Fuzzy Logic Approach in Metals Fatigue

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ABSTRACT

The fatigue behavior of metal structures is extremely complex. Many types of uncertainty exist in metal fatigue studies, including member geometry; shape and size of fatigue cracks; type, shape, and size of defects and discontinuities in the structural detail; loading and environmental conditions; and thermal and corrosive effects. This article reviews a number of factors affecting the fatigue behavior of metal members. An example problem is presented to illustrate the use of fuzzy sets to evaluate the acceptability of a welded structural detail.

KEYWORDS: ***fatigue, fuzzy sets, weld quality, condition assessment, metals***

INTRODUCTION

One of the most notorious fatigue failures was that of the Comet aircraft [1]. Twenty months after these first commercial jet-engined aircraft were put into service, one disappeared into the Mediterranean Sea without any call for help. The aircraft fleet was permanently grounded when a second aircraft crashed several months later. Examination of wreckage dragged from the sea, along with tests of components, revealed that fatigue cracks had initiated at the corners of the windows in the aluminum fuselage at lives much shorter than the 300 hours of flight tests. Short cracks, which were not found during an inspection just four days before the first accident, precipitated the catastrophic failure of the pressurized cabin.

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It has been known for many years that metal structures and components are susceptible to a failure mode known as structural fatigue. Fatigue may be defined as the exhaustion of the structural capacity of a member, often at a unit stress less than the yield strength, because of the repeated application of loading. Two distinct phases of the cyclic life of a structural member are frequently identified: (a) the number of loading cycles necessary to initiate a fatigue crack, and (b) the number of loading cycles necessary to cause the crack to propagate from a subcritical size to fracture.

The primary objective of this article is to examine the application of fuzzy logic for evaluating the fatigue strength of metal structures. A number of factors that affect the fatigue behavior of metal members are reviewed, and membership functions for these factors are examined. Finally, a simple example involving several fuzzy factors is given to demonstrate one possible application of fuzzy set theory for fatigue design and evaluation.

METALS FATIGUE

Fatigue in Metals

The fracture surface of a fatigue failure often appears to be quite brittle, with very little deformation occurring before fracture. As shown in Figure 1, a simple bar loaded to failure in static tension exhibits considerable deformation before fracture, but a comparable bar that fractures under repeated loadings exhibits very little overall deformation. The crack forms at a nucleus, such as an internal flaw or metallurgical discontinuity, and continues to grow during the repetition of loading with very little plastic deformation. Eventually, the crack grows to such an extent that the stress is significantly amplified by the reduced cross section, and unstable crack growth (fracture) occurs.

A number of theories have been suggested to explain the fatigue phenomenon. For example, Orowan [25] proposed a model with a "plastic inhomogeneity" in an elastic surrounding to explain how yield strength stresses could be attained under elastic loading conditions. The repetition of loading, which results in a corresponding plastic deformation at the inhomogenity, eventually causes a crack to form. Other notable models include Freudenthal's model [13] for crack formation by fragmentation of crystallites and Shanley's model [26] for progressive failure on slip planes as a result of unbonding upon repetitive cycling.

All these proposed models for the explanation of fatigue damage at the microscopic level deal with very simple geometries and loading conditions. Use of such fatigue models to evaluate the fatigue behavior of structural connections is not practical, however. Most connections have complicated geometrical configurations and nonuniform internal stress distributions. Consequently, most

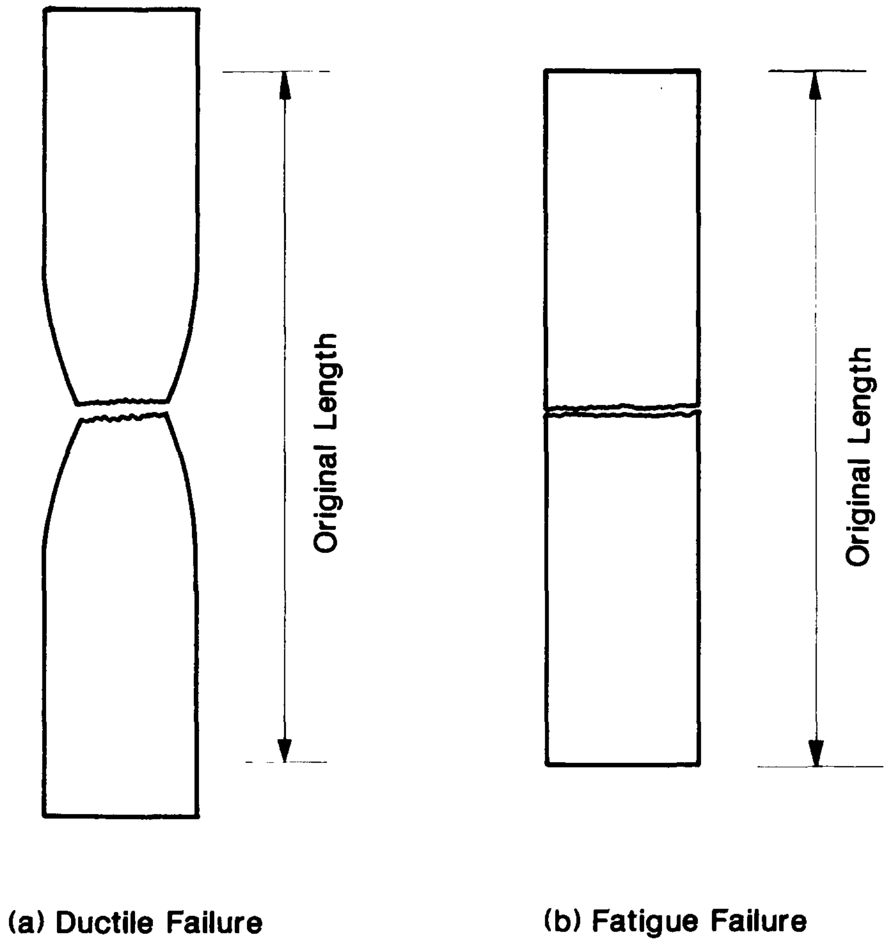

Figure 1. Failure of Simple Bar in (a) Static Tension, (b) Fatigue

structural systems with connections that are susceptible to fatigue are designed and evaluated using empirical relationships developed from laboratory tests. This procedure is quite costly because a large data bank is needed to adequately quantify the fatigue performance of each particular structural detail.

Studies have shown that several factors can influence the fatigue resistance of a structural member. The primary factors that affect the fatigue behavior include the member geometry, material and chemical properties, stress range, load frequency, and atmospheric condition. The large number of phenomenological factors involved makes it difficult to develop a single mathematical model that provides an exact and unique solution describing the fatigue strength of a given structural member.

Additional Fatigue Factors

Several additional factors related to the fatigue behavior of a metal component or structural system should also be mentioned. These factors include the following, which are briefly discussed below: endurance limit, residual stresses, fabrication quality, and corrosive environments.

Endurance Limit

The endurance limit is the maximum cyclic stress below which fatigue failure will not occur. The term was developed from early rotating-beam fatigue tests of smooth steel specimens. It was found that specimens that resisted one million repeated loadings would not fail even if the test were continued for hundreds of millions more cycles. For various steels the endurance limit was found to be approximately equal to half of the tensile strength.

The endurance limit is usually related to constant amplitude or constant stress tests. Consequently, the endurance limit is more difficult to define for spectrum loading or, more particularly, random loadings, which come closer to approximating service loadings for many structures. To ensure infinite life for a structure, it would seem necessary only to keep the stresses below the endurance limit. However, the endurance limit is not a precisely defined property. For instance, for aluminum alloys, failures occur even after 1 million cycles so that values for 20 million or 500 million cycles have been used as endurance limits. Also, failure of steel specimens occurs at lower nominal stresses and at lives beyond 1 million cycles as a result of stress concentrations from geometric or weld discontinuities. This is recognized in several structural design codes—AREA [20], OHBDC [24], AISC [27], and AASHTO [28]—by continuing to lower the allowable fatigue stresses for fillet welds to lives as long as 10 million cycles.

A hostile environment also can reduce the actual fatigue resistance and cause failures to occur at stresses below the supposed endurance limit. For instance, the fatigue strengths of metals are lower in water than in air. Even when variables such as environment and stress ratio are held constant, determination of a value for the endurance limit is subject to the normal scatter found in fatigue testing.

Methods of testing, such as staircase tests to determine an endurance limit or an average fatigue stress at a given number of cycles, use statistical techniques to describe the probable error in the estimate [19]. The endurance limit is not a consideration in all fatigue designs. For a structure that could reasonably be expected to experience only 10,000 loadings in 30 years, the endurance limit would be of purely academic interest. Of course, the uncertainties of determining a fatigue strength for 10,000 cycles would be similar to those for determining the endurance limit.

Of course, the severity and number of loadings may exceed those assumed in the design. For example, bridge designers in the 1940s and 1950s could not have foreseen the drastic increase in the volume of traffic and weight of trucks in recent years. The number of loadings can be grossly underestimated if unexpected vibration occurs. Winds causing structures to vibrate near resonance can produce millions of cycles of significant loadings in a relatively short time. For instance, the blades of several experimental vertical-axis wind turbines failed at the weld ends from aeolian vibration without having been subjected to any of the rotational loadings for which they were designed. Similarly, fatigue cracks developed adjacent to welds of several overhead aluminum sign structures in the presence of winds of from 7 to 12 mph before sign panels were installed [18]. At the measured natural frequency of the trusses, 6.6 cycles per second, 510,000 cycles could be accumulated in one day. The addition of a suitable damper changed the vibration characteristics until the signs could be installed to eliminate the problem.

RESIDUAL STRESS The fabrication of structural systems often produces internal self-equalizing stresses, known as residual stresses, in the vicinity of the joints. Heat associated with the use of welding causes expansion of the metal adjacent to the molten weld. As the weld cools, the contraction is resisted by the solidified weld metal. The first weld pass provides restraint to subsequent passes, thus increasing the level of maximum residual stress in the direction of the weld, across the weld, and through the thickness of the weldment. Accordingly, numerous small passes produce higher residual stresses than a few large passes [17]. With all the restraint in a welded structure, it is probable that some of the joints will have residual stresses at the maximum level possible—the yield strength of the weldment. Accordingly, several codes for welded steel structures [20, 24, 27, 28] assume that the minimum stress is at the yield level so that only the applied stress range need be considered in the design.

Residual stresses are sometimes used to improve the overall structural quality. Shot or hammer peening a weldment produces surface compressive residual stresses at the edge of the weld bead where failure normally initiates. This process can be used to significantly improve the fatigue strength [11, 12, 14, 21].

Of course, residual stresses can be relieved by loadings that produce yielding across the entire section. Thus, proof loading welded cylinders to a pressure higher than the working pressure may beneficially reduce some of the residual stresses. Conversely, an overload could negate some of the benefit of peening a weldment. Residual stresses are also present in riveted and bolted structures. For instance, measurements made when welded sections of an aluminum overhead sign were bolted together indicated stresses of 12 ksi. Naturally, the level of clamping residual stresses depends on the fit of the various components and thus will vary considerably. For normal construction it seems probable that some joints will have relatively high residual stresses.

The fact that overloading can increase the fatigue life was graphically demonstrated, in a negative way, by the Comet failures. The test fuselage had satisfactorily resisted 18,000 pressurizations to service pressures several months before the first failure. Thus, the test life far exceeded the number of pressurizations at which failure occurred. However, before this pressure cycling, this fuselage had been subjected to 30 proof-type tests to pressures from 23% to 93% higher than service pressure. Fuchs and Stephens [14] postulate that the high initial pressurizations induced favorable residual stresses at the critical locations in the test frame "so as to falsely enhance the fatigue life of the test component and provide overconfidence."

FABRICATION QUALITY The fabrication quality of a structural connection or detail can influence the overall fatigue behavior. Notches, scratches, and gouges that occur unintentionally during fabrication introduce a localized stress concentration and can lead to the formation of a crack. The early initiation and subsequent growth of a fatigue crack may reduce the useful life of a structural member.

Care must also be exercised when welding is used to join two or more members. Significant discontinuities can occur when inadequate or improper welding procedures are used. Numerous case histories and experimental laboratory studies have shown that both internal discontinuities (such as porosity, slag inclusions, lack of penetration, or lack of fusion) and surface discontinuities (weld toe geometry, undercut, and overfill) can deleteriously affect the performance of welds [3].

CORROSIVE ENVIRONMENTS Data are rarely available for evaluating the effect of true service environments on the fatigue performance of structures. Laboratory tests are conventionally made in either benign environments or relatively severe environments in an attempt to compensate for the accelerated speed of the testing machines.

Corrosion fatigue tests are often performed in a liquid. Testing metal specimens or joints in water lowers the fatigue strength even when there is no apparent pitting or surface roughening to cause early crack initiation. Increased rates of fatigue crack propagation in water for both steel and aluminum specimens are well documented [14]. Naturally, even faster crack propagation has been demonstrated in salt solutions or other more severe environments [10]. However, corrosive action can also actually slow propagation. At low stress intensities, cracks in aluminum specimens were slowed and even arrested by the buildup of corrosion product in the crack [23]. The buildup served to reduce the crack opening; that is, the crack was closed during most of the load cycle so that the maximum loads were no longer creating enough crack opening to cause crack propagation. Conceivably, corrosive action could also retard crack propagation by blunting the crack tip.

Some evaluations have been made using intermittent periods of salt fog. If the loadings are held at maximum for most of the load cycle, the tests might be thought of as interrupted stress corrosion tests or stress-corrosion-fatigue tests. In a test program using such loadings, it was found that some of the fracture surfaces had the appearance of stress corrosion failures [22], whereas most had the striations of conventional fatigue cracks. Service exposures are generally less severe than those described above. It has been shown that exposure of aluminum welded and riveted joints in industrial and seacoast environments for periods up to eight years before they were tested did not significantly reduce their fatigue strength.

It can be seen that the effect of a corrosive environment is not always predictable in that it may vary from stopping crack propagation to greatly reducing the life required for crack initiation and drastically increasing the rate of crack propagation. The corrosive effect is influenced by the composition of the metal, the susceptibility of the metal to the environment, the rate of loading, the time of load, the effectiveness of any protective systems, the stress level, and any synergisms between corrosion and fatigue. The latter are generally unknown for service conditions, but the simultaneous action of corrosion and fatigue would be expected to be generally worse than the sum of their separate effects.

Motivation for Fuzzy Fatigue Analyses

Considerable uncertainty exists in the present mathematical models used to predict the fatigue life of a structural detail, even when all the primary factors known to influence fatigue are held constant. However, the building and bridge structures that civil engineers actually construct do not exist in an environment in which all the influential variables are constant. The loading is generally random, with each new loading excursion different from the previous; the geometry of details that are seemingly identical can vary as a result of inconsistent fabrication practices; and the ambient atmospheric environment of a structure is in a continual state of flux.

Structural engineers must design and evaluate metal structures to ensure an adequate level of safety against fatigue. Often, the engineer must make crude assumptions concerning the loading, the fabrication quality, and the ambient environment. This use of meaningful but imprecise knowledge concerning several influential fatigue factors suggests that fatigue problems are well suited for solution by use of fuzzy logic.

FATIGUE AND FUZZY SETS

The civil engineering application of fuzzy sets began with Brown and Leonard [8]. A philosophical treatise and in-depth discussion were given by Blockley [2]. To broaden the exposure of the structural engineering community, Brown and Yao [9] gave an introduction to the subject matter with simple examples for the purpose of illustration. A review of the state-of-the-art was presented by Brown and colleagues [7].

The general application of fuzzy sets for the safety evaluation of existing structures is summarized and discussed by Yao [31]. Probabilistic methods and treatment of fuzzy events in civil engineering are reviewed and discussed by Yao [30] and Yao and Furuta [32].

Fuzzy Set Applications for Fatigue

The fatigue behavior of structures is an extremely complex phenomenon. Whenever a structure is designed with new geometrical configurations, new loading conditions, and/or new materials, *ad hoc* testing programs should be conducted to obtain experimental data for use in the analysis and design of this particular type of structure. Although there are many fatigue theories and theorems covering microscopic as well as macroscopic levels, none is applicable to all known cases of the fatigue behavior.

Among many types of uncertainty in fatigue studies, the following items may not be clearly defined:

1. Shape and size of fatigue cracks.
2. Relationships for the description of fatigue behavior (e.g., S-N diagrams).
3. Type, shape, and sign of defects and discontinuities.
4. Loading and environmental conditions.
5. Structural response to a given load and environment.
6. Thermal and corrosive effects.

In such cases where insufficient data and/or imprecise information must be used, it is desirable to study the application of fuzzy sets. As examples, the effect of weld defects and discontinuities have been examined by Bowman and Yao [4], Bowman [6], Watada and colleagues [29], Hinkle and Yao [16], and Hinkle [15].

Fuzzy Fatigue Membership Functions

Membership functions provide the basis for evaluating the level of agreement with a particular statement, such as "the fabrication quality of the member is very poor." As noted previously, considerable uncertainty exists in evaluating the fatigue resistance or damage state of structural members. Consequently, the use of imprecise but meaningful evaluations of the parameters that are known to be influential in controlling the fatigue behavior should be quite helpful in evaluating the fatigue damage state of new or existing structures.

Actual structural members are subject to different conditions than their counterparts in the engineering laboratory. The environment, the load history, and the fabrication quality are factors subject to significant variation, even within the same structure. A detrimental condition for any one of these factors, or combinations thereof, could require that corrective actions be taken to prevent fatigue problems.

Figure 2 shows a fuzzy relation between the load and environmental condition and the fabrication quality. The fuzzy relation has been divided into four regions that require different types of corrective action [4]. No action is required for low

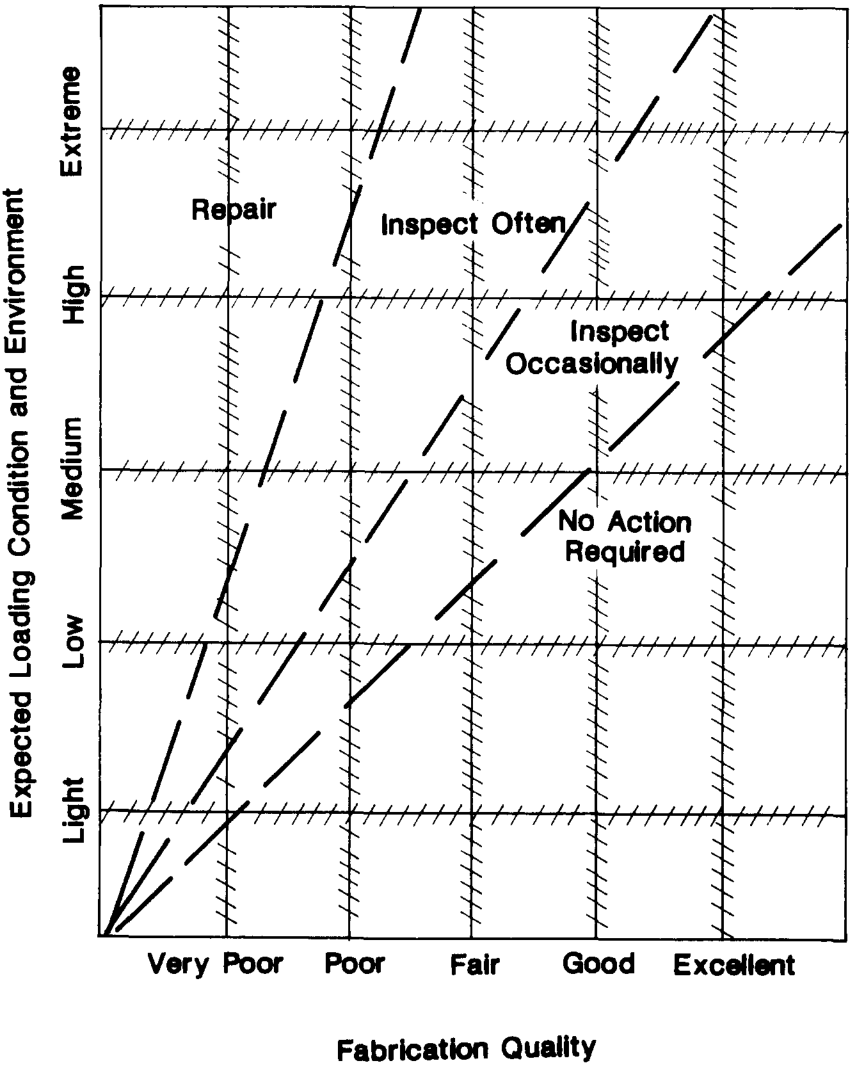

Figure 2. Fuzzy Relation of Loading and Environmental Condition versus Fabrication Quality

loadings and excellent fabrication quality; repair is required for members that are poorly fabricated and subject to large loadings. The role of the membership functions in the fuzzy evaluation process is to estimate the location on the fuzzy relationship that corresponds to the appropriate condition for a particular member. In this manner the required action (repair, inspect, no action) can be determined.

For the purpose of illustration and use in a subsequent example, membership functions for the fabrication quality, loading level, and the environmental condition are given below. It should be noted that although the membership functions presented herein are realistic, they have been selected for illustration purposes only; for specific structures they should be formulated through expert opinion.

FABRICATION QUALITY The fabrication quality selected for review is the weldment quality. Three common weld discontinuities that frequently occur when improper welding procedures are used are slag inclusions, lack of penetration, and porosity, as shown in Figure 3. (A more thorough discussion of weld flaws and fatigue is provided in Bowman and Munse [3] and Bowman and co-workers [5].) The measurable discontinuity features for these flaws that affect the fatigue resistance are slag inclusion length, lack of penetration depth, and percent volume of porosity.

The membership function for fair weld quality in welds containing slag inclusions is given by

$$\mu_F(w) = \begin{cases} 0 & \text{for} \quad 0 \le w < 1 \\ 0.25(w-1) & \text{for} \quad 1 \le w < 5 \\ 2(1-0.1\,w) & \text{for} \quad 5 \le w < 10 \\ 0 & \text{for} \quad w \ge 10 \end{cases}$$

where w = slag inclusion length in millimeters. On the basis of the preceding membership function, the grade of membership for fair weld quality is 1 (complete agreement) for a weld containing a 5-mm inclusion, whereas the grade of membership is 0 (complete disagreement) for a 1-mm inclusion.

The membership function for fair weld quality, $\mu_F(w)$, is shown in Figure 4 as a function of the slag inclusion length. Also shown are the membership functions for excellent weld quality, $\mu_{EX}(w)$, and very poor weld quality, $\mu_{VP}(w)$. It can be observed that an 8-mm slag inclusion length has a slightly greater grade of membership for very poor quality (μ_{VP} = 0.6) than for fair quality (μ_F = 0.4).

The membership functions for excellent, fair, and very poor weld quality are shown in Figures 5 and 6 for lack of penetration (LOP) and porosity, respectively. Accordingly, the membership functions are expressed in terms of either the LOP half depth-to-plate thickness ratio x or the percent volume of porosity, y.

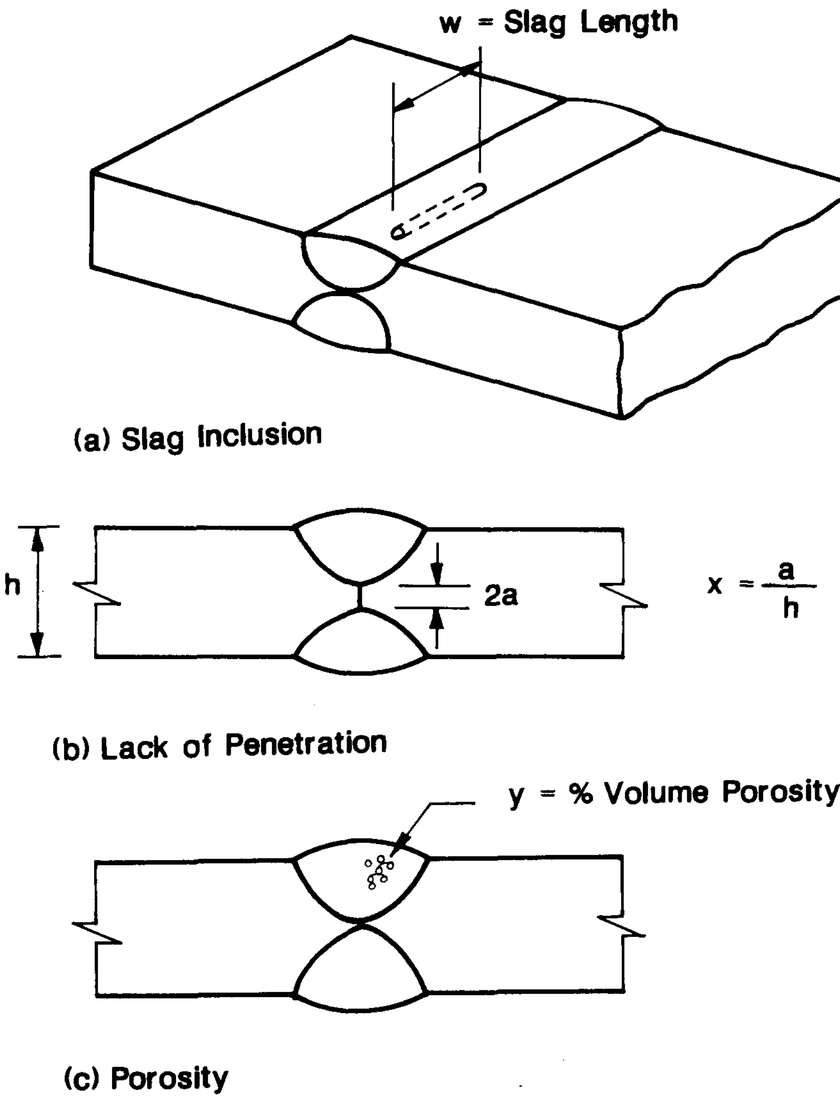

Figure 3. Common Weld Discontinuities

LEVEL OF LOADING The magnitude of the service loading that a member sustains is critically important. Many loading histories are random in nature, making it difficult to define a particular loading level. However, many structural members are designed on the basis of a constant amplitude design loading. Significant reductions in the useful service life of a member can occur when the actual stress range exceeds the design value of the stress range, as shown in

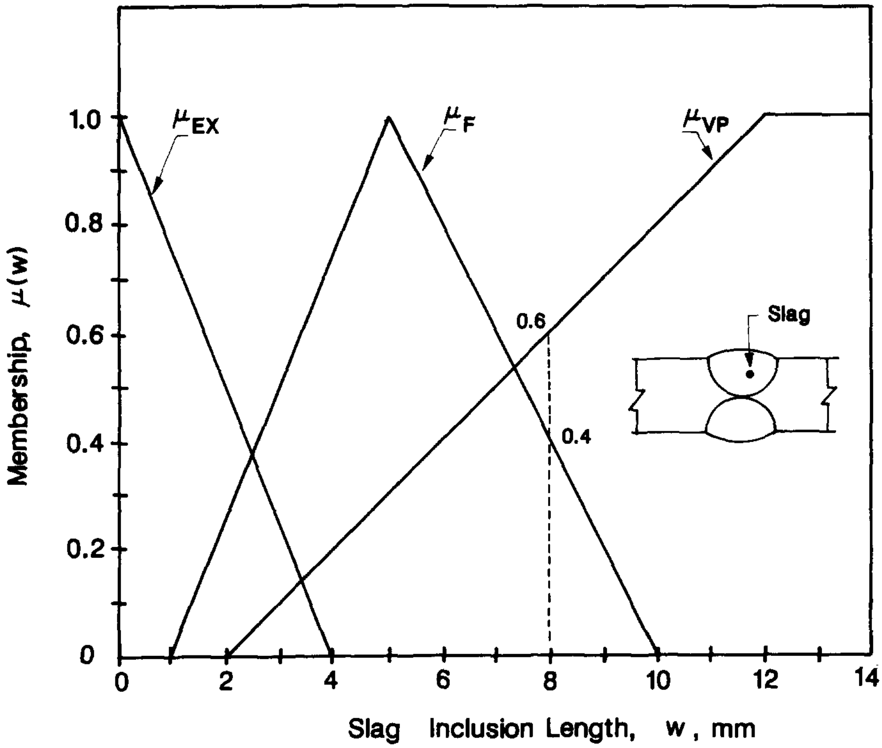

Figure 4. Membership Functions for Slag Inclusions

Figure 7. Conversely, service loadings less than the design load should result in a longer useful life of the structure.

The membership functions used to classify the loading level are based on the ratio of the actual service loading to the design load, q. As shown in Figure 8, five classifications of the loading condition have been selected: light, μ_{LT}; low, μ_{LOW}; moderate, μ_{MOD}; high, μ_H; and extreme, μ_{EXT}.

ENVIRONMENTAL CONDITION Environmental condition is a very broad term that includes several factors related to the ambient environment such as corrosive agents, temperature, humidity, and pressure. Each of these factors influences the fatigue behavior of a member in a different fashion.

The influence of a corrosive agent has been selected for illustrative purposes. Specifically, the effect of sodium chloride on the fatigue behavior and performance is examined. Sodium chloride can rapidly accelerate the corrosion process in steels. Corrosion is a serious problem responsible for the deterioration of highway bridges in certain regions of the country, such as the Midwest and Northeast, where de-icing salts are used in the winter. Another

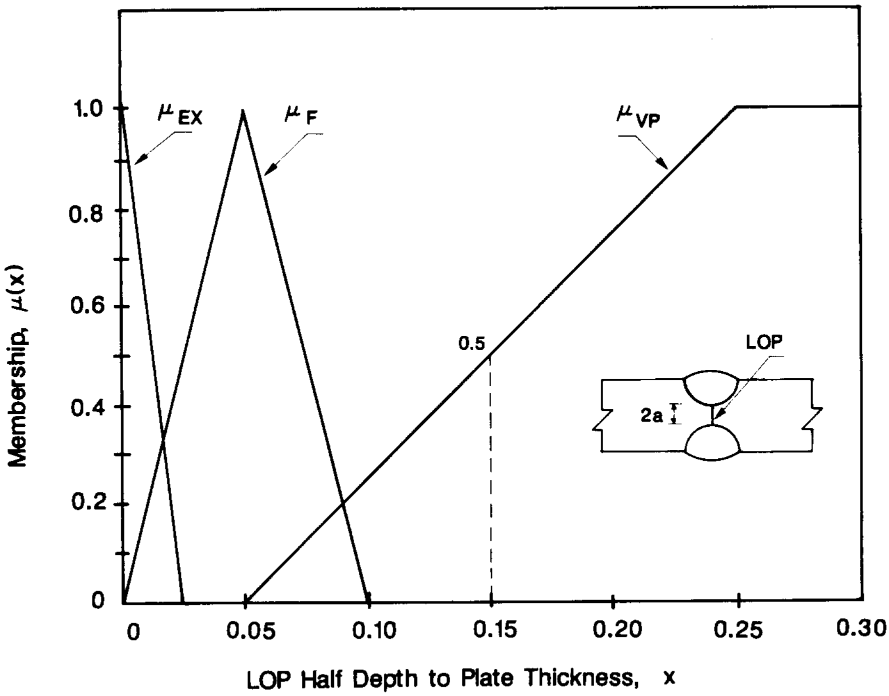

Figure 5. Membership Functions for Lack of Penetration

common application where sodium chloride is a factor is the use of steel near sea water.

The critical parameter used on formulating the membership functions is the percentage of the sodium chloride solution in the presence of the member. As the solution percentage increases, the corrosive effect becomes more severe.

The membership functions are shown in Figure 9. The five classifications used for the environmental condition are the same that were used for loading: light, low, moderate, high, and extreme. The purpose in using the same classifications is for ease in combining the loading and environmental factors. This is appropriate, as the loading and environmental conditions represent the sum of the external influences that can damage a structural element.

EXAMPLE PROBLEM

Problem Statement

The member type selected for examination is a butt-welded, mild carbon steel section used as a tension member in a highway bridge (see Figure 10). This

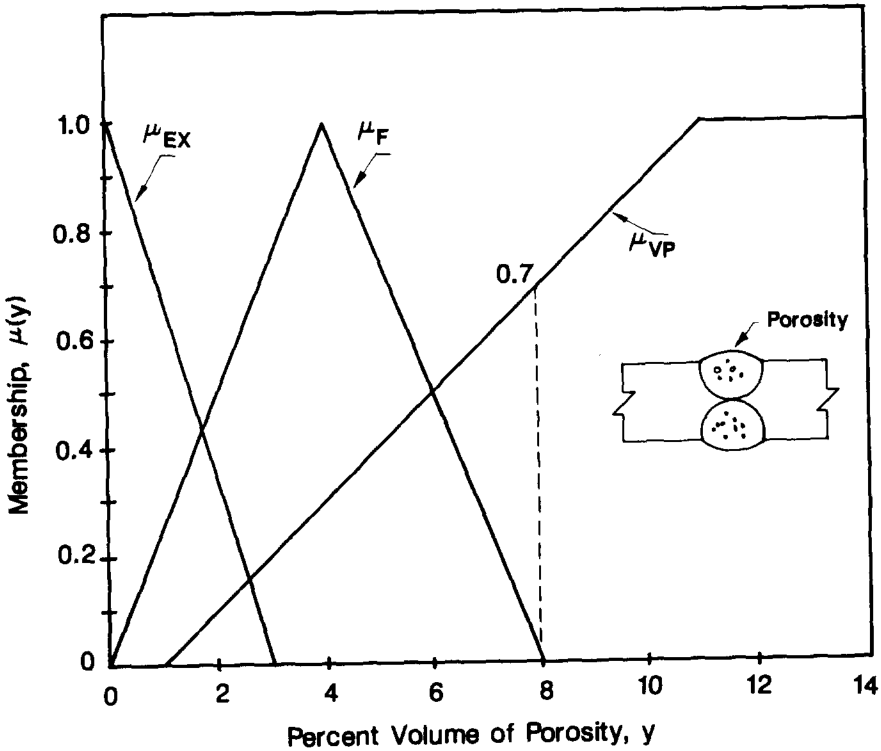

Figure 6. Membership Functions for Porosity

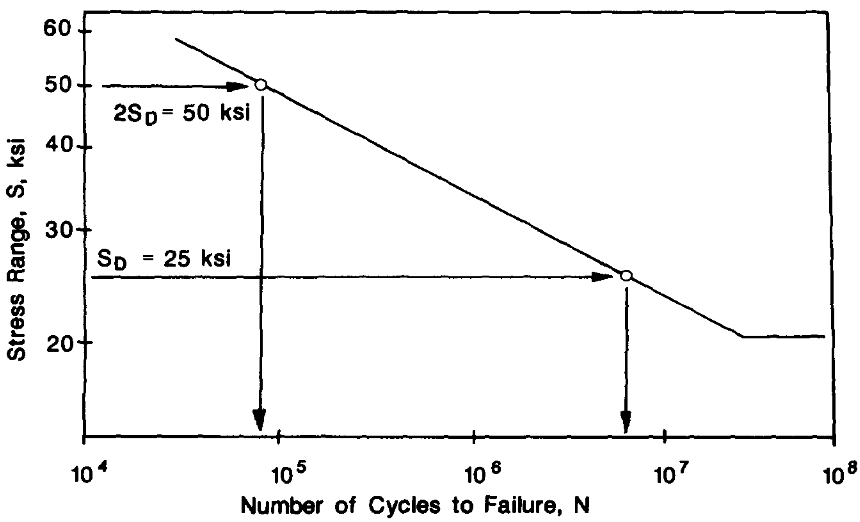

Figure 7. Reduction in Fatigue Life Due to Increased Stress Range

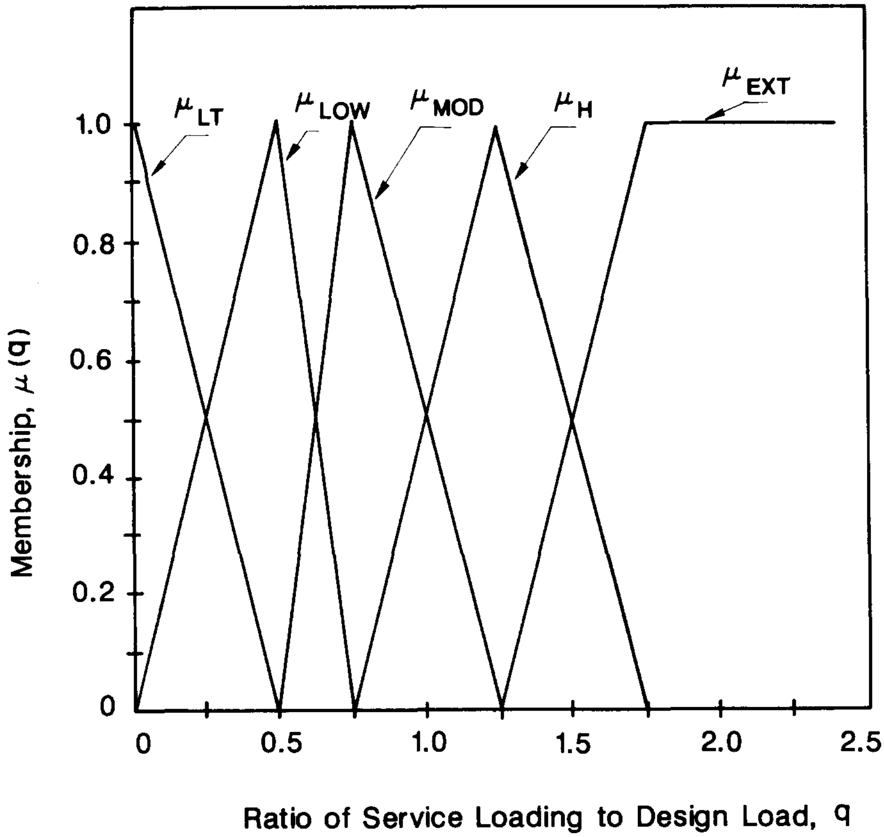

Figure 8. Membership Functions for Service Load Level

could qualify as a fatigue Category B member in the AASHTO Specification [28].

The example problem is presented to illustrate the use of fuzzy logic for evaluating the structural adequacy of the member. Several condition assessments are considered.

Initial Condition

A Category B classification requires that the weldment be nondestructively inspected to ensure adequate weld quality. It is assumed that the nondestructive examination has revealed that the following discontinuities are present:

$$w = 8 = \text{mm slag inclusion}$$

$$x = 0.15 \text{ LOP}$$

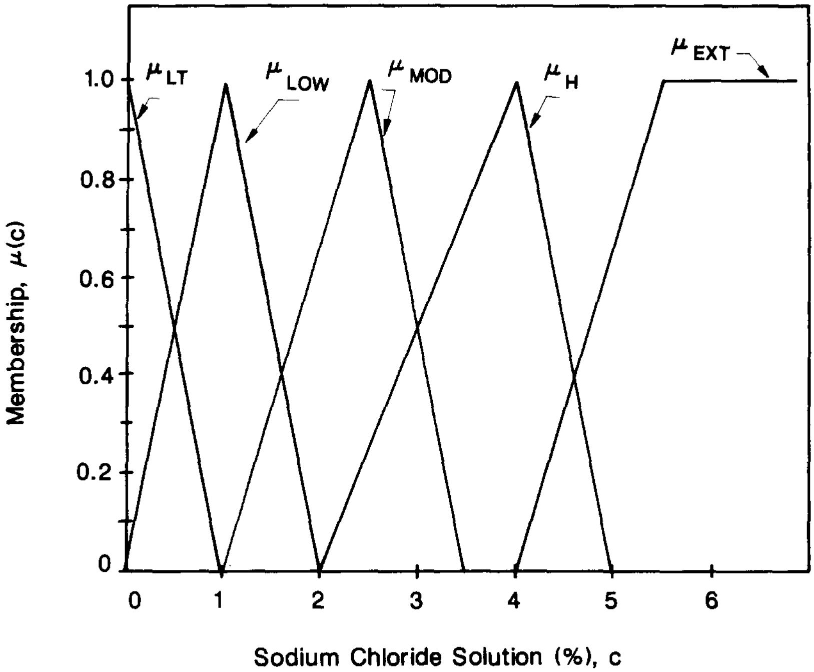

Figure 9. Membership Functions for Environmental Condition

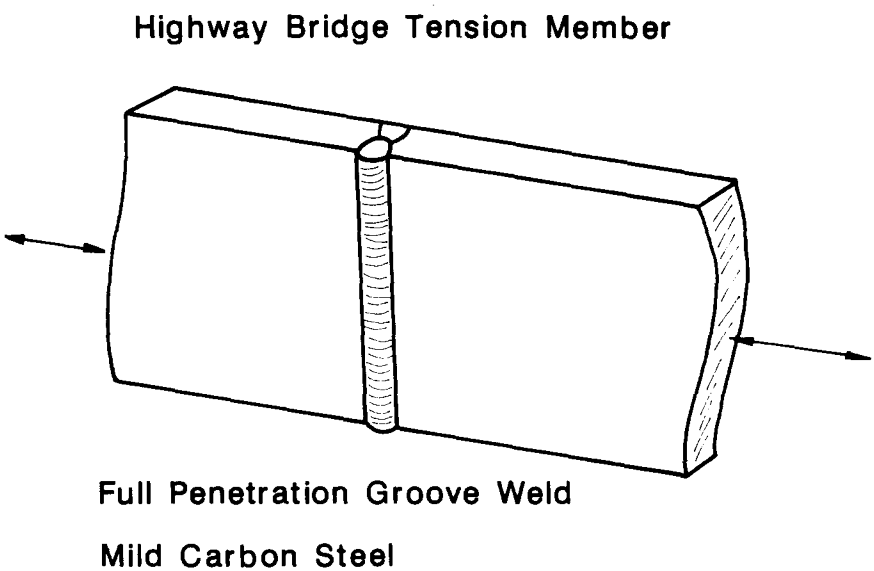

Figure 10. Welded Member for Example Problem

Table 1. Weld Quality Grades of Membership

Membership	Slag $w = 8$ mm	LOP $x = 0.15$	Porosity $y = 8\%$
Excellent	0	0	0
Fair	0.4	0	0
Very poor	0.6	0.5	0.7

$$y = 8\% \text{ porosity}$$

The grades of membership for excellent, fair, and very poor weld quality for each of the discontinuity types are summarized in Table 1.

Because more than one discontinuity was discovered, a method for combining the evaluations of weld quality for each flaw type must be utilized. One method is to examine a range in the behavior that corresponds to either no interaction or complete interaction of the weld discontinuities. The lower limit of this range in behavior occurs when each of the flaws are far apart from one another such that they act separately. The upper limit occurs when the flaws are nearby to one another so that significant interaction is possible and the flaws act effectively as a larger single flaw. Following an analogy in the theory of probability, this range in behavior may be obtained if the union and algebraic sum of the fuzzy sets are used. For example, consider two fuzzy sets A and B with memberships μ_A and μ_B. The union of the fuzzy sets is given by

$$\mu_{A \cup B} = \max\,[\mu_A,\ \mu_B] \tag{2}$$

and the algebraic sum is given as

$$\mu_{A+B} = \mu_A + \mu_B - \mu_A \mu_B \tag{3}$$

Equation 3 can also be expressed in the following form:

$$\mu_{A+B} = 1 - (1 - \mu_A)(1 - \mu_B) \tag{4}$$

A fuzzy damage set D that depends on fuzzy sets A and B will be bounded as follows:

$$\mu_{A \cup B} \leq \mu_D \leq \mu_{A+B} \tag{5}$$

Let us now return to the example and consider the grade of membership for very poor weld quality resulting from slag inclusion, LOP, and porosity. The union of the fuzzy parameters is given as

$$\begin{aligned} \max\,[\mu_{VP}(w),\ \mu_{VP}(x),\ \mu_{VP}(y)] &= \max\,[0.6,\quad 0.5,\quad 0.7] \\ &= 0.70 \end{aligned} \tag{6}$$

The fuzzy algebraic sum for very poor weld quality is given as

$$1-(1-\mu_{VP}(w))\ (1-\mu_{VP}(x))\ (1-\mu_{VP}(y))=1-(1-0.6)\ (1-0.5)\ (1-0.7) = 0.94 \quad (7)$$

Consequently, the classification for very poor weld quality falls in the range

$$0.70<\mu_{VP}<0.94$$

The fuzzy union and algebraic sum must also be evaluated for excellent and fair weld quality. The ranges associated with all three of the weld quality classifications can be summarized as

$$0\leq\mu_{EX}\leq 0$$

$$0.40\leq\mu_{F}\leq 0.40$$

$$0.70\leq\mu_{VP}\leq 0.94$$

It is clear from this example that there is a strong agreement with the "very poor" weld quality classification, and little agreement with the "fair" and "excellent" classifications.

To evaluate the loading and environmental condition, we will assume that (a) the loading is as expected with $q = 1.0$, and (b) the heavy use of de-icing salts results in a sodium chloride solution of $c = 4.5\%$. The grades of membership for the loading and environment, as well as the fuzzy union and environmental condition, are shown in Table 2. The strongest membership appears to be associated with the medium to high classification but is probably closer to the high side.

If the loading and environmental condition evaluation is combined with the weld quality assessment, we obtain point A on Figure 11. Repair procedures are necessary according to the fuzzy assessment procedure. The lines separating the required action regions (repair, inspect often, etc.) are based on expert opinion of the expected fatigue behavior. Serious fatigue problems can be expected to

Table 2. Loading and Environmental Grades of Membership for $q = 1$ and $c = 4.5\%$

Membership	$\mu(q)$	$\mu(c)$	Union	Algebraic Sum
Light	0	0	0	0
Low	0	0	0	0
Medium	0.5	0	0.5	0.5
High	0.5	0.5	0.5	0.75
Extreme	0	0.33	0.33	0.33

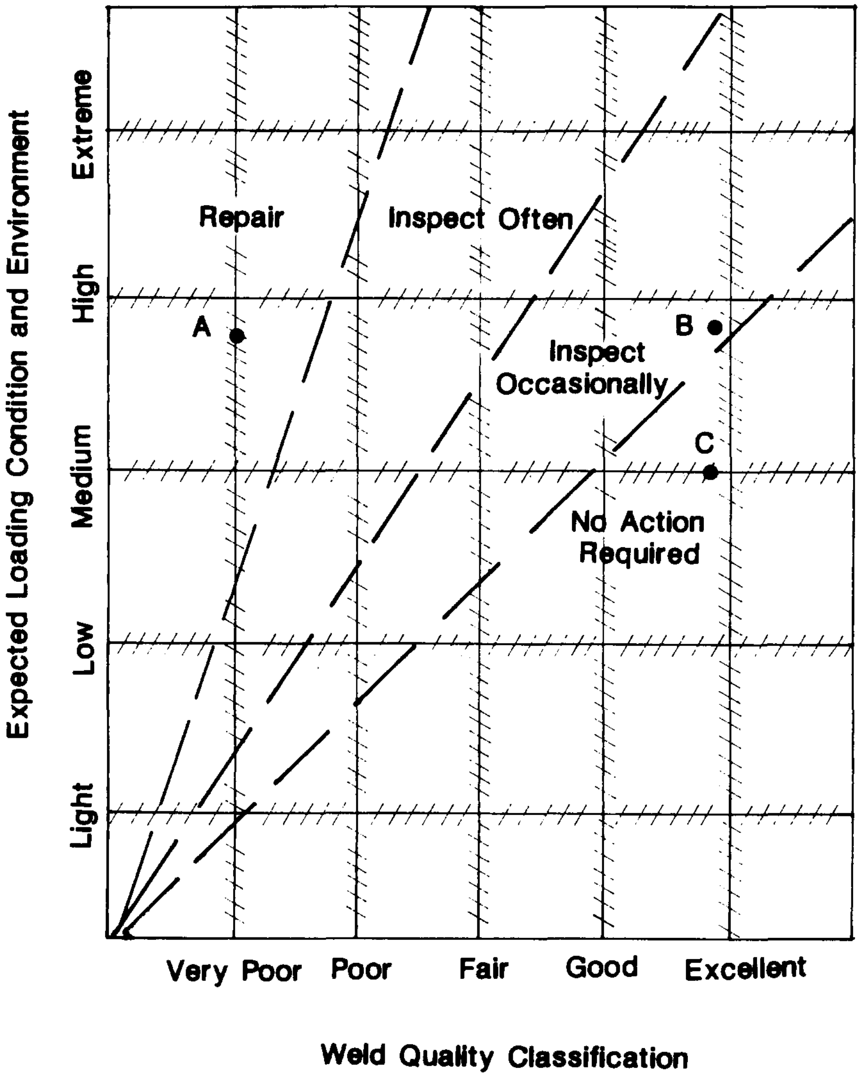

Figure 11. Repair Action Required on the Basis of Fuzzy Relationship

develop if no action is taken for the point A assessment. To avoid necessary and costly repairs, we must significantly reduce the loading and/or improve the environmental condition.

Finally, it should be noted that in the present example equal weighting was assumed for the various flaw types and for the loading and environmental factors. Although this assumption simplifies the example for illustration purposes, it may not always be reasonable. Weighting factors can be used to modify the values of the fuzzy variables to more realistically model their influence when information on the relative importance of the fuzzy parameters is available.

Repair Conditions

A decision to repair the weld in our example appears to be necessary. For the sake of illustration, we will assume that nondestructive examination after repair reveals that the following flaws are still present:

$$w=2=\text{mm slab inclusion}$$

$$x=0.01\ \text{LOP}$$

$$y=1\%\ \text{porosity}$$

The corresponding membership grade ranges for the three weld quality classifications are given as

$$0.67\leq\mu_{EX}\leq0.93$$

$$0.25\leq\mu_{F}\leq0.55$$

$$0\leq\mu_{VP}\leq0$$

The strongest membership is clearly associated with excellent weld quality. If the same loading and environmental conditions exist as before, then we obtain point B in Figure 11. The weld repair has improved the structural condition such that occasional inspection only is required to maintain the structural integrity of the bridge member.

The structural assessment can be improved further if the use of de-icing salts during the winter can be reduced such that the sodium chloride concentration can be cut in half. The membership grades and the fuzzy union and algebraic sum are given in Table 3 for values of $q = 1.0$ and $c = 2.25\%$. A strong membership is

Table 3. Loading and Environmental Grades of Membership for $q = 1$ and $c = 2.25\%$

Membership	$\mu(q)$	$\mu(c)$	Union	Algebraic Sum
Light	0	0	0	0
Low	0	0	0	0
Medium	0.5	0.833	0.833	0.917
High	0.5	0.125	0.5	0.562
Extreme	0	0	0	0

associated with the medium load and environmental condition. When combined with the improved weld quality condition, we obtain point C in Figure 11 for the overall structural assessment. For this combination of load, environment, and weld quality, there is no reason to suspect any fatigue problems and no need for further action.

SUMMARY AND CONCLUSIONS

The use of fuzzy logic in assessing the adequacy of structural members that must carry fluctuating loads has been examined. A number of factors are known to affect the fatigue resistance of a given member.

The study reported in this article classified these factors either as items to which the structure is subjected (loading and environmental condition) or items related to the structure itself (fabrication quality). A fuzzy condition assessment was then used to make decisions regarding the necessary repair or inspection action to ensure adequate fatigue resistance.

The following conclusions and summary remarks can be stated:

1. The use of fuzzy logic for assessing the fatigue resistance of a structure depends on the development of adequate membership functions for each of the fatigue critical factors.
2. The fuzzy relationship between the loading and environmental condition and the fabrication quality should be formulated through expert opinion on the basis of the overall effect on fatigue resistance.
3. The use of computer-based software would significantly improve the fuzzy-logic assessment process once adequate membership functions and combination procedures have been formulated.
4. Additional research and study is needed to further develop fuzzy logic methods for assessment of structural members and systems subjected to cyclic loadings.

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