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Resiliency of Degraded Built Infrastructure

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CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

Infrastructure resiliency depends on the ability of infrastructure systems to withstand, adapt, and recover from chronic and extreme stresses. In this white paper, we address the resiliency of infrastructure assets and discuss improving infrastructure stability through development of our understanding of cement and concrete degradation. The resiliency of infrastructure during extreme events relies on the condition, adaptability, and recoverability of built infrastructure (roads, bridges, dams), which serves as the backbone of existing infrastructure systems. Much of the built infrastructure in the US has consistently been rated D+ by the American Society of Civil Engineers (ASCE). Aged infrastructure introduces risk to the system, since unreliable infrastructure increases the likelihood of failures under chronic and extreme stress and are particularly concerning when extreme events occur. To understand and account for this added risk from poor infrastructure quality, more research is needed on (i) how the changing environment alters the aging of new and existing built infrastructure and (ii) how degradation causes unique failure mechanisms. The aging of built infrastructure is based on degradation of the structural materials, such as concrete and steel supports, which causes failure. Current work in cement/concrete degradation is based on (i) the development of high strength and degradation resistance concrete mixtures, (ii) methods of assessing the age and reliability of existing structures, and (3) modeling of structural stability and the microstructural evolution of concrete/cement from degradation mechanisms (sulfide attack, carbonation, decalcification). Sandia National Laboratories (SNL) has made several investments in studying the durability and degradation of cement based materials, including using SNL-developed codes and methodologies (peridynamics, PFLOTRAN) to focus on chemo-mechanical fracture of cement for energy applications. Additionally, a recent collaboration with the University of Colorado Boulder has included fracture of concrete gravity dams, scaling the existing work to applications in full sized infrastructure problems. Ultimately, SNL has the experience in degradation of cementitious materials to extend the current research portfolio and answer concerns about the resilience of aging built infrastructure.

1. INTRODUCTION

Infrastructure resiliency has recently come into focus, particularly as the number and severity of natural disasters increases [3-5], causing loss of life and significant economic impacts [6, 7]. Recently, a series of high profile natural disasters have highlighted vulnerabilities in current system design [8, 9] that limited recovery following the event. Traditionally, resiliency has focused on the ability of operational systems, such as power grids, to adapt to a failure and provided uninterrupted supply to customers [10]. In addition to the failure of operational system, built (or civil or basic) infrastructure, which includes buildings, roads, bridges, dams, etc. also fail. In this case, infrastructure failure is based on the failure of structural components, which can then cause further cascading failures of power, water, or telecommunications systems, as seen in Fig. 1-1 [11, 12].

Increasing resiliency demands are being placed on existing infrastructure, causing secondary concerns of the quality of existing infrastructure systems. The aging of the nation's infrastructure has been highlighted as a risk by the American Society of Civil Engineers (ASCE), who in 2017 gave the US a D+ in the quality of existing infrastructure [13]. The low quality of US infrastructure includes built infrastructure that have increased challenges during emergency events, including bridges (C+), dams (D), roads (D), energy (D), wastewater (D+), and transit (D-). The construction of new infrastructure is not nearly sufficient to replace the majority of aging infrastructure, much of which was built between 1950-1970 [14].

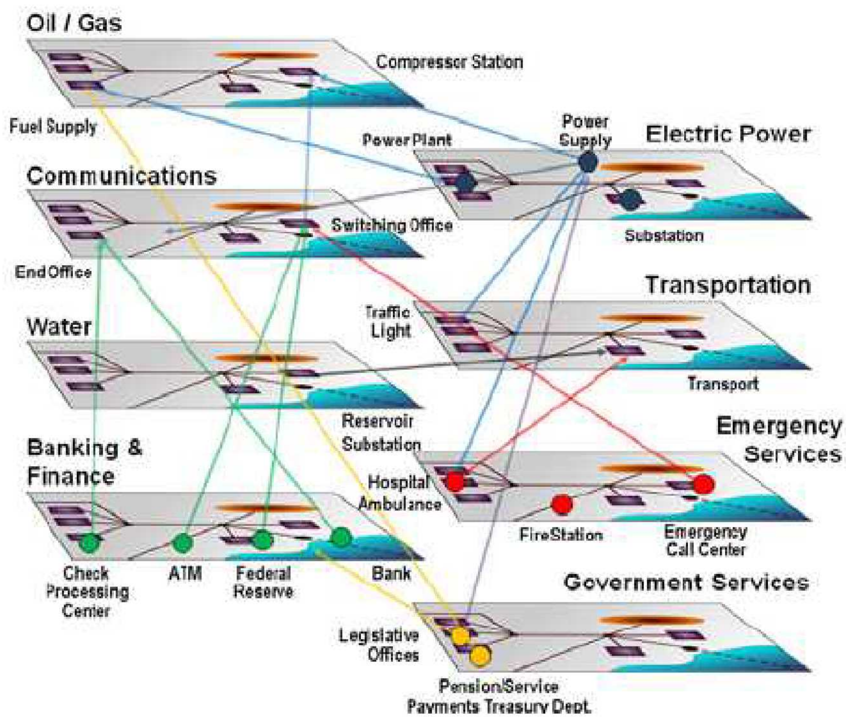

Figure 1-1. A conceptual illustration of the interconnectedness of elements contained within each critical infrastructure. Ref: [15]

For example, the average bridge in the United States is 43 years old [16] and 37% of U.S. bridges are in need of repair according to the 2020 Bridge Report from the American Road & Transportation Builders Association, including high profile bridges such as the Brooklyn Bridge in New York, NY, the Teddy Roosevelt Bridge in Washington, D.C., and San Mateo-Hayward Bridge across San Francisco Bay in CA. Bridges are not the only built infrastructure at risk of failure; the number of dams reported to have structural or hydraulic deficiencies making them susceptible to failure with resulting loss of life tripled between 1999 to 2008 according to a 2010 report by the Association of State Dam Safety Officials, indicating that both age and risk are increasing across varying types of infrastructure in the US. Fig. 1-2 shows that the bulk of the dams that are at risk of failure are 50-60 years old and have exceeded their designed service life.

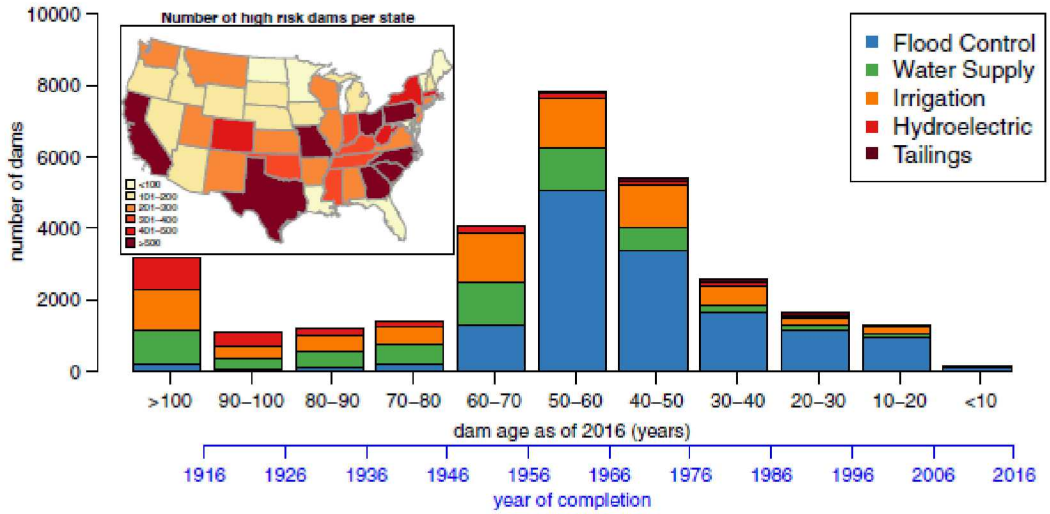

Figure 1-2. Age of dams in the United States (that meet criteria for possible or likely loss of human life in the event of dam failure) with primary uses of flood control, water supply, irrigation, hydroelectric, or tailings dams. Inset: Number of high-risk dams per state (where failure would result in probably loss of human life) Ref: [17]

2. RESILIENCY CHALLENGES

At this point compounded risk is developed regarding resiliency. First, aging infrastructure is weaker [18] and more likely to be damaged [19] as the material itself begins to breakdown. At the same time, the increasing scope and frequency of natural disasters [20] puts demands on built infrastructure that would be difficult to withstand, even for pristine structures. The combination of these two challenges put the United States at an unknown level of risk, as the assessment and impact of aging infrastructure on the resiliency of existing structures is not adequately understood. A 2010 Report by the Department of Homeland Security (DHS) on Aging Infrastructure: Issues, Research, and Technology [21] identified the risk of aging infrastructure in resiliency, noting that "age may also be a factor to consider in prioritizing security and emergency action preparedness in the event of a terrorist attack or natural hazard" and "as bridges age…it is important to note that limits cause impediments to mobility and could therefore impede emergency response".

To alleviate these risks, it is necessary to evaluate how aging of structural materials causes increased and unique failure mechanisms in built infrastructure, in comparison to pristine structures.

2.1. Aging of Building Materials

Built infrastructure is commonly composed on structural materials, including concrete (a combination of cement with a secondary constituent, called aggregate), and steel supports and cables that are at risk due to aging. The primary methods of failure in concrete structures is cracking, scaling, delamination, and spalling of concrete, accompanied by corrosion of the reinforcing steel [21]. The primary component in built infrastructure is concrete and cement, with nearly 33% of the end use of cement in the US going to streets and highways, followed by residential buildings (31%), commercial buildings (10%) , and water and waste management (8%) [22], see Fig. 2-1. Additionally, most structures include some type of steel reinforcement [23], that can cause additional challenges in understanding degradation of built infrastructure.

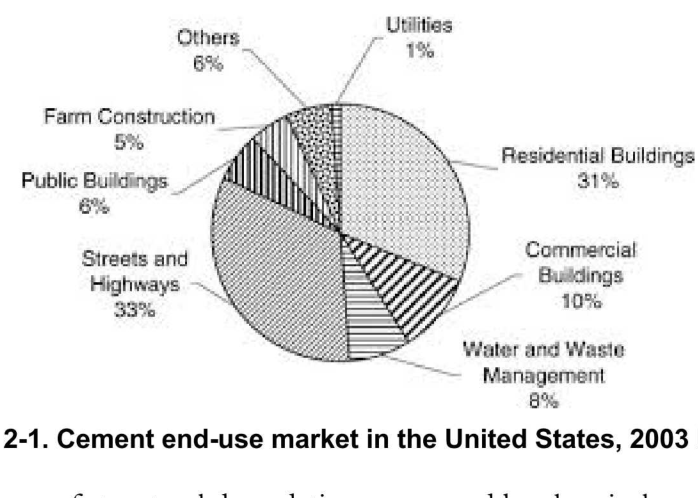

Figure 2-1. Cement end-use market in the United States, 2003 Ref: [22]

The most common types of structural degradation are caused by chemical reactions either (i) between the cement and the environment, including carbonation, decalcification, sulfate attack, (ii) between the cement and the aggregates, which causes the alkali-silica reaction, and (iii) between the reinforcing steel bars and the environment. Identifying mechanisms and impacts of aging structures has been extensively studied, as cement has been a structural material since the material was first put into large scale use by the Romans [24]. Despite the long history of research into cement and concrete materials, there are still significant unknowns regarding degradation including uncertainty of how and when the structure fails, which is exacerbated by the continued development of new cement and concrete mixtures with unique aging properties. Additionally, the variability in concrete compositions and microstructures make translating mechanisms between concretes difficult. Finally, changing environmental conditions can alter the thermodynamics and kinetics of the aging processes. Ideally, all of these factors would be included in ongoing research on concrete aging and degradation.

2.2. Current Research Directions

Current research on degradation of cementitious materials and structural effects can be separated into several categories. First, there is a significant effort to develop cement and concrete mixtures that have higher strength or are resistant to degradation. While manipulating concrete compositions to improve cement properties has been going on for centuries, much of the recent work has focused on the incorporation of modern materials including carbon fibers [25-27] or polymers [28-30] into the cement to add strength, and analyses of the change in degradation mechanisms of the new composite [31-33]. Most structures do not have such additions, making this work valuable for the development of new infrastructure, but does not provide much insight into the resilience of existing infrastructure.

Another area of research is the development of methods for assessing the age and degradation of existing structures. Since infrastructure cannot be broken down into pieces and thoroughly analyzed, methods of assessing the current state of the material uses non-destructive techniques [34-36] or sensors [37], and provide insight into the current state of the material. These studies are an important part of monitoring the health of existing infrastructure, but it is still necessary to establish how much additional risk is present when the material has reached a certain level of degradation.

Finally, degradation of cement and concrete is primarily investigated through reactive transport modeling, using chemical equilibrium between the cement/concrete and the environment to evaluate aging [38-40]. This includes using a model of hydrated cement exposed to three different aqueous solutions to evaluate changes in calcium concentration profiles and evaluation of mineral dissolution and precipitation for subsurface cements [41]. A challenge of evaluating degradation data is that multiple aging mechanisms occur simultaneously, including decalcification, chloride attack, sulfide attack, alkali-silica reaction (in concrete), etc. that complicates that development of codes that capture all these effects.

2.3. Current Research at SNL

Over the last several years, SNL has made several investments that have made inroads into understanding the properties of cement and concrete systems. It is worth noting, that much of this work falls under the auspices of the U.S. Army Corps of Engineers (USACE) , an organization that has long been responsible for the nation's infrastructure under the Civil Works branch, with most research performed by the Engineer Research and Development Center (ERDC), located in

Vicksburg, MS. While several projects at SNL have focused on the stability of concrete structure following impact [42, 43], evaluating high strength concrete for accelerated construction of nuclear concrete structures [44], or decontamination of concrete following exposure to a chemical warfare agent [45] more recent work has focused on degradation related aspects.

Specifically, degradation of cement and concrete has been modeled in two ways at SNL. The first uses a linear interpolation of degraded and pristine concrete properties following decalcification of the material [46], as has been used in the SNL-developed fracture code peridynamics [47, 48]. Fig. 2-2 includes the model geometry and the evolving hydration and deformation as a result of decalcification [46]. Current work concentrates on expanding this capability from 2D to 3D models, and the incorporation of aggregate effects, expanding the work from focusing on cement to concrete materials [49]. This allows for evaluating the evolution of the concrete microstructure and fracture growth as a function of both mechanical stress and chemical degradation, developing an understanding of chemo-mechanical fracture of cementitious materials.

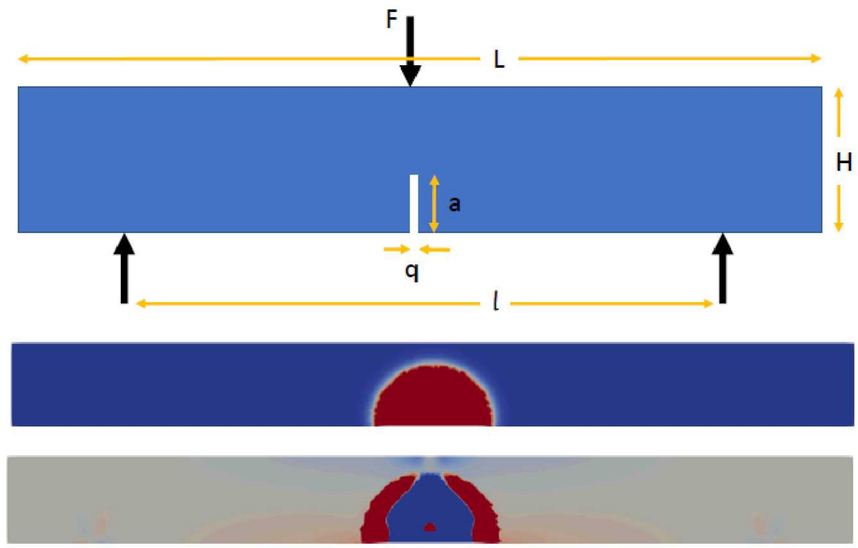

Figure 2-2. (top) Model 3-point bend test geometry for chemo-mechanical modeling of fracture using peridynamics, (middle) water infiltration after loading with red = water concentration, and (bottom) 11 deformation gradient due to water infiltration and loading with blue as the largest deformation. Ref: [46]

Secondly, based on SNL's interest in materials for energy application and subsurface disposal, SNL has modeled reactive transport in cement using PFLOTRAN [50], a reactive transport code. The current application is the prediction of water chemistry in a filled tunnel using transition rate theory for mineral kinetics with applications in subsurface geoemtries [51]. As an accompaniment to this work, SNL is coupling PFLOTRAN to an open source mechanics code, Albany [52, 53], for the modeling of chemo-mechanics in cementitious materials [2], seen in Fig. 2-3.

Figure 2-3: Schematic of Albany and PFLOTRAN structure for flow through fracture cement. Ref: [2]

Previous examples of work on cement and concrete degradation at SNL have focused on degradation of the cementitious materials, the resulting weakening of the material, and the evolution of the microstructure. Recently, additional modeling work has been undertaken with the University of Colorado Boulder (CU Boulder), which uses cohesive zone finite element analysis (FEA) to model full size built infrastructure, in this case gravity dams. The role of cracking in the face of the dam is being explored to identify how the presence of flaws can cause failure of the system. Fig. 2-4 includes the changing von Mises stress contour with a fracture at the base, with one to be added halfway up the face of the dam, as well as various locations of interest. This methodology does not include explicit weakening of the concrete from degradation but provides an opportunity to incorporate a degradation model to capture the impact of aging materials on probability of failure during extreme events. Of value would be the evaluation of spatiotemporal patterns in failure that could be used in evaluation criteria or as indicators of risk to prioritize replacement and remediation.

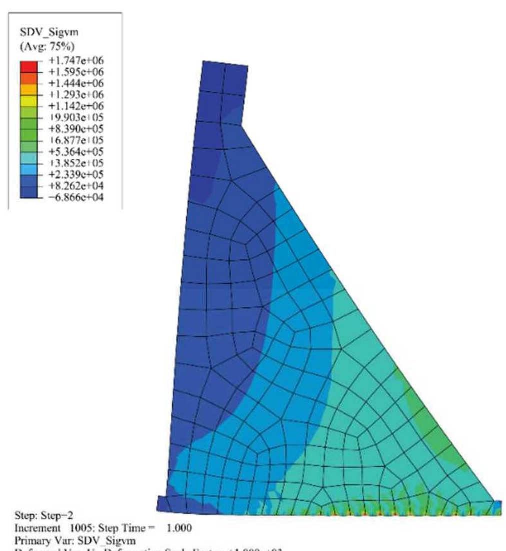

Figure 2-4: von Mises stress contour in the bulk elements of a gravity dam structure. Ref. [1]

3. CONCLUSIONS

Infrastructure resiliency relies on the stability and condition of built infrastructure, which serves as the backbone of the existing infrastructure systems. The aging of existing built structures introduces risk to the system, since poor condition of the infrastructure can cause increased failures, particularly when extreme events occur. To understand and account for this added risk, more research is needed on the aging of new and existing built infrastructure and how degradation can cause different failure mechanisms in aged infrastructure.

The primary method of structural failure in built infrastructure is by degradation of the concrete and corrosion of the reinforcing steel. While the long history of use of cement and steel in structures has resulted in a significant amount of past research, current work on cement and concrete degradation is based on (i) the development of high strength and degradation resistance concrete mixtures, (ii) methods of assessing the age and reliability of existing structures, and (3) modeling of structural stability and the microstructural evolution of concrete/cement from degradation mechanisms (sulfide attack, carbonation, decalcification). SNL has made several investments in studying the durability and degradation of cement based materials, including using several SNL developed codes and methodologies (peridynamics, PFLOTRAN) focusing on chemo-mechanical fracture for energy applications. Additionally, recent collaborations with CU Boulder has included fracture of concrete gratuity dams, pushing the existing work to applications in full sized infrastructure problems. Ultimately, SNL has the experience in degradation of cementitious materials to extend the current portfolio of cement based work to questions of evolving cement and concrete properties under complex geochemical conditions and answer concerns about the resilience of aging built infrastructure.

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