BFX: Operational Expert System for Bridge Fabrication

W. M. KIM RODDIS, HANI MELHEM, MICHAEL R. HESS, AND SRINATH NAGARAJA

The Bridge Fabrication Error Solution Expert System (BFX) was developed to help designers and inspectors determine the severity of fabrication errors on steel bridge members and specify the necessary repairs. Aspects of the development, delivery, and operation of BFX of direct interest to highway bridge and materials engineers are described. The scope of BFX focused on tolerance, drilling and punching, cutting, and lamination fabrication errors that do not have a codified repair procedure. During predelivery testing, BFX provided the correct repair in two-thirds of the test cases, recognized that the test case was not covered by its rule base in one-third of the test cases, and gave the wrong solution for none of the test cases. BFX has been in use at the Kansas Department of Transportation since January 1994. An operational example using BFX is presented.

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 (BFX) was developed to help design engineers and materials inspectors determine the extent of damage due to fabrication errors and specify the necessary repairs. In addition, BFX is intended to be used as a training tool for novice bridge engineers and material inspectors.

BFX was created to provide a unified repair procedure for the Kansas Department of Transportation (KDOT) by gathering domain expertise from designers, inspectors, and fabricators. The goal was to create a system that would provide the most suitable repair solution in the most timely manner. Within this context, it was decided that no answer was preferred to a wrong answer. A design objective was thus a system that would indicate clearly when a submitted problem was beyond the system's scope. The system focuses on fabrication errors that do not have standard code specifications for repair. The completed expert system was delivered to KDOT in January 1994 (*1*).

DEVELOPMENT

The project used expert system software tools and development methodologies tailored specifically to KDOT's mission and needs. The development strategy was designed to deliver a system that would address the real needs of KDOT and would become a functional tool for determining solutions to fabrication errors. Details on the different development stages and the approaches used can be found elsewhere (*2*). The success of expert system development projects is also highly dependent on establishing interaction with target users at an early stage of the project and maintaining this contact throughout the development cycle. To meet these requirements, the system designers used a panel of experts and a panel of users; each panel consisted of six individuals, including design engineers, material inspectors, and a fabricator. The panel of experts was created to resolve steel fabrication error solutions. Panel members gave their expertise on fabrication processes and procedures and acted as the primary experts for knowledge acquisition. The panel of users was established to target users of the developed system. This panel provided information for the scope of the system and interface design.

Each panel had representative members from design, inspection, and fabrication. Gathering experts from all three areas involved with bridge fabrication—design, inspection, and fabrication—allowed more interaction and provided broader information on conditions of errors and repair solutions. Experts in each of the individual areas are exposed to particular parts of a fabrication error. By using representatives of these areas in panel meetings and other interviews, the development system more accurately provided detailed solutions and conditions for fabrication errors. When the panels were formed, the members understood that they would be required to participate in panel meetings and personal interviews, provide data cases, respond to questionnaires, and review the system. The total time spent by all panel members combined was between 2 and 3 person months. This time includes panel meetings, collection of cases, knowledge acquisition interviews, evaluation of system, and training. Table 1 presents the estimated time commitment for panel participants.

SCOPE

BFX deals specifically with errors due to tolerance (dimensional), drilling and punching, cutting, and lamination. The scope of the system was developed using modules and submodules, organized as shown in Figure 1. The tolerance portion of the scope contains mislocated holes, edge distance, end distance, mislocated member, miscut member, misattached member, misaligned member, and stress fracture submodules. The drilling and punching portion contains procedures, misshapen holes, partially drilled holes, and size submodules. The cutting section contains nicks and gouges, mismilled edges, and miscut orientation submodules. Lamination contains surface, internal, and edge submodules. It was very important to limit the scope during system development so that the design criteria could be applied effectively and in more detail.

W. M. K. Roddis, Department of Civil Engineering, University of Kansas, 2008 Learned Hall, Lawrence, Kan. 66045. H. Melhem and S. Nagaraja, Department of Civil Engineering, Kansas State University, 119 Seaton Hall, Manhattan, Kan. 66509. M.R. Hess, HNTB Corporation, 7007 College Boulevard, Suite 150, Overland Park, Kan. 66211.

TABLE 1 Estimated Time Commitments for Panel Participants

Type of Participation	Panel Participation Number	Length (hours)
Panel	4	4
Personal Interview	4	2
Questionnaires	2	4
Panel Meetings	2	4
System Review	3	2

The system was developed and delivered using the Level5 Object shell (*3*), chosen as a standard for KDOT, running on PC-486 machines. The design of the system and the use of Level5 Object development tool allow knowledge to be added and the system to be modified. Many failures with expert systems can be attributed to creating too broad a scope. Success is more likely if goals are well defined and allowance is made for the addition of new knowledge or as other areas of need are defined. BFX was developed with these principles in mind.

There is a broad range of severity that can occur from fabrication errors. The degree of severity depends on the type of error and on the member in which the error occurs. Depending on their severity, many errors are handled entirely within a fabricator's own shop inspection system. Some errors require contact with state inspectors or design engineers for an approved repair method. Some types of fabrication error have standard solutions but still require contact with state inspectors for approval. The knowledge-based expert system provides a "best" solution and any other allowable solutions. The system also documents the basis of the repair solution and, if requested, a history of the knowledge path.

KNOWLEDGE ACQUISITION AND ENGINEERING

The development of an expert system requires both knowledge acquisition and knowledge engineering. The knowledge acquisition stage consists of gathering the knowledge from experts. The knowledge that is elicited or acquired from the expert sources is used to build the knowledge base. The knowledge engineering stage consists of translation and transformation of problem-solving expertise from a knowledge source to a human or computer program destination. Knowledge engineering is thus the process of mapping the knowledge gathered from experts into a programmed knowledge base.

The development, verification, and validation of BFX all depended on the availability of many accurate example cases and interaction with panel members. The knowledge acquisition methodology chosen therefore focused on collecting actual cases of past fabrication errors and successful repairs. Gathering information to put into BFX 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. Using the information gathered, rules were developed and

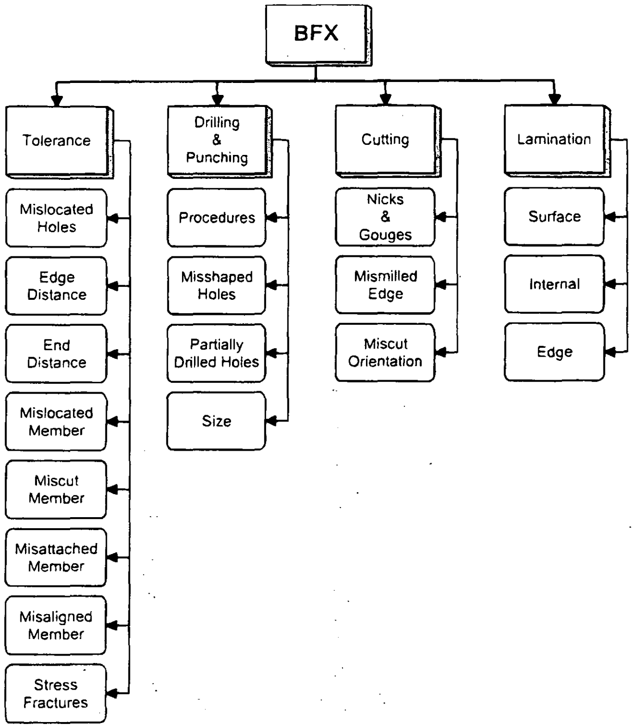

FIGURE 1 BFX knowledge modules and submodules.

implemented into the Level5 Object shell. An automatic generation of rules from the case examples was also investigated using inductive techniques established by artificial intelligence researchers in computer science. The assessment of this investigation is discussed elsewhere (*4*).

These data cases were checked further against technical specifications and documentation of current procedures. These case examples were collected from experts' questionnaires to KDOT bridge engineers, fabrication personnel, and inspectors; historical records such as case studies, maintenance data bases, and inspection reports; and simulation results that were generated internally. Actual data cases were cataloged and checked for completeness; 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 distribution of the 77 actual cases used for development is shown in Figure 2. The percentage distribution of the development cases may be assumed to give a rough measure of the distribution of error types encountered in practice by KDOT, since the development cases were collected from past KDOT experience.

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 to 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. The cases described the errors and their repair solutions.

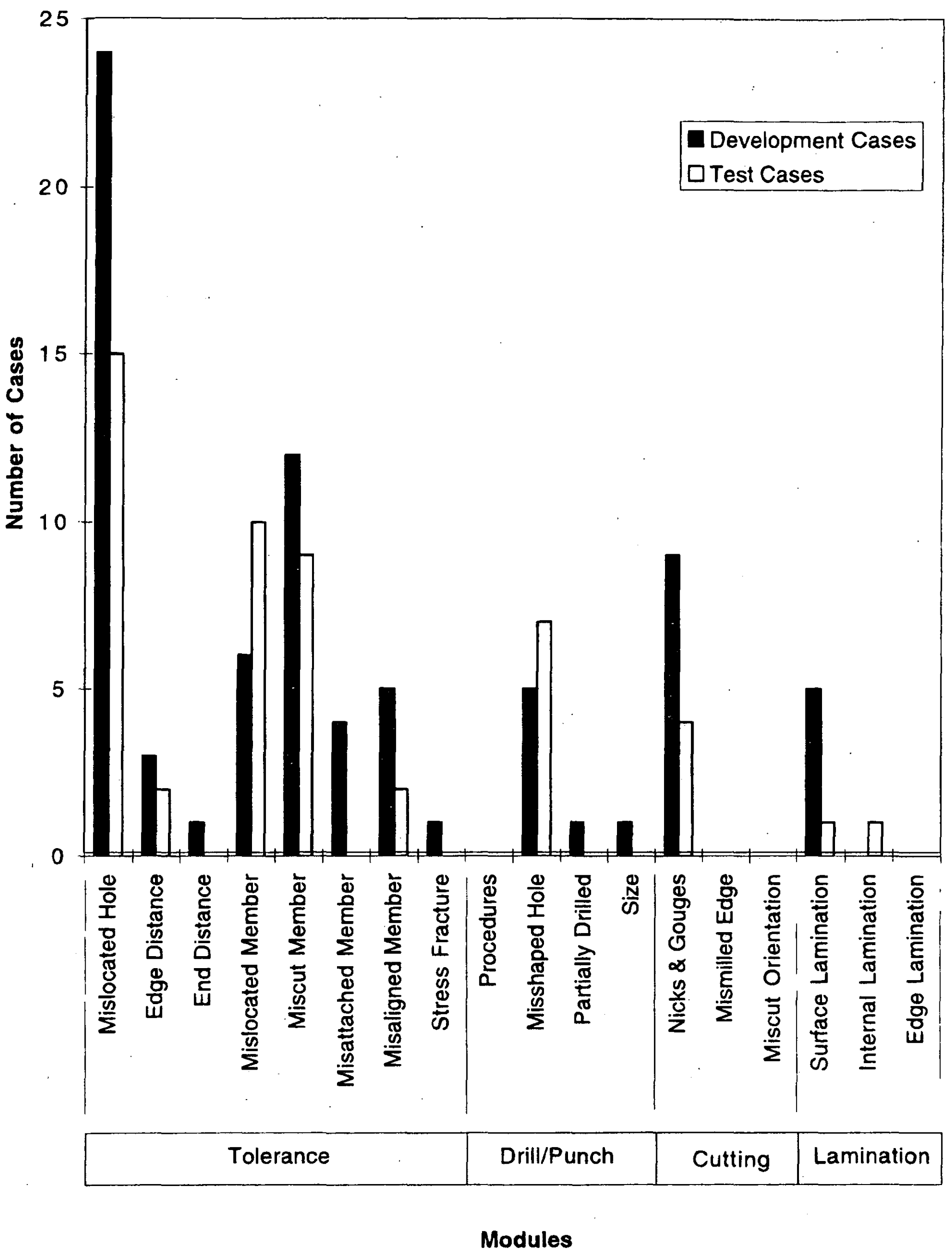

FIGURE 2 Distribution of development and test cases.

More data from the interviews were gained by structuring the interviews around developing repair solutions for prepared actual and hypothetical cases. Information from actual data cases was also verified by panel members during the interview sessions. Secondary interviews were used to finalize the clarification of hypothetical 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 a coverage of error cases as possible. The 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. The 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, the 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.

PERFORMANCE

The capabilities of the BFX were checked by testing the system. Validation and verification of the system were based on two methods. The first method was the actual running of the system using 18 hypothetical test cases by the expert and user panel. The second method was a performance check of the system using 33 test cases that were not used in the development of the system and that met the scope of the system.

The first method of the validation and verification testing was completed on the pilot delivery program using the panel members. The system was then evaluated by using hypothetical test cases provided by the members. Realistic conditions were simulated by having the panel members perform the input and run the cases by themselves. The hypothetical cases were based on actual problems experienced by experts. The total 18 panel test cases resulted in 11 correct solutions, 6 no solutions, and 1 incomplete solution. This first form of testing thus resulted in 61 percent correct solutions, 33 percent no solutions, and 6 percent incomplete solutions. 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 types of fabrication errors have not been found during development of the knowledge base.

A program use questionnaire was provided to panel members after each validation and testing session. The panel members were asked to grade the performance of the system on the basis of the validation and verification criteria and relate information on performance and interface use of the system. Figure 3 presents the results for each module; a score of 5 is very good and a score of 1 is poor. Performance was graded as average to slightly above average in fulfilling expectations of the depth and accuracy of the system. The testing members were very impressed with the overall development and performance of the system based on initial projections.

The second method of validation and verification testing 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

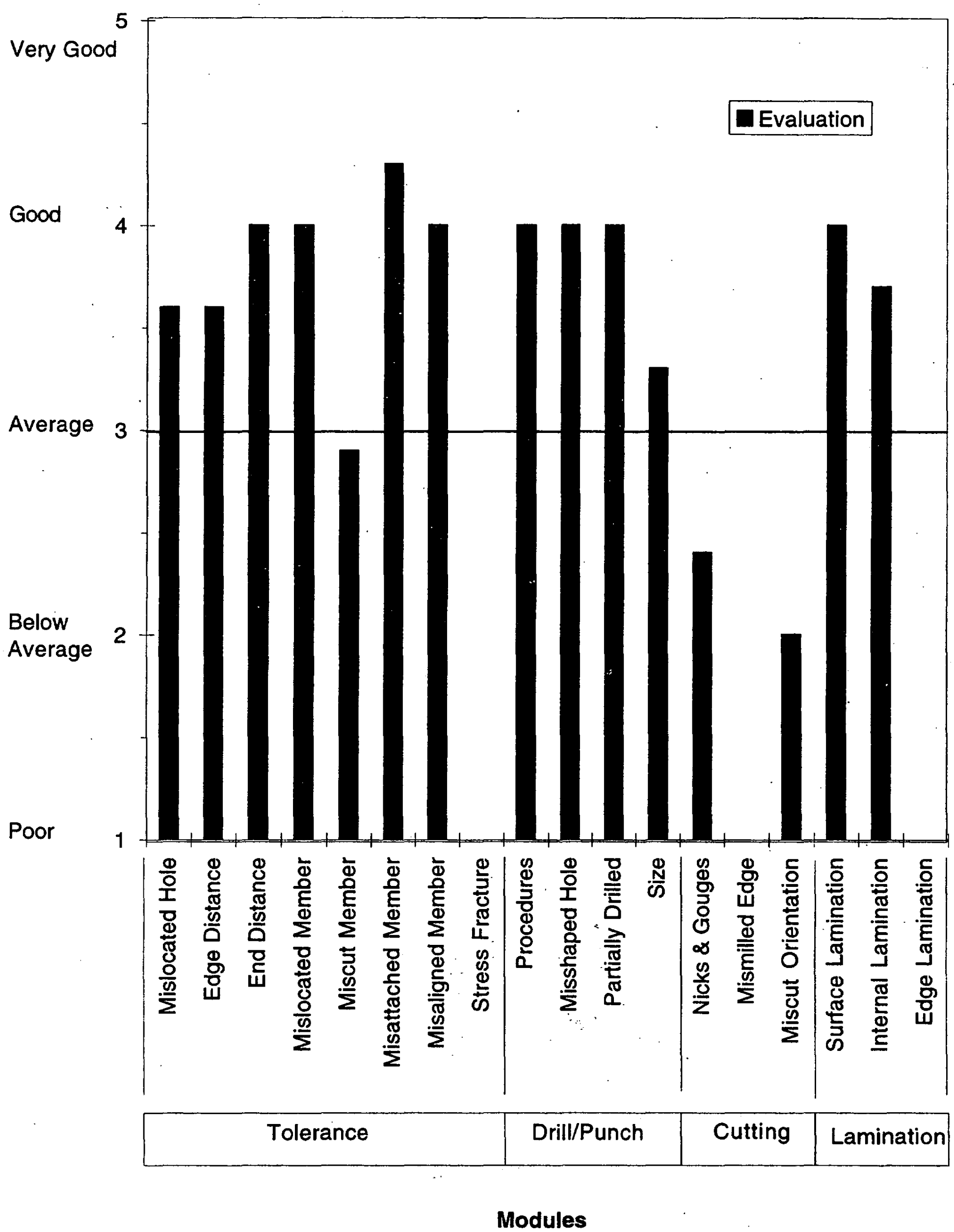

FIGURE 3 Panel evaluation of submodule performance.

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. This second form of testing thus resulted in 64 percent correct solutions and 36 percent no solutions.

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. Combining the 18 hypothetical panel test cases and the 33 actual test cases resulted in 51 test cases distributed as shown in Figure 2. The distribution of development cases by module roughly matches the distribution of test cases by module. Since the development cases were collected from past KDOT experience, it may be inferred that the distribution of development cases by module also roughly matches the distribution of error types encountered in practice by KDOT. Combining both validation methods, BFX reached the correct solution in 63 percent of the cases, determined that the case did not match the contents of the knowledge base and therefore did not make a recommendation in 35 percent of the cases, and provided an insufficiently detailed recommendation in 2 percent of the cases. These results are shown in Figure 4. The BFX system and its performance results were presented to the bridge community and were well received (*5*).

DELIVERY

A successful expert system is one that can be maintained and kept current to accommodate new fabrication errors introduced to the system. To address the issues of maintenance and modification, a training seminar was established on BFX for KDOT personnel. This 2-day training seminar was presented at the offices of KDOT. Its 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. A training manual was prepared to be used during the seminar and in future training (*6*). Training consisted of an introduction to pertinent features of the development tool Level5 Object, an overview of the construction of the knowledge base for the fabrication expert system, and hands-on examples describing how to modify the knowledge base for basic maintenance.

BFX has been in use at KDOT since January 1994. A user's manual was prepared to help new users run the system and understand how it works (*7*). One of KDOT's bridge engineers has made two implementation changes during that time. When originally delivered, BFX did not provide an output file echoing each session input and results. The "session history" feature on Level5 Object, expected to fill the need for such a record file, was found to be awkward and unsatisfactory in practice. BFX was modified to echo input and output to a text file for complete and easy documentation of all cases. A second change deals with the input screens. Many of the input screens request multiple pieces of information on a single screen. Originally, the same input screens were used in various submodules, leading to cases in which some of the requested input was not used. These superfluous input requests have been deleted.

Tracking the system during the first year of operation is important. BFX is being used and tested, with each case being documented for performance and user comments. It is necessary that any areas of incomplete coverage within BFX be documented and revised to meet user needs. The tracking of BFX during initial stages of modification also shows the accuracy of the solutions and coverage of the knowledge domain. Documenting the performance of the system enables it to be modified when necessary. Documentation of the performance includes copies of the error and information on how BFX performed during operation of the error case. This information allows KDOT to make changes to BFX as necessary and to add missing error types to the knowledge domain. Documentation of the performance also allows KDOT to judge the accuracy of BFX and increase confidence in the repair recommendation given by the program. KDOT bridge personnel are maintaining and expanding the knowledge base.

Few operational cases have been run to date on BFX. On the basis of the small sample available, some preliminary findings can be stated. First, coverage of fabrication error types is incomplete, with at least a quarter of the cases resulting in no solution. This incompleteness of the knowledge base was expected because only a few fabrication error types were covered by the development cases. BFX was designed to allow the addition of knowledge to the system and increases in its 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. Initial indications are that this approach was successful and that adding error types to the knowledge base is straightforward.

Second, the cutting module and its constituent submodules (nicks and gouges, mismilled edge, and miscut orientation) require refinement. On one operational case involving a sawcut gouge partially through a coverplate on a rolled beam, BFX recommended a weld repair when a grinding repair was more appropriate. On another operational case involving a web gouge due to a flame-cutter mis-

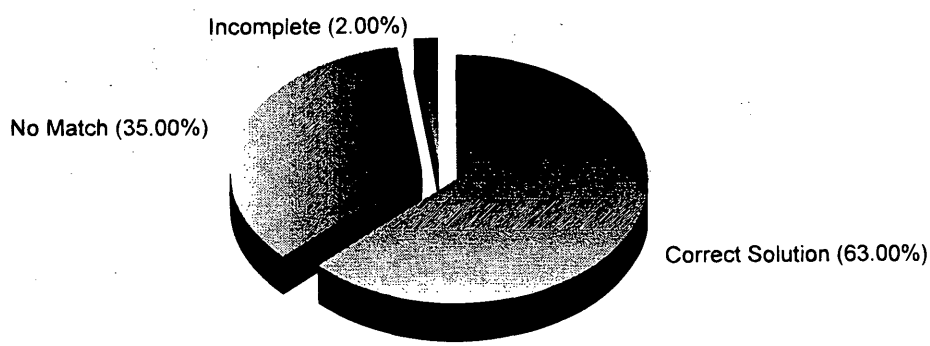

FIGURE 4 Test results.

tracking, BFX recommended replacement of the member when patching with an inset web slug was more appropriate.

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 5. 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 holes submodule selected. The input described the lack of fit problem. BFX's recommended solution was to leave the hole in the main member and make a new

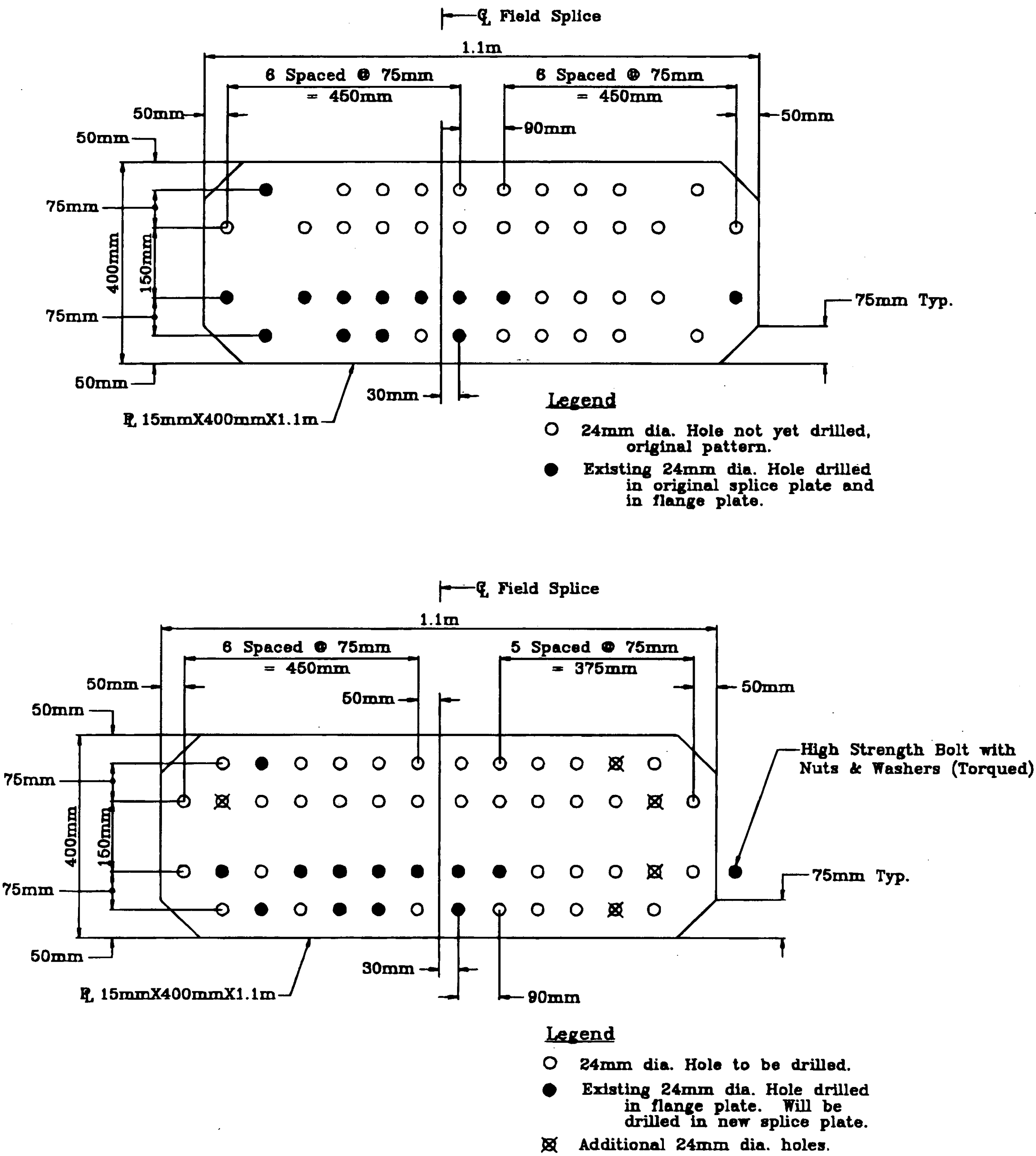

FIGURE 5 Operational example: mislocated holes at flange splice: ***top,*** **misdrilled,** ***bottom,*** **modified (1 in. = 25 mm).**

splice plate to match the existing hole pattern. The repair specified in Figure 5 does indeed use this approach.

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 splice in the specified location and then take one of the following options: (*a*) extend the splice plate to cover the mislocated holes and drill to match, or (*b*) place bolts and washers in the additional holes and leave the splice plate as designed. The repair specified in Figure 5 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 5 takes the first approach. The total repair specified in Figure 5 thus is a superposition of the three approaches recommended by BFX for the three individual problems generated by the hole mislocations.

CONCLUSIONS

The development, delivery, and initial use 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 of experts was successful for this project.
- The modular development of BFX was easier and will simplify maintenance and modifications by KDOT.
- BFX is making a successful transition from an academic development environment to an operational system. As anticipated, the knowledge base must be expanded to cover fabrication error types not included in the development cases.
- The training provided enables KDOT bridge engineers to maintain and expand BFX, allowing KDOT to maintain and update the system.

The system has shown that it provides consistent, logical solutions to the fabrication errors specified in the scope of the development. As users of the system become more confident in the system's repair recommendations, fewer checks with design engineers will be necessary. Increases in the repair turnaround time will be achieved, which will reduce costs for fabricators and ultimately for KDOT. BFX can also be used to help train new inspectors and designers in the repair of fabrication errors. Inspectors and designer will also become more familiar with recognizing possible problems. The use of BFX will also provide better documentation and record keeping for KDOT. BFX is proving to be a useful system for KDOT, and consideration is being given to generalizing and expanding BFX so that it could be used by other states or regions.

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