Bridge Fabrication Error Solution Expert System

Système expert tenant compte des erreurs de fabrication dans les ponts

Ein Experten-System zur Fehlererkennung in der Brückenfabrikation

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SUMMARY

The Bridge Fabrication Error Solution Expert System was developed to help designers and inspectors determine the severity of fabrication errors on steel bridge members and specify the necessary repair. The scope of the system focused on tolerance, drilling and punching, cutting, and lamination fabrication errors that do not have a codified repair procedure. The knowledge acquisition methodology focused on collecting actual cases of past fabrication errors and successful repair. It provided the correct repair in two-thirds of the test cases. This system has been in use at the Kansas Department of Transportation since January 1994.

RÉSUMÉ

Le système expert basé sur la connaissance des erreurs de fabrication des ponts a été établi pour aider projeteurs et vérificateurs à déterminer la sévérité des erreurs dans la fabrication d'éléments métalliques de ponts et à proposer les réparations nécessaires. Le système prend en compte les erreurs de fabrication, la tolérance, le perçage, la perforation, le découpage, et le laminage, qui n'ont pas de procédure codifiée de réparation. L'acquisition des connaissances résulte de cas réels, d'erreurs précédentes de fabrication et de réparations réalisées avec succès. Le système présente une réparation correcte dans 2/3 des cas test. Ce système expert est en usage au Département des Transports du Kansas depuis janvier 1994.

ZUSAMMENFASSUNG

Das Experten-System zur Fehlererkennung in der Brückenfabrikation wurde entwickelt, um dem Konstrukteur und dem Prüfer im Auffinden von ernsthaften Fabrikationsfehlern bei Stahlbrückenteilen zu unterstützen und gegebenenfalls notwendige Nachbesserungen vorzuschlagen. Das System ist auf Toleranz-, Bohrungs-, Stanz-, Schneide- und Laminerungsfehler in der Fabrikation ausgerichtet, die keiner systematischen Nachbesserung unterworfen sind. Die Methode basiert auf dem Festhalten vorhergegangener Fabrikationsfehler und deren erfolgreiche Nachbesserung. Das System schlug eine richtige Besserung bei zwei Dritteln der Fälle vor. Es wird seit Januar 1994 im Verkehrsministerium von Kansas angewendet.

1. INTRODUCTION

Errors arising during the steel fabrication stage may have a catastrophic effect on the performance of a completed highway bridge. More commonly, fabrication errors can cause delays in the fabrication process. All the information needed to support a good decision may not be available at the right time and in the right place to solve the problem in the restricted time necessary to keep the job on schedule. The Bridge Fabrication Error Solution expert system [1] was developed to help design engineers and materials inspectors determine the extent of damage due to fabrication errors and specify the necessary repairs. The development goal was to provide the most suitable repair solution in the most timely manner. The development methodology used a case approach during both the knowledge acquisition stage and the validation and verification procedure. Using the case methodology consisted of gathering cases from actual supporting cases and through interviews with experts (including sample problem-solving protocols). The completed expert system was delivered to the Kansas Department of Transportation (KDOT) in January of 1994.

2. SYSTEM DEVELOPMENT

BFX is a practical example of the successful development of a knowledge-based expert system using modest resources. Approximately 16 person-months of effort were expended on system development, testing, delivery, and training. This effort was largely performed by graduate students under the direction of their supervising professors. BFX was jointly developed by a team from the University of Kansas and a team from Kansas State University [1]. The system was developed and delivered using the Level5 Object shell [2], chosen as a standard for KDOT, running on PC 486 machines.

A specific development methodology with sequential tasks was defined at the beginning of the project consisting of: (1) panel formation and feasibility analysis, (2) conceptual design, (3) knowledge acquisition and engineering, (4) integration and development of pilot delivery application, (5) validation and verification, (6) project evaluation and documentation, and (7) delivery and maintenance. The project development methodology was designed to develop an expert system for any type of domain using the strategies presented in the specified tasks.

Successfully developing a viable expert system required access to and the cooperation of experts in the problem domain. The success of BFX was highly dependent on establishing interaction with target users at an early stage of the project and maintaining contact throughout the development cycle. To meet these requirements, both a panel of experts and a panel of users were assembled, each consisting of six individuals, including design engineers, materials inspectors, and a fabricator. Having participants from all three areas of bridge construction – design, inspection, and fabrication – allowed more interaction and broader input on conditions of errors and repair solutions. Total time spent by all panel members combined was between 2 and 3 person-months. This includes panel meetings, collection of cases, knowledge acquisition interviews, evaluation of the system, and training.

The focus of the system is on fabrication errors that do not have standard code specifications for repair. The scope of the system consists of errors relating to tolerances (dimensional), drilling and punching, cutting, and lamination. The tree graph of the knowledge domain is shown in Figure 1. The errors covered by this program can be classified into four major modules, which are listed below. The tolerance module deals with fabrication errors relating to dimensional tolerances, including hole-boring errors, incorrectly attached members, incorrectly cut members, and stress fractures. The drilling and punching module covers fabrication errors that are the result of incorrect boring procedures, hole sizing, and partially drilled holes. The cutting module covers fabrication errors that result during the cutting process – specifically, gouges and nicks. The lamination module covers fabrication errors that result from edge, internal, or surface lamination defects. It was very important to establish a well bounded scope during development of the expert system so that the design criteria could be applied effectively and in more detail.

The knowledge acquisition occurred in different stages. The first step was to gather case examples directly from fabrication shops, state inspectors' field notes, and bridge project documents. Next, individual interviews were conducted using case studies and hypothetical data case examples based on variations of the actual data cases gathered and interview sessions. Using actual and hypothetical cases, the solution sets for multiple types of errors were determined. Finally, the repair solutions generated were approved by design engineers and inspectors and verified by certified design procedures.

Data cases were gathered from KDOT inspection diaries, fabrication shop quality control records, and bridge design records. These cases were further checked against technical specifications and documentation of current procedures. These case examples were collected from (1) experts' questionnaires to KDOT bridge engineers, fabrication personnel, and inspectors, (2) historical records such as case studies, maintenance data bases, and inspection reports, and (3) simulation results that were generated internally. Actual data cases were cataloged and checked for completeness, then from these actual data cases, hypothetical data cases were created by the knowledge acquisition team to be used during individual interview sessions. The collection of actual cases was partitioned into development examples to be used for knowledge acquisition and test cases to be used for validation and verification.

The personal interviews included one-on-one sessions and, in some cases, two panel members per interview session. These interview sessions were used to gather specific information about certain data cases provided by panel members and also answer hypothetical variations of these data cases. In addition, these sessions were used to discuss the rationale of certain repair solutions associated with problem types described in the data cases. These data cases provided by panel members were actual errors that had occurred during fabrication and were resolved at the fabrication shop. These cases described the errors and their repair solutions.

More data from the interviews were gained by structuring the interviews around developing repair solutions for prepared actual cases and hypothetical cases. Information from actual data cases was also verified by panel members during the interview sessions. Secondary interviews were used to finalize clarification of synthetic data cases and information on technical specification requirements. Interview sessions began by covering actual data cases and clarifying any incomplete information needed for specific data cases. Hypothetical data cases were then presented and repair solutions completed with corresponding information. The documented actual data cases were modified to be hypothetical to collect more information and get as complete coverage of error cases as possible. These hypothetical cases were used to address issues arising from the knowledge base development. The documented data cases were also reviewed during the interviews for confirmation on the repair procedures given. These hypothetical cases included minor and major changes in actual data cases. Repair solutions given for these hypothetical data cases were checked by presenting the cases at subsequent interview sessions with other panel members. Once completed, these cases were included in the prototype development system. Data cases were then transformed into rules for the system program and assisted the design team in understanding the experts' problem-solving techniques.

A Fabrication Error Record document was created to record these cases and information needed for the development system. This document covered all the information needed for the knowledge acquisition of the actual data cases in the development of BFX. The data sheet was distributed to panel members to be referred to when gathering data cases and included the type of documentation required for the individual actual data cases. Initial information gathered at the first panel meetings also helped construct the Case Attribute Value Sheet [3]. This document helped in amassing case data and input necessary for the program development. This document also established a set of classes, attributes, and values that were used consistently for the various program modules.

A dual track was pursued for transformation of the acquired expert knowledge into rules for the knowledge base. One approach was to use inductive learning [4]. Another approach was to extract domain knowledge from literature, documentation of current procedures, and interviews of the experts (including sample problem-solving protocols) [5]. Both approaches made use of the gathered data cases using 77 cases for development and reserving 33 cases for testing. The inductive approach did not prove satisfying for this application due to the incompleteness, irregularity, nonuniformity, and limited number of error cases. Explicit domain knowledge extraction was thus the approach used for development of the BFX knowledge base.

3. SYSTEM ARCHITECTURE

The architecture of BFX consists of a main menu module with six major modules. Two of these major modules – the Help module and the SI units module – are for reference and assistance. These major modules consist of display screens that are available to the user for reference. The Help module has an error index and program module tree graph. This error index includes an alphabetical listing of the errors covered by the system and the submodule in which each can be found. The program module tree graph is an interactive screen that allows the user to select a module or submodule by clicking on the screen, with a text description of that program becoming visible on the screen. Both of these areas of the Help module are able to be modified as additional information becomes available or necessary. The SI units module has three screens which show reference materials on unit conversion and SI unit standards relating to bolt sizes. This module also has the ability to be modified in the future as more detailed information becomes available or necessary.

The other four major modules each consist of submodules that contain specific knowledge areas. The submodules were developed from the scope of the system and are the smallest, most manageable areas that allowed useful development. The user moves from the main menu module to one of the four major modules and then calls the submodule that represents the error type needing to be solve. Once a submodule is called and loaded, all of the necessary knowledge for that particular submodule is resident in the computer's memory. The system allows the user to move among the major modules, submodules, and main menu at different times.

The architecture of BFX was developed using agendas for each submodule. An agenda represents a numbered, hierarchical outline of goals representing the desired hypotheses that can be concluded by a backward-chaining knowledge base [2]. The outline is developed to divide the goals of the knowledge base into logically ordered repair states. The goals are ordered so that the initial goals in the outline require the least information to determine the goal state. Additional goals in the outline are ordered so as to build on the information required of the user. It was important to order the goals in the outline so that a goal state would not be reached before all necessary information from the user was checked for repairs that could occur using the given information. This was done by defining any hierarchical subgoals within any primary set of goals.

Backward chaining was used in BFX to reach the individual goals of the agenda. The system checks the goals by firing individual rules corresponding to the order of the goal statements. The user is prompted for information to prove these rules. As input from the user is gathered by the system, the goal is either proved or disproved. Once a goal has been disproved, the system then selects the next goal state in the hierarchy of the outline. Forward chaining was used once a goal state was successfully proved. The forward-chaining rules fire when the goal state has been proved and cause the corresponding conclusion text to be displayed for the user. Repair recommendations were placed in an array of the system's domain. The hierarchy of the goals does not cause a conclusion to be reached before all necessary information has been entered into the system. During the development and addition of rules to the system, continuous checks of the goal hierarchy were made. The system's repair recommendations were tested with the actual and hypothetical data cases received during the interview portion of the explicit domain knowledge extraction process.

BFX was developed as an expert system that can be maintained and kept current to accommodate new fabrication errors introduced to the system. The activities of the maintenance phase include processing of system modifications and the continual evaluation of the system. Modification may be necessary on the operation, logic, interface, or knowledge base of the system. BFX was designed to allow addition of knowledge to the system and increases in the scope. The system was segmented into individual submodules to allow easier modification and maintenance, with each submodule corresponding to an individual scope area of the system. Strong emphasis was placed on the rule ordering and hierarchy to cover all ranges of responses, allowing the user to answer questions on individual display screens without concerns about the order of the answers. The better the system is maintained, the more comprehensive and useful it will be to KDOT; therefore, it was important that KDOT personnel be trained in procedures and methods of modifying the system.

To address the issues of maintenance and modification, a training seminar was established on BFX for KDOT personnel [6]. The seminar's purpose was to familiarize KDOT personnel with the technical specifications of the knowledge base and provide sufficient instruction for them to perform basic maintenance on the program without outside assistance. Basic maintenance includes direct changes and additions to items in the rule base; however, it does not include fundamental changes in system capabilities or major restructuring of the knowledge base.

4. SYSTEM PERFORMANCE

System performance testing results are summarized in Table 1. Validation and verification of the system was based on two methods. The first method was the actual running of BFX by the panel of experts and the panel of users. Panel members ran a total of 18 hypothetical cases on the system. The hypothetical cases were based on actual cases that the panel members had experienced. The total 18 panel test cases resulted in 11 correct solutions, 6 no solutions, and 1 incomplete solution. The second method was checking the performance of BFX using 33 actual cases provided by panel members. These cases had not been used in system development and met the scope of the system. After running the 33 test cases, 21 of the cases gave the correct repair solution for each case. Twelve of the cases did not match the contents of the knowledge base during runs of the system. When a fabrication error case is run on the system and no match between that particular type of error and the knowledge base occurs, the system will inform the user and suggest that the error case be implemented into the system. No match between the test cases and the knowledge base occurs when these particular types of errors have not been found during development of the knowledge base.

Module	Development Cases		Validation Cases						Results			
Class	Distribution		Panel Cases		Actual Cases		Total Cases		Correct	No Match	Incom-plete	Wrong Solution
Tolerance	56	72.8%	13	72.2%	25	75.8%	38	74.4%	21	17		
Drill/Punch	7	9.1%	2	11.1%	5	15.2%	7	13.7%	6	1		
Cutting	9	11.7%	2	11.1%	2	6.1%	4	7.8%	3		1	
Lamination	5	6.5%	1	5.6%	1	3.0%	2	4.0%	2			
Total	77		18		33		51		32	18	1	0
Percent									63%	35%	2%	0%

Table 1 Case Distribution

No logic errors occurred during any testing stage of the system, which shows that in terms of reliability, the system performed very accurately. This is very important in building user confidence; it is much better to receive no answer than an incorrect one. The distribution of development cases by module roughly matches the distribution of validation test cases by module. The percentage distribution of the development cases may be assumed to give a rough measure of distribution of error types encountered in practice by KDOT, since the development cases were collected from past KDOT experience. Combining both validation methods, BFX reached the correct solution in 63% of the cases, determined that the case did not match the contents of the knowledge base and therefore not making a recommendation in 35% of the cases, and provide an insufficiently detailed recommendation in 2% of the cases.

5. EXAMPLE

One operational case involving several uses of BFX is presented to demonstrate BFX's capabilities. This example deals with mislocated holes at a plate girder flange splice. Several holes were misdrilled in the bottom flange of a plate girder, as shown in Figure 2. The hole mislocations resulted in a variety of fabrication errors. First, the specified splice plate will no longer fit the hole locations in the bottom flange. This problem was entered into the tolerance module of BFX with the mislocated hole submodule selected. The input described the lack of fit problem. BFX's recommended solution was to leave the existing hole in the main member and make a new splice plate to match the existing hole pattern. The repair specified in Figure 2 does indeed use this approach.

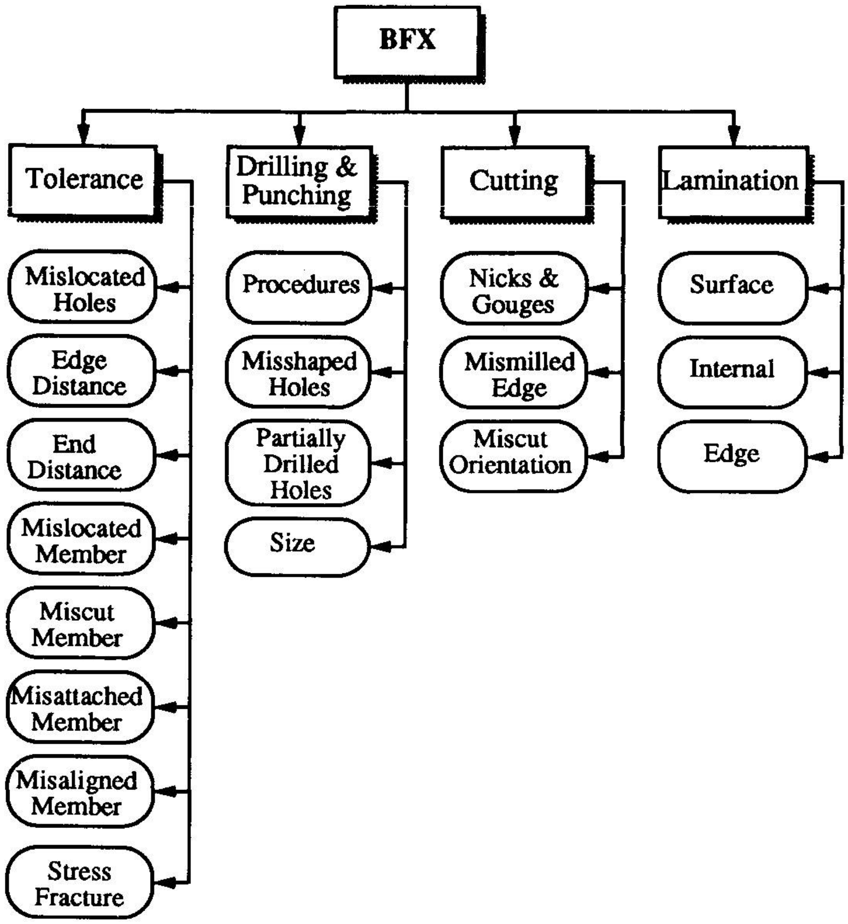

Figure 1 BFX Knowledge Tree

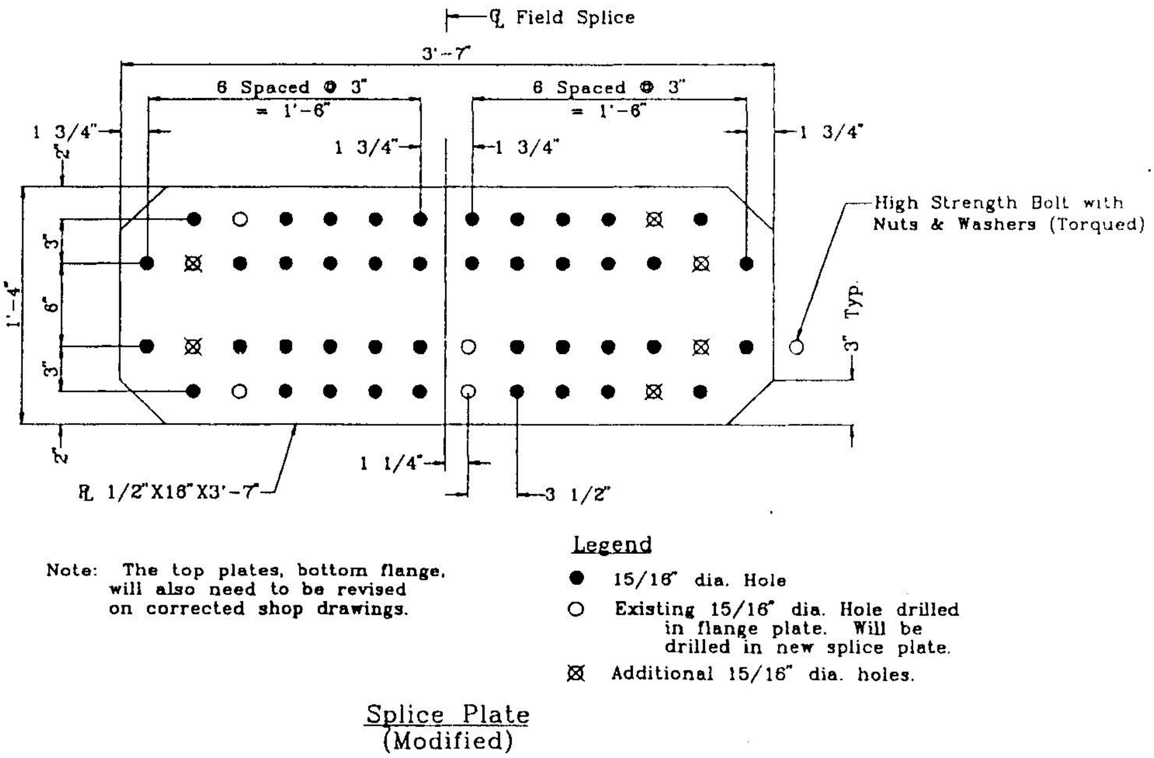

Figure 2 Operational Example: Mislocated Holes at Flange Splice

Second, the mislocated hole on the extreme right is superfluous since it begins an additional row beyond those specified. This problem was entered into the tolerance module of BFX with the mislocated hole submodule again selected. The input this time described the extra bolt line problem. BFX's recommended solution was to leave the existing splice in the specified location and then take one of the following options: 1) extend the splice plate to cover the mislocated holes and drill to match, or 2) place bolts and washers in the additional holes and leave the splice plate as designed. The repair specified in Figure 2 takes the second approach. Third, the two mislocated holes immediately to the right of the splice centerline violate end distance requirements. This problem was entered into the tolerance module of BFX with the end distance submodule selected. BFX's recommended solution was to add additional bolts in the bolt line if possible or cut and replace the member if not possible. The repair specified in Figure 2 takes the first approach. The total repair specified in Figure 2 is thus a superposition of the three approaches recommended by BFX for the three individual problems generated by the hole mislocations.

6. CONCLUSIONS

The development of BFX has resulted in the following conclusions:

- BFX achieved the performance expectations desired by KDOT.
- BFX achieved the desired scope and accuracy established by KDOT. The knowledge domain was very suitable for development.
- The development methodology of using panels and experts was successful for this project.
- Explicit domain extraction was the best method of knowledge acquisition, given the domain and knowledge available.
- Modular development of BFX allowed easier development and will make maintenance and modifications by KDOT less complicated.

ACKNOWLEDGEMENTS

This work was partially funded by the Kansas Department of Transportation Cooperative Research Program (K-TRAN), an ongoing, cooperative and comprehensive research program addressing transportation needs for the State of Kansas. The cooperation and contributions of Dr. Hani Melhem, Mr. Srinath Nagaraja, and Ms. Amy Moran of Kansas State University are gratefully acknowledged.

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