Assessment of Inspection Reporting and Building Conditions in South Florida (Miami-Dade and Broward Counties) – Phase II

Draft Final Report

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Florida Department of Business and Professional Regulation
Florida Building Commission

and

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Executive Summary

This project is a continuation of a study carried out between October 2021 and June 2022 to evaluate the results of existing building inspection practices in place in Broward and Miami-Dade Counties. The initial study collected and analyzed over 250 inspection reports from the 40-year building safety and recertification program in the counties to provide a comprehensive analysis of reported building conditions and inspection procedures. With the passage of Senate Bill 4-D, this project sought to increase the number of collected inspection reports and evaluate the total dataset according to key components of the legislation including the portion of buildings that would require a Phase 2 milestone inspection. The research investigated the maintenance required for each building and accounted for the impacts with respect to the distance to the coastline. The project also sought feedback on various aspects of the new legislation from experienced building inspectors and developed a broad overview of structural and material evaluation technologies and methods that may be used to enhance structural assessment outcomes during inspections.

A set of interview questions was developed and administered to 15 experienced existing building inspectors to determine the professional opinions of the interviewees on Senate Bill 4-D for consideration by the Florida Building Commission in the development of their required response to the legislation. Overall, the respondents have a favorable view of the legislation as originally written and see the benefit of providing building owners with the information needed to maintain the safety of their buildings. The respondents also recognize the challenges associated with implementing the program on such a large scale, including a lack of qualified inspectors, inadequate resources for building department enforcement, and the potential for inconsistent reporting requirements across hundreds of jurisdictions.

This research expanded the dataset of inspection reports used for analysis and was doubled in this phase of the study. An additional 341 inspection reports were requested resulting in reports provided for a total of 521 addresses, representing an average of approximately 4% of the non-exempt buildings in the 12 Miami-Dade and Broward County municipalities included in the study. The data were systematically extracted from the inspection reports according to the methods developed in the first phase of this research project to ensure consistency in the reported results.

Two enhancements were made to the analytical procedures developed in the first phase of this research to enhance the utility of the results, especially as they relate to the new milestone inspection legislation. First, the definition of the coastline used to evaluate reported building conditions according to their distance to the coast was changed to provide a more accurate representation of the exposure of buildings to corrosion-inducing chlorides than the Coastal Construction Control Line used in the first phase of the research. This study demonstrates the need to carefully define the coastline in a consistent manner that can be easily used by counties, building departments, and engineers and that is specifically applicable to the issue of chloride exposure of structural elements.

The second addition to the analysis efforts was the development and application of a repair rating scheme to analyze the nature and extent of the repairs required by the 40-year inspections. The

ratings provide a distinction between repairs required for maintenance, repairs required for signs of substantial structural deterioration, and repairs required for noted substantial structural deterioration. These ratings can be used to infer if, according to the condition and required repairs noted in the inspection report, a building would likely require a Phase 2 inspection according to the milestone inspection legislation.

Approximately one quarter of the buildings in this study required repairs following inspection. Using the repair rating scheme, the most recent inspection reports for each building indicated that 14% would have required a Phase 2 inspection under the new milestone inspection legislation and at least 19% of condominiums that are three or more stories would have required a Phase 2 inspection. Approximately one in eight buildings were reported to have significant concrete cracking or concrete reinforcement corrosion. For buildings with both 40- and 50-year inspection reports it was documented that the reported building condition improves significantly between reports, indicating the benefit of the inspection programs in promoting repairs and maintenance to improve building conditions.

Reported building conditions were assessed according to their distance to the coast using the National Oceanic and Atmospheric Administration (NOAA) Continuously Updated Shoreline Project (CUSP) as the coastline definition. Five coastal zones were established based on proximity to the coastline: 1) < 200 ft, 2) 200 – 600 ft, 3) 600 – 1,500 ft, 4) 1,500 ft to 1 mile, and 5) > 1 mile. Results demonstrate that buildings closer to the coast have higher rates of required repairs and higher levels of deterioration. There is a notable decrease in the required repairs, repair ratings, and observed reinforcement corrosion for buildings over 600 ft from the coast. The results are consistent with studies in the literature that demonstrate the nonlinear dissipation of air chloride concentrations with distance from the coastline until it becomes negligible around 5000 ft (just less than a 1 mile) from the coast. The results may also support earlier and more frequent inspection of buildings that are directly on, or very near, the coastline as defined by CUSP.

Only 4% of the inspection reports reviewed in this study reported using methods or technologies beyond visual inspection when conducting structural assessment; however, several of the interviewees referenced testing techniques, such as core sampling, hammer tests, and ground penetrating radar, as in common use. This report presents a high-level evaluation of these and other available inspection technologies for their ability to enhance current building inspection practices. These methods range from well-established and well documented to emerging and promising, but lacking standardization or widespread adoption for building assessment.

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1 Introduction and Background

The collapse of the Champlain Towers South in Surfside, Florida in 2021 highlighted the need for a broad assessment of building inspection and maintenance practices in the State of Florida. A critical first step toward this assessment is to gain a clear understanding of the reported condition of existing structures through investigation of available building inspection reports in Miami-Dade and Broward Counties. In October of 2021, this research team (UF ESSIE) began work on a research project to achieve this objective. The scope of the project included the identification and collection of inspection reports for over 250 buildings from ten municipalities in these two counties. Analysis and reporting on this inspection data was completed in June 2022.

In May 2022, new state legislation (Senate Bill 4-D) was passed mandating “milestone” structural inspections for condominiums and co-ops that are three or more stories. The legislation defines two phases of the structural inspection: an initial visual inspection (Phase 1) and, if signs of “substantial structural deterioration” are identified, a second, more in-depth structural assessment that may include destructive testing (Phase 2). The legislation called on the Florida Building Commission to review the milestone inspection requirements and make recommendations by December 31, 2022, to the Legislature to ensure inspections are sufficient to determine the structural integrity of a building.

1.1 Project Objectives and Scope

The objectives of this Phase II project were to increase the sample size of inspection reports analyzed and ensure that relevant inspection reporting documentation is obtained, while leveraging the strategies for acquiring, recording, and analyzing inspection report data established in the first project. These data, combined with the data collected in the first phase of the project, provide a comprehensive assessment of current building structural inspection practices that can be used to develop recommendations for inspection practices to enhance the safety of Florida’s building inventory.

This study reviewed and analyzed inspection reports from Miami-Dade and Broward Counties (from both phases of this research project) to evaluate whether the inspection results would have warranted a Phase 2 inspection according to Senate Bill 4-D. The definition of the coastline was re-evaluated in this phase of the research and inspection outcomes were evaluated according to the proximity of the building to the coast. This study also sought feedback on the legislation from experienced existing building inspectors through a formal interview process for consideration by FBC in the formulation of their required feedback to the legislature.

The scope of work for this project consisted of four tasks and accompanying deliverables:

- Task 1: Engineer and/or Architects Feedback on SB 4-D
- Task 2: Building Inspection Report Acquisition
- Task 3: Data Aggregation and Analysis
- Task 4: Inspection Technology Landscape Assessment

1.2 Building Inspection Programs

The 40-year building inspection programs in Miami-Dade and Broward Counties are similar; however, they vary in their histories and current implementation. In Miami-Dade County, the 40-year Building Recertification code has been in place since 1976 while the Broward County 40-year Building Safety Inspection Program was initiated in 2006 and fully phased in by 2011. Both codes exempt minor buildings, single-family residences, and duplexes. In Miami-Dade County buildings of less than 2,000 sq. ft. are exempt while in Broward County buildings of less than 3,500 sq. ft. are exempt. In both counties, inspections are required every ten years following the first 40-year inspection. Both counties require inspectors to be either a Professional Engineer or Registered Architect licensed in the State of Florida.

The Boards of Rules and Appeals in each county issue the guidelines and inspection forms for the programs. In Broward County there are 32 jurisdictions – 31 municipalities and unincorporated Broward County. Each year, the Broward County Board of Rules and Appeals (BORA) staff generates a list of properties that are due for their 40-year or 10-year anniversary inspection. The list is distributed to each jurisdiction in June, who then have the responsibility to notify building owners and follow up on the inspection process. In contrast, the 34 jurisdictions in Miami-Dade County (33 municipalities and Unincorporated Miami-Dade) are responsible for generating their own list of properties due for recertification each year and administering the program. Inspection reports and recertification outcomes are maintained by the individual jurisdictions; neither county has historically collected nor maintained records at the county level associated with the inspection programs.

The milestone inspections mandated by Senate Bill 4-D are required for all condominiums and co-ops that are three or more stories in the State. Inspections are to be carried out by a Registered Architect or Professional Engineer. For buildings within three miles of the coast, the inspections must start when the building reaches 25 years of age, while inland inspections are to start at 30 years. In both cases, structural inspections are to occur every 10 years thereafter. The inspection process is divided into two phases, with the first phase providing an initial visual inspection of the structure. If signs of substantial structural deterioration are noted in the Phase 1 inspection, a building will require a Phase 2 inspection. The purpose of the Phase 2 inspection is to fully assess areas of structural distress to confirm the building is either structurally sound or to recommend repairs to restore the structural integrity of the building.

2 Engineer and/or Architects Feedback on SB 4-D

The objective of Task 1 of this study was to obtain engineer and/or architect feedback on the milestone structural inspection requirements outlined in the new legislation for review by the Florida Building Commission in developing their required legislative response recommendations. After careful review of the legislation, a set of questions were developed for use in inspector phone interviews. In total, 15 interviews were conducted with engineers with direct experience in inspection of aged buildings.

2.1 Approach

Most of the interview candidates were identified from the data collected by the research team as part of the review of inspection reports in Phase I of the project. These data include information from over 300 reports from 40-year building safety inspections carried out in Miami-Dade and Broward Counties from 1977 to 2021, including the name of the engineer or architect who carried out the inspection. From the initial list of approximately 160 inspectors, a subset was selected based on the number of inspections for which they were responsible in the dataset and the date of the most recent inspection they conducted in the dataset. The goal was to find experienced inspectors who are likely to still be conducting inspections. Some additional interview candidates were identified through the research team's professional network, or suggested by another interviewee. All interviews were carried out according to the plan approved by the University of Florida Institutional Review Board (IRB #202201688).

Candidates were informed of the purpose and scope of the interview and were guaranteed anonymity with respect to the reporting of their opinions. Of the 32 inspectors contacted with a request for a phone interview, 15 responded and agreed to be interviewed. While several architects were contacted for interview, none responded. As a result, all interviewees are licensed professional engineers (P.E.s), with four having the additional certification of a Special Inspector (S.I.).

A set of interview questions was developed based on the content of the legislation and distributed to all candidates who agreed to be interviewed (see Appendix A). The first questions were to establish the relevant inspection experience of the engineers and to determine their level of familiarity with the legislation. Subsequent questions were written to solicit feedback on the definitions and processes outlined in the portion of the legislation specifically associated with the structural milestone inspections (Section 3. Section 553.899). A summary of the legislation was also provided (Appendix B). During each call, which lasted approximately 30-40 minutes, interviewees were prompted to answer most questions and to share any other opinions or experiences relevant to the content and language of the legislation; not all questions were addressed if other topics took precedence during the discussion.

2.2 Feedback Summary

Due to the conversational nature of the interviews and the resulting qualitative feedback that was received, the results are presented in an aggregated summary.

2.2.1 *Interviewee Experience and Familiarity with Legislation*

The interviewees are all engineers with 15 to over 30 years of experience in building inspection and assessment, with some also having a structural design background. All but one have direct experience with the 40-year inspection programs in either or both Miami-Dade and Broward Counties. One engineer was part of the Surfside Working Group and two had input on recently developed guidelines for structural inspection in the City of Boca Raton. Most of the engineers have some level of familiarity with Senate Bill 4-D, with a few already conducting reserve study or milestone inspections associated with the new law.

2.2.2 *Non-exempt Buildings*

The legislation requires milestone inspections for all condominiums and cooperatives that are three or more stories. The inspections are to be initiated when the building reaches 25 years of age if it is within three miles of the coast (defined in Florida Statute s. 376.031) or 30 years inland. The interval for subsequent inspections is 10 years, regardless of their proximity to the coast.

The interviewees were asked their opinion on these definitions. The responses are summarized as follows:

- Building use: most say that the requirement for inspections should not be limited to condos and cooperatives; buildings of any use, especially dwellings, should be assessed for safety.
- Building stories: some indicate that lower-rise buildings can also have safety issues that milestone inspections could address (e.g., falling debris from spalling). One respondent thinks that the legislation should be for buildings over three stories to be consistent with the definition of a threshold building in Florida.
- Distance from the coast for earlier initial inspection:
    - Most express an understanding for a differentiation between buildings with saltwater exposure and those inland.
    - Some state that the most important distinction for inspections is the identification of buildings directly exposed to saltwater, especially the exposed portions (balconies, parking garages, pool decks, etc.); such buildings, or portions of buildings, that are directly on the coast or intercoastal waterway may warrant even earlier and more frequent inspections.
    - Some question the scientific reasoning for the three-mile demarcation, while others reason that a line must be drawn so three miles is reasonable. A few suggest that the line may shift in response to additional data that is collected throughout implementation of the inspection legislation.
    - Regardless of what the line is, a few of the respondents see a need for GIS specialists to be involved in creating maps that can be used by the various jurisdictions for identifying coastal buildings; jurisdictions do not have the resources to create these maps.
- Age of initial milestone inspection: Most feel that the ages of initiation are reasonable. A few suggest that earlier initial inspections promote less-costly maintenance rather than waiting for more concerning and costly issues to develop, with 10-20 years being the

appropriate age of initial for buildings in the coastal zone. Another respondent thinks that 40 years is reasonable for a consistent statewide requirement.

- Inspection interval: most feel that 10 years is a reasonable time between inspections. A few indicated that shorter intervals may be better and would align better with other maintenance activities, such as painting, to streamline exterior building access.

Several of the respondents expressed that while they would favor different definitions of buildings and timelines for inspections, they also think that the definitions outlined in the legislation are a reasonable starting point. They anticipate that changes and additions to the buildings that are inspected and their inspections timelines, may shift over time.

2.2.3 Substantial Structural Deterioration

Substantial structural deterioration is defined in the legislation as “substantial structural distress that negatively affects a building’s general structural condition and integrity. The term does not include surface imperfections such as cracks, distortion, sagging, deflections, misalignment, signs of leakage, or peeling of finishes unless the licensed engineer or architect performing the phase one or phase two inspection determines that such surface imperfections are a sign of substantial structural deterioration.” The interviewees were asked their opinion of this definition and how the term is used to differentiate between stages of the inspection process.

Most of the interviewees find the definition to be reasonable and that it is broad enough to allow the inspector to use their engineering judgement in assessing the structural condition. One engineer feels that the word “deterioration” should be replaced with “deficiency” to indicate that the structure no longer meets the code-described ability to carry load. They feel the term “deterioration” implies something that has occurred to the building over time, while some sources of structural concern may be inadequate in the initial design or construction or changes to the building use during its life. In addition, they state that significant deterioration may occur without compromising the load carrying capacity of the structural members due to the high factor of safety present in design codes. As a result, it is asserted that the definition of substantial structural deterioration or deficiency should be made relative to specific definitions of what constitutes a safe structure and cannot be determined without careful analysis of the current structural capacity and demand.

Some of the respondents have concern regarding the first part of the definition provided in the legislation, stating that surface imperfections, with common reference to spalling, are often an indication of structural deterioration or deficiency. Furthermore, such defects are often precursors to issues that may ultimately result in structural compromise. While this concern is somewhat alleviated in the second part of the definition, where the engineer may use their judgement to assess what constitutes a sign of structural deterioration, a few feel that the wording is unnecessarily circular or vague.

2.2.4 Two-phase Inspections

The milestone inspection process is divided into two phases such that an in-depth, possibly more intrusive, and likely more costly inspection is only required after a qualitative visual inspection reveals signs of substantial structural deterioration. Most of the interviewees are in favor of the two-phase inspection process, with many indicating that it reflects how 40-year building safety inspections are already carried out: the engineers conduct an initial walk-through to determine if additional in-depth inspection and testing is required. A few respondents are concerned that breaking the inspection up into two phases may insert an unnecessary delay during the inspection process and even prolong the implementation of time-critical shoring or repairs. One interviewee feels that coastal buildings should automatically require a Phase 2 inspection due to the mechanisms and timelines of their deterioration.

The interviewees that are working on reserve study inspections question the relationship between the milestone inspections and the required reserve study inspections. Specific questions include whether a single inspection can fulfill both requirements and whether they can or should be conducted by different engineers (with possibly very different assessments). They also note that reserve study inspections do investigate roofing, windows, and waterproofing; which could be beneficial to include in the milestone inspections.

2.2.5 Phase 1 Inspections

A Phase 1 inspection is defined as a visual inspection of the habitable and non-inhabitable areas of the building that is intended to provide a qualitative assessment of the structural conditions of the building. The definition of a Phase 1 inspection is reasonable to most of the interviewees. Several interviewees believe that visual inspection conducted by an experienced inspector is adequate to evaluate if there are signs of substantial structural deterioration but not necessarily to determine cause or extent. Some feel that additional inspection techniques, such as hammer/tap tests may be useful during this inspection phase for assessing the level of structural deterioration. One inspector expressed that a visual inspection could still require the removal of finishes as needed, which is not addressed in the legislation.

A common discussion point in many of the interviews was whether the intent of the legislation is to promote maintenance that will ultimately improve structural performance or whether it is to simply identify structural conditions that have already reached a critical level of concern. If the promotion of structural preservation through timely maintenance is desired, then some feel that a Phase 1 inspection should include assessment of components such as windows, waterproofing, and sealing.

2.2.6 Phase 2 Inspections

A Phase 2 inspection is a more in-depth inspection of the structure that may involve destructive or nondestructive testing and may be as extensive or limited as necessary to fully assess areas of structural distress. The purpose of the Phase 2 inspection is either to confirm that the building is structurally sound and safe for its intended use or to recommend a program for fully assessing and repairing distressed and damaged portions of the building. The inspector is encouraged to select testing locations that are the least disruptive, when possible.

A Phase 2 inspection is triggered if the inspector determines that there are signs of substantial structural deterioration under visual inspection (Phase 1). Some interviewees expressed the opinion that, due to liability concerns, many inspectors would recommend a Phase 2 inspection if there is even the possibility of structural deterioration, regardless of whether their assessment can determine if it has reached the level of “substantial”.

There was a lot of discussion on whether a Phase 2 inspection should be required when what may be deemed to be superficial defects, such as spalling or compromised seals, are observed. These defects can be indicative of, or quickly lead to, structural issues even if they do not yet rise to the level of substantial structural deterioration. Several interviewees would like more latitude for the inspector to specify the need for a Phase 2 inspection. Some respondents question whether they can specify the need for minor repairs upon completion of the Phase 1 inspection as preventative measures without having to trigger a Phase 2 inspection.

Most interviewees find the description of the Phase 2 inspection to be adequate and reasonable. Some request more detailed language, such as the requirement to inspect "all exterior surfaces" or to specifically address items such as foundation assessment. One respondent feels that the legislation should address whether an engineer can "fail" the building if unpermitted work is found during the inspection. Several interviewees feel that more specific language provides them backing when they find themselves in the position to convince condominium association boards of the necessity of certain evaluation methods.

There are mixed opinions on what, if any, destructive or non-destructive testing methods are appropriate for structural assessment. A few think that visual techniques can often provide all the necessary information, while most had one or two testing methods they favor for assessment. Methods commonly used by those interviewed include:

- Hammer/tap/sounding – concrete assessment
- Chipping out spalls – spall assessment, corrosion identification and assessment
- Ground penetrating radar (GPR) – rebar location and assessment
- X-Ray – rebar location and assessment
- Core samples – as-built assessment (e.g., cover thickness), chloride content testing, mix assessment
- Thermal imaging/IR cameras – moisture detection
- Geotechnical assessments

These assessment methods, and others, are reviewed in Section 5 of this report. A few respondents have concern that larger engineering firms with more resources may have access to expensive testing equipment and may be more likely to recommend testing that requires it, while smaller firms may not be able to compete.

Almost all the interviewees cite gaining adequate access as the primary challenge to carrying out a Phase 2 inspection. Obtaining unit owner approval for removal of finishes can be a challenge and condo boards do not always provide timely access to necessary inspection locations. A few respondents mentioned the challenges of obtaining original building plans.

2.2.7 Inspection Reporting

Many strongly request that consistent inspection forms be adopted in all jurisdictions. There is concern about the challenges that would be presented with a lack of consistency in reporting requirements. Most are in favor of the requirement for condo boards to provide the inspection report to all unit owners; while a few suggest redacting contact information of the engineers so that all correspondence is carried out through the board.

2.2.8 Timelines and Enforcement

Several of the interviewees express concern regarding the timeline for the initial round of inspections to take place (before the end of 2024). They cite the large number of buildings that will need to be inspected versus the small number of experienced inspectors in the state. This capacity concern is further exacerbated by building departments that may not be adequately staffed to implement the new inspection program and process the inspection reports and subsequent repair permits.

The requirement for repairs to be started within a year of a Phase 2 inspection seems long to some interviewees; six months may be more reasonable with extensions requested as needed. If the repairs are more minor in nature, or to address maintenance concerns, then a year may be reasonable; however, if substantial structural deterioration is observed, repairs should start sooner, if not immediately in some cases. While more timely repairs can be specified by the engineer, a shorter timeline enforced by building departments would provide additional motivation to the owners. Another interviewee does not think that the repair process will move quickly given timelines for creating repair drawings, pulling permits, and competitive bidding as required by condominium laws. Extensions may be filed if the process takes longer than expected.

Several interviewees stressed the importance of role of the building departments in enforcing timelines for inspections and following up on inspections to ensure that building owners are meeting the requirements of the legislation and that inspection and repairs are occur in a timely manner. One respondent suggested that building departments should go to each site to verify repairs and sign off that they have been completed.

Several interviewees expressed concern for inevitable cases when condo boards and building owners do not have adequate funds to perform required repairs.

2.2.9 Inspector Qualifications

Most interviewees do not feel that architects have the appropriate training to carry out milestone structural inspections, especially Phase 2 inspections that may require in-depth structural analysis and design of repairs. In addition, several think that engineers should have a specific background in structural engineering to qualify as milestone inspectors. Almost all support a minimum required level of experience to qualify inspectors to carry out the inspections. This experience could be defined in number of years or number of buildings inspected. There is little support for the requirement of a Special Inspector (S.I.) certification to conduct milestone inspections; it is not relevant experience for this type of inspection and would potentially narrow an already small pool of potential inspectors.

2.3 Inspector Survey Summary

All interviewees have a generally positive opinion of legislation mandating a statewide building inspection program and see the benefit of providing building owners the information needed to maintain the safety of their buildings. Overall, many see the legislation, as it is currently written, as a good starting point and see the opportunity for this program to collect data on building performance that may ultimately provide more information on the most appropriate inspection onset and interval and how the proximity to the coast impacts structural deterioration. There is also recognition of the challenges associated with implementing the program on such a large scale, including a lack of qualified inspectors, inadequate resources for building department enforcement, and the potential for inconsistent reporting requirements across hundreds of jurisdictions.

Many of the interviewees appreciate that the general language in the legislation allows inspectors to apply their judgement in assessing structural condition, determining when a Phase 2 inspection is required, and specifying repairs. Some feel that additional specificity would promote more consistent inspection outcomes and offer the engineer some support in cases where condo boards are resistant to more in-depth evaluation and repairs.

3 Building Inspection Report Acquisition

The objective of Task 2 was to determine the quantity and types of inspection reports required to ensure statistical significance of the final analysis results and to request inspection reports from municipalities in Miami-Dade and Broward Counties accordingly.

To identify the property addresses that would be requested to supplement the data acquired in the Phase I project, the research team first had to determine the number of non-exempt buildings present within each municipality within Miami-Dade and Broward Counties. These numbers provide information on the full dataset (total number of non-exempt addresses, building use, year built, and number of stories) from which to select a representative and statistically meaningful sample size.

The starting dataset from Miami-Dade County was in the form of an Excel spreadsheet with property appraiser information for all properties in the county, both exempt and non-exempt, and in which each individual unit within a condominium was listed as a separate property. A program was developed to automatically consolidate condominiums and remove non-exempt addresses. Data for individual condominium units were collapsed into a single address and folio number per building. Buildings without condominiums and an area below the threshold or with non-applicable building uses were removed from the dataset. The data provided by Broward County BORA was in the form of several Excel spreadsheets (one corresponding to each year of the program since inception in 2006) with a list of non-exempt addresses due for inspection in the respective year. In the first phase of this project, addresses with inspection due dates prior to 2018 were provided; in this phase of the research, the addresses due for inspection between 2018 and 2022 were also provided. Data cleaning for Broward County addresses required consolidation of all individual spreadsheets and removal of any remaining non-exempt properties.

The goal in this phase of the project was to obtain a total of 5% of identified non-exempt addresses in each of the municipalities selected for this study, inclusive of the Phase I and Phase II project. As a result, the research team identified the number of additional addresses required to reach the 5% goal. Some municipalities from which reports were requested in the Phase I project were not revisited in the second round of requests due to a low response rate or simply not having adequate building inventory to warrant additional reports. A few additional municipalities were added in an attempt to achieve a more representative total sample, though some did not respond to the requests. In contrast to Phase I, all municipalities required payment for records requests, which was furnished by the project budget.

The requested inspection reports by municipality are summarized in Table 1, which includes the total number of non-exempt buildings and the number of reports requested and received in Phases I and II of this study. A total of 341 requests were made in each phase of the project, for a total of 682 total requests. The number of addresses for which reports were received was similar for each research phase, with a total of 521 and an overall response rate of 76%. The received reports represent approximately 5.1% and 3.1% of the Broward County and Miami-Dade County non-exempt inventories, respectively. Note that the total number of inspection reports received is higher than the total number of addresses requested due to some municipalities furnishing more than one report per address (e.g. 40-year inspection reports and subsequent 10-year reports) as discussed in the next section.

Table 1. Summary of inspection report requests by county, municipality, and project phase.

		Total Non-exempt	Phase I		Phase II		Total	
			Requested	Received	Requested	Received	Requested	Received
		Totals	341	261	341	260	682	521
County	**Municipality**							
Broward	**Deerfield Beach**	408	13	11	29	29	42	40
	Fort Lauderdale	2121	46	35	71	67	117	102
	Hallandale Beach	-	13	3	0	0	13	3
	Hollywood	1961	24	18	81	56	105	74
	Pompano Beach	-	20	11	0	0	20	11
Miami-Dade	**Coral Gables**	241	18	13	0	0	18	13
	Miami	2254	121	102	20	13	141	115
	Miami Beach	1506	35	33	71	59	106	92
	Aventura	222	0	0	9	0	9	0
	South Miami	255	0	0	10	0	10	0
	North Miami	516	0	0	20	11	20	11
	North Miami Beach	486	0	0	30	25	30	25
	Hialeah	3771	34	25	0	0	34	25
	Sunny Isles Beach	242	17	10	0	0	17	10

4 Data Aggregation and Analysis

The objective of Task 3 was to extract relevant information from the additional inspection reports requested and received during Task 2 and to analyze the extracted data according to the analysis procedures established in the first phase of the research project. Analyses of the combined data from both project phases are provided.

4.1 Inspection Report Statistics

Of the 521 addresses for which reports were received, a total of 573 inspection reports were provided. Any of the provided inspection reports that were generated after building repairs were completed were not included in the analysis. Figure 1 shows the distribution of municipalities represented by the reports received, with the largest percentages of reports coming from Fort Lauderdale and Hollywood in Broward County and Miami and Miami Beach in Miami-Dade County. Figure 2 illustrates the locations of the dataset addresses.

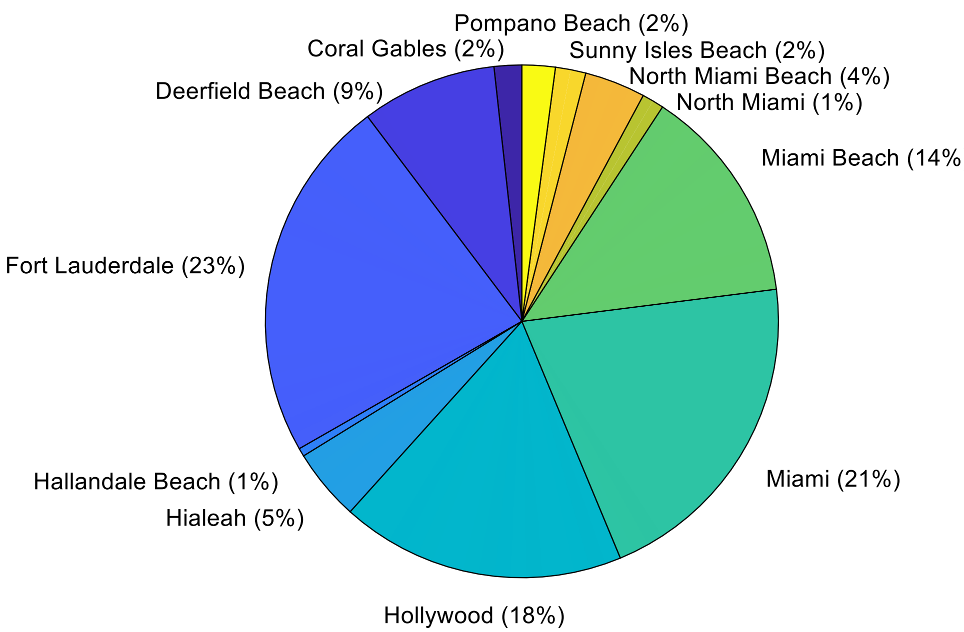


Figure 1. Percentage of inspection reports from each municipality (N = 573).

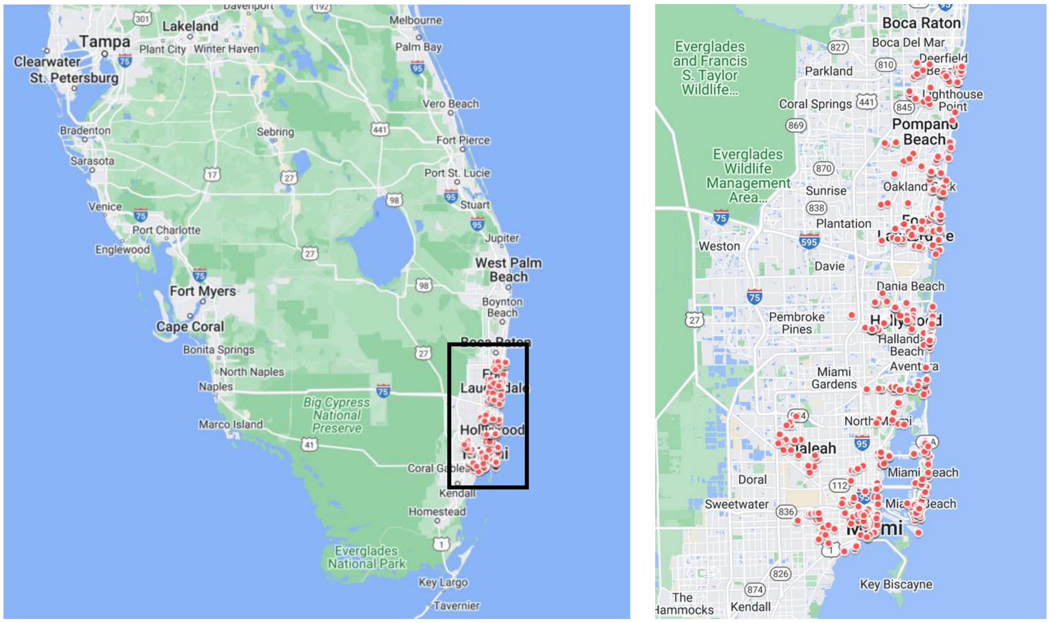


Figure 2. Location of Broward and Miami-Dade County addresses analyzed in this study (left), with inset (right), Google Maps, 2023.

The percentage of building uses is provided in Figure 3 based on the inspection report dataset, with more than half being residential condominiums. Figure 4 shows the distribution of the number of stories of the buildings in the dataset. Two-thirds of the buildings are three or more stories while a quarter are considered high-rise (10 or more stories). Figure 5 shows the distribution of the years the buildings in the dataset were built. Most of the buildings were built in the late 1960s and in the 1970s, which is consistent with a period of high construction activity in the area. Also consistent with regional construction, over three quarters of the buildings are reinforced concrete frame structures, as shown in Figure 6.

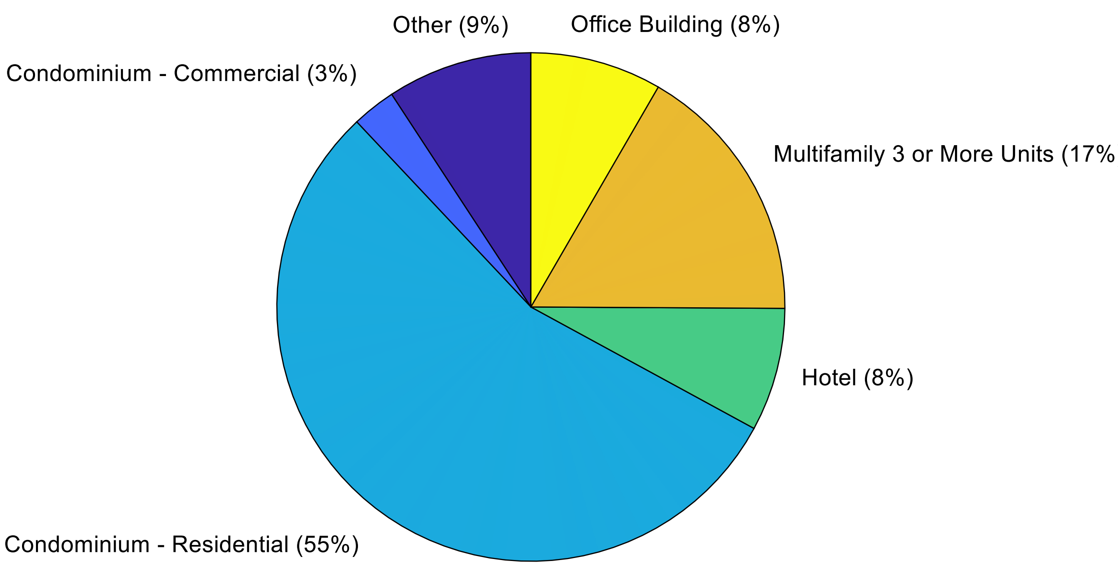


Figure 3. Percentage of inspection reports by building use (N = 573).

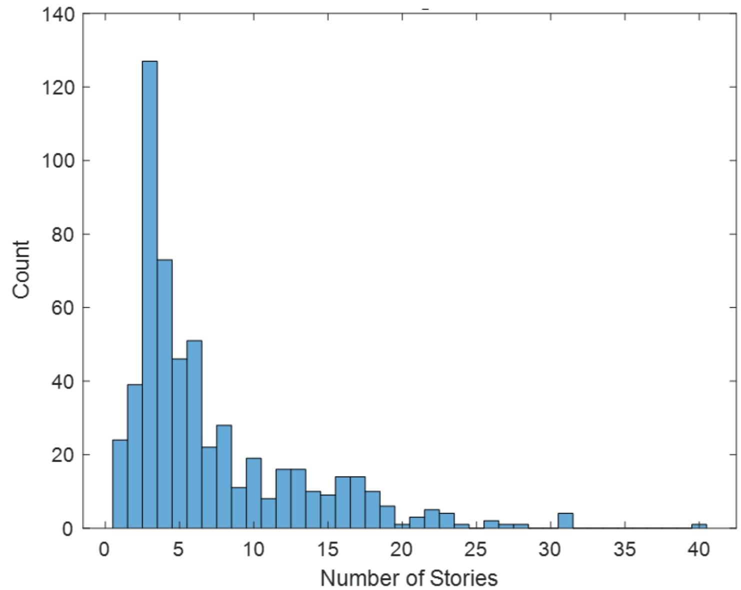


Figure 4. Distribution of the number of stories of the buildings in the inspection report dataset (N=573).

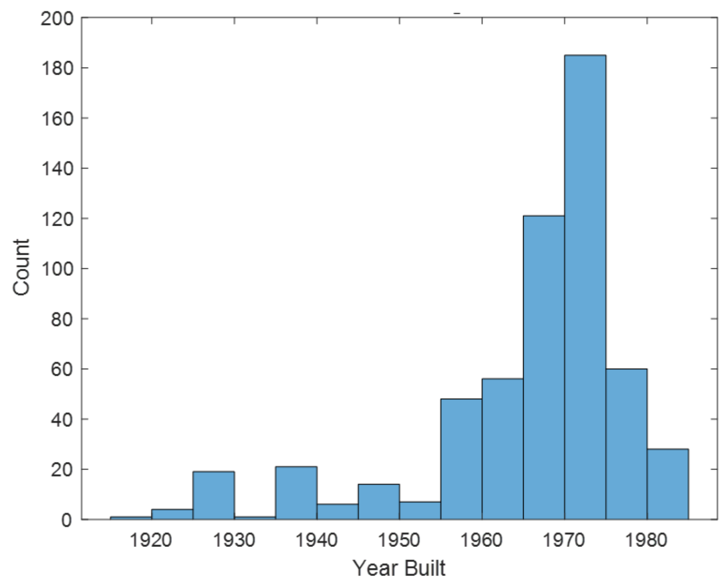


Figure 5. Distribution the year the buildings in the dataset were built. (N = 573).

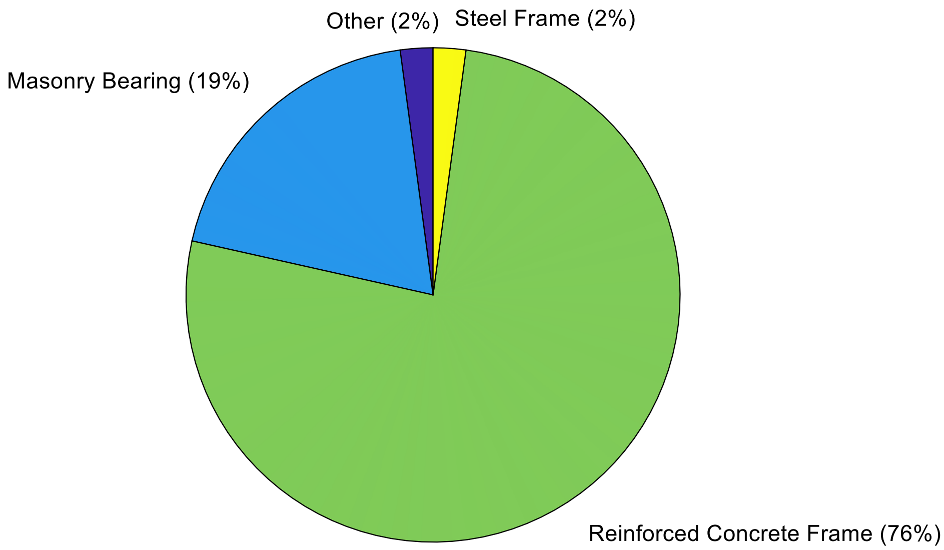


Figure 6. Primary structure type of the buildings in the dataset (N = 563).

Overall, the inspection reports that make up the dataset analyzed in this study, including those acquired in the first research phase, provide a representative sample of approximately 4% of the non-exempt buildings in the urban coastal regions of Miami-Dade and Broward Counties.

4.2 Analysis Approach

The Final Report for the first phase of this research (Bridge et al. 2022) provides an overview of the methods used to ensure consistent extraction of data from the analyzed inspection reports, and the approach used for the data analysis. The following sections provide information on the additional analysis methods that were developed and applied in this second phase of the research and the results of the analysis.

4.2.1 Repair Rating

After the passage of Senate Bill 4-D, the research team added additional inspection report analysis to evaluate the severity of the deterioration and extent of required repairs for each recorded building inspection report. The Phase I project reported the severity of some component defects; however, the overall requirement for repair was reported simply as “yes” or “no”. The purpose of this additional analysis was to use the building inspection reports to determine the extent of the deterioration present at the time of inspection based on the information provided within. The analysis was used to infer if a building would require a Phase 2 inspection according to the language in the current legislation based on the information provided in the inspection report.

The repair rating scheme is shown in Table 2. Ratings of 1 and 2 would likely not require a Phase 2 inspection according to the language of Senate Bill 4-D. Ratings of 4 and 5 would likely require a Phase 2 inspection, with 4 indicating signs of substantial structural deterioration, and 5 indicating defects rising to the level of substantial structural deterioration. A rating of 3 indicates that maintenance repairs were required and that there may be signs of deterioration that would lead to substantial structural deterioration if maintenance is deferred. Depending on the inspector, a rating of 3 could potentially lead to the call for a Phase 2 inspection.

Table 2. Repair rating scheme.

Rating	**1**	**2**	**3**	**4**	**5**
Brief description	No Repairs Required	Maintenance Suggested	Maintenance Required	Signs of Substantial Structural Deterioration	Substantial Structural Deterioration
Detailed Description	No signs of Surface Imperfections. No notable imperfections or conditions. No repairs required.	Some Surface Imperfections that were **not** likely to lead to Substantial Structural Deterioration. Repairs were not required, but repairs **may** be suggested for maintenance.	Surface Imperfections that lead to Substantial Structural Deterioration. Repairs were required for maintenance.	Surface Imperfections that **are** a sign of Substantial Structural Deterioration. Repairs were required.	Substantial Structural Deterioration was found and reported. Repairs were required.
Phase 2?	No	No	Possibly	Yes	Yes
Examples		Doors and windows maintenance, sealing, minor stucco cracking, minor concrete cracking, minor masonry cracking, waterproofing issues	Spalling, concrete cracking, delamination, roofing/ reroofing	Spalling, significant concrete or masonry cracking, rebar corrosion, concrete repair	Section loss, significant spalling or cracking, immediate repairs, concrete repair

4.2.2 Distance to the Coast

One of the considerations for the new milestone inspection legislation is whether to impose different inspection requirements for buildings closer to the coast, and thus subject to harsher environmental conditions (saltwater exposure). A challenge arises in determining an appropriate definition of the coastline and then further determining the distance at which building exposure results in more rapid deterioration. In the first phase of this research study, the coastline definition used to determine the distance of each address to the coast was the Coastal Construction Control Line (CCCL) as defined by the Florida Department of Environmental Protection (DEP). As illustrated in Figure 7 and Figure 8, this definition does not consider buildings beside intercoastal waterways or Biscayne Bay as on the coastline despite the proximity to seawater.

Senate Bill 4-D refers to Florida Statute 376.031 for the definition of the coastline: “the line of mean low water along the portion of the coast that is in direct contact with the open sea and the line marking the seaward limit of inland waters, as determined under the Convention on Territorial Seas and the Contiguous Zone, 15 U.S.T. (Pt. 2) 1606." To be in closer alignment with this definition (though the research team was not able to identify a map with this specific definition), the National Oceanic and Atmospheric Administration (NOAA) Continuously Updated Shoreline Project (CUSP) coastline definition was adopted for use in data analysis. The CUSP coastline provides the most recent definition of the shoreline based on NOAA and non-NOAA data sources (LiDAR, Satellite imagery, and aerial photography). The version of the NOAA CUSP used in this project, also shown in Figure 7 and Figure 8, was downloaded in July 2022.

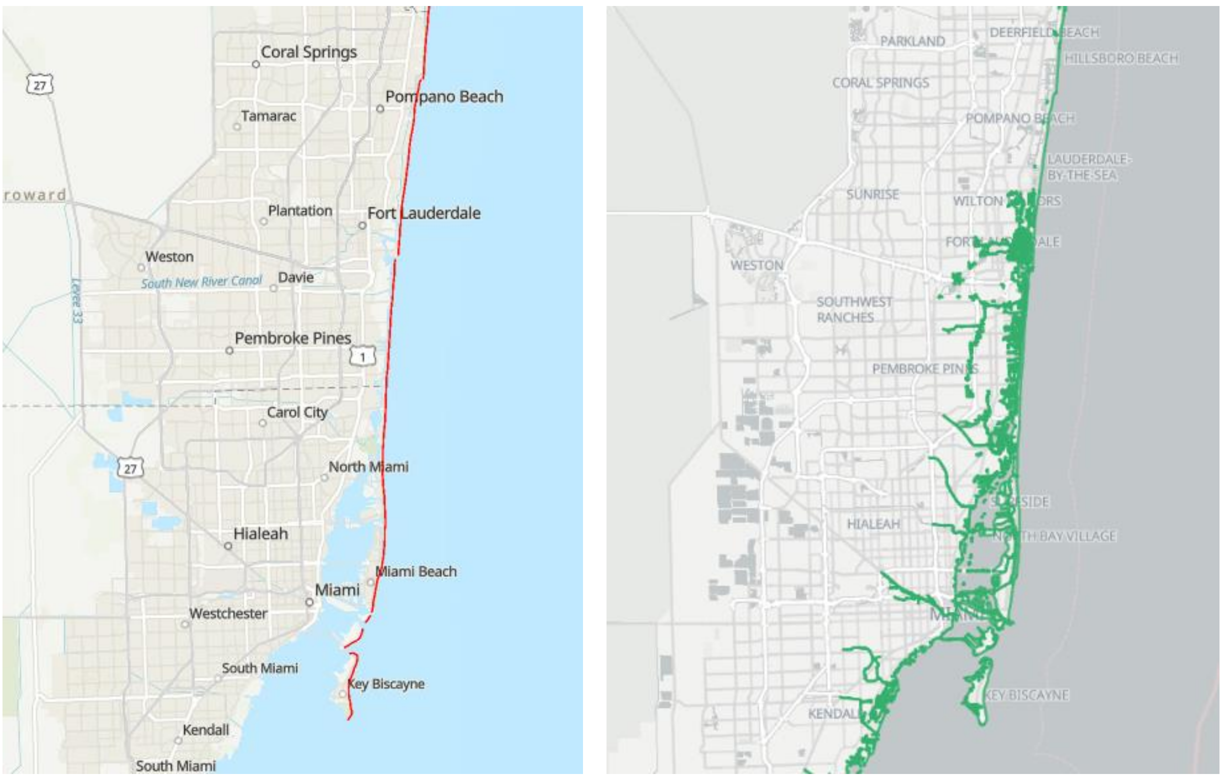


Figure 7. Coastline definitions for the study area: CCCL, shown in red (left) and the NOAA CUSP July 2022 definition shown in green (right).

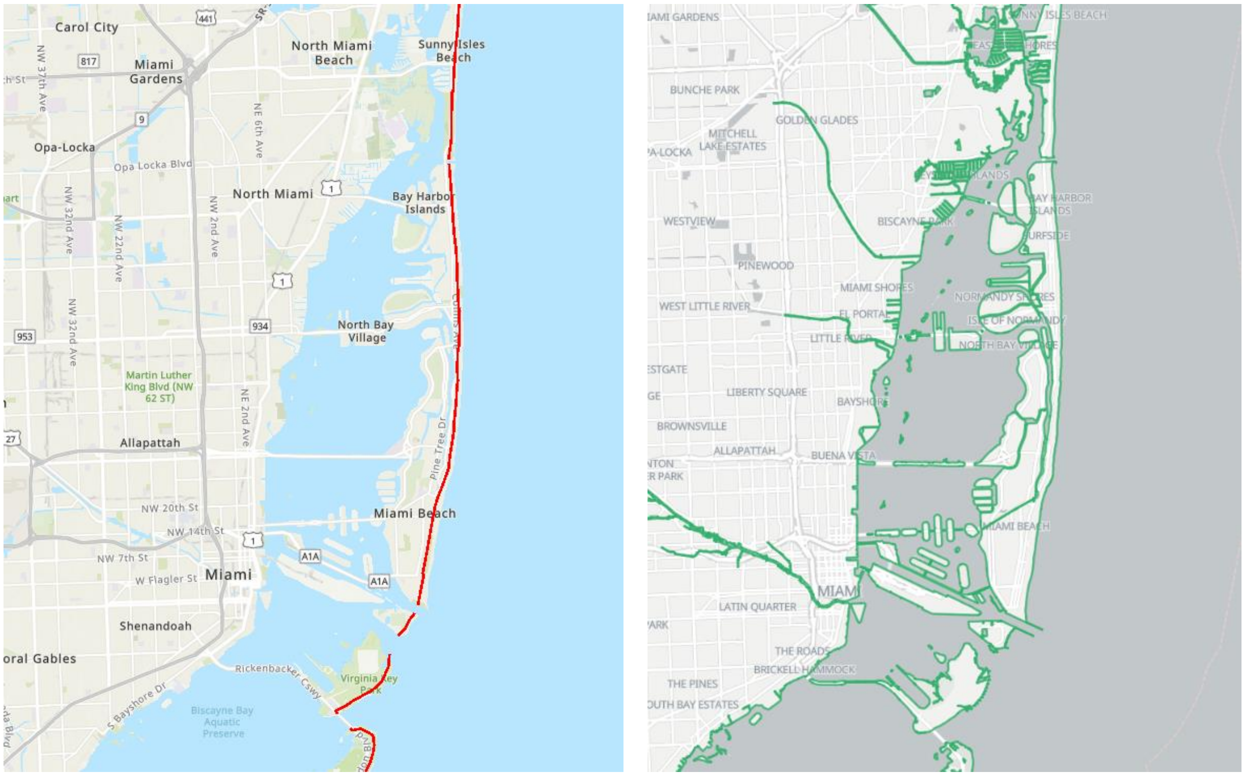


Figure 8. Coastline definitions zoomed in on Biscayne Bay: CCCL, shown in red (left) and the NOAA CUSP July 2022 definition shown in green (right).

To determine the distance to the coast (NOAA CUSP), each property address was converted to coordinates (latitude and longitude) using a mapping tool. The coordinates of the coast were converted from NOAA data to coordinates every 10 ft. Finally, the distance between the address coordinates and the coastline coordinates were determined using built-in MATLAB mapping toolbox functions.

The calculated distances to the coast change with the different coastline definitions, as illustrated in Figure 9. Many of the addresses that were considered three to four miles from the coast using the CCCL are now considered a few hundred feet from the coast with the more detailed NOAA CUSP reference.

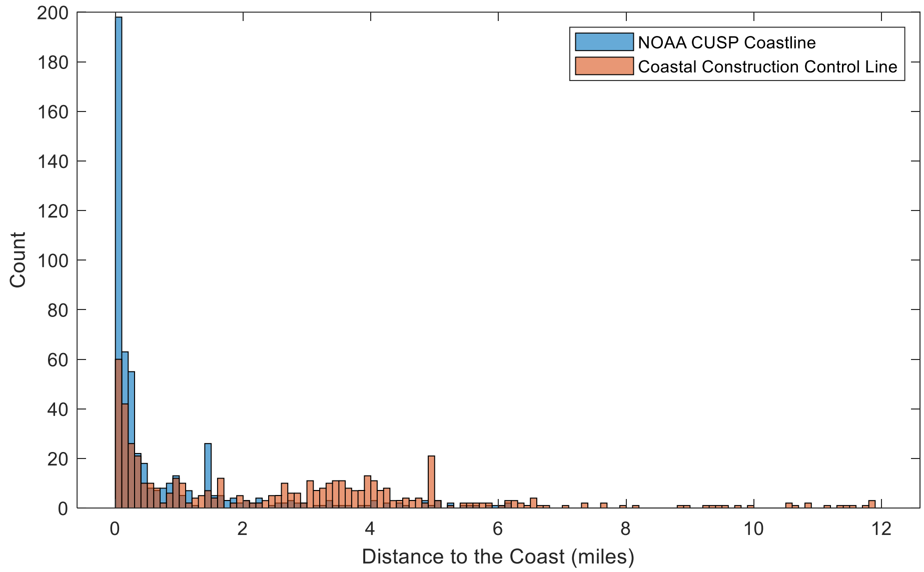


Figure 9. Distribution of the distances of the study building addresses to two different definitions of the coastline.

To enable meaningful comparison, the addresses in this study were divided into five, roughly equal bins of distance to the coast as shown in Figure 10. The resulting distance break points are 200 ft, 600 ft, 1500 ft and 1 mile. Senate Bill 4-D currently identifies a single distance distinction at three miles. This distance was not considered in this study since only 6.6% of the addresses in this study are greater than three miles from the NOAA CUSP defined coast.

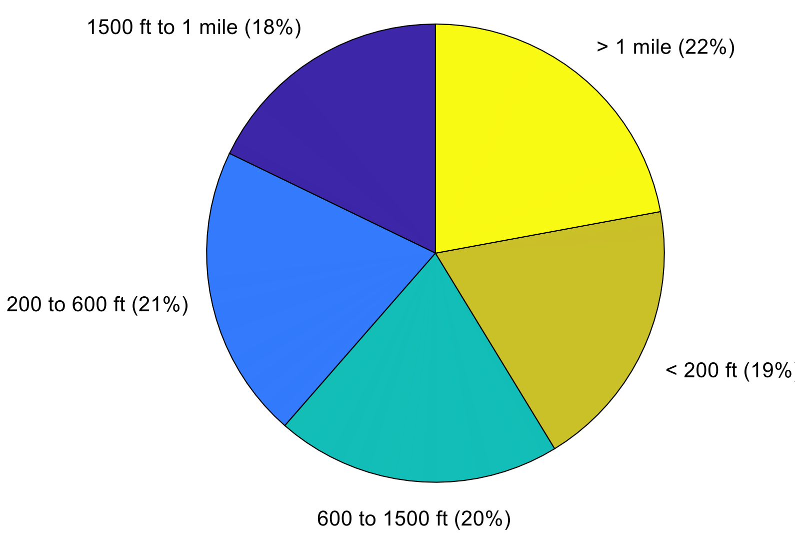


Figure 10. Building address distances to the coastline (N = 516).

4.3 Analysis Results

This section provides the results of the analysis of the extracted inspection report data. First, analysis of the inspection programs is provided. Then the buildings conditions are reported based on the most recent inspection report for each address to provide a snapshot of the current condition of the buildings. Further analysis is provided on how reported building conditions change initial 40-year inspections and subsequent 50-year inspections. This section focuses on the overall requirement for repairs and the condition of the concrete. Additional results on the floor, windows, and roof conditions are provided in Appendix C and Appendix D.

4.3.1 Inspection Program Analysis

Most of the inspections in the study dataset were carried out by Professional Engineers (P.E.s), including some with the additional designation of Special Inspector (S.I.), as shown in Figure 11. Thirteen percent of inspections were performed by Architects.

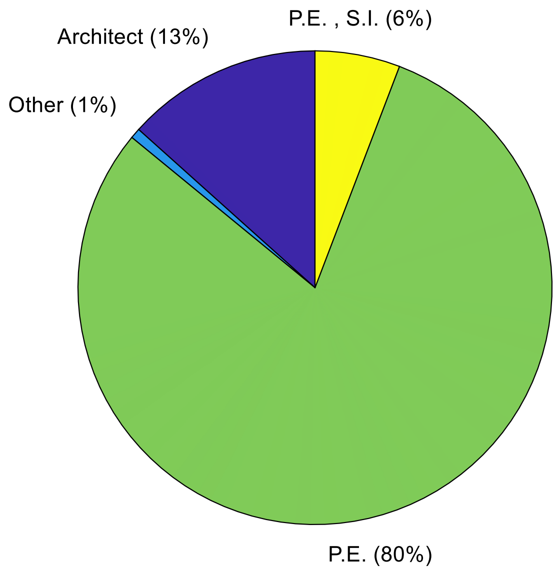


Figure 11. Inspector title (N = 569).

Building owners typically receive notices from their building department when the building is due for a 40-year or subsequent 10-year inspection. The date on which these notices are received varies; most often they are transmitted within the year they are due but sometimes the building department does not send notices in a timely manner. Figure 12 shows the approximate time between when a building is due for an inspection (based on its age, not when the notice is sent) and when the building is inspected. While most inspections are completed within a year of when they are due, 23% are not done within five years of their due date. The final report for the first phase of this research provided recommendations on regarding the improvement of the timeliness of inspections (Bridge et al. 2022), many of which are already being adopted by building departments in Miami-Dade and Broward Counties.

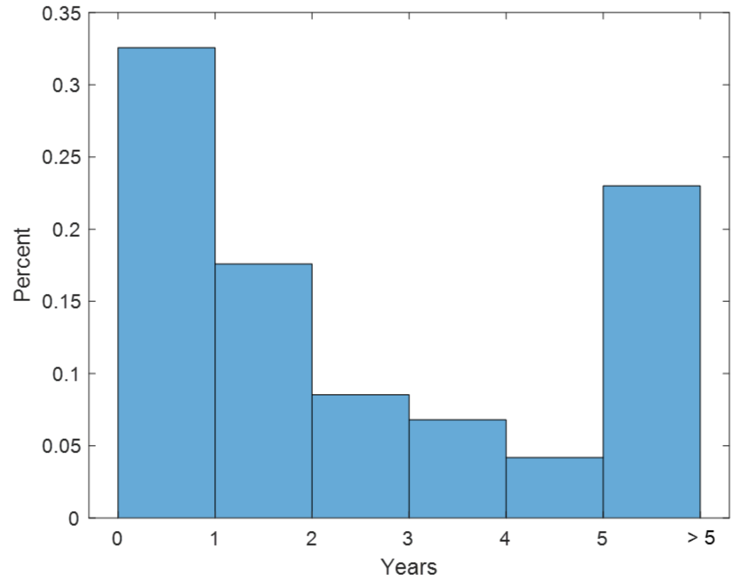


Figure 12. Approximate time from when an inspection on a property is due and when it is performed (N = 536).

Figure 13 shows the years that inspections were performed in the study dataset. Most inspections were performed between 2012 and 2022.

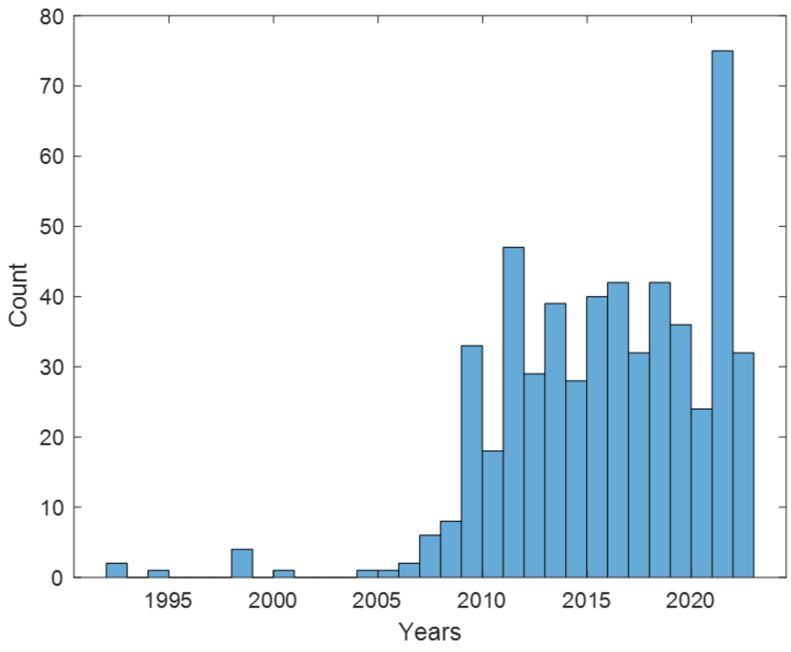
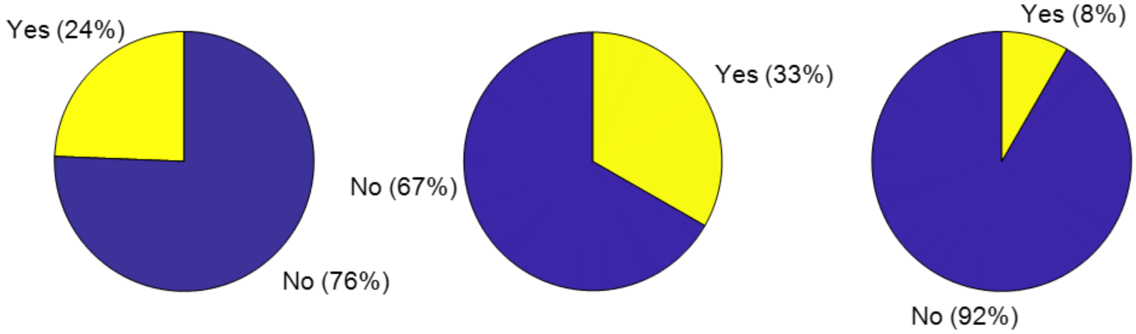


Figure 13. Year inspection performed (N = 573).

Figure 14 shows the extent of supplementary information that inspectors provide with their reports. As reported in the Phase I final report, some inspection reports do not follow the required form or provide inadequate information for a structural assessment. Ten percent of the reports reviewed in this study did not substantially follow the report template resulting in incomplete information. The analysis results presented in this report indicate when no data was reported for the identification of a structural or building component; however, condition results are only reported for the data that was provided. As a result, in some cases the sample size (N) for the condition assessment is less than the sample size given for the component identification.



(a) (b) (c)

Figure 14. Percent of reports that provide a) written data, b) photographs, and c) drawings or sketches (N = 574).

4.3.2 Most Recent Inspection Reports

This section provides an overview of the results of the reported building conditions from the initial inspection report from the most recent inspection period for each building in the dataset. These results are intended to provide information on the current state of the buildings analyzed. Most of the reports in this analysis were conducted in the last 15 years. A limited 40-year inspection report analysis is provided in Section 4.3.3 with details provided in Appendix C.

Approximately one quarter of the most recent inspection reports specified that repairs were required, as shown in Figure 15. The extent of defects and structural repairs identified in the inspection reports are further evaluated via the assignment repair rating. Figure 16 shows the distribution of repair ratings for all of the most recent inspection reports, as well as for condominiums with three or more stories (the current building definition in the new milestone inspection legislation). As discussed in Section 4.2.1, buildings receiving a repair rating of 1 or 2 would not require a Phase 2 inspection, while repair ratings of 4 and 5 would. Repair ratings of 3 may require a Phase 2 inspection, depending on the judgement of the inspector. Figure 17 shows the percentage of all building types and condominiums with three or more stories that would require a Phase 2 inspection. At least 14% of all buildings and 19% of condominiums would require a Phase 2 inspection according to the most recent inspection reports analyzed in this study.

The percentage of required repairs and their ratings, respectively, for the building uses represented in the dataset of most recent inspection reports are provided in Figure 18 and Figure 19. Condominiums (commercial and residential) and hotels show slightly higher requirements for repairs and poorer condition than other building uses. This trend may be, in part, due to their closer proximity to the coast and resulting saltwater exposure.

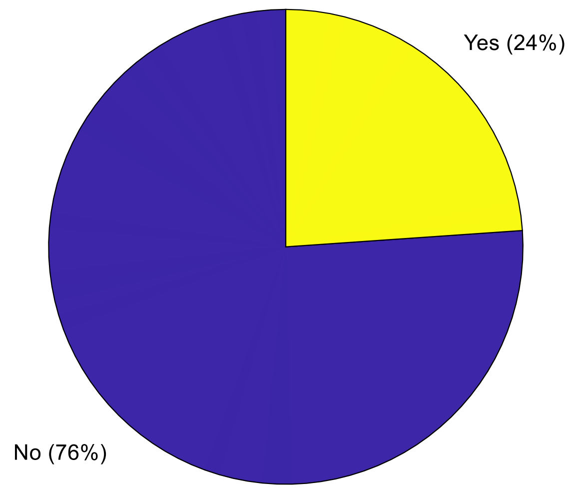


Figure 15. Percentage of most recent building inspections requiring some type of repair (N = 502).

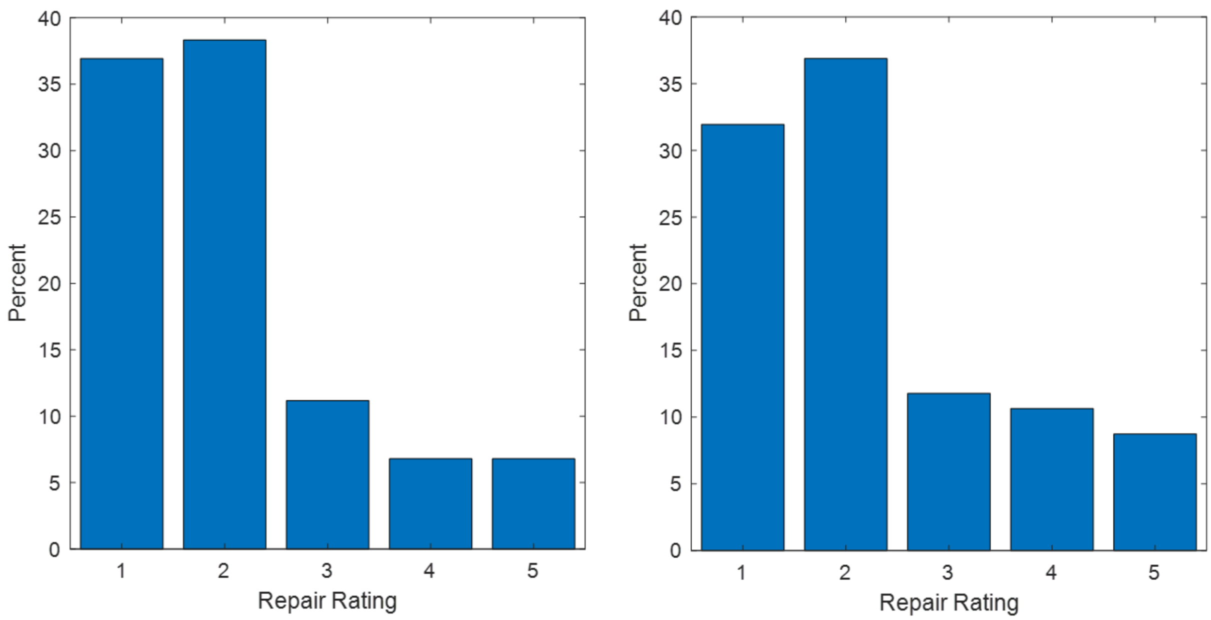
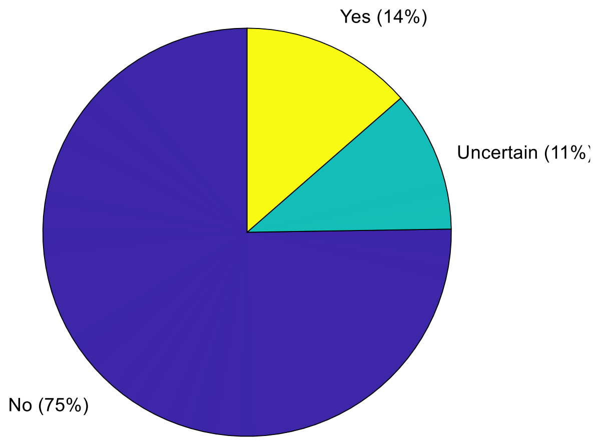


Figure 16. Distribution of repair ratings assigned to the most recent inspection reports for all buildings (left, N = 501) and residential condominiums with three or more stories (right, N = 263).



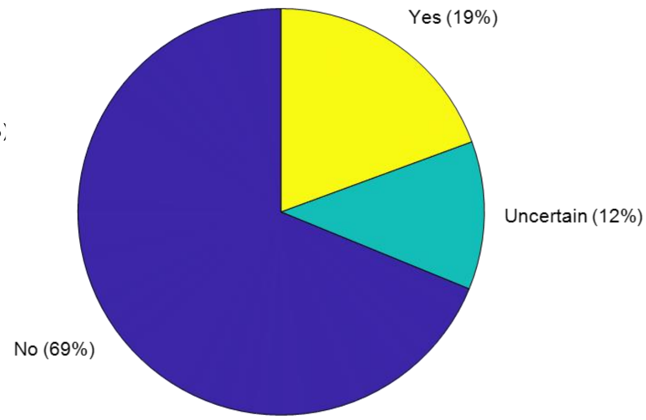


Figure 17. Percentage of recent inspection reports indicating that a Phase 2 inspection would likely be required under SB 4-D for all buildings (left, N = 501) and for residential condominiums with three or more stories (right, N = 263).

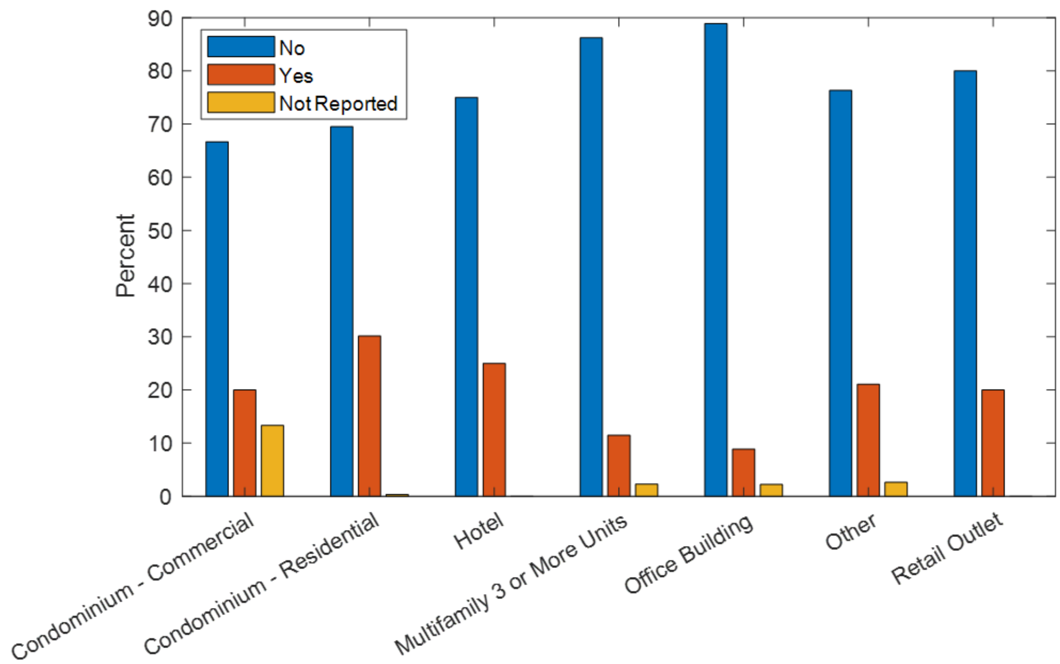


Figure 18. Required repairs by building use reported in the most recent inspection reports. (N = 501).

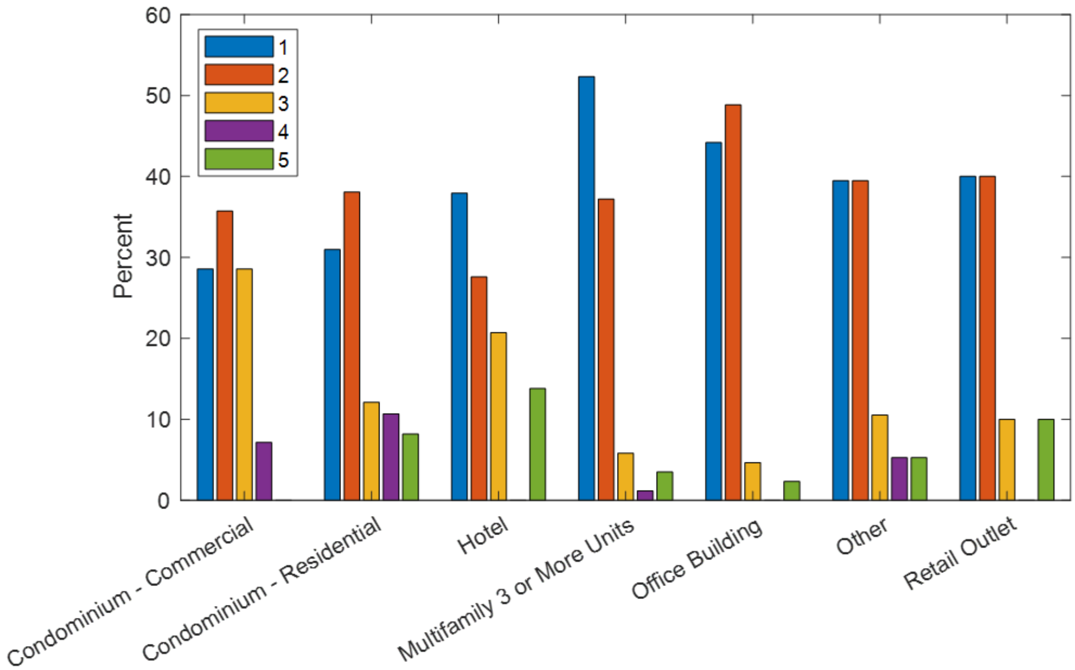


Figure 19. Repair rating by building use reported in the most recent inspection reports. (N = 501).

The requirement for repairs and repair ratings were also examined according to the building distance to the coast, using the NOAA CUSP coastline definition described in Section 4.2.2, as shown in Figure 20 and Figure 21, respectively. There is a slight increase in the requirement for repairs between buildings less than 200 ft and buildings from 200 to 600 ft from the coast. The requirement for repairs decreases notably when buildings are farther than 600 ft from the coast. As the distance to the coast increases, repair ratings of 1 and 2 (minimal to no structural or maintenance deficiencies) steadily increase, while repair ratings of 3 (maintenance repairs suggested) decrease. Buildings under 600 ft from the coast have similar rates of combined 4 and 5 repair ratings (signs of direct evidence of substantial structural deterioration) that are higher than buildings over 600 ft from the coast. This data clearly indicates the impact that the distance to the coast has on building conditions, with a clear distinction in repair requirements and ratings occurring 600 ft from the coast. Higher rates of deterioration for buildings closer to the coast are most likely the result of increased chloride exposure resulting in higher rates of rebar corrosion.

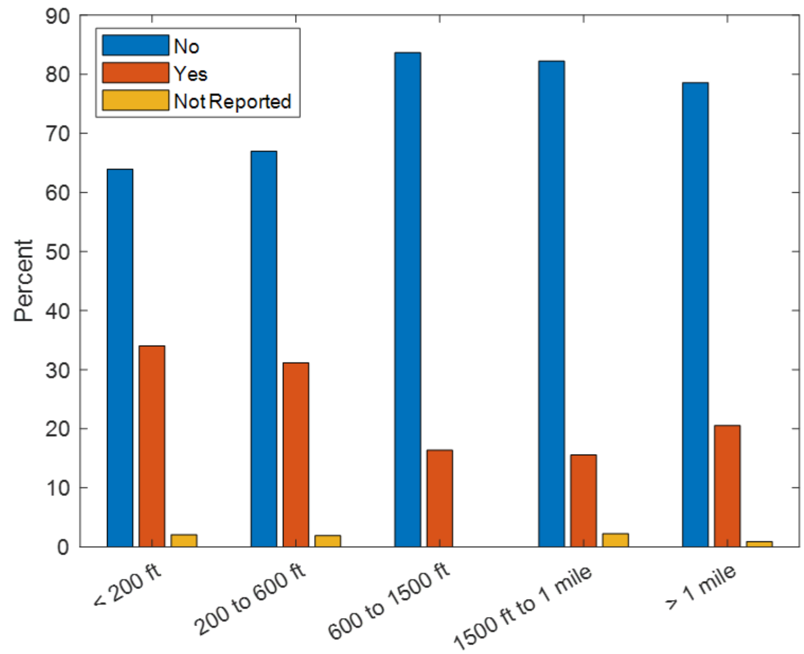


Figure 20. Most recent inspection report requirement for repairs vs. distance to the NOAA CUSP coastline definition (N = 501).

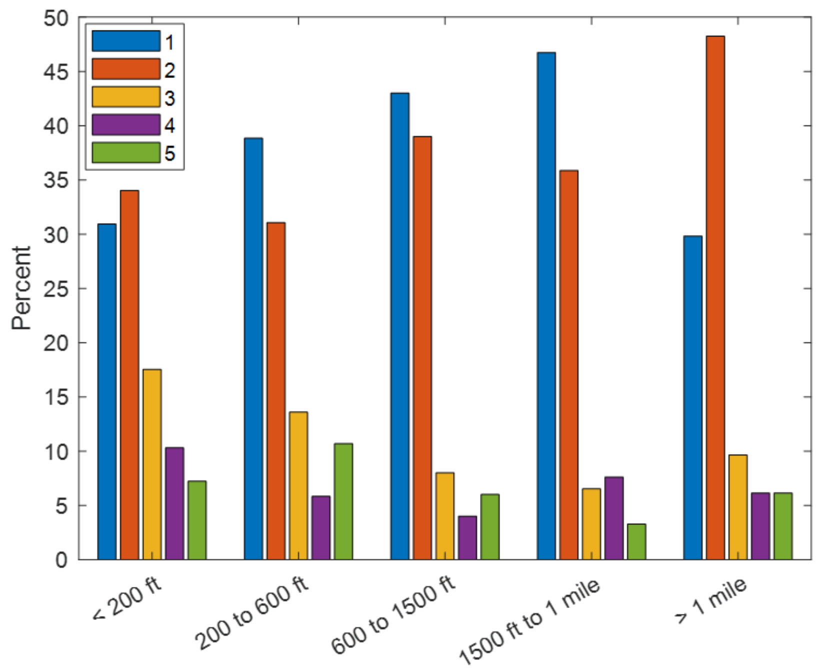
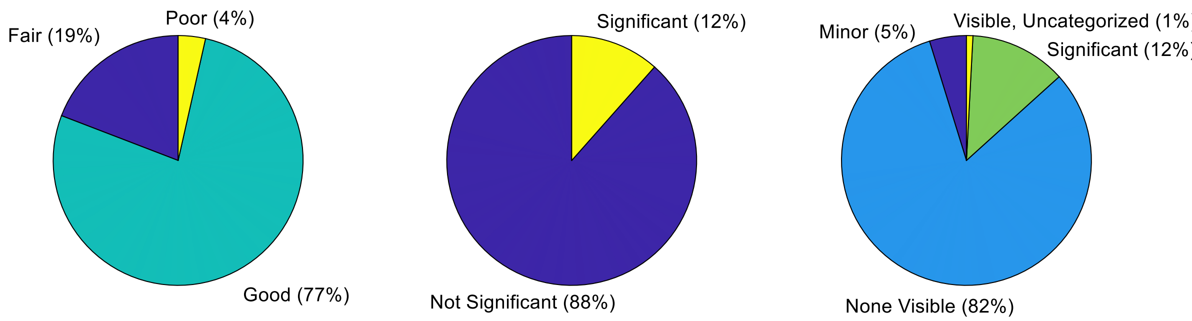


Figure 21. Most recent inspection report repair rating vs. distance to the NOAA CUSP coastline definition (N = 501).

The inspection reports provided information on the general condition of the concrete as well as the presence and significance of cracking and corrosion. 77% of buildings for which data was provided were reported to have concrete in good general condition while 23% were reported as either fair or poor, as shown in Figure 22. 12% of reports that provided information on concrete cracking indicated that it was significant and concrete corrosion was reported in 18% of reports, with 12% considered significant (Figure 22). Reported concrete condition was also examined according to the distance of the buildings to the coast. Figure 23 shows that, with the exception that buildings over a mile from the coast, the reported concrete conditions worsen as buildings are closer to the coast. The evidence of rebar corrosion is higher as buildings get closer to the coast, with a notable increase in corrosion found in buildings less than 600 ft from the coast (Figure 24).



(a) (b) (c)

Figure 22. Concrete conditions reported in the most recent inspection reports: a) general condition (N = 454), b) concrete cracking significance (N = 468), and c) concrete rebar corrosion significance (N = 481).

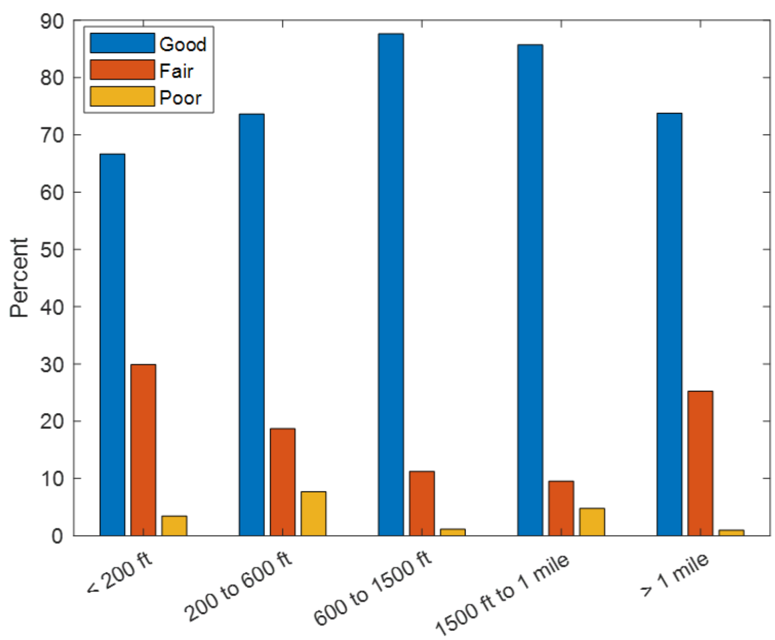


Figure 23. Concrete general condition reported in the most recent inspection reports by distance to the coast (N = 454).

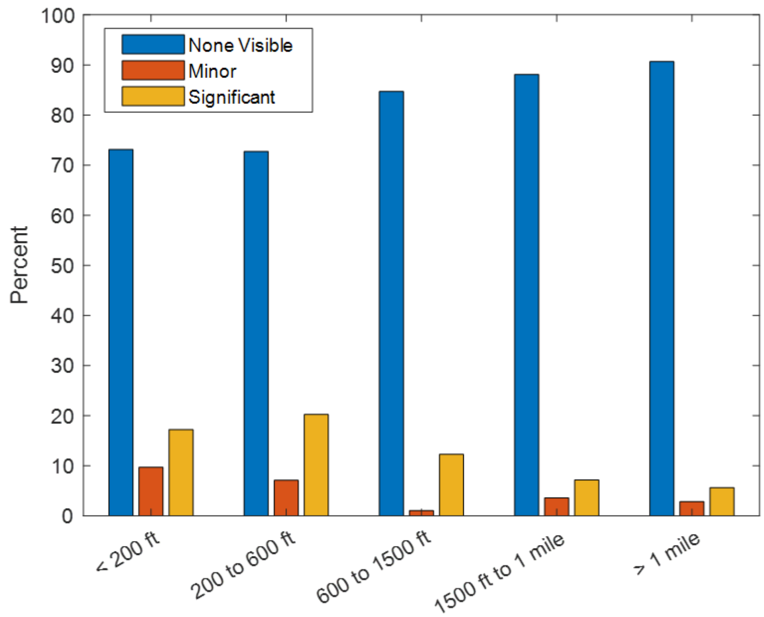


Figure 24. Concrete rebar corrosion reported in the most recent inspection reports by distance to the coast (N = 481).

A number of previous research studies from concrete specimens in the field have established a general consensus that concrete structures located within a proximity of 100 meters (328 feet) to the coastline are subject to the highest levels of chloride exposure. Empirical observations gathered from various field structures demonstrate a significant decline in chloride concentration (approximately 70%) in concrete structures located at distances exceeding 100 meters (328 feet) from the coastline (Chen et al. 2013; Jagerman 1990; Meira et al., 2006). Field data from investigations indicate that the chloride concentration in concrete situated between the distances of 100 meters and 500 meters (328 and 1,640 feet) experiences further reduction. As the distance increases from 500 to 1400 meters (1,640 to 4,592 ft), the reduction in chloride concentration becomes more pronounced, eventually reaching a negligible level beyond this range (Chen et al. 2013; Jagerman 1990; Meira et al., 2006).

4.3.3 40-Year Inspection Reports

The 40-year inspection reports were extracted from the dataset for analysis to assess the reported conditions of buildings when they reach 40 years of age. The full analysis results and figures for the 40-year reports are provided in Appendix D. The results are largely similar to those of the most recent inspection reports provided in the previous section, as more than 50 percent of the most recent reports are 40-year inspection reports. A summary of the comparison between the two datasets is provided in Table 3.

Table 3. Comparison between the most recent report dataset and the 40-year inspection report data subset.

Metric	**Most recent report**	**40-year report**
Repairs required	24%	26%
Phase 2 inspection likely required – all building uses	14%	15%
Phase 2 inspection likely required – condominiums, 3+ stories	19%	19%
Concrete condition fair or poor	23%	19%
Significant concrete cracking	12%	12%
Significant rebar corrosion	13%	12%

The same coastline and coastal zone definitions used for the most recent inspection report analysis were used to evaluate the requirement for repairs and repair ratings versus distance to the coast for the 40-year inspections. The results show that the rate of required repairs and the severity of the defects generally decrease as buildings are further from the coast. Similar to the recent inspection report dataset, a drop in the repair requirements and significance is observed in between buildings that are less than 600 ft from the coast and buildings that are between 600 and 1500 ft from the coast.

4.3.4 Comparison of 40- and 50-Year Reports

Thirty-three of the addresses for which inspection reports were analyzed included inspections conducted at both 40-years and 50-years of age. This subset of the data, from Deefield Beach, Hollywood, Fort Lauderdale, Miami Beach, and North Miami, allowed a direct comparison between the condition of the buildings from one inspection to the next. Figure 25 shows the percentage of buildings that required repairs at the 40-year and 50-year inspections. The percentage of required repairs dropped from 36% to 24%. The distribution of the severity of the defects and extent of repairs also shifted from 40 to 50 years, as illustrated in Figure 26. The percentage of defects considered primarily maintenance (Repair Rating = 3) was reduced to approximately half between inspections while the percentage of substantial structural deterioration (Repair Rating = 5) decreased from 15% to 9% between inspections. These results indicate that the defects identified and resulting repairs required at the 40-year inspection led to improved building maintenance and structural conditions in the subsequent decade.

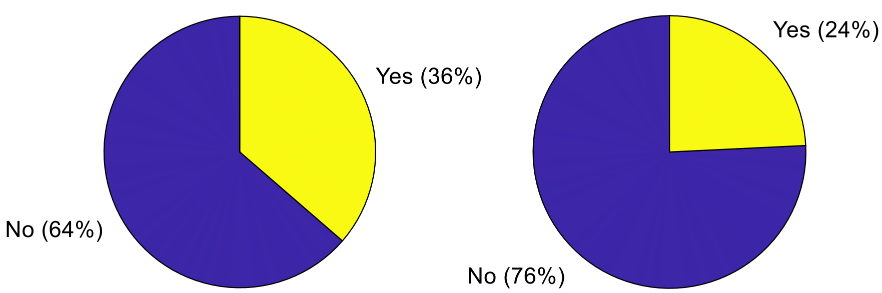


Figure 25. Percentage of buildings requiring repairs in 40-year (left) and 50-year (right) inspection reports for the same addresses (N = 33).

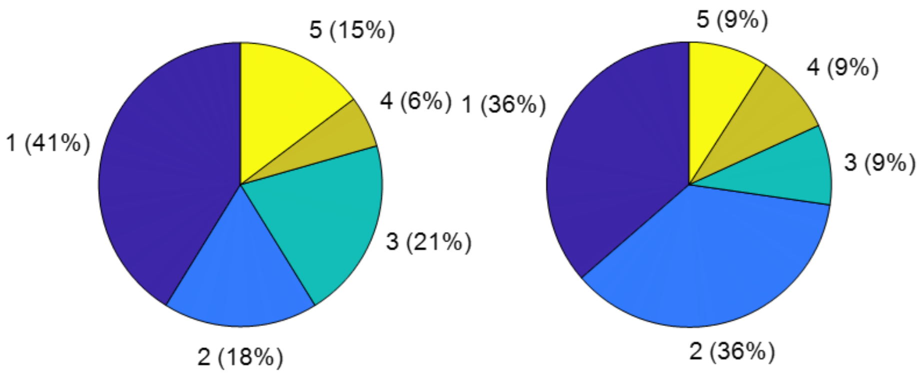


Figure 26. Repair rating assigned to buildings at the 40-year inspection (left) and the 50-year inspection (right) (N = 33).

5 Inspection Technology Landscape Assessment

The objective of Task 4 was to objectively assess and report on destructive and nondestructive structural assessment technologies that are currently available and effective for providing structural condition assessment, as well as emerging methods with promise to enhance inspection practices. There is some industry guidance on structural and material testing for condition assessment, notably SEI/ASCE 11-99; however, they do not capture more recent technology developments, nor do they address the cost associated with implementation. The goal of this section, along with the detailed descriptions provided in Appendix E, is to provide information on commonly used or emerging technologies and techniques that can, or have the potential to, aid in the structural assessment of buildings based on current development, applications, and industry guidance. Each of the methods presented in this report are described according to 14 metrics that provide information on what their theory of operation, capabilities for building/material assessment, their reliability and maturity, relevant specifications or guidance, and their relative cost. This information is meant to provide an objective description of each technology as it currently exists and is provided without reference to specific vendors or contractors.

The following paragraphs describe the metrics used to describe each inspection technology. A summary of the technologies and tools included in this report is provided in Table 4. The detailed description of each technology is provided in Appendix E (and hyperlinked from Table 4).

Description
The description provides a very high-level overview of the technology, including the theory of operation and how it is used in building assessment.

Damage Type/Target Material
This metric describes the types of damage that can be found or tracked with technology, or the type of structural assessment it can achieve. This metric also specifies which material type the technology is limited to, if any.

Contact/Noncontact
A contact sensor or technology must be in contact with, or embedded in, the structural components it is monitoring. Contact sensors may also be able be installed over finishes in some cases. Noncontact sensors or technologies do not require contact with the building finishes or structural elements.

New Construction/Existing Structure
This metric provides information on whether the technology can be used on existing structures or whether it must be installed or implemented at the time of construction. Some sensor types, especially those that are embedded in materials, can only reasonably be installed during construction. Other sensors that are best suited to new construction may be installed during material repair or with appropriate, but costly, retrofitting.

Automated/Manual
Manual assessment technologies require operation by a technician or engineer on site to deploy and guide the technology and to provide real-time interpretation. After appropriate deployment and software implementation, automated technologies can operate with no or minimal operator input. They provide automated data or reporting on the outcomes of their assessment. Some

assessment technologies may have aspects that are manual, such as movement by an operator thought a structure, but employ aspects of automation to achieve faster and more reliable assessment results.

Localized/Global Damage Assessment

Local damage is a specific defect that is present in specific locations within a structure. Examples include cracks, corrosion, delamination, and spalling. Technologies that track localized damage are detecting these conditions and specific locations. Global damage assessment uses overall structural responses, such as dynamic properties, alignment, tilt, deflection to determine the likelihood that the structure has experienced damage that may or may not be visible during an inspection. The outcomes of a global structural assessment may guide the inspector to specific locations to investigate the presence of local damage.

Technology Maturity/Years in Use

Assessment technologies have a wide range of technical maturity, often indicated by how long they have been used in regular practice. The longer a technology has been in use, the more likely it is to have been tested and vetted and its reliability understood. Newer technologies, though less tested, may offer better results than older technologies; however, they may lack standardization and cost more.

Assessment Reliability

This metric provides qualitative information on how reliable the technology is when used for its intended application.

Assessment Frequency

The assessment frequency provides information on whether a technology is used continuously or periodically. For periodic applications, this metric also provides guidance on how often it should be used.

Cost

The cost of a system impacts how accessible it is to engineers and building owners and, coupled with reliability, how viable an investment it is. This metric is difficult to determine in a general sense due to the variability in the types of systems that can be deployed and the variability of the buildings on which they may be used. When possible, this metric is divided between equipment cost and the cost of contractor to implement it.

Standardization

This metric provides information on the level of standardization involved with the use of the technology and any applicable standards or specifications.

Guidance Provided by Industry Consensus

This metric provides reference to any available industry guidelines that apply to the technology.

Certification/Operator Training/Experience Requirements

Information is provided on how the operator/technician receives the necessary training and certification to operate the technology.

Interpretation Training/Experience Requirements

Information is provided on how the technician receives the necessary training and certification to interpret the results provided by the technology.

Table 4. Inspection technology review summary.

Section	Method and Principle	Application
E.1	Acoustic Emission - Measure energy produced by material deformation, fracture, or cracking.	Determine the location of defects in concrete and steel.
E.2	Sounding Techniques - Used for surveying concrete structures to ascertain the presence of delaminations.	Determine the location of near surface defects in concrete.
E.3	Ultrasonics - arrival of reflected pulse is recorded by an adjacent receiver and velocity and reflections are measured.	Determine the location of defects in concrete and steel.
E.4	Ground Penetrating Radar - Uses detected radar pulses generated to create visual maps.	Determine the location of defects, reinforcement in concrete and buried utilities.
E.5	Themography - Technique that uses infrared cameras to capture the thermal radiation emitted by objects.	Determine the location of near surface defects in concrete.
E.6	Fiber Optics - Uses glass fibers to transmit light waves along their length for sensing and information transmission.	Determine the location of defects in concrete.
E.7	Imagery - Uses the reconstruction of photographic images for structural assessment.	Detect global defects and localized surface defects in structures.
E.8	AR / VR Guided Inspection - Uses computer generated images to create an overlay for visual enhancement.	Creates a 3D view of the environment for "reality capture".
E.9	Vibration Sensors/Dynamic Analysis – Uses dynamic properties of the structure calculated from vibration measurements to detect loss of global structural capacity.	Determine global loss of structural stiffness/capacity.
E.10	Integrated Sensors - Instrumentation integrated into the building (can be permanently installed) to acquire data relevant to the structural health of the building.	Provide real-time analysis of building components onsite or remotely.
E.11	X – Ray - Mostly limited to oil / gas, rail, or small parts inspection due to safety issues.	Imaging of mechanical parts, welds, and other components.
E.12	Core Sampling - Process to extract core specimens of concrete building components for analysis.	Provide detailed analysis and can be used for comparative global assessment of building components.
E.13	In-situ Strength Methods - Includes rebound number, penetration resistance, pullout, pull-off, ultrasonic pulse velocity, maturity, and cast-in-place cylinders.	Provide strength of concrete and can be used for comparative global assessment of building components.

E.14	Corrosion Detection and Monitoring Techniques - Uses electrochemical techniques including the half-cell potential method and the linear polarization method.	Detect corrosion of embedded reinforcement in concrete.
E.15	Analysis of Ingress and Transport Properties - The field testing of concrete using NDT methods include water absorption, water permeation, air permeation and diffusion.	Determine the potential for ingress of ionic species into concrete, provide information about durability.
E.16	Analysis of Carbonation - Uses pH measurements to provide information on calcium carbonate formation.	Determine depth of carbonation and potential for corrosion of steel reinforcement.

6 Conclusions

This study performed a comprehensive evaluation of the 40-year building safety and recertification programs in Miami-Dade and Broward Counties through the collection and in-depth analysis of 573 inspection records representing 521 addresses in 12 municipalities. The dataset is representative of the building uses, number of stories, primary structure, and age of the buildings in the municipalities it represents. Over half of the buildings are residential condominiums, more than three-quarters are reinforced concrete frame structures, and two-thirds are buildings with three or more stories. One quarter of buildings required some type of repair before the safety inspection or recertification could be completed. Buildings that were inspected at both 40 years and 50 years showed that the building condition improved after the first inspection, indicating that the inspection programs promote building repairs and maintenance that improve the condition of the building.

To evaluate the extent of deterioration and required repairs, a repair rating scheme with five categories was developed and applied to the inspection report dataset: 1) no deterioration noted and no repairs required, 2) minor surface defects noted with no repairs required but maintenance suggested, 3) surface defects or maintenance issues noted and repairs required for maintenance, 4) signs of substantial structural deterioration requiring repairs, and 5) direct evidence of substantial structural deterioration requiring repairs. According to Senate Bill 4-D, a Phase 2 inspection is required when signs of substantial structural deterioration are found, meaning it would be triggered by a repair rating of 4 or 5. A Phase 2 inspection would have been required in 14% of all buildings inspected and 19% of condominiums with three or more stories. Additional Phase 2 inspections may be required for repair ratings of 3, at the discretion of the individual inspector. Building departments can use these results as they anticipate the scope and plan for the implementation of the milestone inspection requirements in their jurisdictions.

The previous phase of this research used the Coastal Construction Control Line (CCCL) to define the coastline (Bridge et al., 2022); however, this definition considers buildings directly on saltwater bodies, such as Biscayne Bay, to be several miles from the coastline. The onset of corrosion in reinforced concrete is primarily attributed to the concentration of chloride levels in the air, it was deemed critical to capture building proximity to saltwater more accurately. As a result, this phase of the research adopted the NOAA CUSP coastline. The change in the distribution of building proximity to the coast between the two coastline definitions highlights the importance of adopting an appropriate coastline definition for the purpose of evaluating the development of corrosion. Additional efforts to select this coastline should be undertaken and should include the development of mapping tools that can be easily used by building officials and engineers to ensure compliance with coastal proximity requirements in inspection statutes.

Reported building conditions were assessed according to their distance to the coast using the NOAA CUSP coastline. Five coastal zones were established so that approximately equal percentages of the dataset buildings are located in each zone: 1) < 200 ft, 2) 200 – 600 ft, 3) 600 – 1,500 ft, 4) 1,500 ft to 1 mile, and 5) > 1 mile. Results demonstrate that buildings have higher rates of required repairs and that the levels of deterioration are higher for buildings within relative proximity to the coast. There is a notable decrease in the required repairs, repair ratings, and observed reinforcement corrosion when buildings are between 600 and 1,500 ft from the coast over buildings less than 600 ft from the coast. These results are consistent with studies in the literature that demonstrate the nonlinear dissipation of air chloride concentrations with distance from the coastline and may also support earlier and more frequent inspections of buildings that are directly on, or very near, the shoreline.

A group of experienced existing building inspectors provided their insight on Senate Bill 4-D through their responses to a set of interview questions. Overall, they have positive opinions of legislation as a tool for ensuring building maintenance and safety. They see the initial implementation of the program as an opportunity to collect data on building performance that may ultimately provide more information on the most appropriate inspection onset and interval and how the proximity to the coast impacts structural deterioration. The interviewees also recognize the challenges associated with implementing the program statewide, including a lack of qualified inspectors, inadequate resources for building department enforcement, and the potential for inconsistent reporting requirements across hundreds of jurisdictions.

Currently, the inspection programs utilize primarily visual inspection techniques. Non-Destructive Testing (NDT) is an important set of techniques used to assess the condition and integrity of buildings without causing damage. NDT methods allow for the detection of defects, deterioration, and structural anomalies, which can enhance inspections to allow engineers and inspectors make informed decisions regarding maintenance, repairs, and structural safety. The application of sensors and other instrumentation to measure structural and material responses can also provide useful information to evaluate aspects of structural performance when appropriate data interpretation methods are applied. Visual inspection may also be aided and enhanced through imagery and 3D scanning techniques. The requirement for effective building condition assessment on a large scale in Florida will likely encourage more widespread adoption of these technologies. This report provides an objective account of current and emerging condition assessment technologies that can be used to evaluate their effectiveness and appropriate application.

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Appendix A. Interview Question Pool (Task 1)

- Have you been involved in 40-year building safety inspections (in either Miami-Dade or Broward Counties) in the past and, if so, approximately how many buildings have you inspected for building safety inspection programs?
- What is your level of familiarity with Florida Senate Bill 4-D?
- Are the definitions for non-exempt buildings reasonable?
- Describe the inspection methods that are required to adequately assess the structural condition of the building, to determine the presence of substantial structural deterioration, to determine if a building is structurally sound, and to determine appropriate repair and maintenance measures to restore the structural safety of a building.
- Do you think that the definition of "substantial structural deterioration" in the legislation is clear and reasonable? If not, what changes would you suggest?
- Is the description of the phase one inspection in the legislation clear? Are the requirements for the phase one inspection clear? Are there any changes you would suggest to the description?
- Are the conditions that trigger a phase two description clearly outlined? If not, what clarifications would you suggest?
- Is the description of the phase two inspection in the legislation reasonable and clear? Are the requirements for the phase two inspection reasonable and clear? Are there any changes that you would suggest to the description?
- What assessment methods (destructive or nondestructive) could be used in a phase two inspection and under what circumstances?
- What challenges do you see to carrying out the phase two inspection as outlined in the legislation?
- What consideration or challenges do you anticipate regarding the preparation and public distribution of the full inspection report and the inspection summary as outlined in the legislation?
- Does the legislation provide adequate and clear guidelines related to enforcement of milestone inspections?
- What inspector qualifications should be required to carry out milestone inspections?
- What is your overall opinion of the legislation as currently written? What changes or additions would you suggest?

Appendix B. Senate Bill 4-D Summary Sent to Interviewees for Task 1

The full text of legislation (See Section 3, Section 553.899 F.S. – Mandatory structural inspections for condominiums and cooperative buildings)

Definitions:

- Milestone inspection:
    - Structural inspection of a building, including load-bearing walls and the primary structural members and primary structural systems by licensed architect or engineer authorized to practice in Florida.
    - The purpose is to attest to the life safety and adequacy of the structural components of the building and, to the extent reasonably possible, determine the general structural condition of the building as it affects the safety of such building, including a determination of any necessary maintenance, repair, or replacement of any structural component of the building.
- Substantial structural deterioration:
    - Substantial structural distress that negatively affects a building's general structural condition or integrity.
    - Does not include surface imperfections such as cracks, distortion, sagging, deflections, misalignments, signs of leakage, or peeling of finishes unless the licensed engineering or architect determines that such surface imperfections are a sign of substantial structural deterioration.
- Phase one inspection:
    - Visual examination of habitable and non-habitable areas of a building, including the major structural components of a building.
    - Intended to provide a qualitative assessment of the structural conditions of the building.
    - If no signs of substantial structural deterioration are found to any building components under visual examination, a phase two of the inspection is not required.
    - Inspection report shall be prepared and submitted pursuant to subsection (8).
- Phase two inspection:
    - Required if any substantial structural deterioration is identified during phase one.
    - May involve destructive or nondestructive testing at the inspector's direction.
    - May be as extensive or as limited as necessary to fully assess areas of structural distress in order to confirm that the building is structurally sound and safe for its intended use and to recommend a program for fully assessing and repairing distressed and damaged portions of the building.
    - When determining testing locations, the inspector must give preference to locations that are the least disruptive and most easily repairable while still being representative of the structure.
    - Inspection report shall be prepared and submitted pursuant to subsection (8).

Inspection Reports

- Report requirements (subsection 8):
    - Report and summary to be submitted to the condominium/cooperative association and to local jurisdiction building official
    - Seal and signature
    - Manner and type of inspection
    - Identification of any substantial structural deterioration within a reasonable professional probability based on the scope of inspection, describing the extent of such deterioration
    - Identification of any recommended repairs for noted deterioration
    - State whether unsafe or dangerous conditions, defined in Florida Building Code, were observed
    - Recommend any remedial or preventative repair for any items that are damaged but not substantial structural deterioration
    - Identify and describe any items requiring further inspection
- Condominium/Cooperative association must distribute inspection summary to each unit owner and must post a copy of summary in conspicuous place. A copy of the full inspection report must be published on the association's website.

Enforcement and Scheduling

- Initial milestone inspection must occur by December 31 in the year required (25 for buildings within three miles of the coast or 30 years for buildings more than three miles from the coast, from the certificate of occupancy), and every 10 years thereafter.
- Condominium and cooperative associations are responsible for arranging the milestone inspection and for all costs associated with the inspection.
- For buildings with certificates of occupancy issued on or before July 1, 1992, the building's initial milestone inspection must be performed by December 31, 2024.
- The local enforcement agency must provide written notice to the association that an inspection is required.
- The association must complete the phase one milestone inspection (determined by submission of the report by the engineer or architect) within 180 days from receiving notice that the inspection is due.
- Local enforcement agency prescribes timelines and penalties with respect to inspection requirements.
- A board of county commissioners may adopt an ordinance requiring that a condominium or cooperative association schedule or commence repairs for substantial structural deterioration within a specified timeframe after the local enforcement agency receives a phase two inspection.
- Such repairs must be commenced within 365 days after receiving such report.
- If an association fails to submit proof to the local enforcement agency that repairs have been scheduled or have commenced for substantial structural deterioration identified in a phase two inspection report within the required timeframe, the local enforcement agency must review and determine if the building is unsafe for human occupancy.

Appendix C. Detailed Inspection Report Results – Most Recent Reports

<u>Roof Systems</u>

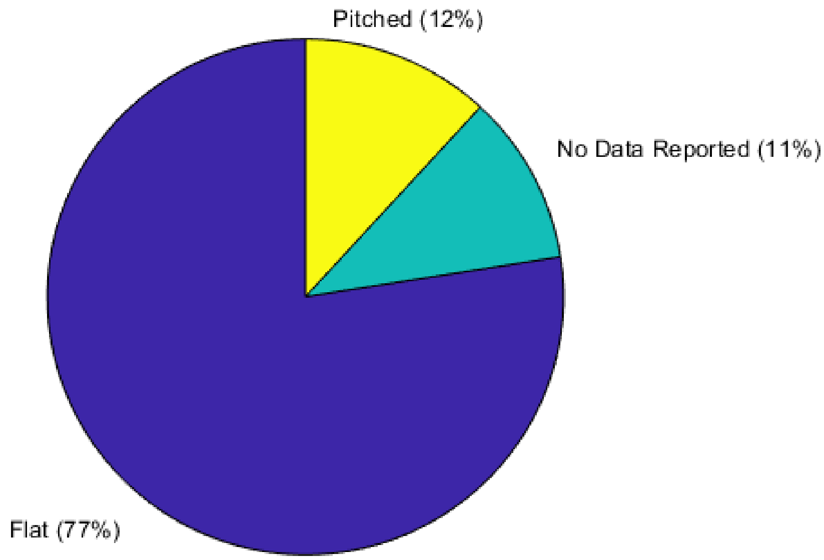

Figure 27. Roof categories identified in the most recent inspection reports (N = 515)

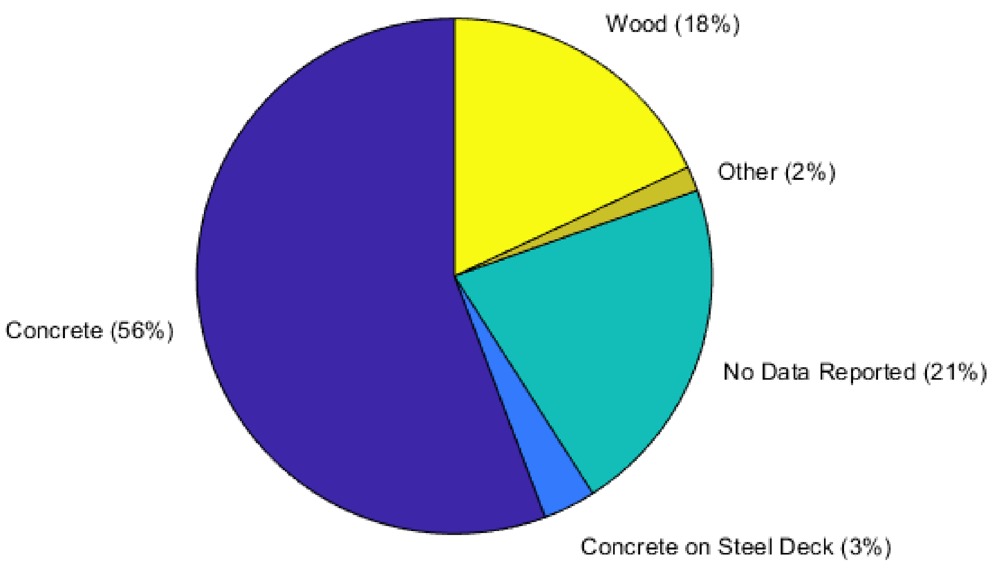

Figure 28. Roof structural systems identified in the most recent inspection reports (N = 515)

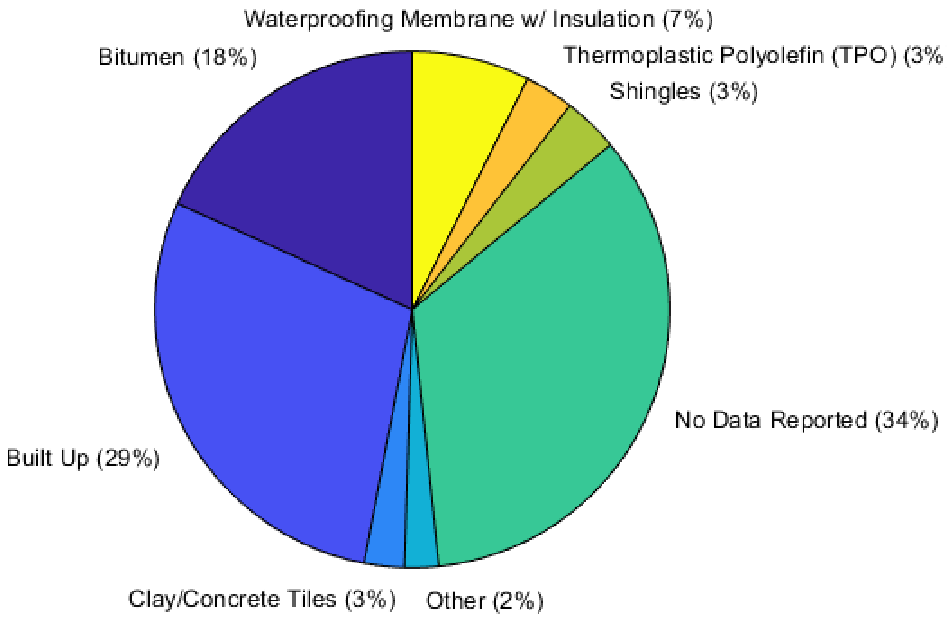

Figure 29. Roof cladding systems identified in the most recent inspection reports (N = 515)

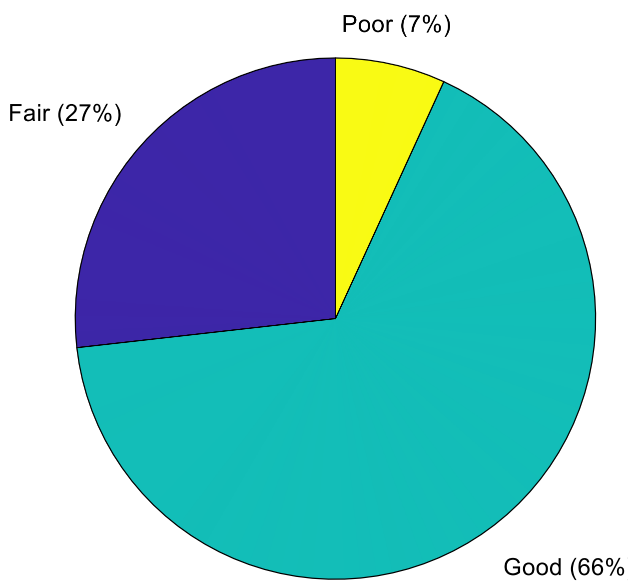

Figure 30. Roof structural system condition reported in the most recent inspection reports (N = 351).

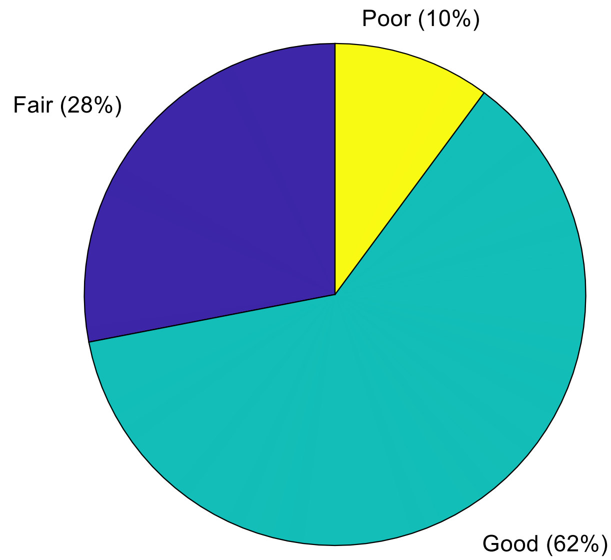

Figure 31. Roof cladding condition reported in the most recent inspection reports (N = 296).

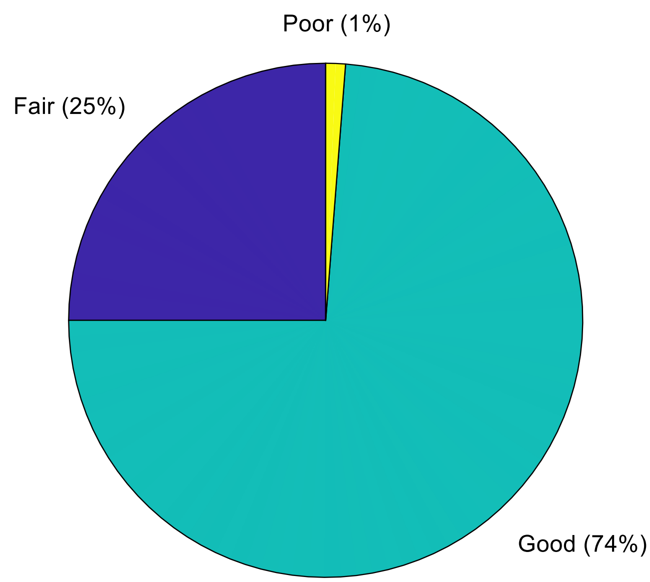

Figure 32. Roof drainage condition reported in the most recent inspection reports (N = 324).

Floor Systems

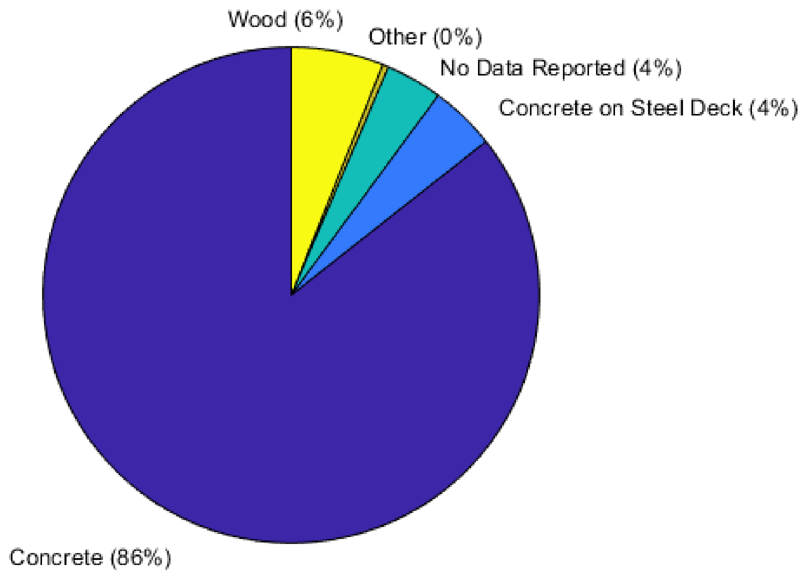

Figure 33. Floor system identified in the most recent inspection reports (N = 515).

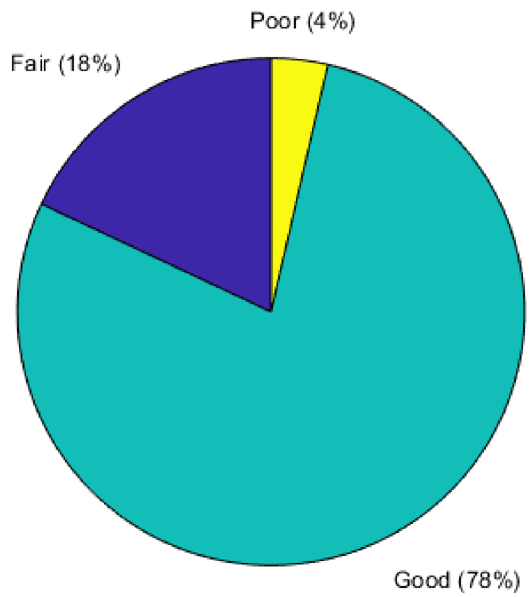

Figure 34. Floor system condition reported in the most recent inspection reports (N = 333).

Windows

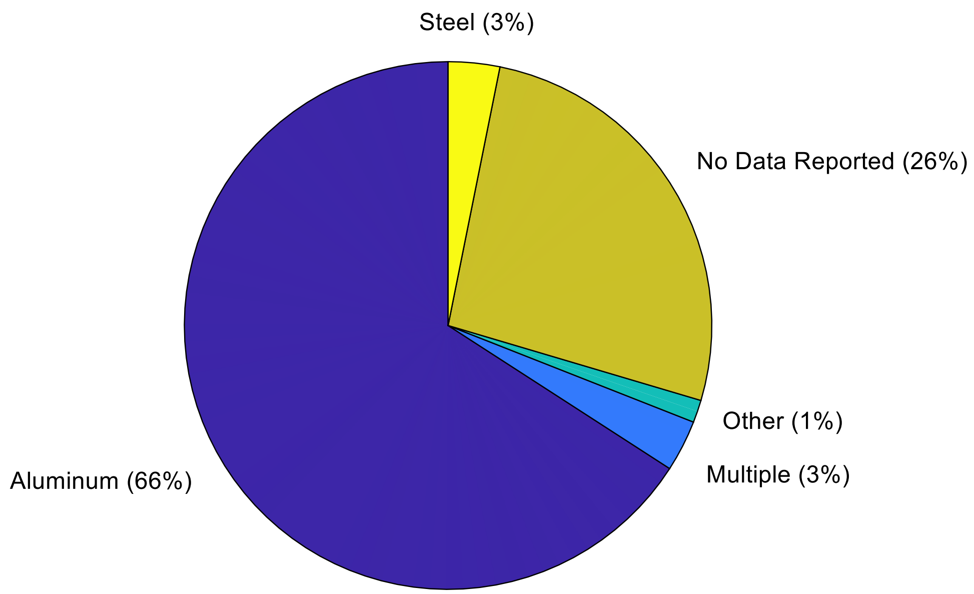

Figure 35. Window category reported in the most recent inspection reports (N = 507).

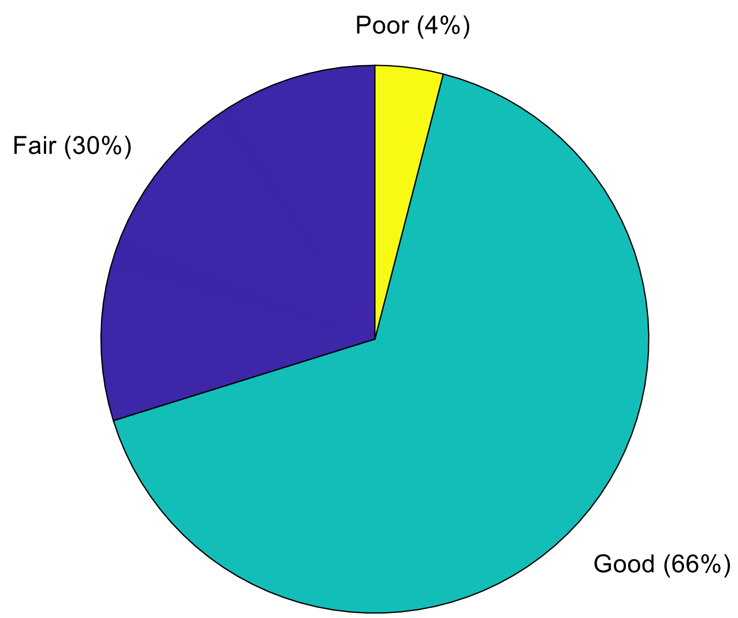

Figure 36. Window general condition identified in the most recent inspection reports (N = 473).

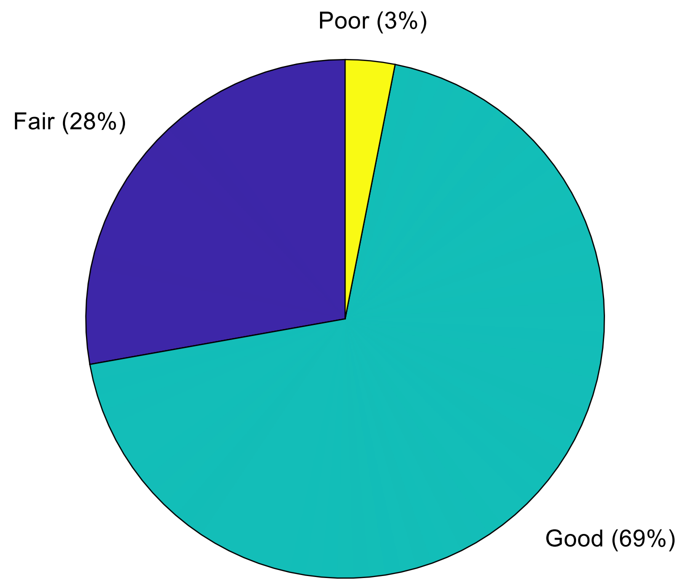

Figure 37. Window anchorage condition reported in the most recent inspection reports (N = 356).

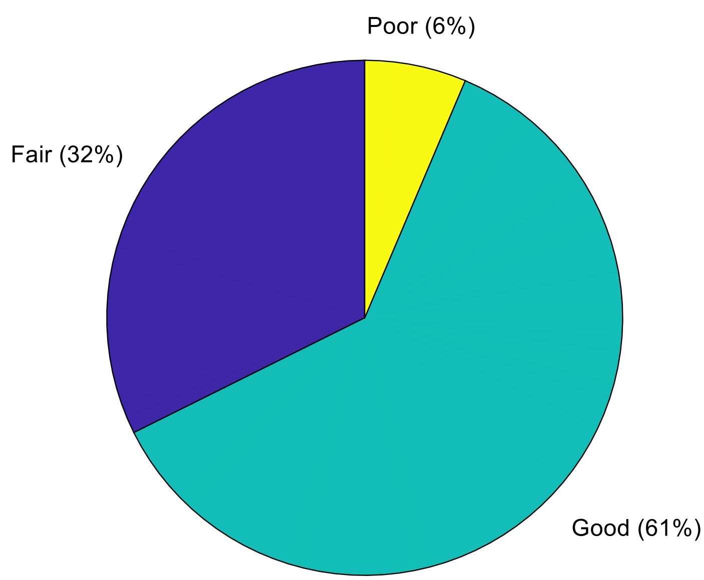

Figure 38. Window sealant condition reported in the most recent inspection reports (N = 408).

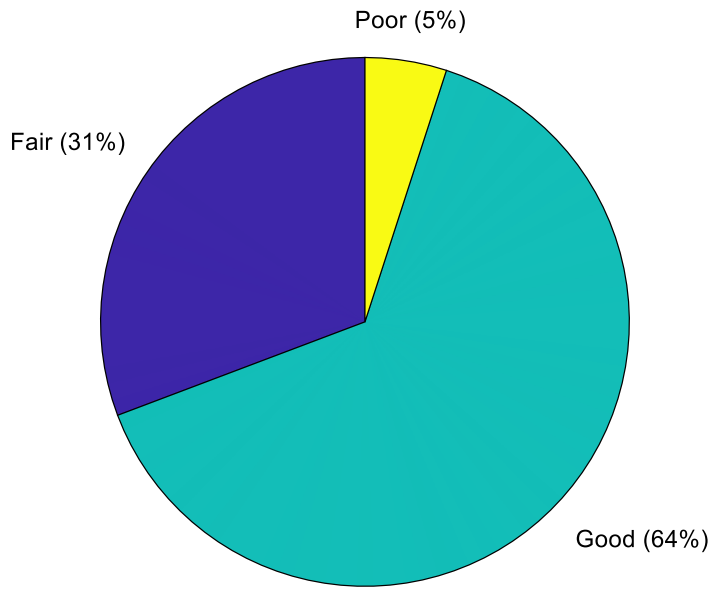

Figure 39. Window interior seal condition reported in the most recent inspection reports (N = 361).

Appendix D. Inspection Report Results - 40-year Inspection Reports Only

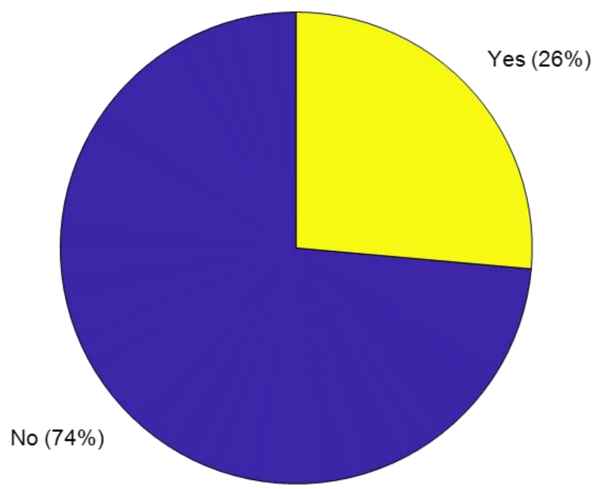

Figure 40. Percentage of 40-year building inspections requiring some type of repair (N = 318).

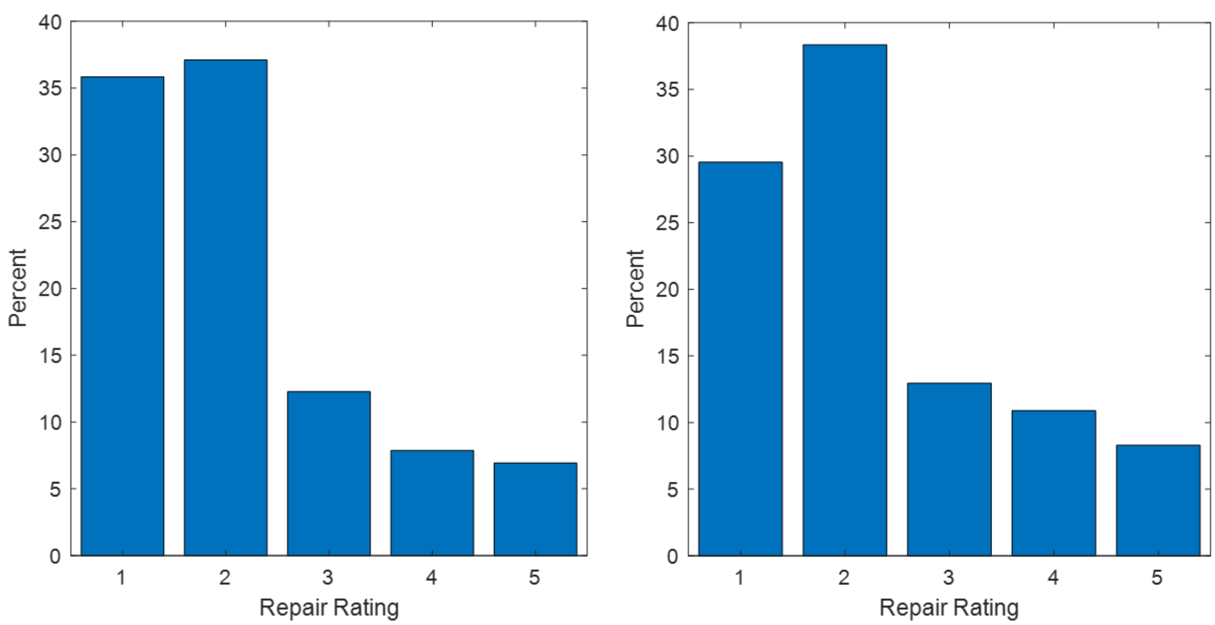

Figure 41. Distribution of repair ratings assigned to 40-year inspection reports for all buildings (left, N = 318) and residential condominiums with three or more stories (right, N = 193).

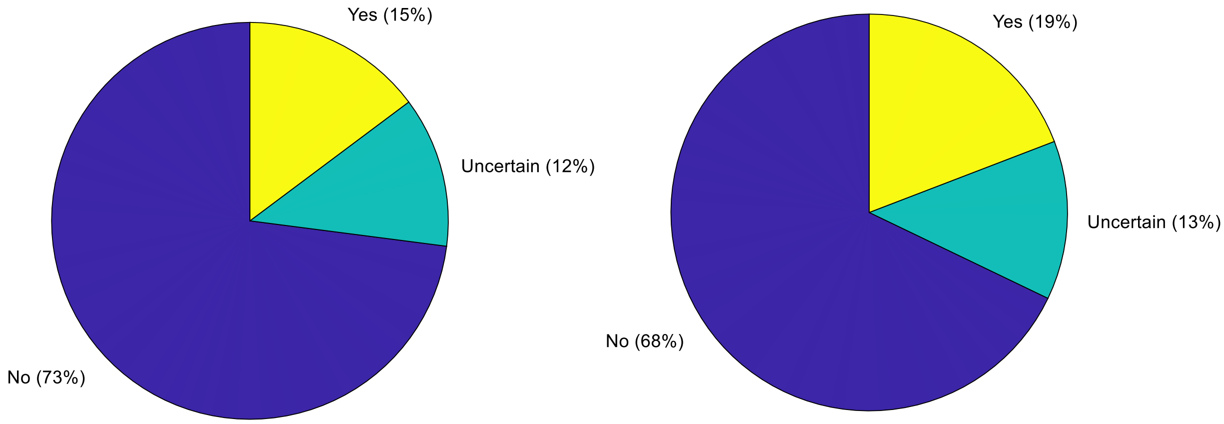

Figure 42. Percentage of 40-year inspection reports indicating that a Phase 2 inspection would likely be required under SB 4-D for all buildings (left, N = 318) and for residential condominiums with three or more stories (right, N = 193).

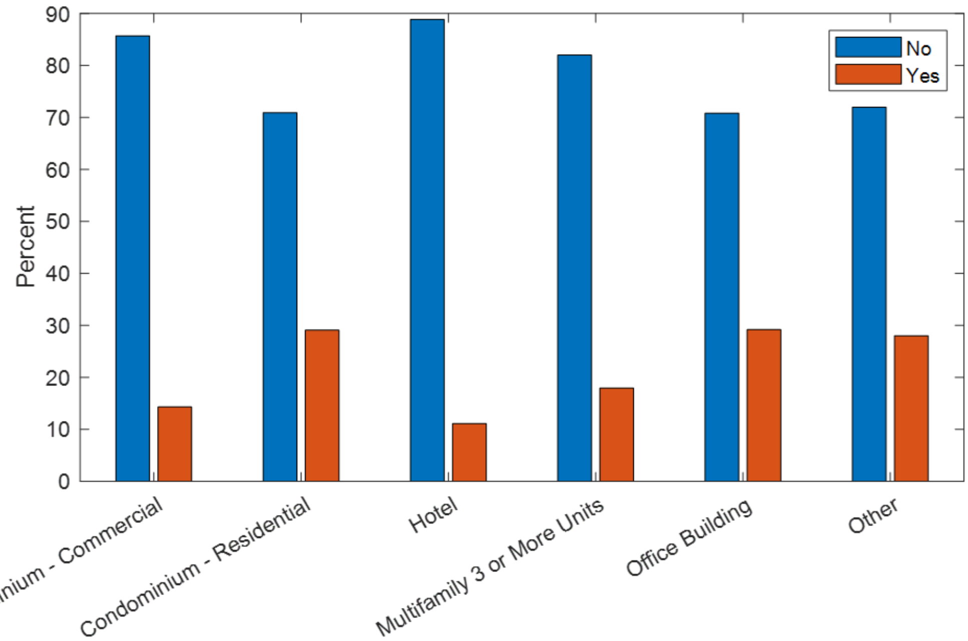

Figure 43. Required repairs by building use reported in 40-year inspection reports (N = 318).

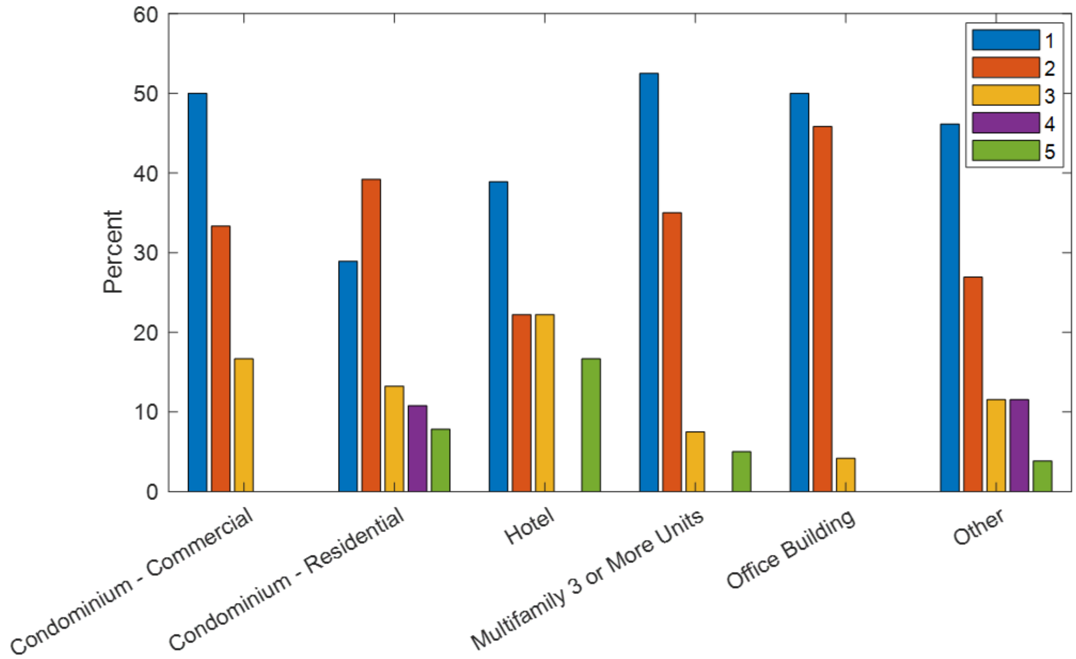

Figure 44. Repair rating by building use reported in 40-year inspection reports (N = 318).

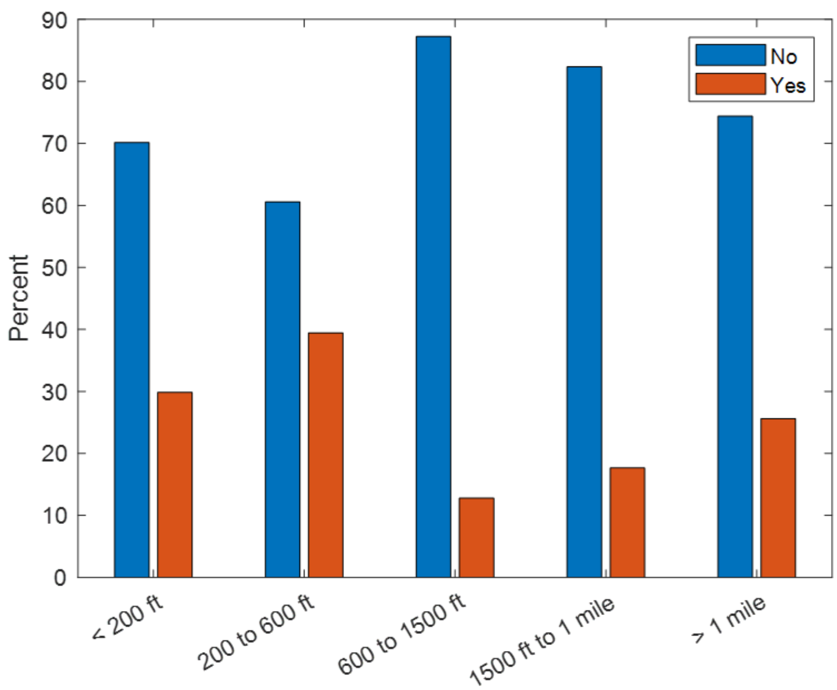

Figure 45. 40-year inspection report requirement for repairs vs. distance to the NOAA CUSP coastline definition (N = 318).

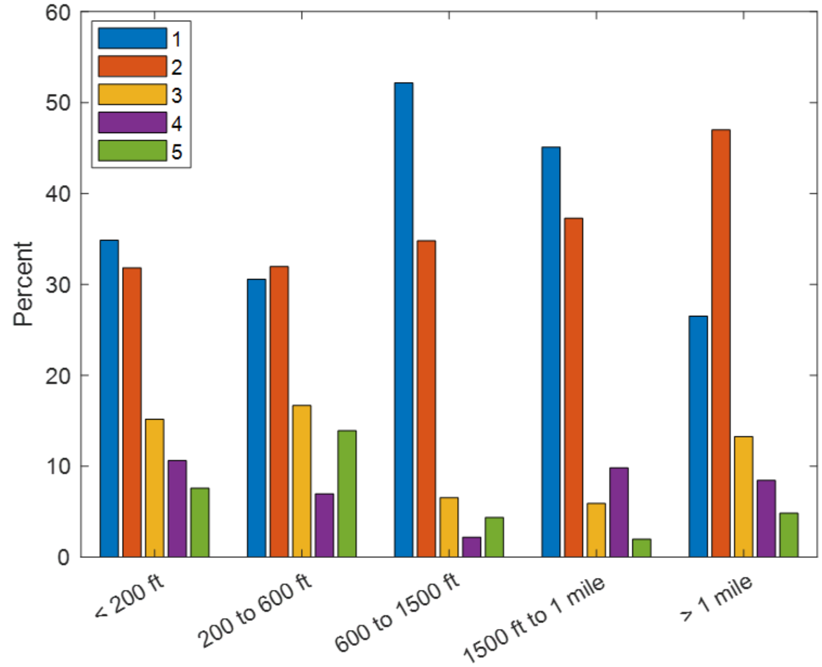

Figure 46. 40-year inspection report repair rating vs. distance to the NOAA CUSP coastline definition (N = 318).

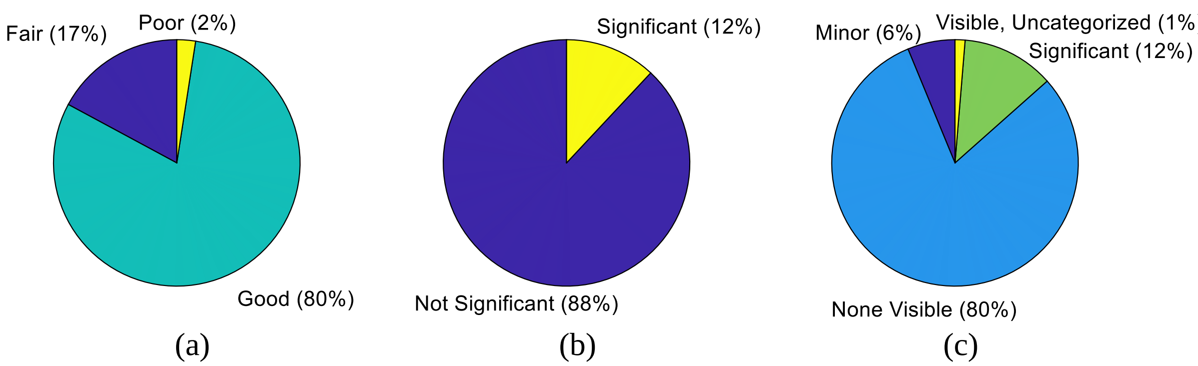

Figure 47. Concrete conditions reported in the 40-year inspection reports: a) general condition (N = 286), b) concrete cracking significance (N = 301), and c) concrete rebar corrosion significance (N = 305).

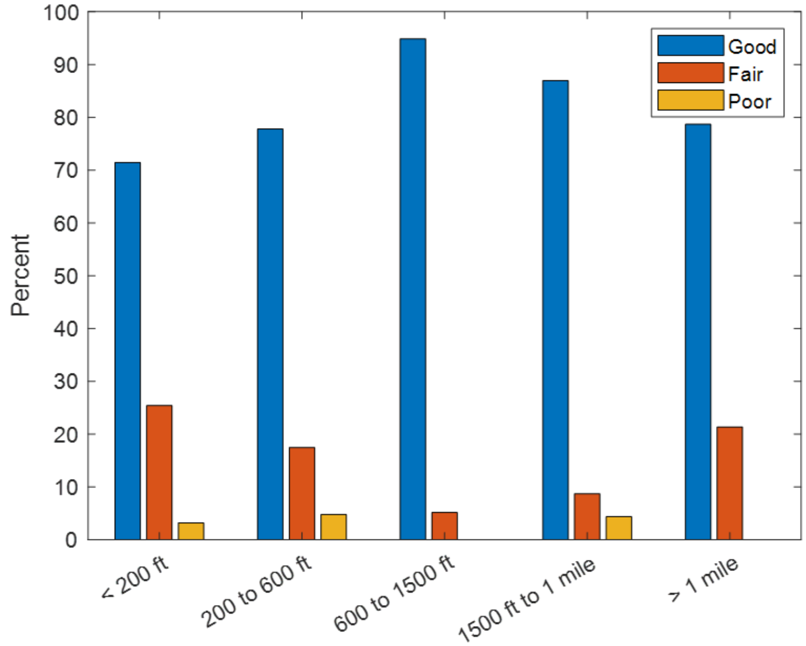

Figure 48. Concrete general condition reported in 40-year inspection reports by distance to the coast (N = 286).

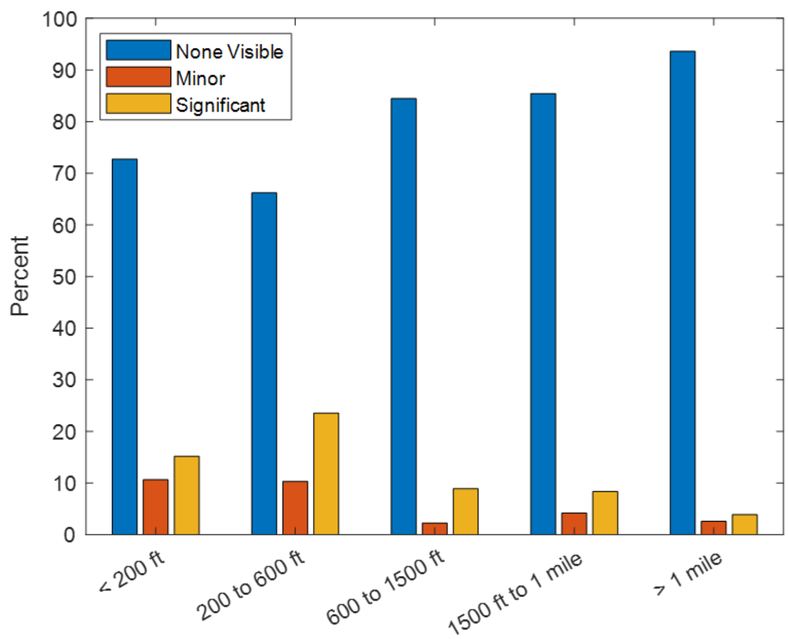

Figure 49. Concrete rebar corrosion reported in 40-year inspection reports by distance to the coast (N = 305).

Roof Systems

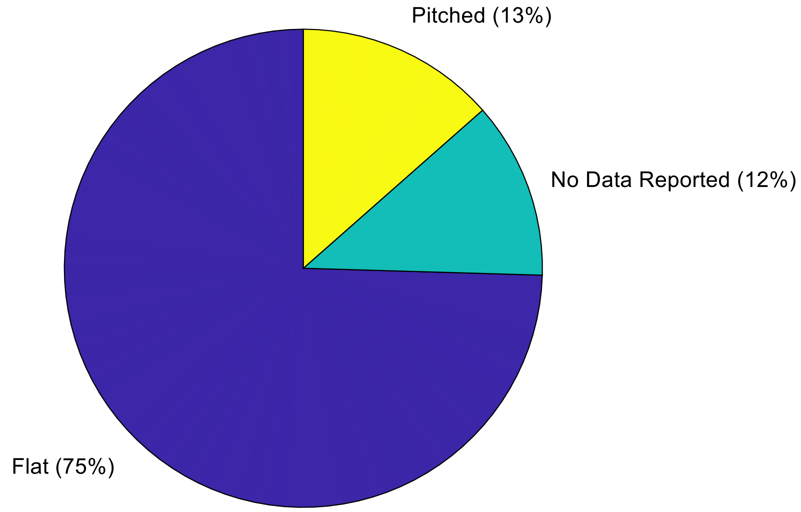

Figure 50. Roof categories identified in the 40-year inspection reports (N = 326)

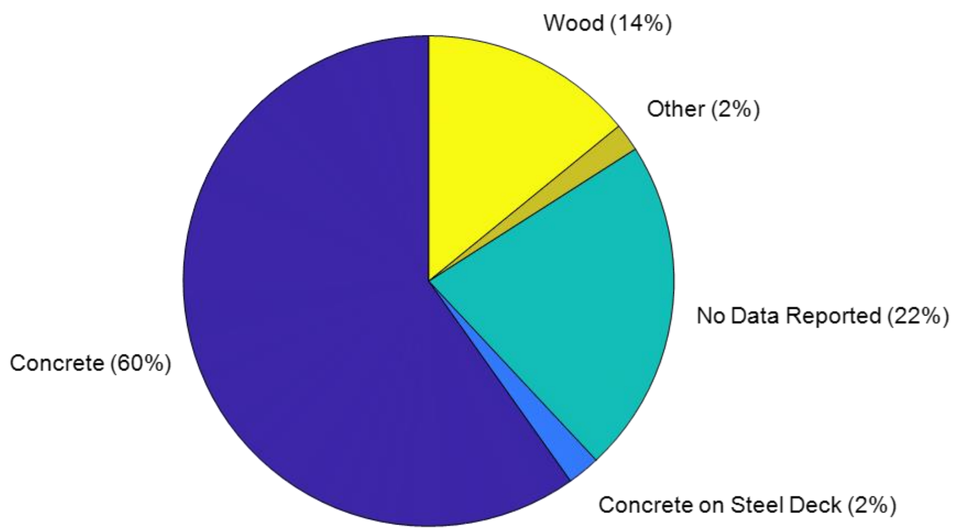

Figure 51. Roof structural systems identified in the 40-year inspection reports (N = 326)

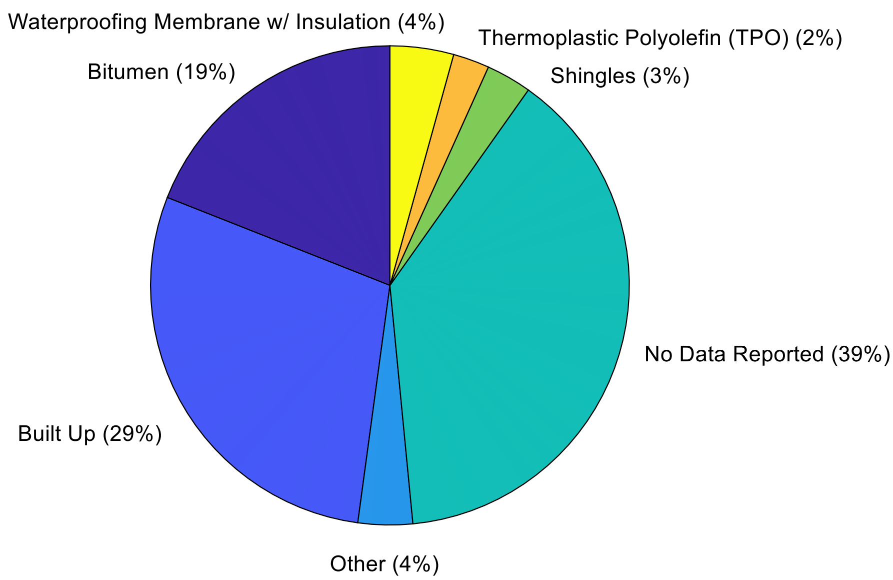

Figure 52. Roof cladding systems identified in the 40-year inspection reports (N = 326)

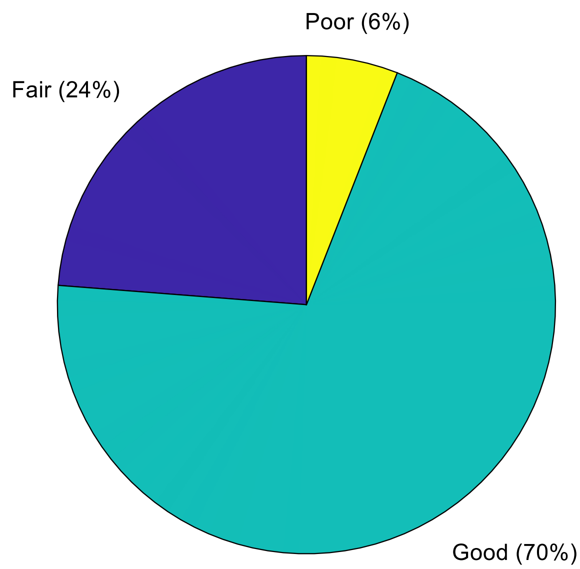

Figure 53. Roof structural system condition reported in the 40-year inspection reports (N = 202).

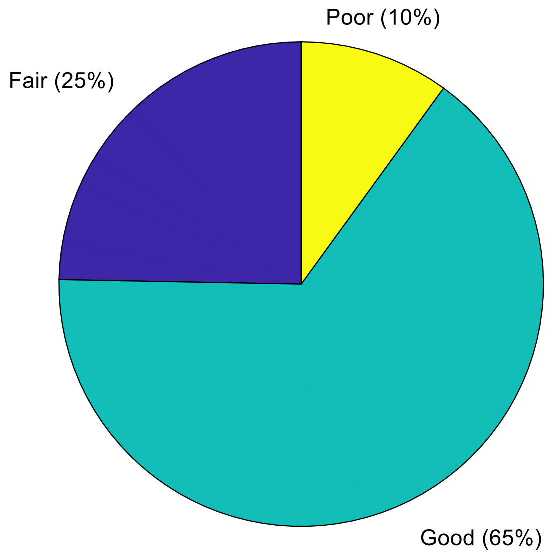

Figure 54. Roof cladding condition reported in the 40-year inspection reports (N = 170).

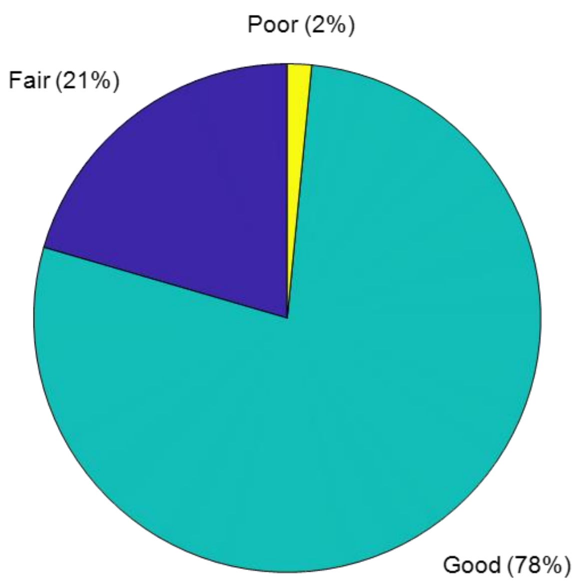

Figure 55. Roof drainage condition reported in the 40-year inspection reports (N = 195).

Floor Systems

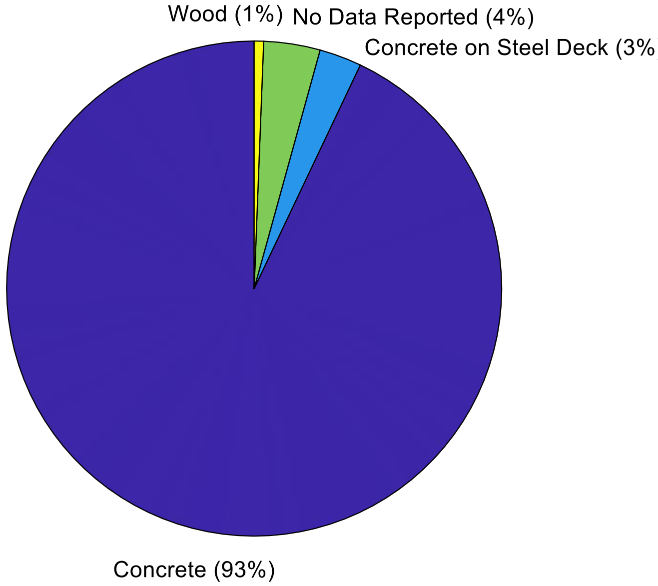

Figure 56. Floor system identified in the 40-year inspection reports (N = 326).

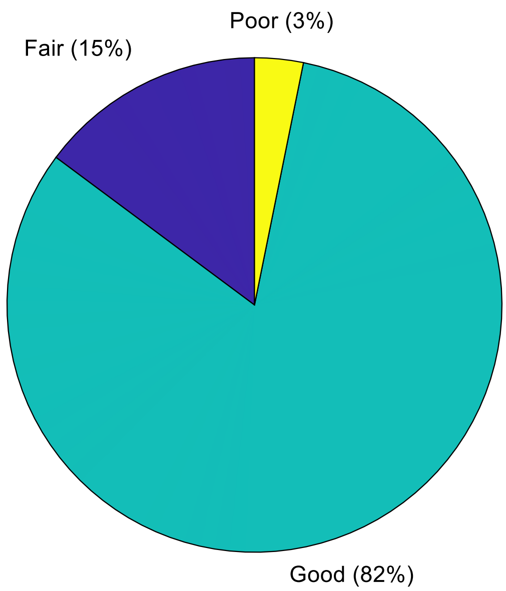

Figure 57. Floor system condition reported in the 40-year inspection reports (N = 189).

Windows

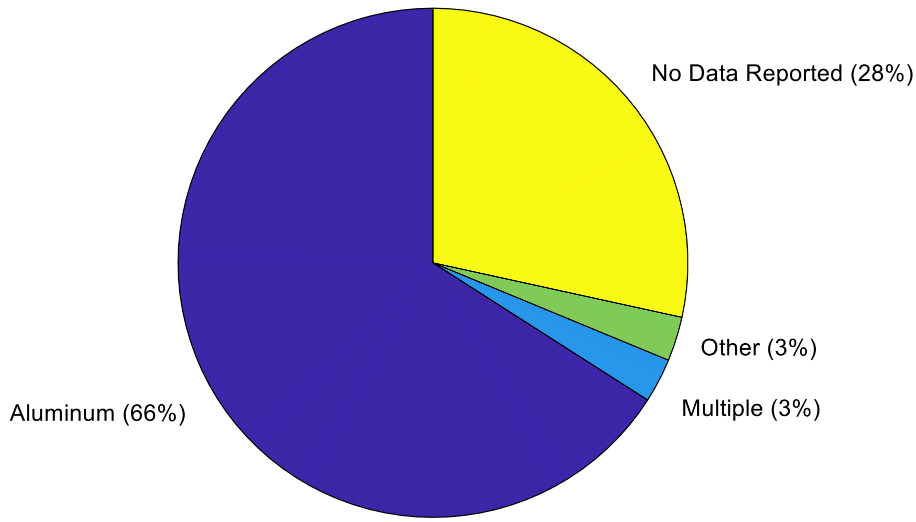

Figure 58. Window category reported in the 40-year inspection reports (N = 320).

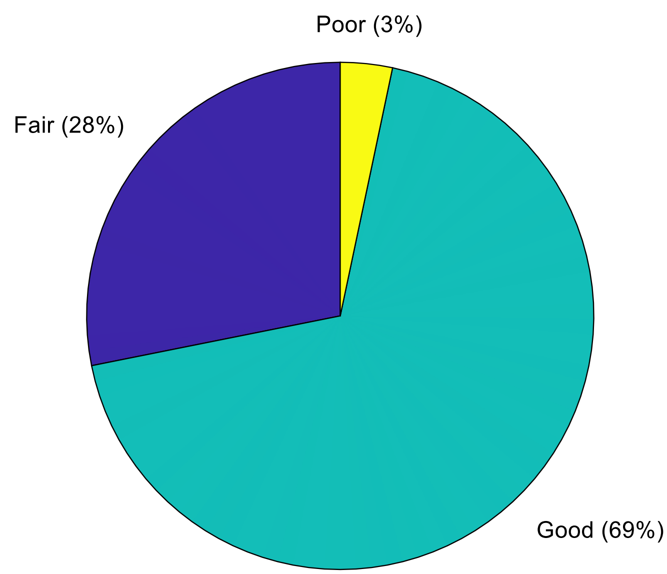

Figure 59. Window general condition identified in the 40-year inspection reports (N = 302).

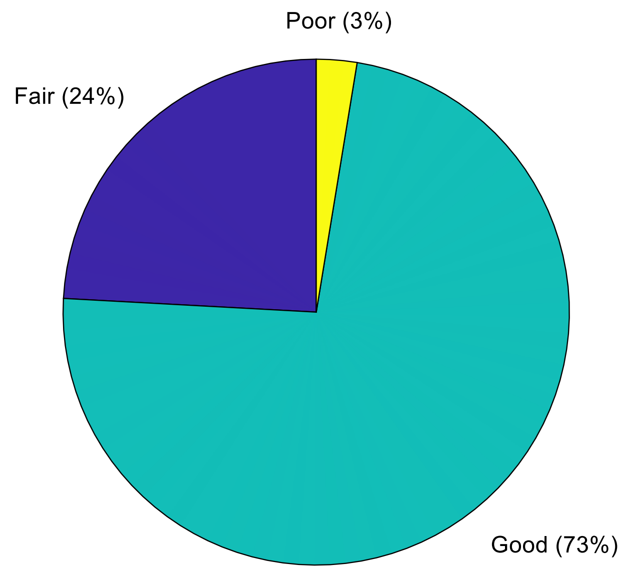

Figure 60. Window anchorage condition reported in the 40-year inspection reports (N = 232).

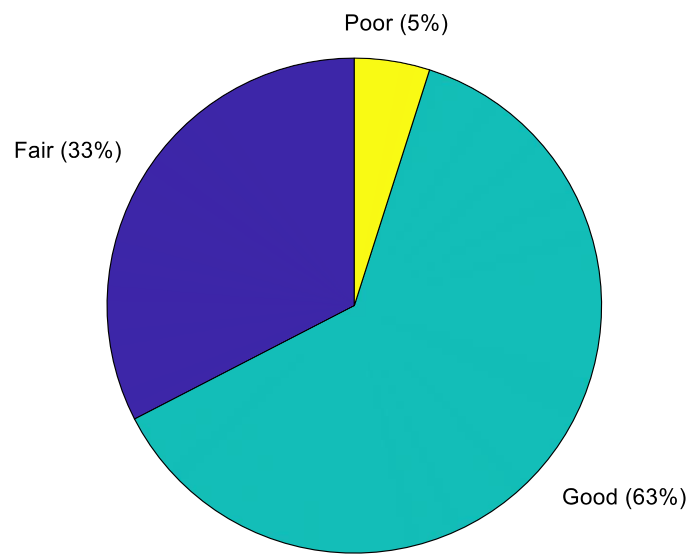

Figure 61. Window sealant condition reported in the 40-year inspection reports (N = 264).

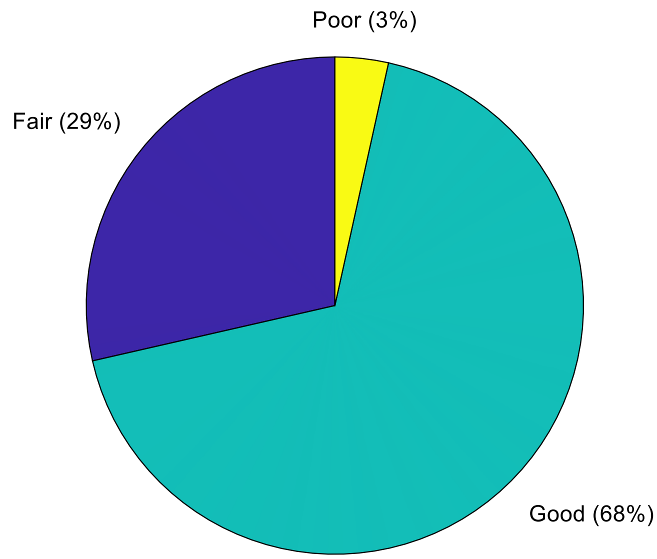

Figure 62. Window interior seal condition reported in the 40-year inspection reports (N = 231).

Appendix E. Building Inspection Technology – Landscape Assessment

E.1 Acoustic Emission

E.1.1 Description

Acoustic emission (AE) is a nondestructive monitoring method which is used to obtain noise or energy produced by material deformation, fracture, or cracking. It can be used to determine the integrity of infrastructure materials. The AE monitoring process typically involves the installation of a network of sensors, such as piezoelectric transducers or accelerometers, on the surface of the concrete structure. These sensors detect the acoustic emissions generated by the structure and transmit the signals to data acquisition systems for analysis. When used for structural assessments in building, AE, is employed as a monitoring technique, and can be used to assess beams, girders, columns and can also be used on lab/floor systems. AE operates passively, emitting acoustic signals exclusively when permanent, nonreversible deformations take place within a material (Ferraro, 2003). Long term monitoring of structures with acoustic emission are performed on structures or their elements under normal service conditions while short term testing typically takes place during controlled load testing of structures or structural elements (ASTM E3100, 2022).

E.1.2 Damage Type/Target Material

In building assessment AE is used on reinforced concrete to detect and locate cracking (also referred to as events) within structural elements. The American Society of Testing and Materials (ASTM) has developed the Standard Guide for the Acoustic Emission Examination for Concrete Structures which provides the basis for application of AE methods for concrete structures and structural elements. (ASTM E3100, 2022).

The evaluation of steel structures and structural elements using AE is typically limited to structures that can be stressed by mechanical or thermal means. In this case, a controlled stimulation, that is, the application of mechanical or thermal load, can generate AE signals from flawed areas of the structure, such as cracks, inclusions, or other defects (ASTM E569).

E.1.3 Contact/Noncontact

AE sensors must be in contact with the material being monitored.

E.1.4 New Construction/Existing Structure

AE is used on existing structures.

E.1.5 Automated/Manual

When configured with the appropriate software, AE systems can operate automatically. When used for controlled stimulation, that is, the application of mechanical or thermal load, AE systems are usually configured to operate with qualified personnel for testing.

E.1.6 Localized/Global Damage Assessment

AE primarily measures local damage through the measurement of signals (events) created by defects. Signal processing and interpretation of measurements must be performed by qualified personnel to infer location, type, and extent of possible damage.

E.1.7 Technology Maturity/Years in Use

AE systems have been in use for structural monitoring since the 1980s. However, the first Standardized test methods were developed in the late 1990's with many successful structural monitoring applications for structural components.

E.1.8 Assessment Reliability

The accuracy and reliability can be limited where significant background noise and structural elements with complex geometries. As a result, location artifacts including location and signal scattering may be observed. Thus, personnel performing examinations should be qualified in accordance with a nationally and internationally recognized NDT personnel qualification practice or standard to ensure reliability.

E.1.9 Assessment Frequency

AE systems are suited to continuous monitoring of structural response. When used for controlled stimulation, that is, the application of mechanical or thermal load, AE systems are usually configured to operate with qualified personnel for onsite / short term testing.

E.1.10 Cost

The cost for AE systems can range from $10k to $50k, depending on the number of channels they support. Typical systems support 8 to 48 sensors. Sensor costs range $150-$1000 per sensor, depending on type. Additional costs will be associated with system installation, commissioning, and monitoring service.

E.1.11 Standardization

The American Society of Testing and Materials (ASTM) has developed the Standard Guide for the Acoustic Emission Examination for Concrete Structures which provides the basis for application of AE methods for concrete structures and structural elements ASTM E3100, 2022. The evaluation of steel structures and structural elements using AE is typically limited to structures that can be stressed by mechanical or thermal means and is specified in ASTM E569, 20).

E.1.12 Guidance Provided by Industry Consensus

Same as standardization requirements.

E.1.13 Certification/Operator Training/Experience Requirements

Personnel performing examinations using AE should be qualified in accordance with a nationally and internationally recognized NDT personnel qualification practice or standard such as ANSI/ASNT CP-189, SNT-TC-1A, NAS-410, ISO 9712.

E.1.14 Interpretation Training/Experience Requirements

Same as operation requirements.

E.2 Sounding Techniques

E.2.1 Description

Acoustic sounding is used for surveying concrete structures to ascertain the presence of delaminations. Delaminations can be a result of poor concrete quality, debonding of overlays or applied composites, corrosion of internal reinforcement, or global softening. The most commonly used test procedures used for delineating performing acoustic sounding inspections of building structures, include tapping and hammer sounding. The purpose of each test is to sonically detect deficiencies in the concrete.

E.2.2 Damage Type/Target Material

See Description.

E.2.3 Contact/Noncontact

Sounding is performed by inspectors and must be in contact with the material being tested. The major drawback of this testing technique is that if the structural element is covered by other materials (drywall etc.) the sounding cannot be performed.

E.2.4 New Construction/Existing Structure

Sonic testing is used on both new and existing structures.

E.2.5 Automated/Manual

Sonic Testing is a manual technique

E.2.6 Localized/Global Damage Assessment

Sounding primarily measures local damage.

E.2.7 Technology Maturity/Years in Use

Sounding of concrete dates to the early 1900s and is well documented for its use in inspection since the 1930s.

E.2.8 Assessment Reliability

The accuracy and reliability can be limited where concrete defects and deterioration are subsurface and in elements with complex geometries. As a result, signals (sounds) obtained do not facilitate location and false positives may be observed. Thus, personnel performing examinations should have extensive field experience to ensure reliability.

E.2.9 Assessment Frequency

As needed. Inspections of small portions of a structure can take less than an hour while full building scans may take more than a day.

E.2.10 Cost

Equipment costs are very cheap. Hammers and other physical impactors are all less than $100.

E.2.11 Standardization

No standardization for building applications.

E.2.12 Guidance Provided by Industry Consensus

The American Concrete Institute (ACI) 228.2 provides guidance on sounding as it pertains to delaminations in concrete.

E.2.13 Certification/Operator Training/Experience Requirements

There are no certifications available for the sounding of concrete structures. On the job training and experience is needed to adequately perform inspections.

E.2.14 Interpretation Training/Experience Requirements

Same as operation requirements.

E.3 Stress Wave Methods - Ultrasonics

E.3.1 Description

The term ultrasonic refers to stress waves above 20,000 Hz, which is considered to be above the audible range (ACI 228.2, 2013). Ultrasonic testing of infrastructural materials relies on the principle where stress waves (or vibrations) are introduced and transmitted through a solid medium and measurement of the velocity and reflections from the stress wave provide information regarding the material itself. The two primary ultrasonic methods used are through-transmission (pulse velocity) and ultrasonic echo methods. Traditionally, the pulse velocity methods have been applied to the NDT of infrastructural materials. However, based on the recent advances in sensor technology, the industry has been widely adopting the use of pulse-echo technology.

E.3.2 Damage Type/Target Material

The use of ultrasonic methods for the NDT of the built infrastructure has distinct requirements depending on the material composition of the target structure. The ultrasonic testing of metallic structures and components utilizes different equipment, sensors, and standards than those used for concrete infrastructure.

Concrete and steel are the two most commonly used building materials for construction that have inherently different behaviors. The two materials are vastly different based composition at the elemental, micro and macro levels. Concrete is a heterogenous material composed of cement, water, aggregates and admixtures. "Thus, concrete can be aptly considered a composite of composites, heterogeneous at both microscopic and macroscopic levels" (Popovics, 2001). Steel on the other hand, is primarily composed of iron and carbon, along with small amounts of other alloying elements which are uniformly distributed throughout the material, resulting in a homogeneous composition. Due to the differences in the materials themselves, the methods in which nondestructive testing can be performed on each, are also different. With respect to

<u>Steel</u>

The nondestructive testing of steel is different than concrete. ASNT has created a certification and testing program dedicated to the NDT inspection of metal components for defect detection and deterioration. The program is mostly geared towards the Oil & Gas industry; however, certificate holders have the qualifications for use inspections of buildings and bridge components. Ultrasonic testing of steel involves sending high-frequency sound waves into the steel material and analyzing the reflected signals to detect defects, measure thickness, and assess the material's integrity.

<u>*Concrete*</u>
The nondestructive testing of concrete involves sending ultrasonic waves into the concrete to evaluate its internal structure, detect flaws, and determine properties like compressive strength and elastic modulus. There is no current program used to certify those who perform inspections of concrete buildings or structural components.

E.3.3 Contact/Noncontact
AE sensors must be in contact with the material being monitored.

E.3.4 New Construction/Existing Structure
Ultrasonic testing can be used on new or used on existing structures, the test is primarily used on existing structures.

E.3.5 Automated/Manual
Ultrasonic testing is a manual assessment method.

E.3.6 Localized/Global Damage Assessment
Ultrasonic testing is a localized assessment technique.

E.3.7 Technology Maturity/Years in Use
Ultrasonic testing is a mature technology that has been well established and in commercial used for the past 70+ years.

E.3.8 Assessment Reliability

Ultrasonic testing is very reliable if used correctly. The selection of the correct radar pulse frequency is critical for accurate results.

E.3.9 Assessment Frequency
As needed. Inspections of small portions of a structure can take less than an hour while full building scans may take more than a day.

E.3.10 Cost
The cost of ultrasonic inspection is driven by labor costs and is approximately $2k per day for one technician.

<u>*Steel*</u>
Ultrasonic systems for steel range from $5,000 to $50,000 depending on type and complexity. Equipment that is suitable for thickness testing of steel is at the lower end of the cost spectrum. Phased array systems that offer more comprehensive testing of steel are at the upper range of the spectrum.

<u>Concrete</u>

Ultrasonic systems for concrete range from $1,000 to $45,000 depending on type and complexity. Basic equipment that can measure travel time through concrete (pundit systems) are at the lower range of the spectrum costing from approximately $1,000 to $10,000. More advanced systems such as dry-coupled shear wave systems which perform phased array testing cost are at the upper end of the spectrum costing between $30,000 - $45,000.

E.3.11 Standardization

<u>Steel</u>

Standardization of Ultrasonic pulse velocity testing for metals are specified in the ASNT Recommended Practice SNT-TC-1A, ANSI/ASNT CP-189, NAS410 and ASNT Standard Topical Outlines for Qualification of Nondestructive Testing Personnel (ANSI/ASNT CP-105). List of ASTMs

- ASTM A 388, Standard Practice for Ultrasonic Examination of Steel Forgings
- ASTM E 114, Standard Practice for Ultrasonic Pulse-echo Straight-beam Contact Testing
- ASTM E 213 Standard Practice for Ultrasonic Testing of Metal Pipe and Tubing

<u>Concrete</u>

The standard method of test for measuring the pulse velocity through concrete is ASTM C597. The test method covers the determination of the propagation velocity of longitudinal stress wave pulses through concrete (Pundit Method). This test method does not apply to the propagation of other types of stress waves through concrete such as shear wave sensors or sensor arrays.

E.3.12 Guidance Provided by Industry Consensus

<u>Steel</u>

Protocols for ultrasonic examination of steel structures are provided by the American Society of Non-Destructive Testing (ASNT). Three levels of certification are provided for the inspection and qualification of testing techniques as follows:

- NDT Level 1 certification teaches an inspector to perform NDT calibrations and evaluations according to written instructions.
- NDT Level 2 certification teaches an inspector to set up, calibrate and use equipment in the field. Level 2 inspectors learn how to organize and report the results of these tests. Qualified to supervise NDT Level 1 personnel.
- NDT Level 3 teaches an inspector to develop, qualify, and approve NDT procedures and techniques; learn how to interpret and report results; train NDT Level 1 and 2 personnel.

<u>Concrete</u>

No guidance is provided.

E.3.13 Certification/Operator Training/Experience Requirements

Same as Guidance provided by Industry Consensus

E.3.14 Interpretation Training/Experience Requirements

Same as Guidance provided by Industry Consensus

E.4 Ground Penetrating Radar (GPR)

E.4.1 Description

Ground penetrating radar (GPR) is a nondestructive technology that uses microwave radar pulses to provide an image below the surface it is assessing. The frequency of the radar pulses used by GPR typically range from 10 MHz to 2 GHz, depending on the application, material, and desired depth of penetration. GPR is moved over the surface of the material, usually with an airgap of ~5 inches and can cover large areas quickly. In building assessments, GPR is most often used to assess slab/floor systems, and can also be used on beams, girders, and columns.

E.4.2 Damage Type/Target Material

In building assessment GPR is used on reinforced concrete to identify the location of reinforcing steel bars (rebar). Rebar mapping can be useful when planning locations to take core samples for material analysis. If the rebar is heavily corroded, GPR may be able to identify this condition through detection of debonding between the concrete and the rebar (which shows up as a void between the steel and concrete). GPR may also be able to detect large cracks (more than 2mm).

GPR is not able to detect minor to moderate corrosion. It cannot detect cracks less than 2mm and it cannot be used to detect “honeycomb” in concrete (hollow spaces and cavities in mass concrete). It cannot detect the size of the rebar and it cannot detect or assess prestressing tendons. There is a limit to the depth of penetration that can be achieved, usually less than 1 meter in structural applications.

GPR is often used for geotechnical applications to detect utility lines or shallow voids in the soil. However, GPR for foundation stability assessment applications is limited due to the penetration depth limit of 3 m. It also cannot be used in locations of clay soil or saturated soil.

E.4.3 Contact/Noncontact

GPR is an air-coupled sensing technique, so it does not require direct contact with the surface of the material. For slap applications, GPR is wheeled over surface with an approximate airgap of 5 inches. Although it does not need to be directly on the surface of the material, removal of finishes for access to structural elements is recommended for more accurate detection.

E.4.4 New Construction/Existing Structure

GPR is used on existing structures.

E.4.5 Automated/Manual

GPR is a manual assessment method, though robotic GPR is in research and development.

E.4.6 Localized/Global Damage Assessment

GPR is a localized assessment technique.

E.4.7 Technology Maturity/Years in Use

GPR is a mature technology that has been well established and in commercial used for the past 10-15 years.

E.4.8 Assessment Reliability

GPR is very reliable if used correctly. The selection of the correct radar pulse frequency is critical for accurate results.

E.4.9 Assessment Frequency

As needed to detect rebar.

E.4.10 Cost

GPR is considered a low-cost NDT method. New equipment is approximately $35k. The cost of GPR inspection is driven by labor costs and is approximately $2k per day for one technician.

E.4.11 Standardization

No standardization for building applications.

E.4.12 Guidance Provided by Industry Consensus

The only guidance for GPR operation is the appropriate frequency to be used for specific applications and penetration depths.

E.4.13 Certification/Operator Training/Experience Requirements

GPR technicians receive on-the-job training. Training for operation and interpretation of results is often provided by equipment manufacturers over a two-day period.

E.4.14 Interpretation Training/Experience Requirements

Same as operation requirements.

E.5 Thermography

E.5.1 Description

Infrared thermography (IR), also known as thermal imaging, is a non-destructive testing technique that uses infrared cameras to capture the thermal radiation emitted by objects. It has numerous applications in various fields, including building structures. The fundamental concept behind using IR thermography (IRT) as a non-destructive evaluation technique is that materials have different thermal conductivity properties. In a uniform homogeneous material, the application of a constant heat flux to its surface results in a uniform temperature increase across the surface. However, if the material is non-homogeneous, the surface temperature will vary. Therefore, IR will detect material defects including air gaps or moisture content material defects including moist areas or areas of low density will provide differences in temperature.

E.5.2 Damage Type/Target Material

Thermography can be used to inspect various materials, but some materials and building components are particularly well-suited for this technique due to their thermal properties and the potential for thermal changes within. Candidate components withing building systems include:

- Building envelopes
- Structural concrete

- Fenestration
- Roofing systems
- Insulation systems
- Electrical systems
- HVAC & Plumbing systems
- Fenestration

E.5.3 Contact/Noncontact

IRT is a noncontact NDT method.

E.5.4 New Construction/Existing Structure

Thermography systems are suitable for new and existing construction. Most new construction involves the detection of defects in building components at the time of installation. IRT is mostly used on existing construction.

E.5.5 Automated/Manual

IRT is a manual assessment method.

E.5.6 Localized/Global Damage Assessment

IRT with appropriate image processing can detect and quantify localized, near-surface damage such as honeycombing, delamination, voids and moisture intrusion. Global assessment of physical deficiencies which includes the presence of conspicuous defects and material deferred maintenance of a subject property's material systems, components, or equipment as observed during a walk-through inspection.

E.5.7 Technology Maturity/Years in Use

IRT is mature technology that has been established for the use in building inspection industry since the 1980s. Initially, the use of infrared cameras was mostly cost prohibitive which was a barrier towards widespread use throughout the industry. However, advancements in technology (especially in the last decade) have led to the development of more affordable and portable infrared cameras, making them more accessible to professionals in the building industry. Today, infrared thermography has become a standard practice for use in building inspections and is used by various professionals, including building inspectors, energy auditors, engineers, and building maintenance managers.

E.5.8 Assessment Reliability

IRT is very reliable if used correctly.

E.5.9 Assessment Frequency

As needed. Inspections of small portions of a structure can take less than an hour while full building scans may take more than a day.

E.5.10 Cost
IRT is considered a low-cost NDT method. The costs of new “spot cameras” are as low as $100 and range from $100 - $2,000. Systems that offer larger operating temperature ranges, more resolution and higher functionality, cost substantially more ranging from $5,000 to $60,000.

E.5.11 Standardization
There are a number of standardized test methods relevant to IRT testing. The ASTM methods relevant to the condition assessment of building components and structural components include:

- ASTM E2018 Standard Guide for Property Condition Assessments: Baseline Property Condition Assessment Process The purpose of this guide is to define good commercial and customary practice in the United States of America for conducting a baseline property condition assessment (PCA) of the improvements located on a parcel of commercial real estate by performing a walk-through survey and conducting research as outlined within this guide
- ASTM C 1153 Standard Practice for Location of Wet Insulation in Roofing Systems Using Infrared Imaging This describes the techniques used to determine the location of wet insulation in roofing systems
- ASTM C1060 Standard Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Frame Buildings This describes the techniques to conduct qualitative thermal inspections of building walls, ceilings, roofs and floors that may contain insulation in the stud bays.
- ASTM D4788 Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography This test method describes how infrared thermography is used for delamination determinations of portland cement concrete bridge decks.

E.5.12 Guidance Provided by Industry Consensus
Same as Certification/Operator Training/Experience Requirements.

E.5.13 Certification/Operator Training/Experience Requirements
Current certification requirements for IRT include the ASNT-SNT-TC-1A recommendations for thermal/infrared testing. The is established by ASNT which stipulates personnel qualification and certification in nondestructive testing. Additionally, the requirements provide guidelines for employers wishing to establish in-house certification programs. SNT-TC-1A establishes the general framework for a qualification and certification program.

E.5.14 Interpretation Training/Experience Requirements
Same as Certification/Operator Training/Experience Requirements.

E.6 Fiber Optic Sensors

E.6.1 Description
Fiber optic sensors (FOS) use optical fibers used to detect environmental changes. Clear glass fibers transmit light waves along their length and can act as both information carriers and sensors. Information is transmitted along the fiber length to a detector in the form of a light beam. The fiber acts as a sensor when the light beam is modulated by property changes in the fiber because of an environmental action. FOS systems require a light source and a detector,

often combined in a single unit called an interrogator. The light source is transmitted with a particular wavelength range, with each sensor along the length of the fiber operating in a predetermined portion of the wavelength range. As each sensor experiences a change due to a physical change, the properties of the wavelength shift within its portion of the total range. Advantages that FOS systems have include multiplexing capabilities (multiple sensors on a single cable), durability, immunity to electromagnetic interference (e.g., lightning strike), and long-range signal transmission.

FOS can be divided into two categories: discrete and continuous. Discrete systems emply sensors at specific and separated points along a single fiber. Continuous systems have very closely spaced sensors (e.g., every 2-3 mm) along a single fiber. Continuous systems can be useful for detecting the onset and propagation of cracking along a region of the structure. Fiber optic measurement systems can support a number of sensor types, including:

- Surface and embedded (e.g., concrete reinforcing steel) strain
- Surface and embedded temperature
- Displacement/crack width
- Vibration
- Tilt
- Acoustic emission

E.6.2 Damage Type/Target Material

Fiber optic strain sensors can provide indirect damage assessment through the measurement of strains on the surface of most materials and internal strains in concrete. Crack sensors can track crack widths in any material subject to cracking. Vibration and tilt sensors can measure global structural responses, while acoustic emission sensors can capture wire breaks in prestressed/post-tensioned concrete construction.

E.6.3 Contact/Noncontact

FOS must be in contact with the material being monitored.

E.6.4 New Construction/Existing Structure

FOS are most suitable for new construction or installation during structural repairs. Most new construction involves the installation of fiber for communications so support for sensors may be convenient. Surface sensors may be used on existing construction, but significant cost may be associated with removal of finishes for appropriate installation. Best suited to new construction, fiber optic is being run anyway.

E.6.5 Automated/Manual

When configured with the appropriate software, FOS systems can operate automatically.

E.6.6 Localized/Global Damage Assessment

FOS primarily measure local damage through the measurement of strain and cracks propagation. Some global measurements can be achieved with tilt and vibration sensors. In either case, appropriate processing and interpretation of measurements must be performed by a qualified engineer to infer location, type, and extent of possible damage.

E.6.7 Technology Maturity/Years in Use
FOS have been in use for structural monitoring since the early 2000s, with many successful structural monitoring applications for bridges and buildings. Due to the ruggedness of the sensors, many systems installed in the last decade are still in operation.

E.6.8 Assessment Reliability
Sensor reliability is high as they are very robust, and durable. Sensors can be subject to challenging environmental conditions and continue to provide accurate measurements. Structural assessment reliability is high for specific applications, including crack detection and tracking, strain measurements.

E.6.9 Assessment Frequency
FOS systems are suited to continuous monitoring of structural response.

E.6.10 Cost
The cost for FOS interrogators can range from $30k o $50k, depending on the number of channels they support. Because of the multiplexing capabilities of FOS, each channel can support 40 sensors, with a16-channel system supporting up to 640 different sensors. Sensor costs range $150-$600 per sensor, depending on the sensory type. Additional costs will be associated with system installation, commissioning, and monitoring service. Installation costs for FOS systems can be significantly less than standard copper-based sensors due to the need to install fewer individual cables/wires. Additional cost savings are realized over the life of a FOS monitoring system due to low maintenance costs.

E.6.11 Standardization
IEEE standard for Fiber Optic Sensors – Fiber Bragg Grating Interrogator Standard – Terminology and Definitions (IEEE Std 2067-2021). This standard was adopted in 2021.

E.6.12 Guidance Provided by Industry Consensus
None.

E.6.13 Certification/Operator Training/Experience Requirements
No specific certification or training requirements for system operation and interpretation, though engineering knowledge is required to provide a structural assessment based on measurements. Vendors often provide training for system operation and interpretation.

E.6.14 Interpretation Training/Experience Requirements
See Certification/Operator Training/Experience Requirements.

E.7 Imagery

E.7.1 Description
Imagery for structural assessment includes the use of 2D images of portions of the structure or 3D images reconstructed from photographic or laser imaging. Photographic images (usually using digital SLR cameras) of a structure and components enable the detection of surface

defects, either through manual assessment of the images or through automated image processing techniques. Images acquired by digital cameras mounted on unmanned aerial vehicles (UAV or drones) or robots, can enable evaluation of portions of the structure difficult or time consuming to reach manually (e.g., exterior façade). Photogrammetry can reconstruct a 3D image of a structure from overlapping 2D images.

Laser scanning or LiDAR is a type of imaging that uses light pulses to measure the distance to points on a surface. LiDAR imaging, specifically static LiDAR, to create 3D point clouds enables reconstruction of the surfaces of the building that can be used to detect changes in alignment or surface defects as well as to create a CAD model for building information modeling (BIM). LiDAR images require specialized software to render 3D scans. Like digital photography, LiDAR scans can be taken by units mounted on the ground using more accurate static LiDAR, or on UAVs using less accurate mobile LiDAR.

E.7.2 Damage Type/Target Material

When appropriately processed and referenced against a datum, imaging can detect misalignment or deflection of elements as well as cracks, spalls, and other surface defects. Imaging is not limited to any specific material, though digital imaging will require adequate light and information on the focal distance and distance to the target surface to provide quantification of defects (e.g., crack width).

LiDAR imaging can work on any material but is limited to operate in dry conditions as water droplets reflect light and may distort the image.

E.7.3 Contact/Noncontact

Imagery (digital photography and LIDAR) is a noncontact method for assessment.

E.7.4 New Construction/Existing Structure

Imagery can be used at any time in the life cycle of a structure.

E.7.5 Automated/Manual

Image collection is mostly manual. UAV or robots may have preset paths to automate image collection, though these automated techniques are not in wide use for structural assessment. Processing of digital images may be manual but automated image processing utilizing machine learning/artificial intelligence is progressing in capability.

E.7.6 Localized/Global Damage Assessment

Imagery with appropriate image processing can detect and quantify localized damage such as cracks, spalling, and element misalignment/deflection. Global assessment of overall structural misalignment or settlement may also be achieved.

E.7.7 Technology Maturity/Years in Use

The use of photography in building inspection has been in common practice for many decades to document structural damage observed visually. Laser scanning and photogrammetry to create 3D point clouds are mature technologies. LiDAR has been in use for over 20 years. Photogrammetry has seen more use since 2010 as the necessary computational power has become available for image processing. Software for 3D image reconstruction and importing to various CAD and BIM platforms continues to advance. The use of UAV mounted image collection has increased in popularity over the past 15 years, though the use of mobile LiDAR on drones has only recently become viable as LiDAR unit costs decrease. Automatic image processing for defect detection is still in the development stage.

E.7.8 Assessment Reliability

Digital image quality may be lowered by poor lighting or limited access to structural elements. Automated image processing is still a fairly new technology and is not yet reliable for most applications. Manual assessment of images can provide results with similar accuracy to manual inspection assessments. 3D point clouds from laser scanning/ static LiDAR can provide millimeter accuracy (<4mm) with high reliability.

E.7.9 Assessment Frequency

As needed. Single room scans can take less than an hour while full building scans may take more than a day.

E.7.10 Cost

Equipment costs:

- Digital cameras: $300-$1000
- LiDAR scanners: $20k-$150k
- Static: Entry level unit costs $35k can generate much denser data than mobile units
- Mobile: Units start at $40k - $150k. Though they can operate in real time, they provide much lower resolution than static LiDAR.
- UAV with camera: $2000+
- UAV with integrated LiDAR: $40k-$150k (very low resolution)
- Additional costs associated with software and licensing

Service costs:

- Scanning: $2k-$4k/day
- Additional costs may be associated with generating CAD/BIM files

E.7.11 Standardization

ASTM standard for 3D imaging (ASTM E57).

E.7.12 Guidance Provided by Industry Consensus

None.

E.7.13 Certification/Operator Training/Experience Requirements

UAV operation for commercial use requires Remote Pilot Certificate (RPC), also known as a drone license or a Part 107 certificate. The use of laser scanners/LiDARs requires training for operation, often provided by vendors. Safety training is required for the use of laser scanners.

E.7.14 Interpretation Training/Experience Requirements

The interpretation of images or 3D scans requires training on the use of appropriate software.

E.8 AR/VR Guided Inspection

E.8.1 Description

Augmented reality (AR) allows a user to overlay computer-generated images onto what they see in a real-world environment. AR can be achieved using a screen (phone or tablet) held at certain locations and orientations within an environment or the use of a specialized headset or glasses that provide a "see-through" lens so that real components can be seen while viewing overlayed images. AR images must be anchored, or tied to, a real environment, making it computationally challenging to use in a large, whole building environment. AR is better suited to observing a small region, such as a single piece of equipment or structural component. As computing continues to improve, AR has the potential to operate in larger areas with images updating in real time. AR is in development and early adoption in the management of construction projects where design and construction teams can benefit from visualizing designs prior to construction to avoid clashes or other problems. As the technology develops, there may be opportunities to use it during building inspection where previous images and 3D scans can be overlayed on the current structure to detect changes in the structure. AR is currently used to automate accurate measurements in physical spaces.

Virtual reality (VR) provides users an immersive, 3D view of an environment using a specialized headset. In contrast to AR, VR separates the user from the environment being viewed, allowing for remote interaction. If appropriate 3D imaging, or "reality capture", is available from LiDAR or photogrammetry imagery (see Section 7), then it could be used by inspectors to "visually" evaluate a building without being physically onsite. In addition to direct use for building inspection, VR is a potentially useful tool for inspector training. VR is currently in use for construction design review by larger general contractors and is expected to see increased use for such applications in the next five to ten years.

E.8.2 Damage Type/Target Material

AR/VR can be used in place of visual damage detection and assessment so it can be used in any building environment to detect damage that can be seen by the human eye.

E.8.3 Contact/Noncontact

AR/VR are noncontact technologies.

E.8.4 New Construction/Existing Structure

AR/VR can be used during construction or for inspection of an existing structure or structural components.

E.8.5 Automated/Manual

AR/VR require manual operation by users.

E.8.6 Localized/Global Damage Assessment

It is expected that VR would be used for localized damage assessment like visual inspection. AR/VR could provide a global assessment of misalignment or settlement when comparing current conditions to previously captured images.

E.8.7 Technology Maturity/Years in Use

Both AR and VR for inspection applications are still in the proof-of-concept stage and are not yet in regular use for building assessments.

E.8.8 Assessment Reliability

Currently not a proven technology.

E.8.9 Assessment Frequency

As needed to support visual inspection.

E.8.10 Cost

VR headset costs range from $300 - $3000 depending on the features and capabilities. The primary cost associated with AR/VR operation are the labor costs associated with generating building scans, optimizing the point clouds, and interpreting the images. See section E.7 for LiDAR and 3D scanning costs.

E.8.11 Standardization

No standardization currently exists, though it is in development.

E.8.12 Guidance Provided by Industry Consensus

No guidance currently exists, though it is in development.

E.8.13 Certification/Operator Training/Experience Requirements

Operation of VR handheld devices requires little training. AR/VR headsets require more training and experience to operate, usually less than an hour. Some headset users experience cybersickness after more than one hour of headset use.

E.8.14 Interpretation Training/Experience Requirements

Training for interpretation is similar to that required by a visual inspector. A licensed engineer or registered architect with inspection experience can interpret digital images.

E.9 Vibration Sensors and Dynamic Analysis

E.9.1 Description

Vibration-based structural assessment uses accelerometers installed at several locations in a building to measure the motion (acceleration) of the building in different directions under different excitation. The structural assessment is performed by processing the vibration data to extract fundamental dynamic characteristics of the building that are expected to change when the structure experiences certain types and levels of damage or deterioration. Most often, the goal is to evaluate changes in structural stiffness that may be inferred from shifted dynamic properties. Some vibration-based methods require the building to undergo some type of excitation to induce vibration, while others rely on low amplitude motion resulting from ambient conditions. The specific approach will dictate the required sensor characteristics (e.g., sensitivity), the number, orientation, and location of the sensors, and the required monitoring duration.

E.9.2 Damage Type/Target Material

Vibration based damage detection is not limited to a specific material or structural type; however, it is considered a global assessment method and thus will not typically capture very local deterioration that has not progressed to impact structural stiffness, such as spallling or minor cracking. Damage that occurs and beam/column and floor/wall connections or geotechnical failures that have progressed to the point of reducing structural capacity may be detected by vibration assessment.

E.9.3 Contact/Noncontact

Vibration-based structural evaluation requires accelerometers to be in contact with the structure.

E.9.4 New Construction/Existing Structure

Primarily applied to existing structures; however, baseline measurements are suggested at an early stage following construction.

E.9.5 Automated/Manual

Assessments with accelerometers can be continuous (i.e., permanently installed with related equipment) allowing automated monitoring or it can be done as a manual, short term evaluation conducted within a day or two.

E.9.6 Localized/Global Damage Assessment

Vibration-based assessment captures global damage accumulation. Surface defects or damage that has not reduced structural capacity will not be detected.

E.9.7 Technology Maturity/Years in Use

Vibration-based structural assessment has been in use for several decades after its initial development for the aviation industry. It has been a topic of research for over 50 years but has been a commercially available technology over the past 15 to 20 years. The technology is not widely used as the data interpretation techniques require advanced knowledge of structural dynamics.

E.9.8 Assessment Reliability

The assessment reliability is determined by the sensitivity of the sensors, correct sensor placement, and careful interpretation of the data. Global structural degradation may be accurately identified with the appropriate measurements and analysis but only if damage is in proximity to data collection points and has progressed to a point of detection in the measurements. Reliability is further enhanced if measurements can be compared to a baseline assessment. Visual inspection can be used to determine the source of the structural degradation once its presence and general location is identified during data analysis.

E.9.9 Assessment Frequency

Dynamic measurements can be performed continuously or during short-duration tests (less than a day) to provide a snapshot of building performance. The interval between periodic measurements is dependent on the risk; every ten years may be reasonable for routine assessment, while buildings experiencing deterioration may require more frequent assessment.

E.9.10 Cost

Short term test costs depend on the size of the building and can range from $2k to 20k for measurement and interpretation.

E.9.11 Standardization

None.

E.9.12 Guidance Provided by Industry Consensus

The monitoring of building dynamic response is listed as a test method for load testing buildings in SEI/ASCE 11-99, though it states that it may not be applicable for specific deterioration identification and no details on how to perform or interpret tests is provided.

E.9.13 Certification/Operator Training/Experience Requirements

The technicians taking the acceleration measurements require a few days to a week of training and additional hands-on experience.

E.9.14 Interpretation Training/Experience Requirements

A highly qualified engineer with appropriate training and experience is required to perform data analysis (ASCE, 2000).

E.10 Integrated Sensors

E.10.1 Description

Integrated sensors describe a range of instrumentation that is integrated within the building material (e.g., concrete) or permanently installed on structural members behind any finishes or cladding to directly measure material or component behaviors. Examples of integrated sensors include:

- Fiber optic sensors – surface or embedded strain measurement (See Section 7).
- Tiltmeters – member alignment
- Strain gages – material strain (either on the surface or on rebar)
- Embedded aggregate sensors – internal concrete stress
- Vibrating wire gages – internal concrete strain
- Crack gages – crack openings/widths
- Piezoelectric sensors (patches) – surface deformation/strain
- Load cells – post-tensioning strand strain (at anchors)
- Chloride sensors – concrete chloride content (see Section E.15)

Integrated sensors are either wired into or setup in a wireless network for data transmission to a central data acquisition system where their measurements can be tracked over time, on-site or remotely.

E.10.2 Damage Type/Target Material

Integrated sensors are most often used to measure and track over time the responses of the material to which they are attached or embedded. They most often measure surface strains and can be applied to both steel and concrete, depending on the characteristics of the sensors.

E.10.3 Contact/Noncontact
Integrated sensors are in contact with the structure, specifically structural components and/or materials.

E.10.4 New Construction/Existing Structure
The primary application for integrated sensors is in new construction; however, if appropriate finishes are removed, sensors could be installed on existing structures.

E.10.5 Automated/Manual
When connected to a central data acquisition system with appropriate software, integrated sensors can operate automatically. Systems can generate regular reports or provide alerts if thresholds are exceeded.

E.10.6 Localized/Global Damage Assessment
Integrated sensors provide information on local damage indicators, such as excessive strains/stresses, deformations, misalignment, or cracking. When enough sensors are distributed in a structure at the appropriate locations, more global response information may be inferred.

E.10.7 Technology Maturity/Years in Use

- Foil strain gages (for metallic materials) – high maturity, in use for 70+ years
- Embedded aggregate sensors – low maturity, still in research and development
- Fiber optic Sensors: See Section 7.

E.10.8 Assessment Reliability
Assessment reliability varies, depending on the sensor type and interpretation techniques.

E.10.9 Assessment Frequency
Varies depending on the sensor; most integrated sensors will offer continuous monitoring.

E.10.10 Cost
There is a wide cost range for the various sensors and systems that can be installed. While some sensors are relatively inexpensive (e.g. foil strain gages) there may be more significant cost associated with data acquisition systems, data interpretation, and system maintenance.

E.10.11 Standardization
Sensor-dependent.

E.10.12 Guidance Provided by Industry Consensus
Sensor-dependent.

E.10.13 Certification/Operator Training/Experience Requirements
Sensor-dependent.

E.10.14 Interpretation Training/Experience Requirements
Sensor-dependent.

E.11 X-ray

E.11.1 Description
X-ray technology has been used for the non-destructive testing for various materials and applications. Most applications for X-ray use are in component inspection, typically component inspection and casting inspection of relatively small parts (or components) as using scanning systems in a controlled and shielded laboratory environment.

The generation of X-rays poses potential health hazards, primarily due to the nature of radiation which is known to cause tissue damage, risks of cancer and radiation sickness. Based on this, the use of X-ray technology for inspection of infrastructure has been limited to rail, pipelines and within the gas and oil industry; primarily because the structures can be cleared of occupancy with relative ease.

E.11.2 Damage Type/Target Material
X-Ray is typically limited to the evaluation of steel structures and structural elements. Applications to concrete have been limited to mostly research.

E.11.3 Contact/Noncontact
X-Ray is a non-contact method.

E.11.4 New Construction/Existing Structure
X-ray testing can be used on both new and existing structures.

E.11.5 Automated/Manual
X-ray scans in the field (welds / rail / petroleum infrastructure) are performed manually.

E.11.6 Localized/Global Damage Assessment
X-ray can be used for global or localized damage assessment, however due to the expense and

E.11.7 Technology Maturity/Years in Use
X-ray technology for small components and metallic components is a mature technology.

E.11.8 Assessment Reliability
X-ray technology is very reliable for use in the inspection of metallic components.

E.11.9 Assessment Frequency
As needed.

E.11.10 Cost
X-ray systems are costly at approximately $1M while daily rates for testing are approximately $10k.

E.11.11 Standardization

ASTM E 2736, Standard Guide for Digital Detector Array Radiology, a digital detector array is defined as: "an electronic device that converts ionizing or penetrating radiation into a discrete array of analog signals which are subsequently digitized and transferred to a computer for display as a digital image.

E.11.12 Guidance Provided by Industry Consensus

See Certification/Operator Training/Experience Requirements.

E.11.13 Certification/Operator Training/Experience Requirements

- ASNT Recommended Practice No. SNT-TC-1A: Personnel Qualification and Certification in Nondestructive Testing Although not specific to X-ray testing, this recommended practice by the American Society for Nondestructive Testing (ASNT) sets guidelines for personnel qualification and certification in various nondestructive testing methods, including radiographic testing. It outlines the training, experience, and examination requirements for individuals seeking certification in X-ray inspection.
- ASNT Certification of Industrial Radiography Radiation Safety Personnel (IRRSP) is applicable to those individuals who perform or supervise industrial radiography utilizing radiation-producing equipment. It meets the radiation safety certification requirements of both Title 10 Part 34 of the Code of Federal Regulations (10CFR34), and the Suggested State Regulations for Control of Radiation (SSRCR: Part A, General Provisions; Part E, Radiation Safety Requirements for Industrial Radiographic Operations; Part H, Radiation Safety Requirements for Non-Healing Arts Radiation Generating Devices; Part T, Transportation of Radioactive Material).
- ASME Section V: Nondestructive Examination – Section V of the Boiler and Pressure Vessel Code published by the American Society of Mechanical Engineers (ASME) provides comprehensive requirements for various nondestructive examination methods, including radiography. It outlines the qualifications, procedures, and acceptance criteria for X-ray inspection in the context of pressure vessels, piping, and other ASME-regulated components.
- ISO 17636: Non-destructive testing of welds — Radiographic testing; The International Organization for Standardization (ISO) standard specifically focuses on radiographic testing of welds. It provides guidance on the selection of radiographic techniques, film or digital imaging systems, image quality indicators, and interpretation criteria for assessing weld quality.
- IAEA Safety Standards Series No. SSG-15: Radiation Safety in Industrial Radiography Published by the International Atomic Energy Agency (IAEA), this safety standard focuses on the safe use of ionizing radiation in industrial radiography, including X-ray testing. It provides guidance on radiation protection, source handling, equipment requirements, and training of personnel involved in industrial radiography.

E.11.14 Interpretation Training/Experience Requirements

See Certification/Operator Training/Experience Requirements

E.12 Core Sampling of Concrete

E.12.1 Description
Core sampling of concrete is a process used to extract cylindrical samples, or cores, from hardened portland cement concrete. It is commonly performed for various purposes such as quality control, structural assessment, durability evaluation, and investigation of concrete properties.

E.12.2 Damage Type/Target Material
Core sampling is for use on portland cement concrete.

E.12.3 Contact/Noncontact
Core sampling is a physical testing / contact method.

E.12.4 New Construction/Existing Structure
It can be performed on new structures as part of strength determination.

E.12.5 Automated/Manual
The sampling of cores is a manual technique.

E.12.6 Localized/Global Damage Assessment
Core sampling is typically performed to determine localized damage. However, core sampling can be used to establish a relationship between the measured strength of cores with rebound number measurements taken from corresponding locations on a concrete structure. To establish this relationship, at least two replicate cores shall be taken from at least six locations with different rebound numbers.

E.12.7 Technology Maturity/Years in Use
Core sampling of concrete is mature and dates back to prior to WWII.

E.12.8 Assessment Reliability
The single-operator coefficient of variation on cores has been found to be 3.2 % for a range of compressive strength between 4500 psi and 7000 psi. The results of two properly conducted tests of single cores by the same operator on the same sample of material should not differ from each other by more than 9 %

E.12.9 Assessment Frequency
As needed. Core extraction and testing is relatively time consuming.

E.12.10 Cost
Core testing is relatively expensive as typical operation includes mobilization costs. Core extraction and testing is approximately $100-300 per core. The establishment of a relationship between the measured strength of cores with rebound number measurements can cost between $5,000 and $15,000.

E.12.11 Standardization

The standard test method for obtaining and testing drilled cores and sawed beams of concrete is ASTM C42. The standard test method for the compressive strength of concrete is ASTM C39. The standard test method for rebound number of hardened concrete is ASTM C805.

E.12.12 Guidance Provided by Industry Consensus

ACI PRC 214.4 is the document titled "Obtaining Cores and Interpreting Core Compressive Strength Results—Guide" which provides industry consensus with respect to testing of concrete obtained from structures.

E.12.13 Certification/Operator Training/Experience Requirements

The certification program for performing compressive strength testing (ASTM C39) of portland cement concrete ACI Concrete Laboratory Testing Technician—Level 1**.**

The certification program for core extraction (ASTM C42) from structural concrete is ACI Concrete Laboratory Testing Technician—Level 2.

The certification program for rebound hammer (ASTM C805) is an ACI Nondestructive testing specialist.

E.13 In-situ Strength Testing Methods

E.13.1 Description

The most commonly used methods for the determination of in-situ strength of PCC include rebound number, penetration resistance, pullout, pull-off, ultrasonic pulse velocity, maturity, and cast-in-place cylinders.

E.13.2 Damage Type/Target Material

In-situ strength testing methods are applied to PCC.

E.13.3 Contact/Noncontact

Each of the methods referenced are contact methods.

E.13.4 New Construction/Existing Structure

New Construction

Each of the methods can be used for the estimation of for new construction which has value as the concrete in a structure may not have the same properties (and comparative strength) as a standard-cured cylinder at the same test age. Typically, cylinders are tested for acceptance purposes at an age of 28 days; therefore, the results of these tests cannot be used for the determination of strength exists at earlier ages for safe removal of formwork or the application of post-tensioning.

Existing Construction

The rebound number, penetration resistance, pullout, pull-off, ultrasonic pulse velocity can be performed on existing construction.

E.13.5 Automated/Manual

The most commonly used methods for the determination of in-situ strength of PCC are manual methods.

E.13.6 Technology Maturity/Years in Use

Each of the technologies for the determination of in-situ strength of PCC are mature. Each NDT method has an associated ASTM method, industry guidance and a certification program.
The test methods used for strength testing for existing concrete structures with NDT methods include:

- ASTM C597 – 16 Standard Test Method for Pulse Velocity Through Concrete
- ASTM C803/C803M – 18 Standard Test Method for Penetration Resistance of Hardened Concrete
- ASTM C805/C805M – 18 Standard Test Method for Rebound Number of Hardened Concrete
- ASTM C900 – 19 Standard Test Method for Pullout Strength of Hardened Concrete

E.13.7 Assessment Reliability

The reliability for each assessment differs depending on testing type. However, each of the test methods are standardized and provide reliable results when used properly. Precision and bias statements are included with each standardized testing method.

E.13.8 Assessment Frequency

As needed.

E.13.9 Cost

The cost of each of the testing methods are as follows

- ASTM C597 – 16 Standard Test Method for Pulse Velocity Through Concrete - $4,000 – $8,000
- ASTM C803/C803M – 18 Standard Test Method for Penetration Resistance of Hardened Concrete – $2,000 - $6,000
- ASTM C805/C805M – 18 Standard Test Method for Rebound Number of Hardened Concrete $200 – $3,000
- ASTM C900 – 19 Standard Test Method for Pullout Strength of Hardened Concrete - $1000 - $4,000.

E.13.10 Standardization

See: Technology Maturity/Years in Use.

E.13.11 Guidance Provided by Industry Consensus

The American Concrete Institute has published 228.1 which is a report that provides methods for estimating the in-place strength of concrete in new and existing construction. These methods include: rebound number, penetration resistance, pullout, pull-off, ultrasonic pulse velocity, maturity, and cast-in-place cylinders. The principle, inherent limitations, and repeatability of each method are reviewed. Procedures are presented for developing the relationship needed to estimate compressive strength from in-place results. Factors to consider in planning in-place tests are discussed, and statistical techniques to interpret test results are presented. The use of in-place tests for acceptance of concrete is introduced.

E.13.12 Certification/Operator Training/Experience Requirements
The certification program concrete strength testing is ACI **Non destructive Strength Specialist**

E.13.13 Interpretation Training/Experience Requirements
Same as Certification/Operator Training/Experience Requirements

E.14 Corrosion Detection and Monitoring Techniques

E.14.1 Description
There are several techniques that are used to detect and monitor corrosion of steel reinforcement in reinforced concrete. The most common methods are the half-cell potential method and the linear polarization method. The half-cell potential measurement is an electrochemical technique used to assess the corrosion activity in reinforced concrete. It involves placing a reference electrode on the concrete surface and measuring the potential difference between the reinforcement and the reference electrode. Deviations from the normal potential range indicate the likelihood of corrosion. Linear polarization resistance (LPR) is a technique used to measure the corrosion rate of reinforcing steel in concrete. It is based on the principle of electrochemical polarization, where a small potential is applied to the reinforcement and the resulting current is measured.

E.14.2 Damage Type/Target Material
Corrosion detection and monitoring techniques are used to determine corrosion of steel reinforcement.

E.14.3 Contact/Noncontact
The half-cell potential and LPR are contact methods. Both require a connection to the embedded reinforcement.

E.14.4 New Construction/Existing Structure
Corrosion detection systems are mostly used on existing construction.

E.14.5 Automated/Manual
The half-cell potential and LPR are manual methods.

E.14.6 Localized/Global Damage Assessment
The tests methods are local damage assessment techniques. With appropriate processing the method can be used for global assessment of the level of corrosion of reinforcement in a concrete structure.

E.14.7 Technology Maturity/Years in Use
Half-cell potential is mature technology that has been established and in for the use in building inspection industry since the 1970s. Linear polarization has been used since the 1980’s.

E.14.8 Assessment Reliability
The half-cell potential and LPR are reliable methods. The reliability statements are provided in the relevant ASTM standards.

E.14.9 Assessment Frequency
As needed. Inspections of small portions of a structure can take less than an hour while full building scans may take more than several days to weeks.

E.14.10 Cost
The half-cell potential equipment cost range is $3,000 - $7,000 while the LPR equipment cost range is $12,000 - $25,000.

E.14.11 Standardization

- Half-cell potential – ASTM C876: "Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete" – This standard describes the measurement of corrosion potentials, which can be used as an indication of the corrosion rate
- Linear polarization – While ASTM G59 does not specifically focus on concrete, it is commonly used for the measurement of corrosion rates in various materials, including reinforcing steel in concrete.

E.14.12 Guidance Provided by Industry Consensus
RILEM TC 154-EMC: "Electrochemical Techniques for Measuring Metallic Corrosion in Concrete" – This Technical Committee of the International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (RILEM) provides guidelines for electrochemical corrosion rate measurements, including linear polarization resistance.

E.14.13 Certification/Operator Training/Experience Requirements
The ANSI National Accreditation Board (ANAB) provide accreditation to perform testing standard ASTM C876 for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete

E.14.14 Interpretation Training/Experience Requirements
Same as certification.

E.15 Analysis of Ingress and Transport Properties

E.15.1 Description
There are a number of testing techniques for the measurement of the ingress and transport properties of portland cement concrete. A wide range of test methods have been developed to evaluate the durability of concrete surfaces, focusing on capturing the underlying transport mechanisms. The field testing of concrete using NDT methods include water absorption, water permeation, air permeation and diffusion. The transport properties that are measured using field measurements are absorption (typically water) and permeation (typically air).

The Initial Surface-Absorption Test (ISAT) is a test method used to measure the rate of water absorption by a concrete surface. It provides an indication of the permeability and porosity of the concrete, which are important factors in assessing its durability. Other tests similar to the ISAT test for the determination of the absorption of concrete include the Figg water absorption test, the Covercrete absorption test, the surface sorptivity test, and others. Permeability tests used for the determination of the flow of air and other gases through concrete in the field include the Figg air permeability test, Schönlin test, Surface airflow test and the surface air permeability test.

E.15.2 Damage Type/Target Material
Carbonation testing methods are applied to PCC.

E.15.3 Contact/Noncontact
Ingress testing is a contact method which requires small inserts to be made into the structure.

E.15.4 New Construction/Existing Structure
Ingress testing is mostly used on existing construction as carbonation does not typically take place in new construction.

E.15.5 Automated/Manual
Ingress testing is performed manually.

E.15.6 Localized/Global Damage Assessment
Ingress testing measures localized behavior of concrete. However, because the weathering of a concrete structure is typically uniform, carbonation testing is typically considered to be a global test method.

E.15.7 Technology Maturity/Years in Use
The technology is mature as the ingress testing methods for concrete were first used in the 1980s.

E.15.8 Assessment Reliability
The test are reliable when performed properly.

E.15.9 Assessment Frequency
As needed. Ingress testing is relatively time consuming.

E.15.10 Cost
The testing equipment for ingress testing is ranges from $1,000 - $8,000.

E.15.11 Standardization
None

E.15.12 Guidance Provided by Industry Consensus
ACI 228.2 provides guidance on ingress testing methods.

E.15.13 Certification/Operator Training/Experience Requirements
Stated in guidance provided by industry consensus.

E.15.14 Interpretation Training/Experience Requirements
Stated in guidance provided by industry consensus.

E.16 Analysis of Carbonation

E.16.1 Description
Carbonation in concrete is a chemical process in which carbon dioxide from the air reacts with the calcium hydroxide in the concrete, forming calcium carbonate. This reaction reduces the pH of the concrete, making it more acidic. When the pH drops below a certain threshold (typically around 9-9.5), the passive layer on the reinforcing steel, which provides protection against corrosion, can be compromised.

E.16.2 Damage Type/Target Material
Carbonation testing methods are applied to PCC.

E.16.3 Contact/Noncontact
Carbonation testing is a contact method which requires a specimen of the structure to be removed.

E.16.4 New Construction/Existing Structure
Carbonation testing is mostly used on existing construction as carbonation does not typically take place in new construction.

E.16.5 Automated/Manual
Carbonation testing is a manual method.

E.16.6 Localized/Global Damage Assessment
Carbonation testing measures localized damage. However, because the weathering of a concrete structure is typically uniform, carbonation testing is typically considered to be a global test method.

E.16.7 Technology Maturity/Years in Use
The technology is mature as the first tests for carbonation were performed over 100 years ago. Currently, the common test method for carbonation is acquitting a sample of concrete. The test is performed on a freshly broken surface (and cleanly brushed face) where the depth of carbonation is determined by spraying the freshly fractured surface with a phenolphthalein solution.

E.16.8 Assessment Reliability
The test method produces reliable results.

E.16.9 Assessment Frequency
As needed.

E.16.10 Cost
The cost for a single carbonation test can range from $100 - $300. Mobilization and reporting can add to the costs.

E.16.11 Standardization
None

E.16.12 Guidance Provided by Industry Consensus

ACI 228.2 provides guidance on carbonation testing as an NDT test method.

E.16.13 Certification/Operator Training/Experience Requirements

Stated in guidance provided by industry consensus.

E.16.14 Interpretation Training/Experience Requirements

Stated in guidance provided by industry consensus.