Bridge Integrated Analysis and Decision Support - Phase II

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Bridge Integrated Analysis And Decision Support – Phase II

Final Report

By

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Disclaimer

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16. Abstract

In 2004, the Wisconsin Highway Research Program (WHRP) initiated project # 0092-04-15, entitled, "Bridge Integrated Analysis and Decision Support – Case Histories (Phase I)" at the University of Wisconsin-Milwaukee (UWM) to document the existing knowledge related to Wisconsin bridge incidents in the form of a database of case histories. That study was completed in 2007 where for the database for each case study included detailed information on the bridge, past repair and maintenance, description of the events, reporting, and initial and subsequent responses by the responsible parties, and any resulting remediation. The database entitled "**B**ridge **I**ncident **R**esponse **D**atabase" (**BIRD**) is web-based and searchable with "keywords" and it is detailed in the final report (SPR # 0092-04-15) that was published in January 2008.

In January 2008, the WHRP approved this study, "Bridge Integrated Analysis and Decision Support – Phase II," to enhance the database from the Phase I study (**BIRD**) and to develop a decision support system (DSS) that could aid WisDOT personnel in making appropriate decisions in cases of bridge emergencies. The DSS developed under this study, "Bridge Emergency Expert System" (**BEES**), utilizes rules and procedures in the form of a decision tree that is built based on information from visual inspection at the time of the incident and existing records to recommend appropriate initial actions at the site of the incident. **BEES** interacts with the user through a "user interface" and makes recommendations on following safety procedures appropriate with the level of damage present in the structure. It should be noted that the recommended actions from the expert system under this study are not based on performing structural analysis or rating of the bridge at the time of the incident. As such, these recommendations should be considered and implemented by experienced staff or in consultation with experienced bridge engineers.

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Executive Summary

Unpredictable and catastrophic incidents such as impact damage, fire, fatigue cracking, and scour occur in bridges and they can have severe consequences. These incidents result in structural damage, long traffic delays, and adverse economic consequences. The risk of undesirable delays and danger to the traveling public may be minimized if an appropriate rapid response is developed and implemented in cases of bridge emergency incidents. An appropriate and timely action in response to a bridge emergency case can be achieved by combining new technologies and basic civil engineering principles.

In 2004, the Wisconsin Highway Research Program (WHRP) of the Wisconsin Department of Transportation (WisDOT) initiated project # 0092-04-15, entitled, "Bridge Integrated Analysis and Decision Support – Case Histories (Phase I)" at the University of Wisconsin-Milwaukee (UWM). The primary objective of that study was to capture and document the existing knowledge and create an expandable database of case histories for incidents in Wisconsin bridge structures. The study was completed in 2007. As a part of that study, a database of case histories of incidents for sixteen Wisconsin bridges was developed. The database was developed using available archived data from various WisDOT offices and through face-to-face meetings and interviews with several active or retired staff of different Highway Districts/Regions and the City of Milwaukee. For each case history, the database included detailed information on the bridge, past repair and maintenance, description of the events (incidents), incident reporting, and initial and subsequent responses by the responsible parties, and any resulting remediation. The case history documents were accumulated into a web-based "**B**ridge **I**ncident **R**esponse **D**atabase" (**BIRD**) that is searchable with keywords. A final report was submitted to WHRP in August 2007 and it was approved and published in January 2008 – SPR # 0092-04-15.

It was envisioned that the case history database developed under the Phase I study could serve as the basis for a web-based decision support system (DSS) that could be developed as part of a later study. The goal for the DSS system was to provide assistance to the WISDOT personnel in making appropriate decisions in cases of future bridge emergencies and accidents.

In January 2008, the WHRP approved a 3-year study, "Bridge Integrated Analysis and Decision Support – Phase II," at UWM to develop a system that could facilitate making decisions and responding to bridge emergency incidents. The primary objectives of the study were to enhance the existing case history database from the Phase I study and to develop an appropriate web-based decision support system (DSS) that could be used by WisDOT bridge engineers and maintenance staff in cases of bridge emergencies.

As a result of this study, a decision support system was developed which is named "Bridge Emergency Expert System" (**BEES**). This system utilizes all available information from the existing Bridge Incident Response Database (BIRD) as well as those collected at the time of the incident to recommend appropriate initial actions at the site of the incident. The system utilizes a standard procedure for visual inspection at the time of incident to provide necessary information for decision making. Based on the data stored in the system (i.e., BIRD), as well as information provided by the user, safety steps are recommended according to the level of damage present in the structure. The available data includes those from the previous case histories, research articles, incident reports, computer databases, books, and interviews with experts. A system of rules and procedures in the form of a decision tree was used to organize the gathered knowledge. The system's knowledge base was created with rules and facts written as IF-THEN expressions in a forward chain process. Two open source software packages were used to develop a user interface and process the rules and facts. These are PYTHON, an object-orientated programming language, and CLIPS, an expert system development program.

The BEES system operates based on interaction with a user through a "user interface" which assembles all necessary incident information and transfers it to the expert system. The user interface is based on dialog windows that offer various questions and possible answers. It also includes other features including additional recommendations, emergency contact lists, bridge characteristics, and information related to other similar incidents.

The expert system's knowledge base and resulting recommendations have been evaluated to ensure practical system performance. This evaluation has been done through using test cases, case histories, and knowledge from experts. The results obtained have been shown to be appropriate in providing assistance bridge engineers or owners to ensure safety at the time of a bridge emergency.

The recommended actions from the expert system under this study are not based on performing structural analysis or rating of the bridge at or after the time of the incident. The system relies only on available data and visual evaluation of the structure at the time of incident. It should also be noted that the accuracy and relevance of the recommendations provided by BEES depend on the information provided by the user. As such, the provided recommendations should be considered or implemented only by experienced personnel or in consultation with experienced bridge engineers.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Unpredictable incidents such as impact, fire, fatigue, and scour occur in bridges, and sometimes with catastrophic consequences. In addition to structural damage from these incidents, they can also lead to long traffic delays and adverse economical consequences. These events can cause inconvenience to the traveling public, risks to their safety, as well as requiring major repair and maintenance costs.

The risk of undesirable delays and danger to the public may be minimized if an appropriate rapid response capability is developed and implemented. An appropriate and timely action in response to a bridge emergency incident can be provided by combining new technologies and basic civil engineering principles.

A Decision Support System (DSS) is an appropriate tool for providing solutions to transportation emergencies. Such DSS should be able to integrate the information collected at the time of the incident with existing records and related knowledge from previous experiences, in order to recommend appropriate actions.

A recent study supported by the Wisconsin Highway Research Program (WHRP) lead to the assembly and documentation of bridge structural design and maintenance records as well as histories of past emergencies in Wisconsin. The study is entitled “Bridge Integrated Analysis and Decision Support System: Case Histories – Phase I” [1]. The case histories compiled in that study serve as the basis for developing an expert system for Wisconsin bridges that gives appropriate recommendations in cases of emergency incidents. The recommendations are also based on information provided by the user through an interactive question-and-answer session. The case histories documented in the Phase I study and other

supportive documents are included as reference documents in the final recommendation given by the system.

1.2 BACKGROUND AND SIGNIFICANCE OF THE WORK

According to the National Cooperative Highway Research Program (NCHRP), project 12-21 [2, 3], approximately 200 prestressed concrete bridges are damaged every year within the United States. Over 80 percent of these bridges are damaged due to collisions by over-height vehicles. Another study supported by the Texas Department of Transportation [4], documented that the occurrence of impact damage within Texas rose by 50 incidents every year between 1987 and 1992. In this study, about 14% of the impacted bridges are classified as severely damaged and the remaining bridges are classified as moderately or minimally damaged. Considering that the need for our national infrastructure is continuously growing, the number of bridge related incidents are likely to remain high.

Limited information and resources are available for evaluating damage and recommending quick and appropriate actions in bridges in cases of emergency incidents. There is currently no effective source that provides guidance and recommendations at the moment of a bridge incident. Hence, there is a need for a system that provides rapid and effective guidance in cases of bridge emergency incidents, ensuring the safety of the traveling public as well as the integrity of our in-service bridge structures. This research merges previous experience and findings with new technologies to develop a new tool to handle emergency events successfully and efficiently.

In some cases, although a bridge incident may first seem to be severe, there may not actually be a major damage to the structure and the structure could resume its service after an initial evaluation. An example of such a case is a 1992 fire incident at a Marquette Interchange bridge in Milwaukee, Wisconsin. This bridge was constructed in 1968 and removed in 2006 during the construction of the new interchange.

On Friday, November 27, 1992, a gasoline truck lost control over the bridge before 10:00 a.m., and dropped, through a protective concrete barrier, 33 feet onto a parking surface, where it exploded into flames and damaged several nearby vehicles [1]. The fire from the gasoline explosion resulted in heavy scaling and delamination of concrete in piers supporting the bridge (see Figure 1).

Figure 1. Column with Scaling and Delamination Due to Fire

The incident was first reported by a 911 emergency call to the Milwaukee Fire Department at 9:54 a.m. The fire was contained in about 30 minutes. Personnel from the Milwaukee County Sheriff's department arrived at the scene at 9:56 AM and assisted with traffic control, securing the accident site, and contacted the Milwaukee County Department of Public Works (DPW) and the local Wisconsin Department of Transportation (WisDOT) regional office.

A WisDOT representative responded to the call and performed a visual examination of the structure. He verified that the fire damage was restricted to the surface and that the pier and superstructure were still intact. Loose concrete was removed off of the affected surfaces but it was decided to reopen the interchange as soon as all traffic safety provisions could be made. The traffic control included re-

routing of the traffic from interstate highways I-94 and I-43 onto other county and city roadways. After the area was secured and debris removed, the roadways and interchange ramps were reopened. Traffic restrictions remained enforced for approximately four hours.

In highway bridges with high average daily traffic (ADT), i.e., ADT larger than 50,000, a rapid response after an accident can minimize the time of traffic interruptions or restrictions. In the case of the Marquette Interchange bridge, although there was a rapid response to the incident, the traffic restrictions were enforced over a relatively long period of time. The initial assessment of the damage in the bridge could have been made easier if an appropriate tool was available to the DOT representative at the time of the evaluation. The system proposed in this study is able to estimate the damage in the structure based on findings from a visual inspection as well as available information from previous case histories and expert knowledge.

1.3 OBJECTIVES

The primary objectives of this study were: (1) to review, collect and synthesize information on the application of various available Bridge Management Systems (BMS), Decision Support Systems (DSS), and expert systems in bridge engineering, (2) To develop an easy to use Bridge Emergency Expert System (BEES) that will assist the DOT personnel in responding to emergency incidents, and (3) To merge information in an existing case history database [1] with the Bridge Emergency Expert System (BEES).

1.4 STUDY APPROACH

In order to accomplish the objectives of this study, the following steps were taken: identification of relevant methods, conceptualization, formalization, implementation, and testing [5]. Figure 2 illustrates the study's step-by-step approach that was followed for the development of the BEES.

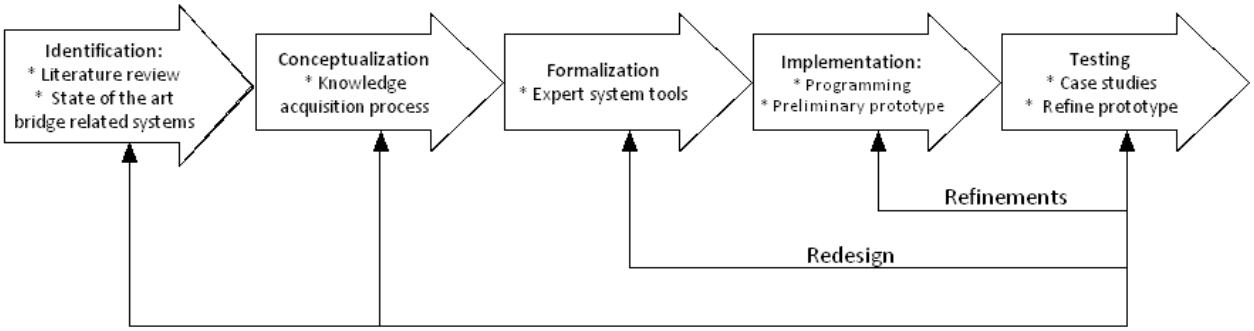

Figure 2. Step-By-Step Approach for Completion of This Study

To address bridge incidents through the use of an expert system, it is important to review and understand the state of the art in bridge management and expert systems. Books, articles, interviews, and on-line databases were the primary sources of the literature review for this study.

The knowledge acquisition process included obtaining information from a variety of sources such as emergency case histories, interviews and research articles. The acquired information included possible emergency incidents and resulting damage that was subsequently transferred to the knowledge base of the system.

In the formalization process, two commercially available software packages were used to develop the required expert system for this study. These packages included an object-orientated programming language (PYTHON), and an expert system development program (CLIPS). These software packages are open source tools, are easily accessible online, and are regarded as cutting-edge technology tools.

A first prototype was implemented based on key concepts, relations, and information collected in previous stages. Several refinements and tests were performed on this first prototype to develop a final version of the software.

The testing was based on using knowledge from case histories from past bridge emergency incidents to ensure practical and meaningful system performance. Recommendations that were offered and implemented by bridge engineers at the

site of past incidents were compared with the recommendations provided by this study's expert system to enhance the outcome of the developed system.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Roads and bridges are designed to facilitate safe and efficient travel for the public and for the flow of commerce. Therefore, keeping them open and operational is a primary objective.

After the 1967 collapse into the Ohio River of the Silver Bridge in Point Pleasant, West Virginia, the first Bridge Management System (BMS) was developed in the United States to prevent reoccurrence of this type of accident. The failure of this structure showed the need for an effective tool that could be used in bridge inspection and bridge management practices. Subsequently, as a result of the Federal-Aid Highway Act of 1968, the U.S. Secretary of the Department of Transportation was required to develop and implement the National Bridge Inspection Standards (NBIS). The primary purpose of this legislation was to locate and evaluate existing deficiencies in bridges and to ensure the safety of the traveling public. In the early 1970's , the National Bridge Inventory (NBI) was created where information from inspections, inventories, and condition ratings of bridges are stored in this database. Currently, the National Bridge Inventory forms the basis for the allocation of resources and federal funding [6].

Major Bridge failures, such as the Silver Bridge collapse, raised the interest of researchers within the US and around the world to create different approaches for the development of bridge related expert systems. This chapter describes some of the existing Bridge Management Systems (BMS), Decision Support Systems (DSS) and generic expert systems. This chapter also includes definitions for various

damage types that occur due to bridge incidents. These damage types are classified depending on the damaged bridge member.

2.2 BRIDGE MANAGEMENT SYSTEMS

Although the practice of bridge management was initially based on utilizing written documents such as national standards or inspection and maintenance manuals, various bridge owners and researchers have been able to develop and implement more enhanced and effective automated decision support models. Bridge Management Systems (BMS) are developed based on merging different disciplines among which are engineering, operation research, economics, planning, and information technology. The combination of these disciplines in a BMS assists bridge owners to manage the overall requirements of a highway system in a more effective way.

Currently, the more sophisticated bridge management systems include elements of a decision support system (DSS) that can assist bridge engineers and owners in decision making and solving bridge related problems. A DSS is an interactive software-based system that helps the user to compile information that can be analyzed to recommend solutions to various problems. A well-structured DSS consists of a database system and a knowledge-based system.

The database stores the information required by an expert system to arrive at a decision. The information contained in the database must be periodically updated in order to provide a relevant solution. A bridge DSS database generally contains structural data, reference information such as identification, technical and administrative data, as well as maintenance- and rehabilitation-related documents such as maintenance records, inspection reports, and inspection specifications.

Expert Systems or Knowledge-based systems are software that provide recommended solutions to problems or clarify uncertainties. The knowledge required to provide this response is drawn from the existing databases, therefore, the provided recommendations are as good as the information contained in the

databases. Expert systems are normally developed for a specific application such as bridge design, rating, damage assessment, or inspection.

The following flow chart illustrates the general relationship among BMS, DSS and expert systems.

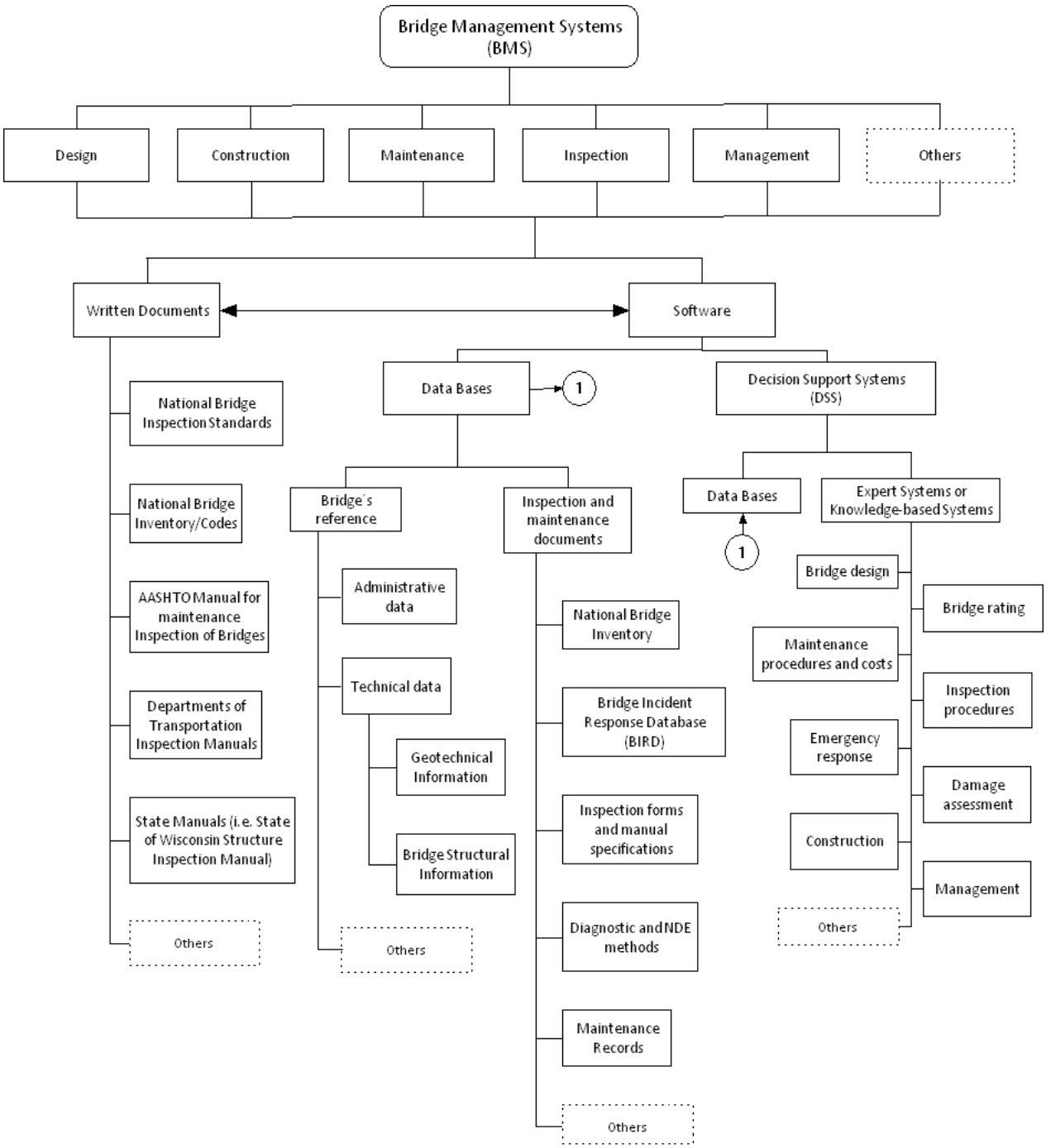

Figure 3. Bridge Management Systems Flow Chart

The development of a BMS depends primarily on the user's needs or requirements. Therefore, the elements presented in Figure 3 may be altered to meet those specific needs. Table 1 summarizes the most relevant existing BMS developed within the United States. A general description and some features implemented in each package are also presented.

Table 1. Available BMS Systems within the United States

SOFTWARE	GENERAL INFORMATION	CHARACTERISTICS AND FEATURES
BRIDGIT [7]	Developed by the National Cooperative Highway Research Program (NCHRP) and the National Engineering Corporation. A beta versions of the software was released in the early 1990's	Handles large bridge inventories.
		Uploads US National Bridge Inventory data directly from the DOT's NBI file.
	Aids in the development of bridge maintenance, rehabilitation and replacement programs based on life-cycle costing and incremental benefit cost analysis	Provides guidance on how to allocate funds on a bridge network. It also recommends specific actions for each bridge by considering the costs and benefits of many possible actions.
		Has a bottom-up approach of optimization. Uses a project-level-based optimization strategy to provide network level recommendations. [6].
PONTIS [1]	Developed by the Federal Highway Administration (FHWA) in conjunction with six state DOT´s, including Wisconsin. A beta version of the software was released in the early 1990's.	The condition data is more detailed than the requirements of the NBI. Each bridge is subdivided into individual elements within the same materials.
	Stores bridge inventories and records inspection data. It does not include evaluation modules.	Provides a systematic procedure for allocation of resources for preservation and improvement of the bridges in a network.
		Employs a top-down approach by optimizing first over the network [6].
Pennsylvania Department of Transportation BMS [8]	Its development began in 1983 by the Bridge Management Task Group of the Pennsylvania Department of Transportation. By 1986, the system	The two main parts of the BMS consist of the subsystems for Maintenance and Rehabilitation/replacement.

SOFTWARE	GENERAL INFORMATION	CHARACTERISTICS AND FEATURES
	was operational statewide.	Yields recommendations and associated cost estimates.
	Has a strong decision system, both at the maintenance and Rehabilitation/Replacement level. It gives less attention to the inspection module.	Predicts present and future needs and associated costs to perform maintenance.
		Provides a basis for recommending regional distribution of budgeted funds.
BRUFEM [8]	Complete rating system developed in 1990 to rate the majority of bridges in Florida.	Finite element based software.
		The pre-processing prepares the input file\element program for a variety of concrete and steel bridges.
		Based on the finite element analysis results, rating calculations are performed according to the service level.
		The post-processing allows three rating options: inventory rating, operating rating and load factor rating.
IBMS [9]	The development of the Indiana Bridge Management System (IBMS) was started in the late 80s by the Indiana Department of Transportation.	It is a planning tool which organizes, presents and analyzes information related to the maintenance and improvement of highway bridges.
		It is a project level system the foundation of which is the Project Selection Module.
		Contains four submodules: decision tree (DTREE), life cycle cost analysis (COST), multicriteria ranking (RANK) and optimization (OPT)

Although a wide range of BMS systems have been developed within the US, only a few are currently being used. PONTIS has been more successful and commonly used by bridge owners. Figure 4 is a map of the United States indicating states that have license for using PONTIS. As seen in the figure, approximately 85% of the US state DOTs own this BMS. Other states, such as Washington, are currently using BRIDGIT, while Missouri, Indiana, North Carolina and Ohio are using customized systems developed internally. Among the systems developed by various

states, the Missouri's management system is noteworthy. Although this system is not a management system exclusive to bridges, it is a sophisticated Transportation Management System (TMS) that includes a bridge module as well as travel routing features, traffic module, safety module, and pavement module. The bridge module stores bridge element/component inspection information, cost analysis based on maintenance and construction estimates, and contains both on-system and off-system bridge inventory. In addition, it has the ability to interface with other bridge management system such as PONTIS [10].

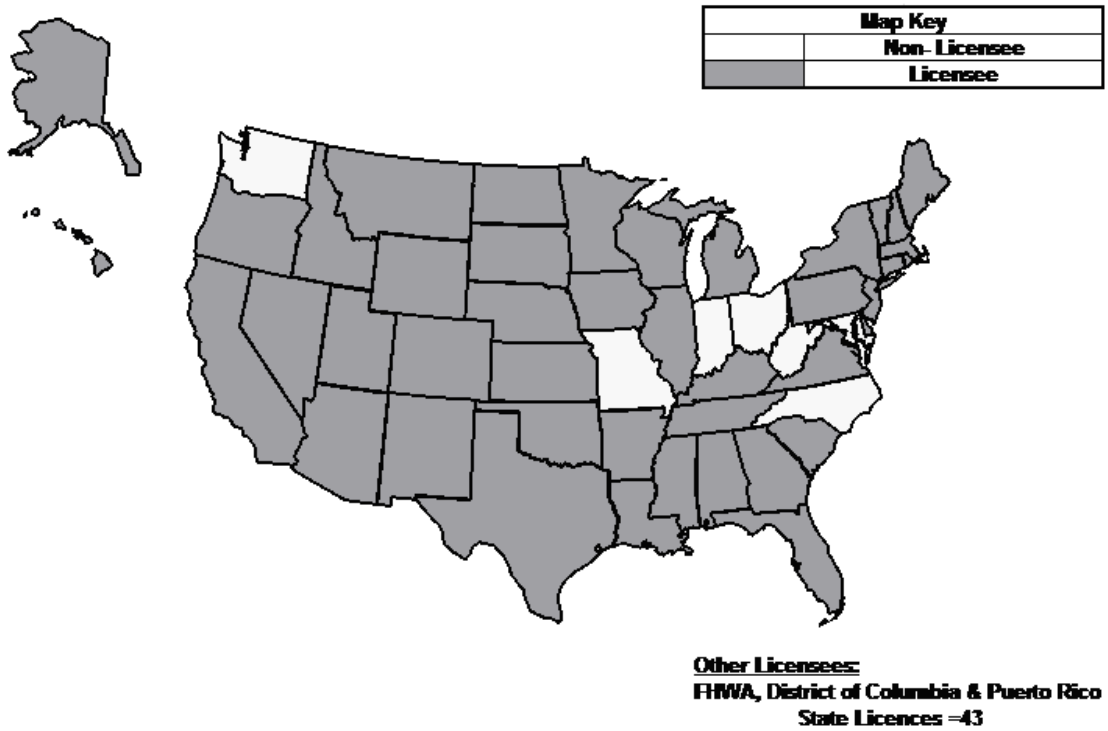

Figure 4. States Using PONTIS Within the United States*

BMS have been also developed outside the US. Table 2 summarizes some of these systems.

* Provided by Michael Baker Jr., Inc. AASHTO Ware Products Contractor.

Table 2. BMS Systems Developed outside the United States

SOFTWARE	GENERAL INFORMATION	CHARACTERISTICS AND FEATURES
OBMS (Ontario Bridge Management System) [11]	Created by the Highway Engineering Division of the Ontario Ministry of Transportation. Its development began in 1998 and was first implemented in 2000 with bridge inspection and data management features.	Created to handle vast amounts of information and to make decisions at the inspection site and at the office.
		Capable of creating, updating, and storing inspection/rating data.
		Designed with equal priority given to project-level and network-level features.
COSMOS (Computerized System for the Management of Structures) [12].	Used by the Surrey County Council in the UK in its bridge management activities. Developed in the 1990's.	It is the interface between the user and an ORACLE data base system which stores all structural information.
		The system includes modules which generate site instructions and inspection notices, monitors expenditures, and allows for publication and circulation of information.
DANBRO [13], [14]	Management and maintenance system developed by the Ministry of Transportation of Denmark This system has been used in Denmark since 1988.	Developed to provide bridge authorities with a tool that helps guarantee the safety and functionality, collects data, optimizes the use of the funds and provides technical-economic backup.
	BMSs based on DANBRO have been implemented for the national highway administrations in Thailand, Saudi Arabia, Mexico, Colombia, Honduras, Croatia and Malaysia.	The structure of the system is modular. Each administration can choose which modules to implement.
BRISA-Portugal Highways BMS [8]	Developed by Portugal Highways S.A., the concession holder responsible for most of the Portuguese Highways since 1970's.	Has a complete data base that contains information such as geometric and structural characteristics, inspection and measurements forms.
		The inspection subsystem allows the detection of defects in the bridge components as well as their classification.
SAGGI (Advanced Systems for the Global Management	It is the result of a research project financed by the Italian Ministry for Research (2005-2009)	The project aimed at developing a BMS that integrated various elements such as surveillance and assessment, allowing the treatment of both visual and instrumental data.

SOFTWARE	GENERAL INFORMATION	CHARACTERISTICS AND FEATURES
of Infrastructures) [15]	Developed based on the old Italian BMS (SAMOA).	Incorporates automation of visual bridge inspections, traditionally carried out by trained personnel
		Based on information provided by a 3D laser scanner, an expert system will detect and classify specific geometric configuration data and deteriorations.
PONTIS based Hungarian system [16]	In 1998 Hungarian experts established the Project-Oriented BMS based on PONTIS.	Finds the optimal (minimum cost) maintenance solution. The program calculates cost optimization and explains its results for all bridges.
		PONTIS sources from the American National Bridge Inventory were converted to the Hungarian National Road Databank
KUBA (From the German "KUnstBAuten" or road structures) [17]	Its development started since 1991 by the Swiss Federal Roads Office.	The system consists of four components: a road structure inventory, a preservation planning tool, a reporting tool, and a heavyweight transport evaluation tool.
		The last version of the system, KUBA 4.0, was released in 2007. The next version was released in April 2010 and includes features such as a geographic information system and a tunnel data collector.

The majority of the BMS systems shown above have various elements of bridge management systems but none could be considered a fully developed system. The lack of inspection modules, high speed data processing, and effective expert systems is considered a shortcoming of these systems, but it offers a motivation for most of the developers to improve the current modules. SAMOA, the old Italian BMS, is an example of this continuous progress. New modules were added to the original software to develop SAGGI in 2005. After these modifications, visual inspection modules were recently incorporated and further topics, such as evaluation of seismic behavior, are now being implemented.

A bridge management system named Bridge Management in Europe (BRIME), was introduced in March 2001 with the goal of unifying bridge management practices in Europe for the European road network [18]. The project was being

carried out under the auspices of the Forum of European Highway Research Laboratories (FEHRL). The primary objective of this project was to develop a framework for a bridge management system and to identify the input and output requirements for the system.

In the US, the AASHTO BRIDGEWare Task Force has worked since 2001 to link together its bridge related software products, such as Pontis for bridge management, Virtis for load rating, and Opis for bridge design. The primary objective of this effort is to create a unique system known as BRIDGEWare to fully support tasks such as design, inspection, rating and permitting. The system will also analyze against deterioration and will plan for maintenance at the network and project levels [19].

Virtis and Opis were developed simultaneously by AASHTO in 1997 to replace earlier AASHTO software packages, BARS for bridge load rating and BDS for design. Opis is a bridge superstructure design-review system that uses the AASHTO LRFD Bridge Design Specifications. The system employs the same database and graphical user interface as AASHTO's rating system or Virtis. Efforts have being made to develop support tools for reporting, design process management, and comparison of design alternatives. Virtis is a comprehensive bridge rating in accordance with the AASHTO Bridge Standard Specifications. It provides a database where rating inputs and outputs can quickly be stored, reviewed and reused [19].

Virtis and Opis developers have continued to enhance the systems' capabilities since they were first developed . Due to this constant development, these systems have become very popular among private and public agencies in the United States. Figure 5 and Figure 6 show a map of the United States that identifies states that currently use Virtis and Opis, respectively.

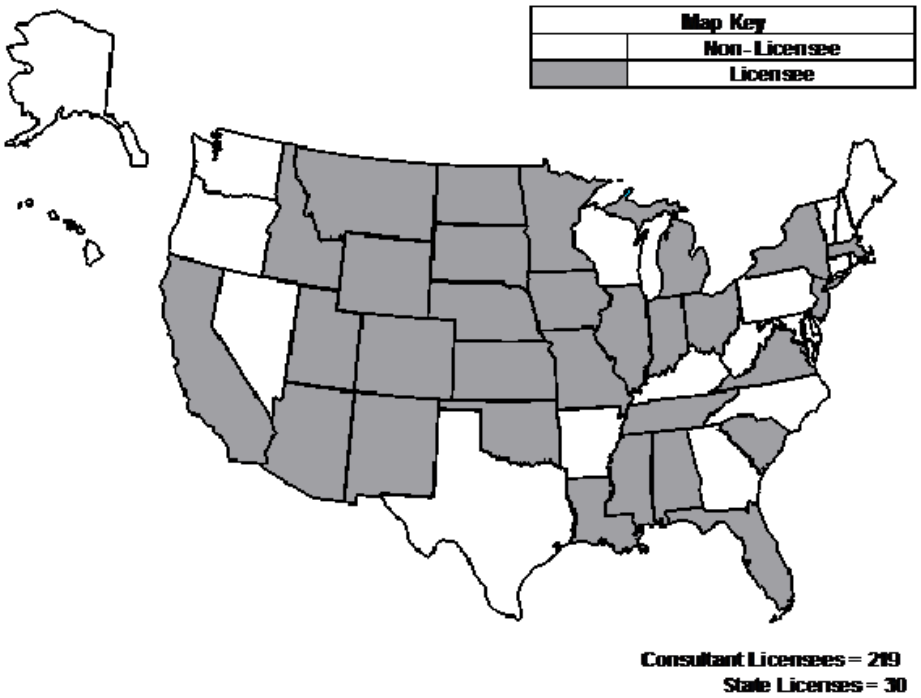

Figure 5. US States using Virtis*

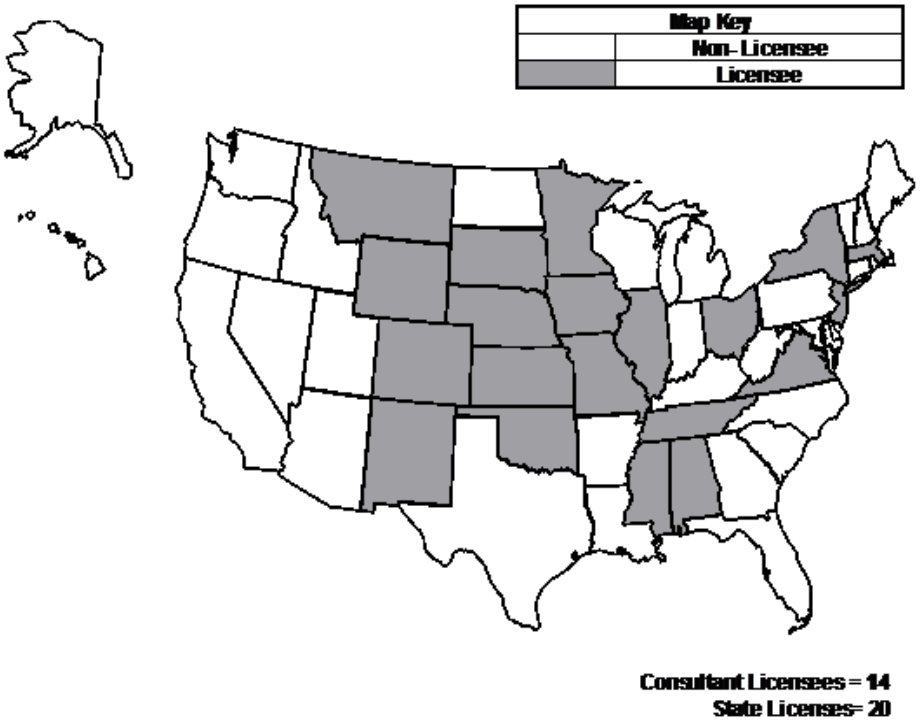

Figure 6. US States Using Opis*

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* Provided by Michael Baker Jr., Inc. AASHTOWare Products Contractor

2.3 DECISION SUPPORT SYSTEMS AND EXPERT SYSTEMS

Decision Support Systems (DSS) are computerized information systems that support decision-making activities. A DSS may assist bridge management systems in the following ways:

- Standardizing various actions and documentation processes, including inspections and their reports as well as decision-making activities.
- Standardizing applicable criteria to minimize subjective decision making.
- Optimizing the use of available resources such as personnel, equipment, time and money.
- Minimizing bureaucratic procedures that delay decision-making processes.
- Making decisions, based on economic and engineering requirements.

A DSS system consists of subsystems such as data management, model management, knowledge base management, and user interface. The knowledge-based management subsystem may consist of one or more intelligent expert systems that offer solutions based on specific required expertise [20].

Expert systems, like BMS, are developed based on specific functions for which they are intended for. Therefore, specific expert systems have been developed to fulfill different needs. Table 3 lists several existing expert systems for bridges along with their unique characteristics.

Table 3. Knowledge Based Expert Systems for Bridges

SYSTEM	GENERAL INFORMATION	CHARACTERISTICS AND FEATURES
Management		
BEADS (Bridge Expert Analysis and Decision Support System) [21]	Developed by the Alberta Transportation Department. The system is part of a larger department-wide integrated Transportation Infrastructure Management System (TIMS).	The primary objectives are to facilitate decisions to optimize the allocation of bridge funds, evaluate system performance, plan and manage bridge construction, rehabilitation and maintenance.
		Provides a project-level (bottom-up) analysis based on site-specific data.
		Developed with Visual Basic for Applications within Microsoft Excel.
Design		
KYBAS (Kentucky Bridge Analysis System) [22]	Partially funded by the Kentucky Department of Transportation and developed in 1990 by the J.B. Speed Scientific School of the University of Louisville. It was created for highway bridge design and analysis.	Rule-based decisions are made through finite element modeling.
		The numeric modules are coupled with the expert system to perform analysis and design in a collection of engineering analysis algorithms.
		Coded in FORTRAN with an expert system and related interfacing modules in C. It is developed using CLIPS as shell.
BDES (Bridge Design Expert System) [23]	Developed by Duke University in 1987. It designs superstructures for small to medium span highway bridges.	The knowledge base is partitioned into knowledge modules and represented by rules.
		Knowledge modules organize sets of rules and facts for different design stages.
EXSTRUCT [24]	Developed by the University of Pavia, Italy in 1995. It is an expert system for the preliminary design of structures.	The knowledge is organized into models that establish relationships between structural types and behaviors.
		An abductive inference mechanism (inference to the best explanation) leads to reasonable solutions based on specifications, quantities and costs.

SYSTEM	GENERAL INFORMATION	CHARACTERISTICS AND FEATURES
Decision Support for Preliminary Bridge Costing (DSPBC) [25]	Developed by the Cardiff Decision Support Systems Group of the University of Wales, UK in the early 90s.	Provides the designer with an efficient way to obtain a preliminary bridge costing which can be compared to other designs.
		Based on the principle of heuristic (experience-based technique) substitution, and provides a preliminary costing estimate which can be used in the conceptual design process.
Construction		
BFX (Bridge Fabrication Error Solution Expert System) [26]	Developed in 1994 by The University of Kansas. Partial funded by the Kansas Department of Transportation Cooperative Research Program (K-TRAN).	Developed to help designers and inspectors to determine the severity of fabrication errors on steel bridge members and to specify any necessary repair.
		The development methodology uses a case approach during the knowledge acquisition and the validation/verification procedures. The cases are documented based on prior experience and interviews with experts.
Rating		
BREX (Bridge Rating Expert System) [27]	Developed by the Engineering Department of the Yamaguchi University, Japan.	Evaluates the performance of bridge members in terms of factors such as serviceability, load-carrying capacity, and durability.
		The performance of a bridge is evaluated based on available technical data and visual inspection. In the knowledge base of the system, the diagnostic process is stored in terms of if-then rules with fuzzy variables in order to perform fuzzy inference.
Maintenance		
CAESAR (Catalog and Expert Evaluation of Scour Risk and River Stability) [28]	Developed by the University of Washington Seattle under NCHRP project 24-6 [28].	Assists bridge inspectors by acquiring, cataloguing, storing, and retrieving information necessary for the evaluation of a bridge for the presence of scour.
		Provides scour risk evaluation with its explanation and suggestions to mitigate it.
		It is written in Visual Basic and integrates Bayesian network as the generic logic framework with bridge scour.

SYSTEM	GENERAL INFORMATION	CHARACTERISTICS AND FEATURES
ANFIS (Adaptive Neuro-Fuzzy Inference System) [29]	This project was developed in 2007 by the Institute of Soft Science, Fuzhou University, China, and the School of Mechanical, Aerospace and Civil engineering of the University of Manchester. It was funded by the UK Engineering and Physical Sciences Research Council.	Intends to help highway agencies to determine the maintenance priority ranking of bridge structures based on 506 bridge maintenance projects for all levels and types of bridge risk assessment.
		Is a multilayer feed-forward network which uses neural network learning algorithms and fuzzy reasoning to map inputs into an output. It is a Fuzzy inference system implemented in the framework of adaptive neural networks.
Neural network-based system for truss bridge joints [30]	Developed in 2007 by the Civil and Industrial Engineering Departments of the Tarbiat Modares University, Tehran, Iran.	Uses a neural network identification approach for the estimation of the damage percentage of joints for truss bridge structures.
		Is a multilayered feed-forward neural network that consists of an input layer, one or more hidden layers, and an output layer.
		The input and output relationship of a neural network are determined by weights assigned to the connections between nodes in two neighboring layers.
FPNES (Fuzzy Petri Net Based Expert System) [31]	Developed in 2000 by the department of civil and Computer Science and information departments of the National Central University, Taiwan.	Contains a fuzzy petri net approach to modeling fuzzy rule based reasoning, and a tool supporting the damage assessment of bridges.
		A probabilistic logic based approach that deals with uncertain and imprecise information.

To improve performance, one may integrate various subsets of artificial intelligence concept, such as neural networking or computing, with an expert system. Neural computing is developed based on the concept of simulating human brain functions and it is utilized in expert systems to reduce analysis time and enhance learning capabilities [20].

In general, the three major components of an expert system are the knowledge-base, inference engine, and user interface. The knowledge-base component contains the relevant knowledge necessary for understanding and

solving specific problems. The inference engine performs the process of interpreting this knowledge. The user interface provides a link between the first two components and the user. In addition to facilitating the communication between the user and the system, the user interface accepts entries, displays data and graphics, and provides other capabilities [20]. Figure 7 illustrates the interaction among the knowledge base, inference engine, and user interface in an expert system.

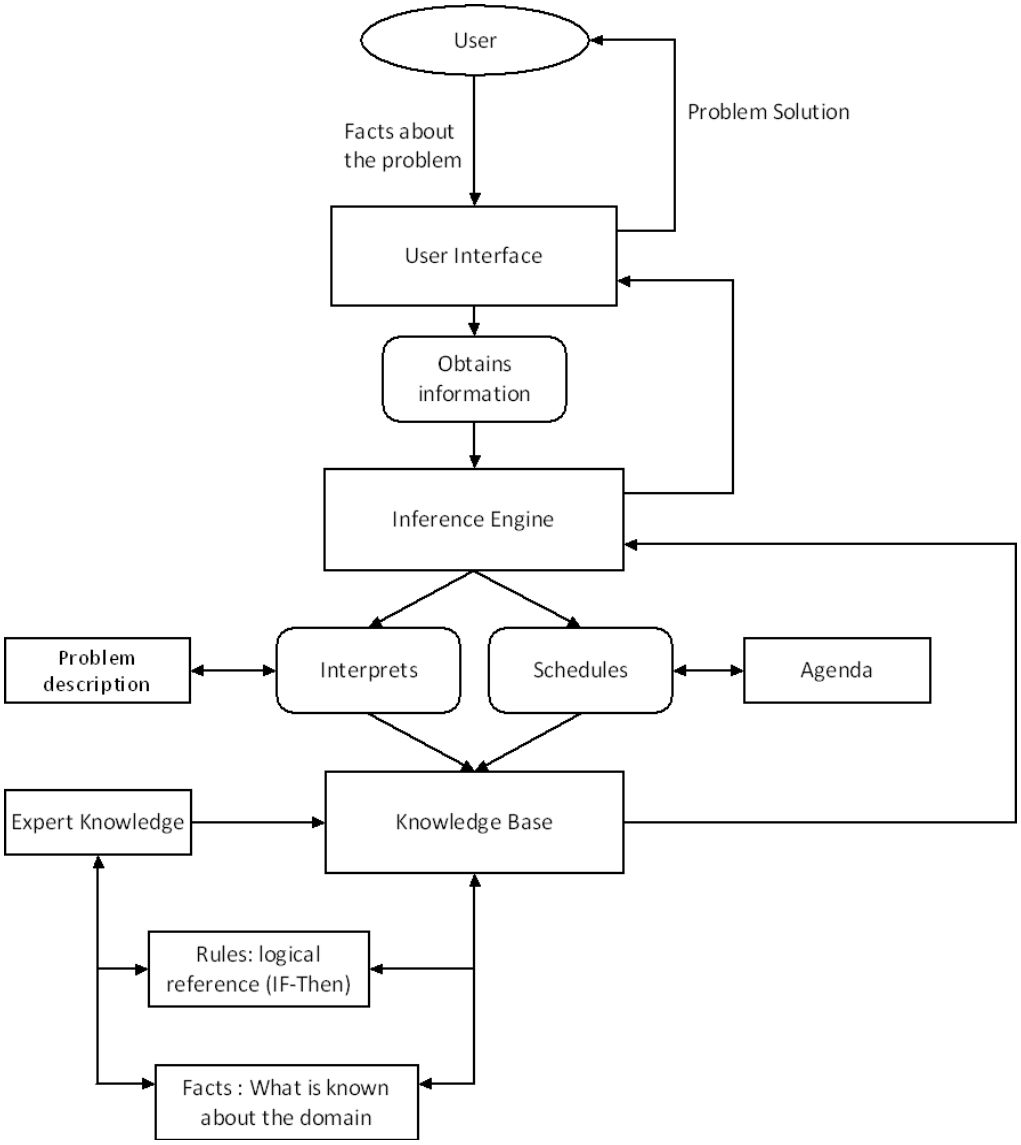

Figure 7. Interaction Among An Expert System's Primary Components

The information in the knowledge-base is stored in terms of facts and rules. Rules are based on premise (facts) and conclusions are constructed in terms of "IF-THEN" expressions. Each rule in the knowledge-base is systematically verified to see whether its premise or conclusion is satisfied by previously made assertions. This process can be done based on backward or forward chaining. In forward chaining, the premise clauses match one or more conditions and then the process attempts to assert the conclusion. In backward chaining, a conclusion is given while the system tries to determine whether the facts match the prescribed conditions for the conclusion [20].

After a review of the available literature related to expert systems, it was concluded that there is no DSS or expert system available that could satisfy the requirements of this study. The shortcoming of existing systems primarily included a lack of a bridge emergency database that includes case histories and absence of a bridge emergency knowledge base. Available features and tools, as well as advantages and disadvantages of the existing expert systems were evaluated to benefit the development of the new system for this study.

During the development of the new Bridge Emergency Expert System (BEES), the information needed for the knowledge-base was obtained using a case approach as done in the BFX and DSPBC. In this study, the cases were constructed based on previous experiences or past bridge emergency case histories [1]. In addition, the knowledge is organized in the form of modules depending on the damage type and affected components in the bridge.

The rules and facts processed in the inference engine of the Bridge Emergency Expert System (BEES) were written as IF-THEN expressions in a forward chain process. The rules were written in CLIPS, a C Language Integrated Production System, developed by NASA at the Johnson Space Center [32]. This approach was also implemented for the development of KYBAS and ANFIS.

The new expert system created under this study provides support and facilitates the decision making process at the incident site. The emphasis has been placed on providing recommendations to address immediate problems at the bridge site rather than providing routine or long-term repair and maintenance solutions. The system is not designed to replace the knowledge and experience of a bridge engineer, but it is intended to be used as a tool to aid the bridge owners and engineers in making decisions in cases of bridge emergency incidents.

2.4 BRIDGE DAMAGE TYPES

According to the Highway Structures Information (HSI) system of the Wisconsin Department of Transportation (WisDOT), approximately 69% of Wisconsin's 10,740 bridges, excluding box and pipe culverts, are concrete structures. About 26% are steel bridges, and the remaining are either aluminum, masonry or timber bridges. Figure 8 shows the number distribution of such Wisconsin bridges.

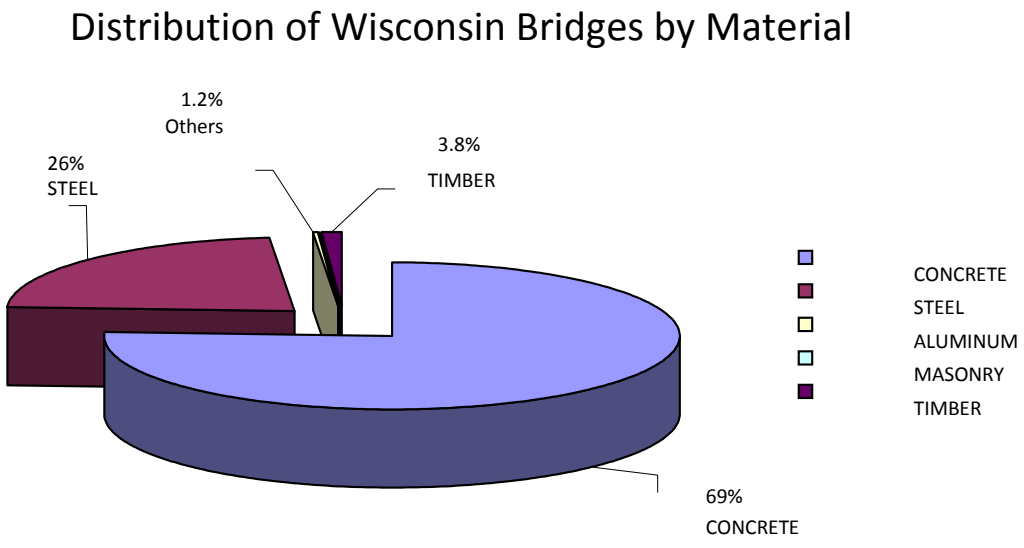

Figure 8. Primary Material Classification in Wisconsin Bridges

Since the majority of bridges in Wisconsin are concrete and steel structures, the following chapters summarize the most commonly documented emergency events for these types of bridges. These events include impact and fire incidents

associated with the superstructure and substructure of concrete bridges as well as impact damage to steel bridge superstructures.

The priorities considered by the Bridge Emergency Expert System (BEES) when providing recommendations for such incidents are based on the WisDOT Emergency Traffic Control and Scene Management Guidelines [33]. In accordance with these guidelines, the emergency response to an incident should focus on life safety, incident stabilization, and protection of property as main priorities. Safety of the traveling public, personnel that respond to the incident, and those involved in the incident, should be the first priority when dealing with a bridge emergency. In addition, the conditions at the incident site must be stabilized as soon as possible to enhance safety, facilitate the traffic flow, and minimize the diversion of vehicles to less suitable routes. Actions such as preventing secondary failures, protecting evidence, and placing appropriate and adequate traffic signage must be taken to protect the travelling public and the structure.

Although general procedures such as the ones described above provide some guidance on how to respond to an incident, specific actions will be required depending on the type of the structure affected and the level of the severity of the incident. The WisDOT Emergency Traffic Control and Scene Management Guidelines [33] provide a general classification of incidents depending on the expected closure time for the structure. A "*major* " traffic incident is identified as having a closure time of more than 2 hours and may involve hazardous materials, fatal traffic crashes, closure of all roadways, or other natural or man-made disasters. An "*intermediate"* traffic incident may have a closure time of 30 minutes to 2 hours. It usually involves roadway debris, overturned vehicles and other minor incidents. A *"minor"* traffic incident involves a closure time of less than 30 minutes. According to this classification, incidents that affect bridge structures are considered either "*major*" or "*intermediate*" since they require an assessment of the affected structure by an appropriate authority who will require at least 30 minutes or longer for arrival and structural evaluation.

2.4.1 DAMAGE TYPES IN CONCRETE SUPERSTRUCTURES

For the purpose of this study, a bridge superstructure is defined as all elements above the substructure units. The superstructure supports the deck and all live and dead loads. Superstructure components such as, beams, slabs, girders, decks, and railings are included in the following damage descriptions.

2.4.1.1 IMPACT

Although there is no available data-base related to the frequency of over-height vehicle collisions against bridge components, there is an increasing concern among the bridge owners about this type of incidents [34]. Impact damage to girders has become frequent in highway bridges. Interstate highway bridges or other major highway bridges in metropolitan areas are more likely to be affected and the resulting traffic disruptions are more consequential.

Girders that are struck by vehicles such as over-height trucks, flatbed trucks with oversized loads, or water-borne vessels could be severely damaged and they can experience significant reduction in the structural capacity and stiffness. Damage to prestressed or reinforced concrete girders due to impact includes cracking, spalling, loss of cross sections, loss or damage to strands or reinforcing steel, or a combination of the above.

According to a recent study by the New York State Department of Transportation [35], there are several factors that contribute to bridge hits. Based on visits to different regions of the state, it was found that the contributing factors for bridge hits include:

- Low or below the legal limit under-clearance,
- Low under-clearance signs placed either on the bridge or too close to it,
- Low under-clearance signs hardly visible during the night,
- Truck drivers not aware of the height of their truck with the cargo,

- Trucks with oversized/overweight permits traveling off-road, and
- Truck loads that malfunction during travel (i.e., rising bucket on a backhoe).

Although impact damage can cause major problems in bridges, the majority of the events are considered to cause minor to moderate damage [36]. Minor or moderate damage for concrete bridge hits range from isolated cracks and shallow spalls, to large cracks and spalls that expose undamaged prestressed strands or steel bars (see Figure 9 and Figure 10). A severe damage is defined as rupture of prestressing strands or reinforcing bars and large concrete spalls (see Figure 11). In addition to the damage to the girder from such accidents, traffic delays due to lane closures, rerouting, and repair work are also of major concerns.

Figure 9. Minor Damage - Shallow spalls, scrapes and minor cracking

Figure 10. Moderate Damage - Large spalls, minor loss of section and exposed strand

Figure 11. Severe Damage - Severe cracking, major loss of section, and damaged strands

Damage is usually assessed by visual inspection and/or non-destructive testing methods. Usually, a visual evaluation is the first step. In cases where the damaged caused by the incident is evident, a visual inspection may be enough for an assessment. However, in some cases non-destructive testing methods or a complete structural analysis may also be required. Internal damages that may

extend beyond the areas evaluated by visual inspection can be better assessed with non-destructive methods [37]. Table 4 summarizes some of the applicable inspection tests for damage types resulting from impact incidents in concrete bridges.

Table 4. Non-Destructive Test Methods (NDE) for Bridge Damage Inspection

Test Technique	Description	Applicability
Rebound/Schmidt Hammer [38]	Works by impacting a spring loaded mass on a plunger which is in contact with the surface. The hammer mass rebounds and engages an indicator on a sliding scale which records the rebound distance.	• Assess variation of concrete strength within a structure. • Determines areas of delaminated and cracked concrete.
Ultrasonic Pulse Velocity [38]	A pulse generator produces voltage pulses that are received by a transducer coupled to the concrete surface. After receiving the pulse, it is amplified so the timing circuit considers the travel time of the pulse to calculate its velocity.	• Assess the strength of concrete. • Detects voids and cracks. • Estimates thickness of layers that have different sound propagation properties.
Impact Echo [39]	An impact device and one or more receivers are used to analyze any reflected impact waveforms to detect defects or artifacts inside the concrete.	• Detects defects in concrete through its thickness
Radiography [39]	X-ray and Gamma ray radiography provide photo images of the interior of a concrete member and record the resulting images on film or in digital form by receiving sensors or detectors.	• Provides the location of voids, embedded materials as well as the deterioration of pre/post-tensioned strands.
Acoustic Emission [39]	Sensors are placed at critical areas with the purpose of detecting the released elastic energy due to a cracking.	• Monitors the release of energy in the structure when microscopic cracks occur. • Determines the location and occurrence of cracking.
Spectral Analysis of Surface Waves [39]	An impact is used to generate a surface wave (R-wave) and two receivers are used to monitor the motion as the R-wave propagates along the surface.	• Measures changes in the elastic properties of concrete. • Describes the stiffness of the member.

Test Technique	Description	Applicability
Hammer Sounding [39]	The structure is hit by a hammer. Regions of delamination have a hollow sound compared to a solid sound for satisfactory concrete.	• Detects localized delamination zones in concrete members.
Thermography [39]	Differential heating and sensing at the surface of the structure will reveal areas of defects such as delamination.	• Delamination in plate-like structural elements such as bridge decks.

The Bridge Emergency Expert System (BEES) considers only visual inspection as the principal damage evaluation method. It provides recommendations based on the user's input and presents a list of possible non-destructive methods for support purposes.

2.4.1.2 FIRE

Reinforced concrete bridges are vulnerable to fire caused by tanker truck accidents, wildfires, arson or terrorist attacks. Heat damages concrete by weakening the cement paste. This causes the reinforcing steel to relax, increasing deformations and cracking [39].

Concrete behaves well in resisting the effects of damage by fire since its heat conductivity is relatively low. In addition, the effects of high temperatures may be limited to the outer surfaces if the exposure to the fire is not prolonged. The fire damage in concrete members depends on the exposure time and the moisture content of the concrete.

The effects of high temperatures on prestressed steel can be much more significant. The strength of the strand can be reduced by up to 50 percent at 750°F [38]. Concrete girders exposed to fire can lose a significant portion of their strength by the reduction in steel modulus of elasticity and by excessive elongation of prestressed strands.

Explosive spalling may occur during early stages of the fire, progressively leading to the removal of sections of the concrete, possibly due to the level of the outer layer of reinforcing steel [39]. In addition, the sudden application of water to fire-heated concrete from the fire fighting efforts can also lead to sudden cracking and spalling. Visual inspection of concrete structures can allow detection of physical damage such as cracks, spalls, color changes, and exposed reinforcement.

The intensity of the fire and the concrete damage level after being exposed to flames can be identified based on the resulting color. According to the Precast/Prestressed Concrete Institute (PCI), concrete that is not discolored and has been heated and then cooled did not reach temperatures above 600°F. If the concrete has turned into a pink color due to fire, it could have reached temperatures between 600°F and 1100°F. Concrete heated above 1100°F and then cooled tends to develop a whitish-gray surface; and for above 1700°F some concretes turn to a buff or yellowish color [40] (see Figure 12).

Figure 12. Concrete Girder Damaged by Fire (Buff color)

Some research has been done to determine the effect of major fire damage in bridge structures. A study [41], in which fire-damaged girders were loaded, revealed that significantly damaged girders have sufficient remaining flexural capacity to serve their intended purpose in the short term. However, long term

flexural capacity of a girder may be affected. Damage can be sufficient to allow aggressive chemicals to penetrate the structure. With time, those agents accelerate deterioration of the concrete and the bottom row of strands.

Although visual inspection may be helpful to detect physical signs of fire damage, it is often necessary to obtain additional information through the use of other test methods in order to make a full evaluation of the damage. Table 4 summarizes some of the non-destructive test techniques that may be used to detect the extent of fire damage in bridges.

Besides the non-destructive tests mentioned in Table 4, other tests such as petrographic examination that require the removal of concrete cores are commonly employed in the assessment of concrete structures damaged by fire. Petrographic analysis is frequently performed to determine chemical and physical irregularities in concrete, specifically to determine chemical attack, identification of reactive aggregates, strength, mixture proportion estimates, degree of carbonation, aggregate size and distribution, and presence of alkali-aggregate. Examinations are carried out in compliance with guidelines provided in ASTM C856 “Standard Practice for Petrographic Examination of Hardened Concrete”.

Testing methods such as the ones mentioned above may be used to validate the information obtained from a visual inspection. A recent study [42] has demonstrated that visual color mapping and identification of physical defects can correlate well with the variation of concrete hardness obtained from the Schmidt and Rebound Hammer tests. The Bridge Emergency Expert System (BEES) classifies the damage based only on the user’s visual inspection results. BEES also recommends to the user appropriate non-destructive test methods to obtain supplementary information.

2.4.2 DAMAGE TYPES IN CONCRETE SUBSTRUCTURES

A bridge substructure is composed of all elements that support the superstructure and it transfers all of the bridge live and dead loads to the foundation

[43]. For the purpose of this study, impact and fire events on pier columns are considered.

2.4.2.1 IMPACT

A common impact damage to substructures occurs in over water bridges due to collisions from various size vessels or ships. The effect of the impact on the structure depends on the presence and type of protective structure at the bridge, the velocity and mass of the vessel or motor vehicle, and the depth of water.

In a case of a pier collision, all the integrating members including the column, cap beam, footing and underlying soil, experience the resulting acceleration from the impact. All these members should be designed for the expected impact forces. Normally, the footing is designed and constructed in a way to allow prevention against a direct impact to the column, which is designed to transfer part of the impact force shared by the superstructure [44]. For highway bridges, protection against motor vehicle collisions is provided by constructing guard rails and energy absorbing crash barriers.

According to the WisDOT's Structure Inspection Manual [43], signs of pier impact damage include scrapes, chips, cracks, spalls, and possibly a fractured section of a pier component. In cases of severe collisions, reinforcing bars can be exposed or damaged. The WisDOT manual classifies the impact damage into three condition states based on the observed evidence on the structure. These include: Condition state 1 - that is defined as having previously repaired damage and new minor evidence of impact, Condition State 2 – with unrepaired former minimal damage including spalls and exposure of a few reinforcing steel bars, and Condition State 3 – with evidence of severe damage to cause concerns for public safety or serviceability of the member or structure (see Figure 13).

Figure 13. Example of a Severe Impact Damage to Substructure

Visual inspection of substructures may be complemented by conducting appropriate non-destructive or other tests to make a more complete condition assessment of the damaged members from impact forces. Table 4 includes a list of available non-destructive test methods that may be appropriate for evaluation of substructures in bridges.

2.4.2.2 FIRE

The effects of fire incidents in concrete piers are similar to those in other concrete members. Delamination, cracks, spalls and deformation of the members may be evident depending on the temperature and exposure time. The absence of any significant deflection, distortion, and color changes may indicate that no severe damage has been experienced by the member. Surface delamination may be more common in pier columns due to the presence of shallow reinforcing, rapid expansion of the steel and spalling of the concrete cover [45].

Non-destructive testing may be used to obtain additional information and to confirm the results from the visual assessment (see Table 4).

2.4.3 DAMAGE TYPES IN STEEL SUPERSTRUCTURES

2.4.3.1 IMPACT

Steel has become one of the most common materials for highway and railroad bridge construction since the first cast iron bridge was built near Coalbrookdale, UK in 1779 [46]. Although steel was used mostly in short-span bridges initially, its advantages due to high strength and light weight became more apparent when it was used in the construction of arch and suspension bridges with longer spans.

The use of steel in bridges has been characterized by successful applications but also by unfortunate events such as structural collapses. According to a recent study of bridge failures [46], structural collapses in highway bridges may be classified according to their causes. According to the study, a random selection of 350 bridge collapses from around the world showed that 65% were caused by the effect of natural or ill-intended man-made forces including earthquakes, floods, avalanches, hurricanes, and acts of terrorism. The remaining collapses included 12% by accidental overload and impact, 9% by structural and design deficiencies, and 9% by scour. Other causes such as lack of maintenance and supervision as well as construction errors made up the remainder 5% of the collapse cases. Figure 14 shows the distribution of collapses due to various causes in bridges excluding those by the effects natural forces and acts of terrorism.

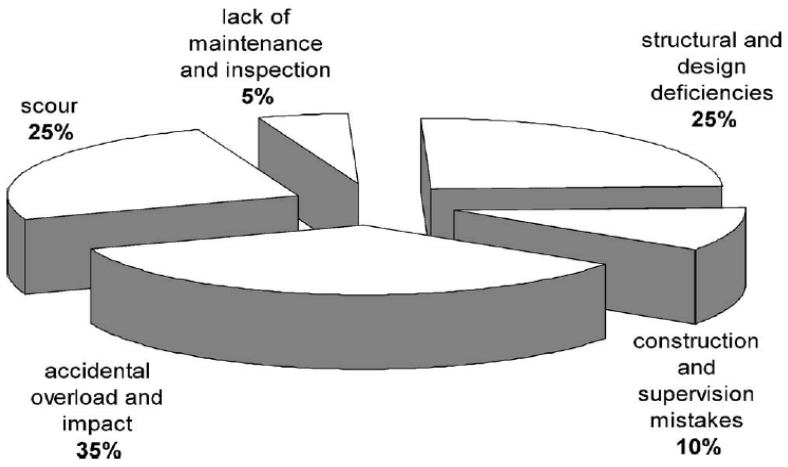

Figure 14. Distribution of Bridge Collapses Due to Causes Excluding Natural Forces [46]

Although the data included in the study did not correspond only to steel bridges, it was found that regardless of the material type the frequency of bridge collapses due to different causes is the same [46].

Accidental impacts in bridges are the most common causes of not only collapses but also minor structural damage. Bridge members that are hit most often are the fascia girders and truss portals. Older highway bridges with lower vertical clearance are most likely to be struck by over-height vehicles, although over-height cargo on trucks and high floating marine vessels can also strike bridge superstructures [43].

Depending on the type of impact load, the affected bridge member can experience different levels of distortion and damage. In tension members, even minor impacts could cause notches or tears that could act as stress raisers leading to fatigue cracking or fracture. Signs of impact damage in a bridge member may include scrapes on the member's underside, distorted members, and nicks or gouges as well as cracks and tears in plate elements of the affected member. Severe collisions may lead to large fracture of steel or to permanent deformation in the bridge[43].

The Wisconsin Structure Inspection Manual [43] defines three condition states to describe the damage produced by an impact to a steel bridge superstructure:

- Condition State 1: When there is previous damage that has been repaired.
- Condition State 2: When there is unrepaired previous damage and the new damage is minimal and does not cause any safety concern. Repairs may not be required. (see Figure 15).

Figure 15. Condition State 2 for a Steel Girder Moderately Damaged by Impact (scrapes and minor distortion of the bottom flange)

- Condition State 3: When the damage causes concerns regarding safety or bridge's serviceability. The member may have been severely damaged to the extent that it may no longer possess its original structural capacity. In such cases, an appropriate structural analysis will be warranted to determine the member's new capacity. Accordingly, appropriate repairs should be implemented for the affected structure (see Figure 16).

Figure 16. Condition State 3 for a Steel Girder Severely Damaged by Impact (major distortion of the web and bottom flange)

Guidelines have been developed through other studies [47] for the assessment of damaged steel bridge members from impacts and other accidents with recommendations regarding repairs and replacement. According to these guidelines, tension members or components are considered fracture critical and as such must be examined carefully for effects due to impact or damage. The effect of vehicular impact on steel bridge members based on the materials properties and temperature must also be considered. It is known that brittle fractures can occur in ductile materials at lower temperatures. In addition, it is known that plastically strained and aged steel can exhibit overall lower ductility levels with higher fracture transition temperatures.

Considering a typical stress-strain diagram for bridge steels (see Figure 17), it can be seen that an A36 steel continues to plastically deform beyond the yield point for a total displacement of about 15 times of that for the yield point without a significant increase or decrease in the applied stress. Beyond this level of

displacement, strain hardening occurs in the steel and further deformation will take place only if there is some increase in the level of the applied stress. Shanafelt and Horn [47] state that for steel strains bellow 5% from impact loads on bridge members there will be little effect on the materials properties. It must be noted however that most of the strain caused by vehicular impacts in steel bridge members would fall within 5 to 10 times the strain at the point of yield. As such, no significant degradation can be expected in the affected steel unless cracking or fracture occurs.

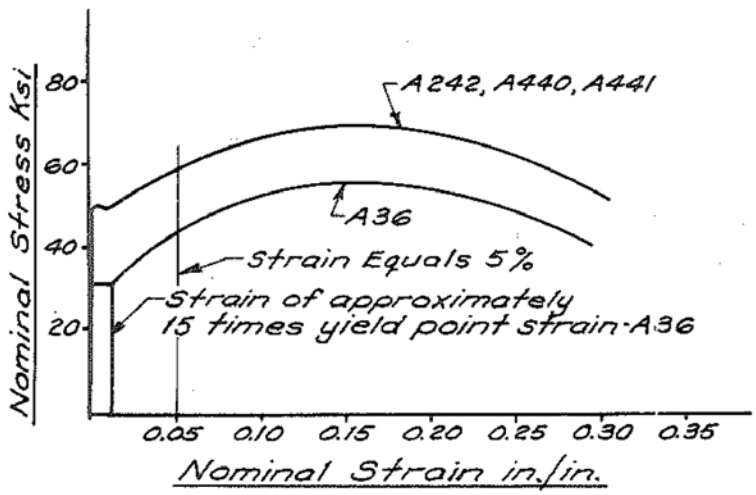

Figure 17. Nominal Stress Strain Diagrams for Typical Bridge Steels

When evaluating damage from impact loads in steel bridge members, both the immediate vicinity of the point of impact as well as locations away from the area should be considered. It has been recommended that evidence such as paint peeling and scale can point to unusually high strain levels in the affected areas due to impact loads [47]. Also, attention should be given to the examination of the toes of butt and fillet welds in the areas subjected to damage as cracks often occur in such areas due to the presence of stress concentration.

Although visual inspection is usually performed as the first attempt in any bridge condition assessment, supplementary methods such as non-destructive testing (NDT) may be used to provide a more complete understanding of the extent

of the damage. Critical areas in steel bridge members that may require closer inspection for cracking or fracture include [39]:

- Welded connections and details
- Locations with intersecting welds
- Details that induce out-of-plane distortion in the member
- Details and regions that are subjected to high levels of tensile stress ranges, and
- Details that contain coped sections.

Table 5 lists some of the currently available non-destructive test methods that may be used to evaluate the condition of steel members in bridge structures. Sometimes cracks in steel members may be covered by scale, rust, or paint that should be removed before some of these techniques can be applied. Most of the NDT methods listed in the table have the disadvantage of requiring extensive time that may not be desirable in an emergency response scenario. The interpretation of the results, the cost and the time required to implement a NDT method can be a consideration when they are considered for implementation. As such, the development of the Bridge Emergency Expert System (BEES) in this study has been made to rely only on the results of visual inspection procedures. The use of NDT methods is proposed as complementary tests to be performed at later times to obtain additional information.

Table 5. Non-Destructive Test Methods (NDE) for Impact Damage in Steel Bridge Members

Test Technique	Description	Applicability
Magnetic particle [39]	This technique introduces a magnetic field into the steel surface and small metallic particles in the vicinity of possible cracks.	• Detects small cracks • Capable of testing any steel surface for cracking
Dye penetrant [39]	Dye is allowed to penetrate a crack in the metal and excess dye is removed. A developer material is applied and the dye at the cracks is drawn out, identifying the extent of the cracking on the surface.	• Used to identify the extent of surface cracking in steel • May be applied to Aluminum and stainless steel
Ultrasonic Testing (UT) [39]	Introduces an ultrasonic pulse into the metal and the reflection of the signal from the internal boundaries of the material gives indications of the types and extent of defects.	• Is commonly used to detect internal or hidden cracks • Can be utilized for nearly all steel components of a bridge including areas difficult to reach
Radiographic Testing [39]	In this method a radiation source is introduced at one side of the member and an image is captured on a film at the other side.	• Detects cracks and evaluate their extent • Determines internal and subsurface characteristics of the steel material
Coating Tolerance Thermography (CTT) [39]	It involves the application of heat to either side of the possible defect. A camera is used to capture resulting thermographic images. The cracks or corroded areas are differentiated in black and white on the thermographic images.	• Determines cracking extent • Capable of identifying subsurface and surface cracking in steel materials
Acoustic Emission (AE) [39]	It monitors the release of energy into the structure when microscopic cracks occur. Sensors are placed at crack prone areas. The sensors detect this released energy due to the cracking.	• Can be used to detect and monitor active cracks in local areas

CHAPTER 3

BRIDGE EMERGENCY EXPERT SYSTEM

3.1 INTRODUCTION

Bridge related incidents are sometimes complex where the use of an expert system can be helpful in the decision making process. To support this process, knowledge based expert systems can provide helpful and standardized procedures as necessary tools.

The expert system developed through this study utilizes a standard procedure for visual inspection and provides safety recommendations for bridge emergencies. Initial safety procedures are recommended first to ensure safety of the responders, users, and the travelling public. In addition, based on the data stored in the system as well as information provided by the user, safety procedures and actions are recommended according to the level of the damage in the structure. This damage level is determined based on only the information obtained from the visual inspection and the data stored in the system. No structural analysis or rating is performed as a part of this process.

This chapter summarizes the design and development as well as features of the Bridge Emergency Expert System (BEES). It includes details of the software development as well as the assumptions made to provide appropriate recommendations. Features such as the contact finder, search engine, bridge information finder, and help menu are described at the end of the chapter.

3.2 SOFTWARE DEVELOPMENT

3.2.1 KNOWLEDGE ACQUISITION

Knowledge acquisition was essential in every stage of BEES' development. This process consisted of gathering knowledge from a variety of sources to create a

knowledge base for BEES. Information was collected from available case histories, research articles, incident reports, computer databases, books, and interviews with experts.

Books, articles, and databases from previous research on bridge systems were reviewed in order to understand various bridge incidents, structural behavior, emergency actions, and state of the art bridge management and decision support systems. The internet was an important source of information, because it provided the most recent research materials, development techniques, and types of expert systems that have already been developed. The software used for the development of BEES as well as the support documentation required for this process were obtained via the internet. Interviews with experts were regularly scheduled and conducted in order to complement this research and acquire information. In addition, available reports and case histories of different types of incidents were analyzed to create facts, procedures, and judgment rules in the software.

The process of refinement, representation, and elicitation of the knowledge obtained was performed manually. Interviews, case study analysis, critical incident analysis, discussion, and brainstorming were employed. These methods were applied by the research staff (software designer) to integrate the acquired knowledge into the software. Figure 18 shows the knowledge acquisition process that was followed for the development of BEES.

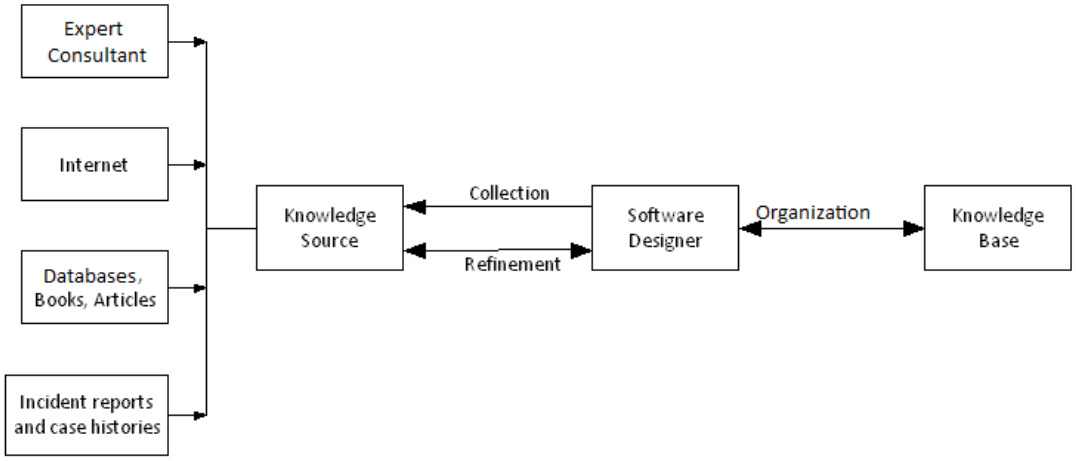

Figure 18. Knowledge Acquisition Process for Developing BEES

3.2.2 KNOWLEDGE REPRESENTATION

After the information was gathered, statements and observations were made to represent the knowledge into a form suitable for a computer to perform reasoning logic. This included the process of making available the information (input) and producing reasonable conclusions.

A system of rules and procedures were created in the form of a decision tree, as shown in Figure 19, to organize the collected information. The nodes of the decision tree represent the questions presented to the user while the links represent the options given for each question. The interaction between these components determines the nodes to follow and an eventual recommendation when the process is completed. The questions are organized based on following a format of hierarchy, so the most general or relevant question is considered first. When the more general questions are answered, more specific questions are asked and the final recommendation is provided at the completion of the process.

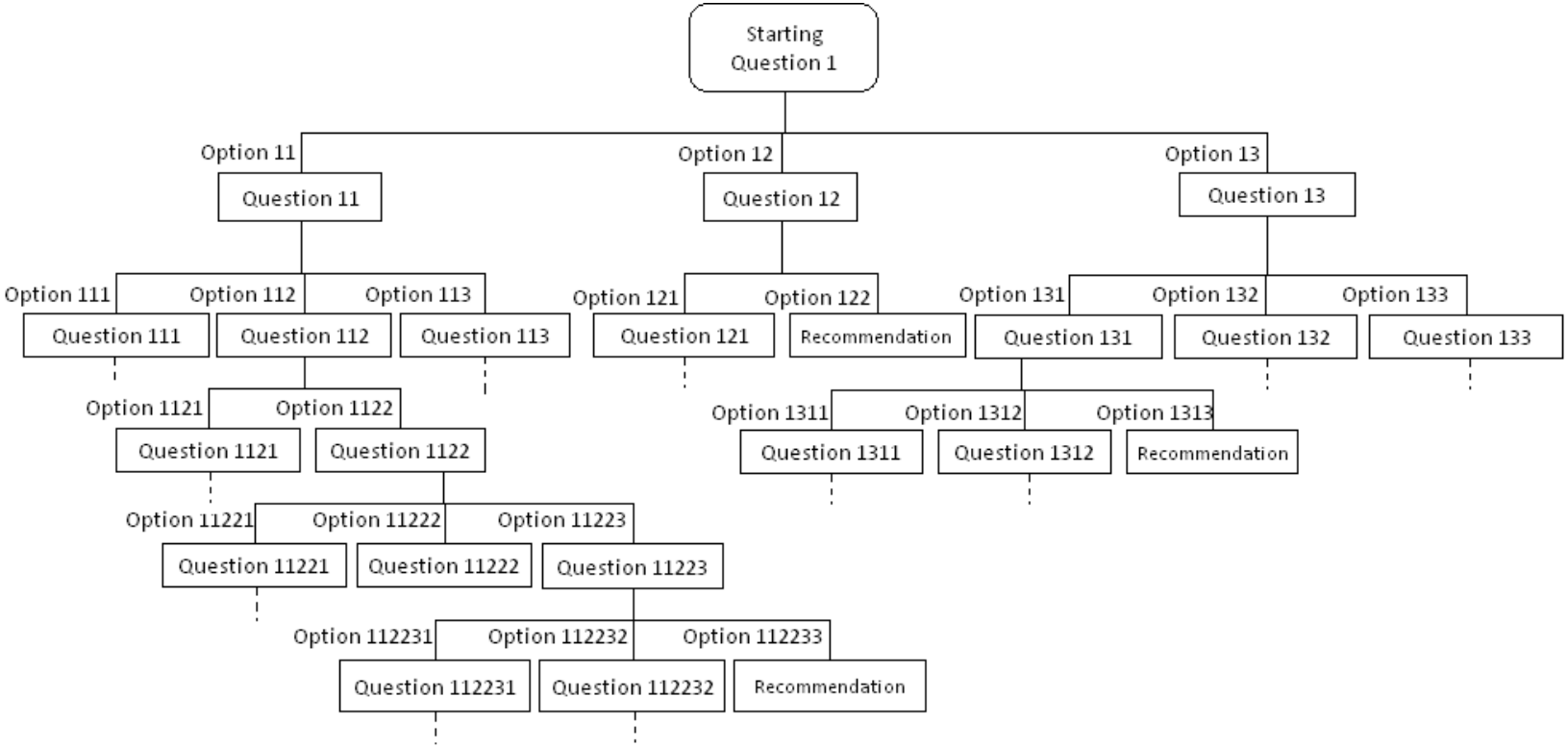

Figure 19. General Decision Tree used for Developing BEES

Every rule-related part of the general decision tree is created based on the information available in the BEES' knowledge base. Each of these rules consists of a precondition and an action. The precondition describes a situation in which a relevant action to be taken. Based on this principle, a production of rules was created in the form of IF-THEN pairs, i.e., IF this condition exists, THEN some action will take place. Figure 20 shows an example of a precondition and action as related to rules in BEES.

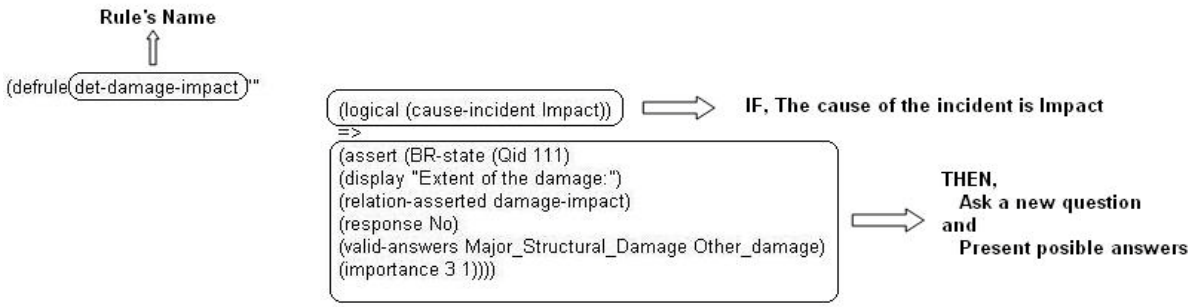

Figure 20. An Example of Precondition and Action in BEES

The process of selecting which rules to choose and which action is performed is determined by the inference engine. The research staff selected and used an inference engine (CLIPS) that offers a complete environment including procedures and algorithms for developing the required expert system for this study. The IF-part is stored as a fact in the database, indicating that it is considered to be true. A rule is issued only when all the rule's hypotheses are satisfied. Subsequently, the conclusion drawn is stored in the assertion base. The process of evaluating whether the premise is satisfied by previous assertions is preformed in a forward chaining format. This search strategy controls how the inference engine determines when rules are needed, which rules to select, and how rules should be processed.

The way the knowledge has been catalogued in this system makes BEES a rule-based expert system that provides a clear record of the processed knowledge. The system's rules are easy to read, understand, and modify as required. In

addition, the division of the knowledge into different fragments makes it in a form of modular-based knowledge source, which means that rules are, in most cases, independent and therefore can be modified without affecting other rules.

3.2.3 USER INTERFACE

The user interface is designed to gather necessary information from the user and to interact with the expert system. Python, an object-oriented programming language, was used to create a user interface for BEES. Various features were included in the user interface to obtain entries, display information, and provide guidance to the user. A description of each of these features can be found in section 3.6 of this report.

The user interface in BEES is developed based on dialog windows that present various questions and possible answers. Selectable options presented in the windows as “Previous” and “Next” allow the user to move to an earlier or later window (see Figure 21).

A menu bar was created to allow the user to access different available features, review information, or obtain help. The File menu contains access to the bridge information, WisDOT personnel information, and the option to exit the program. The Help menu provides more detailed explanation for each question presented and corresponding answers. In addition, a status bar located at the bottom of each window was created to provide details of the option to be selected from the menu.

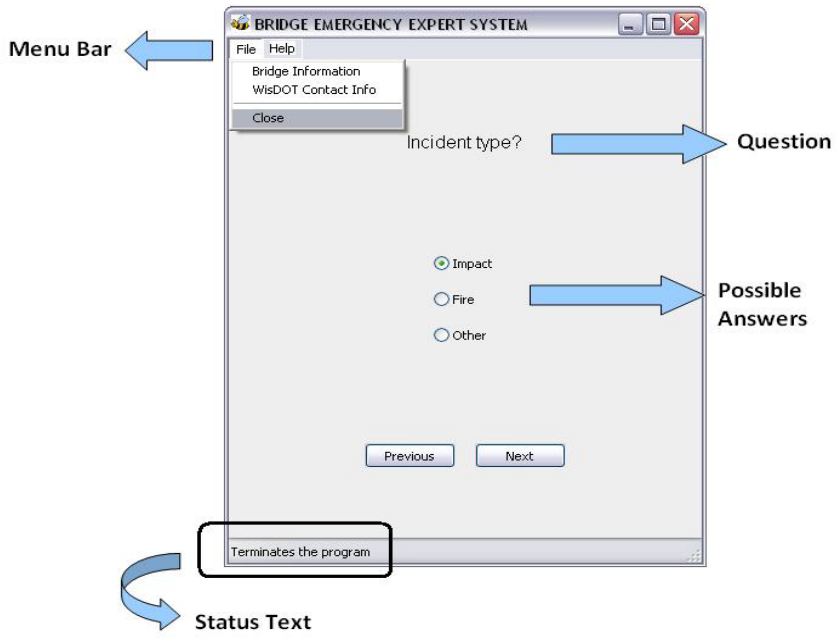

Figure 21. A Typical User Interface Window in BEES

3.2.4 KNOWLEDGE EVALUATION

Once the first prototype of the expert system was created by the research staff, the knowledge was evaluated to ensure practical system performance. This evaluation has been done through using test cases, case histories, and knowledge from experts.

Test cases were created to verify that all questions and responses were meaningful and practical as designed. For each individual rule, the system was executed to confirm appropriate system response and performance. In addition, scenarios based on the available information from the existing case histories [1] were created and the system was executed to compare the system response with those from the actions of the experts documented in the case histories. Table 19 in CHAPTER 5 presents the scenarios from the available case histories that were executed by BEES and the results for the purpose of the system's evaluation.

3.3 SOFTWARE

The Bridge Emergency Expert System (BEES) was designed and developed by combining two public domain software packages: CLIPS 6.3 and Python 2.5. CLIPS was used as the inference engine and Python was employed to develop a user interface for BEES. The integration of these two software packages was performed employing PyCLIPS, a module of Python that embeds CLIPS functionality into Python features.

3.3.1 CLIPS

CLIPS is a software package designed to develop expert systems. Its name is an acronym for "C Language Integrated Production System". It was first developed by NASA and written in ANSI C. The first prototype version of CLIPS was developed in 1985 with the purpose of replacing LISP as the base language for expert system software tools at that time.

Since its development, CLIPS has become one of the most widely used expert system tools primarily due to its important features including [32]:

- Knowledge Representation: CLIPS supports three different programming styles: rule-based, object-oriented, and procedural,
- Portability: CLIPS can be installed in operating systems such as Windows XP, MacOS X, and Unix without requiring code changes,
- Integration/Expansion: CLIPS can be easily embedded, integrated, and extended in or through other platforms,
- Easy Development: various public domain software modules may be downloaded from the CLIPS's web site and users can utilize on-line debugging aids as well as an integrated editor, and
- Fully Documented: extensive documentation including a Reference Manual, User's Guide, and source code are available for CLIPS. Due to its popularity

additional help and information can be found on-line through interactions with other users. Useful on-line application examples, forums, and tutorials are also available.

3.3.2 PYTHON

Python is a software package that is used to offer a user interface with CLIPS. The software and its complete documentation can be obtained as a public domain package online. Some of the advantages of Python include:

- Contains a large and comprehensive library,
- It is modular,
- Can be easily integrated with other software,
- It may be used in all major operating systems, and
- It is fully documented on-line.

Python´s modules may be used to solve a large variety of problem domains. For the purpose of this research, different types of modules and extensions were used for the development of BEES. Table 6 lists the modules that were used in developing BEES.

Table 6. Python Modules and Extensions Used for the Development of BEES

Module or Extension	Description	Applicability
PyCLIPS	Module to interface Python and CLIPS' expert system shell and library	Used to embed BEES' rules into the main code written in Python
wxPython	Graphical user interface (GUI) toolkit that allows creating a user interface	Applied on BEES' user interface
PyPdf	PDF toolkit that allows the manipulation of .pdf files	Used to read, search, and open .pdf files
xlrd	Library to extract data from Microsoft Excel spreadsheet files	Required to open, read and extract information from .xls files

3.4 DAMAGE ASSESSMENT AND CLASSIFICATION

The assessment of the structure is performed based on visual inspection of the bridge at the site of the incident. Questions are asked to obtain the information necessary to classify the damage into three categories of minor, moderate and severe. This classification of the damage is based on scores assigned to each answer provided by the user. The following sections contain a description of each of the damage classifications considered.

3.4.1 CONCRETE SUPERSTRUCTURES

3.4.1.1 IMPACT

The damage caused by impact incidents on concrete superstructures is classified as follows:

1. *Minor damage*: when the visual inspection does not show any evidence of structural damage. Isolated and minor concrete cracks, nicks, shallow spalls,

and/or scrapes are considered the main characteristics of a minor damage. Evidence of cracking with crack widths smaller than 0.1” for reinforced concrete girders and smaller than 0.009” for prestressed girders [43] is classified as minor.

2. *Moderate damage*: If the visual inspection indicates the presence of large cracks located in the area of the impact or other critical locations, and shallow spalls and/or loss of section large enough to expose undamaged prestressed tendons then the damaged caused by the impact is classified as Moderate. A crack width between 0.1” and 0.19” for reinforced concrete girders and between 0.009” and 0.03” for prestressed concrete girders is considered as causing moderate damage [43]. It is considered here that such cracks, and moderate spalls and/or loss of section are not severe enough to be classified as causing major structural damage. Partial damage that does not comprise the safe usage of the structure is also considered as moderate (see Figure 22).

Figure 22. Moderate Damage – RC Girder Damaged by Impact (spalls and exposure of undamaged steel bars)

3. *Severe Damage*: If the visual inspection indicates damaged strands or tendons, deep spalls with loss of significant concrete cross section, severe

cracking, and/or girder distortion, the damage is classified as severe. Cracking is considered severe for example when it propagates from an impacted flange into the web of the girder. In cases of severe damage, a crack width will exceed 0.19” for reinforced concrete girders and 0.03” for prestressed concrete girders [43]. Due to the severity of the damage, it is considered that the structural integrity has been compromised (Figure 23).

Figure 23. Severe Damage – PS Concrete Girder Damaged by Impact (extensive spalls and loss of section, severe cracking and multiple exposed or damaged strands)

The following table summarizes the classification of the damage considered by BEES for impact in concrete bridge superstructures:

Table 7. Impact Damage Classification for Concrete Superstructures

	Minor	Moderate	Severe
Structural Failure	-	• One or more lanes of the bridge are affected but the remaining structure is stable and can be in service • The capacity of the bridge is not compromised • Overall structural integrity is not compromised	• Complete collapse • Structural integrity is compromised
Cracks	• Isolated concrete cracks • For reinforced concrete girders: Crack width < 0.1'' • For prestressed concrete girders: Crack width < 0.009'' • No structural damage	• Large concrete cracks located in the area of the impact • Cracks may be deep enough to expose undamaged reinforcement • The damage is not severe enough to cause structural failure • Crack width between 0.1''-0.19'' for reinforced concrete girders • Crack width between 0.009''-0.03'' for prestressed concrete girders	• Several cracks originating on the impacted side and propagating along and across the lower flange • Cracks propagating from the damaged flange into the web of the girder • Crack width > 0.19'' For reinforced concrete girders • Crack width > 0.03'' for prestressed concrete girders • Exposed and damaged strands or reinforcement
Spalls	• Nicks, shallow spalls, and/or scrapes • No structural damage	• Localized shallow spalls large enough to expose undamaged reinforcement • Damage is not severe enough to be considered as causing structural failure	• Severe deep spalling that includes exposed and damaged strands, tendons, or reinforcement
Major spalling with loss of section	-	• Lost section large enough to expose undamaged strands or reinforcement	• Significant loss of concrete cross section • Prestressed strands or tendons are exposed and damaged • The structural integrity is compromised
Deformation	-	-	• Girder distortion resulting in lateral or vertical misalignments

3.4.1.2 FIRE

Damage caused by fire incidents in concrete bridge superstructures is classified as:

1. *Minor damage:* For fire damage to concrete girders or decks, a minor damage is defined as the presence of isolated cracks, few spalled and delaminated areas, and no exposure of reinforcing steel or prestressed strands. Under this condition, the structural integrity of the member or structure is not compromised. If scaling is evident, it will be considered minor if the cement paste loss is limited to 1/4 inch deep, and it is accompanied with only surface exposure of course aggregates (see Figure 24). The detrimental effects of concrete exposed to temperatures below 600°F are considered minimal, since the damage is mostly limited to the surface. Concrete below this temperature is not discolored or damaged. For the identification of the concrete color after the fire, it is necessary to remove the soot that mask the actual color.

Figure 24. Minor Damage – Concrete Girder Damaged by Fire (minor spalling with no reinforcement exposure)

2. *Moderate damage*: Under this classification, concrete contains greater amounts of cracking, and spalled and delaminated areas as those classified under *minor damage*. Scaling is classified as moderate if there is a cement paste loss of from 1/4 inch to 1 inch deep, and the exposure of the sides of the course aggregates [43]. Steel may be exposed under this classification but there should be no visible signs of loss of prestressing force, member sag, or flexural cracks (see Figure 25). Concrete members exposed to temperatures between 600°F and 1700°F are somewhat permanently damaged. At these temperatures, the color of the concrete exposed directly to the flames changes. A pink coloration appears if temperatures between 600°F and 1100°F are reached due to the formation of ferrous salts. At temperatures above 1100°F and below 1700°F, concrete exhibits a white-gray coloration. At temperature exposure below 1700°F, the damage level is not considered severe enough to compromise the structural integrity of the member. Partial damage that does not comprise the safe usage of the structure is also considered as moderate

Figure 25. Moderate Damage – PS Concrete Girder Damaged by Fire (rounded concrete edges and exposure of strands)

3. *Severe damage*: A severe damaged is defined as deterioration of the strength-related properties of the affected concrete member due to exposure to fire. Possible damage such as significant rounding of concrete member edges due to spalling, and substantial flexural cracking can indicate a severe damage for the affected member [48]. Under this classification, excessive deformation due to elongation of steel reinforcement or prestressing steel may also be evident. This damage level is caused by fire with temperatures above 1700°F. Concrete directly exposed to this temperature shows a gray-buff coloration. Extensive scaling indicates a loss of cement paste around course aggregate with depths greater than 1 inch.

Table 8 summarizes the classification of the damage considered by BEES for fire exposures in bridge superstructures.

Table 8. Fire Damage Classification in Concrete Superstructures

	Minor	Moderate	Severe
Structural Failure	-	• Structural integrity is not compromised	• Complete collapse • Structural integrity is compromised
Deformation	-	-	• Excessive lateral or vertical deformation
Cracks	• Isolated concrete cracks • Non-structural damage	• Moderate amount of cracks • No flexural cracks • Cracks may be deep enough to expose undamaged reinforcement • Non-structural damage	• Severe cracking with evidence of structural damage • Exposed damaged reinforcement
Spalls	• Isolated nicks and shallow spalls • Non-structural damage	• Large shallow spalls to expose undamaged reinforcement • Non-structural damage	• Significant rounding of concrete member edges • Deep spalls and exposed damaged reinforcement • Excessive deformation due to elongation of steel reinforcement or prestressing may be also evident
Scaling	• Random scaling • Surface exposure of course aggregates • Cement paste loss of up to 1/4 inch deep • Non-structural damage	• Larger amours of scaled areas • Cement paste loss of from 1/4 inch to 1 inch deep • Exposed course aggregates' sides • Non-structural damage	• Significant amount of scaled areas • Loss of cement paste around course aggregates with depths greater than 1 inch • Exposed damaged reinforcement • Excessive deformation due to elongation of steel reinforcement and prestressing
Delamination	• Isolated delamination • Non-structural damage	• Moderate and excessive delamination • Non-structural damage	-

3.4.2 CONCRETE SUBSTRUCTURES

3.4.2.1 IMPACT

The damage produced by impact incidents on concrete bridge columns or piers is classified as follows:

1. *Minor damage*: A minor damage is when there is no visual evidence of structural damage to the substructure from vehicular impact loads. Isolated concrete cracks, nicks, shallow spalls, and scrapes are considered typical signs of this damage level.
2. *Moderate damage*: if the visual inspection indicates the presence of large concrete cracks due to the impact or shallow spalls large enough to expose undamaged reinforcement, the damage is classified as moderate. Although some repairs may be required under this damage classification, the damage is not severe enough to create a safety concern or to diminish the structural integrity of the bridge. In cases of severe damage to only a small part of the bridge, it is considered a moderate damage when the major part of the bridge can safely remain open to traffic.
3. *Severe damage*: A severe damage is defined when the safety of the public and structural integrity have been compromised (see Figure 26 and Figure 27). Excessive flexural cracks at the base of concrete columns and horizontal or diagonal cracks at the pier-cap/column interface are signs of excessive lateral bending. This cracking pattern is considered to be a severe damage to the member. Overloads or differential substructure settlement produced by an impact can be identified with mid-height flexural cracks, as well as vertical cracks and crushed concrete [43]. The structural integrity may be compromised if one or more columns are severely damaged or severe spalling and exposure of damaged steel are evident in the affected member.

Figure 26. Severe Damage – Concrete Substructure Damaged by Impact

Figure 27. Severe Damage – Concrete Substructure Damaged by Impact

Table 9 summarizes the classification of the damage considered by BEES for impact incidents on bridge substructures.

Table 9. Impact Damage Classification for Concrete Substructures

	Minor	Moderate	Severe
Structural Failure	-	• One or more lanes of the bridge are affected but the rest of the bridge is stable to remain in service • Structural integrity has not been compromised	• Structural collapse • Structural integrity has been compromised
Cracks	• Isolated and shallow concrete cracks • No structural damage	• Large concrete cracks due to the impact • Expose undamaged reinforcement • The damage is not severe enough to be structural	• Cracks originating on the impacted area and propagating along and across the member • Transverse flexural cracks at the base, and mid-height of the column • Horizontal or diagonal flexural cracks at the pier-cap/column interface • Extensive vertical cracking • Exposed and damaged reinforcement
Spalls	• Nicks, shallow spalls, or scrapes • No structural damage	• Shallow spalls large enough to expose undamaged reinforcement	• Severe deep spalling that includes exposed damaged strands or tendons
Movement	-	-	• Any significant vertical or horizontal misalignment

3.4.2.2 FIRE

Since the effect of fire on concrete piers and columns will be similar to that for other concrete members, the same damage classification that was defined for concrete superstructure elements, as proposed in section 3.4.1.2, will be used for concrete substructures.

3.4.3 STEEL SUPERSTRUCTURES

3.4.3.1 IMPACT

The damage caused by impact loads on steel superstructures is classified as follows:

1. *Minor damage*: A minor damaged is defined if the visual inspection does not indicate any evidence of structural damage. Under this damage classification, structural members or elements may experience minor damage such as dents, scrapes, and distortions but no cracks should exist in the primary and secondary members or at the toes of butt and fillet welds in such members (see Figure 28).

Figure 28. Minor Damage - Steel Girder Damaged by Impact (girder lower flange slightly distorted, scrapes underneath the member)

2. *Moderate damage*: Under the moderate damage classification, there may be considerable deformation, minor cracking, dents or nicks but there will be no safety concerns or diminishing effects on the structural integrity. No immediate repair will be required to keep the structure in service under the moderate damage classification. Critical areas such as welded connections and the area of primary damage must be examined for possible cracking. Evidence of peeling of paint or scaling should be considered as an indicator of unusual strain that could lead to possible cracking (see Figure 29).

Figure 29. Moderate Damage - Steel Girder Damaged by Impact (local distortion of the bottom flange)

3. *Severe damage*: When an impact load causes concerns with the structural integrity and in-service performance of a structure, the damage is defined as severe. Under this damage classification, there may be visual evidence of severe member distortion, extensive cracking or fracture in tension

elements, or severe nicks or gouges on plate edges or member corners (see Figure 30).

Figure 30. Severe Damage - Steel Girders Damaged by Impact (lateral and in-plane distortions of multiple girders)

Table 10. Impact Damage Classification for Steel Superstructures

	Minor	Moderate	Severe
Structural Failure	-	• The capacity of the bridge may be reduced • One or more lanes of the bridge are affected but the remaining structure is safe for use • Structural integrity has not been compromised	• Complete collapse • Structural integrity has been compromised
Cracks	-	• Minor cracking in members or member components that are not under tension • The damage is not severe to cause concerns for safety or serviceability • peeling of paint or scale	• Cracking in tension components of the structure or bridge members • Severe cracking in the locally impacted areas, and toes of butt or fillet welds • It may compromise the serviceability and safety of the structure
Nicks, scrapes or gouges	• Minor nicks and/or scrapes • No structural damage	• Moderate nicks and/or scrapes • The damage is not severe to cause safety or serviceability concerns	-
Torn Steel	-	• Minor torn steel • The damage is not severe to cause safety or serviceability concerns	• Significant loss of cross section • It may compromise the serviceability and safety of the structure
Deformation	• Minor girder lateral distortion	• Moderate girder lateral or in-plane distortions • The damage is not severe to cause safety or serviceability concerns	• Girder distortion resulting in severe lateral or in-plane distortions • Permanent deformation • It may compromise the serviceability and safety of the structure

3.5 RECOMMENDED ACTIONS

Considering that every recommendation provided by the Bridge Emergency Expert System (BEES) intends to ensure safety at any damage level, the expert system presents an initial emergency recommendation before any assessment of the situation is performed (see Figure 31). The following initial safety procedures are recommended regardless of the severity level of the incident:

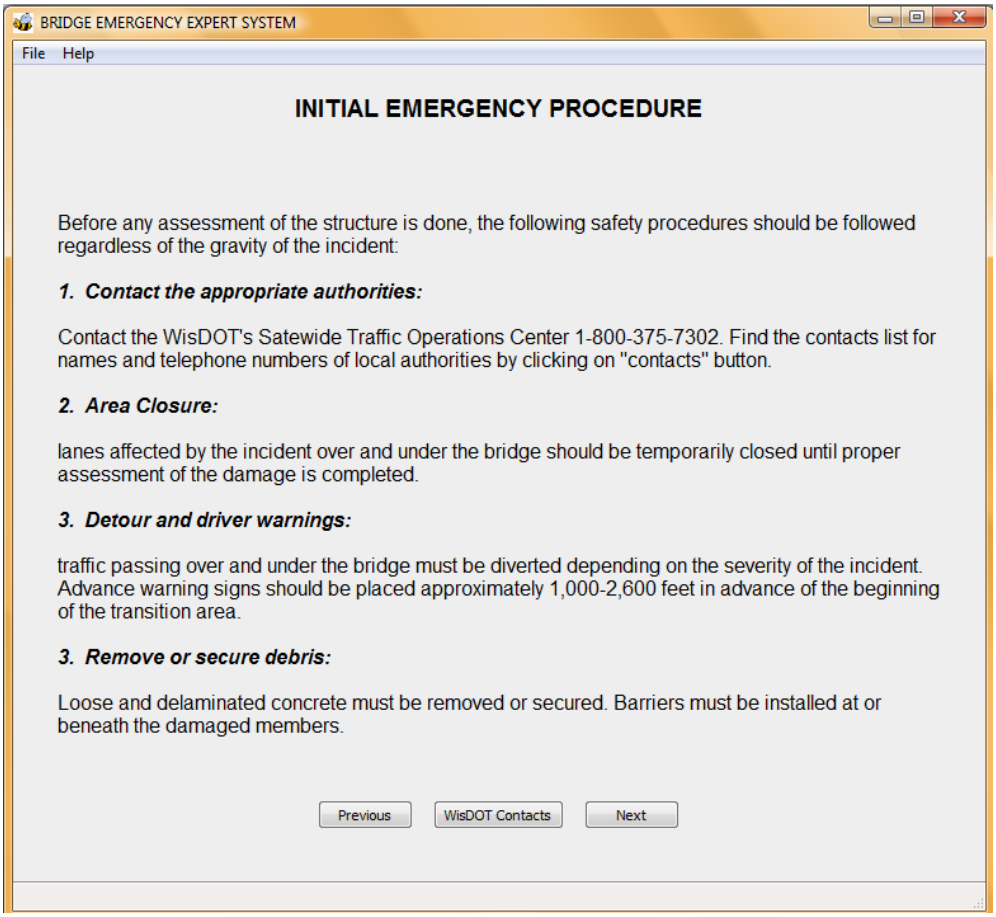

Figure 31. Recommendation for Initial Emergency Procedure

1. *Contact the appropriate authorities*: In order to minimize confusion, reduce unnecessary procedures, and ensure a rapid response, the appropriate authorities have to be contacted as soon as the incident occurs. To facilitate this first emergency action, BEES provides a list of appropriate names and telephone numbers by regions. By clicking on the "contacts" button of the initial emergency procedure window, the user can find the

local authorities to be contacted depending on the location of the incident (see Figure 32). The WisDOT's Statewide Traffic Operations Center's (STOC) number is given as the first contact according to the WisDOT Emergency Traffic Control and Scene Management Guidelines.

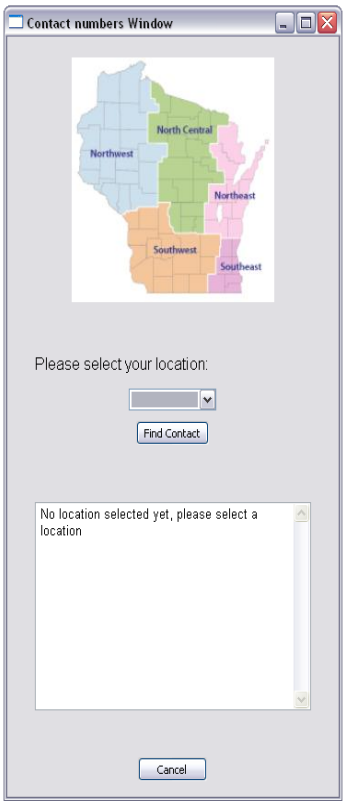

Figure 32. Contact Information Window

2. *Area Closure*: lanes affected by the incident over and under the bridge should be temporarily closed until proper assessment of the damage is completed.

3. *Detour and driver warnings*: traffic passing over and under the bridge must be diverted depending on the severity of the incident. This action is recommended to prevent additional accidents or damage. Approaching traffic should be properly warned of the incident scene. Advance warning signs should be placed approximately 1,000-2,600 feet in advance of the beginning of the affected area.

4. *Remove or secure debris*: loose and delaminated concrete must be removed or secured to ensure safety of the traveling public and the integrity of the structure. Barriers must be installed around and/or beneath the damaged members to prevent accidents by the separated concrete pieces. Adequate protection must be provided for both responders and others at the scene.

Although the initial emergency procedure ensures a level of safety to any type of incidents, BEES helps to assess individual situations in bridge emergencies and provide additional guidance according to the level and type of damage experienced by the structure. Sections 3.5.1 and 3.5.2 of this report present the recommendations provided by BEES for damage due to impact and fire incidents on concrete and steel bridges.

As noted earlier, the recommendations provided by BEES are partly created based on using the available knowledge obtained from the existing case histories. In cases where an accident type in a bridge structure differs from those stored in the BEES' existing case history knowledge base, the system will provide only a general emergency action procedure. This general recommendation will ensure a safety measure to be taken for the structure while an assessment of the damage is being completed by the authorities. Figure 33 shows the general action procedure presented to the user for emergency cases not matching existing case histories in the system:

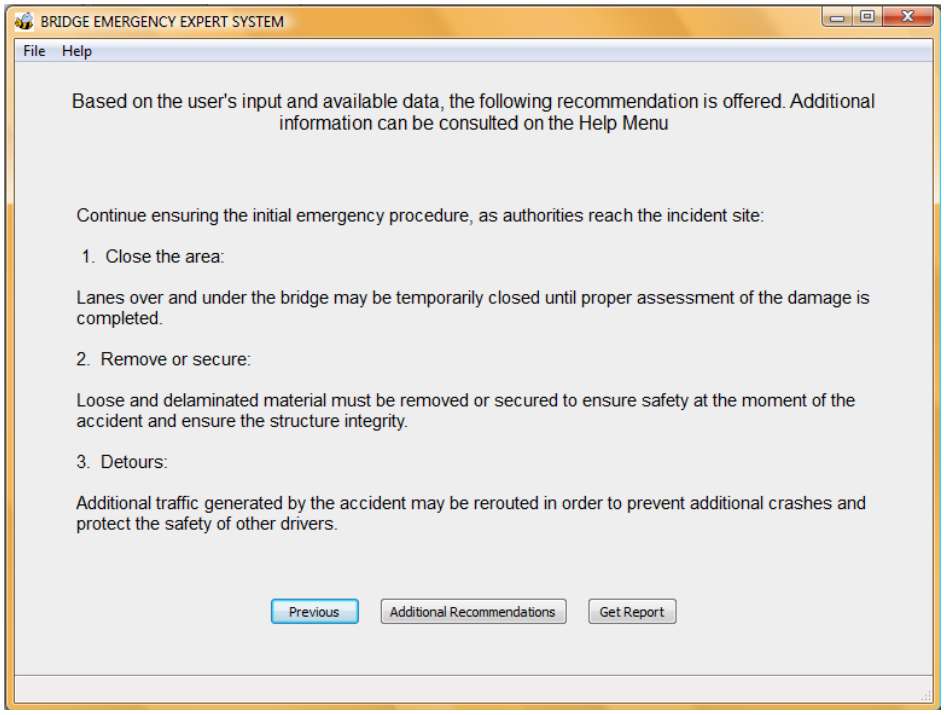

Figure 33. BEES´ General Recommendations

3.5.1 CONCRETE BRIDGES

3.5.1.1 IMPACT

Once the damage is classified as minor, moderate, or severe, the system will create an appropriate recommendation. The following procedures will be recommended by the expert system according to the damage classification.

1. *Minor damage*: a temporary closing of the affected lanes under the bridge or in the vicinity of the damaged members may be performed until the proper assessment and repairs are completed. Lane closures recommended based on the initial emergency procedure may be reopened to traffic. If there is traffic under the affected area of the bridge, it may be diverted to the lanes that were unaffected by the accident. Barriers and signage must be maintained until the proper repairs are concluded.

A *"minor damage"* is not considered to have an effect on the performance of the structure, therefore, later repairs are made to restore durability, protection from environment, and aesthetic of the structure.

2. *Moderate damage*: it is recommended to implement a closure of lanes under and over the bridge that is affected by the impact until proper assessment and repairs are performed. It is necessary to redirect traffic over and under the affected areas of the bridge to the lanes that are not affected by the accident while appropriate barriers are being installed in the vicinity of the damaged member. In addition, debris and loose and delaminated concrete should be removed and temporary shoring should be provided to provide for the structural stability if needed. Truck weight restrictions may be posted at the bridge following guidelines by the WisDOT Bureau of Structures.

   The damage under this classification is considered without structural consequences. After the initial emergency procedures are completed, a structural analysis of the bridge may need to be performed with the consideration of the effects of the damage. Appropriate repair may be made after the analysis and evaluation of the structure have been completed. Prior to the repair, a member preloading may be applied in order to facilitate removal of loose and delaminated material by opening of cracks and voids. The member preloading also allows better installation of repair patch materials and the pre-compression of the repair materials after the load removal [4].

   Non-destructive testing methods from Table 4 may be used to detect and evaluate defects and damage that could not be identified by visual inspection.

3. *Severe damage*: It is recommended to implement a temporary closure of the bridge subject to the severity of the damage. All traffic under and over the bridge must be rerouted and proper warning for the affected traffic should

be posted. Necessary truck weight restrictions should be posted while repairs are being performed. Any other actions taken as an initial emergency procedure, as described above, must be implemented.

Due to the severity of the damage, a visual inspection may not be adequate to ensure a safe operation. Therefore, more advanced NDE techniques as well as a more detailed structural analysis that includes the effects of the damage may be required. A member preloading may be applied prior to the repair work in order to facilitate removal of loose and delaminated material. The repair work including the member preloading should be performed after the state of emergency has been brought under control and when the structural analysis of the affected member and structure as a whole is completed. If the superstructure damage is not too severe to require replacement of the damaged member, repair techniques including splicing of strands in prestressed members may be performed. If the damaged member cannot be safely and economically repaired, its replacement may be considered.

If the damage involves a partial or complete collapse of the structure, safety of the responders and traveling public must be the main priority.

Table 11 and Table 12 summarize the damage classification and the corresponding initial and supplementary recommendations provided for each impact damage case in concrete bridges:

Table 11. BEES' Initial Recommendations for Impact Incidents in Concrete Bridges

	Minor	Moderate	Severe
Structural Failure	-	1. Affected lanes above and below traffic should immediately be closed until proper repairs are performed 2. Lanes that were not affected by the incident and are structurally safe could remain open to traffic 3. Traffic above and below the affected lanes must be diverted or rerouted 4. Signage for traffic above and below the affected lanes must be maintained 5. Truck weight restrictions should be placed 6. Other actions taken as initial emergency procedure should be maintained 7. A structural analysis of the bridge with the effects of the damage should be performed	1. Closure of the bridge is required subject to the severity of the damage 2. Ensure the safety of the area before any rescuers enter the scene 3. Actions taken as an initial emergency procedure should be maintained 4. Maintain traffic rerouting until proper investigation of the incident is completed 5. Barriers and signage for traffic above and below the affected lanes must be maintained
Cracks	1. Consider temporary closing of the lane below the bridge or in the vicinity of the damage, until proper investigation or repair s are performed 2. Reopen the lane above the bridge, if it was initially recommended for closure 3. Traffic below the bridge can be diverted to the lanes that were not affected 4. All debris, loose and delaminated concrete must be removed 5. Barriers and warning signs must be maintained until repairs are completed	1. Lanes above and below the affected area should remain closed until proper investigation and repairs are completed 2. Signage for traffic above and below the affected lanes must be maintained 3. Traffic above and below the affected lanes must be diverted to other lanes 4. Install appropriate barriers and signage 5. All debris, loose and delaminated concrete must be removed 6. Truck weight restrictions should be placed 7. Temporary shoring should be constructed if necessary	1. Temporary closure of the bridge may be required subject to the severity of the damage 2. Traffic above and below the affected lanes must be rerouted 3. Barriers and signage for traffic above and below the affected lanes must be maintained 4. Truck weight restrictions should be placed 5. Actions taken as an initial emergency procedure should be maintained
Shallow Spalls			
Deep spalling with loss of section	-		
Deformation	-		

Table 12. BEES' Supplementary Recommendations for Impact Incidents in Concrete Bridges

<table>
<tr><th></th><th>Minor</th><th>Moderate</th><th>Severe</th></tr>
<tr><td>Structural Failure</td><td colspan="3">No additional recommendations besides immediate actions are provided</td></tr>
<tr><td>Cracks</td><td rowspan="2">Restore aesthetics and durability of the members affected</td><td rowspan="4">1. Apply preload as required prior to repair
2. Restore the damaged area to the original condition
3. If steel is exposed after damage, all corrosion products on the reinforcing steel and prestressed strands or tendons should be removed before any patched repair work
4. A structural analysis of the bridge including the effects of the damage should be performed
5. Additional NDT methods can be used to confirm or complement the visual assessment</td><td rowspan="4">1. Splicing of damaged strands may be considered
2. Apply preload as required prior to repair
3. A structural analysis of the bridge including the effects of the damage should be performed
4. If the damage cannot be economically repaired, the replacement of the damaged members should be considered
5. Before any replacement decision is made, NDT methods can be used to confirm or complement the visual assessment</td></tr>
<tr><td>Shallow spalls</td></tr>
<tr><td>Deep spalling with loss of section</td><td>-</td></tr>
<tr><td>Deformation</td><td>-</td></tr>
</table>

3.5.1.2 FIRE

Damage assessment and recommendations that are provided by BEES for fire damage include the following:

1. *Minor damage*: Fire damage under this classification is normally confined to short exposure time and loss of cement paste in shallow depths which have minimal detrimental effects on the structural integrity of concrete structures. To ensure safety, a temporary closing of the affected lanes is recommended to allow for a visual investigation and any minor repairs to be completed. Traffic should be diverted to unaffected lanes or an alternate route with proper signage. Traffic flow may resume once the fire is under control, all debris are removed, and the preliminary investigation are completed. Additional recommendations for this damage level include the restoration of aesthetics and durability of the affected members.

2. *Moderate damage*: This level of damage includes conditions where large areas of the structure are exposed to prolonged fire and the damage is extended deeper into the concrete. A visual color mapping should be performed to identify the variations in concrete damage and hardness. Although a routine visual inspection is normally performed, it can be complemented by non-destructive test methods as listed in Table 4. It is recommended to enforce closure of the affected lanes above and below the affected bridge members until safety is ensured and repairs are performed. Traffic should be diverted to other lanes or routes with the introduction of proper signage and barriers in appropriate locations. Preloading may be applied prior to the repair work to dislodge and remove loose concrete from cracks and the damaged locations. Additional reinforcement may be installed where a significant amount of concrete is lost.

3. *Severe Damage*: This damage classification includes conditions where concrete is exposed to fire for an extended period of time and extensive

damage to the material and/or reinforcing steel is evident. Under this condition, it is recommended to perform a temporary closure of the bridge until an investigation or immediate remedy such a shoring is completed. Traffic above and below the affected lanes must be rerouted and proper signage should be installed. Actions taken as an initial emergency procedure must be maintained. Additional recommendations include performing a structural analysis and using other non-destructive methods (see Table 4) to complement the visual damage assessment. A replacement of the damaged member should be considered if repairs are not feasible or cost effective. If partial or complete structural collapse has occurred, traffic restriction/re-routing and securing the site are of paramount importance to ensure the safety of all involved.

Table 13 and Table 14 summarize the initial and supplementary recommendations provided by BEES for all damage levels defined for fire incidents.

Table 13. BEES' Initial Recommendations for Fire Incidents in Concrete Bridges

<table>
<tr><th></th><th>Minor</th><th>Moderate</th><th>Severe</th></tr>
<tr><td>Structural Failure</td><td>-</td><td>1. Lanes above and below the affected lanes should be closed until safety is ensured
2. Lanes that were not affected by the incident and are structurally safe could remain open to traffic after fire is controlled
3. Traffic above and below the affected lanes must be diverted or rerouted
4. Signage for traffic above and below the bridge must be maintained
5. Actions taken as initial emergency procedure should be maintained
6. Truck weight restrictions should be placed
7. A structural analysis of the bridge should be performed</td><td>1. Immediate closure of the bridge is recommended
2. Ensure safety of the area before other personnel enter the site
3. Actions taken as an initial emergency procedure should be maintained
4. Maintain traffic rerouting until proper investigation of the incident is conducted
5. Barriers and signage for traffic above and below the bridge must be maintained</td></tr>
<tr><td>Deformation</td><td>-</td><td>-</td><td rowspan="4">1. Temporary closure of the bridge may be required subject to the severity of damage
2. Safety of the responders and users must be ensured
3. Traffic above and below the bridge must be rerouted
4. Barriers and signage for traffic above and below the affected lanes must be maintained
5. Truck weight restrictions should be placed
6. Actions taken as an initial emergency procedure should be maintained</td></tr>
<tr><td>Cracks</td><td rowspan="4">1. Remove soot for better identification of the damage
2. If repair is needed, consider temporary closing of the affected lanes
3. Barriers and warning signs must be maintained until repair is completed
4. All debris, loose and delaminated concrete must be removed
5. If repair is not required, the bridge can be reopened to traffic</td><td rowspan="4">1. Remove soot for better identification of the damage level
2. Traffic above and below the affected lanes should remain closed until proper repair is performed
3. Signage for traffic above and below the affected lanes must be maintained
4. Traffic above and below the affected lanes must be diverted to other lanes
5. Install appropriate barriers and signage
6. All debris, loose and delaminated concrete must be removed
7. Truck weight restrictions should be placed
8. Shoring might be applied</td></tr>
<tr><td>Spalls</td></tr>
<tr><td>Scaling</td></tr>
<tr><td>Delamination</td><td>-</td></tr>
</table>

Table 14. BEES' Supplementary Recommendations for Fire Incidents in Concrete Bridges

<table>
<tr><th></th><th>Minor</th><th>Moderate</th><th>Severe</th></tr>
<tr><td>Structural Failure</td><td colspan="3">No additional recommendations besides immediate actions are provided</td></tr>
<tr><td>Deformation</td><td>-</td><td>-</td><td rowspan="3">1. A structural analysis of the bridge should be performed
2. If the damage cannot be economically repaired the replacement of damaged members should be considered
3. Before any replacement decision is made, NDT methods can be used to confirm or complement the visual assessment</td></tr>
<tr><td>Cracks</td><td rowspan="4">Restore aesthetics and durability of the affected members</td><td rowspan="4">1. Restore the damaged area to the original configuration
2. Apply preload as required
3. A structural analysis of the bridge including the effect of the damage should be performed
4. If steel is exposed after damage, all corrosion products should be removed before repair
5. Additional NDT methods can be used to confirm or complement the results of the visual assessment</td></tr>
<tr><td>Spalls</td></tr>
<tr><td>Scaling</td></tr>
<tr><td>Delamination</td><td></td></tr>
</table>

3.5.2 STEEL BRIDGES

3.5.2.1 IMPACT

Many of the recommendations offered by BEES for concrete bridges damaged by impact are also applicable for steel bridges subjected to the same type of damage. These recommendations primarily ensure safety of the structure, the traveling public, and the responding personnel.

Table 15 and Table 16 list the recommendations provided by BEES for all damage levels in steel structures subjected to impact loads.

Table 15. BEES' Initial Recommendations for Impact Incidents in Steel Bridges

<table>
<tr><th></th><th>Minor</th><th>Moderate</th><th>Severe</th></tr>
<tr><td>Structural Failure</td><td>-</td><td>1. Affected lanes above and below the bridge should immediately be closed until proper repairs are performed
2. Lanes that were not affected by the incident and are structurally safe could remain open to traffic.
3. Traffic above and below the affected lanes must be diverted or rerouted
4. Signage for traffic above and below the affected lanes must be maintained
5. Truck weight restrictions should be placed.
6. Other actions taken as initial emergency procedure should be maintained
7. A structural analysis of the bridge including the effects of the damage should be performed</td><td>1. Closure of the bridge is required subject to the severity of damage
2. Ensure the safety of the area before any rescuers enter to the scene
3. Other actions taken as initial emergency procedure should be maintained
4. Maintain traffic rerouting until proper investigation of the incident is conducted
5. Barriers and signage for traffic above and below the affected lanes must be maintained</td></tr>
<tr><td>Nicks, Scrapes or gouges</td><td rowspan="2">1. Consider temporary closing of the lane below the bridge or in the vicinity of the damage, until proper repairs are performed
2. Reopen the lane above the bridge, initially recommended to be closed as a safety procedure
3. Traffic below the bridge can be diverted to the lanes that were not affected
4. Signage and barriers beneath the damage member must be maintained until repairs are completed</td><td rowspan="4">1. Lanes above and below the affected lanes should remain closed until proper repairs are performed
2. Barriers and signage for traffic below and above the affected lanes must be maintained
3. Traffic above and below the affected lanes must be diverted to other lanes
4. Truck weight restrictions should be placed.
5. Shoring should be applied if necessary</td><td>-</td></tr>
<tr><td>Deformation</td><td rowspan="3">1. Temporary closure of the bridge may be required subject to the severity of damage
2. Traffic above and below the bridge must be diverted or rerouted
3. Barriers and signage for traffic below and above the bridge must be maintained
4. Truck weight restrictions should be placed
5. Actions taken as an initial emergency procedure should be maintained</td></tr>
<tr><td>Cracks</td><td>-</td></tr>
<tr><td>Torn Steel</td><td>-</td></tr>
</table>

Table 16. BEES' Supplementary Recommendations for Impact Incidents in Steel Bridges

<table>
<tr><th></th><th>Minor</th><th>Moderate</th><th>Severe</th></tr>
<tr><td>Structural Failure</td><td colspan="3">No additional recommendations besides immediate actions are provided</td></tr>
<tr><td>Nicks, Scrapes or gouges</td><td rowspan="2">Restore aesthetics and durability of the structures or members affected by the impact</td><td rowspan="4">1. Restore the damaged area to the original configuration
2. Additional NDT methods can be used to confirm or complement the results of the visual assessment</td><td>-</td></tr>
<tr><td>Deformation</td><td rowspan="3">1. A structural analysis of the bridge including the effect of the damage should be performed
2. If the damage cannot be economically repaired the replacement of damaged members should be considered
3. Additional NDT methods can be used to confirm or complement the results of the visual assessment</td></tr>
<tr><td>Cracks</td><td>-</td></tr>
<tr><td>Torn Steel</td><td>-</td></tr>
</table>

3.6 FEATURES IN BEES

This section describes various features of the Bridge Emergency Expert System (BEES) to guide and assist the users of the system. BEES contains pull-down menus for “File” and “Help” that would allow the user to access these features during the damage assessment process.

3.6.1 FILE MENU

3.6.1.1 BRIDGE INFORMATION FINDER FEATURE

The first step in the BEES’ damage assessment process is to obtain all the necessary information for the affected bridge structure. The “File” menu in the BEES may be selected by the user as the initial step of the question-and-answer session and to access the bridge information as stored in the system (see Figure 34).

Figure 34. BEES Feature to Access Bridge Information

The use of BEES begins after the Initial Emergency Procedure window is displayed. A valid Wisconsin bridge number must be entered in the text entry spaces provided in the window (see Figure 35). The “Next” button must be clicked to begin the search of the information through a database which has been prepared and stored in BEES in the Microsoft Office Excel format. The database includes information on all Wisconsin bridges and is created based on the information provided by the WisDOT’s Bureau of Structures.

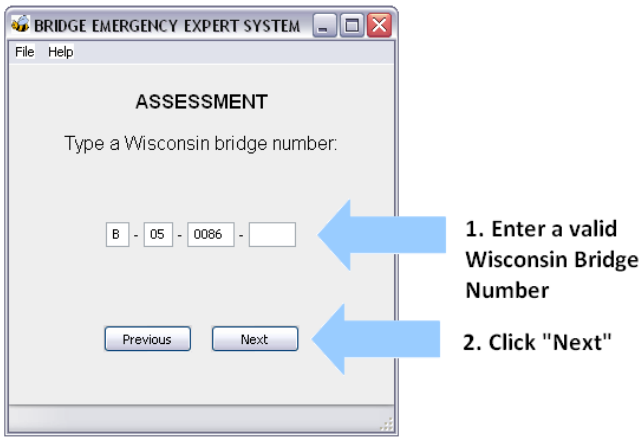

Figure 35. Bridge Information Search

A progress window will show the advance of the search (see Figure 36). If the entered bridge number does not correspond to any of the existing bridges in the database, a message window will be shown to indicate that (see Figure 37). The "OK" button must be clicked to return to the bridge information search step.

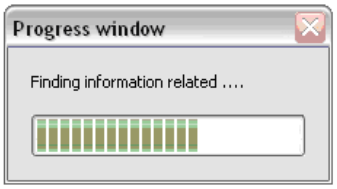

Figure 36. Bridge Information Search – Progress Window

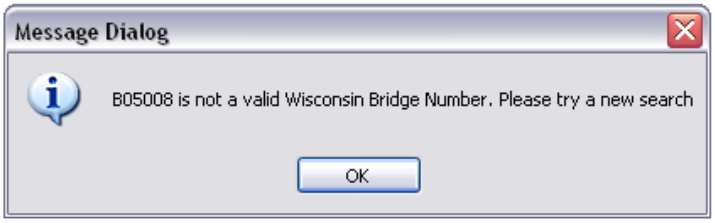

Figure 37. Bridge Information Search - Message Window

Once the Wisconsin Bridge Number is located in the database, the bridge information will be displayed in a new window (see Figure 38). The bridge data is organized under five tabs including: "Estimated Data", "General Information", "Geometric Information", "Capacity Information", and "Span Information". The "Estimated Data" tab contains information that is calculated or estimated by the software (for data not included in the WisDOT database), while the remaining tabs list all available information provided by the WisDOT. Before the user initiates the

question-and-answer session, he/she must accept the data presented by clicking on the check-box, located on the lower left side of the window. Once the data is accepted, the “OK” button must be clicked to resume the bridge assessment process. The obtained bridge information can be used at any time during the assessment process using the “File” menu.

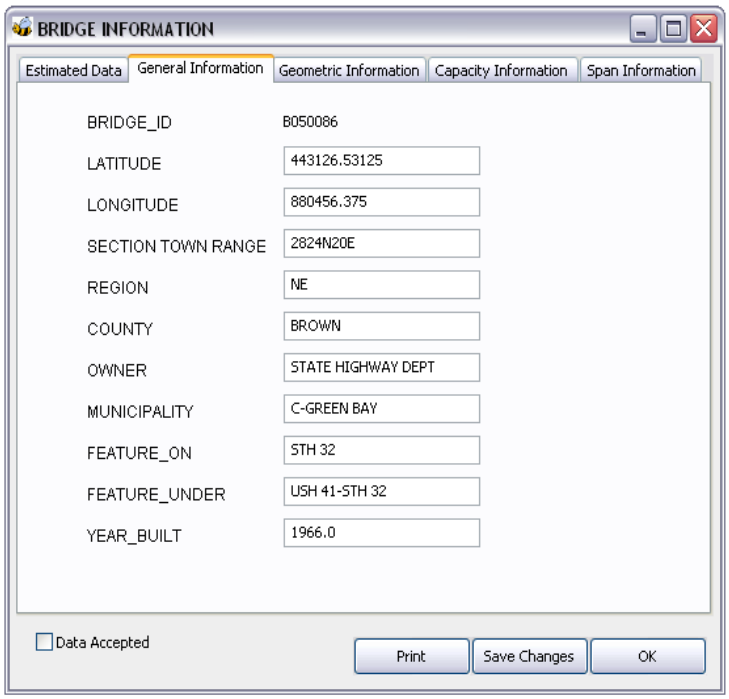

Figure 38. Bridge Information Search – Bridge Information Window

The displayed bridge data may be updated by the user through substitution of information if necessary. Any changes to the bridge data may be saved by pressing the “Save Changes” button (see Figure 39). The saved data will be used by the system for the damage assessment purpose but the original data in the database will not be altered. The user may obtain a printable report of the data by clicking the “Print” button.

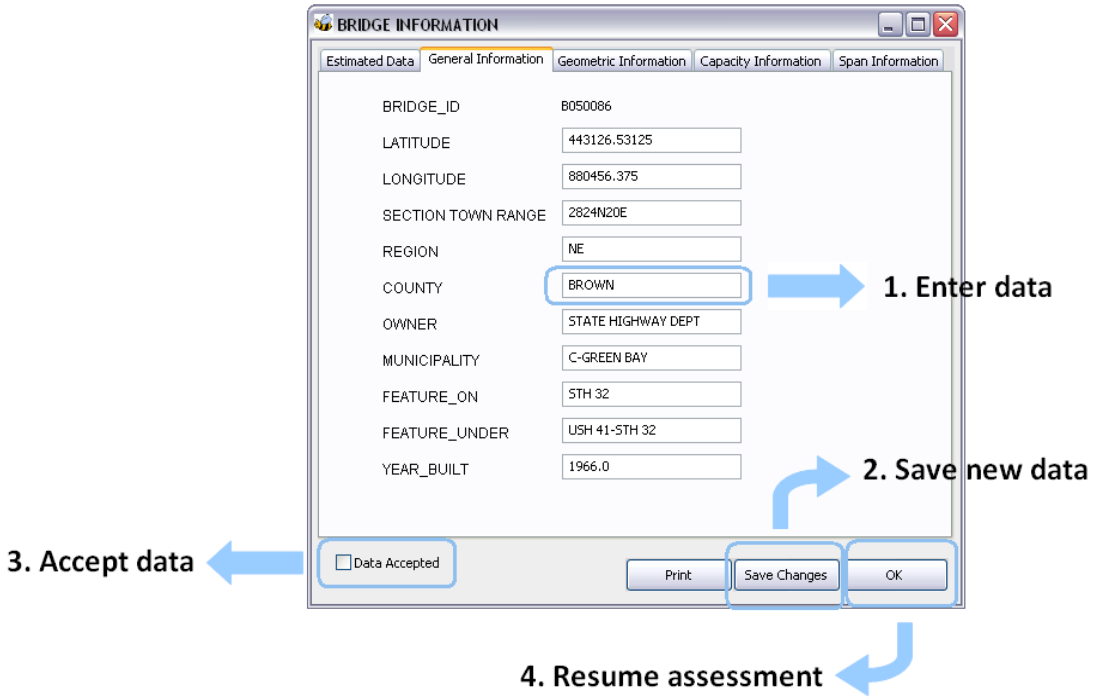

Figure 39. Bridge Information Search - Data Modification Options

3.6.1.2 CONTACT SEARCH FEATURE

The main objective of this feature is to provide the user with a list of emergency contacts including names, telephone numbers, and email and office addresses. This feature can be accessed from the File menu by clicking on the "WisDOT Contacts…" option (see Figure 40). In addition, access to this feature is also available when the Initial Emergency Procedure window is used by the user (see Figure 41).

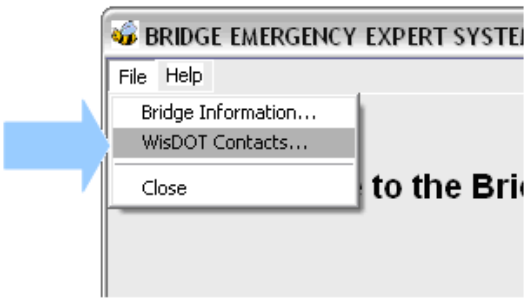

Figure 40. Contact Search Accessed from the Menu Bar

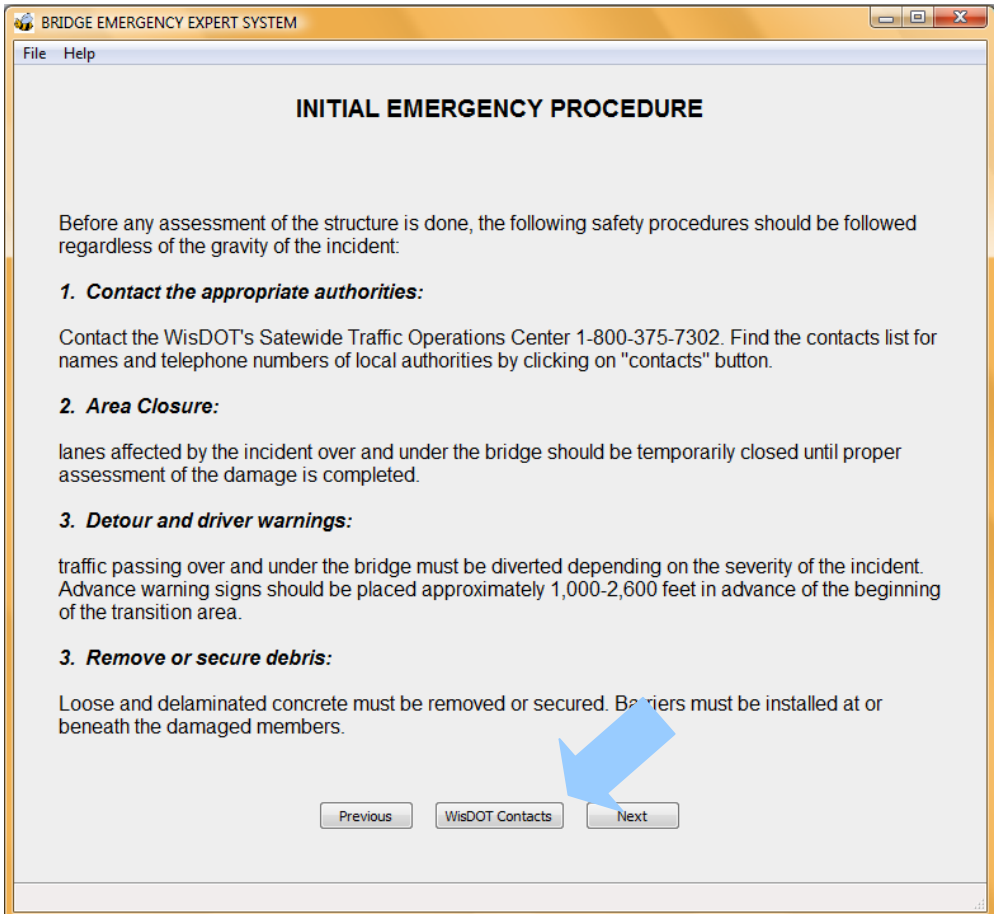

Figure 41. Contact Search Accessed from the Initial Emergency Procedure Window

A new window is opened when “WisDOT Contacts” button is clicked. To find the appropriate contact information, the user must first select the bridge location. A Wisconsin regional map is provided as a guide to the user. After the location of the incident is selected, the button “Find Contact” must be clicked to search the required contact information. The information will be shown in a text box located on the lower part of the window. A list of counties that are a part of the selected region will be shown first, followed by a list of contact personnel including names, addresses, telephone numbers, and e-mail addresses (see Figure 42).

To cancel or exit the above feature, “Cancel” or “Ok” button must be clicked. The program will resume BEES assessment process once the window is closed under this feature.

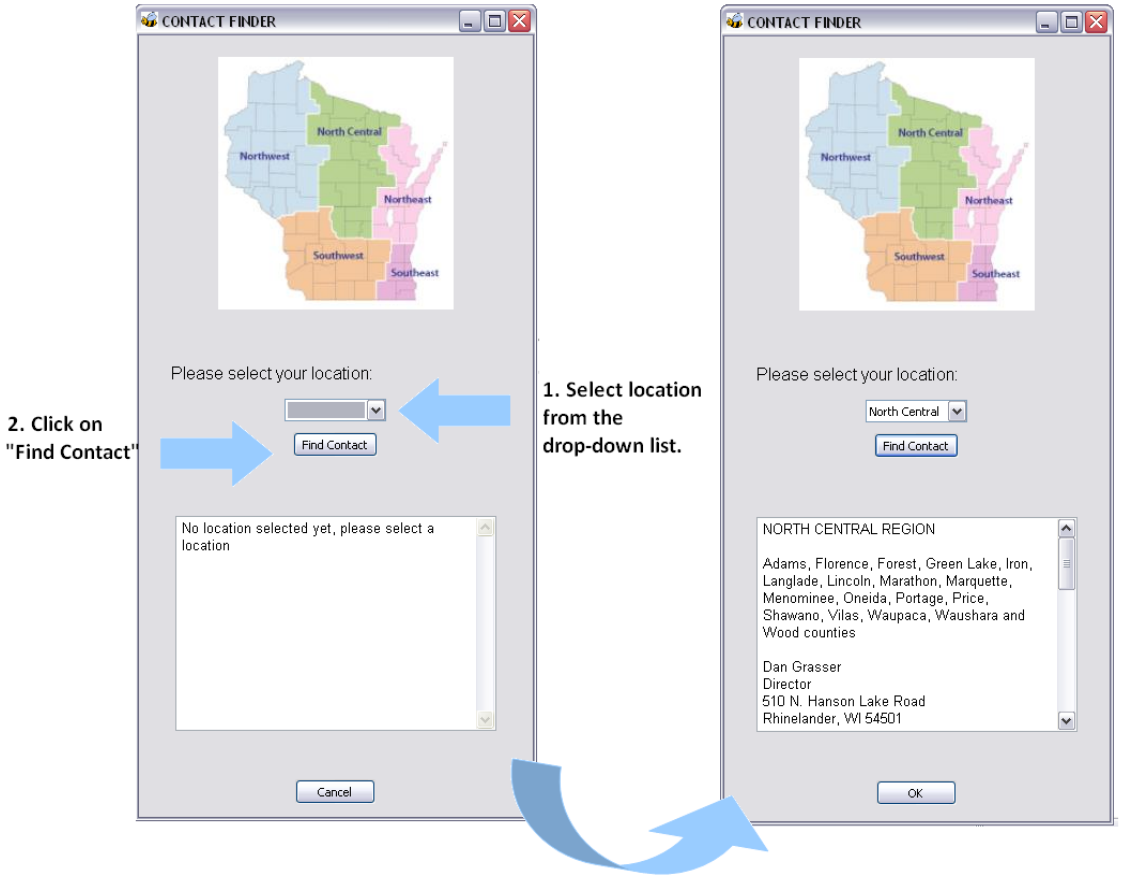

Figure 42. Contact Search

3.6.2 REPORT PRINTER FEATURE

This feature allows the user to obtain a printed report for the bridge information and the assessment session. It is accessible from the bridge information window by clicking on the “Print” button as well as from the final recommendation window by clicking on the “Get Report” button (see Figure 43). The user can either print or save the displayed information by clicking on the “File” tab and use the given menu options.

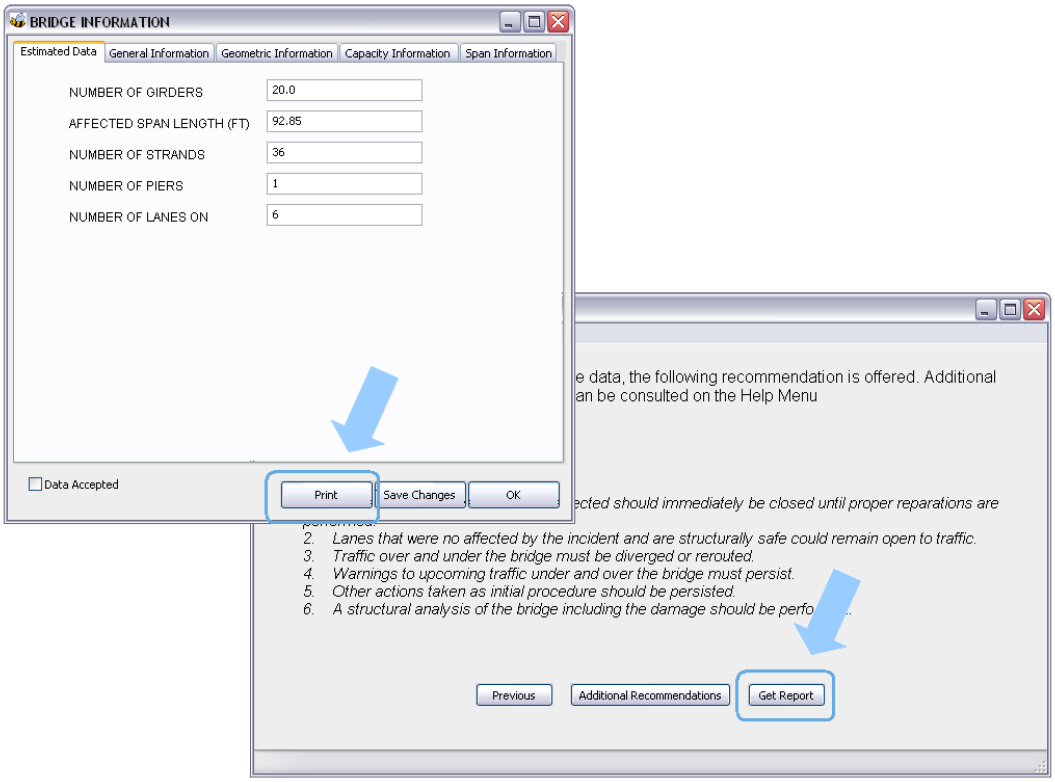

Figure 43. Report Printer Windows

3.6.3 HELP MENU

3.6.3.1 SEARCH ENGINE /CASE HISTORIES SEARCH FEATURE

This feature provides additional options to access information that may be helpful to the user in making appropriate decisions in a bridge emergency situation. It is accessible through the “Help” menu by clicking the “Case Histories Finder...” button (see Figure 44). Case histories database consists of sixteen bridge incidents in Wisconsin when emergency responses were required to mitigate them. These case histories were compiled in a previously completed study entitled “Bridge Integrated Analysis and Decision Support System: Case Histories – Phase I” [1].

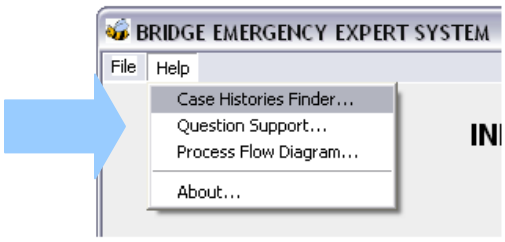

Figure 44. Case Histories Search Access

A search by key-words option may be executed through the case histories database when this feature is selected. BEES provides an initial list of keywords that can be reduced, expanded, or modified by clicking the "Modify" button (see Figure 45). The "Search" button may be clicked to start finding and displaying relevant case histories based on matches in the database with the selected key-words.

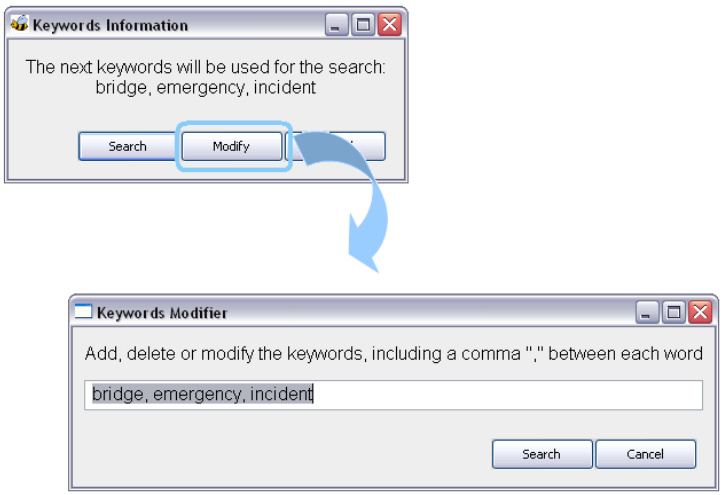

Figure 45. Search Engine - Initial Keywords and Keywords Modifier

Once the search is concluded, a new window will display a list of case history files arranged in the order of significance with respect to the extent of matching key-words that were selected by the user (see Figure 46). The displayed matched percentage for each case history corresponds to the percentage of matched key-words between the user's selection and those within the case history document. The user can open one or more case history files by selecting them from the list and clicking on the "Open File" button. The text part of the database is in the Portable Document Format (PDF).

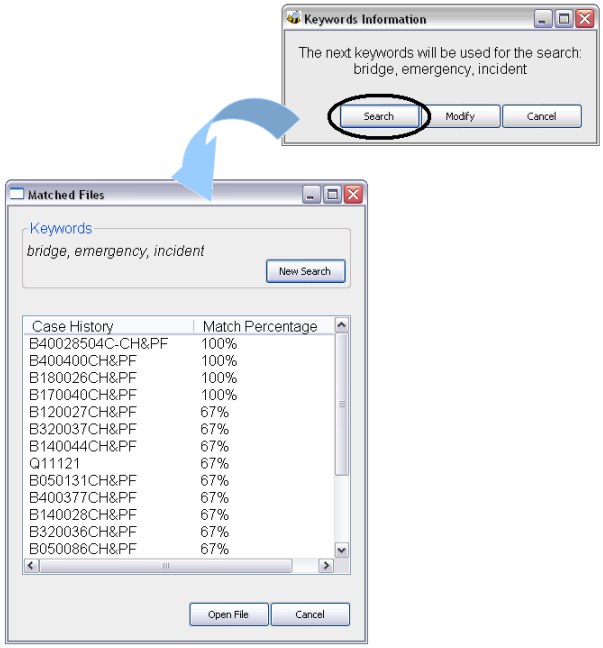

Figure 46. Search Engine for Case Histories and the Results from the Search

By clicking on the "New Search" button the system will return the user to the keywords modifier window shown in Figure 45. Once the search is completed, the user may resume the damage assessment process by closing the search engine or clicking on the "Cancel" button.

3.6.3.2 QUESTION SUPPORT FEATURE

This feature provides assistance to the user regarding the questions that are presented by the system during the damage assessment process. This feature may be accessed from the help menu during the question-and-answer session (see Figure 47).

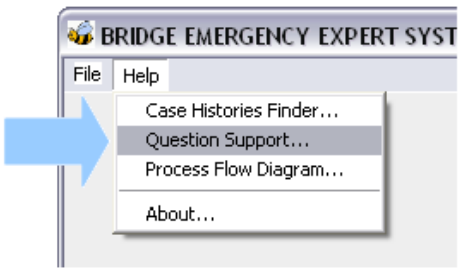

Figure 47. Question Support Access

When the question support option is selected, a .pdf file will be displayed in a new window that presents additional details of the question being asked at that moment. In addition, each of the options given as possible answers is further described. The assessment process can be resumed by returning to BEES' window.

Other files including case histories and help documents may be reviewed at any time.

3.6.3.3 PROCESS FLOW DIAGRAM FEATURE

This feature includes the WisDOT's incident response procedures in the form of process flow diagrams. These diagrams were developed as a part of a recent study entitled "Bridge Integrated Analysis and Decision Support System: Case Histories – Phase I [1]." They were developed through consultation with appropriate staff from the different regions of the WisDOT.

This feature is accessible from the help menu by clicking the "Process Flow Diagram option…" button (see Figure 48). Each flow diagram contains general procedures for activities such as reporting and notification, damage evaluation, and repair/replacement approval.

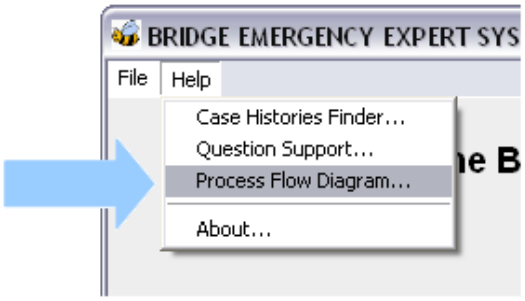

Figure 48. Process Flow Diagram Access

The damage assessment process may be continued by clicking anywhere on BEES' window. This feature can be accessed at any time during the question-and-answer session.

CHAPTER 4

KNOWLEDGE VALIDATION - EXAMPLES (Case Studies)

In this chapter a description of two case histories executed in the Bridge Emergency Expert System (BEES) is presented. A summary of the incidents as well as the input information are included for each case. In addition, the recommendations provided by BEES are compared to the actions taken by the authorities at the time of the incident.

4.1 MASON STREET BRIDGE (STATE HIGHWAY 54) OVER U.S. HIGHWAY 41

4.1.1 BRIDGE LOCATION

The Mason Street (State Highway 54) Bridge is located in the southwestern part of the City of Green Bay, Wisconsin (see Figure 49). The bridge was constructed in 1966 and carries six lanes of traffic that are over four lanes of traffic in U.S. Highway 41 (USH 41). The bridge is identified with the number B- 05- 0086.

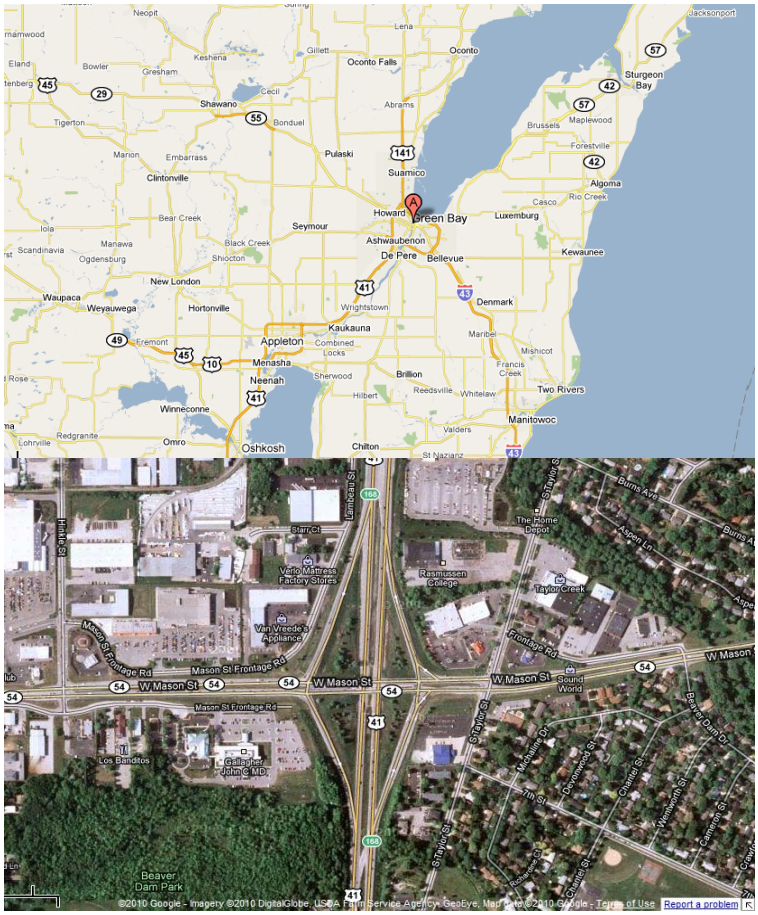

Figure 49. Location of the Manson Street Bridge (B-05-0086)

4.1.2 BRIDGE DESCRIPTION

The bridge consists of two spans with each span having twenty prestressed concrete girders. The span lengths are 92.0 (28.04 m) and 90.0 feet (27.43 m). The bridge deck´s width is 100.0 feet (30.48 m) and the deck area is 18,570 sq. ft (1725.21 sq m). It has retaining type abutments with 12 in (0.31 m) treated round timber pilings and a round column bent with 12 in (0.31 m) treated round timber pilings. The following load ratings are specified for the bridge: H20 for design, HS41 for operation, and HS20 for inventory. The bridge was designed for over 2,000,000 stress cycles [1].

4.1.3 ACCIDENT DESCRIPTION

The Mason Street Bridge girders were struck by a front-end loader/excavator due to its excessive height while being transported on a trailer in the northbound lanes of USH 41. The impact resulted in extensive damage to several concrete girders with debris scattered over the roadway and striking a vehicle immediately behind the transporting truck.

In addition, the following damage on the structure was visible:

1. Severe damage to the first exterior girder (girder 1) with six exposed prestressing steel strands and one severed strand. (see Figure 50)

Figure 50. Detailed View of Severely Damaged Exterior PS Concrete Girder

2. The bottom flange of the exterior girder 1 had severe cracking that extended into the web.

3. The impact caused repair concrete patches placed over previously damaged areas on girders 6 and 7 to fall off and exposing prestressing steel strands. (see Figure 51).

Figure 51. Failure of Previously Repaired Locations in Girder Flanges (separated concrete patches)

4.1.4 BEES APPLICATION

According to the damage description provided, three different types of damage are evident:

1) Severe cracking that extended into the web,
2) Shallow spalling of concrete in Girders 6 and 7, and
3) Deep spalling with Loss of section in Girder 1.

Once the BEES is started, the first window presented to the user is the welcome window as shown in Figure 52.

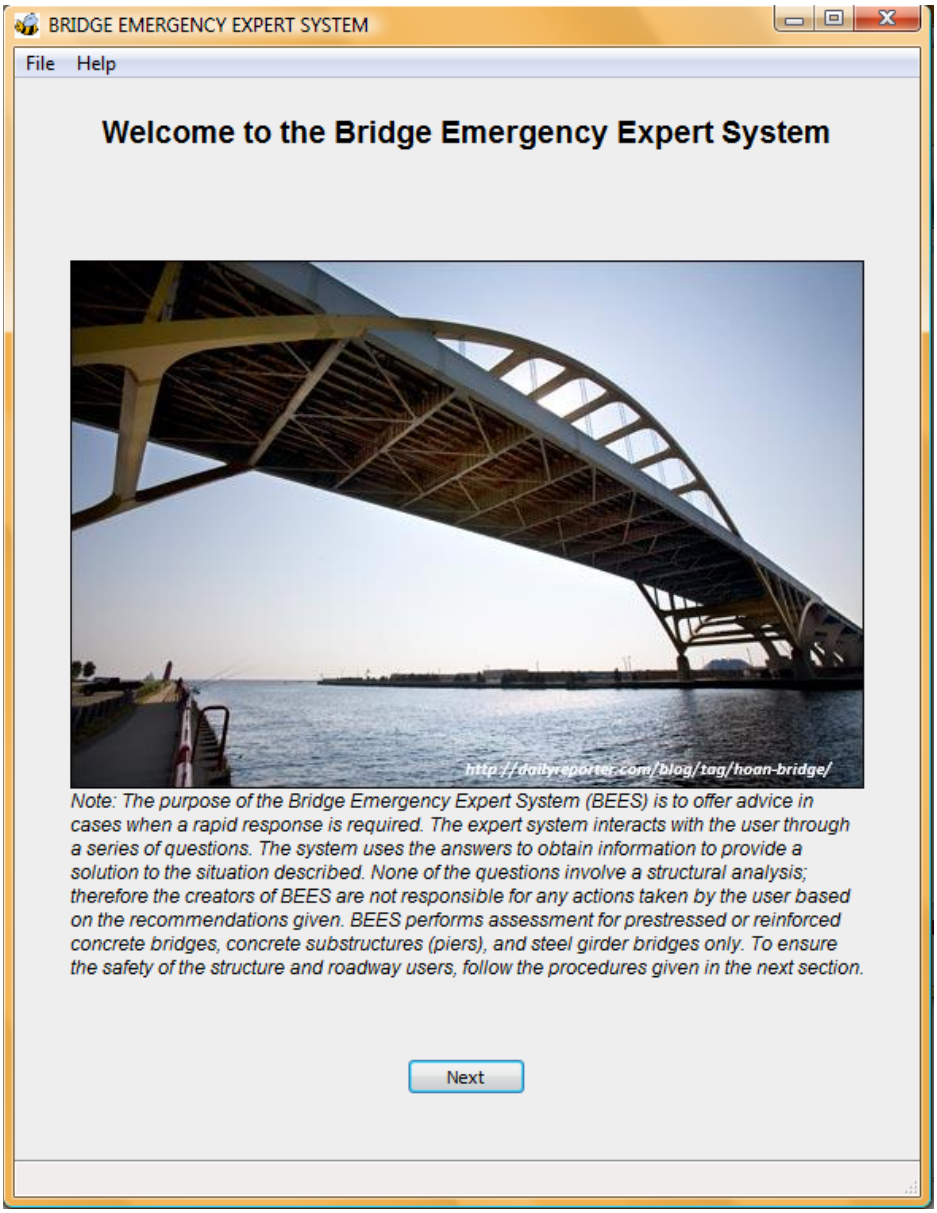

Figure 52. BEES Welcome Window

After clicking the “next” button in the welcome window, an initial emergency procedure is recommended to ensure the safety of the structure and the general public before beginning of the assessment of the damage (see Figure 53)

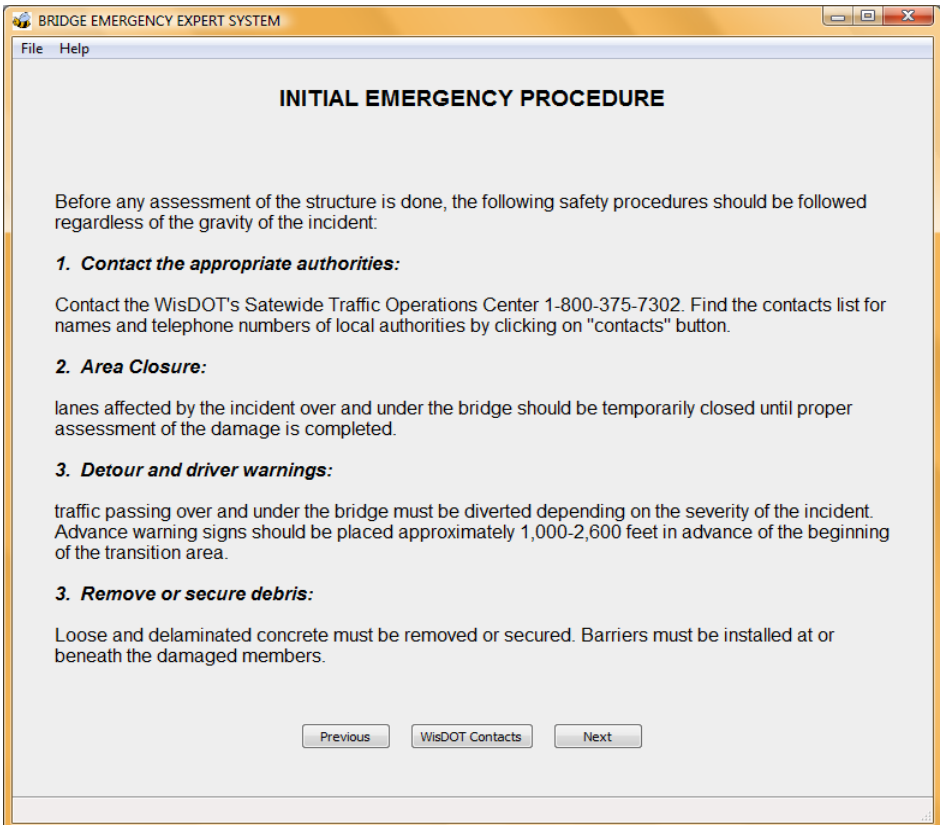

Figure 53. BEES Initial Emergency Procedure Window

The bridge damage assessment begins by selecting the “Next” button on the Initial Emergency Procedure window where the first required input “the Wisconsin bridge identification number” is entered (see Figure 54).

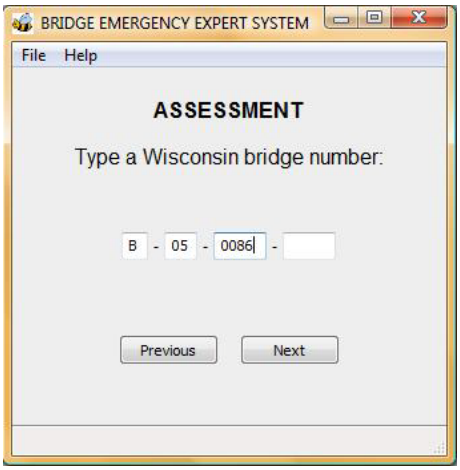

Figure 54. BEES Window for Entering the Bridge Number

Once the Wisconsin bridge identification number is entered and the “Next” button is clicked, BEES will search for the bridge information available in the system’s database. After the search is concluded, the following window is displayed:

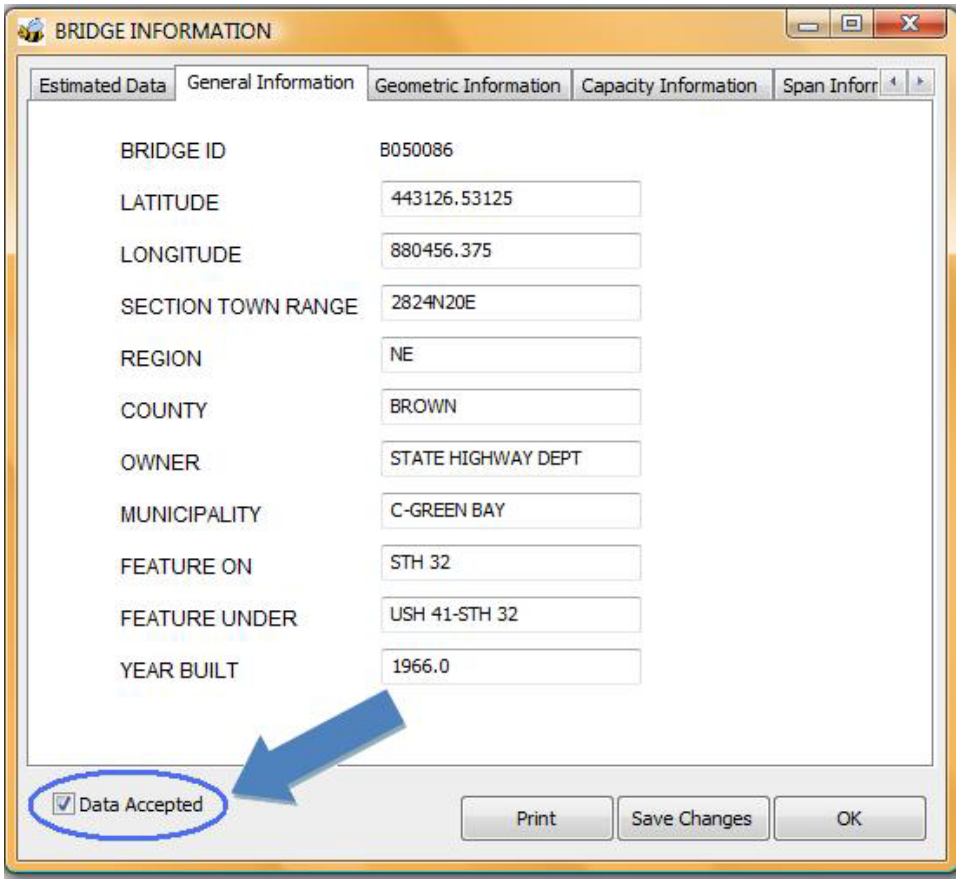

Figure 55. BEES Window for Bridge Information

The user may review or update the bridge data and must accept the displayed information by placing a check mark in the box next to the “Data Accepted” text in the window at the lower left corner. The “OK” button is clicked then to resume the question-and-answer session. The following figures show all relevant windows that are displayed for this particular case study.

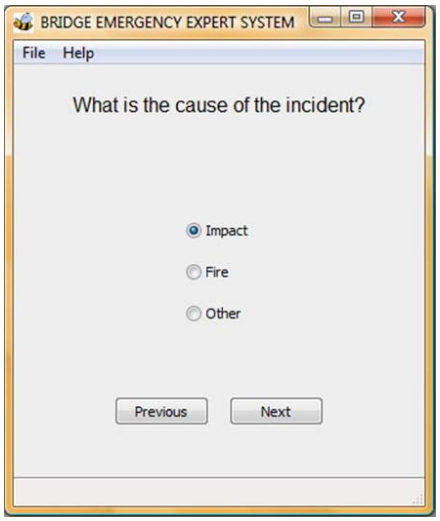

Figure 56. BEES Window (Question 1 – incident cause)

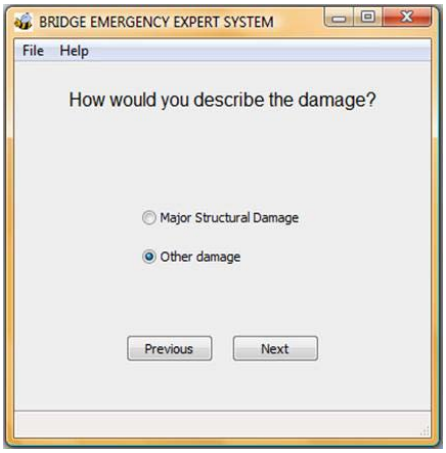

Figure 57. BEES Window (Question 2 – damage description)

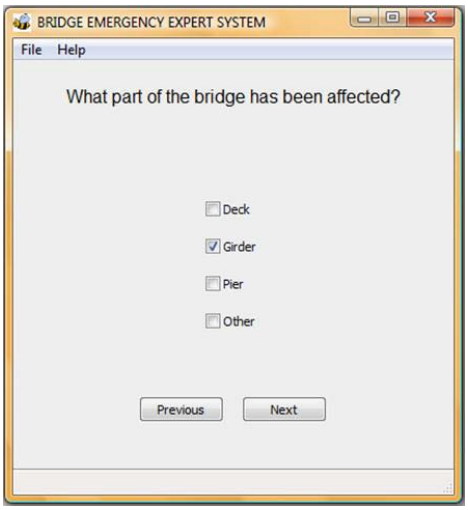

Figure 58. BEES Window (Question 3 – Damaged areas)

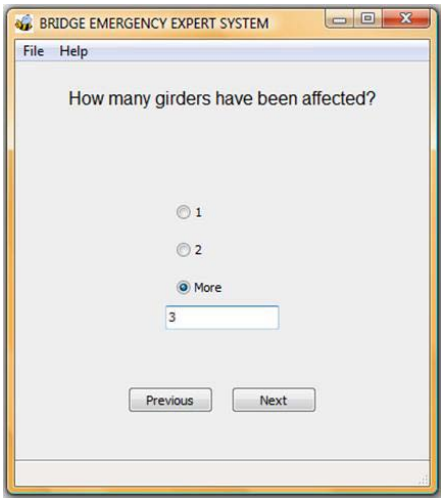

Figure 59. BEES Window (Question 4 – # of damaged members)

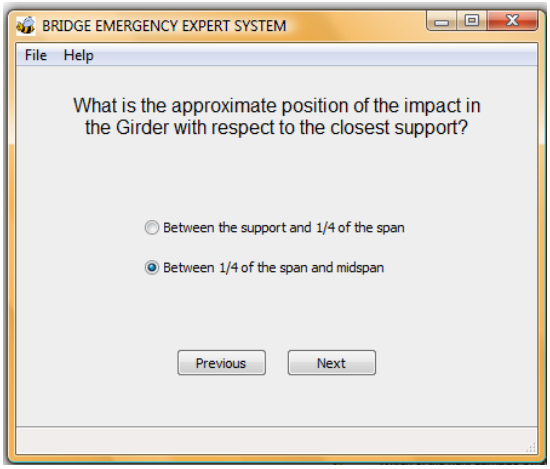

Figure 60. BEES Window (Question 5 – damage location)

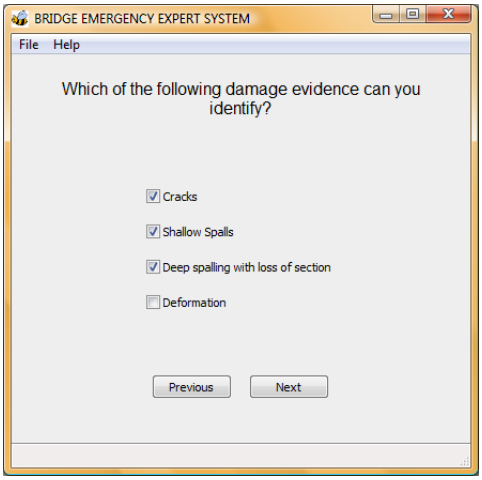

Figure 61. BEES Window (Question 6 – additional damage evidence)

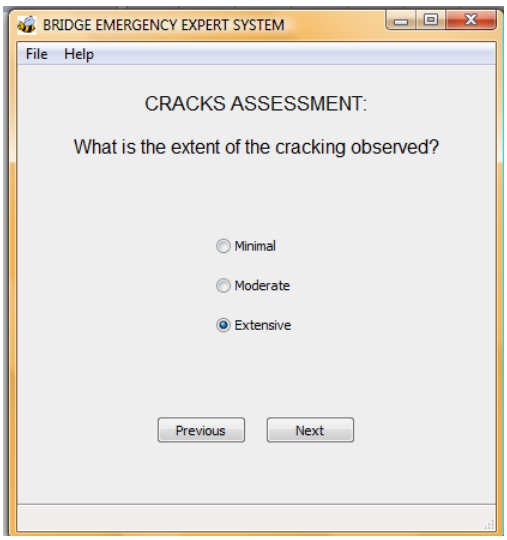

Figure 62. BEES Window (Question 7 – level of additional damage)

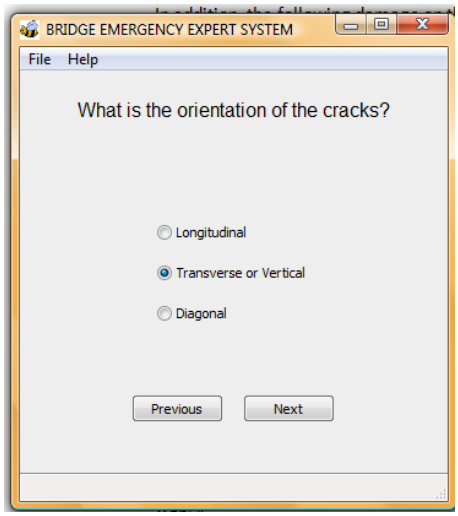

Figure 63. BEES window (Question 8 – orientation of additional damage)

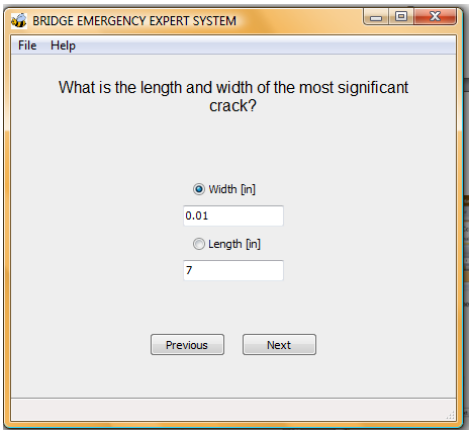

Figure 64. BEES Window (Question 9 – Size of additional damage)

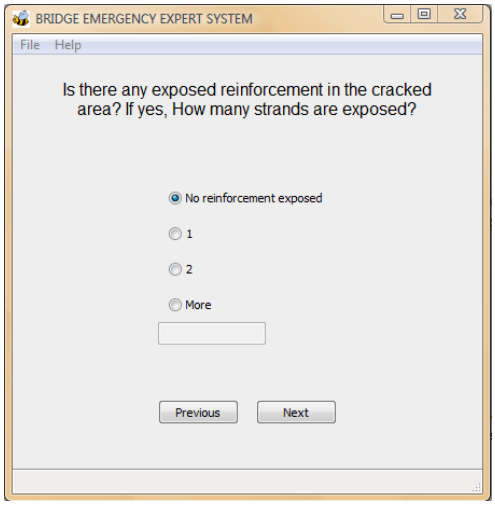

Figure 65. BEES Window (Question 10 – exposed steel bars/strands)

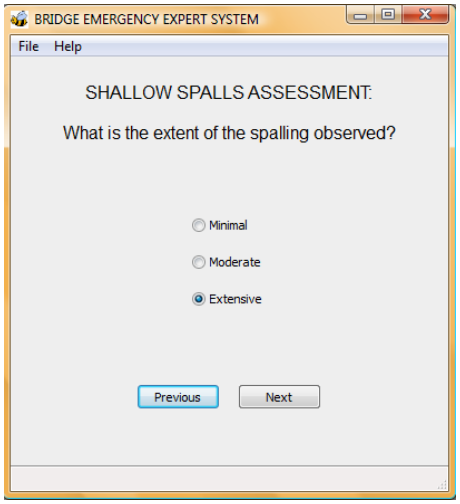

Figure 66. BEES Window (Question 11 – spalled concrete)

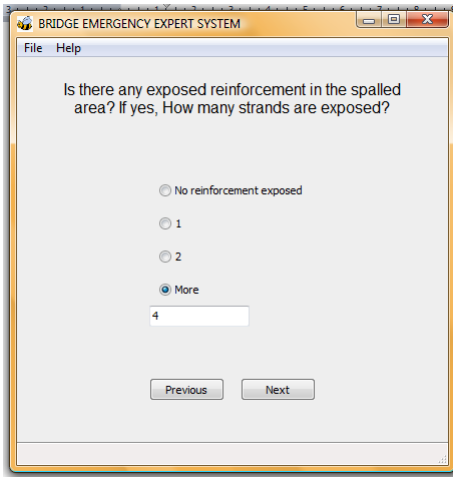

Figure 67. BEES Window (Question 12 – exposed steel bars/strands)

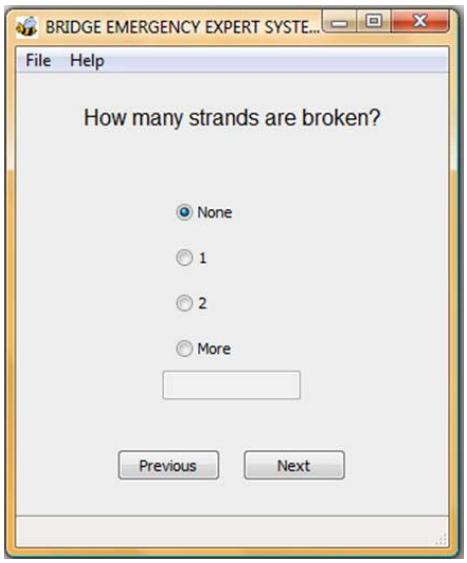

Figure 68. BEES Window (Question 13 – fractured steel bars/strands)

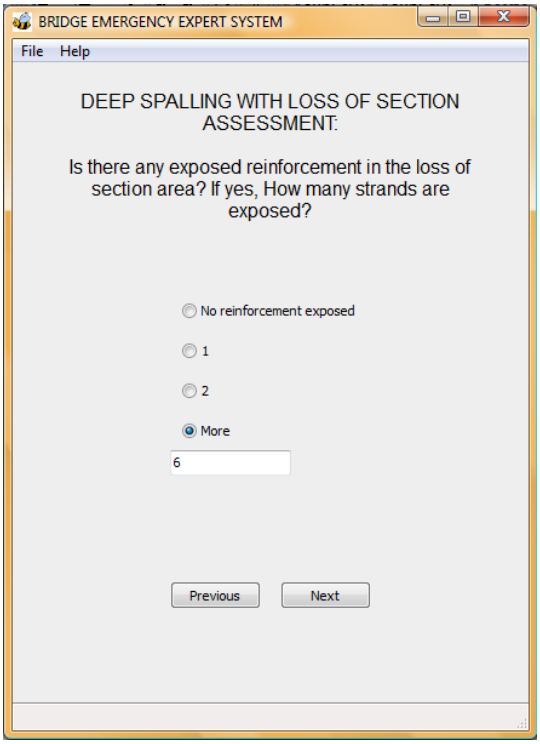

Figure 69. BEES window (Question 14 – exposed steel bars/strands)

Figure 70. BEES Window (Question 15 – fractured steel bars/strands)

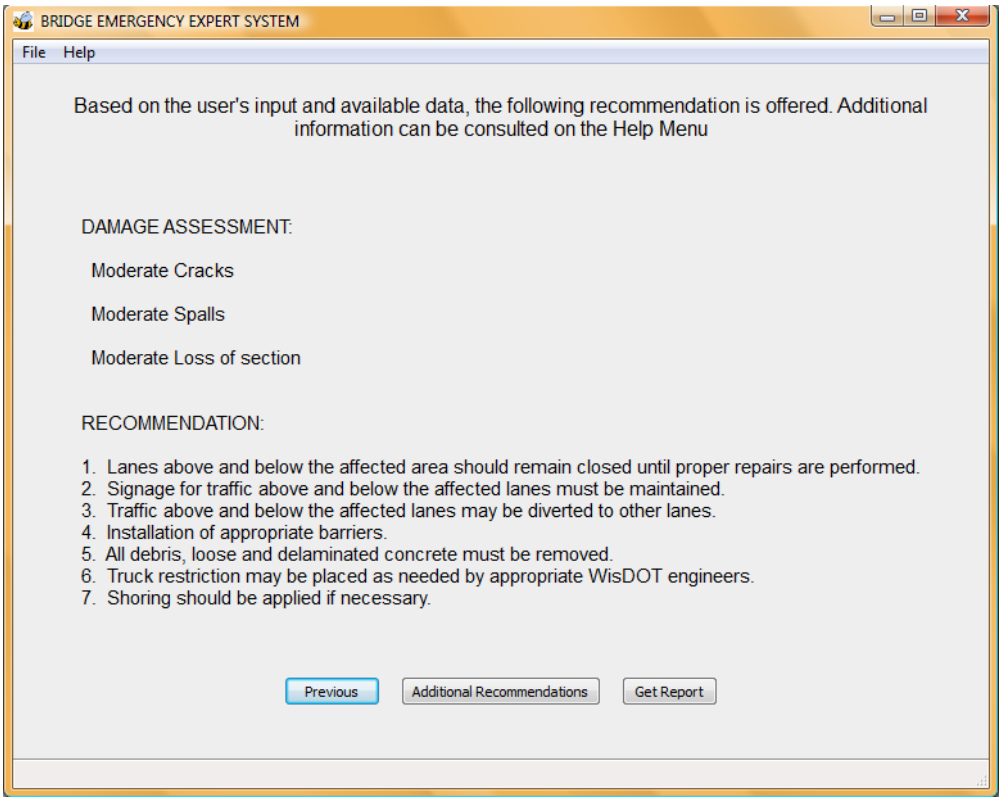

Figure 71. BEES Window - Initial Recommendations for Bridge Id # B-05-0086

According to the results obtained by BEES the damage produced by the Loss of section is more critical than the damage produced by the spalls, therefore a recommendation for the worst damage is offered to the user.

Once taking all emergency precautions are completed, complementary recommendations may be obtained by clicking on the "Additional Recommendations" button in the recommendation window. The following window will be displayed for this particular case study:

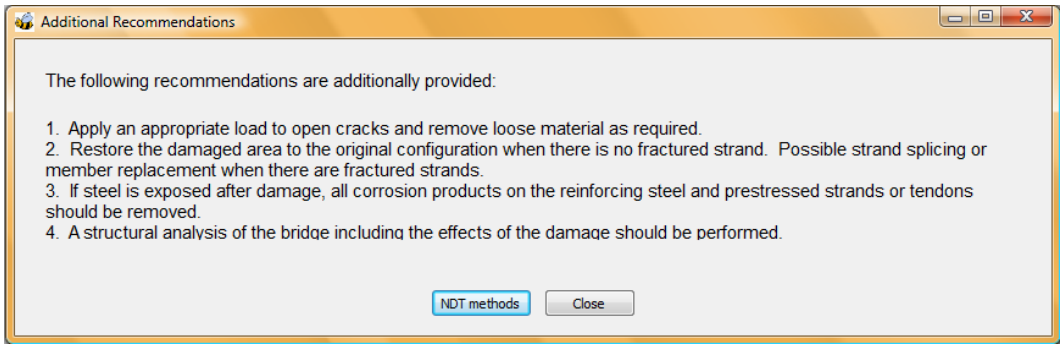

Figure 72. BEES Window - Complementary Recommendations for Bridge ID # B-05-0086

4.1.5 BEES RECOMMENDATIONS

Table 17 presents the recommendations given by the BEES system as well as those provided by the DOT officials at the time of the accident.

Table 17. Mason Street Bridge Assessments by BEES and WisDOT Officials

BEES RECOMMENTATIONS	WisDOT RECOMENDATIONS
Assessment result: Moderate Cracks Minimal Spalls Moderate Loss of section **Initial Recommended Actions**: 1. Lanes above and below the affected area should remain closed until proper repairs are performed 2. Signage for traffic above and below the affected lanes must be maintained 3. Traffic above and below the affected lanes must be diverted to other lanes 4. Installation of appropriate barriers 5. All debris, loose and delaminated concrete must be removed 6. Truck weight restrictions should be placed 7. Shoring should be applied if necessary **Additional Recommendations:** 1. Apply preload as required 2. Restore the damaged area to the original configuration 3. If steel is exposed after damage, all corrosion products on the reinforcing steel and prestressed strands or tendons should be removed 4. A structural analysis of the bridge including the effects of the damage should be performed 5. Additional NDT methods can be used to confirm or complement the visual assessment	It was recommended that : * Because of the extensive cracking, girder 1 to be replaced * Although the damage, especially to girder 1, was extensive it was decided that the bridge was still structurally sound and no restrictions were placed on its use * Both of girders 6 and 7 to be repaired

According to the results, the recommendations given by BEES are in line with the actions taken by the WisDOT officials at the time of the incident. BEES does not recommend any repair procedures but provides guidance for further actions such as structural analysis and the use of NDT methods.

4.2 COUNTY HIGHWAY M OVER STATE HIGHWAY 16

4.2.1 BRIDGE LOCATION

The County Highway M Bridge is located on the northern boundary of the City of Watertown, where it spans over State Highway 16 (see Figure 73). The bridge was constructed in 1960 and carries two lanes of traffic. The bridge is identified with the number is B-14-0044.

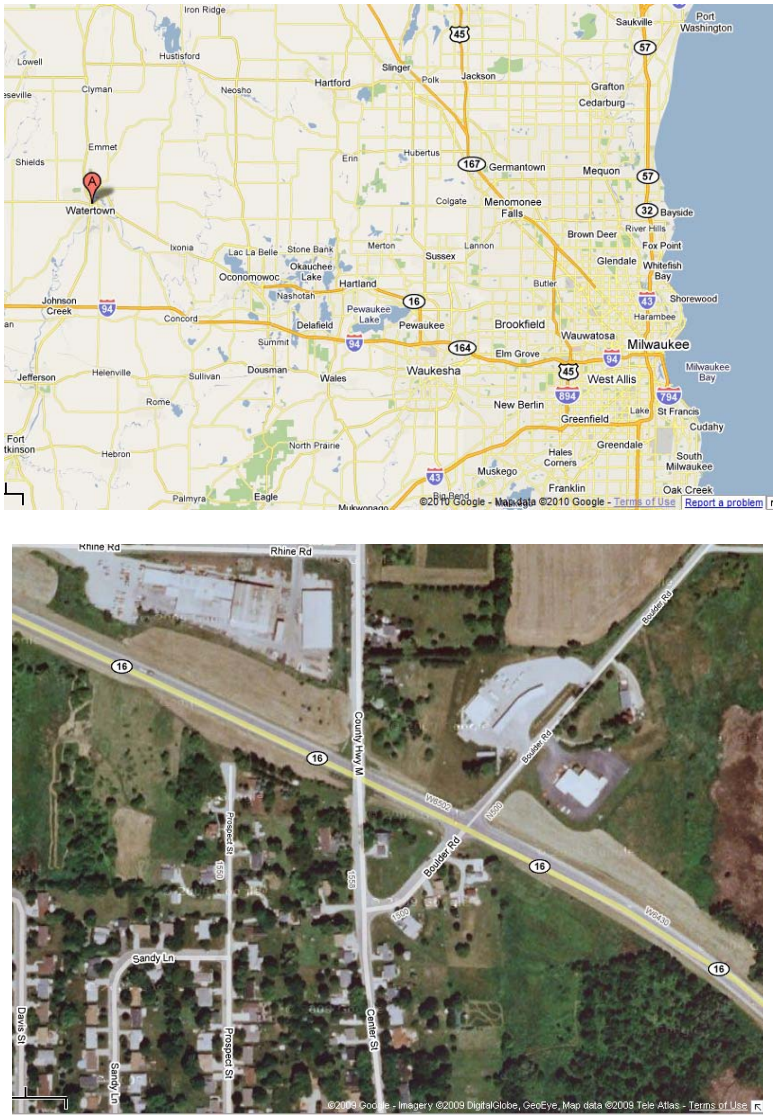

Figure 73. County Highway M Bridge Spanning over State Highway 16 (B-14-0044)

4.2.2 BRIDGE DESCRIPTION

The bridge has three continuous steel girder spans (five girders in each span) of lengths 35.0 ft, 52.0 ft, and 52.0 ft for a total structure length of 143.2 ft. The deck width is 37.0 ft and the deck area is 5,298 sq. ft. The north abutment is an open pedestal type structure and the south abutment is a sill with bearings style. Both abutments are constructed from reinforced concrete without pilings. There are two round column bent piers that are also constructed without pilings. Load ratings are specified as H20 for the design, HS24 for an operating load rating, and HS14 for the inventory load rating. The bridge was designed for over 2,000,000 stress cycles and the girders were manufactured with ASTM – A572 (AASHTO Grade 50) structural carbon steel [1].

4.2.3 ACCIDENT DESCRIPTION

The County Highway M Bridge was struck in span 2 by an oversize semi tractor-trailer traveling eastbound on State Highway 16. The collision resulted in extensive distortion of all five girders in the span (see Figures 74 and 75).

Figure 74. Impact Damage to Steel Girders in Bridge ID # B-14-0044 (side view)

Figure 75. Impact Damage to Steel Girders in Bridge ID # B-14-0044 (underside view)

4.2.4 BEES APPLICATION

The welcome window will be first opened when The Bridge Emergency Expert System (BEES) is executed (Figure 52). To immediately enhance safety at the site of the bridge incident, an initial emergency procedure is recommended by BEES prior to the question and answer process and condition assessment of the structure (see Figure 53). Once the "Next" button in this window is clicked, BEES will start the damage assessment process for the structure. The user must provide the appropriate Wisconsin bridge number for the affected structure as a first step in the assessment process (see Figure 76).

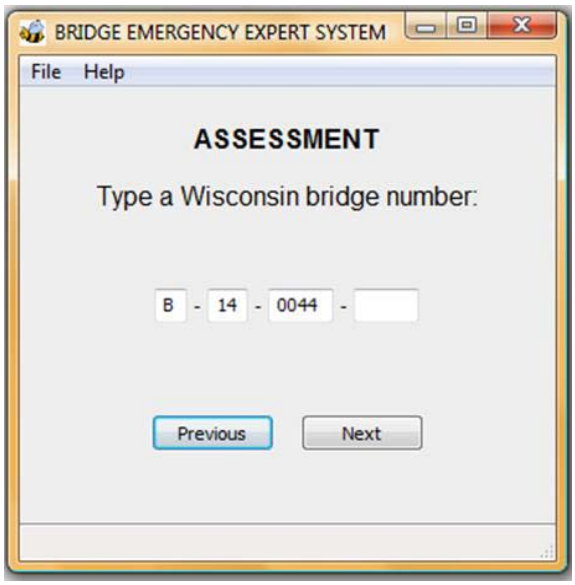

Figure 76. BEES Window for Entering the Bridge Number

After clicking "Next" the system will retrieve the relevant bridge information and will present to the user (Figure 77). In order to continue the assessment, the user must verify or modify the data and enter a check mark in the box next to the "Data Accepted".

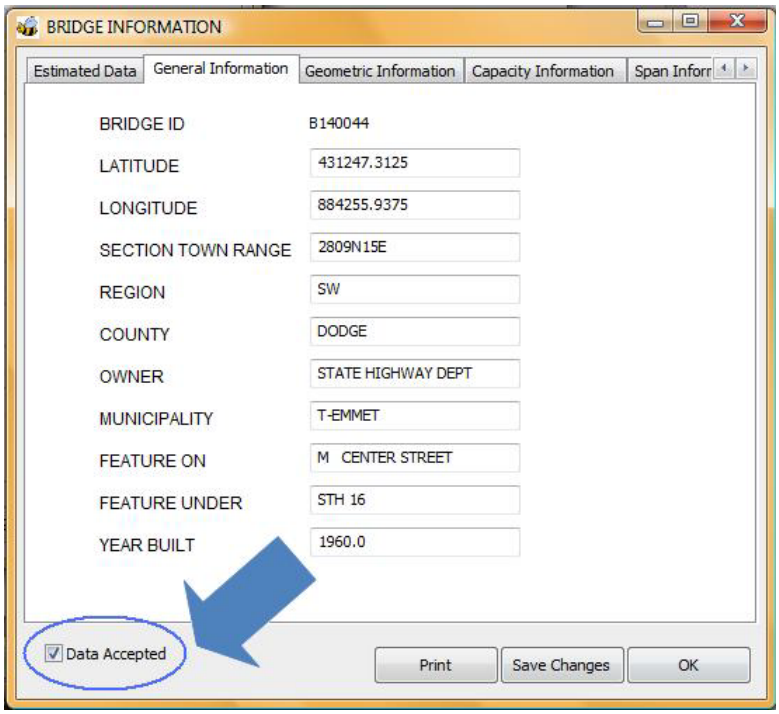

Figure 77. BEES Window for Bridge Information

The next step includes clicking the "OK" Button to begin the question-and-answer session. The following figures show all relevant windows that are displayed for the condition assessment process for this case study:

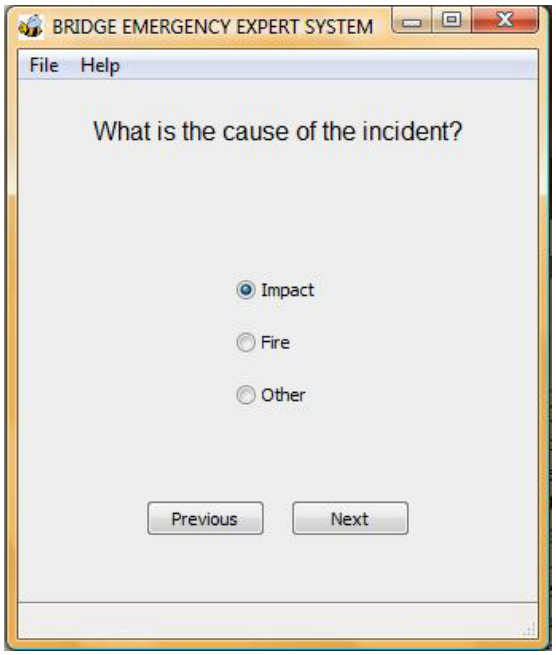

Figure 78. BEES Window (Question 1 – incident cause)

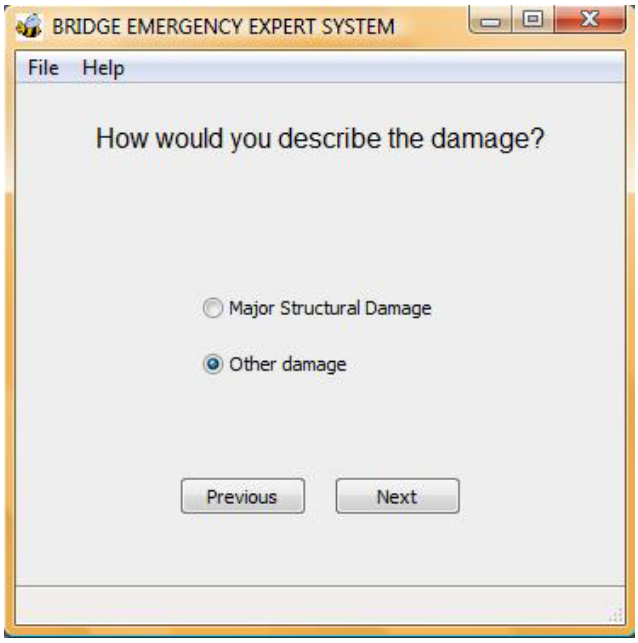

Figure 79. BEES Window (Question 2 – damage description)

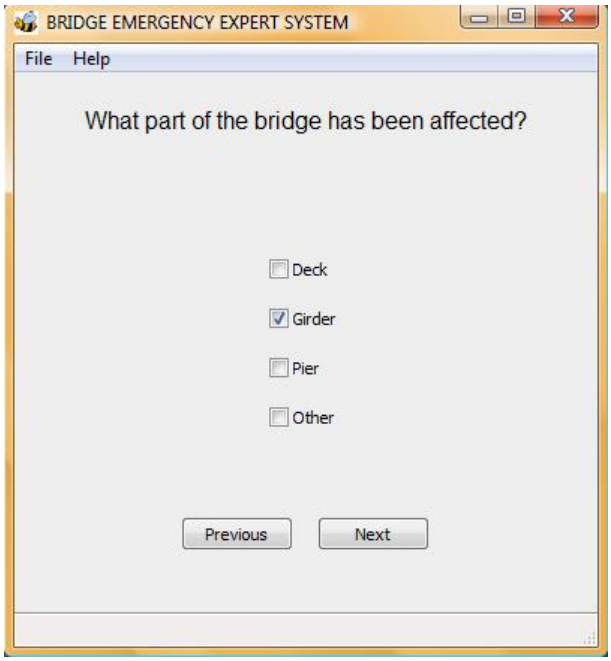

Figure 80. BEES Window (Question 3 – damage location)

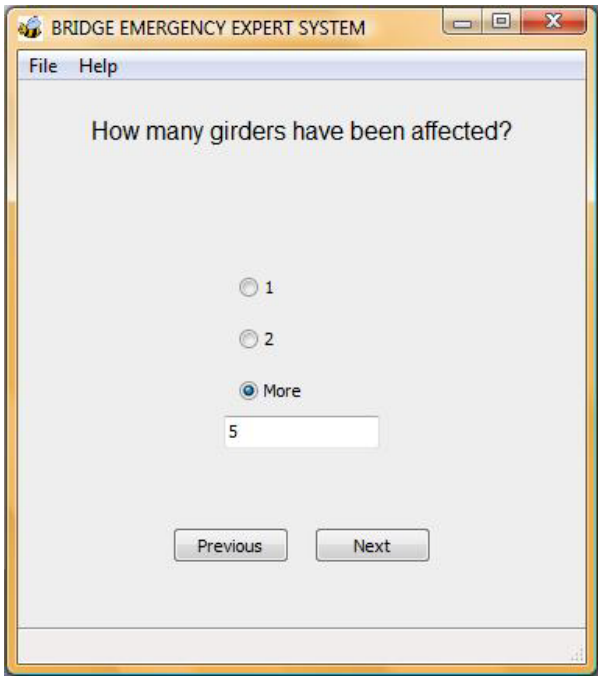

Figure 81. BEES Window (Question 4 - # of damaged members)

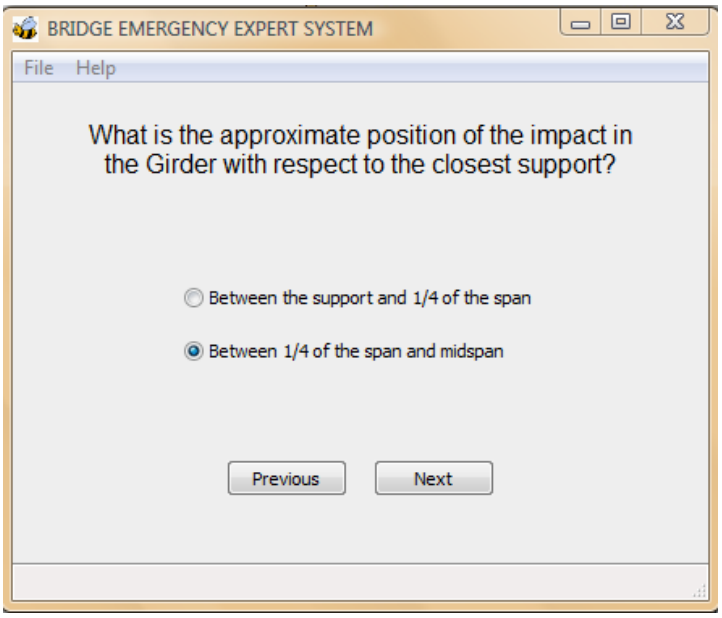

Figure 82. BEES Window (Question 5 – damage location)

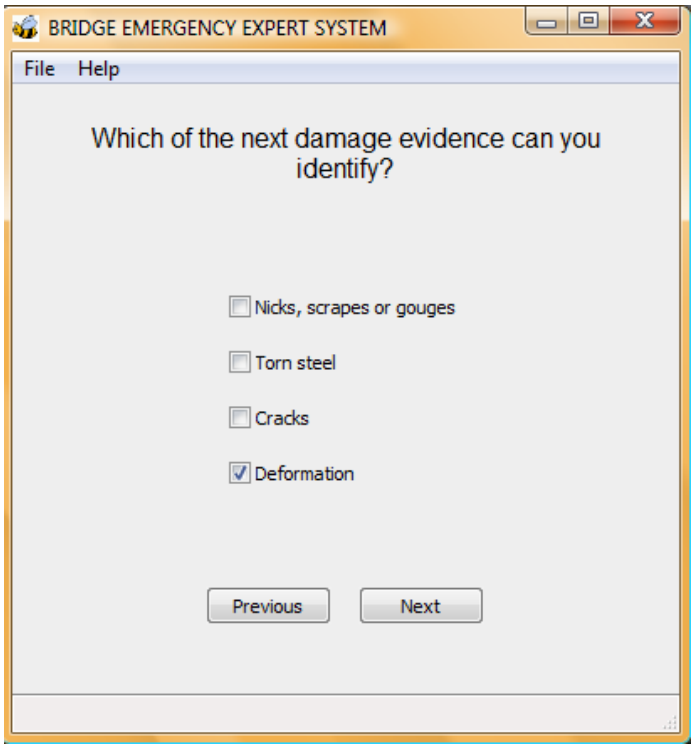

Figure 83. BEES Window (Question 6 – additional damage evidence)

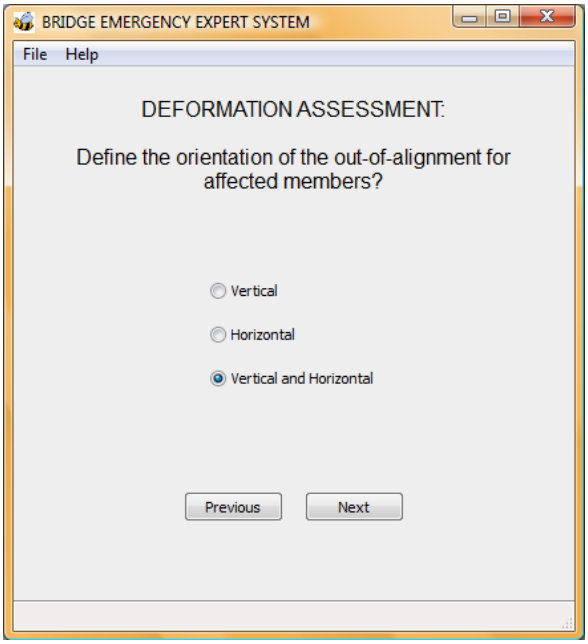

Figure 84. BEES Window (Question 7 – deformation type)

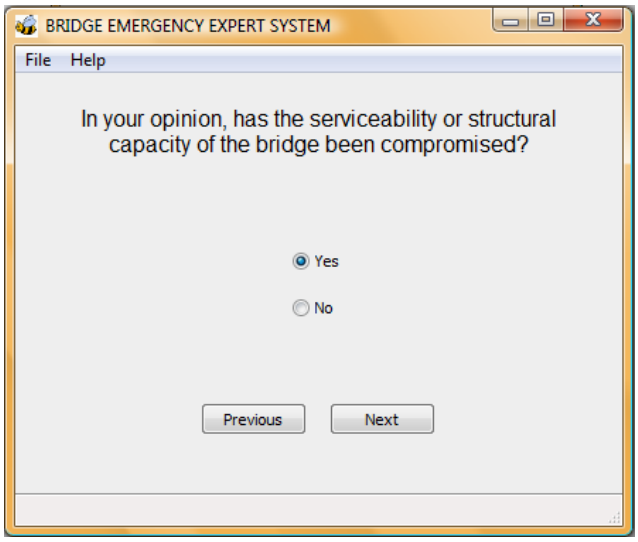

Figure 85. BEES Window (Question 9 – structural capacity)

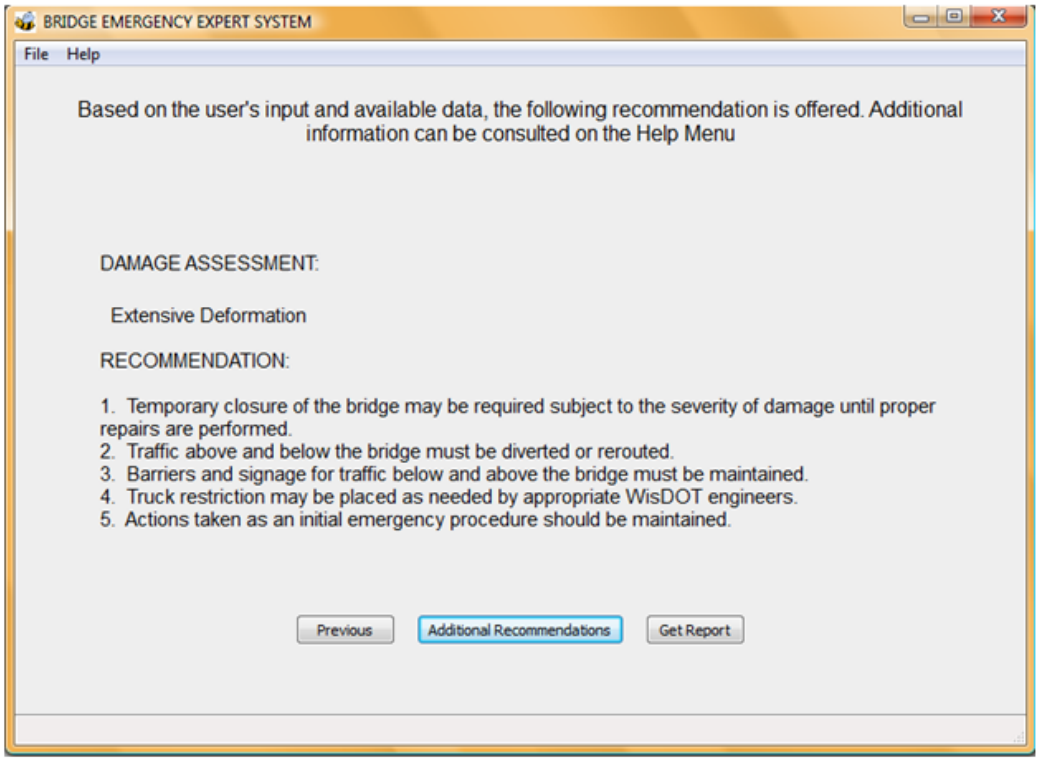

Figure 86. BEES Window - Immediate recommendations

After the emergency is controlled, additional recommendation can be consulted by clicking on "Additional Recommendations" button. The following window will be shown to the user in this particular case:

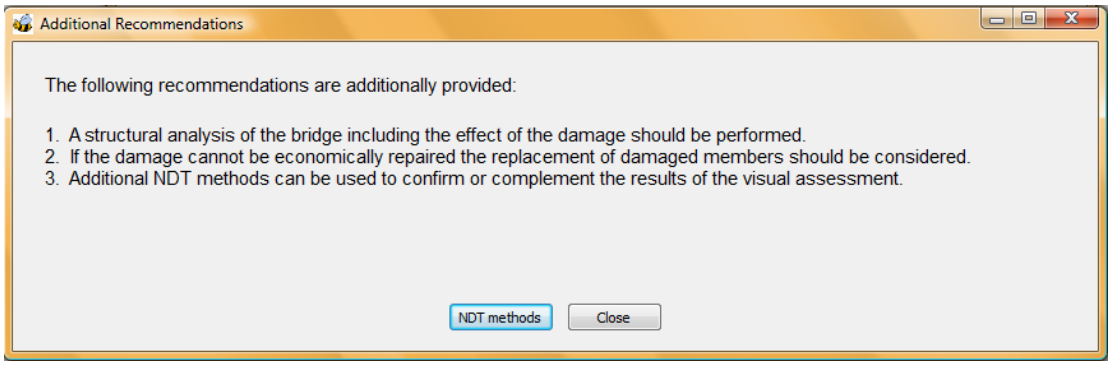

Figure 87. BEES Window - Additional Recommendations

4.2.5 BEES RECOMMENDATIONS

Table 18 compares the recommendations provided by BEES as well as those implemented by the DOT officials at the incident site.

Table 18. County Highway M Bridge Assessments by BEES and WisDOT Officials

BEES RECOMMENTATIONS	WisDOT RECOMENDATIONS
Assessment result: Extensive Distortion/Deformation **Immediate Recommended actions**: 1. Temporary closure of the bridge subject to the severity of damage 2. Reroute traffic above and below the bridge 3. Placement of barriers and signage for traffic below and above the bridge 4. Place truck weight restrictions for the bridge 5. Maintain actions taken as an initial emergency procedure **Additional Recommendations:** 1. Perform a structural analysis of the bridge including the effect of the damage 2. If the damage cannot be economically repaired, consider the replacement of damaged members 3. Utilize NDT methods to confirm or complement the results of the visual assessment	After arrival at the scene and an initial investigation, the WisDOT officials removed the traffic restrictions on State Highway 16 that was implemented by the highway patrol. However, the bridge on County Highway M was kept closed pending additional investigation. The bridge closure and traffic rerouting remained in effect until the repairs to the bridge were completed. Further lane closures and traffic rerouting on State Highway 16 were enacted when bridge repair was in progress. Due to the severity of the damage the County Highway M Bridge required the removal and replacement of five girders in span 2 as well as several other related repair tasks.

From the above comparison, it can be seen that the recommendations given by BEES and the DOT officials at the site regarding the bridge closure and girder repair/replacement were in good agreement. BEES offers to the user a more comprehensive set of recommendations including engineering analysis and testing. The user will have the discretion of implementing recommendations that are appropriate according to other site and engineering considerations.

CHAPTER 5

RESULTS AND DISCUSSION

Several available case histories from the Phase I study [1] were used as examples of incidents in the Bridge Emergency Expert System (BEES) to compare the recommendations provided by the system with the actions taken by the DOT authorities at the time of those incidents. Table 19 presents a summary of damage assessments and recommendations by BEES and WisDOT officials for these selected incidents.

An evaluation of the recommendations provided by BEES for each case study shows that the system has been successful in providing appropriate recommendations to ensure overall safety of the structures and personnel at the time of a bridge emergency. Furthermore, the system performance is rapid, simple, and consistent, which meets the objectives of this research. BEES´ recommendations have been found to be in agreement with the actions taken by the responsible DOT officials for the majority of the available cases. In cases when BEES recommendations differed from the actions taken by the DOT authorities, they include a more conservative approach with the requirements for additional analysis, testing, and evaluation. It must be noted that the use of BEES does not intend to replace the decision making by experts. The system's primary goal is to serve as a decision making tool that can assist the user.

Although BEES does not provide damage assessment and recommendations for every possible emergency bridge incident, general recommendations are provided for cases that have not yet been included in the BEES´ knowledge base. It is the systems primary objective to ensure safety of the traveling public, responding personnel and the structure in any type of bridge incident. In addition, through modification of existing modules or creation of new modules, the expert system may be expanded in the future to include updates and new case histories.

Table 19. Case Histories Damage Assessments and Recommendations §

BRIDGE ID	STRUCTURE TYPE	INCIDENT TYPE	DAMAGE DESCRIPTION	BEES´ ASSESSMENT AND RECOMMENDATIONS	WisDOT´S ACTIONS
B-05-0131 (Harbor Lights Road Bridge over U.S. Highway 41/141	Steel	Vehicle impact	The impact resulted in heavy damage to the northernmost exterior girder on the bridge. Although the steel girder was moderately distorted by the impact, it was decided that the structural integrity of the bridge had not been compromised.	*Assessment:* Moderate Deformation *Recommendations:* 1. Lanes above and below the affected lanes should remain closed until proper repairs are performed 2. Barriers and signage for traffic below and above the affected lanes must be maintained 3. Traffic above and below the affected lanes must be diverted to other lanes 4. Truck weight restrictions should be placed 5. Shoring should be applied if necessary	Traffic on the westbound lane of Harbor Lights Road (located over the damaged girder) was restricted. This restriction remained in place until the structural repairs were completed. All four lanes of USH 41/141 remained open to traffic after the loft boom fixture was removed from the roadway. It was recommended that the girder be heat straightened and repainted.
B-37-0082 (Alderson Street Bridge over State Highway 2)	Concrete	Vehicle impact	The impact resulted in heavy damage to the exterior girder. There were multiple cracks, smaller spalls, exposed and fractured prestressing strands, and other delaminations.	*Assessment:* Moderate Cracks and Minimal Spalls *Recommendations:* 1. Lanes above and below the affected area should remain closed until proper repairs are performed 2. Signage for traffic above and below the affected lanes must be maintained 3. Traffic above and below the affected lanes must be diverted to other lanes	The two southbound lanes (over the damaged girder) on the Alderson Street Bridge were temporarily closed restricting all traffic to the two northbound lanes. All four lanes of STH 29 remained open to traffic after the logging truck and debris were removed from the roadway. Based on the extent of damage suffered

§ Information related to damage description and Expert´s actions for each case study was obtained from the final report for "Bridge Integrated Analysis and Decision Support: Case Histories Phase I" study [1].

BRIDGE ID	STRUCTURE TYPE	INCIDENT TYPE	DAMAGE DESCRIPTION	BEES´ ASSESSMENT AND RECOMMENDATIONS	WisDOT´S ACTIONS
				4. Installation of appropriate barriers 5. All debris, loose and delaminated concrete must be removed 6. Truck weight restrictions should be placed 7. Shoring should be applied if necessary	by the bridge, it was recommended that girder #1 in span #1 be replaced.
B-17-0040 (Wilson Street Bridge over U.S. Interstate Highway I-94)	Concrete	Vehicle impact	The east pier column was completely demolished and the pier cap was severely cracked at the center column.	*Assessment:* Severe Structural Damage *Recommendations:* 1. Affected lanes above and below traffic should immediately be closed until proper repairs are performed 2. Lanes that were not affected by the incident and are structurally safe could remain open to traffic 3. Traffic above and below the affected lanes must be diverted or rerouted 4. Signage for traffic above and below the affected lanes must be maintained 5. Truck weight restrictions should be placed *6.* Other actions taken as initial emergency procedure should be maintained *7.* A structural analysis of the bridge including the effects of the damage should be performed	Lanes on the Wilson Street Bridge and all four lanes of I-94 were closed because of the possible collapse of the unsupported structure. Column and girders were replaced.

BRIDGE ID	STRUCTURE TYPE	INCIDENT TYPE	DAMAGE DESCRIPTION	BEES´ ASSESSMENT AND RECOMMENDATIONS	WisDOT´S ACTIONS
B-18-0026 (U.S. Interstate Highway I-94 Westbound Over State Highway 37/85)	Concrete	Vehicle impact	In this incident four concrete girders were struck with girders #18 and #19 in span 3 being severely damaged.	*Assessment:* Moderate Structural damage *Recommendations:* 1. Affected lanes above and below traffic should immediately be closed until proper repairs are performed 2. Lanes that were not affected by the incident and are structurally safe could remain open to traffic 3. Traffic above and below the affected lanes must be diverted or rerouted 4. Signage for traffic above and below the affected lanes must be maintained 5. Truck weight restrictions should be placed 6. Other actions taken as initial emergency procedure should be maintained 7. A structural analysis of the bridge including the effects of the damage should be performed	Closures of both northbound lanes of STH 37/85, the entrance ramp to westbound I-94, the exit ramp from eastbound I-94 to northbound STH 37/85, and the ramp at the STH 93 exit were put into effect. The Director of the WisDOT Northwest region declared the situation as an "emergency" requiring immediate attention. The extent of the damage required removal and replacement of the severely damaged girders.
B-13-0264 (Seminole Highway over Madison, WI Beltline)	Concrete	Vehicle impact	The three westerly girders were damaged beyond repair. The collision resulted in large pieces of concrete being dislodged from the support girders and striking two other westbound vehicles on U.S. Highways 12/14/18/151.	*Assessment:* Extensive Loss of Section *Recommendations:* 1. Temporary closure of the bridge may be required subject to the severity of the damage. 2. Traffic above and below the affected lanes must be rerouted 3. Barriers and signage for traffic above and below the affected lanes must be maintained 4. Truck weight restrictions should be	Debris from the collision was removed from the westbound lanes on U.S. Highways 12/14/18/151 and the southbound lanes of Seminole Highway on the bridge were closed. The bridge closure and traffic rerouting remained in effect until the repairs to the bridge were completed. The damage to the Seminole Highway Bridge required the removal and

BRIDGE ID	STRUCTURE TYPE	INCIDENT TYPE	DAMAGE DESCRIPTION	BEES´ ASSESSMENT AND RECOMMENDATIONS	WisDOT´S ACTIONS
				placed. 5. Actions taken as an initial emergency procedure should be maintained	replacement of the three westerly girders of the north span as well as several other subsidiary tasks.
B-32-0036 (U.S. Interstate Highway I-90 Eastbound over U.S. Highway 53 and State Highway 35)	Steel	Vehicle impact	This impact caused a hole to be torn in the web of the girder and bending of approximately 8 in out of plane. Furthermore, six stiffeners were buckled in the impact and a 3/16 in long crack was formed on the bottom flange of the girder.	*Assessment:* Moderate Torn and Moderate Deformation. *Recommendations:* 1. Lanes above and below the affected lanes should remain closed until proper repairs are performed 2. Barriers and signage for traffic below and above the affected lanes must be maintained 3. Traffic above and below the affected lanes must be diverted to other lanes 4. Truck weight restrictions should be placed 5. Shoring should be applied if necessary	All of the northbound lanes on STH 35 were reopened but the shoulder on eastbound I-90 was closed with drums, signage and a message board. This closure remained in effect until the completion of the bridge repairs.
B-32-0037 (U.S. Interstate Highway I-90 Westbound over U.S. Highway 53 and State Highway 35)	Steel	Vehicle impact	In this incident the exterior girder was bent 5.5 inches out-of-plumb and several stiffeners in the inside of the girder were bent, broken, or separated from the girder. Furthermore, two other girders were struck resulting in small amounts of out-of-plumb deformation and several bent stiffeners.	*Assessment:* Moderate deformation *Recommendations:* 1. Lanes above and below the affected lanes should remain closed until proper repairs are performed 2. Barriers and signage for traffic below and above the affected lanes must be maintained 3. Traffic above and below the affected lanes must be diverted to other lanes 4. Truck weight restrictions should be placed 5. Shoring should be applied if necessary	All of the southbound lanes on STH 35 were reopened and no traffic restrictions were initiated on westbound I-90.

BRIDGE ID	STRUCTURE TYPE	INCIDENT TYPE	DAMAGE DESCRIPTION	BEES´ ASSESSMENT AND RECOMMENDATIONS	WisDOT´S ACTIONS
B-40-0377 (U.S. Interstate Highway I-43 116th Street Bridge)	Concrete	Vehicle impact	The west fascia girder sustained damage to the portion of the web and bottom flange located over the northbound lanes of I-43. Furthermore, five concrete reinforcement rods were exposed and three were severed. The east fascia girder, line 6, was also damaged, with an 18”x3” deep spall in the bottom flange resulting in two exposed reinforcement rods.	*Assessment:* Minimal Spalls and Extensive Loss of section *Recommendations:* 1. Temporary closure of the bridge may be required subject to the severity of the damage. 2. Traffic above and below the affected lanes must be rerouted 3. Barriers and signage for traffic above and below the affected lanes must be maintained 4. Truck weight restrictions should be placed 5. Actions taken as an initial emergency procedure should be maintained	Debris from the collision was removed and the shoulder of the southbound lane on 116th Street was closed. While repairs were underway, traffic control on northbound I-43 consisted of single lane closures.
P-40-0654 (Menomonee River – North 25th Street Bridge)	Steel	Watercraft Impact	The impact resulted in a deflection of 3.25 inches of the bottom flange of the plate girder. Also, the stiffener at the intermediate diaphragm failed at its connection to the bottom horizontal angle, and the bolt hole in the bottom horizontal angle was elongated where the angle connects to the stiffener. Some minor damage to a concrete pier was sustained.	*Assessment:* Moderate Deformation *Recommendations:* 1. Lanes above and below the affected lanes should remain closed until proper repairs are performed 2. Barriers and signage for traffic below and above the affected lanes must be maintained 3. Traffic above and below the affected lanes must be diverted to other lanes 4. Truck weight restrictions should be placed 5. Shoring should be applied if necessary	The bridge was closed until an inspection could be completed. All traffic was diverted to other city roadways.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The software system created under this study, the "Bridge Emergency Expert System" (BEES), is a knowledge-based system that provides a simple way to perform damage assessment. It offers recommendations for a quick response in cases of bridge emergency. The system utilizes available structural data, information from existing case histories, and general engineering judgments to arrive at appropriate recommendations but does not perform structural analysis and rating of the structures. The system also relies on the results of visual evaluation of the structure at the time of incident. BEES may be used by responsible DOT authorities at the accident site to minimize the reaction time at the time of an incident. It should be noted that the accuracy and relevance of the recommendations provided by BEES also depend on the quality of the information provided by the user to the system. As such, care must be taken at the incident site so an accurate assessment of the condition of the structure is made and provided to the BEES system.

The development of the Bridge Emergency Expert System (BEES) required combining new technologies with basic civil engineering principles. The BEES system was developed using available software platforms and an existing bridge emergency case histories database. The system's knowledge base was created with rules and facts written as IF-THEN expressions in a forward chain process. Two open source software packages were used to develop a user interface and to process the implemented sets of rules and facts. These are PYTHON, an object-orientated programming language, and CLIPS, an expert system development program.

A review of causes of damage and damage effects in bridges shows that the most commonly documented emergency events in highway bridges are impact and fire incidents. Based on these findings and considering that the majority of bridges in Wisconsin are concrete and steel bridges, bridge emergencies for this study are

classified based on the material type for damaged bridge elements, the incident type, and the level of damage to the structure. Five major classification groups used in this study: 1) concrete superstructures damaged by impact incidents, 2) concrete substructures damaged by impact incidents, 3) concrete superstructures damaged by fire incidents, 4) concrete substructures damaged by fire incidents, and 5) steel superstructures damaged by impact incidents. In addition, for each of these groups minor, moderate, and severe damage levels were defined based on visual evidence at the site of each incident. Recommendations are presented by the BEES system for immediate actions that could be taken by the system's users to assure the safety of the traveling public, emergency responders, and the structure.

The enhancement of the developed expert system was based on knowledge from the available case histories. Actions taken by bridge engineers at the site of previous incidents were compared with the recommendations provided by BEES to improve the outcome of the developed system. Although this effort led to a significant improvement, it must be noted that the number of available case histories is very limited and further system improvement will be necessary. Continued system evaluation by a panel of experts, and use of additional case studies or field testing will be imperative to the future improvements of BEES.

The Bridge Emergency Expert System is not intended to replace the judgment and action of the experts or experienced bridge engineers. It is designed to be used as a tool to help in providing a quick, efficient and suitable response to a bridge incident.

Recommendations for possible applications and enhancements of BEES include:

- Through conducting a future study, efforts should be made to integrate an appropriate bridge analysis and rating capability into the current BEES system. The analysis and rating should consider the

extent of damage to one or more bridge members and can provide essential information to the expert system for offering engineering-based and reliable recommendations. This new capability combined with the existing knowledge-based expert system will result in a powerful tool for bridge engineers and owners to respond to emergency incidents.

- Through conducting a future study, the current BEES system may be extended to include a knowledge database for one or more critical bridge networks, i.e., a series of important bridges on a particular interstate highway. Specific bridge structural and other data, site condition data, traffic re-routing details, and other critical information should be made available to the system so more specific emergency response recommendations could result from using the system. This will facilitate and expedite emergency responses at each accident time for these selected bridge structures.
- A future study may be used to make the current BEES system available on-line or via a wireless network. Easy access of the system from devices such as cell-phones or laptops will provide the quick guidance required by the personnel that is involved in a bridge emergency.
- Efforts should be made to have the system´s knowledge base continuously maintained and updated. The continuous acquisition of knowledge will improve the system´s performance by providing more effective and reliable recommendations for different types of incidents. The updating of the system's knowledge base should be an integrated part of any future studies in this area.

- Due to the fact that bridge accidents are uncertain events, it is proposed to conduct a future study that includes various elements of such uncertainty in BEES´s inference engine. Numeric, graphical, and symbolic methods may be included in the study and applied under this future study.
- BEES may be used as a useful didactic tool to assist in educational environments. Using BEES, virtual bridge emergency cases may be created to provide training to inspectors, maintenance engineers, and other personnel who could be involved in handling bridge emergencies.

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