A Conceptual Approach to Prevent Crack-related Failure of Steel Bridges

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Although the safety record of steel bridges is undoubtedly superior to many other engineering structures, there have been a few catastrophic bridge failures. These include the Kings Bridge in Melbourne, Australia (1962), the Silver Bridge in West Virginia (1967) and one span of the Mianus River Bridge in Connecticut (1983). At times, localized failures have rendered an entire bridge unsafe, resulting in emergency repairs and/or corrective measures. These and other failures suggest that not only is there a need for emphasis on thorough inspection and reinspection, but also for greater understanding of the factors which influence the behavior of crack growth.

Laboratory tests have shown test specimens of identical materials under equal loads, but different crack sizes, will not exhibit the same fatigue life. Crack size is important in determining the useful remaining life of a particular bridge member. In many situations, the smaller, hard-to-detect cracks can be much more serious in fracture-critical bridge members than the apparent ones which may occur in redundant members. With the advent of fracture mechanics concepts, the significance of crack size and its interrelationship with applied stress and fracture toughness has been recognized by bridge engineers. Progress has been made not only in understanding crack growth through fracture mechanics, but also in crack detection through non destructive testing techniques.

There are various inspection and testing methods which can be applied to detect cracks and other discontinuities in steel bridge members. Inspections are necessary not only during maintenance after opening of the bridge to traffic, but also during the fabrication and construction phases to mitigate and limit the size of a possible built-in discontinuity which could have the potential to grow under fatigue loading. While visual inspection undoubtedly is the most effective method to determine the general condition of bridge components, like other nondestructive testing (NDT) methods, it has limitations. Discontinuities on the surface can be observed by the inspector, but very small cracks can go undetected by the human eye. Many of the serious discontinuities (such as cracks) can be very tight, sometimes obscured by the geometry of the surface, or rust and paint, and consequently difficult to detect by visual inspection, even with magnification.

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NDT methods such as magnetic particle, liquid penetrant, ultrasonic, radiographic and acoustic emission testing have the potential to assist bridge inspectors in finding cracks, if the appropriate method(s) is selected intelligently and then implemented properly. These NDT methods are not new to bridge inspectors. Although significant improvements have been achieved over the past 10 years, in many cases bridge owners are reluctant to use a certain NDT method because of lack of confidence in its test results. The general mistrust of ultrasonic testing, for example, is understandable in light of its complexity and personnel qualification-related concerns. Each NDT method should be thought of as an available tool, but its potential and suitability for a particular application may have limitations. Since there is presently no single method capable of detecting all types of discontinuities in all possible orientations in steel bridges under in-service conditions, selection of the proper method or combination of methods is of paramount importance.

A SYSTEMATIC APPROACH TO CRACK DETECTION

Because it is not practicable or economical to perform NDT on each and every inch of a steel bridge, a systematic approach is necessary to integrate NDT into the overall scheme of bridge inspection. Although there are many factors to be considered when deciding the extent and type of NDT to be used, a plan which considers the following three conditions will increase the overall effectiveness of NDT applied to bridges:

1. The problem-causing or defect-prone areas should be determined in advance *(where to look)*.
2. The optimum NDT method(s) suitable for the area and type of suspected defects must be determined *(how to look)*.
3. The NDT method(s) must be performed by suitably trained and knowledgeable personnel *(hands-on people)*.

Determining where the problem areas are *(where to look)* is not typically an NDT inspector's responsibility. These (where to look) people should be knowledgeable of bridge types, including joint and member details and also the associated fabrication and in-service defects and related characteristics. It is only after recognizing where inspections are to be made that inspection personnel can effectively plan and make meaningful inspections. The importance of determining whether a member is fracture-critical or redundant cannot be overstressed. To establish effective inspection priorities of suspect areas, those members subjected to tensile or reversible stresses should be identified in advance.

Such planning requires an advance review of plans, sketches and specifications to select and prioritize areas requiring in-depth inspections. Codes, standards and specifications at times do not provide all necessary controls for the nondestructive testing to meet specific needs of a particular job. When no specific guidelines are available for determining which details need to be examined, it is essential that *where-to-look* personnel have a structural engineering background and adequate experience in bridge inspection.

The second condition, selecting the proper NDT method or combination of methods, *how to look,* requires a thorough understanding of NDT methods. The *how-to-look* people must have more than just a practical sense of how each NDT method works. They should either be a Level III, certified in accordance with industry standards or the equivalent of an NDT Level III*. The Level III, sometimes called an NDT engineer, should be able to develop written NDT procedures to be used by inspectors, recommend the appropriate equipment necessary to properly perform the test and determine the significance of the test results. Rarely is an NDT method unsuccessful because of inadequate sensitivity (least detectable discontinuity size). More often the problems include inadequate surface preparation, geometry and accessibility, environmental constraints, poorly written or nonexistent NDT procedures and unqualified personnel performing the test.

Finally, the NDT method(s) must be properly performed. Those (the hands-on people) who are asked to perform NDT should have necessary qualifications, experience and training commensurate with the complexity of the particular NDT method. This can range from four hours to two weeks of classroom and hands-on training, and from a couple of weeks to one year of hands-on experience. Personnel performing NDT methods should at least meet certification requirements of an NDT Level II or equivalent, which typically requires both written and hands-on performance qualification tests (practical examinations). They must also be familiar with and capable of implementing the written procedural requirements for the applicable NDT method(s).

This team, in concept, will be capable of determining the type and location of problems or suspect areas in a given bridge—the *where-to-look* role. The proper NDT method can be selected based on this determination—the *how-to-look* role. The NDT methods can then be performed by a properly qualified individual, the *hands-on* role. Of course, it may not be necessary to have a separate person for each role. For example, many Level III individuals can also perform an NDT test; and conversely, some Level II individuals have sufficient understanding of NDT methods to select the proper NDT method. Some state DOTs are fortunate to have engineers with sufficient understanding of NDT to fill both the NDT Level III and the structural engineer roles. Other states may rely almost entirely on testing laboratories for NDT technical services.

An idea worthy of consideration is formation of a sort of "NDT SWAT Team" comprised of state bridge inspectors/engineers who are trained and properly qualified in various NDT disciplines. The team could be called upon when problems arise during fabrication, erection, maintenance or failures, and return to their regular duties when no longer needed. However accomplished, it is important to recognize a coordinated team of combined technical expertise, NDT and bridge inspection experience, can produce economically meaningful inspection results which can be used to evaluate the structural integrity of steel bridges.

After the size of discontinuities in a bridge member have been found and estimated, the next step is to determine the seriousness of the problem and whether or not remedial measures are warranted. Some discontinuities are given a low priority for repairs because they are in a compression zone, or are so called self-extinguishing, or because they are very shallow, to name a few. This is not to say those responsible for a bridge are entirely comfortable with the knowledge of the existence of a crack or discontinuity. Many bridges with serious cracks have been repaired by completely bolt-splicing over the cracked member(s). The question of "what is a serious crack?" is sometimes answered by observing factors such as the criticality and connection location and the crack depth and length. To assist engineers in judging the seriousness of borderline or growing cracks (which may or may not warrant immediate attention), fracture mechanic concepts are available.

A THREE-PRONGED ATTACK

The nature, assessment and significance of discontinuities, such as weld discontinuities and the required magnitude of fracture toughness, will be much more meaningful if the interrelationships of crack size, material toughness and the stress-intensity factor are understood and practiced. Various published data indicate a relationship of these three basic parameters, shown in Fig. 1 and discussed:

**Refer to American Society for Nondestructive Testing published guidelines SNT-TC-1A developed by the Society in recognition of the fact that personnel responsible for nondestructive testing must have adequate capabilities for meaningful testing and evaluation.*

Figure 1 shows a relationship between crack size and applied stress for given stress-intensity factor of K_1. The mathematical expression representing the curve varies with crack geometry, orientation and location, e.g. edge crack, surface crack, through-thickness crack, etc. and can be expressed in the general form as

$$K_1 = f(g)\,\sigma\,\sqrt{a}$$

Where

$f(g)$ is a parameter that depends on the specimen and crack geometry. Through extensive investigations and research, values for various situations are available in the literature.

K_1 = Stress-intensity factor
σ = Applied nominal stress
a = Crack length
K_{1C} = Critical stress-intensity factor $K1$ = material toughness

Because points below the K_{1C} curve represent a stable crack and points on or above the K_{1C} curve indicate an unstable crack and resulting fracture, observe that crack size a_1 can be tolerated (stable crack) with applied stress (including residual and secondary stresses) as high as σ_1 without causing fracture in a material with a stress intensity value of K_1. Should the crack size be increased to a_2, with a stress intensity value K_1, the tolerable applied stress must be reduced to at least σ_2 for the crack to remain stable. Thus, for a given steel of given toughness there are many possible combinations of critical crack sizes and tensile stresses represented by the K_{1C} curve.

Furthermore, for a steel of greater toughness, the curve shifts to the right (in the direction of the arrow) and allows greater tolerance than σ_1 when crack size is a_1 or allows a stable crack size greater than a_2 for applied stress magnitude σ_2.

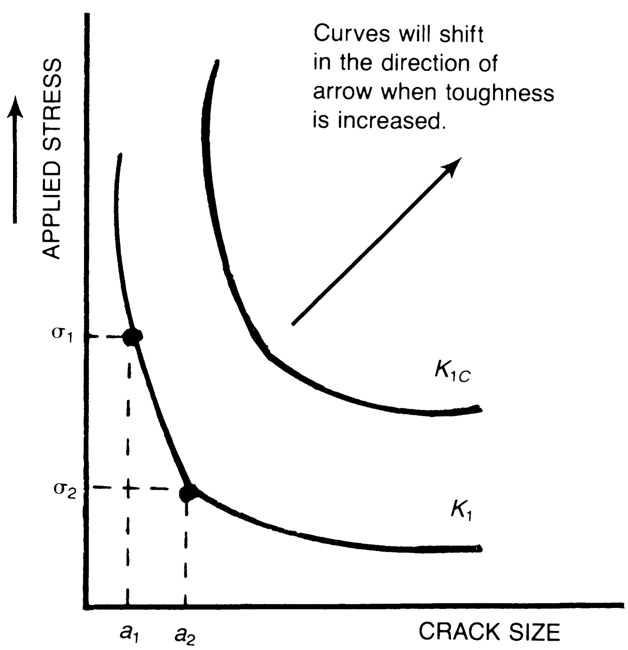

Figure 1

It is apparent that any factors which influence the fracture toughness of the material or the applied stress can affect the tolerable (stable) size of the crack or discontinuity. However, in actual practice economic considerations may dictate certain limitations. For example, material toughness can be increased by heat treatments such as normalizing. But high-toughness requirements should not be applied arbitrarily since it increases the cost of the material, and also higher toughness may not be necessary for the particular application. It should also be recognized increased material toughness alone may not be sufficient to prevent a failure. The consideration to control applied stress and detectable crack size by state-of-the-art NDT equipment is also important and can be explained similarly. On the other hand, it should be possible to understand why poor fabrication practices can result in higher stress concentration or localized lower fracture toughness, or both, and thereby increase the potential for cracking. Improper design can also increase stress concentrations and design stresses, resulting in possible increases in total stress.

SUMMARY

Progress has been made in the area of quality control and assurance, design and fabrication, research and training by the bridge builders including designers, fabricators, steel industry, owners and code writing bodies and others, yet more can be done to make bridges safer and have longer life.

Crack-related failure prevention should be a team effort involving those in design, fabrication, construction and maintenance. By understanding and using the interaction concept of three basic parameters—applied stress, fracture toughness and crack size—bridge owners will be better equipped to mitigate crack-related failures and costly repair of steel bridges. Recognizing these three basic parameters must reach a critical value before fracture occurs provides engineers with an opportunity to control their values or factors affecting them.

The most easily monitored and controllable parameter on in-service bridges is the crack size. Therefore proper fabrication and thorough inspection are very important. Although visual inspection is by far the most universally used and reliable inspection method, for which there is no substitute, other more sensitive methods are available, and in some cases may be more suitable. The selection and application of an NDT method should be considered carefully since no single method is categorically superior. A systematic approach is necessary to integrate NDT into everyday bridge inspection, and this should be accomplished by a team of combined technical knowledge. The optimum team would consist of both NDT and bridge inspection personnel with the necessary technical expertise to adjust the inspection and testing procedures based on the specific condition.