoning procedures, and professional association governance (27, 28). Some researchers have even proposed technologies for automated quality control (42, 43). Many forensic investigations have included low-quality concrete among the causes of building collapse accidents (6). Recent research in Kenya has found that substandard steel is available to builders (44), and some has concluded that many buildings in the country are vulnerable
to collapse in the event of moderate intensity earthquakes or even high intensity rainstorms (45). Building on these studies and others, this paper takes a closer look at the quality control activities on construction sites in Kenya by analyzing the $f_c$ from an audit of seventy-five buildings in Nairobi, and comparing actual $f_c$ to values of $f_c$ reported in laboratory certificates for eleven of those buildings.

Methods

We asked 116 real estate developers for permission to access their construction sites in Nairobi to take samples and review their quality documentation between June and September 2012. However, accessing construction sites proved difficult. From the point of view of the builders, satisfactory test results would generate minimal benefits, but their reputations and large investments would be threatened should faults be discovered and reported.

Additionally, testing methods commonly used in Kenya, such as taking core samples of concrete from built structural elements (46), were rejected by the building owners, as they were considered unnecessarily disruptive. The most precise method for determining $f_c$ in built elements requires cutting core samples of 50 to 95 mm in diameter from the structures (46, 47). The cores are capped and crushed in the same hydraulic presses used for testing cube samples. Core testing is a disruptive and relatively expensive method that, if done incorrectly, can weaken the structures tested. Therefore, core testing is typically used as a last resort, when concerns about the quality
of concrete need unequivocal resolution. Instead, non-destructive testing methods (NDT) are frequently used in quality control in many developed nations (48, 49).

For these reasons, the decision was made to use non-destructive test (NDT) methods whenever possible, and to give assurance to the building owners that only anonymized or aggregated results would be published. Only seventeen developers accepted. Some developers had several on-going projects employing different contractors.

We collected field data from twenty-four building construction sites. The sample included industrial, residential, commercial and religious structures. These construction sites were sufficiently diverse with regards to location, construction company size, building type, and design. They were considered a representative cross-section of that industry (37).

The data collected between June and September 2012 includes photographs or photocopies of certified laboratory reports of $f_c$ for concrete in eleven new buildings under construction, the results of $f_c$ from on-site NDT tests on concrete, and laboratory tests of steel that we sampled from those eleven as well as from thirteen other construction sites. Most builders were naturally apprehensive to see researchers auditing their work. Perhaps because of this, we were able to access laboratory reports from only eleven out of the twenty-four sites.

NDT data were collected using two rebound hammers, a Profoscope® electromagnetic rebar locator to avoid rebar in selecting hammer test sites, and an ultra-sonic pulse velocity sensor (UPV). One of the hammers was the traditional Schmidt Type-N
mechanical hammer, in which an internal spring propels a hardened steel plunger into the test surface (Figure 3). The plunger’s rebound travel is correlated to $E$ (50). The other hammer works in a similar way, but instead uses a hall-effect sensor and a microprocessor to measure the speed of the plunger as it rebounds (51). The UPV instrument estimates $E$ from the speed of transmission of ultra-sonic pulses through the specimen (52). Even though these instruments are easy to operate, attention to detail is necessary since rebound hammer readings and UPV speeds on concrete can deviate by up to 25% from the true value of $E$ unless care is exercised during the tests and calibration curves are adjusted to control for the variation in the ingredients (53). The research team collected samples of the aggregates and the cement at every site and prepared control specimens. All the builders were using the same aggregates from quarries near Nairobi, and Type II pozzolanic Portland cement. The rebound hammers were calibrated against six core samples taken from the buildings. The readings from the mechanical rebound hammer were found to be within +/- 3 MPa of the compression results for the control specimens. The electronic rebound hammer, set at Proceq Curve C, was used as a calibration verification tool.
Figure 3. Rebound hammer tests on a column. The lines mark the location of rebar. Deep indentations indicate weak concrete. Readings for this column were 15 MPa (+/-3 MPa).

Field work between June and October 2013 surveyed fifty-one existing buildings using the same testing methods. However, laboratory reports on the concrete and steel used in these buildings were unavailable.

Results

Most building sites visited for this study had few tools, old equipment, and unsafe scaffolding. Because wage rates are low (between $4 and $9 per day) (40), equipment and materials become the dominant cost factors in the construction budget. Builders therefore have incentives to minimize the use of both to achieve a competitive advantage (37) (Figure 4).
Figure 4. A commercial building under construction in a high-income suburb of Nairobi.

**Tensile Strength of Steel:** We visited five steelmakers around Nairobi. These manufacturers, as others in East Africa, use *minimills* to produce rebar from scrap steel following proven processes and quality control procedures (54, 55), which enables them to make rebar compliant with international standards like BS 8666:2005. Samples of rebar from twenty-four construction sites in Nairobi were tested and found to comply with the design specifications for tensile strength. All the buildings visited were using steel that had been purchased from one or more of the five steel manufacturers mentioned. Unfortunately, we cannot determine whether this code-compliant steel was correctly installed during construction without destroying the structure.
Our results contradict those reported in a recent study by researchers at the Jomo Kenyatta University of Agriculture and Technology (JKUAT), which suggests that there is large variability in the quality of rebar steel used in East African construction and reports that 69% of the rebar steel sold in hardware stores does not comply with accepted standards outlined above (44). JKUAT used samples from a mix of locations and nations. They collected samples from two steel mills in Kenya and six hardware stores and two construction sites in Rwanda and the Democratic Republic of Congo. All the samples tested for our study were taken from multi-story residential and commercial construction sites in and around Nairobi. The discrepancy in results and conclusions may owe itself to the differing natures of the samples.

\( f_c \) in laboratory reports

The reports of laboratory tests of \( f_c \) obtained at eleven new construction sites contained results from 154 concrete crush tests (56) conducted by materials laboratories in Nairobi for three types of concrete, designated C20, C25 and C30. “C25” stands for concrete with a minimum required \( f_c \) of 25 MPa. Results from samples of C25 concrete are expected to lie between a lower limit of 25 MPa and an upper bound of 33 MPa (Figures 5 and 6). Results lower than 25 MPa should have triggered investigations. Results above 33 MPa should have alerted the concrete makers that they were using too much cement. In nine of the eleven sites, the laboratory data showed a median value of \( f_c > 25 \) MPa. Sites ST9 and ST12 had reported values of \( f_c \) below specifications, and therefore some
intervention by the engineers in charge of these projects would have been required. There was no evidence of any such interventions at the time of this study.

Figure 5. Box plot, by construction site, of the officially reported laboratory results of $f_c$ from eleven construction sites in Nairobi.
Figure 6. Empirical cumulative distribution function for the aggregated results across the eleven construction sites in Nairobi of officially reported laboratory results of $f_c$.

Results from NDT tests of $f_c$ on structural reinforced concrete elements in twenty-four construction sites in Nairobi

Over 65% of the NDT tests resulted in estimates of $f_c < 25$ MPa (Figure 7). Some buildings are better than others, but even for the projects with better concrete there was a large variance and many weak outliers (as low as 15 MPa). Pooled data can be approximated by a Gamma distribution $G(6.23, .28)$. The quality of concrete in buildings erected by large firms was not significantly different from that in projects being built by smaller companies. In some of the reports issued to the developers, we suggested remediation or demolition. To our knowledge, in two of these buildings the
property owners acted on those recommendations, demanding partial demolition in one case and costly remediation work in the other.

**Figure 7.** Estimated $f_c$ from NDT readings at twenty-four buildings in Nairobi. **(Top)** Box plot results by construction site. **(Bottom)** Empirical cumulative distribution function and the plot of the fitted Gamma distribution.
NDT test on structural elements in 51 older building in Nairobi

The unexpectedly low values of $f_c$ in new construction naturally raise the question of whether this is a new phenomenon, perhaps caused by the stiff competition in the local market as new contractors enter the market, or if low quality of concrete is a systemic problem. To answer this question, fifty-one additional buildings were surveyed, all of them judged, from their styles and locations, to be less than thirty years old. Twenty-six of these are located in the central zone of Nairobi, which includes the Central Business District, commercial and high-income residential areas. We denote these as constituting Area A. The other twenty buildings are in middle-income areas of the city, including Buru Buru, Eastlands and others, and these constitute Area B.

Access to existing buildings was granted by their administrators and, as with the previous survey, we assured them that only anonymous aggregated data would be published. Fewer elements could be tested in each of these buildings, compared to the number of structural elements tested before at new construction sites, since most of the concrete had been covered by plaster and other decorative finishes. Most of the tested elements were columns, beams and slabs located either in machine rooms or in-building parking areas. Two-hundred and forty-four structural elements were tested: N=112 in Area A, and N=132 in Area B.

When concrete is exposed to ambient moisture, $f_c$ increases with age, though at a much lower rate than during the initial 28 days (57). However, when concrete is kept dry instead, it reaches a peak strength by its third year and stabilizes thereafter. Therefore, $f_c$ of exposed concrete in older buildings is expected to be higher than of newer concrete.
Experiments by Sharon L. Wood (1991) indicate that $f_c$ for concrete using ordinary Portland cement (Type I) and a water/cement ratio of 0.53 can increase by up to 25% by its third year, as compared to $f_c$ at 28 days, and by 40% by year twenty. (Figure 8)

**Figure 8.** Maturity curves for concrete as reported by Wood 1991. “w/c” represents water/cement ratio. The curve in the middle, for concrete of w/c = .53, was used to adjust for age the results from the survey. 1 MPa = 145 psi.

The age of most buildings was not known but, from the styles and locations, we estimate that few are older than twenty years; most were probably built between five and twenty years ago. To estimate the strength of these samples at 28 days, which would make it possible to compare these buildings to the previous results from our survey of new construction, we scaled down the values of $f_c$ obtained from NDT tests on older
structures by an adjustment factor of .75, derived from the results published by Wood (1991) for exposed concrete five to twenty years old.

Pooled Area A data adjusted for age follows a similar pattern to that of new construction, but with a larger portion (90%) of the concrete with $f_c < 25$ MPa. These results ($N=112$) can be approximated by Gaussian distribution $N(18.2, 4.1)$. (Figure 9) Raw test results, not adjusted for age, paint a less dramatic but still alarming picture with over 60% of concrete $f_c$ lower than common design specifications. Documentation on design strength of concrete for these buildings was not available. However, in conversations with two structural engineers who have considerable experience in construction in East Africa (names withheld), they estimated that most, if not all, of the columns and beams in building within Areas A and B would have been designed for C25 concrete, as it is the default value of $f_c$ used by designers in that region.
Figure 9. Empirical CDF and fitted Gaussian distribution $N(18.2, 4.1)$ for the results (N=112) a non-destructive test survey of existing buildings in Nairobi (Area A). The results were adjusted for age following Wood 1991.

The buildings in Area B used concrete that is even weaker. In this case, none of the concrete (N=132) reached design $f_c$. Figure 10 shows a cumulative distribution function for pooled data from Area B. The mean is 13.9 MPa and the maximum results (adjusted for age) was 20 MPa.
Figure 10. Empirical CDF of the results (N=132) of a non-destructive test survey of existing buildings in Nairobi (Area B). The readings were adjusted for age following Wood 1991.

**Discussion**

These data suggest that the concrete poured on-site in our sample of buildings is weaker than required and that a significant portion of laboratory reports correspond to samples that are not representative of the concrete used in the structures. The concrete used in building was found to be, on average, 9 MPa weaker than the official reports claim.

Figure 11 shows cumulative distribution function plots of compressive strength data from the laboratory test reports and the non-destructive-tests for new and existing buildings. The estimated distribution for concrete in Area A was obtained by sampling proportionately (to sample size) from the distributions of NDT results from new and existing buildings.
Figure 11. Cumulative distribution function plots of compressive strength data from the laboratory test reports and the non-destructive test surveys. The arrows denote the medians.

The discrepancies between the values of $f_c$ reported by the laboratories and those obtained from on-site concrete are too large to be explained by NDT instrument error. Perhaps, the best explanation for the divergence between laboratory results and our tests on the buildings is fraud (i.e., “an act of deceiving or misrepresenting”) (58). It seems less plausible that the disparities are the result of unintentional error because, in eight of the eleven sites where both laboratory results and NDT readings were obtained, the former were consistently higher (Figure 12).
Figure 12. Plot of median estimates of $f_c$ from NDT readings versus official laboratory results for eleven buildings in Nairobi. The error bars denote minimum and maximum values. The diagonal line is where the plots would be should the laboratory reports represented samples of actual concrete used in construction. The lower-right quadrant contains weak concrete reported by the laboratory as $f_c > 25$ MPa.

These findings tell a more alarming story than those of Mwasame 2012 (45), who found that the tested C25 concrete fitted a Normal distribution (N 25.6, 8.6) with about 30% of the samples below design $f_c$. Our results find lower strength concrete because: a) the
NDT tests were done after the concrete had been mixed and poured, and the builder did not know that these test would be performed until a month later; or b) the installed concrete we tested suffered from delayed pouring, late vibration, or improper curing.

At the construction sites we visited, the tasks of collecting the samples, taking them to the laboratory, and forwarding the test results to the engineers had been delegated to the building contractors themselves. The contractors could have asked the materials testing laboratory to send their technicians to collect the samples, and to submit the test reports to the engineers directly, but they did not.

The new construction sites were located in the same areas of the city, and are comparable in terms of size, design quality and use, to the older buildings surveyed in 2013 (Area A). The concrete in the new construction sites and in the older structures in Area A was found to be of better quality than that of Area B, though still far from acceptable standards. This could probably be explained by their building location. The high visibility of Area A make it reasonable to assume that most of its building projects were designed and supervised by certified engineers and architects. The new construction was all under the supervision of certified construction and engineering professionals too, which is why they were more comfortable extending invitations to our assessment team. Area B, on the other hand, is less visible, and construction is more likely to go on unsupervised.

Even though the data suggest that use of substandard concrete is pervasive in Nairobi’s construction industry, there is no reason to believe that builders are maliciously seeking to harm others. If the practice of using weaker concrete is as widespread as the data and
the experts suggest, and most builders send unrepresentative specimens prepared to meet design specifications to the laboratory for testing, then behaving differently would put them at a competitive disadvantage. In that case, policy-makers looking to improve the building quality control process should take into account not only the viable verification technologies, but also the incentives that motivate builders and the industry’s other actors.

Conclusions

The data suggest that the quality control mechanisms for structural concrete currently used in Kenya are not as effective as they should be. Architects and engineers routinely certify buildings as safe for occupation based, in part, on inaccurate or false laboratory reports. These findings highlight an example of lax quality control in the construction industry that could be pervasive in East Africa, as in developing countries elsewhere. Thousands of dangerously weak buildings will be built, and unless better control systems are implemented, millions of people will likely be exposed to unnecessarily higher risks for generations. National governments and international organizations interested in safer and more sustainable cities should give high priority to improving construction quality control processes and regulation. Policymakers in government, non-governmental organizations, and professional organizations must catalyze institutional change in the construction industry as a matter of urgency. Their efforts will be most effective if attention is given to the promotion and enforcement of prudent quality
control protocols that encourage engineers and inspectors to assume less and verify more.

References and Notes


37. Consultation with two former contractors, Mr. A.S. Virdi and Mr. E. Kinhara, and Mr. B.M. Ratna, owner of MCC Construction (July 2012) (2012).


Appendix

**Table S1.** Cement consumption in East Africa. (Source: East African Community, Arusha, Tanzania)

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**Figure S1.** (Left) Histogram of results reported by the materials laboratories. (Right) Histogram for results of NDT field tests.
**Table S2.** Median of Lab and NDT results

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**Figure S2.** Examples of laboratory reports. Identification information has been removed.
Table S3. Reported $\xi$ from materials laboratories in eleven projects in Nairobi. Construction sites are labeled ST#. (Partial list)

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Figure S3. Report of tensile strength of rebar steel from building sites in Nairobi.
Figure S4. Number construction permits issued by the Nairobi City Council

Table S4. Example of an NDT audit record

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CONCRETE QUALITY AUDIT REPORT

Introduction

The NDT audit was carried out on 5th September, 2012 for Serenity Park Development along Hamisi Road in Kileleshwa. Estimated concrete compressive strengths were measured for concrete works 28 days and more. For each element tested, at least 10 readings were taken. Outliers smaller or greater than 6MPa from the mean were removed. The reported estimated strength is the mean of the 10 readings for each structural element.

Results

The results reported in Table 1 are the average (mean) of 10 readings taken on each structural element sampled on site. The minimum target (design) concrete strength for these elements was 25 N/mm². None of the sampled elements reached the stipulated minimum compressive strength.

<table>
<thead>
<tr>
<th>No.</th>
<th>Element ID / Specs</th>
<th>MEAN (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RETAINING WALL PT 1</td>
<td>17</td>
</tr>
<tr>
<td>2</td>
<td>RETAINING WALL PT 2</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>RETAINING WALL PT 3</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>RETAINING WALL PT 4</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>COLUMN 1</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>RETAINING WALL PT 5</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>UNDERPASS RETAINING WALL (lower)</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>UNDERPASS RETAINING WALL (upper)</td>
<td>16</td>
</tr>
</tbody>
</table>

Official Laboratory Test Results reported by the appointed materials laboratory are significantly higher than the results from our survey. The 34-day strengths are above 25N/mm² and the younger samples (14 and 7 days) are well within the expected strength for that age of concrete. But –again- these are substantially different to our survey results.
Table 2: Cube crush strength as reported by the appointed materials lab.

<table>
<thead>
<tr>
<th>Element</th>
<th>Age of cube (Days)</th>
<th>Compressive Strength of concrete (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office Strip Foundation</td>
<td>34</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>28.1</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>26.7</td>
</tr>
<tr>
<td>Water Tank reinforced Concrete wall</td>
<td>14</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>19.3</td>
</tr>
<tr>
<td>Reinforced Concrete Retaining wall</td>
<td>7</td>
<td>17.9</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>18.5</td>
</tr>
<tr>
<td>Column Bases C2</td>
<td>7</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>19.2</td>
</tr>
</tbody>
</table>

Data Analysis

For further analysis, the data were fitted to the Gaussian (Normal) Distribution. In Figure 1 the dark line corresponds to the distribution of the samples taken on site. The dotted distribution is the curve we should have expected for C25 (Class 25) concrete. The vertical line marks the minimum design strength. The dark line should have appeared close to the dotted line, with most results right of the vertical line.

Figure 1. Statistical distribution of the site survey results.
Remarks

From the analysis of the data obtained after testing the concrete elements, we suspect that a large portion of the concrete does not meet the design compressive strength of 25 N/mm². None of the elements tested indicated average concrete compressive strengths of 25 N/mm² or above. In contrast, all the laboratory results indicate concrete always better than 25 N/mm² (in the case of elements 34 days old), or on the way to reach acceptable strength in the case of younger elements. The difference in the Schmidt hammer test results and the cube test laboratory report could be an indication of the kind of workmanship while laying the concrete in terms of vibration and curing, or perhaps the samples taken to the lab did not come from the same concrete mix used on site.

We acknowledge that the Impact Hammer test is not considered conclusive. However, it provides a good idea of the general qualities of the concrete tested. When NDT methods like the impact hammer show consistently low results further tests are often required, further tests are advisable.

Conclusion

While all labs results seem to indicate that the concrete on-site is within design specifications, our results are significantly different. We would recommend further consultation with the Structural Engineer to determine if the structure is safe even though the concrete compressive strengths maybe of significantly lower strength than required. Perhaps further tests such as coring would help gather more accurate data and guide the decision process.

End.
Carnegie Mellon University

Carnegie Mellon University
Baker Hall 129
5000 Forbes Avenue
Pittsburgh, Pennsylvania 15213

June 11, 2012

RE: Free Structural Quality Audits in Nairobi for Engineering Research

Dear: (******)

Why have we contacted you? The Department of Engineering & Public Policy (EPP) at Carnegie Mellon University is conducting research on building reliability in emerging economies and Kenya has been chosen as the focus location. We hope that our efforts will help improve the safety of concrete structures in many places throughout the world. In collaboration with Strathmore University and Questworks Ltd., we will be offering Free Structural Quality Audits on selected on-going construction sites in Nairobi.

How are the Audits done? We will use non-destructive testing (NDT) equipment as well as traditional lab equipment from Strathmore University. The audit will include sampling and testing of rebar steel, of on-site concrete installations and some verification of concrete cube samples using Ultra-Sound Pulse equipment, SilverSchmidt Impact Hammers, a Hydraulic compression press and a ProfoScope Electromagnetic rebar locator. NDT testing does not cause any harm or disturbance on the structures. These techniques are often used in the diagnostics of critical structures all around the world. In case defects are detected by NDT, we may then contact you to request your approval for additional tests, again at no cost to you.

How can you benefit? It’s always good to know if you are getting the reliable structure you expect in your buildings. Material testing is done in all construction sites, but seldom with the detail and care that we will put in into these audits. This process is time-consuming and costly, thus most construction projects go along with the minimum testing required by the law and established protocols. You are bound to benefit in all possible scenarios.
If the audits results are positive, you will gain peace of mind knowing that your buildings are reliable. You may want to use our report as a selling point if you are targeting sophisticated buyers or tenants.

If the audit shows defects, you can use our report to inform the engineers so they determine if the structural elements are within safety margins. If the engineers decide that modifications are needed to make the structure safe, you can request them at an early stage, all at the contractor’s cost. If the contract specifications are not met but the structure is still safe, you can demand discounts from the contractor so that you pay for the specific quality of materials that you are getting and not more.

However, the main beneficiaries of our efforts will hopefully be humanity at large, and especially people who will occupy the buildings that will be built in the next decades in emerging economies. Thus, we appeal to your generosity and interest in the welfare of future generations to ask you to help us in our research efforts by inviting us to your construction sites. An invitation letter by email is all we need from you right now.

**Why is this done for free? Is there a catch?** There is no catch. As researchers we need field data and these tests will provide essential information for our study. We will use your data in aggregated form to determine the state of the industry and guide us as we study ways of improving the processes for the benefit of many people. We can offer the audit for free because the principal researcher for this project is associated with Strathmore (which will provide the lab equipment) and Questworks Ltd. (which will facilitate support for the data collection).

**What will happen with the data?** Your private report will include the data from your construction and recommendations that you will find valuable. The specific results from your buildings will be known only by you and by no one else. Our research report will only include aggregated results in way that prevents the readers from knowing to which specific project the data belongs. The data log containing original identifiable data will be kept under lock at the archives at Carnegie Mellon University in Pittsburgh is as required for all research projects.

**Who are we?** EPP is part of the College of Engineering at Carnegie Mellon. EPP is the leading academic department in the world addressing problems in technology and policy in which the technical details are of central importance. We have identified the problems of building reliability as an area where rigorous research could yield valuable insights. And if done right, our work— with your help— could have significant real world impact in helping make buildings safer everywhere.

**Who are the Researchers?** My name is Raul Figueroa and I am the lead researcher for this project. I am an EPP PhD Student at Carnegie Mellon. For 9 years I worked for Strathmore as their Projects Manager on the construction of close to 80% of their total build area. I am also the Lead Consultant at Questworks, and Adjunct Faculty at Strathmore Business School,
where I lead two Executive Education Seminars. Professor M. Granger Morgan is the Lead Advisor for this project. He is the Lord Chair Professor in Engineering, and Head of EPP. For more than 30 years, Morgan has been a leader in a field that combines technological know-how with effective strategies for implementation.\(^1\) Professor Paul S. Fischbeck is Director of the Center for the Study and Improvement of Regulation at Carnegie Mellon. He applies the tools of decision analysis and behavioral social science to policy problems, paying particular attention to the quantification and communication of uncertainty.\(^2\)

Yours,

Raul H. Figueroa P.E.

raul@questworks.co.ke  /  raulf@cmu.edu

Mobile 0738-348900

\(^1\) Carnegie Mellon University Faculty Profiles. http://www.cmu.edu/corporate/pod/faculty_spotlight/granger-morgan.shtml

\(^2\) CMU Engineering & Public Policy Faculty Bios. http://www.epp.cmu.edu/people/bios/fischbeck.html
Chapter 3: Eliciting experts to assess, diagnose and rank interventions to improve reliability of Kenyan construction

Abstract

Poor construction quality is often the culprit in spontaneous building collapse accidents worldwide, and of catastrophes in the event of earthquakes in developing countries (1–4). Previous research has found that industry practice in Kenya is not effective at ensuring that the concrete used meets the minimum required strength. Therefore, most concrete is weak, and the buildings that use it are at a higher risk of failure. In this study eleven experts in the Kenyan construction industry were asked to: a) predict the results of Non-Destructive Tests (NDT) of compressive strength of concrete ($f_c$) in on-going building construction in Nairobi; b) estimate the $f_c$ of concrete used in rural Kenya; c) assess what portion of the concrete samples that are submitted for testing over the course of a construction project that are actually taken from the concrete used in construction; d) list and rank the probable causes of building collapse in East Africa in the last decade; and e) propose and rank plausible solutions to solve the problem of poor construction quality in Kenya. The accuracy of their predictions of the results of NDT of $f_c$ of concrete used in Nairobi, which were found to be considerably lower than the results contained in certified laboratory reports for the same projects, confirmed their expertise in Nairobi construction. Their insights into the causes of poor construction quality, and their recommendations on how to improve quality control practices, provide guidance for policy formulation.
One sentence summary

Experts accurately predicted low strength of concrete in Kenyan construction, and listed and ranked probable causes and plausible solutions to the problem of unsafe construction practices in Kenya.

Introduction

Poor construction quality has been identified as a major cause of building collapse accidents worldwide. In Kenya at least seventeen buildings have spontaneously collapsed since 2006, killing 84 people and injuring over 290. (Table 1) Previous research by the authors has found that, in Kenya, the quality control methods used in the construction industry often do not produce reliable data. Close to 75% of the structural concrete in Nairobi, and all of concrete sampled in the outskirts of the capital, does not meet design strength (Figure 1). Therefore, construction professionals and building inspectors are approving buildings for occupation that do not meet structural safety standards (Chapter 2).
Table 1. Incidence of building collapse in Kenya from 2006 to 2014. Despite the public concern caused by these accidents, new structures continue to be built with the same construction methods. (Sources: CNN, The Daily Nation, Standard-Media, Architectural Association of Kenya, Fox News) (5–9)

<table>
<thead>
<tr>
<th>Municipality</th>
<th>Year</th>
<th>Deaths</th>
<th>Injured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nairobi</td>
<td>2006</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td>Ngala St.</td>
<td>2009</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Kiambu</td>
<td>2009</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>Kisii Town</td>
<td>2009</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Kiambu</td>
<td>2010</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Kiambu</td>
<td>2011</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Embakasi</td>
<td>2011</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Langata</td>
<td>2011</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Ngara</td>
<td>2011</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Mathare</td>
<td>2011</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>Luanda</td>
<td>2011</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>Bungoma</td>
<td>2012</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Kisii</td>
<td>2012</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Mulolongo</td>
<td>2012</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Kisumu</td>
<td>2013</td>
<td>9</td>
<td>35</td>
</tr>
<tr>
<td>Nairobi</td>
<td>2013</td>
<td>11</td>
<td>90</td>
</tr>
<tr>
<td>Thika</td>
<td>2014</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>84</td>
<td>291</td>
</tr>
</tbody>
</table>
Figure 1. Cumulative distribution function plots of compressive strength data from: non-destructive test (NDT) surveys of new construction as well as existing buildings in central Nairobi (Area A); NDT surveys of existing buildings in outer Nairobi (Area B); and data from laboratory reports from 11 buildings in Area A.

Non-destructive testing (NDT) and building audits using other low-cost techniques (10–12), provide metrics of the strength of concrete and steel used on a building, but do not always shed enough light on the causes of material failure. Petrography is a reliable forensics technique to find the cause of low concrete strength (13). However, the high cost of petrography precludes its use as a regular quality control method in many developing countries, which are the focus of this research. In diagnosing the causes of
poor concrete quality, and more broadly the quality of construction, one alternative is elicitation of judgments from industry experts.

Expert elicitation (EE) is the process of gathering probabilistic models from specialists with subject matter expertise. Properly conducted EE has allowed the coding of valuable and uncommon knowledge. Experts with significant subject matter expertise, help researchers assess the overall state of particular industries, to estimate variables that are difficult to measure, such as the cost of new nuclear reactors (14), or to estimate the probability of rare events (15). This method has been successfully applied to many fields including climate response predictions and decision making (16, 17), anti-terrorism prediction (18), estimating the value of ecosystem services (19), and predicting health impacts of pollutants (20). Morgan 2014 (21) provides a more detailed summary of expert elicitation methods, suggests guidelines to make it useful in informing policy decisions, and warns against some inappropriate ways to doing it.

**Methods**

**Expert Elicitation**

Eleven experts in Kenyan construction agreed to participate in elicitation sessions held at Nairobi’s Strathmore University in July 2012. The group of experts included two construction managers (both of whom were former contractors), five architects, three structural engineers, and one quantity surveyor. Their experience in East Africa supervising construction projects that used Reinforced Concrete (RC) ranged from eleven to thirty-eight years with an average of eighteen years. They were asked to: a)
predict the results of NDT tests of the compressive strength of concrete ($f_c$) that were to be performed only days after the elicitation session at a set of ongoing building construction projects in Nairobi; b) estimate the $f_c$ of concrete used in rural Kenya; c) assess the likelihood that concrete samples submitted for testing were representative of the concrete actually used in the construction; d) list and rank probable causes of structural failure in East African buildings in the last decade; and e) propose and rank plausible solutions to solve the problem of poor construction quality in Kenya. The elicitation there of judgments about the first three questions was conducted using the SHELF2 Roulette protocol (22, 23). This protocol uses casino chips (each expert was given twenty), which the experts distribute among ten bins that contain probable values for the variable in question (Figure 2). As in all good protocols (24–26), the sessions began with a ninety minute review and discussion of probabilities, cognitive heuristics, the dangers of overconfidence in estimation and the value of explicit consideration of uncertainty. Full details of the protocol can be found in (27). The listing and ranking of causes and proposed solutions followed another method described below.

Figure 2. Experts placed casino chips into some –at least three- of the ten equally value-spaced bins.
The elicitation of each value began by asking the experts to determine collectively the range of all possible values for the variable in question. The range was split into ten equal bins. Then, individually, the experts placed chips in the bins according to their estimates of the probability that the true values would fall on each bin. They were asked to use at least three of the bins, as recommended in The Sheffield Elicitation Framework (23, 27). The results were a histogram-like arrangement of chips for each expert. The number of chips in each bin was used to fit probability distributions using software routines written in the statistical language R (28, 29). Experts were shown probability density plots of their distributions, which they either approved or modified until they were judged to be representative of their beliefs. (Figure 3). Most of the printed probability plots were accepted by each expert the first time around. A group discussion followed each elicitation session and yielded valuable insights into the details of the problem as each expert saw it.

To identify probable causes of building collapse, the experts were asked to individually list what they judged to be the ten most frequent causes of spontaneous collapse in construction projects in Kenya. All the probable causes were written on a blackboard. After an open discussion, they were asked as a group to reduce the collective list to the ten most likely causes. Then, using their twenty chips, the experts individually placed bets on how often they would expect to find each of these causes in failed structures. The bets for each cause from all the experts were aggregated and the results used to rank causes in order or expected frequency. Lists of causes of low compressive strength of concrete and probable solutions were assembled in the same way. To rank probable solutions in order of their expected effectiveness, we asked the experts to estimate how
effective each would be in making 95% of the results of the NDT survey of concrete be equal or greater than 25 MPa, were the survey performed a year after each solution was implemented. Answers for each proposed solution were summed across experts, and the ranking was done based on their aggregated “effectiveness” scores.

**Figure 3.** Output from the statistical package (27) (Top) Graphical representation of the chip in the bins. (Bottom) Probability density function plot for the best fitting distribution
Results

The experts believed that most official reports of $f_c$ of concrete contain results from unrepresentative samples.

Our experts believed that most concrete samples sent to the laboratory for testing do not come from the concrete being used in the buildings, but rather that most (median=89%) are carefully prepared “for the lab”, and are stronger (median=94%) than concrete used on the actual buildings (Figure 4).

The experts estimated that close to 75% of the installed concrete being used in Nairobi with specified $f_c$ greater than 25 MPa, does not reach the minimum required strength. Our experts estimated distributions of the value of $f_c$ for structural concrete in on-going building projects, first in Nairobi and then in rural East Africa. Aggregated estimates of $f_c$ for concrete in Nairobi follow a Gaussian distribution $N(20.1, 7.2)$. The experts also estimated that, in smaller cities and towns in East Africa, virtually all concrete is weaker than specified. Their estimate follows a Gaussian distribution $N(15.63, 4.83)$ (Figure 5).
Figure 4: Individual and linearly aggregated probability distributions. (Top) Estimates of the portion of concrete samples tests estimated to come from production concrete follow a Beta distribution Beta (1.64, 10.76). (Bottom) Estimates of the portion of unrepresentative samples that are made stronger than the actual concrete in the structures follow a Beta distribution Beta (21.4, 1.53). The arrows shows the medians.
Figure 5. (Top) Estimated value of $f_c$ for structural concrete specified as C25 in on-going construction projects in Nairobi. (Bottom) Estimated values of $f_c$ for concrete being used in smaller cities and towns in East Africa.
Low cement content was estimated to be the most frequent cause of weak concrete and structural failure

Six of the list of ten probable causes of building collapse were linked to concrete quality.

Not surprisingly, low cement content (called “shorting” by some) was considered the most frequent cause of failure. Concrete is one of the most abundant construction material in East Africa, and cement accounts for close to 70% of the cost of the materials in concrete (30–32). Our experts also stated that, although steel is the structurally dominant component in reinforced concrete, errors and fraud related to steel are easier to detect, which explains the lower relative frequency assigned to them. (Figure 6)

![Figure 6: Ranking of probable causes of building failure in Kenya from the aggregated votes of the experts. The order reflects the estimated relative frequency of the causes, not their severity compared to other causes. The horizontal axis represent the sum of chips in each category across all experts. Darker bars highlight those causes linked to concrete quality. The total number of chips is 220; 20 for each experts.](image)

Most of the causes of low concrete strength also appear on the previous list of most likely causes of collapse. (Figure 7) Insufficient curing was considered the second most likely cause. Concrete requires moisture to attain its maximum compressive strength. Curing concrete involves ensuring that it is hydrated, either by constantly pouring water on it or by using moisture-retaining membranes (33). Curing is most critical during the first 28 days after the pour. Improper curing can reduce concrete strength to as low as 50% of that originally intended. (34, 35).

Figure 7. Ranking of probable causes of low-strength concrete in Kenya from the aggregated votes of the experts. The horizontal axis represent the sum of chips in each category across all experts. This list contains most of the same causes as the list of most likely causes of collapse.

Compacting, the third most important cause of low concrete strength, is the process of removing bubbles and voids in the poured concrete that would diminish the strength of the structural element. This is done by vibrating the concrete using electrical or gasoline-
driven vibrators. Insufficient vibration would leave voids. Excessive vibration, on the other hand, could cause stratification of the aggregates and the cement paste, reducing the strength of the structural element. Self-compacting concrete, which was developed to reduce labor, is widely used in most developed countries. It is a more fluid mix and uses more cement per volume of concrete than the regular, drier, variety (36, 37). In developing countries, where the relative cost of cement is higher than labor, regular concrete is still used widely. Therefore, vibration or compacting is an important task during the pour in Kenyan construction.

The quality of concrete depends on the strength of the cement, gravel, and sand used. It also depends on sufficient mixing and prompt placement. Delayed placement or prolonged mixing become a problem as the concrete begins setting and loses workability. A common practice to retain plasticity is re-tempering by adding water but that can significantly reduce concrete $f_c$. (38)

**Ranked list of plausible solutions**

Our experts believed that the solutions expected to have most impact were: a) instituting regular independent audits of construction activities; b) requiring that structural concrete is mixed with large mixers and its ingredients dispensed by batching plants equipped with weight or volume sensors; c) the diffusion of non-destructive testing methods within the construction industry, especially for $f_c$; d) using surveillance CCTV at construction sites; and e) requiring inspections before occupation certificates are issued, a move that would necessitate new regulation. (Figure 8)
Figure 8. Ranked list of solutions to the problem of low-strength concrete as a proxy for poor construction quality. The ranking represents how effective (percent) each solution would be in improving construction quality to internationally accepted standards for safety.

Discussion

Expert estimates of $f_c$ for concrete in ongoing Nairobi construction closely matches empirical data for central Nairobi presented earlier (Chapter 2) (Figure 9).
Figure 9. Cumulative distribution function plots of: results from an NDT survey for new and existing buildings in central Nairobi (Area A); the estimates of experts of compressive strength of concrete in Area A; and data from the laboratory test reports for buildings in the same area of the city.

Experts also judged that most concrete test samples, on which the official test certificates reports are based, are carefully prepared to produce acceptable values of $f_c$ for reporting and approval purposes. The experts also estimated alarmingly low values for $f_c$ of concrete in rural East Africa; for the most part, these results coincide with the NDTs we performed on buildings at peripheral areas of Nairobi (Chapter 2). There, close to 90% of the concrete was estimated to be of lower strength than required. (Figure 10)
Figure 10. Cumulative distribution function plots of: results from an NDT survey in outer Nairobi (Area B); the estimates of experts of compressive strength of concrete in construction sites in rural East Africa.

Additional insights from the elicitation

After the elicitation sessions, but before the final group discussion, the experts were asked to answer three questions in writing: 1) “Do you think that current quality control and assurance practices are effective enough to ensure that new built structures are safe?”; 2) “If you had the power, what would you do to make new structures safer?”; and 3) “Has this expert elicitation session changed in any way your opinion regarding common industry practices in Kenya? If so, please tell us how.” Here we present some
of those answers that we consider most insightful. These and others answers are also available in the appendix.

- There is too much laxity in enforcement of the design and little supervision. The penalties for fraud are mild.
- There is a high rate of corruption at all levels: Local Authorities, Purchasers, Site Agents, Clerks of Works, and even Consultants
- Most test are carried out by a few labs and specialist who can be compromised.
- Ensure that mandatory technical audits and also financial audits are done by an independent audit team before an Occupation Certificate is issued.
- Quality Control and testing should be done by independent labs.
- Create a body to be able to check buildings and supervise during construction.
- Educate construction personnel on good construction practices.
- Enforce laws pushing more supervision by consultants (and perhaps pay them more).
- Have the Structural Engineer responsible for collecting test cubes and their results.
- Use more post-construction testing methods as the building goes up.
- The common practice of taking concrete cube samples that are used in our sites is complete nonsense as way of controlling the quality of concrete and is more a way of professionals reassuring—protecting—they themselves.

After further discussion, the experts agreed that the problems of low cement and steel quality may be less severe now than in years past, and should perhaps have been assigned lower likelihoods. Since 2003, the Kenya Bureau of Standards (KEBS) has required testing and certification of the cement and rebar steel destined for use in Kenyan construction. These efforts by KEBS and others seem to have helped improve the
quality of cement and steel supplied, according to the experts. Data from 72 trial mixes performed by Strathmore University using all brands of cement available on the Kenyan market in 2009 (Bamburi-Lafarge, ARM, East African Portland) showed that all performed at or above their specifications, both Ordinary Portland Cement (OPC 42.5) and Pozzolanic Portland Cement (PPC 32.5) (32). New trial mixes for concrete designed for $f_c > 25$ MPa carried out in July 2013 with cement from three new factories (Mombasa Cement, Savanna Cement, and National Cement) also performed well. Similarly, randomly chosen steel bars sampled directly from the four main rebar manufacturers in 2009 performed well within specifications (Chapter 2).

Even though errors in design, particularly in the detailing of rebar steel, were considered a serious problem, experts expressed optimism about the quality of analysis and design, which has improved and is likely to keep doing so. They justified their positive outlook based on a combination of improved curricula at local engineering schools and a more detailed certification process for engineers. They also noted the widespread use of specialized analysis and design software, some purchased but most pirated, among the younger generation of engineers.

Unstable formwork, ranked the sixth most frequent problem affecting the likelihood of building collapse, can reduce the strength of concrete in structural elements, since disturbances during the curing period can cause cracks in the concrete mass or reduce the bonding strength to the rebar. Delays in placement, ranked seventh on one list and the ninth on the other, are also a cause of the low $f_c$ of installed concrete. However, during the discussion, some of the experts, with more on-site experience (especially the
two experts who had been contractors for years) pointed out that unstable formwork and delayed placement occur more frequently than acknowledged. They argued that one reason for this is that supervisors discourage any waste of concrete. As a consequence, concrete that has been left to dry and set on a pile over lunch break or accumulated as spill-over at a transfer station -sometimes called “burnt” concrete- is re-constituted by adding water, re-mixed and placed on the forms. The combination of delayed placement and excess water content reduces concrete strength to a fraction of its design \( f_c \). Equally, when formwork creeps or moves after the pour, the builders rarely report it, as the solution would likely entail demolition and re-casting.

**Conclusions**

Experts with field experience in Kenyan construction estimated the strength of installed concrete in new construction in Nairobi, including both higher and lower income areas. Their estimates closely matched the results from field test conducted soon after, which confirms that most of the concrete in Nairobi is weaker than the minimum required by design strength and that current quality control practices are ineffective and easily circumvented. This match confirms that our group of experts is especially aware of the state of the local construction industry, and of the problems it faces. Their accuracy in predicting the value of variables that we could independently measure should motivate policy-makers to solve the problem at hand by paying special attention to the probable causes they predict and the plausible solutions that they proposed.
Our experts recommended that policy-makers look at ways to promote through incentivization or regulation- the institution of regular, independent audits of construction projects. Moreover, they recommended that structural concrete preferably be batched by automated machines and mixed in large mixers, that efforts be made to facilitate the diffusion of non-destructive testing methods, that surveillance measures be implemented, and that new regulation is passed requiring documented inspections before occupation certificates are issued. These measures, if implemented and enforced, could well transform then Kenyan construction industry and save lives in the process.

References and Notes


10. C. G. Petersen, B. Sc, M. Sc, in LOK-TEST and CAPO-TEST pullout testing, twenty years experience (The British Institute of Non-Destructive Testing, Liverpool, 1997).


29. MATCH, (available at http://optics.eee.nottingham.ac.uk/match/uncertainty.php#).


34. National Ready Mixed Concrete Association, Concrete in Practice: CIP 11 - Curing In-Place Concrete. Concrete (2000).


Appendix

Document S1: answers from the experts consulted.

Note: “E#” denotes a particular expert.

Q.2 Do you think that current quality control and assurance practices are effective enough to ensure that new built structures are safe?

All said NO.
E2.
There is too much laxity in enforcement of the design and little supervision. The penalties for fraud are mild.
E4.
There is lack of supervision and few adhere to specifications
E5.
Inspection by consultants on-site is minimal
E6.
The construction site is largely governed by the contractor and not by consultants
E7.
Most test are carried out by a few labs and specialist who can be compromised. The responsibility is mostly in the hands of the contractor/builder.
E8.
In the case of concrete the test cubes are handled totally by the Contractor and there is too much room for fraudulent manipulation
E9.
There is a high rate of corruption at all levels: Local Authorities, Purchasers, Site Agents, Clerks of Works, and even Consultants
E10.
Current methods (often incorrectly) assume and depend on many factors that affect the strength of built concrete structures.

Q.3 If you had the power, what would you do to make new structures safer?

E1.
A. Testing of concrete in-situ to ensure that what is built is as per specifications.
B. Improve (the) training especially of workmen so that they know why compaction, curing, etc., are important.
C. Testing of steel in the factories by regulatory bodies to ensure that standards are met.
E2.
A. Ensure that mandatory technical audits and also financial audits are done by an independent audit team before an Occupation Certificate is issued.
B. Ensure that the Design and Construction teams have qualified personnel to undertake the project.
C. NDT should be done randomly as construction progresses in all buildings
E3.
A. Always require the assistance of qualified engineers and train them better
B. Quality Control and testing should be done by independent labs
C. Create a body to be able to check buildings and supervise during construction
E4.
A. Random building inspections
B. Random sampling and testing of the materials
C. Verify that buildings and structures designed by duly qualified and registered professionals
D. Ensure that skilled personnel on site are qualified.
E5.
A. Educate construction personnel on good construction practices
B. Enforce laws pushing more supervision by consultants (perhaps pay them more)
C. Zero tolerance on sub-standard materials, especially steel.
D. Ensure that the Council that approves also inspects the projects
E6.
A. Mechanization of concrete mixing and placing
B. Better testing and quality control
C. Verification of sources of materials
D. Laws to enforce quality of concrete (and steel) in buildings
E. Enforce (good) building methods
E7.
A. Test should be done by consultants/specialist and not left in the hands of the contractor
B. Ensure that designs are simulated and information/calculations are verified by an independent body
C. Punitive measures to both the contractors and the consultants if they were involved (in defective buildings)
D. Training of technicians and craftsmen
E. Encourage the use of machines and tools
E8.
A. Have the Structural Engineer responsible for collecting test cubes and their results.
B. Use more post-construction testing methods as the building goes up
C. Sensitization and education of Consultants on how to control structural safety. Most do not follow out of ignorance.
D. Encourage the use of ready-mix concrete as quality control is easier that way.
E9.
A. Punish and remove corrupt officials in local authorities and enforce proper inspections
B. Blacklist consultants and contractors
E10.
A. Insist on quality check using NDT on site
B. Check quality and announce the results
C. Demolish in not of the quality required
D. Increase concrete batch sizes
E. Improve the methods of placing concrete
F. Site supervision every day
G. Site training
E11.
A. Combine the design and manufacturing process e.g. more Design-Build
B. Client/owner to be required to appoint independent quality auditors and submit audit reports to local construction authorities.

Q5. Has this Expert Elicitation session changed in any way your opinion regarding common industry practices in Kenya?

E1.
The common practice of taking concrete cube samples that are used in our sites is complete nonsense as way of controlling the quality of concrete and is more a way of professionals reassuring themselves (covering their backs)
E2.
Yes. The expert results from the graphs give a real indication of what is really happening in the industry. It is amazing!
E3.
It has. As a professional I had never though so clearly (about) the malpractices that take place during the testing and the loop holes that contractors are able to exploit.
E4.
Yes. I have to do better quality control practice and (more) thoroughness in supervision
E5.
Yes. It has given an open platform to debate the truth happening in the construction industry
E6.
No.
E7.
Yes it has. From now on I will be present to collect and sign the cube samples. Keep them in my office and do my own independent tests.
E8.
It has enlightened me on the poof follow-up by consultants and the concrete testing. Too much trust given to the contractors.
E9.
I am more determined to demand a more transparent process in the testing of concrete on site.
E10.
Yes. Highlights the process and all areas that contribute and possible reasons that can lead to lower concrete strength. Incentives are wrong.
E11.
(It has given me) awareness that extremely poor quality is possible and does happen in construction sites.
Table S1: Estimated relative frequency of the ten more probable causes of structural failure in new building in East Africa

<table>
<thead>
<tr>
<th>Probable cause/Expert(E)</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
<th>E5</th>
<th>E6</th>
<th>E7</th>
<th>E8</th>
<th>E9</th>
<th>E10</th>
<th>Votes from Experts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced Quantity of Steel</td>
<td></td>
<td>1</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delayed Placing</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insufficient Mixing</td>
<td></td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Low Steel Strength</td>
<td></td>
<td></td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Unstable Formwork</td>
<td></td>
<td>4</td>
<td></td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Errors in Design</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Improper Compacting</td>
<td></td>
<td>1</td>
<td></td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Low Strength of Aggregates</td>
<td></td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>Insufficient Curing</td>
<td></td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>38</td>
</tr>
<tr>
<td>Low Cement Content</td>
<td></td>
<td>8</td>
<td>7</td>
<td>4</td>
<td></td>
<td>9</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>52</td>
</tr>
</tbody>
</table>
Chapter 4: A model to estimate the effects of improved construction quality on reinforced concrete buildings in central Nairobi

Abstract

Loss estimation models provide governments and policy makers with information that can help improve decisions before and after an earthquake, including the prioritization of seismic risk-mitigation activities. Poor construction quality increases the risk of building damage or collapse during seismic events. This paper demonstrates a simple and inexpensive method to estimate the risks that result from low construction quality of reinforced concrete-framed buildings. We use central Nairobi as our case study, though this method can be adopted to other cities in developing countries that often lack accurate inventories of their building stock. Our method: a) estimates the characteristics of the building stock in Nairobi from satellite images and walk-by surveys; b) adapts the collapse (CP) and severe damage (SD) fragility functions derived elsewhere, to generate a family of fragility curves for different levels of CQ; c) uses findings from previous investigations into concrete quality (Chapters 2 and 3) to estimate construction quality (CQ) of buildings in a sample area within central Nairobi; and, d) incorporates the estimated distributions of CQ, of the building stock and the fragility curves into a model that uses Monte Carlo simulation to estimate the damages that would result in several earthquake scenarios, including scenarios that assume different policies to improve CQ and consider seismic loads during design and construction.
One Sentence Summary

This model estimates the square meters of buildings in Nairobi that would either collapse or suffer severe damage in case of earthquakes with different spectral accelerations (Sa).

Introduction

Loss estimation models provide governments and policy makers with information that can help improve decisions before and after an earthquake. These include the prioritization of seismic risk-mitigation activities and the selection of construction locations, codes and methods. Low-quality construction increases the risk of damage or collapse during seismic events (1). The findings of previous investigations (Chapters 2 and 3) suggest that construction quality (CQ) in Nairobi is poorer than required by design. As a consequence, the occupants of these structures are exposed to unnecessarily high levels of risk in the event of even moderate seismic events.

Building professionals in Kenyan industry and academia have predicted disaster in the event of a moderate earthquake in Nairobi or elsewhere in Kenya. For example, in the wake of the 2010 Haitian earthquake, and of a spontaneous collapse accident in Nairobi (one of seventeen in the last decade), the spokesperson for the Architectural Association of Kenya said, “In the event of a disaster such as last month’s earthquake in Haiti, 70 percent of buildings outside central Nairobi would collapse”, adding that, “the structural stability of buildings countrywide was very poor.” (3) Professor Opiyo, of the University of Nairobi stated that, "If
a quake similar to Haiti’s hit Nairobi, the damage would be unthinkable. Many buildings would not withstand the impact because we have been putting up structures as if an earthquake could never occur in Kenya. We are building structures as though Nairobi were in a stable position, but it isn’t.”(4)

Some attempts have been made to estimate seismic risk in East Africa by surveying data from international sources (5), or by estimating a “structural reliability index” from samples of construction materials (6). However, there are no published reports or models that attempt to quantitatively assess seismic risk on a city-wide scale in Nairobi. Such a task is important given the city’s growing population and the booming construction scene of the last decade, which—based on findings from our previous investigations—may have produced (and may still be producing), a large number of vulnerable buildings. Few resources have been allocated to work such as this for a number of reasons, one of which is the mild seismic activity in Kenya since 1928 when an earthquake of magnitude 6.9 on the Richter scale struck Subukia, about 200km northeast of Nairobi (7). Strong earthquakes have been relatively uncommon in the country.

Quality control during the construction of reinforced concrete (RC) frames for regular buildings is not technically challenging. Rather it is a managerial task for engineers, construction supervisors and inspectors. In most developed countries, with their mature construction industries and strong institutions, quality control activities and approvals of structural elements are generally carried out following standard protocols (8–10), often by trained and licensed personnel. Consequently, few papers report on the effects of varying degrees of construction quality on building fragility (CQ) (1, 2, 11, 12). But, in
Nairobi, as seems to be the case in others countries that also experience abnormally frequent incidents of spontaneous building collapse, quality control in construction is insufficient or inadequate to ensure the safety of the structures.

Computer simulations, most based on finite element modeling, can help predict the behavior under load of structures, with known design and material characteristics. The Earthquake Engineering Research Institute, the National Institute of Standards and Technology, and others are working on projects to count and characterize structures in different geographical regions to enable more accurate risk assessments (13–15). When the as-built characteristics are unknown, or when the goal is to quantify seismic hazards on a city-wide or regional scope, many institutions rely on a combination of risk models based on the estimated fragilities of hypothetical buildings representative of those in the area of interest, historical records from past accidents or seismic events, and the opinions of experts in structural design and forensics (16–18).

The United Nations Office for the Coordination of Humanitarian Affairs (UN-OCHA) estimates that there is a 20% probability of an earthquake exceeding a Modified Mercalli Intensity Scale (MMIS) Cat VII (magnitude 6.1 on the Richter scale) in Kenya’s central region in any fifty year period (19). The 2013 Global Assessment Report on Disaster Reduction estimates an earthquake hazard, within a 250-year period, of spectral acceleration (SA) between .05 and 1g for Nairobi (20). The U.S. Geological Survey’s (USGS) Worldwide Seismic Design Tool suggests that designers in Nairobi build for 1-second Sa of .05g, and .2-second Sa of .32g. (21)
This paper demonstrates a simple method of estimating risk that can be implemented by practitioners in developing countries at a low-to-moderate cost. It can also be useful in assisting policy-makers when selecting among alternative policies to reduce earthquake risks. We apply this model to Nairobi because we are interested in quantifying its seismic risk and helping the Government of Kenya, and in particular its National Construction Authority, who’s General Manager for Registration and Compliance, has expressed interest in using our research as a basis for probable new regulation and policy. Our case study can be seen as an example that can be replicated in other cities in developing countries that face similar regulatory challenges and resource constraints.

Methods

A model was developed that estimates the square meters of buildings in Nairobi that would either collapse or suffer severe damage in case of earthquakes with different spectral accelerations (SA). From these results, it estimates the number of people who would be affected (bodily harm, or loss of domicile or workplace), as well as the replacement cost of damaged buildings in 2012 US Dollars. The model uses Monte Carlo simulations, drawing random samples from statistical distributions of: fragility curves for exceedance of the collapse (CP) and severe damage (SD) states; estimates of the distribution of the building stock; estimates of occupancy levels; of new construction and repair costs; and of construction quality (CQ). It was coded in the statistical language \( R \) (22), and used the \( R \) Studio integrated development environment (23), as well as several open-source packages that work within \( R \) (24, 25).
To estimate the square meters of damaged and collapsed buildings, the model calculates the entries of two 3-by-3 matrixes: one that distributes the estimated built area by three floor-height groups and by three levels of construction quality, and another that contains the probability of exceedance of either collapse or severe damage by floor-height group and level of CQ. The entry-wise product (also called the Hadamard product) of these two matrixes is the main result of each model run, with each entry being either square meters collapsed or square meters severely damaged.

**Compressive strength of concrete (fc) as a proxy for CQ**

Even though $f_c$ is one of the determinants of CQ, it neither alone defines construction quality, nor is it the sole cause of building failure. Buildings subjected to abnormal loads can fail for reasons other than low concrete strength (26, 27). However, weak concrete increases the probability of structural collapse (28, 29). To prevent shear and crushing failures, structural designers establish $f_c$ early in the design process, and assume $f_c$ and all other properties dependent on $f_c$ (such as $E_c$ = modulus of elasticity of concrete and $f_r$ = modulus of rupture of concrete, etc.) as constants (30, 31). In construction projects of common residential, commercial and other typical structures, achieving the $f_c$ required by design is rarely a challenge. As a consequence, there are no published models that quantify changes in probability of collapse due to changes in the value of $f_c$ alone. While there is no doubt that a lower $f_c$ than that required by design increases the probability of failure, there is no published research that reports the amount of increase.
However, we argue that $f_c$ can be used as a convenient proxy for CQ, and that, for various reasons, it is as a proxy for CQ that reports of $f_c$ are most useful. First, construction quality, as defined by (11), includes variations in the quality of concrete and in the detailing of the reinforcement steel (rebar). When it comes to affecting fragilities, the strength and quality of rebar installation often dominates the variations in concrete quality. But, while $f_c$ can be assessed with relative ease, the quality of rebar material and placement can typically only be assessed after the structural elements in question have been destroyed for verification, or have become part of the rubble of a collapsed building. The literature reporting on investigations of building failures in Haiti (29, 32) and other events in Kenya, Bangladesh and Ghana, suggests the construction defects that increase the risk of collapse seldom show up in isolation. Second, non-destructive and minimally-destructive test methods allow for quick and inexpensive verification of $f_c$, even for structural elements that have been in place for many years. Third, reductions in steel and cement content yield the highest financial benefit for a builder unconcerned with quality and safety of the building (Figure 1). Achieving good concrete strength also requires the collaboration of many actors, making supervision harder. Therefore, it would be reasonable to expect low strength concrete, less steel, or both in low quality buildings, as well as positive correlation between CQ and $f_c$. Conversely, it would also be reasonable to expect that supervision efforts and the expense invested into achieving high $f_c$ of installed concrete, would be accompanied by improvements in other activities that affect CQ, especially when those activities are not particularly capital intensive, such as careful installation of rebar steel and the use of stable molds and formwork.
Figure 1: Experts listed and ranked the ten most likely causes of building collapse in Kenya (horizontal axis) (Chapter 3). Later, professionals in construction costing in Kenya estimated the number of people typically employed to perform each task (vertical axis), the illicit gains in U.S. Dollars possible while casting a 100 m2 slab without risk of detection, given the quality control practices in Kenya (size of the balloons). The horizontal axis are the number of votes that each defect received for most frequently encountered (see Methods in Chapter 3). “Less concrete” was estimated as occurring most frequently; it is the product of the work of 10 people; and can be a source of illicit gains of $300.
Estimates of the building stock in Nairobi

To assess city-wide risk, it is necessary to have an accurate building inventory (15). However, developing countries often lack the data-gathering institutions that would make possible accurate characterizations of the building stock. Kenya does not have an updated building inventory: data are scant and sometimes outdated. From June to September of 2013, attempts to obtain building inventory data from local government agencies proved fruitless. The inventory of buildings in Nairobi is a work in progress. Furthermore, the sources queried (Nairobi City Council Planning Office, Kenya Land Register, Kenya Revenue Authority, Kenya Private Developers Association and the Kenya National Bureau of Statistics) lacked data from which an inventory could be constructed. To circumvent this obstacle, we estimated the building stock from satellite images and street photos taken at representative locations within the city of Nairobi through the process described below. A summarized description of the model in tabular form can be found in the appendix.

To calculate the first matrix, the entries of which estimate the square meters of RC-framed buildings by floor height and by level of CQ, we began by demarcating central Nairobi into ten zones judged to be reasonably homogeneous in terms of the characteristics of their buildings. (Figure 2) Then, from satellite images (33), we calculated the footprint of the buildings in each zone by outlining the rooftops on the satellite images, and used AutoCAD® to measure the rooftop area in each zone. (Figure 3)
Figure 2. Satellite Image of Central Nairobi. Ten zones are demarcated and the sample streets for each zone are marked with pins and colored lines.

There is uncertainty about these estimates because with satellite imagery it is not always possible to distinguish buildings from other types of man-made structures such as, empty parking lots, or light temporary structures. For this reason the estimates were developed as ranges instead of point-estimates. (Table 1) Each run of the model draws estimates of footprint in each zone from a Triangular distribution centered at the mid-point of the range estimated from the satellite image.
Figure 3: Outline of rooftops used to calculate the footprint of buildings in each zone. AutoCAD® was used to mark and measure footprint of buildings visible on the satellite images from ©Digital Globe on Google earth.
Table 3: Building footprint, distribution of buildings per floor-height group, and occupancy. These were estimated based on satellite images and walk and drive-by surveys in a street judged representative of each of the ten zones in which the study area was divided.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Building footprint (1000 m²)</th>
<th>Distribution of buildings per floor-height group</th>
<th>Occupancy (persons per m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
<td>3 Floors</td>
</tr>
<tr>
<td>1</td>
<td>220</td>
<td>260</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>350</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>110</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>240</td>
<td>300</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>170</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>170</td>
<td>220</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>160</td>
<td>210</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>350</td>
<td>400</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>210</td>
<td>260</td>
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</tr>
<tr>
<td>10</td>
<td>110</td>
<td>150</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Walk-by photographic surveys were performed on streets representative of each zone, in terms of building types, to create a distribution of buildings by floor-height groups, and their occupancy levels (Figure 3). The ten streets surveyed are indicated by pins and colored lines on Figure 2. The buildings were classified into one of three groups: 1 to 4 floors high, 5 to 7, and 8 or more. (Table 1) These groups were labeled 3, 6 and 9,
respectively. In four of the zones the survey had to be performed driving-by since some people threatened to become violent. They were apprehensive about strangers photographing their buildings, and understandably so, because the city had recently suffered terrorist attacks.

![Image](https://example.com/image.jpg)

**Figure 4.** Some photos taken in Nairobi's central business district as part of the surveys to estimate the distribution of buildings into height-groups and occupancy.

The choice of height categories was a matter of convenience: first, families of fragility curves exist that consider variations in CQ and other sources of uncertainty for buildings 3, 6 and 9 floors tall, and second, we observed that most buildings in central Nairobi are between 2 and 10 floors tall. Each run of the model calculates a new allocation of random values for square meters per height group per zone, adding uniformly distributed noise of +/-10% to the estimates from the survey, as a way of capturing some of the uncertainty from the walk-by estimates. This spreads the results.
symmetrically. The result, for each model run, is a 3-by-10 matrix with random estimates of the square meters built by floor-height groups and by zone.

Occupancy levels (in persons per square meter of built area) were estimated during the survey by observing the type and use of buildings (residential, commercial, industrial, etc.) and considering common occupancy levels used in the design of the types of buildings dominant in the zone (see appendix). Values for the minimum, best estimate and maximum were estimated for each zone (Table 1). The model uses these estimates of occupancy as parameters of triangular distributions from which it draws values in each run when calculating the number of people affected by collapsed or severely damaged buildings.

Then, the built area per each floor height group was allocated to one of three levels of CQ by drawing samples from the distribution of the compressive strength of concrete (f_c) that resulted from previous investigations in the same locations within Nairobi (Chapters 2 and 3). Cut-off points for levels of CQ were drawn from these distributions: Triangular (19, 20.5, 22) was taken as the upper limit for “low quality construction”, while Triangular (27, 29.5, 32) was taken as the lower limit for “high quality construction”. Middle values of f_c were assigned to “average quality of construction”. The result is a 3-by-3 matrix with entries containing random estimates of square meters per floor height group and per level of CQ. These cutoff points were chosen because samples from well mixed and placed concrete, formulated to yield f_c > 25 MPa, which is most commonly specified in the structures of interest, are expected to follow a Gaussian distribution, typically similar to Normal (34, 4.5) but in all cases resulting in less than 1%
of the average of three consecutive tests falling below 25 MPa, and the same chance of any single test value under 21.5 MPa \( (34) \). (Figure 5) However, even though we assume a positive correlation between \( \ell \) and CQ, it is reasonable to expect varying levels of overall CQ between building sites with the same mean \( \ell \).

![Cumulative distribution function plots of \( f_c \): A) from non-destructive tests on new construction and existing buildings in Nairobi, performed between June 2012 and August 2013; and B) expected from samples of well mixed and placed concrete.](image)

**Figure 5**: Cumulative distribution function plots of \( \ell \): A) from non-destructive tests on new construction and existing buildings in Nairobi, performed between June 2012 and August 2013; and B) expected from samples of well mixed and placed concrete.

**Families of fragility curves for collapse and severe damage**

To populate the second matrix, entries of which estimate the probability of either collapse or severe damage as a function of floor-height and CQ, our model draws probabilities from families of fragility curves produced by Celik \((2)\). Fragility curves are
cumulative distribution function plots that show the probability of a system or component reaching a limit state as a function of seismic intensity (35). Several research efforts have produced and used fragility curves, typically characterized as log-normal distributions, for many components and sample structures (35–49). Most of the tests and simulations used to develop fragility curves are done on components and sample structures assumed to have been built as designed. These simulations are often used to compare the performance of buildings of different designs, with the goal of improving building codes. Some, however, have explored the effects of irregularities in construction quality on fragilities and have derived families of curves that account for the uncertainty generated. Celik’s 2010 (2) families of fragility curves characterize the roles of aleatoric and epistemic uncertainty; among the sources of these are the compressive strength of concrete, the quantity of reinforcing steel, the quality of the steel installation, and other determinants of CQ. Table 2 contains the means and standard deviations of curves for the two states of interest: collapse (CP) and severe damage (SD). Figure 6 shows the plots of the same.

Rajeev 2012 (50) derived similar families of fragility curves considering irregularities and, like Celik, included various concrete and steel qualities as independent variables in their model. Dimova 2005 (I) reported that design formulas might overestimate the performance of RC elements when quality of construction is wanting, and estimated a 20% reduction in that performance.
Table 4. Means and standard deviations of upper and lower limits of the families of fragility curves by Celik, for the probability of collapse (CP) and of severe damage (SD).

<table>
<thead>
<tr>
<th>Floors</th>
<th>Log Mean</th>
<th>Log Standard Deviation</th>
<th>Log Mean</th>
<th>Log Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.25</td>
<td>0.442</td>
<td>0.771</td>
<td>0.439</td>
</tr>
<tr>
<td>6</td>
<td>0.679</td>
<td>0.442</td>
<td>0.418</td>
<td>0.459</td>
</tr>
<tr>
<td>9</td>
<td>0.549</td>
<td>0.442</td>
<td>0.344</td>
<td>0.459</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.49</td>
<td>0.531</td>
<td>0.338</td>
<td>0.445</td>
</tr>
<tr>
<td>6</td>
<td>0.32</td>
<td>0.562</td>
<td>0.217</td>
<td>0.482</td>
</tr>
<tr>
<td>9</td>
<td>0.275</td>
<td>0.597</td>
<td>0.189</td>
<td>0.44</td>
</tr>
</tbody>
</table>
Figure 6: Upper and lower limits of fragility curves families for (Top) severe damage state and (Bottom) collapse probability, for buildings 3, 6 and 9 floors tall. Redrawn from Celik (2010)
To estimate the probabilities of collapse or severe damage given earthquakes with various spectral accelerations, measured in terms of gravitational acceleration \( \text{Sa}[g] \), we used seismic fragility curves from (2). These curves are derived from structural computer models of buildings of 3, 6 and 9 floors high that are designed only for gravity and wind loads, which are then subjected to seismic loads in the OpenSees seismic modeling platform (51). The models were built to characterize reinforced concrete-framed buildings common in Memphis, Tennessee. These curves were deemed the best available approximation for reinforced concrete-framed buildings in Nairobi since, like Memphis, the city is not located in an area of high seismic hazard. As a consequence, in Nairobi as in Memphis, most buildings have been designed and built for gravity and wind loads, but not to resist earthquakes (4). Furthermore, a large portion of buildings in the Kenyan capital fall within the same three floor-height categories. For each floor-height group and for each of the two states of interest (collapse and severe damage), each run of the model generates three families of fragility curves, one for each level of CQ (low, average and high). It does this by taking the entire range of families from (2), drawing a random cutoff value for the logs mean and the standard deviations of the 30th and 70th percentile and adding uniformly distributed noise of +/-10% at each cutoff. (Figure 7) In this way we attempt to account for some of the additional uncertainty inherent to estimating probabilities of collapse from convenient fragility curves. The results are 3-by-3 matrixes with random values for probabilities of collapse or severe damage per floor-height group and level of CQ.
Figure 7. Examples of “bands” of fragility for severe damage or collapse for buildings 9 floors tall (Top), as well as for 3-floor buildings (Bottom).
To obtain estimates of square meters collapsed we calculate the entry-wise product of matrix with values of probabilities of collapse, by the previously computed matrix, which entries contain estimates of square meters per floor height group and per level of CQ. Estimates of square meters severely damaged are calculated in the same way, but substituting the matrix of probabilities of collapse for the one with probabilities of severe damage. The number of people who would be affected is estimated as the product of the sum of the number of square meters collapsed or damaged and the estimate of occupancy per square meter in each zone. To estimate building replacement cost the model draws from a Triangular distribution with a minimum cost of 40,000 Kenyan Shillings (Kshs), a best estimate of Kshs 60,000, and a maximum of Kshs 80,000 per square meter collapsed. To estimate repair cost per square meter severely damaged, the random value for replacement cost is multiplied by a factor drawn from a Triangular (0.1, 0.25, and 0.5) distribution. These values were chosen in consultation with professionals in construction costing in Nairobi (52). Note that this is a simple replacement or repair cost for the buildings and their content, and does not include any of the others costs associated with the loss of a building, which are likely to be multiples of the simple replacement cost estimated here.

**Results**

Because of the many uncertainties that are involved, the values estimated by the model have wide ranges. Figure 8 shows histograms of some of the outputs reported in square meters collapsed, square meters severely damaged, number of people affected,
replacement and repair cost, and histograms of square meters to collapse in central Nairobi as well as in a hypothetical (ideal) new city built with a tighter quality control during construction alone, without any other improvements in design and building codes.

The model was run in twenty-four scenarios, with values of Sa (g) of .2, 3. and .4 g; two different construction codes, one considering only gravity and wind loads, and the other including moderate seismic loads; and four probable future scenarios of building replacement in the next 15 years. Two of these scenarios are “business as usual” (BAU) substitutions of existing buildings for new ones. Hass Consult (53), in reply to a private email request, estimated that a minimum of 10% of the existing buildings in Nairobi will be naturally substituted, with a best guess estimate of 25% and a maximum of 35% during the next 15 years. The other two scenarios consider regulated substitution, including one in which all buildings built with concrete with mean f<sub>c</sub> <= 12 MPa are either rebuilt or reinforced. The other sees the same thing done to buildings of mean f<sub>c</sub> <= 15 MPa. These account to roughly 10% and 22% of the estimated built area, respectively, estimated from our previous studies (Chapters 2 and 3). Figure 9 displays CDFs of f<sub>c</sub> sampled from buildings in Nairobi (Chapter 2), and hypothetical distributions of f<sub>c</sub> that we would expect if all new buildings, in the four future scenarios considered, were to be built under a policy that enforced adequate quality control during construction. For each run on a future scenario, the model draws samples from the hypothetical distributions of f<sub>c</sub>, instead of from the empirical distribution produced by the audits.
Figure 8: Histograms of different outputs from our model under a scenario of current CQ, non-seismic design, and an earthquake of $Sa = 0.3g$ for: \(\text{(A)}\) square meters collapsed, \(\text{(B)}\) severely damaged, \(\text{(C)}\) people affected, \(\text{(D)}\) replacement and repair cost, and \(\text{(E)}\) histograms of square meters to collapse in central Nairobi, and in a hypothetical (ideal) city built with a tighter quality control during construction.
Figure 9. CDFs of $f_c$ sampled from buildings in Nairobi (Chapter 2), and of hypothetical distributions of $f_c$ that could be expected if the new buildings, in the future scenarios considered, were of high quality.

Figures 10 and 11 display CDFs for estimates of square meters collapsed, and cost of replacement and repair under the four hypothetical futures, the present state, and a new city where all the buildings were constructed with good CQ. Here $S_a = .3 \ g$. 

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Figure 10: Cumulative distribution functions of thousands of square meters collapsed in the case of a seismic event of $\text{Sa} = .3 \text{ g}$, under several plausible futures: a new ideal suburb with similar types of buildings as the area studied here, BAU, and four substitution scenarios. Two lines trace one another: one corresponds to a scenario with 25% random substitution (violet), and the other to a policy mandating the substitution or refurbishment of buildings with $f_c < 12 \text{ MPa}$.
Figure 11: Cumulative distribution functions of replacement and repair cost in the case of a seismic event of $S_a = .3 \, g$, under several plausible futures: a new ideal suburb with similar types of buildings as the area studied here, BAU, and four substitution scenarios.

Fragility curves for structures designed for seismic loads have, as expected, larger means and medians. For the scenarios with designs that account for at least moderate seismic loads, we shifted the fragility families from Celik 2010, for CP and SD by .3 and .2 respectively. (Figure 12) These values were chosen such that these buildings have low probabilities of collapse and severe damage in the event of an earthquake of $S_a = .32 \, g$. The Worldwide Seismic Design Tool (Beta) (21) suggests that design in Nairobi take into account events with .2-second spectral acceleration of $ .32 \, g$. 

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Figure 12. Shifted fragility curves as would be expected for buildings designed considering seismic loads of $S_a = .3 \, \text{g}$. As before, the plots show the upper and lower limits of the ranges in the families of curves for (Top) the probability of severe damage and (Bottom) the probability of collapse.
The resulting fragility curves describe lower seismic performance than those developed for buildings designed for locations of high seismic activity (48). However, and despite the increased safety, we believe that codes deemed too demanding would face significant pushback (due to increased cost of construction) from both the market and a large number of engineers. This would make implementation unduly difficult, if not impossible, in locations like Nairobi. Figure 13 allows comparisons of plausible risk reduction from regulatory environments that enforce more effective quality controls, building codes that consider seismic loads, or both. Our model suggest that a policy that enforces that new designs consider seismic loads and that construction meets high quality standards could significantly reduce building collapse in case of a moderate earthquake in Kenya.
Figure 13: Estimates of square meters that would collapse under four policy scenarios and earthquakes causing three spectral accelerations. The U.S. Geological Survey, Worldwide Seismic Design Tool recommends values of spectral response acceleration of $0.32g$ at $0.2$ seconds and $0.15g$ at $1$ second for the design of buildings in Nairobi (27).

Discussion

The results of our model illustrate that, compared to the current state of Nairobi’s building stock, it may be possible to attain a more than $30\%$ reduction in the risk of collapse and severe damage from a moderate ($Sa=0.3g$) earthquake. This further emphasizes the need for increased construction quality in the structural elements of reinforced concrete-framed buildings. These reductions seem modest when compared to
the opinion of experienced professionals and academics in Nairobi who have consistently criticized the local construction industry for the poor workmanship and material quality, especially after incidents of spontaneous building collapse. Certainly, good construction quality alone does not guarantee invulnerability to earthquakes, and in the case of seismic events of spectral acceleration above \(0.5g\), would not help if the design failed to consider seismic loads. However, in case of events of \(Sa < 0.3g\), significant risk reduction is achievable at low cost in most cases, and the money would be spent on closer supervision and quality testing.

The values for \(Sa\) used were based on 10%-in-50-year peak ground acceleration values \((2f)\), which means that earth motion event of this characteristics have an estimated return period of 475 years. These are the values recommended by the International Building Code for the design of non-critical structures.

**Conclusions**

“Doing nothing” may at times be the best policy decision, but not in this case. Losing between 1.5 and 2.5 million square meters, which translates to between 800 and 3500 residential and commercial buildings, along with thousands of deaths and injuries, and billions of dollars in reconstruction would have catastrophic effects for Kenya’s capital. The combination of seismic resistant designs and strict control over quality seems a policy imperative. In case of moderate earthquakes, such as those expected in the Rift Valley region, well-built concrete structures could be damaged, but few would collapse, as the case has been in regions where building codes have been strictly enforced \((16)\).
That said, the question of what to do about the existing building stock has no simple, low-cost answer. The results from our model suggest that a policy mandating the reconstruction or reinforcement of lower quality buildings, in this case characterized by $f_c < 15$ MPa in cases where concrete with $f_c > 25$ MPa had been specified, would achieve twice the risk reduction expected from a 25% turnover of buildings stock in business-as-usual conditions. If improvements in CQ are accompanied by seismic resistant design, the risks of new building collapse or severe damage, subjected to a moderate earthquake, could be driven even lower.

Our model attempts to capture as much uncertainty as possible without becoming cumbersome for policy-makers in developing countries, and it seeks to inform them of the effects of actuating the various policy levers at their disposal. The model is most sensitive to the choice of fragility curves, to the criteria used in assigning levels of CQ and the spectral acceleration specified for the seismic event in each run. A considerable, extensive and probably expensive effort would be needed to reduce the uncertainty in these variables, and it could very well be a worthwhile endeavor. However, it is probably imprudent to delay considering implementing policies that, at the very least, prevents the addition of risky structures to Nairobi’s building stock.

References and Notes


14. W. T. Holmes, Concrete Model Building Subtypes - Recommended for Use in Collecting Inventory Data (National Institute for Standards and Technology, United States, 2010).


41. C. Burningham, G. Mosqueda, R. R. Saavedra, “Comparison of seismic fragility of free standing equipment using current testing protocols and recorded building floor motions” (Buffalo, NY).


44. J. W. Baker, in *The 14th World Conference on Earthquake Engineering* (The 14th World Conference on Earthquake Engineering, Beijing, China, 2008).


52. Questworks Building Economists, Qube, (available at http://qbe.co.ke/).

53. HassConsult Real Estate, (available at http://www.hassconsult.co.ke/).
### Appendix

**Table S1:** Details of the variables and used in the model

<table>
<thead>
<tr>
<th>ID</th>
<th>Variable Name</th>
<th>Units</th>
<th>Value</th>
<th>Description and assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Footprint of buildings in each zone</td>
<td>m²</td>
<td>Drawn from symmetric Triangular distributions, the parameters of which can be found in Table 1</td>
<td>Estimated from satellite images</td>
</tr>
<tr>
<td>B</td>
<td>Distribution of buildings per floor-height group</td>
<td>Portion</td>
<td>Portion of buildings 1 to 4 floors high, 5 to 7, and 8 and above in each zone. (Table 1)</td>
<td>Walk-by photographic surveys were performed on a streets representative of each zone</td>
</tr>
<tr>
<td>C</td>
<td>Built area by floor-height groups and by zone</td>
<td>m²</td>
<td>A 3-by-10 matrix in which each value is the product of the building footprint in a zone (A) by the portion of that corresponding to each height group (B) by the number of floors (either 3, 6 or 9)</td>
<td>Uniformly distributed noise of +/-10% is added on each run to the estimates in B to capture some of the uncertainty in the estimates from walk-by surveys.</td>
</tr>
<tr>
<td>D</td>
<td>Occupancy</td>
<td>Person per m²</td>
<td>Drawn from Triangular distributions, the parameters of which</td>
<td>Occupancy was estimated by observing the type and use of buildings, and considering common occupancy levels used in the design of the types of</td>
</tr>
</tbody>
</table>
can be found in Table 1

<table>
<thead>
<tr>
<th>E</th>
<th>Built area per floor height group and per level of CQ</th>
<th>m²</th>
<th>A 3-by-3 matrix with entries calculated by dividing the sum of the build area per height group in the region of study, into 3 levels of CQ by drawing values from a Gamma (6.232, .282) and using cut-off points for levels of CQ that were drawn from these distributions: Triangular (19, 22) was taken as the upper limit for “low quality construction”, while Triangular (27, 32) was taken as the lower limit for high quality construction. Middle values of $\xi$ were assigned to “average quality of construction”.</th>
<th>The built area per each floor height group was allocated to one of three levels of CQ. The distribution of the compressive strength of concrete ($f_c$) resulted from previous investigations in the same locations within Nairobi. These cutoff points were chosen because samples of concrete, formulated to yield $f_c &gt; 25$ MPa, are expected to follow a Gaussian (34, 4.5) distribution, or similar.</th>
</tr>
</thead>
</table>

| F | Families of fragility curves, for each of the three level of CQ, for 2 damage states and for 3 building height groups | Families of log-normal distributions 3-by-3 matrixes with random values for probabilities of collapse or severe damage per floor-height group and level of CQ | From families derived by Celik, we draw a random cutoff value for the logs mean and the standard deviations of the 30th and 70th percentile, and add uniformly distributed noise of +/-10% at each cutoff. These curves were deemed the best available approximation for RC buildings in Nairobi since, like Memphis, the city is |
not located in an area of high seismic hazard. Noise was added to account for some of the additional uncertainty inherent to estimating probabilities of collapse from convenient fragility curves.

<table>
<thead>
<tr>
<th><strong>G</strong></th>
<th>Built area collapsed we calculate</th>
<th>m²</th>
<th>The entry-wise product of matrix with values of probabilities of collapse ($P$), by the previously computed matrix ($E$), which entries contain estimates of square meters per floor height group and per level of CQ</th>
<th>Each run ($n=10,000$) of the model produces a single estimate that is indexed in a vector for subsequent analysis.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H</strong></td>
<td>Built area severely damaged</td>
<td>m²</td>
<td>The entry-wise product of matrix with values of probabilities of severe damage($F$), by the previously computed matrix ($E$), which entries contain estimates of square meters per floor height group and per level of CQ</td>
<td>Each estimate is indexed in a vector for subsequent analysis.</td>
</tr>
<tr>
<td><strong>I</strong></td>
<td>Number of people that would be affected</td>
<td>People</td>
<td>The product of the sum of square meters collapsed or damaged and the estimate of occupancy per square meter in each zone.</td>
<td>People affected is broadly defined here as suffering bodily damage or significant financial loss.</td>
</tr>
<tr>
<td></td>
<td>Building replacement cost</td>
<td>USD</td>
<td>The product of built area collapsed (G) and an estimate of cost per square meter drawn from a Triangular (40K, 60K, 80K) in Kenyan Shillings and converted to Dollar using $1=87 Kshs</td>
<td>These values were chosen in consultation with professionals in construction costing in Nairobi.</td>
</tr>
<tr>
<td>---</td>
<td>---------------------------</td>
<td>-----</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>K</td>
<td>Building repair cost</td>
<td>USD</td>
<td>The product of built area severely damaged but not collapsed (H - G) and an estimate of cost per square meter drawn from a Triangular (40K, 60K, 80K) multiplied by a factor from a Triangular (.1,.25,.5) in Kenyan Shillings and converted to Dollar using $1=87 Kshs</td>
<td>The professionals consulted estimated that repair costs on a damaged building would range between 10% and 50% of the cost of new construction</td>
</tr>
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</table>
Figure S1: Correlation matrix for sensitivity analysis
### Table S2: Guidelines used to estimate occupancy

<table>
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<tr>
<th>Type of Building</th>
<th>Type of Room</th>
<th>Area per Person ($\text{m}^2$)</th>
<th>Persons per (m(^2))</th>
</tr>
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<td>Apartments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly building</td>
<td>Lecture room</td>
<td>0.6</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Library</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Cinema</td>
<td>0.6</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Concert hall</td>
<td>0.6</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Theatre</td>
<td>0.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Hotels</td>
<td>Rooms</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Lobby</td>
<td>0.6</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Assembly room</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Offices</td>
<td>Single office</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Meeting room</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Restaurants</td>
<td>With service</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Without service</td>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>Schools</td>
<td>Lecture rooms</td>
<td>0.6</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Class rooms</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Corridors</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Laboratory</td>
<td>3</td>
<td>0.3</td>
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<tr>
<td>Shops</td>
<td>Retail</td>
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<td>0.5</td>
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<tr>
<td></td>
<td>Supermarkets</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>Sports</td>
<td>Gymnasium</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Swimming pools</td>
<td>4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Source (http://www.engineeringtoolbox.com/number-persons-buildings-d_118.html)
Chapter 5: Policy recommendations to improve the structural safety of reinforced concrete buildings in Kenya

Abstract

Building collapse is the main cause of death during earthquakes (1). Our previous studies (Chapter 2 and 3) show that current quality verification methods can easily be -and frequently are- circumvented. As a result, thousands of potentially risky structures continue to be built in ever increasing numbers (2). Better construction practice would improve the strength of new buildings, and reduce the level of risk exposure for millions of people in Kenya (Chapter 4). Here we recommend four policy interventions to improve building safety for new buildings in Kenya, and to reduce the risk of collapse or severe damage to buildings in the event of an earthquake. These recommendations are the product of a consultative process, which started in 2012 and ended in October 2014, with the Kenya National Construction Authority and other stake-holders in Kenya, and with faculty at Carnegie Mellon University, most of whom are in the Department of Engineering and Public Policy. The proposed strategy entails the simultaneous development and implementation of a) an open-access reporting system modeled after the Toxic Release Inventory program operated by the U.S. Environmental Protection Agency; b) an educational and forum web portal; c) the promotion of non-destructive testing of concrete during construction; and d) a risk communication program. The immediate goal is to achieve an increase in the public demand for safer buildings that a greater number of building professionals feel obliged to meet, as well as an increase in
the effectiveness of the regulatory bodies responsible for ensuring building safety. The end goal is robust, replicable and transparent system of checks and balances that will significantly reduce the loss of lives in earthquakes and under spontaneously collapsed buildings. Our approach is designed to be transferable to other developing countries around the world. While the large existing stock of inadequate buildings means that Kenya and other African nations will remain vulnerable for many decades, our primary objective is to begin to reduce, and certainly to avoid increasing, that vulnerability in the coming years.

One sentence summary

Policy interventions that combine open-access to quality control records from construction, affordable non-destructive testing, risk communication, and internet forums would improve construction quality and make buildings safer.

Introduction

Building collapse is the main cause of death during earthquakes (1), and resulting building damage is the source of most financial losses. Governments and regulatory agencies can help reduce mortality and economic loss in the case of earthquakes by promoting and enforcing effective design and construction standards (3). In Kenya, even without seismic events, at least seventeen buildings have collapsed in the last decade, causing death and injuries. This suggests strongly that a large number of buildings are
unsafe and their occupants are at risk (4–6). Reports from local authorities and experts investigating those events attribute most of these accidents to the use of low-quality construction materials and to inadequate building techniques. However, these events and reports have not motivated significant change. The quality control protocols used in Kenyan construction today are, for the most part, identical to those recommended by the Kenya Building Code of 1968 (7). Our previous studies (Chapters 2 and 3) show that these quality verification methods can easily be - and frequently are - circumvented. As a result, thousands of potentially risky structures continue being built annually and the rate is increasing (2). Because these weaker structures can remain in use for decades before a seismic event reveals their weaknesses, sufficient public concern needed to generate real change does not occur.

There is evidence that builders, even those with limited equipment and lacking formally trained personnel, can build strong buildings should they decide to do so. As part of an audit of new construction in July 2012 (Chapter 2), we visited seven construction sites whose builder had, four years earlier, been forced to demolish and rebuild the superstructures of two buildings in Nairobi. He did this at his own cost. Though not perfect, these seven buildings employed better materials and methods, and thus had stronger concrete than most buildings in the same audit (Figure 1). When asked about this result the builder replied, referring to the costly events of years past, “Those demolitions were too painful. You learn that way.”
Figure 1: Box plot of the 24 random construction sites, as well as six additional sites from the same builder (green). This small building company had consistently stronger concrete. We expected the compressive strength of concrete to be positively correlated to the size and prestige of the construction company, but we found no such correlation.

The incentives that builders can consider during construction are obvious. However, it is important to recognize that architects and engineers have incentives that could dissuade them from devoting time and resources to quality control activities. In Kenya, engineers and architects are in practice exempt from responsibility for flaws in construction of the buildings they design and supervise. The following text, or similar, is part of the preamble in most architecture and engineering contracts for construction in Kenya.
“The responsibility for the construction of the project and performance of the contractors does not rest with XYZ Consulting, therefore it cannot in any way be held responsible for any failure of contractors to fulfil their obligations under their contract with the client. In the event of the non-performance or compliance by the main contractor with the contract conditions, the architects will advise the client on the recourse available under the contract.” (8)

Furthermore, most design contracts stipulate that 75% of consulting fees are paid before construction begins. As a result, architects and engineers have weak incentives to spend time in quality control. The professionals consulted for this study reported that most give low priority to supervision and verification of the construction.

Likewise, the materials testing laboratories lack motivation to verify the origin of the samples that they test and ensure the integrity of the information that they report. Under current practice, the materials testing laboratories do not report the test results of concrete and steel used in a project, but rather on samples given to them by the builders. Figure 2 illustrates the process. The orange blocks represent the quality control activities for concrete.
Figure 2. Swim lane diagram of the reinforced concrete construction process and the quality control protocol used in many parts of East Africa. The orange blocks denote the current quality control activities for concrete. A better process is one in which the collection of samples and handling of the reports is not delegated to the builders.

“24.1 The Contractor shall arrange for and furnish to the Architect, samples of any materials, goods or workmanship and perform any tests that may be called for by the Architect for his approval. Any samples and tests approved by the Architect shall be deemed to represent the minimum standard for the part of the Works to which they apply.”

Builders are regularly given responsibility for collecting, or as our study found (Chapter 3) too often carefully preparing, the samples to be sent to the testing laboratory, and for collecting and distributing the test reports. Obviously, this contract clause should be modified to prescribe that sampling and testing of construction materials be performed by independent laboratories under the supervision of the architect or engineer. However, that alone is not likely to result in much of an increase or improvement on quality control in construction.

Better construction practices would improve the strength of new buildings and reduce the level of risk exposure for millions of people in Kenya (Chapter 4). This is true in many other developing countries as well. In this paper, we evaluate and recommend policy interventions to improve building safety for new buildings in Nairobi and to reduce the risk of spontaneous collapse and the risk of collapse or severe damage in the event of an earthquake. Many of these recommendations could be replicated in similar cities in East Africa and elsewhere. They combine:
1. An open-access reporting system modeled after the Toxic Release Inventory (TRI) program operated by the U.S. Environmental Protection Agency;

2. An educational and forum web portal where the public can find information on safe construction techniques and quality control methods;

3. The requirement of transparent and verifiable non-destructive testing of concrete; and

4. A risk communication program.

Methods

The policy interventions suggested here are the product of a consultative process analyzing the results from investigations into the strength of the concrete used in Nairobi construction. Early in our brainstorming we hit upon the idea of using TRI as a template for a government-supported initiative. The TRI program makes public all reports on released toxic chemicals. These reports are submitted annually to the EPA by all facilities required by law (10, 11). Research has found that firms, in the United States, with significant decline in their stock price after the publication of their self-reported data on emissions by the TRI, often reacted by subsequently reducing emissions of toxic chemicals more their peers (12); and that the TRI contributed to a significant reductions in pollution in the United States (13, 14). Other self-reporting programs have also been found useful (15), even when the information collected by the agencies was not made part of a public database, as in the TRI. However, there is evidence that suggests that, in Kenya, unpublished self-reporting programs have been ineffective (16).
In our case, such a system would require a new regulation mandating builders and engineers to submit quality control reports for buildings under construction, the creation and operation of an open-access database where those reports would be published, and the institution of control mechanisms to ensure the integrity of the public data.

Other ideas were also considered. Among them were legislation imposing more severe penalties on those convicted of fraud in construction, and the institution of new government bodies to audit construction sites. Solutions hinging on technologies (some new and others adapted) for quality monitoring and verification were also considered, such as: light detection and ranging scanners (17), radio-frequency identification (RFID) (18), and video surveillance (19). These and other ideas were discussed with:

1. The faculty at Carnegie Mellon University’s Departments of Engineering and Public Policy, Civil and Environmental Engineering, and the School of Architecture;
2. Officers at Kenya’s National Construction Authority (20);
3. Kenya’s Property Developers Association (21);
4. The Construction Project Management Group of the Architectural Association of Kenya (22);
5. Hass Consult (23), a real estate marketing firm in East Africa; and
6. The faculty at Strathmore University’s Business School and School of Law (24, 25).

These consultations were conducted as open conversations, with at least two representatives of each institution, between August 2012 and October 2014. The
findings from previous studies were discussed with each, and they formed the basis for
discussions on how best to address the problem of poor construction quality.

Despite the attractiveness of the latest technologies, the TRI idea was judged most
practical and promising to solve the problem in Kenya, and the easiest to replicate in
other countries with construction industries in a similar state of development and facing
the same problem.

The TRI model was discussed with the stakeholders listed above, and served as the seed
idea for a workshop held in Nairobi with Kenyan construction professionals and lawyers,
to collectively outline a quality control and reporting system for the construction
industry in Kenya. Eight construction professionals and two advocates participated in
the workshop held at Strathmore Business School in February 2014. The workshop was
conducted using a “red-teaming” process (26, 27), in which each of two teams designed
a reporting and auditing system and the other played the devil’s advocate, critiquing the
designers’ assumptions and procedures, and proposing ways to improve their designs.
Teams were asked to outline a system based on a website that could provide
construction professionals with a relatively easy way to report results from quality
control activities during construction and make public the content of the reports through
a web-hosted database. The lawyers were asked to ensure that the proposed policy
suggestions were plausible under the Kenyan Constitution. The workshop began with a
presentation of the results from our previous investigations (Chapters 2 and 3), of how
the TRI works, of how other entities, such as eBay™ and Angie’s List™, rely on the
reputations of sellers and buyers to improve trade, and of how these concepts could be used as a template for their design. (Figure 3)

![Red-teaming workshop at Strathmore Business School. Construction professionals and advocates suggested ideas for a reporting system for the construction industry in Kenya.](image)

**Figure 3.** Red-teaming workshop at Strathmore Business School. Construction professionals and advocates suggested ideas for a reporting system for the construction industry in Kenya.

Each of the two teams was composed of four construction professionals (engineers, quantity surveyors and contractors), and a lawyer. In the ninety-minute sessions, each team collectively designed the most robust practical system they could. Then they presented their design to opponents, who offered their critiques and identified shortcomings. Each identified vulnerability was discussed until a consensus was reached to accept it or not. The weaknesses of each design were noted on a blackboard. The
resulting list containing the vulnerabilities of both designs was later used during a plenary session to craft a list of recommendations that could serve as a starting point for a team—led by the National Construction Authority—charged with the task of deploying a TRI-like system for Kenyan construction.

Results

The conversations with faculty and stake-holders, the results of the red-team exercise, and the expert elicitation sessions reported on Chapter 3 provided interesting insights. Some are listed here as broad guidelines to be used when implementing the policy recommendations in this paper. We suggest broad guidelines and then propose an outline for an integrated solution involving four parts. All four steps need to be implemented to be successful.

Broad guidelines

1. Surveillance and policing technology alone will not suffice since people will eventually adapt and work around such technology.
2. Effective solutions will most likely result from research that takes into account the psychological processes and incentive structures governing the decision-making of people in the construction process.
3. Risk communication will play a crucial role in promoting and reinforcing appropriate behaviors.
4. Solutions must be affordable.
5. Assuming that social circumstances motivate people to focus on actions that have benefits in the short term, and that this paradigm facilitates unethical behavior (28), interventions would be more effective if they incentivize actors to consider the long-term consequences of their actions.

Policy recommendations

Part I: A reporting and open-data program by Kenya’s National Construction Authority

A system based on mandated reporting and publication of data is possible for all new multi-story construction in Kenya since the government established the National Construction Authority (NCA) in 2013 (20) to address the problems of spontaneous collapse of buildings in the country (Chapter 2). Like the TRI, such systems would rely on the power of publicity to shape the behavior of construction professionals, as proposed a century ago by U.S. Supreme Justice Louis D. Brandeis who held that “sunlight (is) the best disinfectant: electric light the most efficient policeman” (29). Moreover, the publication of such reports should be facilitated by Kenya’s Open Data Initiative (30), which encourages Kenyan government agencies to publish their data on a website. The data would be accessible to over 14 million people, approximately 35% of Kenya’s population, who have wireless internet data plans (31).

Summarizing the recommendations from all stake-holders and professionals mentioned before, we suggest that in implementing a program like this, the NCA should:

1. Elaborate a quality control protocol that specifies how, when and by whom data should be reported. These data should contain, at the very least, test results for
steel and concrete used in construction and the result of geo-technical surveys of the building location;

2. Make structural engineers responsible for the completeness and veracity of the test data reported in relation to structural construction;

3. Encourage the use of photography and video as part of the construction quality reports;

4. Implement proven data security mechanisms that ensure the integrity of the data published on their website or on that of the Open Data Initiative if that vehicle is preferred;

5. Require that each building project is independently audited by trained professionals, other than those supervising the works, appointed by the building developers;

6. Allow officers from the NCA, as well as from other organizations with standing, such as the ones consulted during this study, to re-audit the projects unannounced; and

7. Ensure that self-reports, and the result of audit and re-audits be made part of the public database.

Part II: An educational website, forum, and quality awards program by a new institution guided by the stakeholders

Solving the problem of poor construction quality in Kenya while developing a system that can be replicated elsewhere in Africa and other continents will require sustained efforts. To do this as swiftly as possible, it will be necessary to combine the regulatory
power of the NCA with the reach and influence of other institutions that desire to improve Kenyan construction, such as those consulted in this work. For this reason, the stake-holders agreed on the creation of a new institution under the guidance of an advisory board, composed initially by them, and later incorporating representatives from relevant professional bodies, industry and academia in Kenya. This institution will be called the Building Construction Quality Institute (BCQI) (bcqi.org) and will be housed - again initially - in Strathmore University. Its goals would be to support the efforts of the NCA by:

1. Creating a website to provide education on construction techniques and quality control methods;

2. Creating and maintaining a forum where participants can ask questions, suggest improvements to the website and to the methods promoted by the NCA, and report on irregularities observed at new construction and in existing buildings sites as well;

3. Instituting a quality award program to recognize those who perform the best, based on the data published on the NCA site;

4. Supporting academic research focused on solving problems in Kenyan construction;

5. Promoting the use of non-destructive testing methods in Kenyan construction; and

6. Seeking collaboration with governmental, academic and professional bodies in other countries in Africa that could benefit from the lesson learnt Kenya.
**Part III: Promoting non-destructive testing of concrete during construction**

Non-destructive tests (NDT) enable auditors to verify the characteristics of materials without damage. An excellent summary of NDT for concrete structures can be found in (32). NDT offers many advantages over destructive testing: some NDT methods require minimal training; the result can be replicated and verified; and, in the case of concrete, the result reflects the quality of installed concrete, the strength of which depends on many factors (Chapter 3).

However, NDT tools are currently rare in Kenyan construction. Only a handful of companies use them (mostly material testing laboratories). As a consequence, only a few traders sell NDT equipment and do so at a very high price (8). The NCA and the BCQI can stimulate trade in NDT instruments with the goal of making them available at the lowest possible cost. The NCA can do this by providing incentives such as exemptions from the 17% value-added tax (VAT) or by other fiscal mechanisms. The BCQI can provide online training content and operate an inventory of instruments for low-cost rental or free lending, depending on the solicitor. The operation of these instruments and the protocols to produce reliable results are simple enough that they can be learned through online training videos.

**Part IV: Risk communication**

Some attempts have been made by the media and some professional bodies in Kenya, to educate the public about the risks arising from inadequate construction methods. The
creation of the NCA is a laudable product of those efforts. However, the fact that construction methods have remained mostly unchanged and that the quality of much structural construction remains inadequate, suggests that a large portion of the public is not sufficiently concerned to call for more action, or still believes that their buildings are safe. The Kenyan government, now through the NCA, has the duty to communicate risks generated by sub-standard construction. An effective risk communication program could build on the findings from our investigations (Chapters 2, 3 and 4), on the forensics reports from building that have spontaneously collapsed in Kenya in the last decade, and on studies of catastrophes in other countries that had a large number of defective buildings when an earthquake struck (33).

The design of the risk communication program should be commissioned to a team with expertise on risk communication. Ample research and abundant literature is available to guide their efforts (34–40). The commissioned experts would be best poised to design and implement such a program. However, here we provide suggestions that can help inform policymakers about what to look for when commissioning this work. The goal of this risk communication program should be to provide the public with the information they need in order to make informed decisions regarding construction activities that affect safety. Research should inform the design of the risk communication program and it should be carried out following well established risk communication theory.
Discussion

The problems of non-compliance and fraud that can result in unsafe buildings can probably not be solved by any single silver-bullet technical solution. The interventions proposed are meant to achieve behavioral change across the entire industry including construction professionals, builders, inspectors, government officials, financers and the occupant of the buildings. This makes sense, since the problem of shoddy construction practices seems to be caused more often by wrong choices than by technical limitations (Figure 1 and Chapter 3).

An information system, modeled after the TRI, could be effectively and efficiently implemented for construction quality in Kenya and in many other countries. However, mistrust of government institutions in Kenya is real, and undeniable (41). For this reason, the information reporting scheme must be transparent. By facilitating access to non-destructive test methods, by encouraging construction audits by other parties with standing, and through collaboration with professional associations, property developer, and academia, the NCA can make their system more credible and, therefore, more likely to be used for decision making. Brandeis’ sunlight is most effective if it is allowed to shine on all.

Risk communication programs have helped people choose healthier lifestyles (42) and generated support for more protective environmental regulation. The experience gained from successful programs, and the research that underpins them can guide ours. An immediate goal of this communication program should be to increase the sense of self-
efficacy among the general public. It is crucial that people believe that the right behaviors on the part of the construction professionals and the builders that they hire can save them and their families if an earthquake strikes. It is also important to bear in mind that, since earthquakes are rare and uncertain events, knowledge and good intentions can be forgotten. Long intervals between earthquakes and probable inadequate economic and societal pressures to maximize the built area at the lowest cost can hinder progress towards our goal. For this reason, a sustained effort will be necessary, and it should address the problem not only as one of individual choice, but also as one of societal attitude.

Studies show that a large portion of the laboratory test results for concrete in Nairobi do not correspond to the concrete used in the buildings (Chapter 2), and that experts predicted this to be a pervasive phenomenon (Chapter 3). Publishing these results will likely exacerbate mistrust of existing institutions. The risk communication program design should also aim to reform and reinforce those institutions, while continually providing the public with the information they need to effectively police the industry.

**Other policy alternatives considered**

*Doing nothing is not an option*

“Doing nothing” is at times a viable policy alternative. That is not so in the case of weak construction. Those who would prefer to avoid policy interventions could argue that the economic growth in Kenya by 2035, forecast by the Carnegie Endowment for International Peace (43), could triple wages, making the mechanization of the concrete-making process economically advantageous, as is the case today in most developed
countries. In this scenario, it would seem reasonable to assume that economic development will also force changes to improve the quality of construction. Construction will improve to acceptable levels as a natural consequence of progress. However, if current practices remain unchanged until then, thousands of unsafe buildings will be added to the building stock in Nairobi and elsewhere, exposing hundreds of thousands of people to unnecessarily high risks.

*Interventions that focus primarily on the certification and registration of engineers and architects, or on mandating that registered professionals are put in charge of all new construction projects will not necessarily result in safer buildings.*

As previously shown, (Chapters 2 and 3) approximately 70% of the concrete used in Nairobi was weak, despite most of the certificates reporting otherwise. These buildings were all under the supervision of registered professionals. Therefore, while certification and registration must be encouraged, they alone will likely not suffice as a solution.

*Advanced inspection and monitoring technologies could help, but are unaffordable and insufficient.*

Technologies, such as RFID sensors, tomography, petrography, laser scanners and others could help. However, these technologies are not yet affordable, are rarely used by builders in developed nations, and will likely not be adopted in countries with smaller and less regulated construction markets. Furthermore, these technologies alone, even when employed correctly, cannot detect all possible defects during construction, and would have to be combined with frequent inspections. For example, NDT cannot detect problems if unstable formwork was used to cast concrete - one of the frequent flaws in
Kenyan construction according to experts, whose opinions were elicited in July 2012 (Chapter 3). Instead, by combining affordable non-destructive tests (NDT), such as verification of concrete strength with rebound hammers, with frequent inspections, construction quality can be verified more effectively and at a lower cost.

That said, affordable instruments that measure cement content of fresh concrete at the job site would facilitate quality control by helping prevent the installation of weak concrete. However, such instruments are not yet commercially available. Efforts to develop appropriate quality diagnostic tools for concrete, through either academic research or through competition, should be encouraged and funded.

**Some foreseeable difficulties**

*Better quality can increase construction cost, but not enough to noticeably restrict access to housing*

It could be argued that encouraging or mandating the use of better quality materials in construction could have the unintended consequence of restricting access to housing for the poorest. However, note that the money saved by reducing cement is less than two percent of the project revenue (and may not be a savings realized by the builder). Therefore, interventions that increase construction quality could result in an increase in the cost of construction of similar magnitude. But such increase is not a necessity. Some builders are able to provide high quality materials at current market rates (Chapter 2). We suspect that most others would do the same if the risk of getting caught cheating were high enough. Certainly, many in Kenya cannot afford adequate housing, and making housing affordable should be a priority. The main barrier limiting access to housing is
not high construction costs, but rather a combination of high levels of unemployment, low incomes, and high mortgage rates of between 14% and 16% (44). A change in a few percentage points on the cost of buildings, whether up or down, is unlikely to noticeably reduce or increase demand.

Some push back may come from construction professionals.

Special efforts should be made to promote collaboration and avoid acrimony. It is reasonable to expect some resistance from construction professionals, since the risk communication program and the open data systems proposed here, while not intended to harm careers, can certainly do that. In fact, the power of such information systems derives from that capacity. It is, therefore, crucial to effectively communicate the positive aspects of this intervention and to promote rewards for those doing things right. Engaging those in charge of the local engineering bodies, on the implementation of these policy recommendations, could increase buy-in from practitioners, without whose collaboration, improving construction quality would likely be unnecessarily steep, if at all possible.

Conclusion

The four policy interventions we have proposed are motivated by the findings of previous studies of the problem of low construction quality and its consequences. These consequences have included eighty four deaths and over two hundred and ninety injuries in Kenya since 2006, and thousands more worldwide, when buildings have spontaneously collapsed (Chapters 2 and 3). Poor construction quality has also caused
the deaths of hundreds of thousands of people under collapsed buildings during earthquakes. Our recommendations are the product of consultation with stakeholders and construction professionals in Kenya, and faculty at Carnegie Mellon University’s Department of Engineering and Public Policy and other departments. The suggested policy interventions are: an open-access reporting system modelled after the Toxic Release Inventory (TRI) program operated by the U.S. Environmental Protection Agency; an educational and forum web portal; the promotion of non-destructive testing of concrete; and a risk communication program. The immediate goal is to achieve behavioral change in the form of increased public demand for safe buildings, a greater number of building professionals who feel obliged to ensure structural integrity of the buildings they make, and an increased effectiveness of the regulatory bodies that encourage and enforce good practices. If we can avoid the loss of more lives under spontaneously collapsed buildings, first in Kenya first, and then elsewhere, and reduce the level of loss in future major earthquake events such as the one suffered by Haitians in 2010, our efforts will have been a success!
References and Notes


9. Consultation with two former contractors, Mr. A.S. Virdi and Mr. E. Kinhara, and Mr. B.M. Ratna, owner of MCC Construction (July 2012) (2012).


Chapter 6: Conclusions

These studies have shown that the quality control mechanisms for structural concrete currently used in Kenya are not as effective as they should be. Architects and engineers routinely certify buildings as safe for occupation based, in part, on inaccurate or false laboratory reports. As a consequence, thousands of dangerously weak buildings have and will be built, and unless better control systems are implemented, millions of people will likely be exposed to unnecessarily higher risks for generations.

Experts with experience in Kenyan construction accurately estimated the strength of installed concrete in new construction in Nairobi, including both higher and lower income areas of the city. Their estimates closely matched the results from field test conducted soon after, which confirms that most of the concrete in Nairobi is weaker than the minimum required by design and that current quality control practices are ineffective and easily circumvented. This match also confirms that our group of experts is especially aware of the state of the local construction industry, and of the problems it faces. This should motivate policy makers to pay special attention to the solutions proposed by them.

Our simulation model estimated that between 1.5 and 2.5 million square meters, which translates to between 800 and 3500 residential and commercial buildings, could be lost in central Nairobi in the event of a moderate (acceleration = .3g) earthquake. The consequence would be thousands of deaths and injuries, and billions of dollars lost, with
catastrophic effects for Kenya’s capital. The combination of seismic resistant designs
and strict control over quality seems a policy imperative.

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previous studies. The suggested policy interventions are: an open-access reporting
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regulatory bodies that encourage and enforce good practices.

If we can avoid the loss of more lives under spontaneously collapsed buildings, first in
Kenya and then elsewhere, and reduce the level of loss in future major earthquake events
such as the one suffered by Haitians in 2010, our efforts will have been a success!
However, this is only possible with concerted and sustained efforts to put into practice
these ideas and others. Together with the stakeholders named in the previous chapter,
we intend to do that.