QUALITATIVE REASONING ABOUT STEEL BRIDGE FATIGUE AND FRACTURE[1]

by
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ABSTRACT

Engineering problem solving involves not only quantitative knowledge but also extensive heuristic knowledge of the behavior of physical systems. Qualitative reasoning provides a means of bridging the gap between these disparate types of knowledge. The strategy of using a connective qualitative reasoning layer manipulating engineering models to connect a heuristic and predominately symbolic layer with a quantitative layer that is numeric and largely procedural is applied to problem solving in the structural engineering domain of fatigue and fracture in steel highway bridges. The testbed domain demonstrates the usefulness of qualitative reasoning for guiding quantitative analysis in an engineering context.

1 Introduction

1.1 Linking heuristic and quantitative reasoning

It is commonly recognized that engineering uses knowledge that is quantitative and precise to analyze the behavior of physical systems. In addition there is a wealth of heuristic, usually unarticulated, engineering knowledge that is used to formulate, direct, and interpret the quantitative methods. Searching for a solution by reasoning with a simplified model and then verifying, revising, and refining the rough model lies at the heart of engineering problem solving. Solving an engineering problem requires use of knowledge about: how to gather data to define the problem, how to structure the data into an engineering model, and how to analyze the model to get numeric data. The definition, modeling, and interpretation steps are largely symbolic while the analysis step is largely numeric. Intelligent computer-aided engineering tools require a way of bridging the gap between heuristic, largely symbolic, knowledge and quantitative, largely numeric knowledge. Indeed, the need to represent and reason about both heuristic and quantitative knowledge arises

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frequently in problem solving, not only in engineering domains. Qualitative reasoning provides a means of bridging this gap.

1.2 Selection of application domain

A specific engineering task was used as a testbed to investigate the validity and utility of using qualitative reasoning as the mechanism to make the transformation from heuristic knowledge to an engineering model suitable for mathematical manipulation. The domain of fatigue and fracture in steel bridge details was chosen as the test domain because of the confluence of professional need and technical feasibility. Of the almost 600,000 highway bridges in the United States, more than 40 percent are rated substandard. The number of experts for identification, inspection, evaluation, and repair of fatigue and fracture damage in steel bridges is far below the level required. The risks of fatigue and fracture failures will increase as the bridge population ages and as older bridges exceed their design life.

The problem area is a significant and substantive one of inherent engineering interest and usefulness, representative of a broad class of engineering problems. Failure analysis of cracking in a plate girder bridge is a typical analytic engineering problem. There are certain tools available to the engineer that are expressed in mathematical terms. These tools can be used to simulate the physical response of the actual plate girder. The changes that the girder is subjected to are expressed in terms of physical parameters such as load and temperature, the response is described in terms of stress and strain. To be able to apply available mathematical tools to the problem at hand the engineer constructs an analytic model to capture the relevant physical features in a suitable way for the particular mathematical tool. The analysis is then performed, and the results are evaluated and interpreted to describe a solution or direct model refinement and additional analysis. The model construction is not algorithmic, but is guided by largely heuristic knowledge that usually travels under the rubric "engineering judgment".

The character of this problem domain is well suited for use as a testbed for the selected computational approach as evidenced by the following. This is a practical problem where the knowledge exists but is frequently not utilized. The knowledge is of diverse types (statistical, heuristic, engineering principles, etc.) but circumscribed and well contained so that it is possible to provide a complete coverage of the knowledge needed to solve the problem. There are multiple uses of the same knowledge (for analysis of failures, for determination of causes of distress and prescription of fixes, for prediction of remaining service life, and for verification and optimization of design) so the adequacy of the knowledge representation and reasoning schemes may be tested for flexibility of knowledge use.

The inherent qualitative nature of observations strongly argues for qualitative methods.

Bridge inspection data is often incomplete and stated in non-numeric terms. Parameters having a major effect on crack growth life and residual strength capacity of structures are frequently known inexactly and incompletely. These parameters include: initial crack size which is a measure of quality; stress history which is a measure of usage and location; material properties which are a measure of material resistance to cracking; and structural properties which are a measure of the geometric configuration in the vicinity of the crack. Faced with such extensive uncertainties in controlling parameters, engineers make use of qualitative methods as part of the problem solving process.

1.3 Qualitative Reasoning

Although it is widely acknowledged that commonsense reasoning must be incorporated into intelligent computer aided engineering tools, there is not a broad consensus on the specific manner in which this requisite knowledge may be captured. However, qualitative reasoning may be identified as a major attempt to represent and manipulate knowledge of the behavior of physical systems [Bobrow 85, Weld & deKleer 90].

Qualitative reasoners have used a variety of notations and signed algebras [Bobrow 85]. For continuous state variables, the continuous domain is quantized into a discrete symbol set called a quantity space. The confluence approach uses the {-, 0, +} quantity space for qualitative values [Iwasaki & Simon 86; deKleer & Brown 85]. Qualitative process theory uses a notation that separates magnitudes of quantities from their signs [Forbus 84]. Qualitative simulation uses a notation that allows an arbitrary number of symbols in the quantity space and an associated direction of change {decreasing, steady, increasing} [Kuipers 86].

This last approach of qualitative simulation as implemented in QSIM [Kuipers 86] was selected as the representational scheme for the bridge cracking problem. A standard version of this approach is rigorously defined and readily available. The expressive power of a notation expanded beyond the{-, 0, +} quantity spaces of confluences was expected to be useful for describing the target engineering domain. The selected notation is readily understood by relatively novice users. This particular use of qualitative reasoning does not make use of the domain to scenario distinction supported by the QPE implementation of qualitative process theory and therefore the narrower focus of QSIM on the required qualitative simulation aspects was deemed appropriate for this investigation.

2. Composition of CRACK

To investigate the utility of using qualitative reasoning as a mechanism to integrate heuristic and quantitative methods for a real world engineering task, the specific domain of fatigue and fracture in steel bridges was addressed in CRACK (Consultant Reasoning About Cracking Knowledge) [Roddis 88]. CRACK's performance was verified for solving failure analysis, predictive modeling, and design critique tasks for welded plate girder and rolled beam bridges.

Engineering problem solving uses multiple levels of understanding, examining the physical situation at various levels of abstraction in order to integrate overall understanding with detailed knowledge. Engineers attempt a solution at the simplest possible level and then use the ambiguities generated by the simple attempt to guide more sophisticated analysis. The initial problem definition and hypothesis generation steps are approached heuristically in light of accumulated experience. Creation of an abstract model and determination of important parameters, the kinds of physical behavior that dominate, and information that can be ignored are done qualitatively before final numeric methods are used to resolve ambiguity and provide quantified results. For these reasons, a layered approach is taken in CRACK as shown in Figure 1.

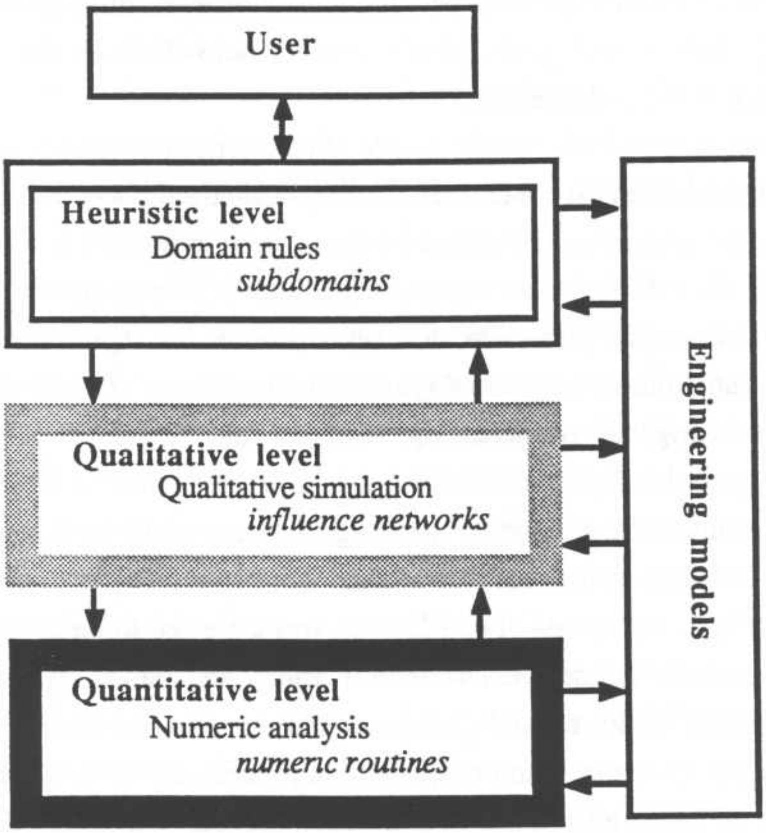


Figure 1

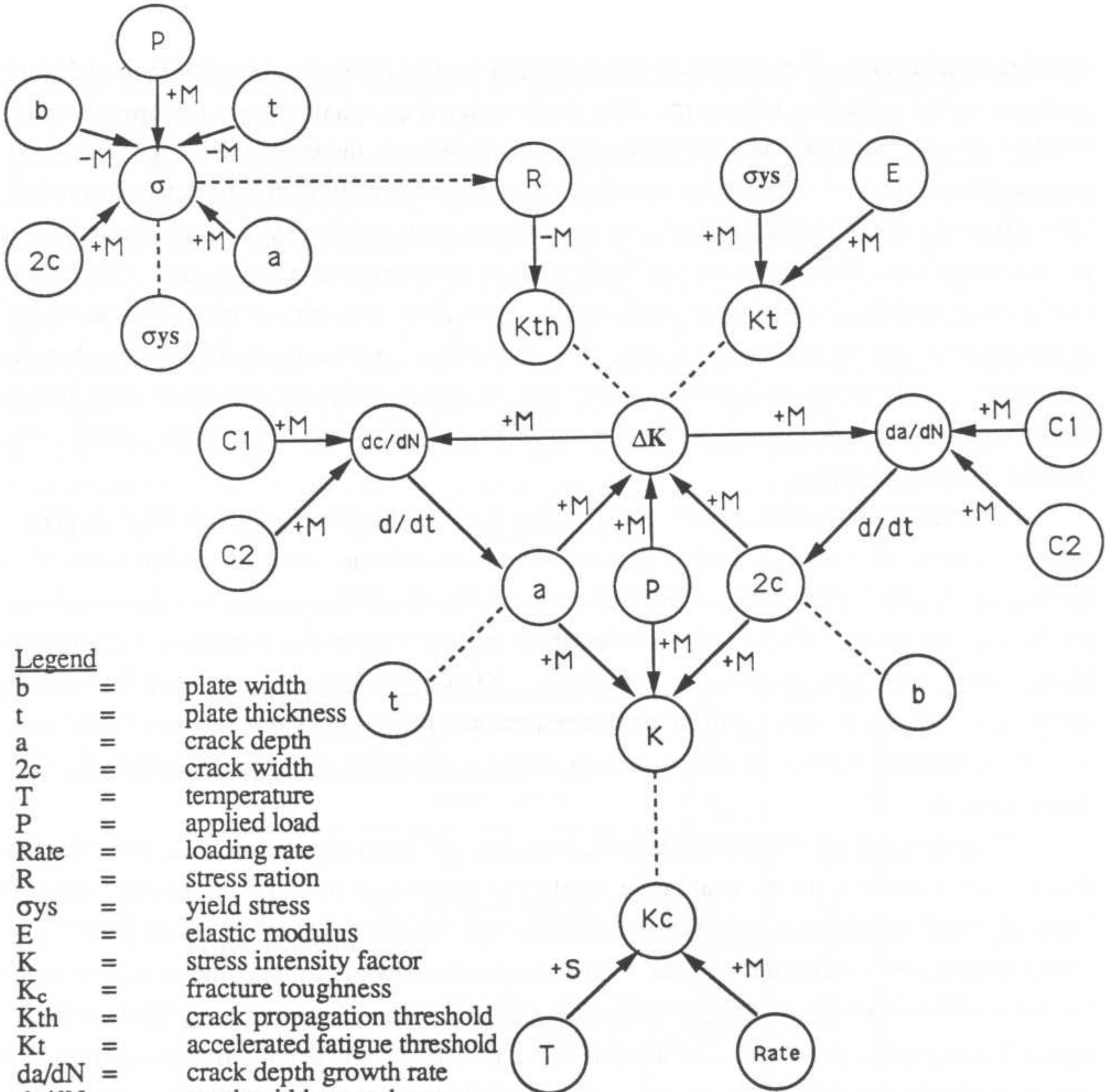
Layered System Architecture Structure of CRACK

The three reasoning levels (heuristic, qualitative, and quantitative) are linked by one common representation scheme for the engineering models. The white bordered layer uses a symbolic rule-based approach to perform the heuristic tasks of problem definition, hypothesis generation, and drawing conclusions. The gray bordered qualitative layer constructs the analytic models and performs model validation/refinement. The black bordered quantitative layer performs numeric analysis and evaluation of analytic results. The arrows between the three reasoning levels show the transitions as the state of problem knowledge is mapped from one abstraction space to another. The arrows between the three layers and the one common representation show how communication occurs between the disparate reasoning levels through the shared language used to describe the engineering models. To apply this architecture of the three reasoning levels plus one shared communication level to the test bed problem domain of fatigue and fracture in bridges, the domain knowledge must be structured according to the heuristic/qualitative/quantitative framework and an appropriate representation developed for the engineering models which act as the means of communication between levels.

The heuristic knowledge represented with rules at the top level is of three types: protocol, hypothesis generation, and physical parameters controlling cracking. The high level protocol rules post the initial appropriate sequence of goals to accomplish the different tasks of failure analysis, prediction, and design critique. Knowledge about causes of cracking in bridges is structured hierarchically and used to generate hypotheses. Knowledge about each of the four major parameters affecting the crack growth life and residual strength capacity of structures (initial flaw size, stress history, material properties, and structural geometry) is grouped into a separate subdomain rule set.

Knowledge about the relationships between the significant physical parameters within the domain is represented at the qualitative level. The qualitative level represents this domain knowledge with constraint equations which define a network of influences among the parameters. These qualitative constraints express dependency relationships among the system's state parameters. The dependency relationships usually represent causal relations among the parameters. Figure 2 is a graphic presentation of the qualitative influences between the fracture and fatigue parameters for the case of a flat plate subjected to tensile loads of varying magnitude.

The central numeric ability required from the system is the computation of crack growth, both for stable and unstable propagation. The methods are those commonly used in linear elastic fracture mechanics [Brock 84, Fuchs&Stephens 80] as applicable to low-carbon steel civil engineering structures [Barsom&Rolfe 87] and steel bridges in particular [Fisher 84]. Crack behavior over time is computed quantitatively by small functions which take all input from, and post all results to, the data structures of the engineering models. The engineering models are assembled from elements contained in a model library. The model library contains plate components and structural connectors from which specific bridge detail configurations can be constructed. These models parallel the physical structure of the actual bridge detail, aiding reasoning about issues such as connectivity and spatial proximity.



<u>Legend</u>

b	=	plate width
t	=	plate thickness
a	=	crack depth
2c	=	crack width
T	=	temperature
P	=	applied load
Rate	=	loading rate
R	=	stress ration
σys	=	yield stress
E	=	elastic modulus
K	=	stress intensity factor
K_c	=	fracture toughness
Kth	=	crack propagation threshold
Kt	=	accelerated fatigue threshold
da/dN	=	crack depth growth rate
dc/dN	=	crack width growth rate
C1	=	crack growth rate coefficient
C2	=	crack growth rate exponent
---▶	=	functional relationship
- - - - -	=	limiting value
+M	=	monotonically increasing
-M	=	monotonically decreasing
+S	=	sigmoidally increasing
d/dt	=	derivative

Figure 2
Qualitative Influence Network for a Flat Plate in Variable Tension

3. Operation of CRACK

3.1 Sequence of Operation of CRACK

To illustrate the operation of CRACK, the steps that the system executes in a case study session are described in sequence below. The role of the three reasoning layers are identified for each step with emphasis placed on the qualitative layer. The phases in the solution process are:

1. Establishing the type of problem to be solved, either design critique, predictive modeling, or failure analysis.
2. Describing the problem by gathering information on the girder's geometry, service history, material properties, and observed cracking symptoms.
3. Hypothesizing a crack cause.
4. Qualitatively simulating possible crack progression sequences to guide quantitative analysis.
5. Performing fracture mechanics calculations to determine critical crack sizes and fatigue lives.
6. Evaluating the hypothesis to confirm it as most probable crack cause (or to reject it, in which case the sequence loops back to step 3).
7. Stating the conclusions.

Phases 1, 2, and 3 are performed by the heuristic level. Qualitative simulation is used for phase 4. Numeric analysis routines perform phase 5. The final phase 6 and 7 are again done using the heuristic level.

The plate girder shown in Figure 3 is used for this example. The case study at hand is a failure analysis type of problem. The solution sought is an explanation of the failure which matches a crack progression sequence to the observed facts. The heuristic layer includes domain specific problem solving methods in the form of protocol rules which contain knowledge about the conventional order for data gathering and ways of decomposing the overall task into a series of simpler steps.

These protocol rules guide the information gathering phase. The structural configuration is specified as shown in the upper portion of Figure 3. Facts concerning the bridge's service history are requested next, followed by material properties. The final group of information requested is the crack extent and surface features, as shown in the lower portion of Figure 3. This completes the information gathering phase, all of which is controlled by the heuristic level using domain rules representing knowledge about fatigue and fracture, grouped according to whether they address initial flaw size, stress, history, material properties, or structural geometry.

At this point, a model can be postulated. This step is also handled by the heuristic layer. The knowledge base contains a rule set to hypothesize the crack cause based on the user supplied facts describing the plate girder geometry, service, materials, and cracking. Using this rule set, the

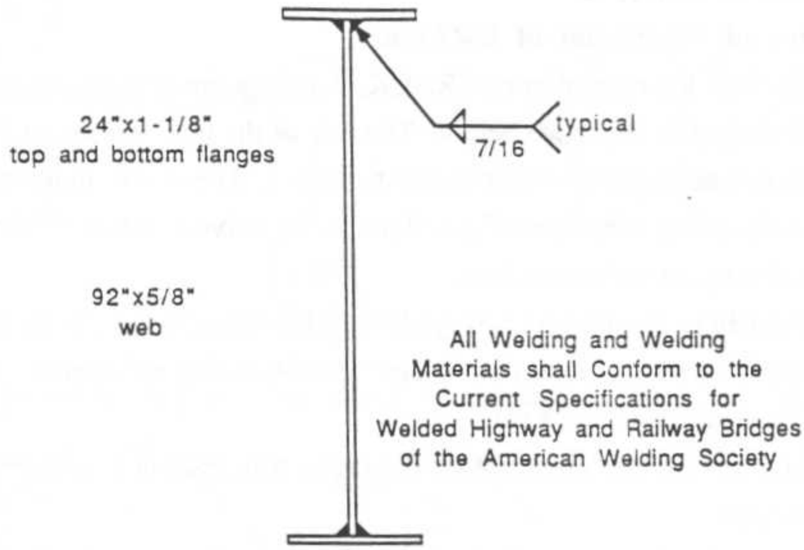
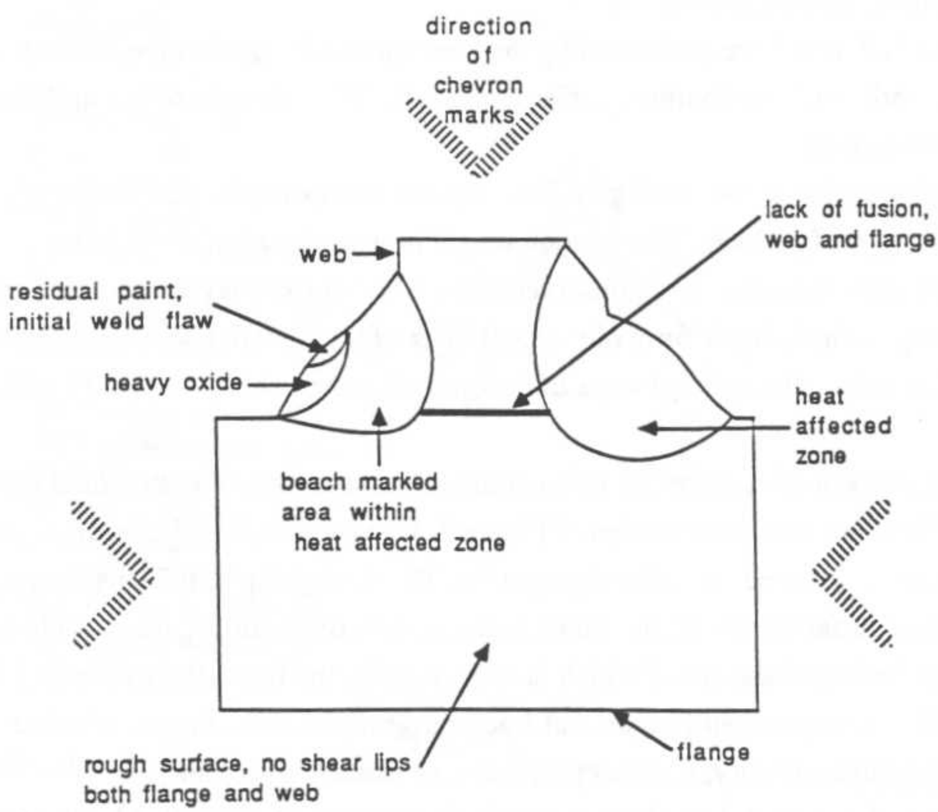


Plate Girder Cross Section



Sketch of fracture surface near origin of crack

Figure 3
Bridge Failure Analyis Case Study

likely origins of transverse cracking in a welded plate girder without attachments are [Fisher 84]:

1. a weld flaw in the tension flange-web connection
2. a weld flaw in the compression flange-web connection
3. a notch in the flame-cut edge of the flange tip.

These hypotheses are ordered from most to least likely. CRACK operates by trying to explain the observed failure facts by assuming the most likely hypothesis. Only if the first hypothesis predicts behavior which does not match the facts will it be discarded. The next hypothesis would then be tried in turn.

The next phase consists of qualitatively simulating possible crack progression sequences to guide quantitative analysis. The primary task of the qualitative level is to envision the possible ways a postulated crack could grow, constructing a tree of the different states the crack may pass through from initiation to failure. This qualitative information is used to set up the quantitative analyses of the individual crack growth stages and the connection of the stages into chains of possible behaviors. This avoids a "big switch" approach to quantitative analysis, which would only allow the use of pre-enumerated solutions. Instead of taking this pre-enumerated approach, CRACK builds up a complete quantitative analysis by assembling partial solution stages under the guidance of the qualitative level. The qualitative level is used to plan and reason about the underlying quantitative knowledge of the physical world.

CRACK's approach toward constructing the qualitative model for a particular case is as follows. The problem description contained in the case's engineering model is used to build the appropriate quantity spaces and initial state. The qualitative model is thus tailored to the specific case. The setting of initial conditions depends on assumptions about which parameters are varying and which remain constant. If the trial is unsuccessful, these assumptions are heuristically changed and a new trial is attempted.

This example details the growth of a fatigue crack through multiple elements of a cyclically loaded plate girder. The simulation begins with a small initial flaw in the weld connecting the girder's bottom flange to the web. As the girder is loaded and unloaded repeatedly, the flaw becomes a sharp crack and propagates within the weld. As the fatigue crack grows, rapid fracture can occur in the weld, failing the girder, or the crack can continue to grow through the weld and into the flange. Once the crack enters the flange, fracture of the flange is inevitable. However, other important behaviors must be accounted for. The flange may fail while the crack is small relative to the cross sectional dimensions of the flange, or the crack may grow deep enough to penetrate the flange and continue to grow before failure occurs. This type of information is critical in selecting the proper numerical model to determine crack growth rates as a function of cyclic stress and to predict the life of the girder. The physical situation described above was modelled in QSIM. The defined quantities are given on the following page. Figure 3 graphically illustrates the resulting behaviors.

QUANTITY		QUANTITY SPACE	INITIAL CONDITION
a -	the crack length (one dimensional measure of the crack size)	[0,btflg_con,btflg,btflg_pent]	btflg_con,increasing
da/dN -	the crack growth rate	[0,da/dN_init,+inf]	da/dN_init
Temp -	the temperature of the steel	[temp_init]	temp_init,constant
K_c -	the fracture toughness of the steel (toughness of weld metal is assumed to be equal)	[K_c]	K_c,constant
K -	the stress intensity factor (K_c is the critical or limiting value of K)	[K_init,+inf]	K_init
K_r -	the residual toughness (K_c - K = K_r, here K_r is a fictitious quantity for convenience)	[0,K_r_init]	K_r_init
ΔK -	the stress intensity range	[ΔK_init,+inf]	ΔK_init
F_{esg}-	a factor accounting for crack shape, intersection with free surfaces, stress gradient	[F_{esg}_init]	F_{esg}_init,steady
F_w -	a width factor	[0,F_w_init,+inf]	F_w_init
F -	total factor ($F = F_w + F_{esg}$)	[0,F_init,+inf]	F_init

The simple QSIM model consists of the following relations:

$K_c = K_r + K$ (enforces $K < K_c$ by defining failure when K_r goes to zero)

$F = F_w + F_{esg}$

F --[M+]--> K (K increases monotonically with F)

F --[M+]--> ΔK (ΔK increases monotonically with F)

a --[M+]--> F_w (F_w increases monotonically with crack size)

a --[deriv]--> da/dN (da/dN is the derivative of a with respect to cycles of load or time)

da/dN --[M+]--> ΔK (ΔK increases monotonically with crack growth rate)

Temp --[M+]--> K_c (temperature effect on fracture toughness)

[constant Temp] (Temperature is held constant in this case)

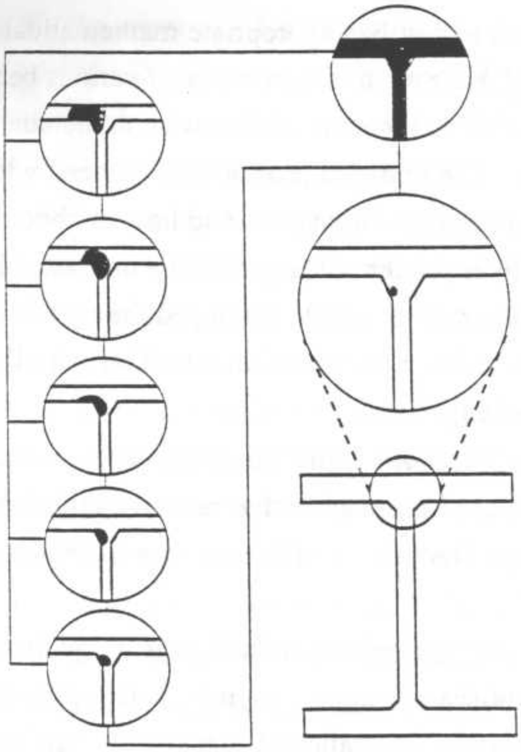


Figure 3
Crack Growth Through Multiple Girder Elements

The results of the qualitative simulation and information about the suspected originating flaw are used to set up the analytic model simulating crack growth. The appropriate model for a surface weld flaw at the flange-web junction is an edge crack. Numeric fracture mechanics routines are then executed.

Having simulated cracking behavior based on the chosen hypothesis, the next phase is to compare the predicted and observed facts. This step is again performed by the heuristic level. If the predictions match the observations, the hypothesis is a good one. If the predictions contradict the evidence, the hypothesis must be discarded and the next one must be evaluated. This cycle continues until a satisfactory match is made. If the hypothesis list is exhausted, CRACK reports its failure to generate a solution.

The only task remaining is to summarize the results and concisely state the conclusion. A text summary of the results is generated by using template sentences and filling in the blanks with the appropriate user supplied or inferred values.

4. Results from CRACK

Engineering problem solving requires a useful, fundamentally based understanding of a system's response to its conditions of use, such as a structure's behavior under service loads. The requisite knowledge is interdisciplinary, spanning such specialties as material science and continuum mechanics. To select and utilize appropriate mathematical tools for design and service evaluation, a qualitative feel for the relative importance of various behaviors is essential. Expertise encompasses knowledge of what to ignore as well as what to include, what cases to investigate and what assumptions to change. The knowledge of how to proceed with partial information, how to focus on promising regions of the solution space, and how to choose and bring to bear applicable solution techniques is largely dependent on a qualitative understanding of the system's behavior. For problem solving in a domain with a well developed theory of causality, the approach used in CRACK provides a path to build a computational tool which allows the solution of complex problems by less experienced engineers.

A major objective of the work of implementing and evaluating CRACK was to determine the capabilities and limitations of a representative current qualitative reasoning technique for solving a realistic engineering problem different from the test cases explored by the developers of the qualitative reasoner.

The results of the three reasoning levels (heuristic, qualitative, and quantitative) with a communication mechanism of shared engineering models CRACK system architecture was satisfactory but this experiment was not an unalloyed success. In particular, the qualitative level was found to be difficult to control and to fully utilize. Further advances in the AI technology seem required before qualitative reasoners will be powerful enough to deal with realistic engineering problem solving beyond a research setting. Recent work in the field of common sense reasoning has promise for overcoming some of these technological short-comings.

5. Modelling Issues

During the construction of the simple qualitative models, such as detailed in the example of section 3, several difficulties arose. Four of these issues, some of which are interrelated, are discussed in turn. The first is that in a QSIM model, landmarks, within a given quantity space, cannot be influenced by other quantities. Second, testing to see if two quantities are equal requires developing fictitious relations which lead to undesired behaviors. Third, the value of a quantity cannot be fixed throughout a simulation by statements in the initial conditions. Finally, spatial reasoning, extending the model from one dimension to two and three dimensions, provides some challenges.

Intuitively, as qualitative models in the domain of fracture and fatigue are constructed, some landmarks, within a given quantity space are not constant but are influenced by other quantities. These landmarks, or boundary points, are actually quantities themselves. They are also boundary points or landmarks because they divide a quantity space up into qualitatively different behaviors. However, QSIM does not allow a landmark to also be a quantity.

In the previous example, K_c is a critical value or landmark in the quantity space of the parameter K, when K reaches K_c the metal will fail suddenly. K_c is dependant on temperature, while K is not. Notice that this differs from the example of the boiling point landmark within the quantity space of temperature in a simple steam model. The boiling point is influenced by pressure and volume in the same manner as the temperature quantity itself, making it unnecessary and indeed incorrect to explicitly model the boiling temperature as a quantity. The need to represent the temperature dependence of K_c, which demarcates regions in the quantity space of K which have different behaviors, led to using fictitious variables (and relationships) to relate a boundary point (defined as a quantity) to the quantity it bounds.

In order to determine if a quantity has reached a boundary defined by another quantity, it is necessary to determine if the quantities are equal. This requires creating a fictitious variable and a relationship relating the two quantities to this variable. In the preceding example, this is illustrated by the relationship ($K_c + K_r = K$), where K_r is a fictitious variable. The results may then be interpreted that if K_r goes to zero then K must become equal to K_c. Unfortunately, this approach also leads to large numbers of spurious behaviors if both K_c and K_r are allowed to vary. In the preceding example, K must be always increasing as it depends only on crack size. However, the above relationship allows K_r to vary so as to force K to decrease. These spurious behaviors have to be eliminated through other controls in order to produce only the desired set of behaviors.

When trying to construct a general model that includes many parameters, the model quickly becomes computationally intractable. It is thus necessary to limit the model by fixing some parameters and allowing only those of interest in a particular case to vary. The initial conditions of all parameters may be specified but it is not possible to fix a quantity for the duration of a simulation through initial conditions. This must be done in the body of the model using the statement (constant X). In the preceding example, the temperature is held constant in order to examine only the effects of load over time. Thus, the model must be modified for particular cases, or a graph of models is necessary to construct a manageable, generally applicable model.

Another question is one of moving from the one dimensional measure of a crack, used in the preceding example, to two and three dimensions. This is necessary in various situations to completely describe the behaviors of the physical system. A crack may grow through the thickness of a girder flange, but it may instead grow across the width of the flange which requires a different numerical model and thus the qualitative reasoning method used must distinguish between these cases. Additionally, representing more complex states of stress than uniaxial tension may be necessary.

Some work has already been done in terms of extending the qualitative model to two dimensions. The description of crack size has been divided into a width and a length parameter and the two measurements are allowed to grow at different rates, although they are influenced by the same parameters. Beginning with a elliptical surface crack, growing in a flat plate, the model produces the graphical state tree shown below.

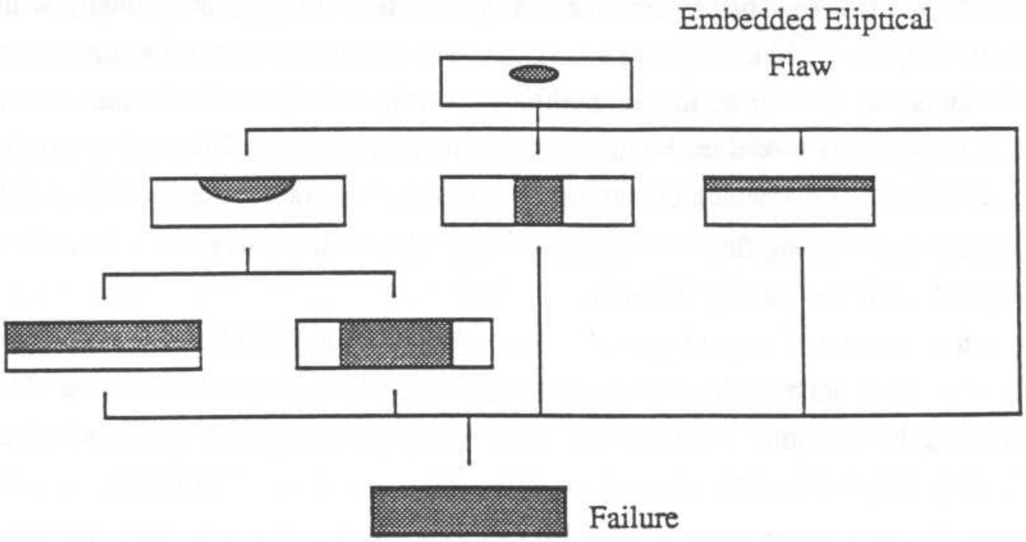


Figure 5
Two Dimensional Crack Growth Stages

As the crack dimensions reach the dimensions of the plate itself the model transitions to a modified version where no further crack growth can occur in a direction where the crack intersects a free surface. This simple approach works well, but requires building tailored models for many parts of the complete domain.

6. Work in Progress

An important distinction between qualitative *domain* models and *scenario* models was articulated by Forbus [Forbus 88]. If a special purpose qualitative model is built for a particular situation, that scenario model is not necessarily of use for another special purpose. If instead a powerful domain model is constructed that describes a class of related phenomena, appropriate scenario models can be derived from the domain model. Since engineering encompasses many domains and utilizes several kinds of reasoning, it is clearly desirable to pursue a methodology of qualitative physics that enables accumulation of knowledge.

The qualitative model used in CRACK is a special purpose *scenario* model, not a general purpose *domain* model addressing a range of related physical phenomena. The small scenario qualitative model serves as a demonstration of the feasibility of constructing a qualitative model in this domain capable of predicting interesting behaviors of the physical system.

Work in progress applies qualitative physics techniques to develop and evaluate a general purpose qualitative domain model in the area of material behavior, specifically for fatigue and fracture of metals. A generic, flexible, prototypical fatigue and fracture domain model is being developed and used to perform qualitative studies using the different strategies for qualitative reasoning of qualitative simulation as implemented in QSIM and qualitative process theory as implemented in QPE. The domain model will be used to generate special purpose scenario models from a specification of the modeling assumptions to be incorporated for the individual scenario. The single domain model will thus capture material behavior for multiple physical regimens. This generalization approach reduces the overall number of qualitative models that need to be developed to support intelligent computer-aided engineering. The results of this research will be the encapsulation of domain knowledge about fatigue and fracture within a robust and extensive qualitative domain model along with a systematic understanding of the capabilities and limitations of the model to predict valid behaviors of relevant physical systems under various scenario assumptions.

In building the current models, it has become clear that abstracting from a large collection of numeric models to obtain narrowly applicable qualitative models is of little use. It seems that the use of available numeric information in conjunction with a general qualitative model is a better approach to solving problems in this domain. It is, therefore, our intent that the bulk of future work will focus on integrating qualitative and quantitative methods at a finer level of granularity than in previous work.

Thus far the approach has been top-down in that having a large number of well developed numerical relationships, we have abstracted from them a broad qualitative model, loosing a great deal of useful information in the process. Once the model is behaving as it should we have tried to use the complete qualitative description of its behavior as a guide for applying numerical techniques. This has been of limited success.

The approach we intend to focus on now is to use a bottom-up approach, where all available numeric information is used with the existing numeric relationships and then the question is posed, "What if this piece of information was unavailable?". The resulting qualitative model and corresponding set of behaviors may be of more use than the abstracted general models built thus far. We hope that increased integration of the two methods will allow a large domain model to be adequately constrained by first using all readily available numeric information to prune the behavior tree and focus the analysis.

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