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Cost-Effective and Rapid Concrete Repair Techniques

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16. Abstract Concrete is a principal component of many transportation structures. While highly durable, a variety of processes degrade and damage concrete. Replacement is expensive. Many cases warrant repair instead of replacement. Since many damage processes are progressive, early and properly timed repairs can reduce costs. Overall lifetime cost of ownership approach to selection and design of repairs has merit, but requires good information about costs and outcomes. There is a possibility that effective timing and application of repairs can be of great benefit to maintenance activities – including lifetime costs and rapid techniques that allow for expedited designs of repairs and minimizing repair times. The specific objectives of this research were to: (1) Assess present practices of concrete repair – This will establish what is being done in Vermont and elsewhere. (2) Develop flow chart of		

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ABSTRACT

Concrete is a principal component of many transportation structures. While highly durable, a variety of processes degrade and damage concrete. Replacement is expensive. Many cases warrant repair instead of replacement. Since many damage processes are progressive, early and properly timed repairs can reduce costs. Overall lifetime cost of ownership approach to selection and design of repairs has merit, but requires good information about costs and outcomes. There is a possibility that effective timing and application of repairs can be of great benefit to maintenance activities – including lifetime costs and rapid techniques that allow for expedited designs of repairs and minimizing repair times.

The specific objectives of this research were to: (1) Assess present practices of concrete repair – This will establish what is being done in Vermont and elsewhere. (2) Develop flow chart of decision-making and options for repair practice and evaluation – This will create a guide with recommendations for maintenance personnel and engineers. (3) Develop procedures for integrating repair options and decisions into asset management – This will aid in reducing lifetime costs of ownership and assist in statewide maintenance planning. (4) Recommend areas for further study and tech transfer to make cost effective repairs.

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1. INTRODUCTION

The overarching goal of this project is to identify concrete repair practices that work best for the climate and infrastructure conditions in Vermont. Concrete is a principal component of many transportation structures. While highly durable, a variety of processes degrade and damage concrete. Replacement is expensive. Many cases warrant repair instead of replacement. Others can benefit from early-stage mitigation treatments or increased levels of condition monitoring. Since many damage processes are progressive, early and properly timed repairs can reduce costs. Overall lifetime cost of ownership approach to selection and design of repairs has merit, but requires good information about costs and outcomes. There is a possibility that proper timing and application of repairs can be of great benefit to maintenance activities – including lifetime costs and rapid techniques that allow for expedited designs of repairs and minimizing repair times. Realizing the advantages of concrete repair requires effective execution of damage identification, damage assessment, repair design, repair, and post-repair assessment.

The Vermont Agency of Transportation (Vtrans) has been engaged in a long-term effort to improve the condition of its bridges. In 2017 Vtrans has 2,723 bridges over 20 ft. in length in its inventory (VAOT 2017). The bridge replacement, rehabilitation and preventative maintenance budget of \$87 million dollars in 2016 supported 31 projects. The overall condition of the structures, as measured by the amount of structurally deficient and functionally obsolete bridges, has been steadily improving, Figure 1.1.

The criteria used by Vtrans to list a bridge as Structurally Deficient are [VAOT2017]:

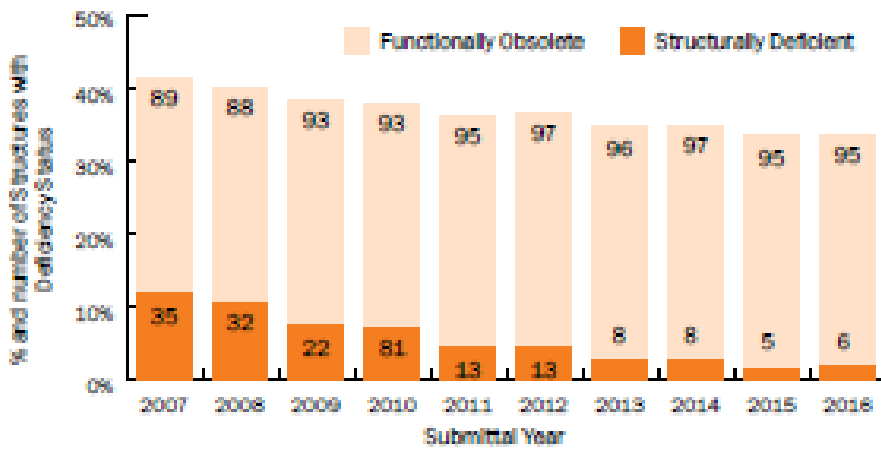
A bridge becomes structurally deficient when at least one of six items from the National Bridge Inventory (NBI) reaches a set threshold. The criteria are a Deck Condition Rating, Superstructure Condition Rating, Substructure Condition Rating, or Culvert Condition Rating of 4 (Poor Condition) or less, or a Structural Evaluation Appraisal Rating or Waterway Adequacy Appraisal Rating of 2 (basically intolerable, requiring a high priority of replacement) or less. Any bridge that is classified structurally deficient is excluded from the functionally obsolete category.

The criteria used by Vtrans to list a bridge as Functionally Obsolete are [VAOT2017]:

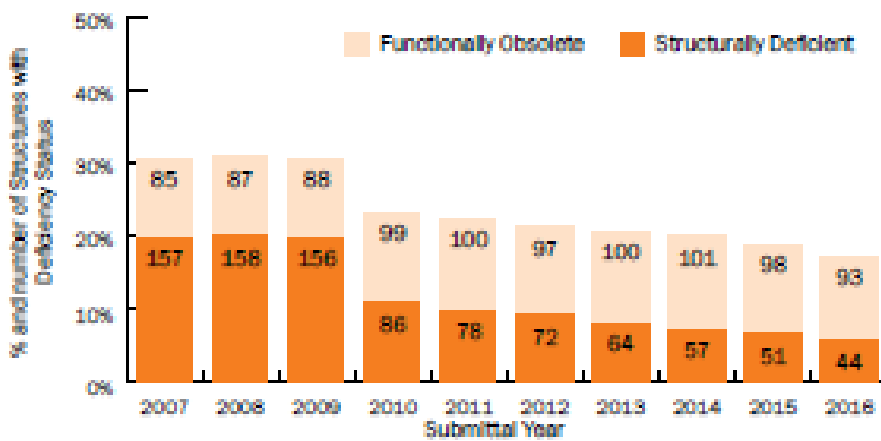
A bridge becomes functionally obsolete when at least one of five items from the National Bridge Inventory reaches a set threshold. The criteria are a Deck Geometry Appraisal Rating, Underclearances Appraisal Rating, Approach Roadway Alignment Appraisal Rating, Structural Evaluation Appraisal Rating or Waterway Adequacy Appraisal Rating of 3 (basically intolerable, requiring a high priority of corrective action) or less. Any bridge that is classified structurally deficient is excluded from the functionally obsolete category.

Nonetheless, the combination of age and severe environmental loading has led to numerous bridge structures in Vermont with distressed concrete. The latter chapters in this report document some of these bridges. It should be noted that even though these bridges may be in need of maintenance, repair or even replacement, the bridges are not inherently unsafe. If inspections determine that a bridge is unsafe, it is either closed or posted to permit only reduced loads.

Interstate Structure Trends



State Highway Structure Trends



Town Highway Structure Trends

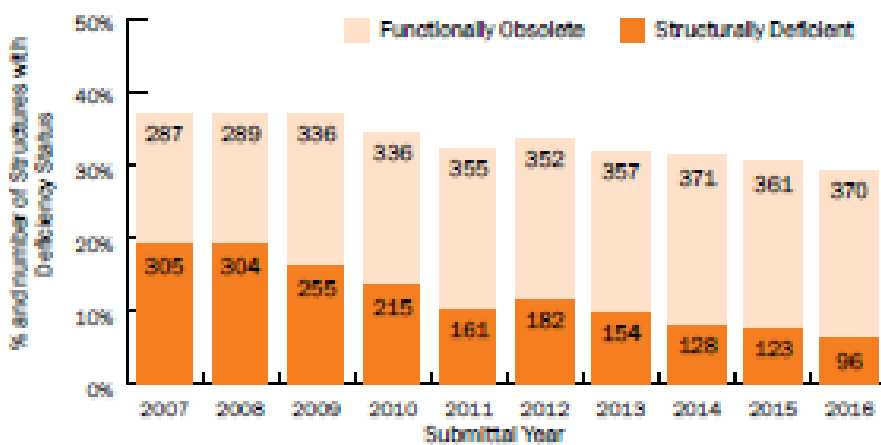


Figure 1.1 Downward trends of percent structurally deficient and functionally obsolete bridges in Vermont (VAOT 2017)

Concrete repair is a technically challenging endeavor. The U.S. Army Corps of Engineers reports that over half of their concrete repairs turn out less than satisfactory [ACI, ICRI. (2013)]. Concrete repair is typical of most structural maintenance activities in that it is a cyclic process, Figure 1.2. The four primary steps are: 1. *Inspection and Monitoring* – This may be performed on a periodic or usage basis, or motivated by reports of damage or extreme loading; 2. *Assessment* – This determines the severity of damage, cause and prognosis; 3. *Decision Making* – The course of action may be either to repair the structure, close and demolish, or do nothing, except possibly increase the rate and depth of detail of future inspection and monitoring. If it is decided to repair the structure, then a decision is made about the type, scope and timing of repair; 4. *Action* – repair, demolish or leave alone; and then repeat the cycle.

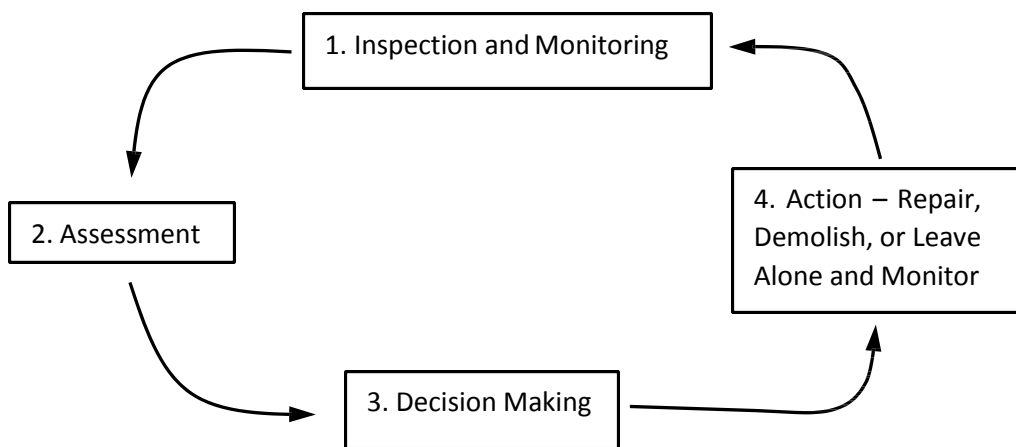


Figure 1.2 Cyclic nature of structural maintenance and repair

The primary objectives of this research project are:

Objective 1: Assess present practices of concrete repair – The objective is to identify repair practices for concrete transportation infrastructure in Vermont and neighboring states. This includes damage identification, damage assessment, repair design, repair, and post-repair assessment.

Objective 2: Develop flow chart of decision-making and options for repair practice and evaluation – The flowchart can lead to a guide with recommendations for maintenance personnel and engineers, with an emphasis on cost-effective procedures that minimize imposing additional burdens on inspection and maintenance personnel.

Objective 3: Develop procedures for integrating repair options and decisions into asset management – This will aid in reducing lifetime costs of ownership and assist in statewide maintenance planning.

Objective 4: Recommend areas for further study and tech transfer to make cost effective repairs - This is an effort to identify topics of importance to Vermont and achievable within present resource constraints.

Objective 5: Describe a future Phase II effort that would take the procedures that seem to work the best and apply them in the field.

The methodology for achieving the objectives involved:

Task 1: Met with VTrans personnel concerning present damage problems and repair practices.

Task 2: Reviewed literature on concrete repair.

Task 3: Identified damage processes specific to Vermont and/or New England.

Task 4: UVM personnel accompanied VTrans personnel to examine highway bridges in various states of repair.

Task 5: Reviewed documentation provided by Vtrans on recent concrete repairs to highway bridges.

Task 6: Synthesized information and created a computer-based graphical user interface with three primary components; 1. Inspection information input, 2. Repair procedure options, 3. Decision-making flowchart.

Task 7: Developed recommendations for future concrete research efforts.

Task 6: Prepare report – The emphasis is on Steps 3 and 4 in Figure 1.2, i.e. *Decision Making*, and *Action – Repair, Demolish, or Leave Alone and Monitor*.

The deliverables for this project are:

Deliverable 1: Report with flowchart describing decision-making and repair practices for concrete.

This flowchart includes a catalog of possible damage types, recommended assessment tools for each damage type, recommended options for repair for each damage type, and considerations for decision-making, including issues of effective timing, i.e. avoid costly repairs while also avoiding unnecessary repairs.

Deliverable 2: Recommendations on how to get concrete to function better in the long term.

The recommendations considers the following items:

- a. Performance criteria – What are useful quantitative measures of concrete performance?
- b. Life-cycle cost considerations
- c. Small footprint palliative procedures for concrete, such as the periodic application of sealers.
- d. Substantial repair processes, i.e. those requiring removal of concrete, replacement and patches.

- e. Durable and sustainable design of new structures – Are there low-cost details that if implemented during fabrication will contribute substantially to durability? What is the possible role of membranes, polymer pier caps, etc.?

Deliverable 3: Procedures for inclusion of repair decisions into the asset management database

This includes an evaluation of present asset management practices, identify practical methods of inserting repair information into asset management practices, and a rationale for the utility of such an effort.

Deliverable 4: Recommendations for future concrete repair and tech transfer research

These recommendations could serve as a roadmap for improving concrete repair practices in Vermont and elsewhere.

2. CONCRETE REPAIR TECHNIQUES AND METHODS

Concrete repair is a multifaceted topic that requires consideration of structural assessment, repair procedure and material selection, repair design, implementation of the repair and post-repair assessment. In this context, a comprehensive survey of the available literature on concrete repair was undertaken. Sources were: 1. Codes, standards and recommended practices published by technical organizations, such as AASHTO, ACI and ICRI; 2. Manuals of recommended practice published by state and other governmental transportation agencies; 3. Refereed journal publications and technical conference proceedings; and 4. Literature from trade organizations and commercial enterprises. In all, this comprised over 100 publications with direct relation to the repair of concrete in transportation infrastructure. The synthesis of the literature organizes the information into the following categories: 1. Inspection and Assessment; 2. Overall Repair Guides; 3. Element Repair Techniques; and 4. Specialized Repair Techniques.

2.1. Inspection and Assessment Methods

A first step in concrete repair is assessing the present state of damage in the structure, the causes of damage and the prognosis for damage progression and overall structural safety and health. In many respects, structural assessment is beyond the scope of this synthesis. The following is a brief summary of some topics related to the assessment of concrete transportation structures.

2.1.1 Overall Inspection and Assessment Techniques

Several publications address overall inspection and assessment techniques. Raina VK (1996), Ohio Department of Transportation (2014) and Wisconsin Department of Transportation (2011) describe methods of inspecting concrete bridges. Portland Cement Association. (2016) covers overall methods of assessing concrete damage. Moore et al. (2000) studied the quality and repeatability of bridge inspection methods. Huston (2010), and Ettouney and Allampalli (2011) provide in-depth discussions of structural health monitoring, condition assessment and prognosis methods.

2.1.2 Component Inspection

Concrete decks and slabs carry vehicles as they traverse bridges. Decks are supported on steel beams and girders, or concrete beams. Slabs span (generally 20 – 40 ft.) directly between substructures. Delaminations are a common failure mode and be detected by manual and automated acoustic methods (Seegebrecht ,2016), along with ground penetrating radar (Goulias and Scott, 2015; Huston et al., 2002).

2.1.3 Database Integration

Inspection is an information-laden process. Electronic databases being able to organize, store and manage last pools of heterogeneous information are natural tools for handling the results of structural inspection and condition assessment. Integrating inspection information into databases is an emerging activity. Vtrans is presently implementing a Transportation Asset Management Plan and is developing a bridge management system that will integrate bridge inspection data for project considerations (VAOT 2017). Vtrans (2014) describes the rail bridge management program in Vermont.

2.2. Overall Repair Guides

There are several documents that provide broad guidance on the overall topic of structural repair with concrete repair appearing as chapters and subsections.

2.2.1 Design for Repair

In a study aimed at identifying design practices that allow for bridges to last 100 years or more Azizinamini et al. (2014a), as a key feature, identified designing the structure so that it can be serviced and repaired.

2.2.2 AASHTO, Federal and State DOT Maintenance and Repair Manuals

State agencies of transportation (Delaware, Georgia, Iowa, New York, Pennsylvania, and Wisconsin), AASHTO and U.S. federal agencies have published a series of guides and recommended practices on bridge maintenance and repair (AASHTO, 2007; Taavoni, 2012; PennDOT, 2010; Army and Air Force, 1994; WisDOT, 2016; NYDOT, 2014; GDOT, 2012; and Iowa Highway Research Board, 2014). Maintenance personnel and engineers comprise the primary audience for these manuals.

Of particular note is the guide by PennDOT (2010), which describes a fascia beam collapse in (2005) and procedures for railing and parapet repair in Chapter 14. A document from the World Road Association (Technical Committee 4.3, 2015) describes the successful use of several relatively new concrete repair methods including Fiber Reinforced Polymer (FRP) strengthening of concrete beams following impact, external post-tensioning members on beams, suppression of expansion joints, corrosion inhibitors and water jet removal of deteriorated concrete.

2.2.3 ACI and ICRI Repair Documents

The American Concrete Institute (ACI) and International Concrete Repair Institute (ICRI) have published a set of codes, guides and manuals giving recommendations for concrete repair practices. ACI, ICRI. (2013) is a 900+ page two volume collection of documents on concrete repair. This is a comprehensive coverage that includes buildings and other structures, along with concrete bridges. ACI Committee 546. (1997) covers the repair of concrete bridge superstructures, and describes only well-documented practices with significant track records of use. ACI Committee 345 (2016) is an overall guide to the maintenance of concrete bridge members. ACI Committee 546. (2014a) guides material selection for concrete repair. ACI

Committee 562. (2014b) is a code covering the repair of concrete buildings, with ACI Committee 546. (2014b) and ACI Committee 562, International Concrete Repair Institute (2014a) providing supporting documentation.

2.3. Element Repair Techniques

Many structural elements have specific repair techniques. These are described in reports and case histories.

2.3.1 Anchorages

Many older concrete girders used simple terminations as anchorages for reinforcing steel. The stress concentrations along with shear loads at the ends of the girders can cause cracking and degradation. Supplemental strengthening with external metal rods can alleviate some of these difficulties Higgins et al. (2016). The practice in Vermont is not to do much strengthening, but generally to post the bridge for a lower weight rating and schedule for a major rehabilitation or replacement.

2.3.2 Bearings

Many bridges in Vermont have ‘frozen’ bearings due to leaking expansion joints. This has transferred the superstructure movements due to thermal expansion/contraction directly to the substructures, often causing delamination and cracking of the concrete in the bearing areas.

2.3.3 Beams and Girders

Concrete beams and steel girders are integral elements of bridge structures, with Vermont having mostly steel beam bridges. Beams and girders are subjected to normal structural loads, environmental loading and occasional extreme loads – including fire, all of which can cause damage. Beam and girder repair procedures are often required, along with the need for external strengthening Waheed et al. (2005).

Zhang Y. (2012) in a series of laboratory experiments examined the advantages and disadvantages of several repair techniques for ordinary non-prestressed girders. These include jacketing and increasing the section with more concrete, external bonding of Fiber Reinforced Polymers (FRPs), external attachment of strengthening tendons and epoxy injection into cracks. In many cases, epoxy injection proved to be the most convenient.

Impact damage from overheight vehicles is a common damage mode for concrete bridge girders. FRP patches are a common repair method (Kasan and Harries, 2016; and Miller (2006).

The ends of beams and girders, especially prestressed variants, are often highly stressed and form cracks that need mitigation and repair. Hasenkamp et al. (2012) recommends procedures for the repair of precast and prestressed girders with end zone cracking. The ends of beams are also subject to chloride

ingress through micro-cracking, and geometries that favor chloride loading. Hosteng et al. (2015) investigates the performance of various coatings as mitigating treatments for concrete beams.

2.3.4 Bridge Curbs

Kansas Department of Transportation (2015) addresses the repair of concrete bridge curbs.

2.3.5 Columns

Jacketing with extra concrete, FRP and metal strips are methods of strengthening and repairing concrete columns (Fukuyama et al., 2000; and Frangou et al., 1995).

2.3.6 Fascia and Parapets

Fascia and parapets tend to be difficult repairs for bridges in Vermont. PennDOT (2010) describes fascia and parapet repairs in detail, with the overall technique being the removal of damaged concrete and reinforcing bars, and then rebuilding and replacement. Annual or biannual washing of bridges combined with a periodic application of sealer, such as silane, has the potential to significantly extend the life of concrete curbs, thereby delaying or eliminating these costly repairs.

2.3.7 Foundations

Leaking foundations are occasionally an issue with concrete transportation structures. Concrete Network (2016) describes coating and sealers that can waterproof and damproof foundations. It is not clear if these techniques are of much direct utility for the foundations typically found in transportation structures.

2.3.8 Pavements

Concrete pavements appear on most interstate highways and some other routes in Vermont. Sutter (2015) lists some repair techniques for materials-related distress in concrete pavements, but notes that for environmental degradation there are presently not many good options. Vermont has very few concrete pavements, with only a few short sections in Chittenden County.

2.3.9 Reinforcing Bars

Concrete repair operations, such as the removal of damaged concrete can leave reinforcing bars exposed. These processes typically damage epoxy coatings. Repainting epoxy onto the bars is recommended, but may be inadequate and require supplemental treatments, such as anodic protection ACI Committee 364 (2015).

2.3.10 Piles and Piers

KSDOT (2008) discusses the repair of bridge piles and piers.

2.3.11 Sidewalks

Oregon, Ohio (2016) shows how to repair concrete sidewalks.

2.3.12 Slabs and Decks

Portland Cement Association (2001) Indiana DOT. (2014) are guides covering the broad topic of repairing concrete slabs and decks. Sealers and overlays can prevent the ingress of chlorides, as long as they stay intact. Damage to sealers and overlays can create hot spots that accelerate deterioration. It is possible to repair sealers and overlays (Russell, 2012; McLean 2012).

2.3.13 Surfaces

Concrete Network. (2016) presents methods for repairing discolored concrete surfaces with muriatic acid.

2.3.14 Wingwalls and Abutments

Marchione (2014) describes wingwall and abutment repairs.

2.4. Specialized Repair Techniques

Certain repair techniques are specialized in the type of repair. Often these techniques have broad applicability across a range of concrete structural elements and components.

2.4.1 Cast in Place Methods

Cast in place is perhaps the most common concrete repair technique. The repair site is prepared by the removal of the damaged concrete and fixing the reinforcing bars as needed, FHWA (2016). Concrete is cast into the repair site and cures in place. Conventional or high-performance concrete can serve as the repair material. Examples are; fiber-filled concrete Constructor (2016), a variety of mortar mixes Dave (2014), silica fume (on Vermont bridges) Mills (1992), and shotcrete Hanskat (2014). Debonding and cracking of the repair patch is a concern, Kim et al. (2014).

2.4.2 Cracks

Cracks can be ubiquitous in concrete structures. Many are benign, others indicate underlying problems, and some are troublesome and need repair. Andrews-Phaedonos (2010) and American Concrete Institute (2007) give broad overviews of concrete cracking mechanisms and repair. Johnson et al. (2009) surveyed the literature on the concrete crack and surface sealer treatments followed with recommendations for use in Minnesota and the central U.S.

2.4.3 Electrochemical Chloride Extraction

The penetration of chloride ions through the outer surface of concrete elements and down to reinforcing bars through diffusion and wicking is a primary driver of corrosion damage. Electrochemical chloride extraction (ECE) uses the ionic nature of chlorides to force migration out of concrete. Similar electro-osmotic processes can realkalize carbonated concrete. ECE is an involved process, but can be effective in extending the life of reinforced concrete structures, Velivasakis et al. (1997) and Sharp (2016).

2.4.4 Fiber Reinforced Polymers

Fiber Reinforced Polymers (FRPs) are typically used in the repair and strengthening of concrete members by external bonding techniques (EISafty and Graeff, 2012). The relative novelty of FRP repairs implies that the long-term performance behavior is not fully understood. Some observations indicate that degradation with time can occur (Atadero et al., 2013). Debonding of FRP patches and strips from the concrete is a primary failure mode that can be alleviated with mechanical anchors (Grelle and Sneed, 2013).

2.4.5 Overlays and Sealers

Overlays and sealers are surface add-ons that protect and seal the exterior of concrete elements. The compositions vary, are often proprietary and can include cementitious, polymer and/or oil-based components. The exposure of overlays and sealers to environmental and traffic loads causes them to wear and need recurring replacement in order to remain effective. Field and laboratory testing is the standard method of establishing expected performance (Sprinkel and Mokarem, 2009; Weyers et al., 1995; and Hagen, 1995).

3. DECISION-MAKING METHODS

3. Decision-Making

Decision-making in the context of the repair of concrete transportation entails two main phases. The first phase is to decide whether to repair the structure or to follow-up with a non-repair option, i.e. leave alone, leave alone and increase monitoring and inspection rates, post for reduced loads or demolish. If it is decided to repair the structure, then a second phase of decision-making ensues regarding the extent, type, details and timing of the repair. Both phases involve combining technical information on repair processes and options with economic considerations and overall transportation network development.

Timing of the repair is a key item not often mentioned in the repair decision-making process. Since many forms of damage are progressive, intervening with repair and mitigating measures and the right timing can minimize the overall cost of ownership of the structure. The cost of repairs is often seasonal depending on the amount of work available for contractors, and can be weather related. The long term growth and change of the transportation network can affect repair or replacement decisions.

3.1 Heuristic and Matrix Methods

Heuristic methods are perhaps the most common repair decision-making method. The standard heuristic approach is to use experienced engineers, maintenance personnel and planners to synthesize technical, economic and network planning information. Matrix methods are simple graphical techniques that aid the heuristic methods by listing the various options, along with advantages and disadvantages, and provide the ability to assign numerical weights to competing options.

Hearn et al. (2007) is a synthesis of overall best practices among U.S. transportation departments for highway bridge maintenance. Azizinamini et al. (2014b) present a decision-making framework, beginning at the design stage, for maintenance of bridges so that they can be in service for over 100 years. Snover et al. (2011) list key ingredients for specifying a good concrete repair work plan. Michigan DOT (2016) contains several tables with repair options for concrete bridges and pavements. Ainge (2012) has a decision matrix for bridge concrete repair including scour countermeasures. Venner (2014) presents case studies on decision-making for culvert and storm drains in Vermont, Oregon, Ohio, and Los Angeles County. Ramírez (1996) provides an evaluation of ten different concrete column repair methods. Beuerman (2009) describes methods of repair masonry arch bridges including a design table. Bashum (2006) covers concrete cracking. Missouri Department of Transportation (2016) has a 12-month calendar indicating favorable times to perform various maintenance activities on bridges.

3.2 Databases

The amount of information related to the design, condition, inspection, and maintenance of bridges can be voluminous both at the individual level and at the transportation network level. Electronic databases have become a necessity in managing this information (Sinha et al., 2009; and Clement, 2014). For

example, VTrans has an extensive database of many years of inspection data. Efforts are underway to use the data to develop reliable deterioration models for estimating future bridge needs.

3.3 Decision Trees

Decision trees organize the decision-making process with a tree-like logical structure that guides when to make decisions, clarifies the options at each step and indicates the follow-on steps. Advantages of the decision-tree approach are that it provides consistency in the decision-making process, allows for documentation of the thought processes and promotes a framework that can be aided by computerized and graphical user interfaces. Decision trees have been proposed for decision-making in accelerated bridge construction (Phares and Cronin, 2015; and Culmo, 2011).

3.4 Probabilistic and Optimization Methods

Many of the decisions required for concrete repair have to be made with incomplete and uncertain information. Uncertainties pervade the structural condition assessment, prognosis of damage progression, future loading, probability and measurement of repair performance and economic conditions. The probabilistic and optimization approach to decision-making in many respects follows the reliability methods used in structural design. A drawback to using these methods is that there tends to not be sufficient data available on repair performance to quantify the uncertainties for use in the models. If these uncertainties can be quantified, then it is possible to put in place a framework for maintenance and repair decision-making that predicts and optimizes the life-cycle performance and cost of ownership of structures (Frangopol et al., 2017; Kim et al., 2013; Kotze et al., 2015; and Pallasch et al., 2014). Probabilistic methods can provide better predictions of the service life of structures (Kotze et al., 2015), and describe the prognosis for various failure modes, such as chloride attack (Bentz et al., 2014). If sufficient data is available, it is possible to set quantitative thresholds that govern no-repair versus repair, and repair versus replacement decisions, as in prestressed concrete girders (Kasan and Harries, 2016).

4. CONCRETE REPAIRS IN VERMONT

4.1 Overview

VTrans engaged in 21 substantial repair operations to concrete bridge elements and components in 2013 and 2014. Cost data and descriptions, along with a set of before and after photographs of the repairs were provided by JB McCarthy of VTrans. Table 4.1 lists the bridges and overall cost of the repairs. The most expensive repair was the fascia/curb reconstruction on the New Haven US 7 bridge. The following sections show the repairs organized by element and component repair type.

Table 4.1 Bridge concrete repair projects with costs by Vtrans in 2013 and 2014

<u>Yr Repaired</u>	<u>Town</u>	<u>Route</u>	<u>Bridge #</u>	<u>Scope of work</u>	<u>Cost</u>
2013	Berlin	VT 12	70	Head Wall/Wing Wall Reconstruction	\$150,000.00
2014	Berlin	VT 903Conn	1	Replaced Joint	\$230,000.00
2013	Elmore	100	95	Wing Wall Encasement	\$100,000.00
2013	Hartford	VT 14	7	Wing Wall/ Cut-off Wall Reconstruction	\$180,000.00
2013	Hartford	I91	42 N/S	Abutment/Pier Repairs/Drain System	\$125,000.00
2014	Hartford	US4	65A	Pier/Pedestal Reconstruction	\$150,000.00
2014	Londonderry	VT 11	27	Pier Repairs	\$120,000.00
2013	Middlesex	I89	45S	Bearing Seat/Pier repairs	\$150,000.00
2014	New Haven	US7	129	Fascia/Curb Reconstruction	\$350,000.00
2013	Pawlet	VT 30	78	Wing Wall reconstruction	\$80,000.00
2013	Pawlet	VT 30	77	Wing Wall/ Cut-off Wall Reconstruction	\$100,000.00
2014	Richford	105A	2	T Beam/Deck Reconstruction	\$150,000.00
2013	Richmond	I89	55S	Bearing Seat/Pier repairs	\$150,000.00
2014	Rutland City	River Street	27	Pier Repairs	\$180,000.00
2014	Stowe	VT 108	10	Wing Wall Encasement/ Other Repairs	\$200,000.00
2014	Stowe	VT 108	11	Footing/ Stem Scour Repairs	\$60,000.00
2013	Vershire	VT 113	11	Deck/Wing Wall Repairs	\$150,000.00
2014	Williston	I89	60	Pier Repairs	\$150,000.00
2014	Williston	I89	62	Pier Repairs	\$150,000.00
2014	Winhall	VT 30	45	Flow Line Replacement	\$250,000.00
2014	Woodstock	VT 12	19	T Beam/Deck Reconstruction	\$150,000.00
				Total	\$3,325,000.00

4.2 Bearing Seat/Pier Repairs

Many highway overpass bridges have expansion joints above piers and bearings. The flow of deicing salts and water onto the piers and bearings leads to corrosion damage to the pier caps, bearing seats and bearings. Figure 4.1 shows the I-89 Middlesex/Richmond Bridge #45 S with severe spalling damage to the pier caps. Figure 4.2 shows the bridge with repaired and strengthened pier along with some of the construction formwork.



Figure 4.1 I-89 Middlesex Br.#45 S



a.



b.

Figure 4.2 I-89 Richmond Br. #45 S - REPAIRED Bearing Seat/Pier repairs, \$150,000

4.3 Expansion Joints

Expansion joints are included in bridge decks to allow freedom of movement due to thermal expansions, small foundation movements and deflection due to traffic loading. Being on the traveling surface, expansion joints are subjected to severe loading, such as snow plow impacts, and often wear out. Figure

4.3 shows a damaged steel expansion joint and bearing for Vt. Rte. 903 Conn Berlin Br. #1. Figure 4.4 shows a replacement that eliminates the steel joint.



a.



b.

Figure 4.3 Vt. Rte. 903 Conn Berlin Br. #1



a.



b.

Figure 4.4 Vt. Rte. 903 Conn Berlin Br. #1 – Repaired Replaced Joint, \$230,000

4.4 Fascia/Curb Reconstruction

Vermont has multiple highway overpass bridges with severely distressed fascia. Spalling concrete is a safety issue for vehicles passing underneath. Many of the fascia have integrated guard rail systems and pose a safety risk if the rails fail to contain out of bounds vehicles. Figure 4.5 shows a severely damaged fascia on US 7 New Haven Br.#129. Figure 4.6 shows the reconstructed curb and fascia, along with new guard rail and fencing.



a.



b.

Figure 4.5 US7 New Haven Br. #129



Figure 4.6 US 7 New Haven Br. #129 – REPAIRED Fascia/Curb Reconstruction, \$350,000

4.5 Flow Line Replacement

Bridges with integrated water flow structures, such as corrugated steel arches, can suffer damage at the water flow line due to corrosion and erosion. Figure 4.7 shows the Vt. Rte. 30 Winhall Br. #45 with a severely damaged corrugated steel flow line. Figure 4.8 shows a repair that replaced the flow line with concrete.



a.



b.

Figure 4.7 Vt. Rte. 30 Winhall Br.#45



a.



b.

Figure 4.8 Vt. Rte. 30 Winhall Br. #45 – Repaired with Flow Line Replacement, \$250,000

4.6 Footing/ Stem Scour Repairs

Concrete footings placed in stream flows are constantly subjected to hydraulic erosion effects. Figure 4.9 shows a footing on Vt.Rte.108 Stowe Br. #11 with erosion damage. Figure 4.10 shows a cast-in-place repair to the footing.



a.



b.

Figure 4.9 Vt. Rte. 108 Stowe Br. #11



a.



b.

Figure 4.10 Vt. Rte. 108 Stowe Br. #11 – Repaired Footing/Stem Scour Repairs, \$60,000

4.7 Pier Repairs

Many bridge piers in Vermont suffer distress due to deicing salts leaking through expansion joints. Figure 4.11 shows a severely damaged pier and pedestal on US 4 Hartford Br. #65A. Figure 4.12 shows a repaired pier and pedestal reconstruction. Figure 4.13 shows a severely damaged pier cap on Vt. Rte.11 Londonderry Br. #27. In Figure 4.14 the pier is restored with the addition of a strengthening section at the top, armoring at the bottom and more cover on the sides. Figure 4.15 shows I 89 Richmond Br. #55 S with spalling and loss of a corner section in a pier cap. Figure 4.16 shows bearing seat/pier repairs. Figure 4.17 River Street Rutland City Br. #27 has severe spalling on the pier columns. A cast-in-place encasement repair of the columns that changes the shape from a circular to square profile appears in Figure 4.18. Figure 4.19 shows a pier cap on I89 Williston Br. #60 with distressed ends. Figure 4.20 shows the corresponding repair. Figure 4.21 I89 Williston Br. #62 has spalling and loss of section damage to the pier caps. Figure 4.22 shows a cast-in-place encasement repair.



a.



b.

Figure 4.11 US 4 Hartford Br. #65A



a.



b.

Figure 4.12 US4 Hartford Br. #65A – REPAIRED Pier/Pedestal Reconstruction, \$150,000



a.



b.

Figure 4.13 Vt. Rte. 11 Londonderry Br. #27



a.



b.

Figure 4.14 Vt. Rte. 11 Londonderry Br. #27 – REPAIRED Pier Repairs, \$120,000



a.



b.

Figure 4.15 | 89 Richmond Br. #55 S



a.



b.

Figure 4.16 | 89 Richmond Br. #55 S – REPAIRED Bearing Seat/Pier repairs, \$150,000



a.



b.

Figure 4.17 River Street Rutland City Br. #27



a.



b.

Figure 4.18 River Street Rutland City Br. #27 – REPAIRED



a.



b.

Figure 4.19 I 89 Williston Br. #60



a.



b.

Figure 4.20 | 89 Williston Br. #60 – REPAIRED Pier Repairs, \$150,000



a.



b.

Figure 4.21 | 89 Williston Br. #62



a.



b.

Figure 4.22 | 89 Williston Br. #62 – REPAIRED Pier Repairs, \$150,000

4.8 T Beam/Deck Reconstruction

Many short span bridges in Vermont use combinations of integrated concrete beams and decks, with T-beam/deck combinations as common variants. The integration of concrete beams and decks produces an efficient structural form, but can result in combined damage to both the deck and beams, which leads to combined repairs. Figure 4.23 shows damage to both the deck and beams in Vt. Rte. 105A Richford Br. #2. Figure 4.24 shows a reconstruction repair. Figure 4.25 shows Vt. Rte. 12 Woodstock Br. #19 with considerable spalling from both the deck and the beam. Figure 4.26 shows the repaired bridge.



a.



b.

Figure 4.23 Vt. Rte. 105A Richford Br. #2



Figure 4.24 Vt. Rte. 105A Richford Br. #2 –REPAIRED T Beam/Deck Reconstruction \$150,000



a.



b.

Figure 4.25 Vt. Rte. 12 Woodstock Br. #19



a.



b.

Figure 4.26 Vt. Rte. 12 Woodstock Br. #19 – REPAIRED T Beam/Deck Reconstruction, \$150,000

4.9 Wing Wall

Wing walls serve the dual purpose of helping to channel the flow of water under the bridge (as opposed to around it) and to provide foundational support for the bridge structure. Wing walls can be subjected to severe environmental loading, especially during flood and ice jam events, as well as to the processes that degrade many concrete structures. Most of the repairs are cast-in-place restorations. Figure 4.27 shows a damaged wing wall on Vt.Rte.12 Berlin Br. #70. Figure 4.28 shows the repair. Figure 4.29 Vt.Rte.12 Elmore Br. #95 shows a wing wall with cracking and severe loss of section. Figure 4.30 Figure 4.31 shows a cracked and rotated wing wall on Vt.Rte.14 Hartford Br. #7. Figure 4.32 shows the repair. Figure 4.33 shows a cracked and rotated wing wall on Vt.Rte.30 Pawlet Br. #78. Figure 4.34 shows the repair along with supplemental riprap. Figure 4.35 shows a cracked and rotated wing wall and cutoff wall on Vt.Rte.30 Pawlet Br. #77. Figure 4.36 shows the repair. Figure 4.37 shows wing walls with severe loss of section on Vt. Rte. 108 Stowe Br. #10. Figure 4.38 shows an encasement and other repairs.



a.



b.

Figure 4.27 Vt.Rte.12 Berlin Br.#70



Figure 4.28 Vt. Rte. 12 Berlin Br. #70 - REPAIRED Head Wall/Wing Wall Reconstruction, \$150,000



a.



b.

Figure 4.29 Vt. Rte. 12 Elmore Br. #95



a.



b.

Figure 4.30 Vt. Rte. 12 Elmore Br. #95 - REPAIRED Wing Wall Encasement, \$100,000



a.



b.

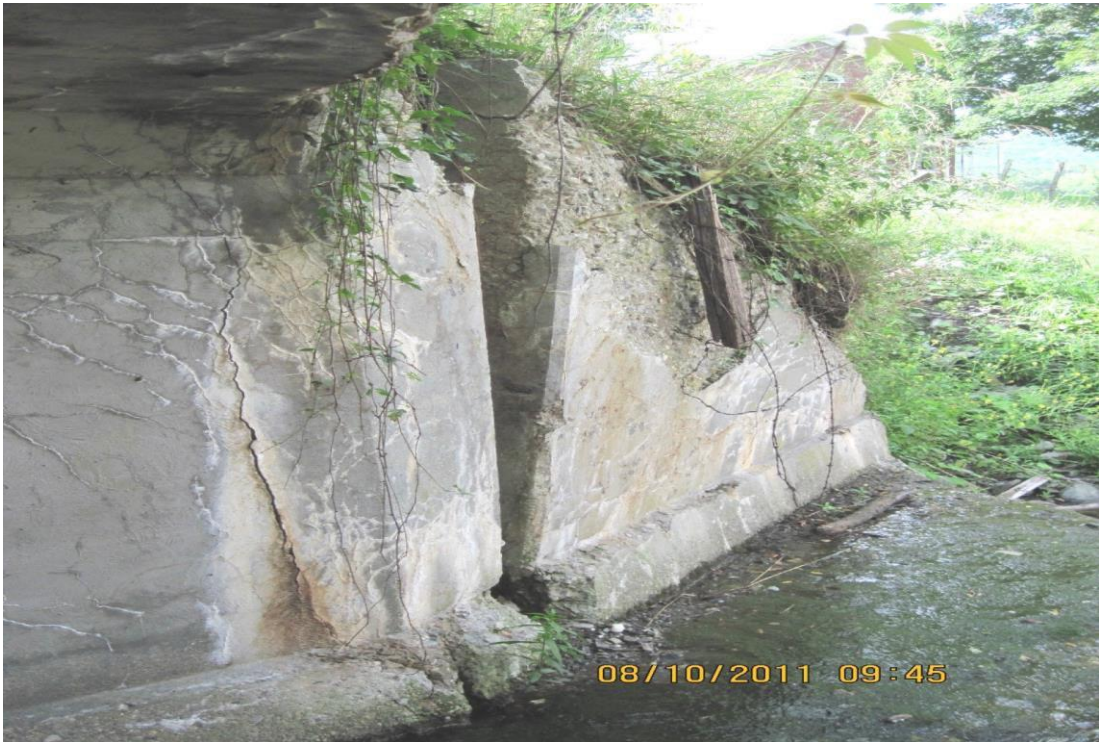
Figure 4.31 Vt. Rte. 14 Hartford Br. #7



Figure 4.32 Vt.Rte.14 Hartford Br.#7 - REPAIRED Wing Wall/ Cut-off Wall Reconstruction \$180,000



a.



b.

Figure 4.33 Vt. Rte. 30 Pawlet Br. #78



Figure 4.34 Vt. Rte. 30 Pawlet Br. #78 - REPAIRED Wing Wall reconstruction, \$80,000



Figure 4.35 Vt. Rte. 30 Pawlet Br. #77



Figure 4.36 Vt. Rte. 30 Pawlet Br.#77 - REPAIRED Wing Wall/ Cut-off Wall Reconstruction \$100,000



a.



b.

Figure 4.37 Vt. Rte. 108 Stowe Br. #10

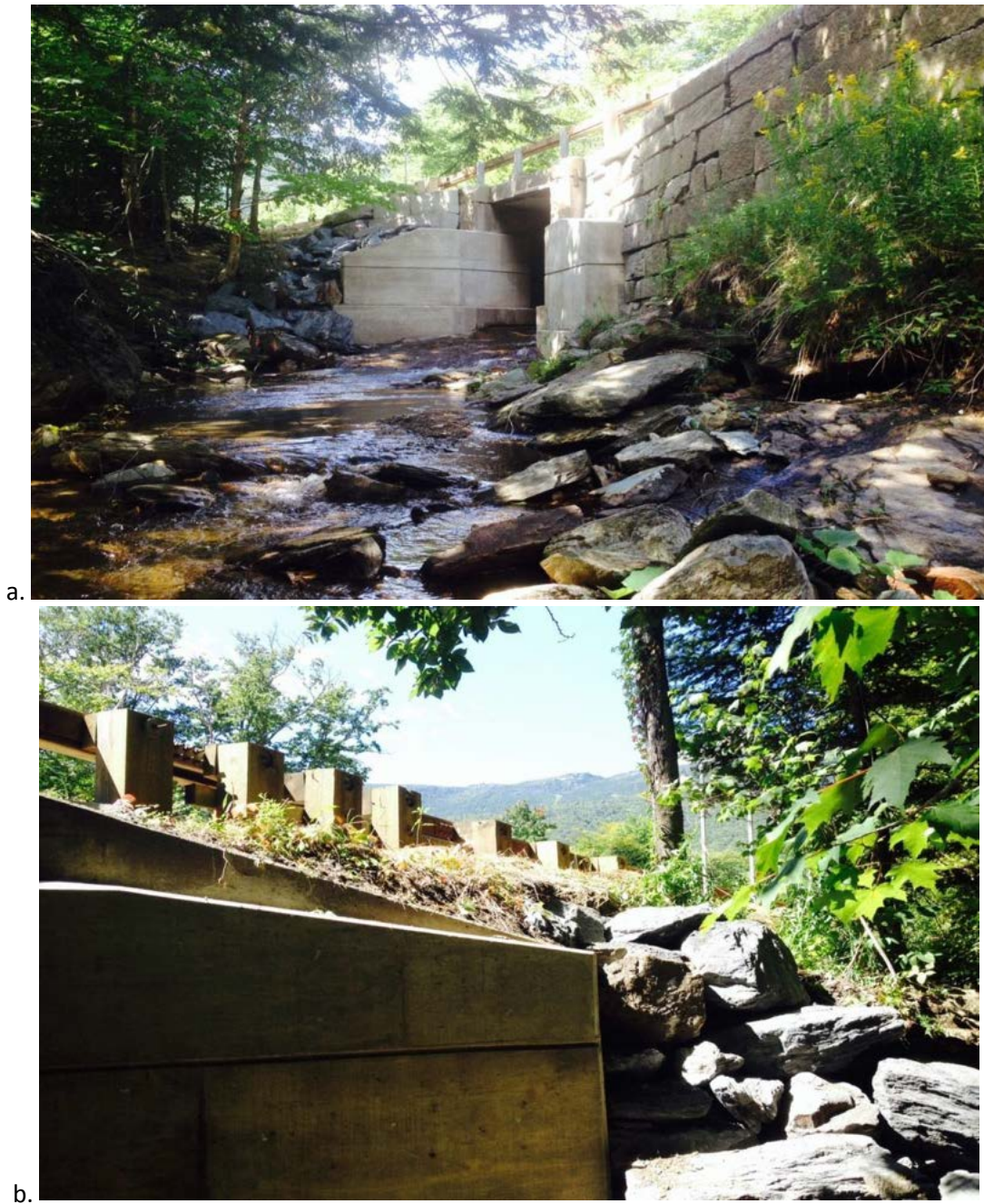


Figure 4.38 Vt. Rte. 108 Stowe Br. #10 – Repaired Wing Wall Encasement/ Other Repairs, \$200,000

4.10 Multiple Component Repairs

Some bridges suffer more than one type of damage. In these cases, it can be expeditious to perform multiple component repairs in one setting. Figure 4.39 I 91 Hartford Br. #42 N/S had damage to the abutments, piers and drainage system. Figure 4.40 shows the repairs. Figure 4.41 Vt. Rte. 113 Vershire Br. #11 had severe damage to both the deck and wingwalls. The repairs appear in Figure 4.42.



a.



b.

Figure 4.39 | 91 Hartford Br. #42 N/S



a.



b.

Figure 4.40 | 91 Hartford Br. #42-REPAIRED Abutment/Pier Repairs/Drain System \$125,000



a.



b.

Figure 4.41 Vt. Rte. 113 Vershire Br. #11



Figure 4.42 Vt. Rte. 113 Vershire Br. #11 - REPAIRED Deck/Wing Wall Repairs, \$150,000

5. VERMONT BRIDGES VISITED

Seven bridges in various states of repair were visited and photographed. Vtrans personnel accompanied UVM personnel to five of these seven site visits.

Prior to the visit a series of questions were prepared:

1. What is the most common type of deterioration occurring to these overpass bridges?
2. When were these types of overpasses built?
3. What is an average amount of time that passes until noticeable deterioration is found?
4. At what frequency are bridges inspected?
5. At what extent of deterioration is some sort of maintenance done?
6. Do you use a standard ranking system to bridge maintenance urgency?
7. What are the common repair techniques and materials used for: Cracks? Spalling? Corrosion?
8. What are the differences in repair techniques for different structural elements? (Deck, column, railing & beam)
9. What factors are taken into account when deciding a particular repair method?
10. Is there a decision making flow chart set in place or certain guidelines to choose the correct repair method?

Selected photographs, observations and photogrammetric reconstructions follow.

5.1 Swanton I-89 Overpass Bridge

The first bridge visited was the I-89 overpass bridge in Swanton, VT on July 25, 2014. The pier caps had recently been strengthened by the addition of FRP strips, Figure 5.1 and Figure 5.2. The repaired bridge was photographed using low-cost cameras. 2-D still shots from the cameras produced a fish-eye lens effect. Photogrammetry software compensated for the fish-eye distortion and converted the 3-D stereo images into 3-D surface point clouds, which were then imported into a Building Information Modeling (BIM) database and then converted into a 3-D printed solid model, Figure 5.3 through Figure 5.8.

It was observed that the FRP strengthening strips used a large number of small diameter anchor bolts to secure the strips to the pier cap.



Figure 5.1 Swanton I 89 overpass bridge with FRP strengthening strips bonded to the pier cap



Figure 5.2 Swanton I 89 overpass bridge with FRP strengthening strips bonded to the pier cap, bonding bolt pattern is discernable.

3D Cloud point data of Pier 1 in Auto Desk RECAP PRO



Figure 5.3 Photogrammetric 3-D point cloud rendering of Swanton I 89 overpass bridge pier from right side.



Figure 5.4 Photogrammetric 3-D point cloud rendering of Swanton I 89 overpass bridge pier from right side.

Pier 1 Scan to BIM in Revit

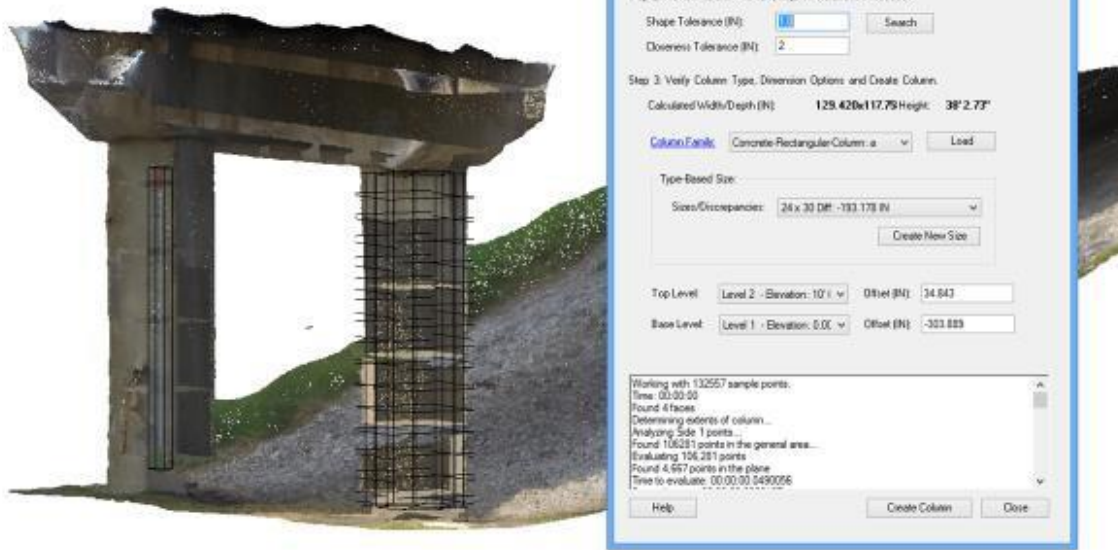


Figure 5.5 Integration of point cloud data of Swanton I 89 overpass bridge into Building Information Modeling (REVIT BIM) database

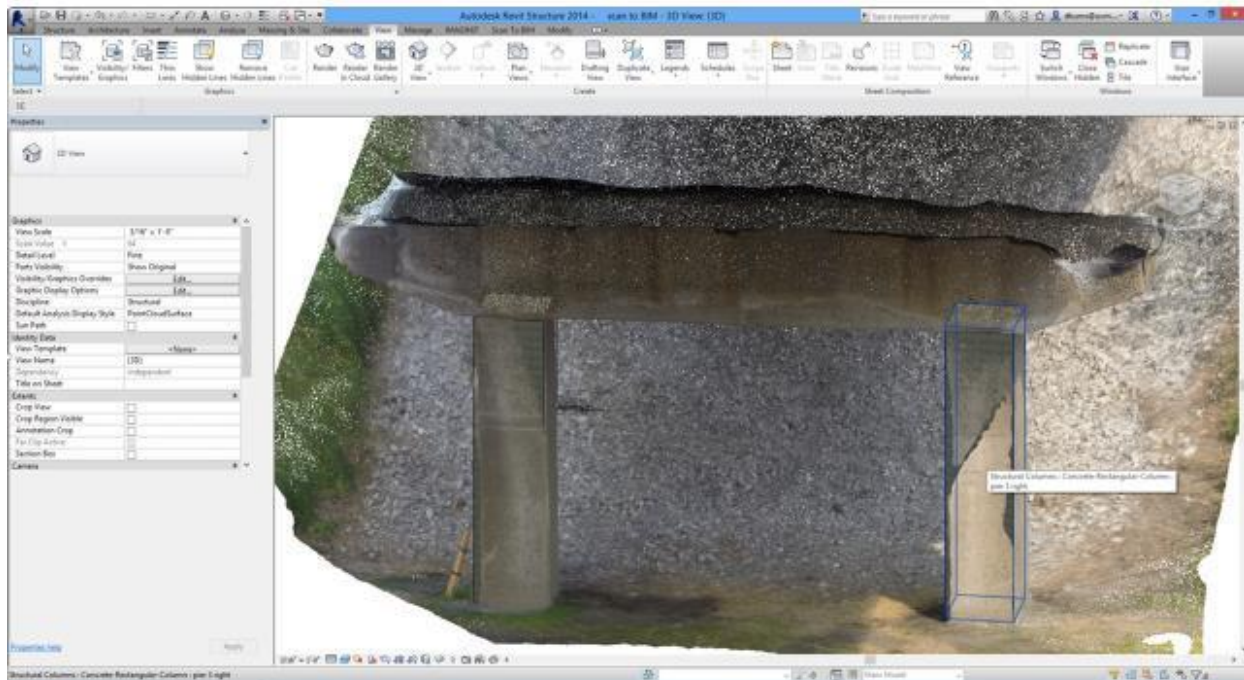


Figure 5.6 Fitting of point cloud data for Swanton I 89 overpass bridge into generic BIM shapes



Figure 5.7 3-D print rendering of Swanton I 89 overpass bridge from Autodesk Momento



Figure 5.8 3-D printed model of Swanton I 89 overpass bridge pier

5.2 Colchester/Milton I-89 Bridge

This bridge was visited on October 21, 2014. It is at the Milton Exit 17 on I 89 in Colchester VT, with coordinates 44°35'23.9"N 73°10'12.9"W. I 89 runs under US 2. The concrete members of the bridge are showing signs of distress. Spalling, cracking and steel corrosion was underway on all of the piers, which sit under expansion joints. Figure 5.9 shows a column with some cracking and rust stains, presumably due to reinforcing bar corrosion and swelling. Figure 5.10 to Figure 5.12 show the piers and underside of the deck with spalling and cracking damage. Figure 5.13 is a photogrammetric point cloud rendering of one of the piers. Figure 5.14 is a close-up view of one of the columns with cracking and spalling. Figure 5.15 shows various photogrammetric 3-D renderings of the column. **Error! Reference source not found.** shows a rubber-asphalt expansion joint over one of the abutments.

An important consideration in planning the repair of this bridge is that this highway interchange is tentatively scheduled for a major upgrade with new lanes and added capacity. It may be more cost-effective to wait and replace this bridge, rather than repair it.



Figure 5.9 Column on Colchester/Milton I-89 Bridge showing cracking, likely due to swelling corroded reinforcing bars



Figure 5.10 Spalling on underside of pier on Colchester/Milton I-95 Bridge. The deck is also showing some distress.



Figure 5.11 Spalling on pier cap of Colchester/Milton I-89 Bridge



Figure 5.12 Spalling on column of Colchester/Milton I-89 Bridge



Figure 5.13 3-D photogrammetric point cloud rendering of Colchester/Milton I-89 Bridge



Figure 5.14 Column with distress on Colchester/Milton I-89 Bridge

3D data

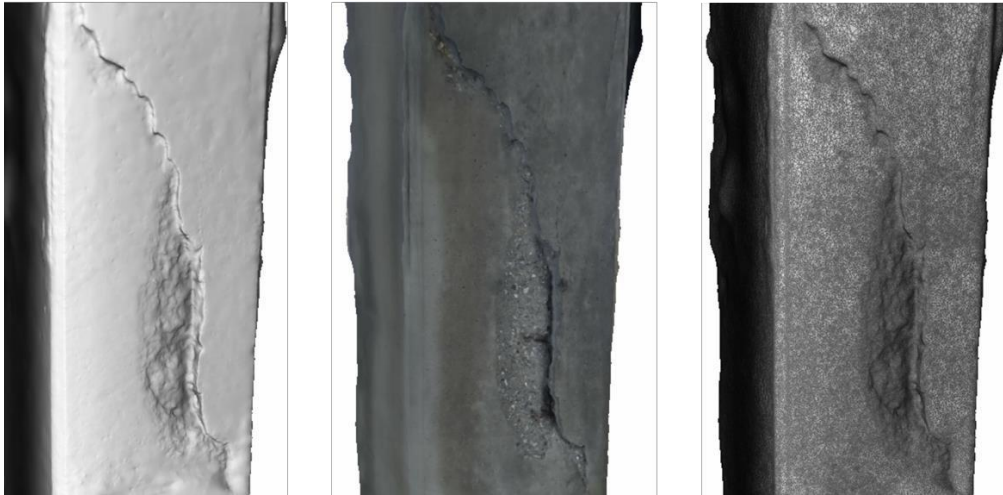


Figure 5.15 Various 3-D photogrammetric renderings of distress column on Colchester/Milton I-89 Bridge



Figure 5.16 Rubber-asphalt expansion joint over abutment of Colchester/Milton I-89 Bridge

5.3 Milton US 2 Lamoille River Crossing Bridge

This bridge is off I 89 Exit 17 on US 2 North over the Lamoille River, with coordinates: 44°36'12.7"N 73°12'16.7". This bridge was visited on October 21, 2014.

The bridge is in overall very good shape. It uses a relatively uncommon design for Vermont – mid-span hanger bolt connections. These have the effect of moving the expansion joints away from the piers. Expansion joints do sit over the abutments, where there is some small scaling and cracking. This bridge has a bare deck.

Figure 5.17 shows a finger expansion joint. Note that this type of joint, while being highly durable, does permit water with road salt to flow through. Figure 5.18 shows the bridge piers and a hanger joint.



Figure 5.17 Finger expansion joint on US 2 Lamoille River Crossing Bridge



Figure 5.18 US 2 Lamoille River Crossing Bridge with hanger pin joints

5.4 Williston I-89 Overpass Tafts Corner

This bridge is off I 89 Exit 12 near Tafts Corner in Williston VT. It is an overpass where US 2 runs below and I 89 above. The coordinates are: 44°26'22.3"N 73°06'53.9". This bridge was visited on October 21, 2014. The piers were repaired by encasement approximately fifteen years ago.

Figure 5.19 shows a pier column that has been encased with visible cracks. It is likely that these cracks are not new and are due to shrinkage during curing of the encasement. Figure 5.20 shows a similar pier encasement on the I 189 Spear St. Overpass Bridge. This photograph was taken in 2000 shortly after encasement. Cracks are visible. Figure 5.21 shows the bridge with distressed fascia and failed expansion joint gutter. Figure 5.22 is a close-up of the distressed fascia and expansion joint gutter.



Figure 5.19 Encasement repaired column on Williston I-89 Overpass Tafts Corner, with visible cracking



Figure 5.20 Spear St. I 189 Overpass Bridge pier in 2000 recently encased, with cracks



Figure 5.21 Williston I-89 Overpass Tafts Corner with encasement repair of the pier, failed expansion joint gutter and distressed fascia



Figure 5.22 Closeup of Williston I-89 Overpass Tafts Corner with encasement repair of the pier, failed expansion joint gutter and distressed fascia

5.5 Williston I-89 Oak Hill Rd Underpass Bridge

This bridge is on I 89 south of Exit 12 in Williston. It is on the underpass where I 89 runs below Oak Hill Rd. with coordinates: 44°26'03.3"N 73°04'14.9"W. This bridge was visited on October 21, 2014.

The pier columns suffered damage on the sides facing the road, presumably due to salt water spray. These columns were repaired by patching. The procedure used 1060 patch mix. Concrete was removed and edges are cut around deteriorated concrete. Formwork was strapped onto the columns, followed by the placing and curing of the patch concrete.

Figure 5.23 through Figure 5.26 show column repair patches. Figure 5.27 shows underside spalling from the deck. Figure 5.28 shows abutment damage.



Figure 5.23 Small column patch repair #1 on Williston I-89 Oak Hill Rd Underpass Bridge



Figure 5.24 Small column patch repair #2 on Williston I-89 Oak Hill Rd Underpass Bridge



Figure 5.25 Large column patch repair #1 on Williston I-89 Oak Hill Rd Underpass Bridge



Figure 5.26 Large column patch repair #2 on Williston I-89 Oak Hill Rd Underpass Bridge



Figure 5.27 Underside Deck Spalling on Williston I-89 Oak Hill Rd Underpass Bridge



Figure 5.28 Scaling on Abutment and Beam on Williston I-89 Oak Hill Rd Underpass Bridge

5.6 Richmond I-89 US 2 Underpass Bridge

This bridge carries US 2 over I 89 in Richmond VT, with coordinates: 44°24'03.0"N 72°59'04.2"W. The bridge was visited on October 21, 2014.

The piers on this bridge show significant spalling damage. It is notable that much of this damage only recently appeared, as it was not reported on a previous routine biannual inspection. Figure 5.29 through Figure 5.36 show columns and pier caps with spalling damage. Figure 5.37 and Figure 5.38 show a pier cap with the loss of a corner section that was big enough to cause a bearing to fail and the deck above to settle. Figure 5.39 shows parts from the failed bearing. Figure 5.40 shows the differential settlement of the deck at the expansion joint above the failed bearing.



Figure 5.29 Distressed column on Richmond I-89 US 2 Underpass Bridge



Figure 5.30 Close-up of a distressed column on Richmond I-89 US 2 Underpass Bridge



Figure 5.31 Distressed footing of a column on Richmond I-89 US 2 Underpass Bridge



Figure 5.32 Pier cap with spalling on Richmond I 89 US 2 Underpass Bridge



Figure 5.33 Square column with spalling at the corners on Richmond I-89 US 2 Underpass Bridge



Figure 5.34 Square column with spalling at the corners and pier cap on Richmond I-89 US 2 Underpass Bridge



Figure 5.35 Column with spalling at the corners on Richmond I 89 US 2 Underpass Bridge



Figure 5.36 Column with spalling at the corners and side on Richmond I 89 US 2 Underpass Bridge



Figure 5.37 Pier cap with lost corner section leading to subsided bearing on Richmond I 89 US 2 Underpass Bridge



Figure 5.38 Close-up of pier cap with lost corner section leading to subsided bearing on Richmond I 89 US 2 Underpass Bridge



Figure 5.39 Pieces from subsided bearing on Richmond I-89 US 2 Underpass Bridge



Figure 5.40 Subsided bearing leading to vertical misalignment of expansion joint on Richmond I-89 US 2 Underpass Bridge

5.7 Stowe Rte 100 Gold Brook Crossing Bridge

This bridge is on Rte 100 and crosses over Gold Brook, near Stowe, VT, with coordinates: 44°26'34.3"N 72°42'10.9"W. This bridge was visited on October 21, 2014.

This is a new bridge, built in 2014, Figure 5.41. The bridge uses prefabricated post-tensioned double-T girders with an integral cast-in-place concrete deck. Almost immediately following fabrication and construction, the bridge experienced cracking issues. Cracks appeared both in the deck, Figure 5.42, and in the girders, Figure 5.43. Sealant has been applied to the cracks, Figure 5.44.

The cracks are likely to be a serviceability and cosmetic issue, but not a safety issue. Load testing revealed no strength problems



Figure 5.41 Stowe Rte 100 Gold Brook Crossing Bridge



Figure 5.42 Deck patterned with cross-span cracks, approximately every 200 mm on Stowe Rte 100 Gold Brook Crossing Bridge



Figure 5.43 Girders have multiple cracks in top flanges, Stowe Rte 100 Gold Brook Crossing Bridge



Figure 5.44 Girder cracks sealed Stowe Rte 100 Gold Brook Crossing Bridge

5.8 I 89 Waterbury Overpass Bridge

These bridges carry I 89 over Waterbury, VT, along with on/off ramps. The bridge was visited on September 16, 2016.

The piers are being repaired by patching. The decks are being replaced using corrugated steel bottom-pans as integrated formwork. Figure 5.45 to Figure 5.47 show a pier base that is being prepared for patching repairs. Damaged concrete has been removed by manual and mechanically-assisted manual methods. Figure 5.48 shows pier columns with corners prepared for patch repair. Figure 5.49 to Figure 5.52 shows pier columns with patch repairs.



Figure 5.45 End view of pier base with damaged concrete removed on I-89 Waterbury Overpass Bridge



Figure 5.46 End view of pier base with damaged concrete removed on I-89 Waterbury Overpass Bridge



Figure 5.47 Top view of pier base with damaged concrete removed on I-89 Waterbury Overpass Bridge



Figure 5.48 Pier on I-89 Waterbury Overpass Bridge with corners prepared for patch repairs



Figure 5.49 Pier on I-89 Waterbury Overpass Bridge with patch repairs



Figure 5.50 Pier on I-89 Waterbury Overpass Bridge with patch repairs, note the extended gutters on span in background



Figure 5.51 Pier on I-89 Waterbury Overpass Bridge with patch repairs



Figure 5.52 Repaired pier on I-89 Waterbury Overpass Bridge with patch repairs, note the use of integrated corrugated panels on new concrete deck.

5.9 Middlesex

The I 89 Middlesex Overpass Bridge was visited on September 16, 2016. This bridge has a severe fascia spalling problem. Racks have been attached to the bridge to prevent concrete pieces from falling onto vehicles that use the underpass, Figure 5.53.



Figure 5.53 I 89 Middlesex Overpass Bridge with supplemental rack to protect vehicles passing under by catching pieces of concrete that spall and fall from the fascia

6. FLOWCHART AND GUI

Planning the repair of a concrete structure involves considerations of structural assessment, repair options and costs. Since the amount of information can be quite large, an effort was undertaken to automate some of the concrete repair decision-making with digital methods. The result is a computer-based system with a graphical user interface (GUI) that performed two primary tasks: 1. GUI-based input for bridge inspection and condition data; 2. GUI-based decision-making flowchart with links to information concerning repair options. The GUI has been written in MATLAB and can be exported in an executable format, making it a stand-alone application. The system presently runs on PCs, laptops, and MS pads, making it possible to implement the technology out in the field. The architecture of the system is modular so that it can accommodate integrating other components, such as the presentation of data from past bridge inspections. Appendix A contains a user manual for the GUI and outlines in greater detail the steps and utilization of the software.

6.1 Inspection Data Input GUI

The first section of the GUI served to automate the data input during a bridge inspection, and to provide a platform to insert supplemental information. Vtrans bridge inspection and repair reports (provided by J.B. McCarthy) formed the basis of the GUI, Figure 6.1. This version of the GUI allows the user the option to select the type of bridge inspection form, in this case a Field Inspection Form and also access to the Field Inspection Coding Guide, Figure 6.2. The GUI contains multiple pages of fields for data input, Figure 6.3 and Figure 6.4, including forms specifically for member damage and condition assessment, Figure 6.5. The system stores the data and can export the results in an Excel format, Figure 6.6 and Figure 6.7. If the user has questions, a pop-up coding guide can provide definitions and classification information, Figure 6.8.

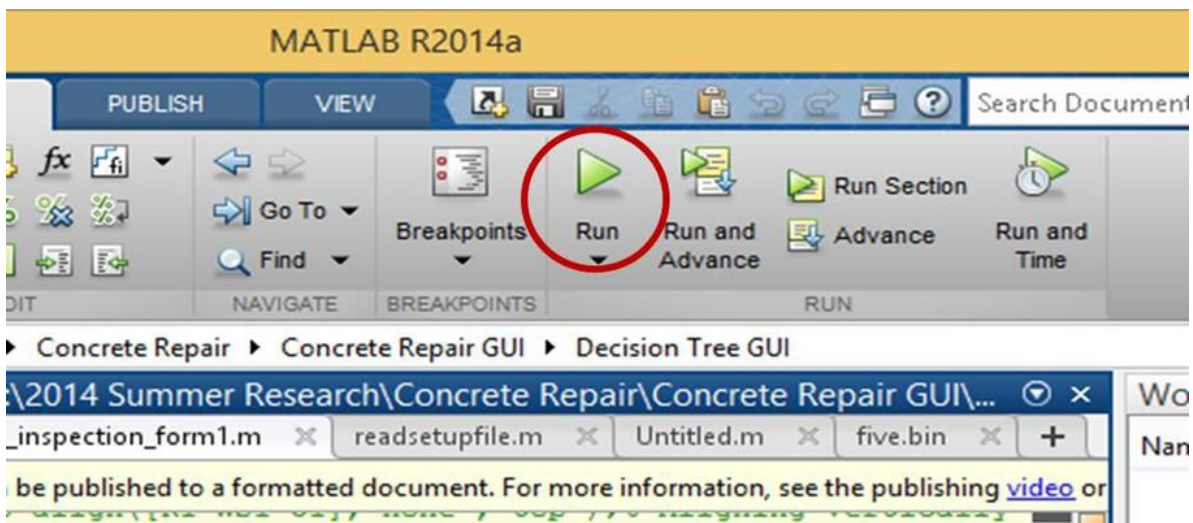


Figure 6.1 Bridge Inspection Form GUI with link to Field Inspection Coding Guide, coded in MATLAB, with executable file, exports Inspection Form to an Excel spreadsheet



Figure 6.2 The Bridge Inspection Form window, with two options: 1. The Field Inspection Form button, which directs the user to the electronic form, and 2. The Field Inspection Coding Guide button, which directs the user to a PDF version of the guide.

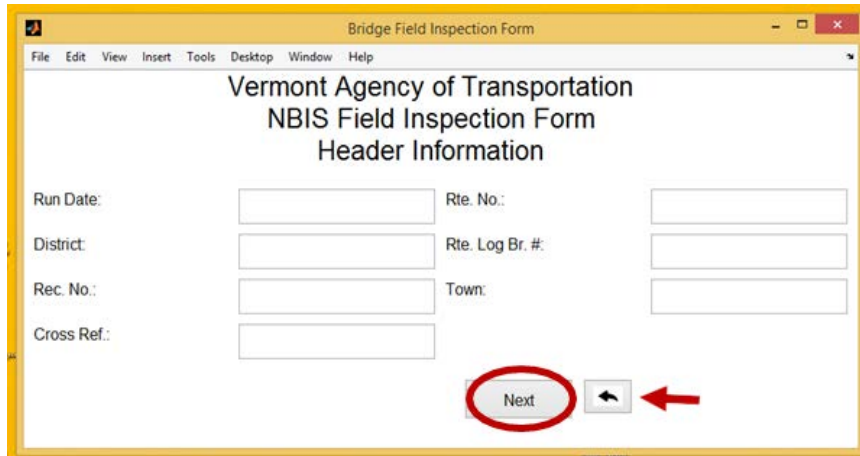


Figure 6.3 Bridge Inspection Form input

Bridge Field Inspection Form

File Edit View Insert Tools Desktop Window Help

Vermont Agency of Transportation NBIS Field Inspection Form Page 1: Further Information

County Code: <input type="text"/>	Functional Classification of Inventory Route: <input type="text"/>
Place Code: <input type="text"/>	Year Built: <input type="text"/>
Inventory Route: <input type="text"/>	Year Reconstructed: <input type="text"/>
Features Intersected: <input type="text"/>	Last Project Number: <input type="text"/>
Facility Carried by Structure: <input type="text"/>	Last Project Name: <input type="text"/>
Structure Number: <input type="text"/>	Lanes On and Under the Structure: <input type="text"/>
Location: <input type="text"/>	Average Daily Traffic: <input type="text"/>
Inventory Route, Minimum Vertical Clearance: <input type="text"/>	Year of Average Daily Traffic: <input type="text"/>
Latitude: <input type="text"/>	Source of ADT: <input type="text"/>
Longitude: <input type="text"/>	Design Load: <input type="text"/>
Bypass, Detour Length: <input type="text"/>	Approach Roadway Width: <input type="text"/>
Maintenance Responsibility: <input type="text"/>	Bridge Median: <input type="text"/>
Owner: <input type="text"/>	Skew: <input type="text"/>

Figure 6.4 Bridge Inspection Form GUI, an electronic version of the VTrans NBIS Field Inspection Form that exports data to an excel spreadsheet.

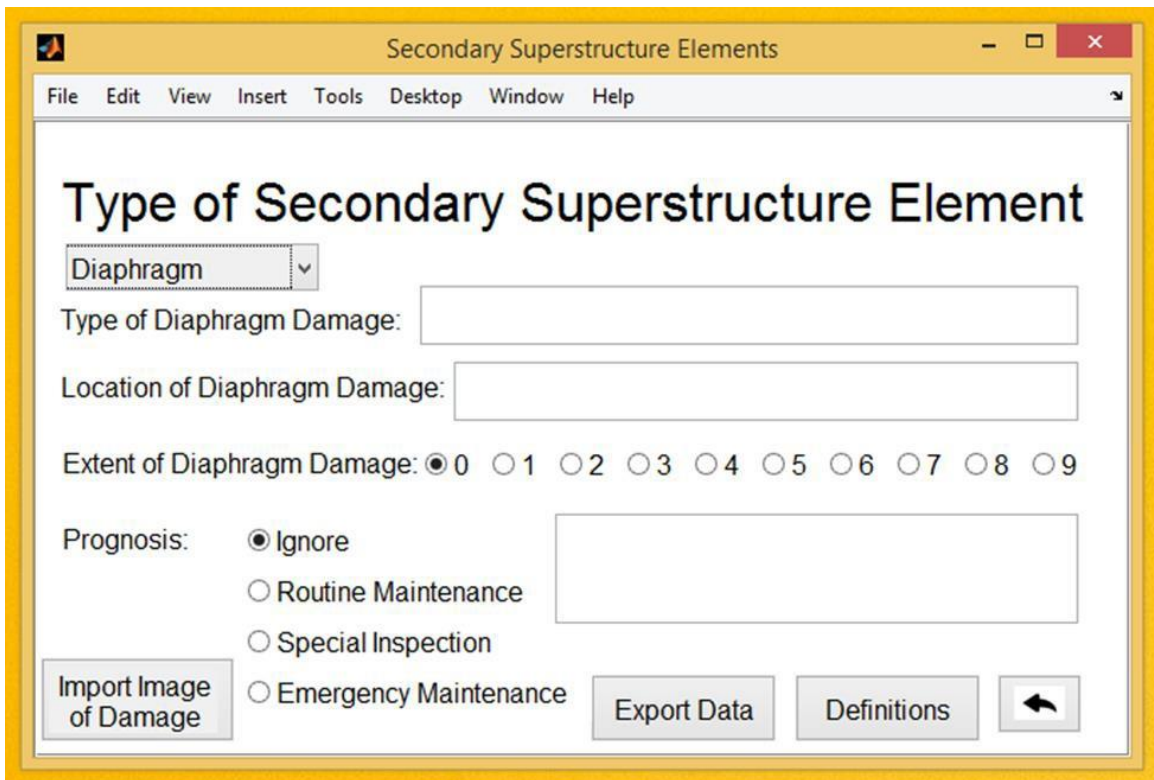


Figure 6.5 Assessment of bridge structure GUI, assessment of damage and prognosis, exports data to an excel spreadsheet. An image of structural damage can be uploaded.

File Edit View Insert Tools Desktop Window Help

Vermont Agency of Transportation NBIS Field Inspection Form Page 4: Further Information

Number of Utilities:	<input type="text"/>	Vertical Clearance Under Bridge (Highway):	<input type="text"/>
Year of Last Maintenance Activity:	<input type="text"/>	Vertical Clearance Under Bridge (Railroad):	<input type="text"/>
Type of Maintenance Performed:	<input type="text"/>	Vertical Clearance Under Bridge (Waterway):	<input type="text"/>
Year of Last Maintenance Activity (1):	<input type="text"/>	Operating Rating:	<input type="text"/>
Type of Maintenance Performed (1):	<input type="text"/>	Inventory Rating:	<input type="text"/>
Year of Last Maintenance Activity (2):	<input type="text"/>	H Truck at 67% YP:	<input type="text"/>
Type of Maintenance Performed (2):	<input type="text"/>	3 Axle Straight Truck at 67% YP:	<input type="text"/>
Alignment of Bridge Deck and Superstructure:	<input type="text"/>	4 Axle Straight Truck at 67% YP:	<input type="text"/>
Type of Bridge Rail:	<input type="text"/>	5 Axle Semi-Trailer Truck:	<input type="text"/>
Type of Approach Railing:	<input type="text"/>	6 Axle Semi-Trailer Truck:	<input type="text"/>
Type of Expansion Joint:	<input type="text"/>	Load Posting Signs:	<input type="text"/>
Type of Expansion Bearing Device:	<input type="text"/>	Federal Sufficiency Rating:	<input type="text"/>
Type of Foundation:	<input type="text"/>	Deficiency Status of Structure:	<input type="text"/>
		Bridge Plans on File:	<input type="text"/>

Figure 6.6 Export of inspection data

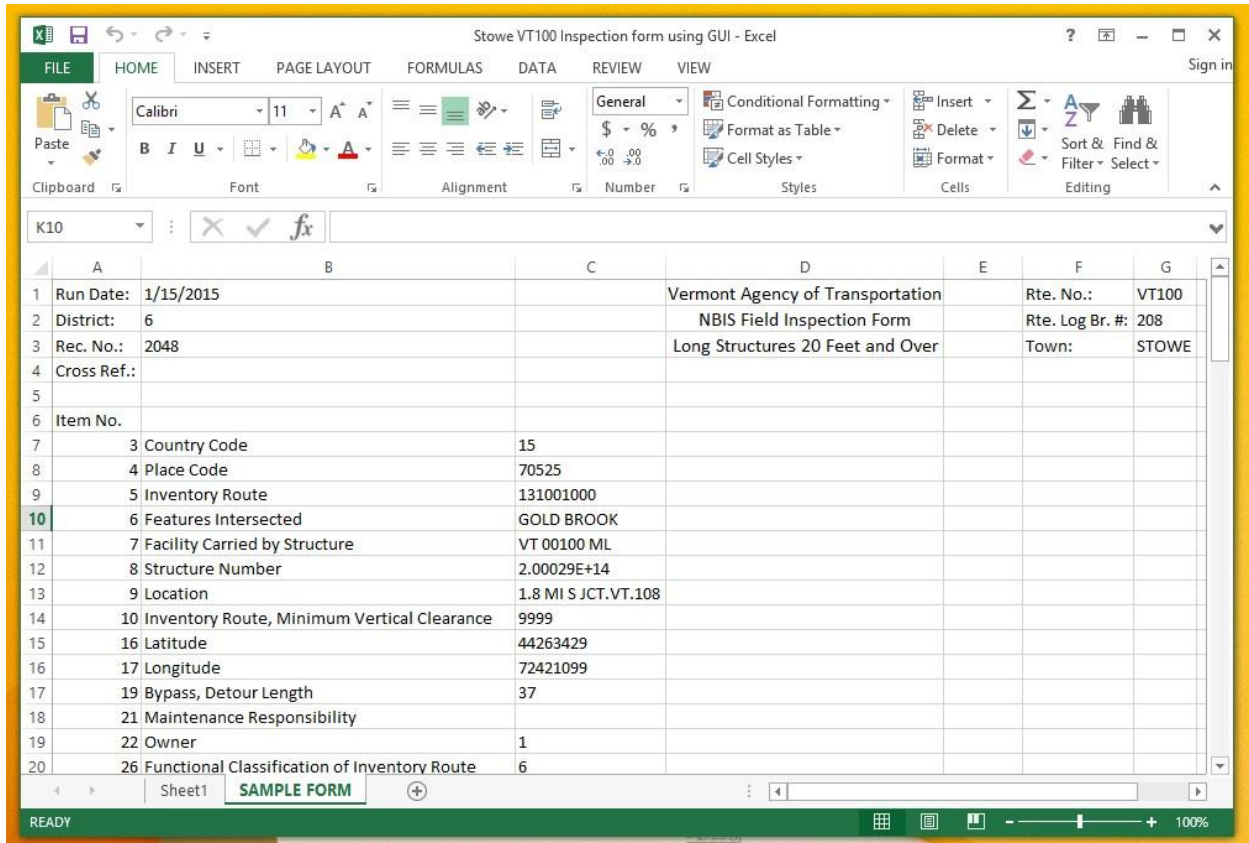


Figure 6.7 Bridge Inspection Form outputting data into an Excel spreadsheet

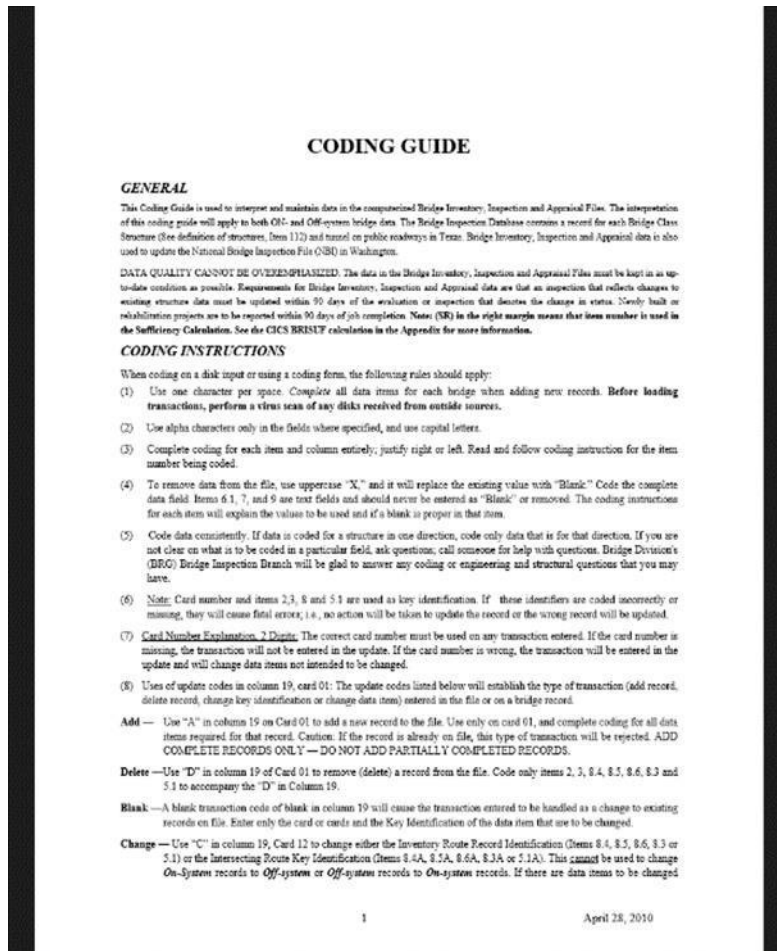


Figure 6.8 If there are questions, a Pop-up pdf of the Coding Guide is available.

6.2 Decision-Making Flowchart GUI

The concrete repair computer aided information and decision-making GUI has the following features:

- Information input Graphical User Interface (GUI)
- Decision Tree GUI
- Flow Chart GUI
- Helps the user determine the proper concrete repair technique for a specific type of damage.
- Gives definitions for bridge structure terminology
- Links user to the most effective repair procedure given the specific type of damage on the particular structural element.
- Opens relevant concrete repair procedures for specific types of structural damage
- Made in MATLAB: File Name (flow_chart_gui2.m)

The selected topics include: fascia, walls, columns and expansion joints. The flow chart allows the user to select the specific structural elements of interest and type of damage. It allows the user to input factors about the damage including: type of damage, location of damage, extent of damage, and prognosis.

In an effort to make the algorithm potentially widely usable without creating copyright issues, the primary source of information has been technical reports readily available on the internet, followed by copyrighted reports and documents from the American Concrete Institute. Nonetheless, some of the information sources are protected under copyright and outside usage would require an accommodation or finding equivalent open-source information.

The overall layout of the decision tree follows that recommended in the ACI Concrete Repair Manual (ACI, 2013). Figure 6.9 shows a top-level layout, Figure 6.10 the deck branch, and Figure 6.11 the expansion joint and fascia branches.

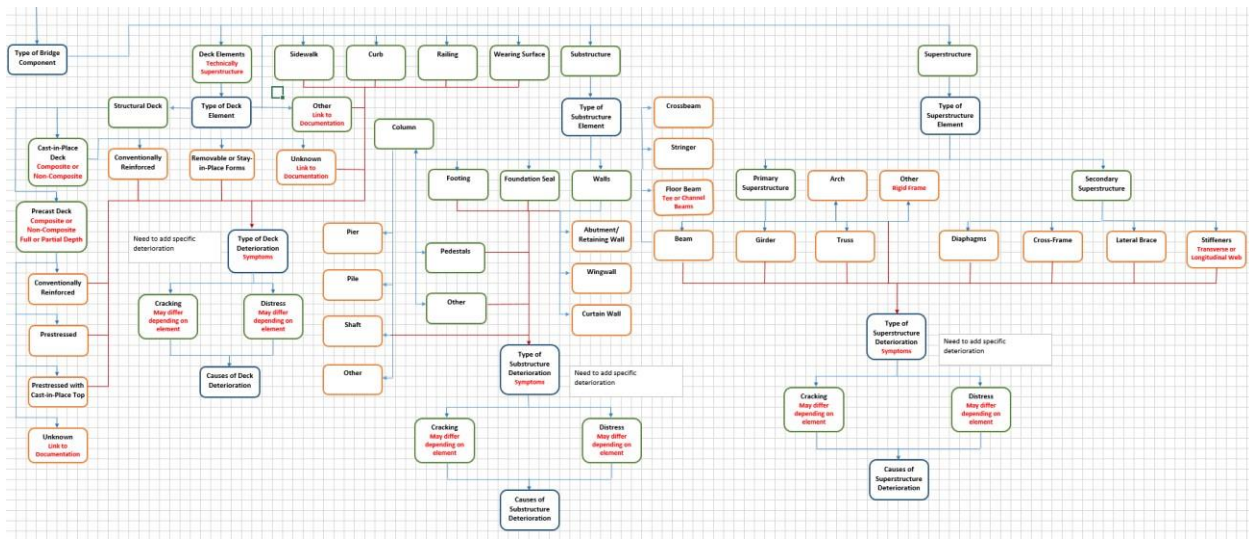


Figure 6.9 Bridge concrete repair decision tree, Adapted from ACI Concrete Repair Process Flow Chart (ACI Concrete Repair Manual 2013).

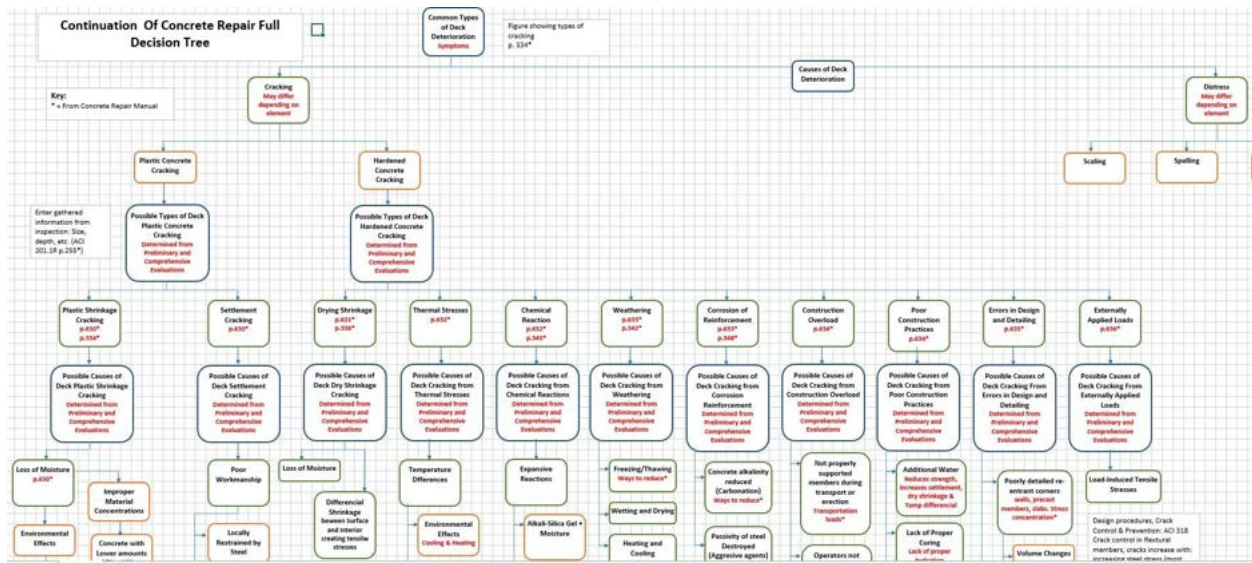


Figure 6.10 Deck branch of concrete repair decision tree, adapted from ACI Concrete Repair Process Flow Chart (ACI Concrete Repair Manual 2013)

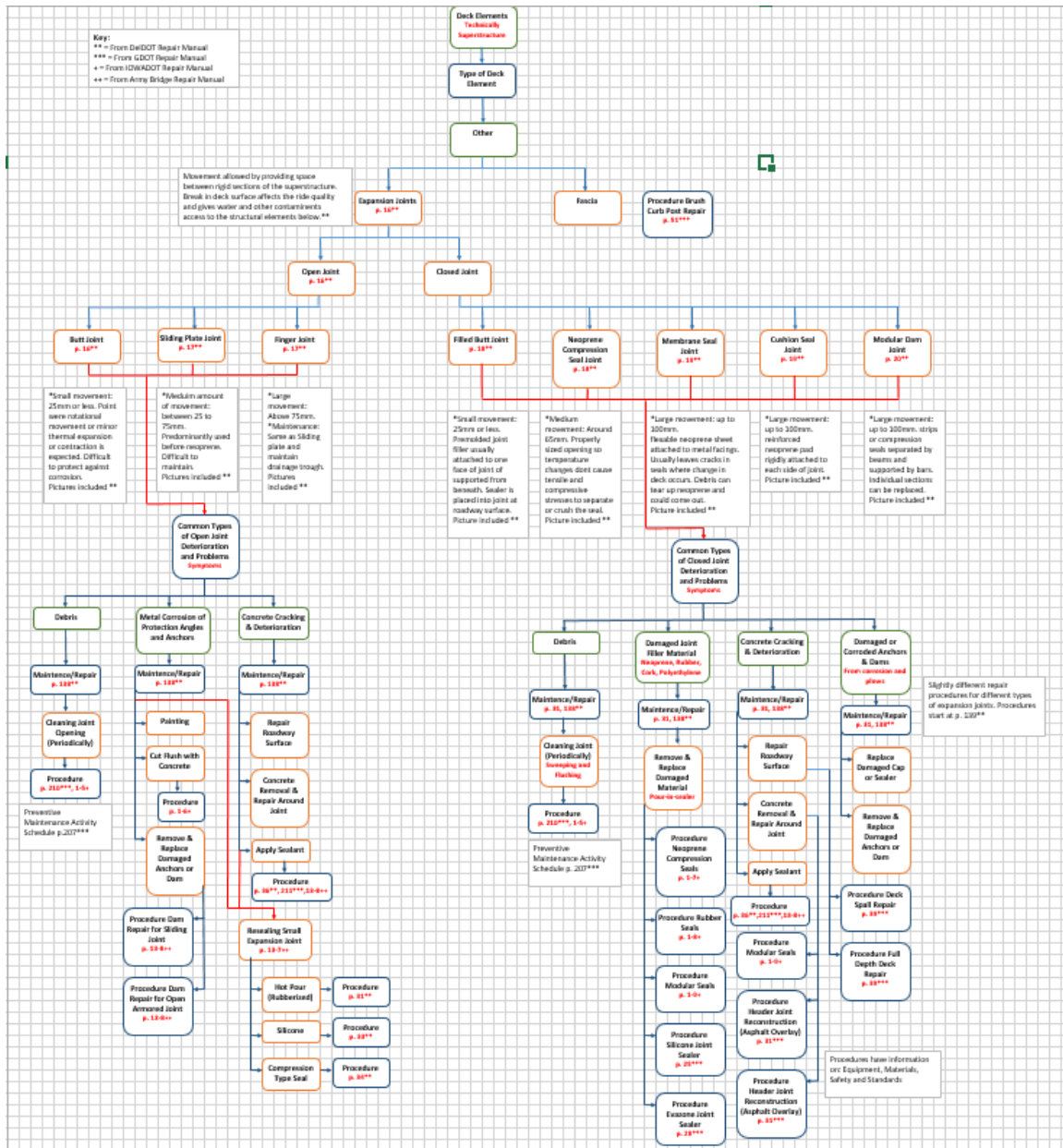


Figure 6.11 Expansion joint and fascia decision tree

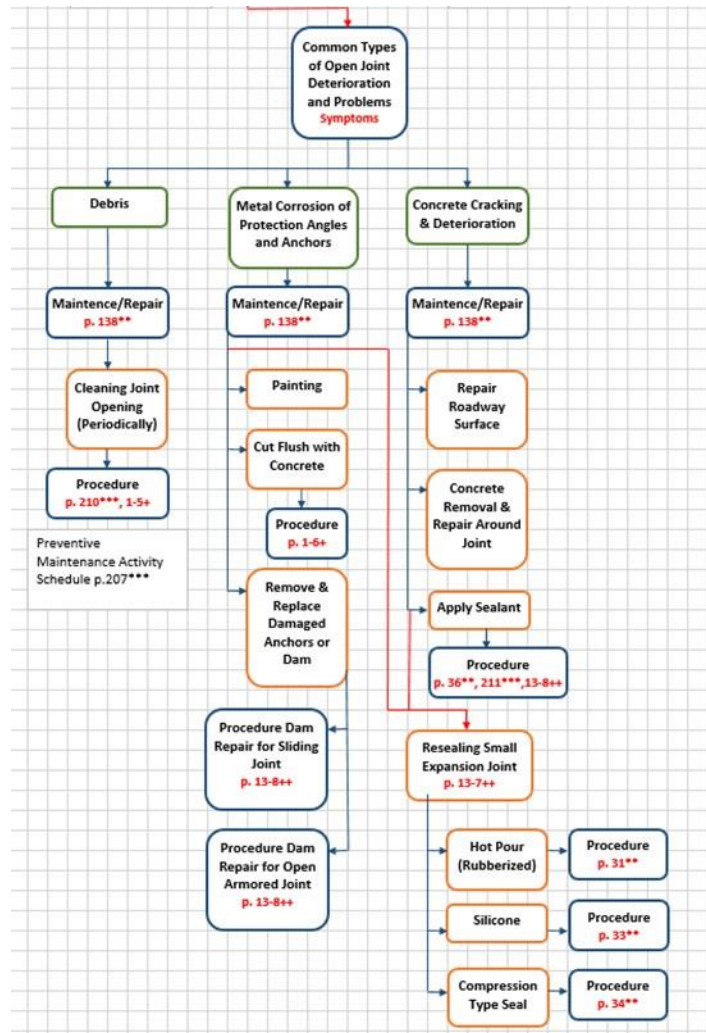


Figure 6.12 Bridge concrete repair decision tree – close-up of open expansion joint branch, adapted from ACI Concrete Repair Process Flow Chart (ACI Concrete Repair Manual 2013)

The GUI captured the framework of Figure 6.9 through Figure 6.11 with a layered set of pages for input and information output. The first step appears as an implementation of the information flowchart. In Figure 6.13, the user selects the element of interest which produces other element-specific windows. Figure 6.14 and Figure 6.15 show typical windows for butt joints.

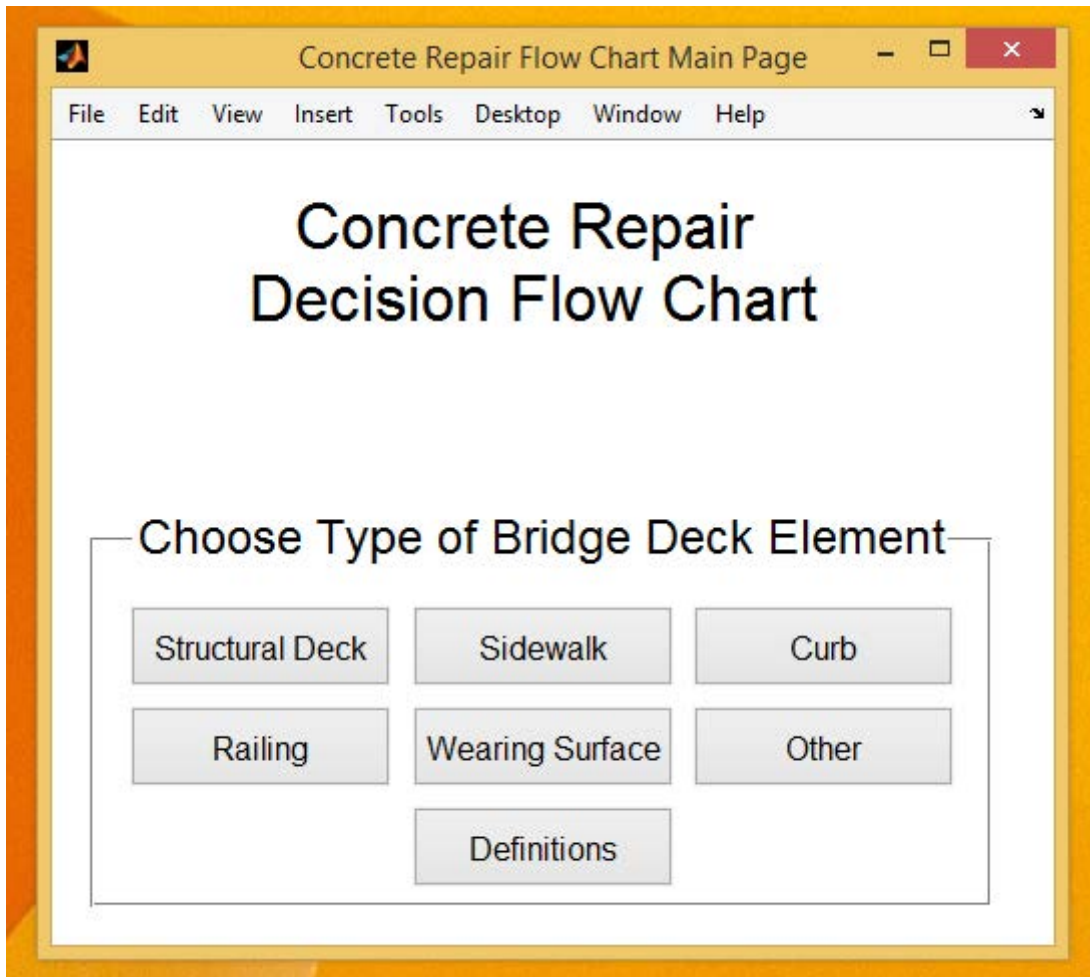


Figure 6.13 Screen shot of Concrete Repair Decision Flow Chart GUI main page, with user friendly features including definitions of terms in current GUI page



Figure 6.14 Screen shot of particular bridge deck element GUI (going through flowchart), enables picking type of damage to element to select proper repair procedure

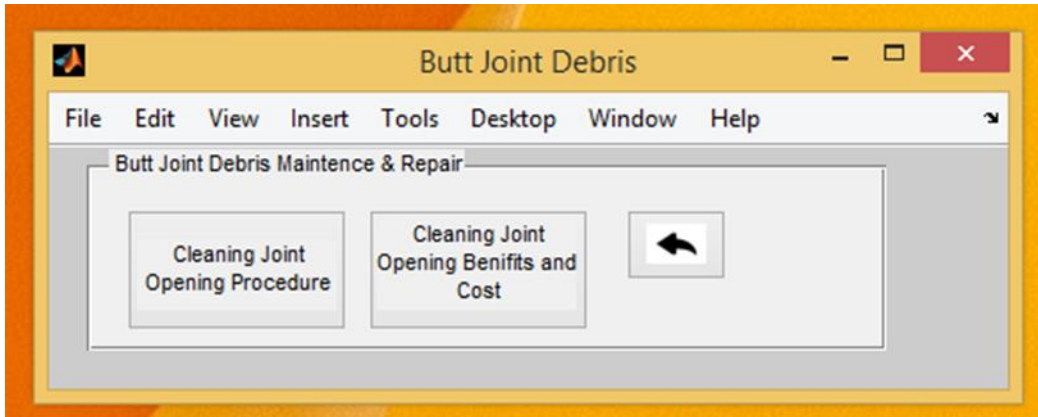


Figure 6.15 Screen shot of particular bridge deck element GUI (going through flowchart) with particular damage, user can pick correct repair procedure (links to repair procedures from list of data files) and determine benefits associated to repair and estimated cost of repair.

The GUI also contains a decision tree for concrete repair. Figure 6.16 shows the top level screen. Typical sub-windows appear in Figure 6.17 and Figure 6.18. The GUI contains clickable pop-up links to definitions, Figure 6.19, and repair procedures, Figure 6.20. The GUI can document the decision-making process, Figure 6. 21.

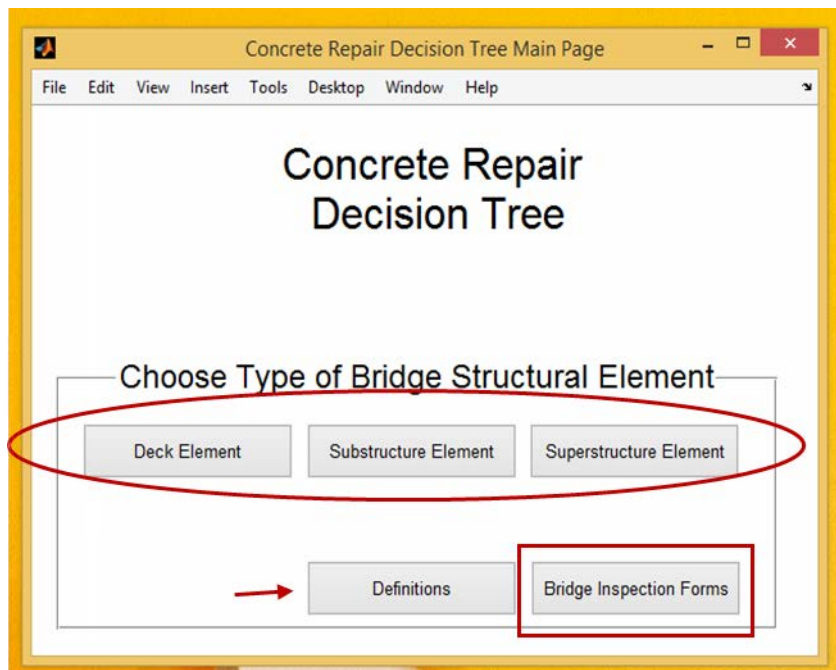


Figure 6.16 Concrete Repair Decision Tree Main Page

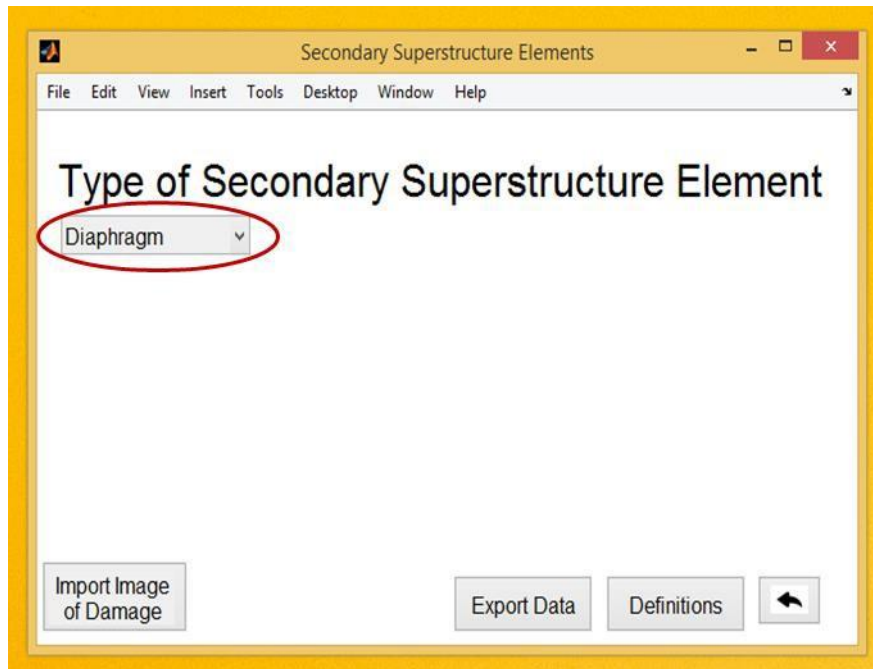


Figure 6.17 Damage and Prognosis Pop-up Window

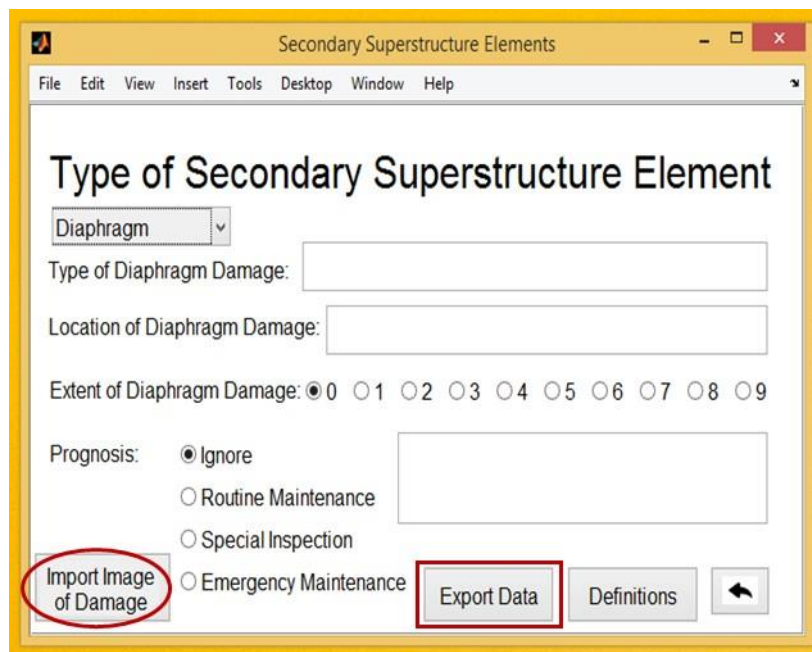


Figure 6.18 Damage and Prognosis Pop-up Window with Full Options

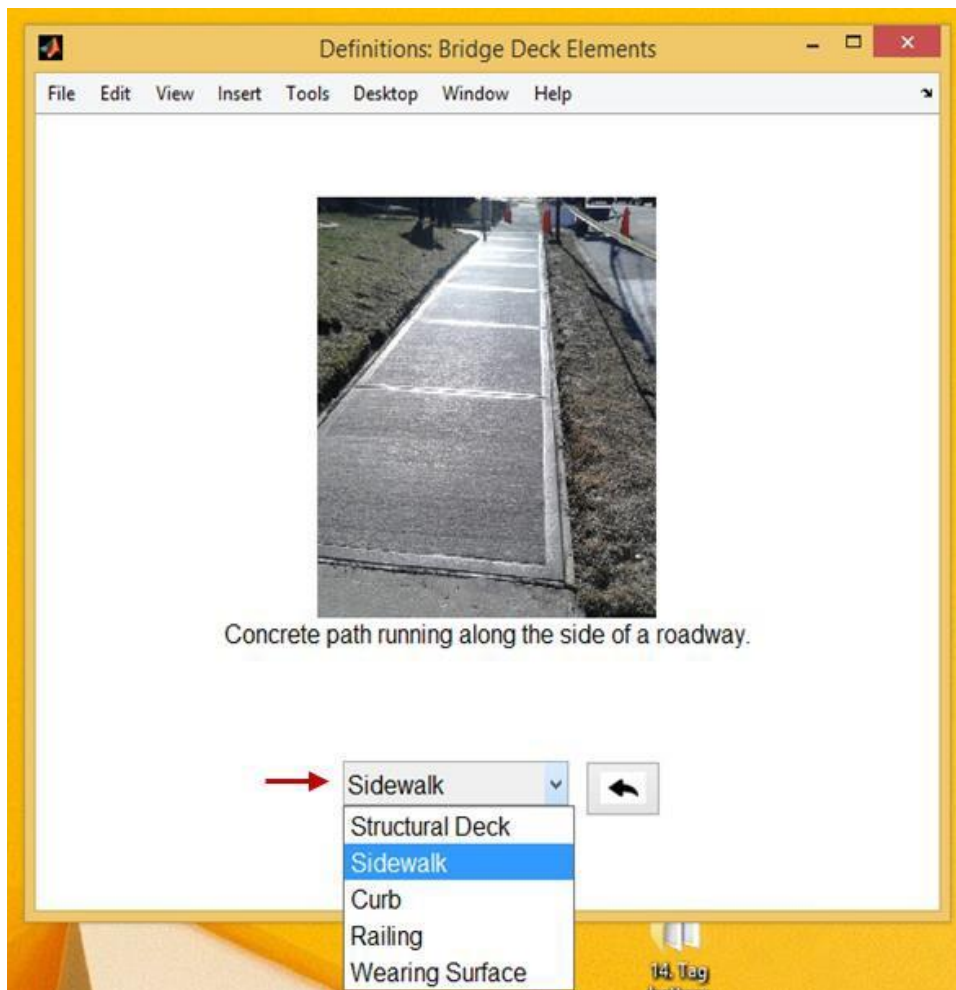


Figure 6.19 Clickable link to definitions

Clean Expansion Joints



Procedure:

Use brooms and shovels to remove excess debris near the joint. Remove debris build up in the expansion joint, exercising care as not to damage the expansion joint material.

Safety:

- Traffic Control
 - GDOT Operations Work Zone Traffic Control, or
 - GDOT Standard Drawings 9100 thru 9107 and MUTCD Part 6 – Temporary Traffic Control

Equipment:

- Traffic Control, as needed.
- Personal safety equipment.
- Brooms/Shovels.
- Wheel Barrow

Materials:

- None

Figure 6.20 Clickable link to repair procedure

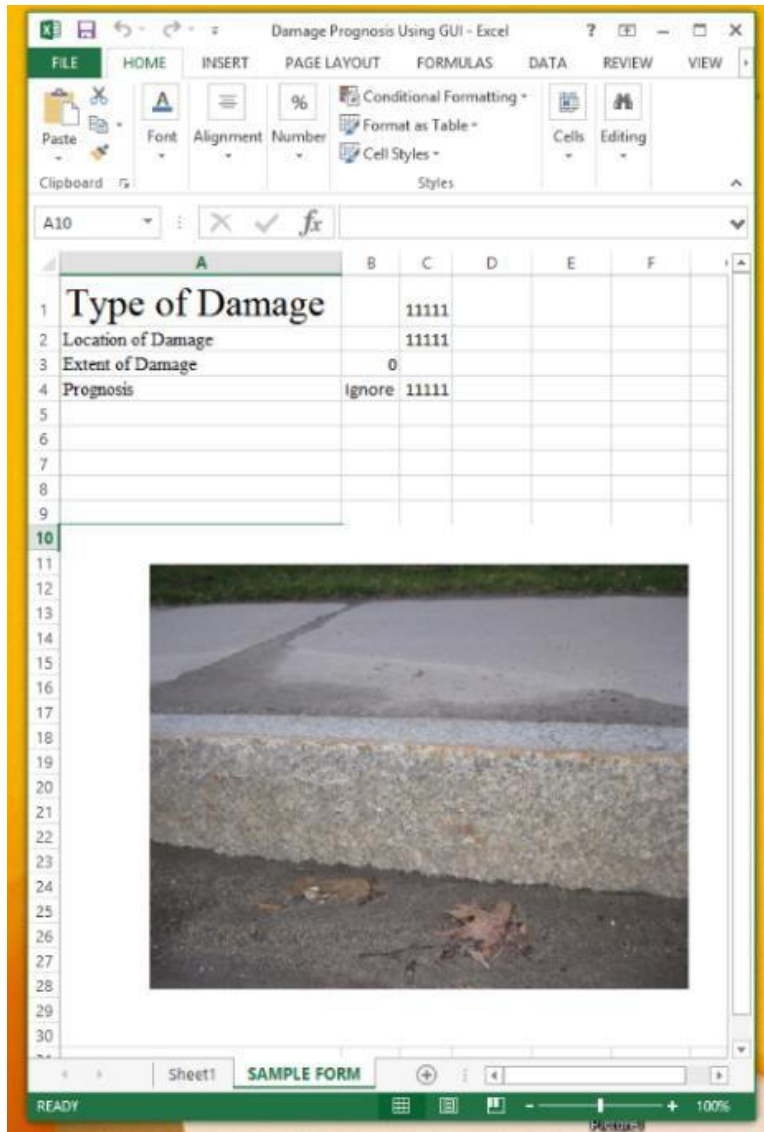


Figure 6.21 Exported Data from Decision Tree GUI

7. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Many concrete elements of transportation structures in Vermont have been exposed to severe environmental conditions. Many of these elements have been in service for over fifty years and are showing signs of distress. It may be possible with suitable repair techniques to extend the lifetime of some of these structures at a relatively low cost.

It should be noted that while this report documents multiple bridges with distressed concrete, these bridges are not inherently unsafe. If the result of an inspection deems a bridge to be unsafe, it is either closed or posted for reduced weight loads.

The primary objectives of this research project have been completed as follows:

Objective 1: Assess present practices of concrete repair – The objective is to identify repair practices for concrete transportation infrastructure in Vermont and neighboring states. This includes damage identification, damage assessment, repair design, repair, and post-repair assessment. *Chapter 2 presents a review of the available literature on concrete repair, with an emphasis on transportation structures. Chapter 3 describes concrete repair and bridge maintenance decision-making processes. Chapter 4 documents a series of concrete bridge repairs in Vermont, primarily during 2013 and 2014. Chapter 5 contains information on a series of distressed concrete bridges in Vermont that are being repaired, scheduled for repair, or possibly awaiting replacement.*

Objective 2: Develop flow chart of decision-making and options for repair practice and evaluation – The flowchart can lead to a guide with recommendations for maintenance personnel and engineers, with an emphasis on cost-effective procedures that minimize imposing additional burdens on inspection and maintenance personnel. *Chapter 6 and Appendix A describe a computer-based GUI that implements a decision-making framework.*

Objective 3: Develop procedures for integrating repair options and decisions into asset management – This will aid in reducing lifetime costs of ownership and assist in statewide maintenance planning. *Chapter 3 describes procedures for integrating repair options and decisions into asset management. Chapter 6 covers a GUI that enables access to relevant documents on various concrete repair options.*

Objective 4: Recommend areas for further study and tech transfer to make cost effective repairs - This is an effort to identify topics of importance to Vermont and achievable within present resource constraints. *The sequel in this chapter contains recommended areas for further study.*

Objective 5: Describe a future Phase II effort that would take the procedures that seem to work the best and apply them in the field. *The sequel in this chapter describes a future Phase II effort.*

Recommendations for future research:

The design of a bridge to last 50 or 100 years requires an understanding of how the overall structure, components, elements and details interact to affect endurance and maintainability. The difficulty is that it is nontrivial to predict long term durability without a track record of long term loading. VTrans is now in the position where it has many bridges with service lives over 50 year and many that are newer. During much of the lifetimes of these bridges, they were not well maintained. VTrans is beginning to address bridge maintenance and preservation with specific funding. Many of the distressed bridges have significant life left in general, but require repairs to the joints, curbs, fascia and bridge seats to realize the expected overall life of the bridge. Some recommendations for future research that can help improve the effectiveness of these efforts are:

1. *Fascia* – Many of the fascia on Vermont overpasses have been in service for over fifty years. The fascia are undergoing a rapid deterioration due to the nonlinear nature of corrosion swelling damage. The result is a severe spalling problem. This is an aesthetic, serviceability and safety issue. Fascia are expensive to repair and difficult to partially repair or mitigate the damage, Figure 5.53. The future research would look at: a. Lower cost repair methods; b. Durable design methods; c. Mitigation strategies, possibly sealers or electrochemical chloride extraction.
2. *Expansion Joints* – Bridges typically use expansion joints to allow the deck to move small amounts to allow movement with minimal stress buildup. Thermal expansions, traffic loads and small foundation movements can all be relieved with expansion joints. Piers are a natural location for expansion joints because of the location of bearings. The expansion joints allow for deicing salts to migrate to the piers and substructural elements, leading to corrosion problems, Figures 5.37 – 5.40. At the moment there are several competing methods of resolving problems with expansion joints. These include various improved joints and jointless configuration. The performance and cost benefit of the various options would be examined by either a retrospective or prospective study of the options. An additional topic would be to look at designing mid-span joints that avoid fracture-critical hanger pins yet provide the ease of expansion and avoid leaking salt and water onto the piers, Figure 5.18.
3. *Piers* – Examine the value in sealing against salt spray and salt leaking through expansion joints, so as to prevent or delay the types of damage appearing in Figures 5.29 – 5.36.
4. *Economic Questions* – Concrete repair is as much of an economic question as technical. Understanding the economics of repair in the context of the market for repair contractors and overall transportation network growth could possibly improve procurement outcomes. This would examine: 1. The timing and scope of repairs versus seasonal construction cycle fluctuations; 2. The timing and scope of repairs versus anticipated network changes; 3. The training of contractors in newer methods, and raising the state of the art in repair techniques used by local contractors.
5. *Repair Techniques* – This would look at the possible role of modern concrete repair methods in the management of Vermont’s transportation infrastructure. Possible questions include: 1. FRP can help with strengthening, what about durability? 2. The value of electrochemical chloride extraction; 3. Long term performance monitoring of all treatments, i.e. joints, deck sealers/membranes, conditions that lead to rapid degradation, and use of digital sensing methods including 3D photogrammetry/lidar.

6. *Integration into Design* – An important question is: How to incorporate durability and maintainability into the design of new bridges and major reconstructions? The design of highway bridges has evolved to include features with improved durability. Many of the older bridges (50 years or more) in Vermont have expansion joints over the piers, and bridge seats, leading to long term durability issues. More recent designs appearing in the past 25 years use a jointless configuration. Many bridges in Vermont use an asphalt overlay with impermeable membrane on the bridge decks to prevent reinforcing bar corrosion. More recent designs use a bare deck with a more impermeable concrete mix, along with epoxy-coated or stainless steel reinforcing bars. These newer designs have considerable potential to increase durability. Maintainability is a separate, but related, design issue that has the potential for both reducing the lifetime cost of ownership and extending the useful life of bridges. Research into these design issues should include a critical evaluation of the performance of existing designs.

7. A possible *Future Phase II* effort that would take the procedures that seem to work the best and apply them in the field. This would use the GUIs as a decision-making tool on upcoming concrete repair work, most likely with the inclusion of past inspection data in the GUI. Determine if it aligns or differs from present practice. Concentrate on some of the key problems in Vermont bridges. These are fascia, expansion joints, and columns and piers under expansion joints.

Utilization and Transfer of Concrete Repair Technology

The combination of age and severe environmental loading in Vermont has created the situation where the concrete in many transportation structures is in distress or well on its way to being distressed. The information collected during this project, along with the computer-based GUI have potential utility to Vtrans in concrete structure maintenance and repair. One overarching concept is that properly-timed applications of relatively low-cost maintenance actions can reduce the rate of degradation, and delay or prevent the need for costly repairs. These actions include the application of sealers to critical components, such as curbs, fascia and piers; the maintenance of proper drainage and gutters on expansion joints; and the maintenance of bearings to allow for proper movement of the bridge structure. A second concept is that concrete repair and bridge maintenance decision-making is a complicated topic requiring consideration of bridge inspection history, structural characteristics peculiar to the particular type of design, available repair techniques, economic considerations and, above all, safety of the public, along with maintenance and inspection personnel. The computer-based GUI developed in this project collects and presents much of this information in a potentially useful manner. It may be possible to use this GUI and the associated information database as the basis of a tool that is directly useful to Vtrans, or as a framework guiding the design and development of such a tool.

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APPENDIX A. CONCRETE REPAIR GUI MANUAL

User's Manual for Concrete Repair GUI

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June, 2015

ABSTRACT

Every second, millions of Americans depend on a vast U.S. infrastructure that extends from coast to coast and is exceeding its design life. The health and state of concrete structures can be more efficiently examined and monitored with the implementation of an interactive Concrete Repair Flow Chart. It will incorporate an easily accessible database of cost-effective and rapid concrete repair techniques that a user can access using a simple Graphical User Interface (GUI). The Concrete Repair GUI software will allow the user arrive to the most effective type of repair technique by properly identifying the concrete structure and analyzing the damage to that particular structure.

ACKNOWLEDGEMENTS

I would like to take this moment to give a special thanks to Dryver Huston Ph.D., Dylan Burns Ph.D., and the VTrans personnel that helped us with this project.

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Graphic User Interface (GUI) Overview:

The American Concrete Institute (ACI) and the International Concrete Repair Institute (ICRI) both have published numerous manuals that serve as the standard references for proper concrete repair methods and procedures. The aim of this project was to create a virtual database of proven concrete repair methods and procedures on a variety of concrete bridge structure elements. To access this database, which would be a compilation of ACI and ICRI manuals in conjunction with a number of published concrete repair manuals from certain states Department of Transportation (DoT), a user friendly computer software would be developed to access the mentioned database. The software would incorporate a simple Graphic User Interface (GUI) that would let the user easily navigate through the database to locate the proper concrete repair procedure for a particular structural element.

Due to the novelty and magnitude of a virtual concrete repair database, a completed product was not conceived. Three working GUI's were completed that serve as individual tools that guide the user through the selection of the proper repair technique for a particular structural element.

The first GUI (Bridge Inspection Form GUI) creates an electronic version of a Bridge Inspection Form which can be easily filled out in the field and instantly be saved as document and sent wirelessly to a specific DoT database. By answering inspection questions in the field through this GUI, office time deciphering notes, recollecting information and typing out an inspection form is eliminated.

The second GUI (Decision Tree GUI) makes it possible for the user to record and assess damage to a particular structural element. This GUI gives the user the options of importing an

image of the damage to the structural element and the option of exporting the data for later use. The information from this GUI will be used in conjunction with other information to select the proper repair technique.

The Third GUI (Flow Chart GUI) makes the user navigate through a flow chart that ultimately leads to proper repair technique based on the type of bridge structure element and the type of damage. All prior GUI's, which were listed above, would be integrated into this GUI. This GUI serves as the foundation that the other GUI's use and be built on. The information gathered from the other GUI's would be funneled through the Flow Chart GUI to arrive at the proper repair technique.

Below are detailed instructions on how to use and navigate through the GUI's mentioned above. A list of the GUI's features and brief descriptions are also included.

Planning and Creation of Concrete Repair GUI

The idea for an electronic version of a Concrete Repair Flow Chart to select the proper concrete repair techniques for a specific bridge structure element came from a project sponsored by the Vermont Department of Transportation (VTrans). This project is a part of a multi-phase project with VTrans. Below is the introduction and the objectives for this project with VTrans titled: “Cost-Effective and Rapid Concrete Repair Techniques.”

Introduction:

The intent of this project is to identify concrete repair practices that work best for the climate and infrastructure conditions in Vermont. Concrete is the principal component of many transportation structures. While highly durable, a variety of processes degrade and damage concrete. Replacement is expensive. Many cases warrant repair instead of replacement. Since many damage processes are progressive, early and properly timed repairs can reduce costs. Overall lifetime cost of ownership approach to selection and design of repairs has merit, but requires good information about costs and outcomes. There is a possibility that proper timing and application of these repairs can be of great benefit to maintenance activities – including lifetime costs and rapid techniques that allow for expedited designs of repairs and minimizing repair times. Realizing the advantages of concrete repair requires effective execution of damage identification, damage assessment, repair design, repair, and post-repair assessment.

Objectives:

Phase I:

- a. Objective 1.1: Assess present practices of concrete repair
- b. Objective 1.2: Develop flow chart of decision-making and options for repair practice and evaluation
- c. Objective 1.3: Develop procedures for integrating repair options and decisions into asset management.
- d. Objective 1.4: Recommend areas for further study and tech transfer to make cost effective repairs – This will be an effort to identify topics of importance to Vermont and achievable within present resource constraints.
- e. Objective 1.5: Describe a future Phase II effort that would take the procedures that seem to work the best and apply them in the field.

Phase II:

- a. Objective 2.1: Identify concrete repair conditions in Vermont that are good candidates for application of the decision-making flow chart. (The structures may include: abutments, barrier railings, bridge decks, columns, pier caps and retaining walls.)
- b. Objective 2.2: Work with VTrans personnel to identify specific structures that are good candidates for use of the decision-making flow chart. (These will preferably be a mix of structural elements and damage conditions to tease out and identify condition-specific flow chart items.)
- c. Objective 2.3: Design an experiment for evaluation of the decision-making flow chart. (The design should include provisions for evaluating the decision-making flow chart on both quantitative and qualitative aspects. Initially the flow chart will be used in parallel

with routine decision-making practices. If, the flow chart proves useful at later stages, it may be used as a direct component of the decision-making process.)

- d. Objective 2.4: Conduct the experiment from Objective 2.3 where the decision-making flow chart is used on repairs that are planned for highway structures in Vermont. (The experiment will be formulated based on consultations with VTrans personnel.)
- e. Objective 2.5: Study results and recommend improvements to the decision-making flow chart. (This will be a critical analysis of the decision-making flow chart.)
- f. Objective 2.6: Recommend a follow-on Phase III study where highly-promising repair techniques are implemented and then studied in detail on selected highway structures. (The Phase III study should be a direct follow-up to Phase I and II leading to improved concrete repair practices.)

Methodology:

- a. Task 1: Meet with Vermont and neighboring state transportation agency maintenance and inspection personnel concerning present damage problems and repair practices.
- b. Task 2: Identify damage processes unique to Vermont and/or New England.
- c. Task 3: Spring and summer 2014 – UVM personnel accompany VTrans personnel on bridge inspections and repairs.
- d. Task 4: Evaluate the inclusion of repair recommendations into asset management database.
- e. Task 5: Develop a future Phase II effort that would take the procedures that seem to work best and apply them in the field.
- f. Task 6: Prepare report.

The Concrete Repair GUI achieves a number of the listed objectives and tasks. The GUI accomplishes objectives 1.1-1.3 and parts of 1.4 and 2.1. Initial meetings between VTrans personnel and UVM contributors were done before October of 2014. Tasks 1-2 were accomplished by that time. VTrans explained their current methods and I researched concrete repair methods that are widely used in the US. My research yielded the documents from many states, ACI and ICRI concrete repair manuals, which initially started our concrete repair procedures and methods database. These documents are referenced in the references section of this manual. Site visits to multiple bridges were done on 10/21/14 and 12/18/14, which accomplish Task 3. Notes from the site visits can be seen in **Appendix A**.

Flow Chart Layout and Organization

The layout and organization of our flow chart was modeled and made to be part of ACI's Concrete Repair Process Flow Chart, which is displayed in the ACI Concrete Repair Manual 2013. The general outline of the flow chart asks questions about the type of bridge structure element and the type of damage it has been subjected to. Stepping through the flow chart the user can access information from the database regarding particular questions. This may include definitions to structural terms, lists of widely used procedures and methods on a particular structural element, tools to analyze damage, cost analysis of repairs and exporting data and reports. Below are images of flow charts that were the blueprints to the Concrete Repair Flow Chart GUI, which include references to the necessary documents.

Full Concrete Repair Decision Tree:

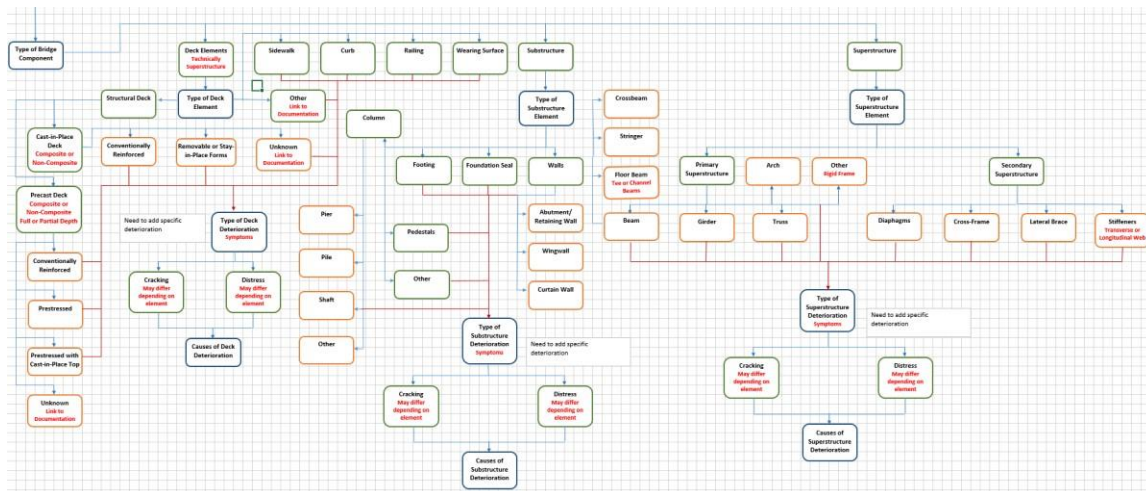


Figure 1: The Full Decision Tree can be accessed as the Excel File: (Concrete Repair Full Decision Tree)

Bridge Deck Repair Decision Tree

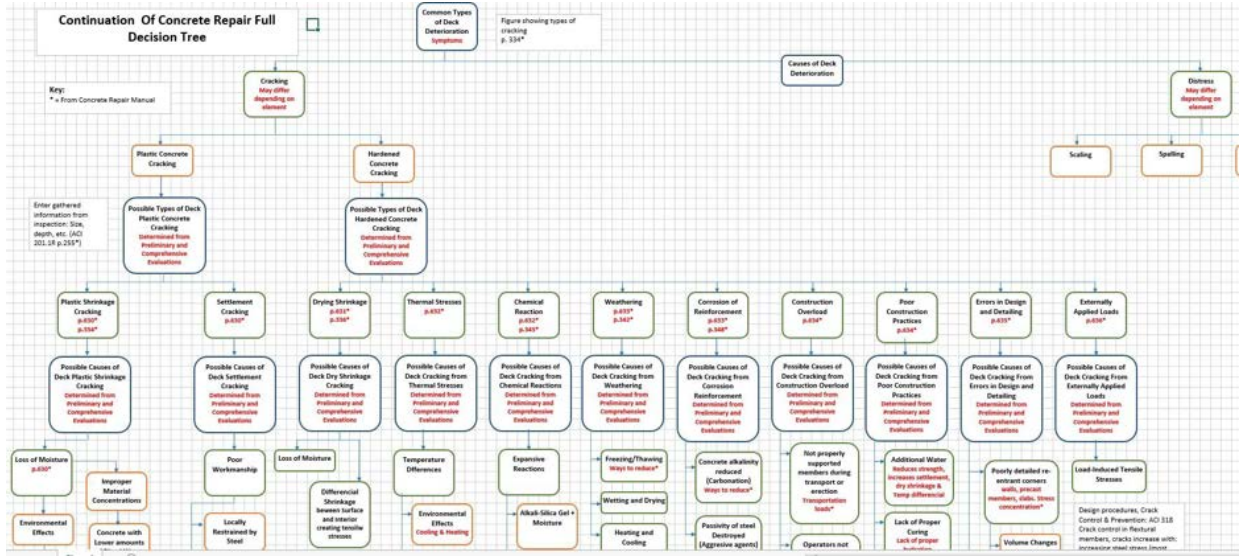


Figure 2: The Full Decision Tree can be accessed as the Excel File: (Deck Deterioration Repair Decision Tree)

Expansion Joint & Fascia Decision Tree

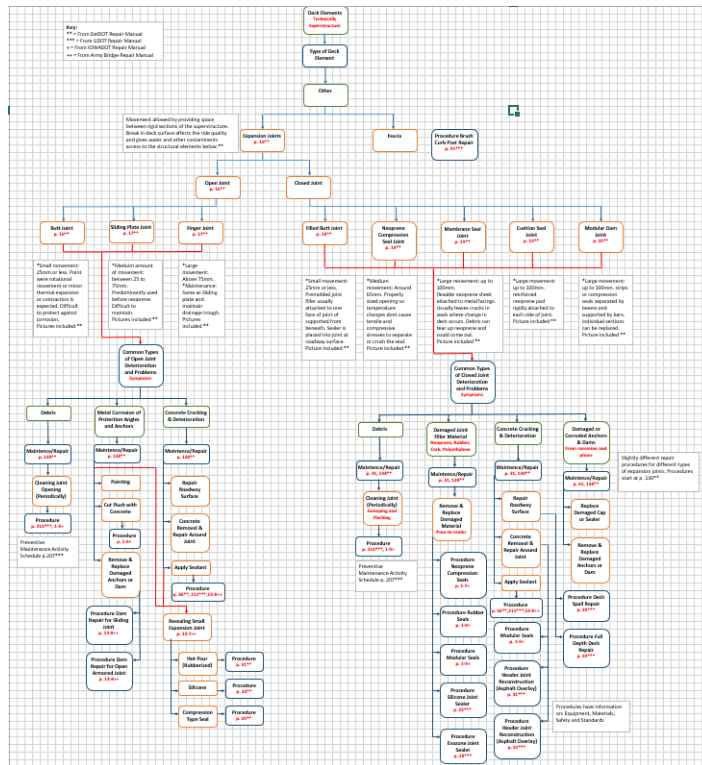


Figure 3: The Full Decision Tree can be accessed as the Excel File: (Expansion Joint and Fascia Deterioration Repair Decision Tree)

Close up Section of the Expansion Joint & Fascia Decision Tree



Figure 4: Figure 3: The Full Decision Tree can be accessed as the Excel File: (Expansion Joint and Fascia Deterioration Repair Decision Tree)

User Manual Summaries

1.1. Bridge Inspection Form GUI

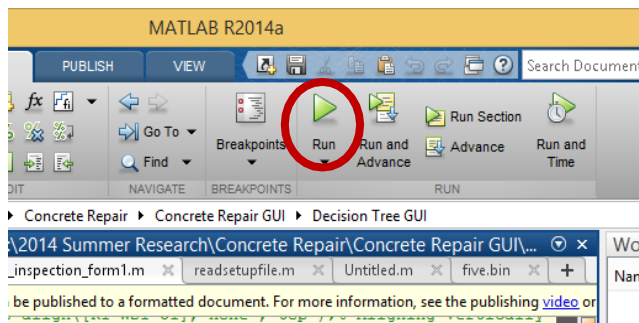
The Bridge Inspection Form GUI is an electronic version of VTrans NBIS Field Inspection Form. The GUI references the Field Inspection Coding Guide if the user has questions on how to code a specific question in the form.

Summary:

- Link to Field Inspection Coding Guide
- Made in MATLAB: File Name (bridge_inspection_form1)
- Made into executable: File Name (bridge_inspection_form_gui)
- Exports Inspection Form to and an Excel spreadsheet in the proper format

Instructions: (MATLAB Version)

1. **Open** bridge_inspection_form1.m file, which is located in the Bridge Inspection Form GUI folder which is a subfolder of the Concrete Repair GUI folder.
2. **Run** the file, by **Clicking** the **Run** button on the top toolbar. Shown below.



3. The **Bridge Inspection Form** window should pop-up, depicted in Figure (Figure 5). The window gives the user the option of clicking between two buttons:
 - a. The **Field Inspection Form** button, which directs the user to the electronic form
 - b. The **Field Inspection Coding Guide** button, which directs the user to a PDF version of the guide.



Figure 5: Bridge Inspection Form GUI Main Page

4. **Click** on the **Bridge Inspection Form** button to open the form window. The header information window, seen in Figure 6) will appear. Enter the pertinent header information for the particular bridge in the blank text boxes.

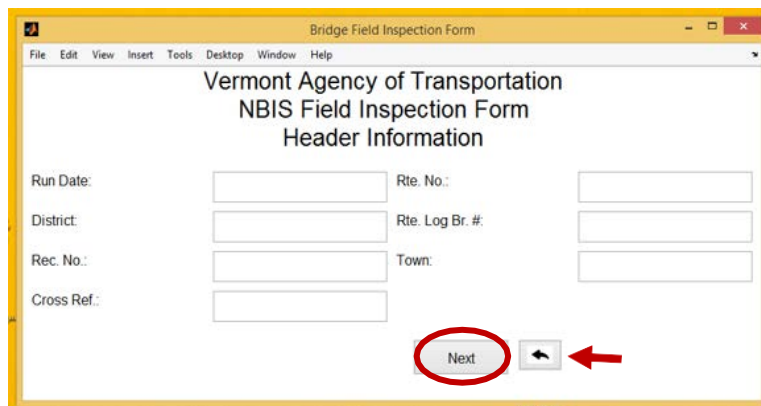


Figure 6: Enter Header Information on Bridge Inspection Form

5. **Click** the **Back Arrow** to go to the previous window (to the left of the red arrow) and **Click** the **Next** button (shown by the red oval) to navigate to the next four windows to answer questions about the structure.

Vermont Agency of Transportation
NBIS Field Inspection Form
Page 4: Further Information

Number of Utilities: Vertical Clearance Under Bridge (Highway):

Year of Last Maintenance Activity: Vertical Clearance Under Bridge (Railroad):

Type of Maintenance Performed: Vertical Clearance Under Bridge (Waterway):

Year of Last Maintenance Activity (1): Operating Rating:

Type of Maintenance Performed (1): Inventory Rating:

Year of Last Maintenance Activity (2): H Truck at 67% YP:

Type of Maintenance Performed (2): 3 Axle Straight Truck at 67% YP:

Alignment of Bridge Deck and Superstructure: 4 Axle Straight Truck at 67% YP:

Type of Bridge Rail: 5 Axle Semi-Trailer Truck:

Type of Approach Railing: 6 Axle Semi-Trailer Truck:

Type of Expansion Joint: Load Posting Signs:

Type of Expansion Bearing Device: Federal Sufficiency Rating:

Type of Foundation: Deficiency Status of Structure:

Bridge Plans on File:

Export Data

Figure 7: Exporting Data on Bridge Inspection Form

6. On the fourth page of the form the user will have the option to **Export** and **Save** the data entered to an Excel spreadsheet. Seen in Figure (Figure 7) by the red oval.
7. The **Exported** file will look similar to the one shown in Figure (Figure 8).

Item No.	Field Name	Value
1	Run Date:	1/15/2015
2	District:	6
3	Rec. No.:	2048
4	Cross Ref.:	
5		
6	Item No.	
7	3 Country Code	15
8	4 Place Code	70525
9	5 Inventory Route	131001000
10	6 Features Intersected	GOLD BROOK
11	7 Facility Carried by Structure	VT 00100 ML
12	8 Structure Number	2.00029E+14
13	9 Location	1.8 MI S JCT.VT.108
14	10 Inventory Route, Minimum Vertical Clearance	9999
15	16 Latitude	44263429
16	17 Longitude	72421099
17	19 Bypass, Detour Length	37
18	21 Maintenance Responsibility	
19	22 Owner	1
20	26 Functional Classification of Inventory Route	6

Figure 8: Exported data from the Bridge Inspection Form GUI

8. If the user has any questions regarding the bridge inspection codes he/she can

reference the **Field Inspection Form Coding Guide** by **Clicking** on the **Field Inspection Form Coding Guide** button, which is shown in Figure (Figure 5). It will pop-up a PDF version of the coding guide. Shown in Figure (Figure 9).

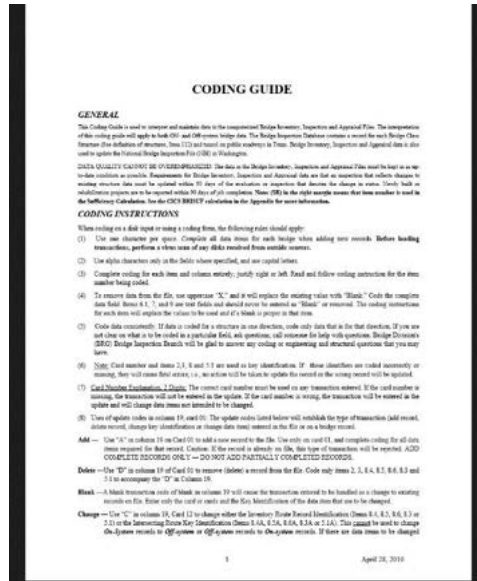


Figure 9: PDF pop-up of Field Inspection Coding Guide

Instructions: (Stand Alone Executable Version)

1. **Open** bridge_inspection_form_gui file, which is located in the bridge_inspection_form_gui folder within the subfolders for_redistribution_files_only or for_testing, which are all within the Concrete Repair GUI folder.
2. The for_redistribution_files_only or for_testing folders also include a Readme file that describes how to install the MATLAB Compiler Runtime software needed to run the executable if you do not have MATLAB. The MATLAB Runtime software is FREE.
3. Once the bridge_inspection_form_gui file is **Opened**, the window shown in Figure (Figure 5) will appear. Follow steps 3-8 from the MATLAB Version to use the GUI.

1.2. Decision Tree GUI

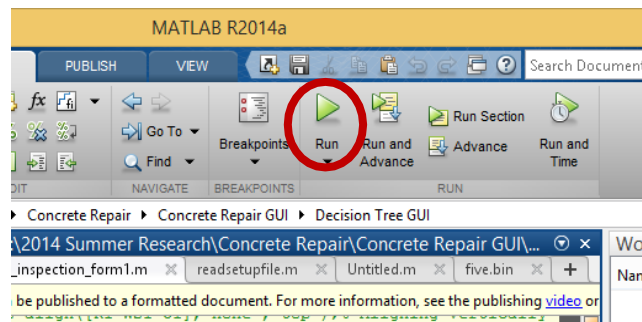
The Decision Tree GUI is a decision making tool that lets the user document and save the damage to a structural element, while also giving an initial prognosis of the damage. The GUI gives definitions for bridge structure terminology and incorporates the Bridge Inspection Form GUI.

Summary:

- Incorporates Field Inspection Form GUI
- Made in MATLAB: File Name (decision_tree_gui1.m)
- Can Import an image of the damage to the structural element
- Exports damage and prognosis data to and an Excel spreadsheet
- **NOT** fully completed (all pertinent definitions are not included, does not have the latest version of the Bridge Inspection Form GUI and only the Superstructure Button is complete)

Instructions: (MATLAB Version)

1. **Open** decision_tree_gui1.m file, which is located in the Decision Tree GUI folder which is a subfolder of the Concrete Repair GUI folder.
2. **Run** the file, by **Clicking** the **Run** button on the top toolbar. Shown below.



3. The **Concrete Repair Decision Tree** window should pop-up, depicted in Figure (Figure 10). The window gives the user the option of clicking between multiple buttons:
 - a. Choose from three structural element categories: **Deck Element**, **Substructure Element** or **Superstructure Element** (shown by red oval)
 - b. The **Field Inspection Form** button (shown by red rectangle), which directs the user to the electronic form
 - c. The **Definitions** button (to the right of the red arrow), which directs the user to a Definitions pop-up window that defines the bridge terminology of the previous window.

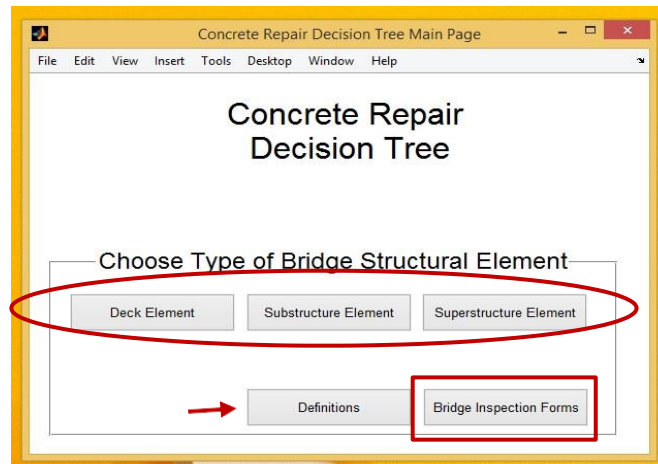


Figure 10: Concrete Repair Decision Tree Main Page

4. To continue with the damage assessment portion of the **Decision Tree GUI**, choose a type of bridge structure element. *In current state only **Superstructure Element** button works*
5. The **Superstructure Elements** window will pop-up and give you two options to further identify the structural element.
 - a. The **Primary Superstructure Element** button (currently inactive)
 - b. The **Secondary Superstructure Element** button
6. In this window the user can also access the **Definitions GUI** and go **Back** to the previous window.
7. Once a type of superstructure element has been chosen, the **Damage and Prognosis** window will pop-up. Shown in Figure (Figure 11). It will have a pop-up list box (shown by the red oval) with a list of possible structural elements that pertain to the specific category. (Currently only the **Diaphragm** option is active)

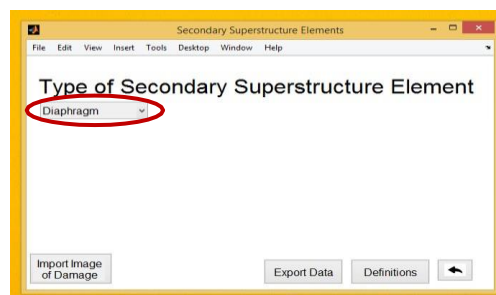


Figure 11: Damage and Prognosis Pop-up Window

8. When the specific type of element is identified from the list box, questions regarding damage to the structure, a note box and a list of prognosis options will appear on the **Damage and Prognosis** window. Shown in Figure (Figure 12). Along with the following options:
- The **Import Image of Damage** button (shown by the red oval), which lets the user import an image of the damage on the particular element
 - The **Export Data** button (shown by the red rectangle), which **Exports** the data entered in the window to an Excel spreadsheet along with the imported image of the damage on the element

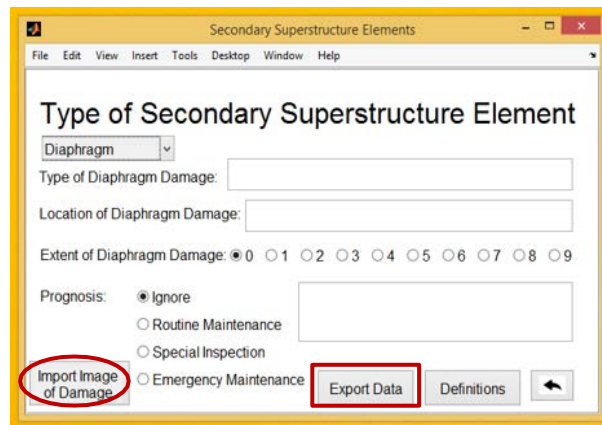


Figure 12: Damage and Prognosis Pop-up Window with Full Options

9. Once the user **Exports** the data from the **Damage and Prognosis** pop-up window the data will be stored and saved as an Excel spreadsheet, like the one shown in Figure (Figure 13).

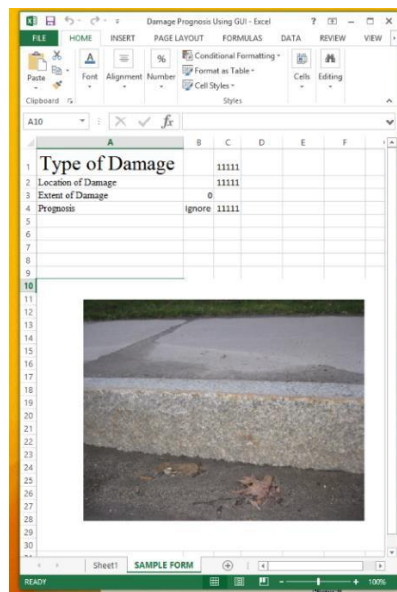


Figure 13: Exported Data from Decision Tree GUI

10. To access a **Definitions GUI** on a window where the option is available, **Click** the **Definitions** button. An example of the option can be seen in Figure (Figure 10) to the right of the red arrow.
11. A **Definitions** pop-up window will open, much like the one seen in Figure (Figure 14). A list box containing pertinent terms from the previous window will be visible at the bottom center of the definitions window (to the right of the red arrow). When a specific term is selected a relevant image appears in the center of the window with a definition under it. The user can return to the previous window using the **Back Arrow**.

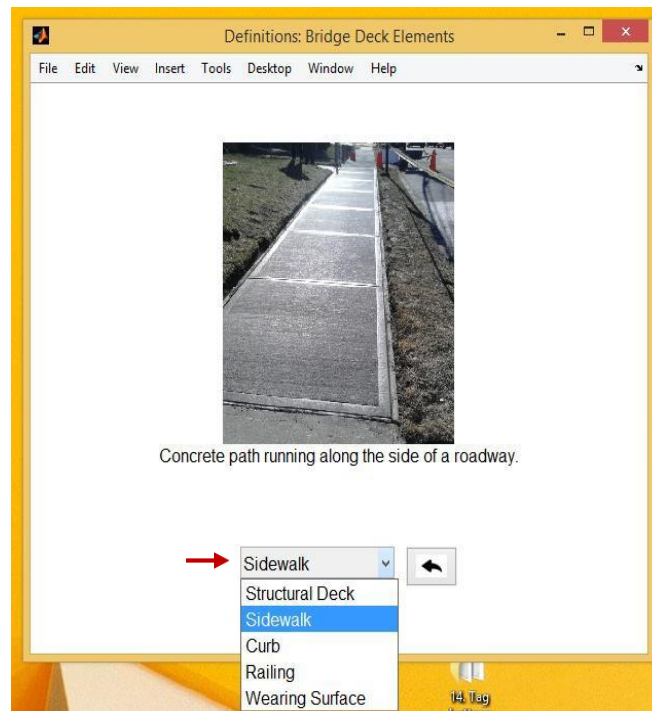


Figure 14: Definitions GUI

12. The user can access the **Bridge Inspection Form GUI** by **Clicking** on the **Bridge Inspection Form** button (shown by the red rectangle) in Figure (Figure 10). By clicking on this button the **Bridge Inspection Form GUI** will open. Reference **1.1. Bridge Inspection Form GUI** for help and further information about this option.

1.3. Flow Chart GUI

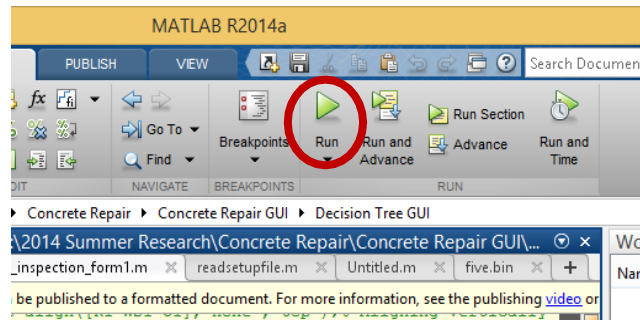
The Flow Chart GUI is the foundational framework that other decision making GUI's are built on and helps the user determine the proper concrete repair technique for a specific type of damage. The GUI gives definitions for bridge structure terminology and refers the user to the most effective repair procedure given the specific type of damage on the particular structural element.

Summary:

- Opens relevant concrete repair procedures for specific types of structural damage
- Made in MATLAB: File Name (flow_chart_gui2.m)
- This GUI starts with concrete deck elements. When combined with the **Concrete Repair Decision Tree GUI** there would also be one for substructure and superstructure elements.
- **NOT** fully completed (all pertinent definitions are not included and only the certain options through the **Other** Button is complete)

Instructions: (MATLAB Version)

1. **Open** flow_chart_gui2.m file, which is located in the Flow Chart GUI folder which is a subfolder of the Concrete Repair GUI folder.
2. **Run** the file, by **Clicking** the **Run** button on the top toolbar. Shown below.



3. The **Concrete Repair Flow Chart** window should pop-up, depicted in Figure (Figure 15). The window gives the user the option of clicking between multiple buttons:
 - a. Choose from six deck elements: **Structural Deck, Sidewalk, Curb, Railing, Wearing Surface** or **Other** (shown by red oval) *Only **Other** is currently active*
 - b. The **Definitions** button (to the right of the red arrow), which directs the user to a Definitions pop-up window that defines the bridge terminology of the previous window. *For Further Information on the **Definitions** window, reference **Step 11** in **1.2. Decision Tree GUI**.*

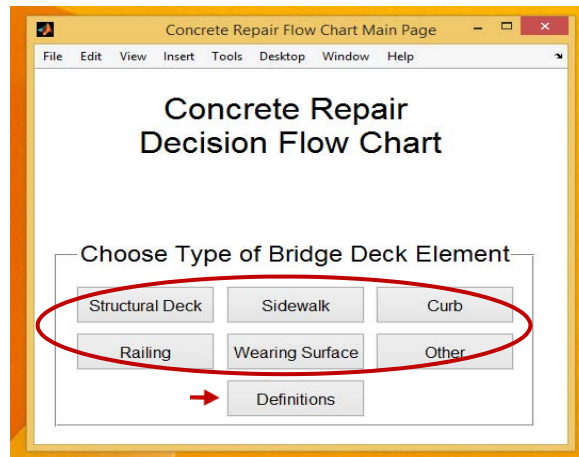


Figure 15: Concrete Repair Flow Chart Main Page

4. To further identify the structural element and the type of damage it may have to select the proper repair technique, choose from the list of structural elements. *In current state only **Other** button works*
5. A sub-window will pop-up and give you several options to further identify the structural element. The number of options on a sub-window and the amount of sub-windows will vary depending on the type of element.
6. Once the user has properly identified the structural element that is damaged, a window will pop-up that lists the most common types of damage to that element. The user must **Choose** the type of damage to the structural element. Figure (Figure 16) shows an example of this window for a Butt Joint. In this window the user can also go **Back** to the previous window. *In the current version of the GUI only the **Debris** button is active*



Figure 16: Butt Joint Pop-up Window

7. Once a type of element damage has been chosen, a final window will appear (shown in Figure (Figure 17)) that:
 - a. Gives the user procedures or methods to most effectively repair the damage to the structural element. *Only the **Cleaning Joint** Procedure is active*
 - b. Gives the user the option to view the benefits to the life of the structure if the element is repaired and a cost estimate of the repair. *Inactive

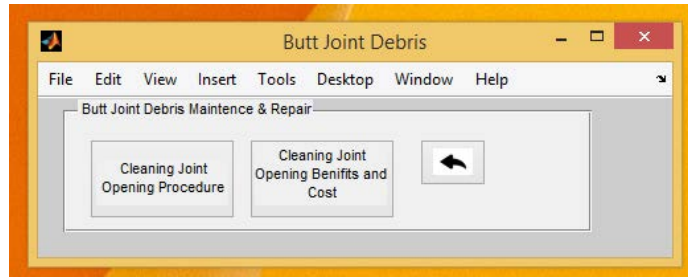


Figure 17: Butt Joint Debris Pop-up Window

8. By **Clicking** on the particular repair **Procedure** button a PDF version of procedure from our database will pop-up. An example procedure can be seen in Figure (Figure18).

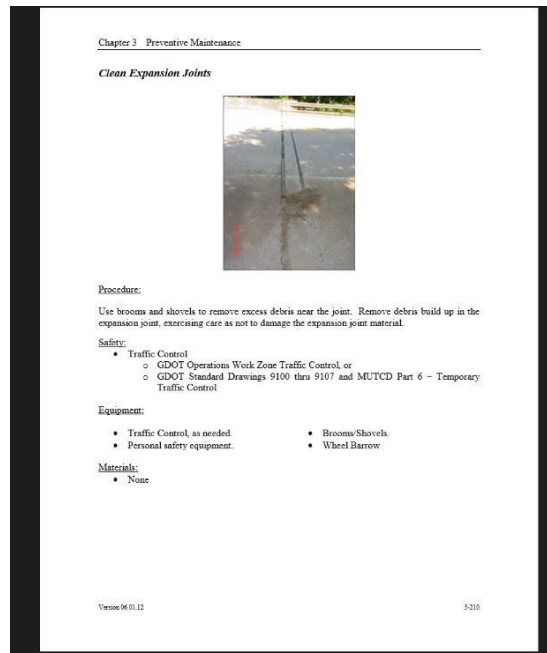


Figure 18: PDF Version of a Procedure from a Database

CONCLUSION AND FUTURE WORK

The aim of the Concrete Repair GUI is create an ever expanding database of concrete repair procedures and methods that can be easily accessible to engineers, technicians and researchers. By making it user friendly we hope that it can be used to more efficiently diagnose damage to a concrete structure and recommend the best repair technique by analyzing data from the damage site and input data from the user.

The current version of the Concrete Repair GUI is just a prototype that acts as a proof of concept. Most of the features have not been fully developed and are broken up between several GUI's. With further development of the algorithm we hope to combine all the GUI's into one working electronic flow chart and decision tree with further damage analysis capabilities. In future versions of the software we hope to expand the library of repair procedures and methods and add imaging processing software that can analyze and determine the extent of damage through images. To make this a useful tool in the field we also hope to incorporate the database of repair methods and procedures to the Cloud, which would make the database more mobile by being accessible from a tablet.

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- [13] Indiana Bridge Management with Decision Tree
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- [20] Field Inspection Coding Guide
- [21] DOTMN

*All References can be found on the Seagate Expansion Drive: Project Backups>Jonathan Razinger>2014-2015 Research>Concrete Repair>Database Documents

*All Files pertaining to the Concrete Repair GUI can be found on the Seagate Expansion Drive: Project Backups>Jonathan Razinger>2014-2015 Research>Concrete Repair>Concrete Repair GUI

*GUI Library can be found on the Seagate Expansion Drive: Project Backups>Jonathan Razinger>2014-2015 Research>Concrete Repair>Library

*Flow Chart Blueprint can be found on the Seagate Expansion Drive: Project Backups>Jonathan Razinger>2014-2015 Research>Concrete Repair>

*VTrans Documentation can be found on the Seagate Expansion Drive: Project Backups>Jonathan Razinger>2014-2015 Research>Concrete Repair>VTrans Documentation

APPENDIX A: SITE VISIT NOTES

Notes from VTrans Bridge Inspections 10/21/14 & 12/18/14:

- **Factors to Consider:**
 - Technical Issues
 - Expansion Joints
 - Details
 - Type
 - Maintenance
 - Gutter
 - Fascia (Better repair options)
 - Nonlinear Accelerating Deterioration
 - How to identify to avoid surprises
 - How to mitigate early at low cost
 - Pier Foundations
 - Columns and Caps
 - Decks
 - Staging and Shoring
 - Extent of Damage
 - Management Issues
 - Expected life usage of bridge vs. Expected life usage of repair
 - 50+ year old bridge → quick & cheap repair
 - More considered for younger bridge
 - Not practical or cost effective to have repair last longer than bridge
 - Environmental Issues and Regulations
 - Contractor Skill Set
 - Can they perform proper repair at low cost
 - Link to life usage of bridge and repair
 - Surprises
 - Not seen during inspection
 - Could have been found with more in depth inspection
 - Cost/Business Aspects
 - Time to bid
 - Competition
 - Budget
 - Politics/Citizen Priorities

- Bridge Specific Costs (From: surprises, traffic management, equipment, staging)
 - Safety
 - UVM's Role
 - Decision Flowchart
 - 3D Imaging and Scan to BIM
 - Reliability and Life Costs
 - New Repair Options for Particular Problems
- **Common Techniques Used:**
 - For Spalling & Steel Corrosion of Large Area
 - Remove Bad Concrete
 - Sand Blast Corroded Steel
 - Repair or Replace Steel
 - Prepare Bonding Surface
 - Concrete Jacket
 - For Scaling or Spalling of Small Area
 - Remove Bad Concrete
 - Prepare Surface
 - Patch (1060 patch material good for vertical fixes)
- **Common Problems:**
 - Expansion Joints
 - Dirty/Not properly maintained
 - Poor design
 - Not Working Properly
 - Chemical Attack (Salt)
 - Freeze/Thaw
 - Fascias
 - Scaling & Spalling
 - Reinforcement Corrosion
 - Safety Issue for cars below
 - Chemical Attack (Salt)
 - Freeze/Thaw
 - Columns & Caps
 - Scaling & Spalling
 - Reinforcement Corrosion
 - Chemical Attack (Salt)
 - Freeze/Thaw

- **Thoughts:**
 - Decision flowchart most likely would be implemented by inspection crew and contractors to document deterioration and recommend proper repair
 - Could some problems be solved by utilizing corrosion resistant steel reinforcement?

Bridge Locations and Types of Deterioration seen

- **Bridge 1:**
 - Exit 17 on I89 in Colchester VT. Overpass where I89 runs below and Route 2 above.
 - Coordinates: 44°35'23.9"N 73°10'12.9"W
 - Built around 50's or 60's



Figure 19: Column and cap Spalling and steel corrosion



Figure 20: Close-up of concrete spalling and steel corrosion on middle column and cap



Figure 21: Other side of middle column. Notice Spalling, cracks and corrosion stains.



Figure 22: Spalling on end cap and a large crack on end column

- Notes: Spalling, Cracking and steel corrosion to some extent on all of the columns with the middle column and the end cap being the worst.

- **Bridge 2:**

- Off exit 17 on Route 2 North over the Lamoille River. Colchester VT.
- Coordinates: 44°36'12.7"N 73°12'16.7"
- Built around the 80's



Figure 23: Bents, deck and beams



Figure 24: Steel finger joint. Notice no overlay on deck



Figure 25: Scaling and cracking on abutment. Corrosion stains from steel beams

- Notes: Bridge in very good shape. Just some small scaling and cracking on abutment emanating from expansion joint.
- **Bridge 3:**
 - Exit 12 on I89 in Williston VT. Overpass where Route 2 runs below and I89 above.
 - Coordinates: 44°26'22.3"N 73°06'53.9"
 - Built around the 50's or 60's



Figure 26: Possible dry shrinkage cracks on concrete column that has had a 6" thick concrete jacket around column.



Figure 27: Spalling and steel corrosion on concrete fascia.

- Notes: Possible dry shrinkage cracks on concrete jacket. Concrete jacket placed to repair deteriorated concrete columns. Spalling and steel corrosion on fascia. Fascia supports metal railing and concrete fragments from fascia could hit cars underneath. Find Betterfascia repair option. Notice unmaintained joint that will ultimately cause end cap to start deteriorating again.

- **Bridge 4:**
 - On I89 after exit 12. Overpass where I89 runs below and Oak Hill Rd. runs above. Williston VT.
 - Coordinates: 44°26'03.3"N 73°04'14.9"W
 - Built around 50's or 60's



Figure 28: Patches on columns to fix spalling and cracking.



Figure 29: Scaling on abutment around bearing and beam



Figure 30: Spalling and slight steel reinforcement corrosion on underneath portion of concrete deck

- Notes: 1060 patch mix was used to fix spalling and cracking on columns. Works well on vertical fixes. Concrete is removed and edges are cut around deteriorated concrete. Bonded surface is prepared, mixed is placed and form is placed to allow for patch to cure properly.

- **Bridge 5:**
 - Route 2 after exit 11 on I89. Overpass where I89 runs underneath and Route 2 above. Richmond VT.
 - Coordinates: 44°24'03.0"N 72°59'04.2"W
 - Built around 50's or 60's



Figure 31: Severe spalling and steel corrosion on column and footing. Notice that some of the steel reinforcement is non-existing.



Figure 32: Spalling and steel corrosion on columns and caps



Figure 33: Spalling and steel corrosion on concrete column. Notice concrete fragments falling near road.



Figure 34: End cap spalling and steel corrosion with non-existing bearing.



Figure 35: Bridge deck and expansion joint. Because of non-existing bearing bridge deck has settled down about 1.5”.

- Notes: The extent of damage on columns, caps and footings can be attributed to poorly maintained expansion joints, causing the bridge deck to slump 1.5” because of a non-existing bearing.

- **Bridge 6:**

- Route 100 North over Gold Brook Stowe VT.
- Coordinates: 44°26'34.3"N 72°42'10.9"W
- Built 2014



Figure 36: Full View of Gold Brook Bridge in Stowe (12/18/14)



Figure 37: Crack on Deck Surface. Highlighted by Red Oval



Figure 38: Underside of Concrete Deck. Left Image: shows cracks going at the way through concrete deck. Cracks are highlighted by red ovals. Right Image: sealant used to seal large cracks.

- Notes: On this new bridge the main concern is the extent of cracking on the deck of the bridge. If not properly fixed corrosion to pre-stressed members will initiate and cause major damage the bridge. Cause of cracking: not yet know. Could be dry cracking caused by inadequate concrete mixture or inadequate dry time. Also might be due to movement of bending of concrete deck or structure as a whole.