Condition Assessment of Steel Structures

By Robert S. Vecchio, Ph.D., P.E.

Figure 1a

Safe and reliable operation of structures has been a major engineering priority. Condition assessment or fitness-for-service evaluation, therefore, plays a fundamental role in ensuring the integrity of such structures. Fitness-for-service (FFS) is a methodology, which accounts for actual service stresses, flaw or damage zone sizes, as-built material properties, and operating environment in determining the safety or reliability of a structure in its present condition or expected future state. Therefore, FFS is a common sense engineering approach to evaluating the suitability of a structure for its intended service. Moreover, a fitness-for-service assessment can provide the foundation for establishing the remaining life of a structure and, thereby, provide a platform for making capital based decisions for repair or replacement.

Steel, in particular, because of its extensive use in a wide assortment of structures (e.g., bridges, buildings, power plants, etc.) and its ability to be easily fabricated by welding, has become the most widely evaluated material with respect to fitness-for-service. Welded joints inherently contain flaws or discontinuities such as cracks, incomplete penetration, slag and/or porosity, and can exhibit altered material properties.

Traditional design of steel structures accounts for weld joint discontinuities and altered material properties by conservatively limiting the size of discontinuities permitted in fabricated joints and applying cautious safety factors to joint stresses. In effect, traditional design assumes that no significant flaws or service-induced damage (e.g., fatigue cracking, corrosion, fire-induced distortion) exists in the structure. In contrast, the fitness-for-service approach acknowledges the presence of flaws, damage, and/or degraded material properties and assesses a structure in its existing or anticipated condition. Thus, the FFS approach is a quantitative assessment, based on a rational evaluation of stresses, material properties, nondestructive examination, and fracture mechanics.

Figure 1b

Figures 1a and 1b: Ductile deformation and fracture of a bridge wind chord. Note the spalled paint in the vicinity of the deformation

Failure-Damage Modes in Steel Structures

In order to properly assess the fitness of a steel structure for continued service, it is important to recognize the potential failure modes, as well as likely types of flaws and damage mechanisms. Generally, failure modes are either instantaneous or progressive in nature, that is, failure occurs with little or no warning or it may be preceded by a considerable amount of detectable crack growth, deformation, or deterioration. Flaws and damage mechanisms can develop during service or be pre-existent. For example, a 4-inch long fatigue crack at the toe of a cover plate-to-flange fillet weld arises due to in-service cyclic loading, whereas a weld fabrication discontinuity, such as incomplete penetration, would be considered a pre-existent crack-like flaw. It is essential, therefore, that damage mechanisms be accurately assessed along with potential failure modes so that proper condition and remaining life assessments can be performed. The primary failure-damage modes for steel structures operating at ambient temperatures are as follows.

Ductile Failure

Of all the failure modes which can occur in steel structures, ductile failure or excessive distortion occurs least often, yet a significant share of almost every design code for steel that utilizes yield strength as the critical design parameter, is devoted to the prevention of ductile failure. Ductile failure is usually characterized by excessive inelastic (non-recoverable) deformation prior to attaining the steel's ultimate or tensile strength. A beneficial aspect of ductile behavior is the large amount of energy absorption that occurs prior to failure. In many instances, extreme or unanticipated loads can be redistributed within the structure without the consequence of failure. Frequently, excessive deformation occurs over a long enough period of time that the structure can be stabilized or abandoned before unacceptable property damage or injuries occur.

Ductile fractures, shown in *Figure 1a* and *1b*, are generally irregular in appearance, exhibit shear lips and localized "necking-down" (thinning of cross-section). Yielding is often identified by cracks or crazes in the paint and/or mill scale.

Brittle Fracture

In contrast to ductile failures, brittle fractures occur with little or no deformation and, therefore, with little or no warning. Brittle fractures initiate and propagate through steel structures at speeds approaching the speed of sound, and often at stress levels below

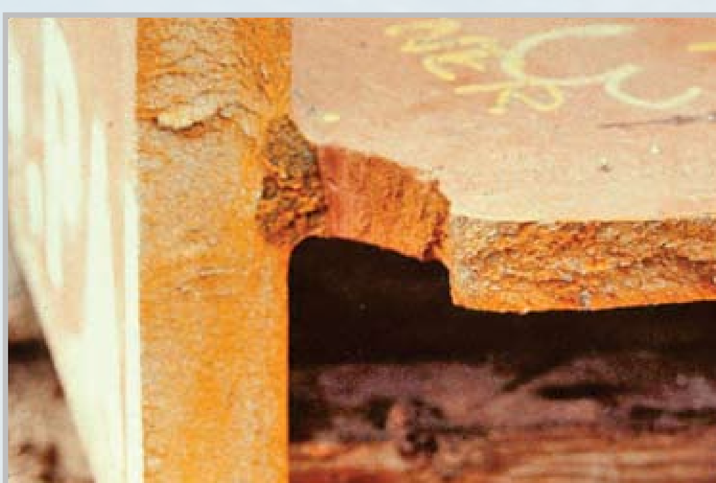

Figure 2: Brittle, low-energy fracture of a jumbo wide flange section used in the tension chord of a roof truss

Figure 3: Local buckling of a building floor beam

the yield strength or design allowable stress levels. The rapidity of brittle fracture propagation precludes the intervention of mitigating measures. Consequently, many brittle fractures result in significant structural damage, catastrophic failure, and/or serious injury.

Brittle fracture, shown in *Figure 2*, is typically characterized by flat fractures with little or no associated inelastic deformation. Most brittle fractures initiate from stress concentrations, such as weld flaws, in steels exhibiting low fracture toughness. It should be noted, however, that when local constraint is severe, brittle-like fractures can occur in steel structures even though they posses good ductility and toughness. The intersection of heavy welded plates creates a local region of high constraint, which limits the deformation capacity of the steel at the plate intersection. In fact, the level of constraint at the notch tip in general governs the brittle behavior of steels. The apparent reduction in notch fracture toughness at low temperatures and/or high loading rates is directly related to the effects that these parameters have on steel's yield strength. Low temperatures and high loading rates tend to increase steel's yield strength. Higher yield strength levels, in turn, generally result in smaller inelastic damage zones at the notch tip and the attendant lower fracture toughness. Fortunately, many currently produced steels are by virtue of improved manufacturing techniques that preclude these effects.

Figure 4a: Fatigue fracture of a structural steel bolt. Note fracture is characterized by a smooth dull appearance and beach marks.

Buckling/Instability

Buckling/instability of steel structures is the only failure mode that is dependent primarily on the structure's geometry and secondarily on steel properties. Moreover, it is the only failure mode that occurs principally under compressive loading, whereas most other failure modes occur largely under tensile loading. In general, column buckling behavior can be predicted by any of a number of Euler-like buckling relationships.

Buckling occurs almost exclusively in long slender members exhibiting large width-to-thickness ratios and can occur globally or locally, but is generally characterized by a rapid change in geometry and excessive distortion, as shown in *Figure 3*. Inelastic deformation usually follows the initial elastic instability. The dominant variable affecting the buckling strength of a column, other than its slenderness and eccentricity/distortion, is fabrication-induced residual stresses. Residual stresses create a stress distribution, which can be asymmetric, thereby creating eccentricity and eventually instability under compressive loading.

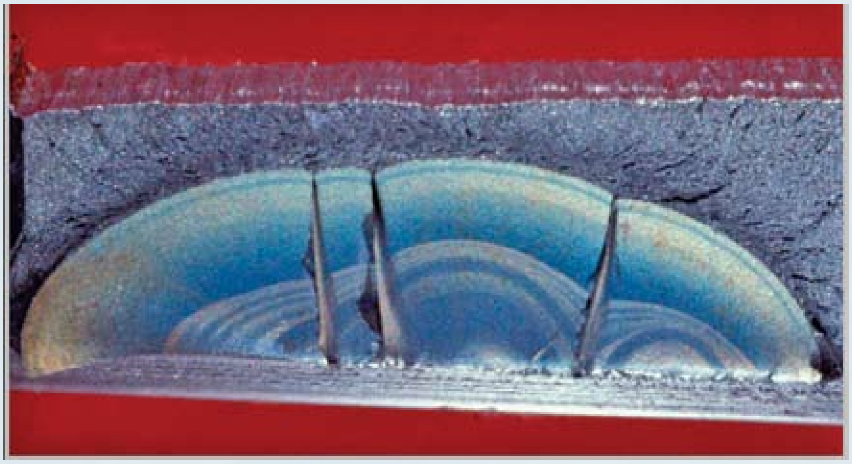

Figure 4b: Fatigue fracture of an aircraft wing. Note fracture is characterized by a smooth dull appearance and beach marks.

Fatigue

Ductile failure, brittle fracture, and buckling/instability usually occur under static loading conditions wherein the applied load exceeds a critical load. In contrast, most structures are subjected to repeating (fatigue) loads of varying magnitude, which are most often below yield strength and design stress levels. Fatigue loading occurs in bridges, buildings, power plants, aircraft, ships, railcars, trucks, and medical devices.

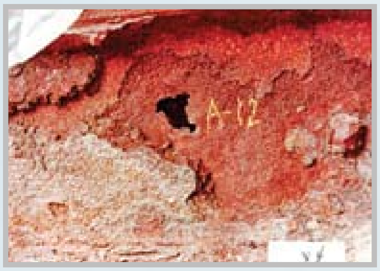

Figure 5: Severe generalized corrosion wastage of a structural steel member web

Fatigue failure is characterized by the initiation and growth of a crack due to repeated loading, which generates microscopic inelastic damage at regions of local stress concentration (e.g. weld flaws). If sufficient inelastic damage accumulates then a small crack develops, which then propagates through the structure. Failure occurs when the crack attains a critical size. Fortunately, fatigue is a progressive damage mechanism and is often identified before significant structural damage arises. Fatigue failures are typically characterized by flat fractures, little or no associated macroscopic inelastic deformation, and crack growth bands (beach marks) on the fracture surface, as shown in *Figures 4a and 4b*.

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Corrosion and Stress Corrosion Cracking

The most common failure mechanism in steel structures is damage due to corrosion. Since steel oxidizes when exposed to oxygen, particularly in moist environments, the opportunities for corrosion of steel structures are endless. Broad corrosion damage is referred to as general corrosion or wastage (*Figure 5*) and consists of overall thinning of a structure. Localized forms of corrosion include pitting, crevice corrosion, and stress corrosion cracking. Generally, it is the localized attack that presents the greatest potential for damage, as well as being the most difficult for detection/inspection and analysis of fitness-for-service.

Fitness-For-Service Assessment Procedures

In general, the concept that a structure with flaws or damage is fit for continued service is not new. Rather, many structures, both old and new, have sustained cracking or damage and continued to operate safely and reliably. Until recently, however, specific guidelines have not been available for structural condition assessment. A number of codes have been developed to address the FFS of existing steel structures such as API 579 (American Petroleum Institute, *Fitness-for-Service*), ASME Section XI *In-Service Inspection of Nuclear Power Plant Components* (American Society of Mechanical Engineers), ASCE *Guideline for Structural Condition Assessment of Existing Buildings* (American Society of Civil Engineers), and BS 7910 *Guide On Methods For Assessing The Acceptability of Flaws In Fusion Welded Structures* (British Standards Institute). The essential elements of a FFS assessment are described as follows:

Operating History and Original Design Review: Prior to performing a fitness-for-service evaluation, all efforts should be made to identify and collect relevant background and operating history data. This should include, but not be limited to, original design and as-built drawings and calculations; required safety margins; load/hydro test results; material certificates; fabrication procedures; operating and maintenance histories; repair records; current operating conditions; anticipated operating conditions; nondestructive examination results; and remaining life requirements.

Flaw and Damage Assessment: It is of utmost importance that the nature and extent of existing damage be quantified. If this is not done properly, then the FFS assessment is likely to be non-conservative.

Stress Analyses: FFS assessments require some level of stress analyses, from review of the original design calculations to detailed strain gage and/or finite element analyses (FEA). Strain gage analyses are particularly useful for cyclically loaded structures, since actual service loading data is far better than any assumed loading or results from an FEA.

Critical Damage Size/Remaining Life: The most important part of an FFS assessment is the calculation of the critical damage size, the largest acceptable crack size or maximum amount of metal loss tolerable for the structure. Once the critical damage size is determined, all other requirements such as remaining life or repair considerations are readily established.

Repair/Replacement: Suitability for continued service is wholly dependent on some form of in-service inspection or monitoring. However, if the rate of corrosion attack or crack growth is not known with sufficient confidence or the FFS assessment indicates that the structure is not suitable for continued service, then repair or replacement is required. Alternatively, if it is determined that the structure can be repaired, the repair method, its effect on the structure, and required inspections must be established relative to the required remaining life.

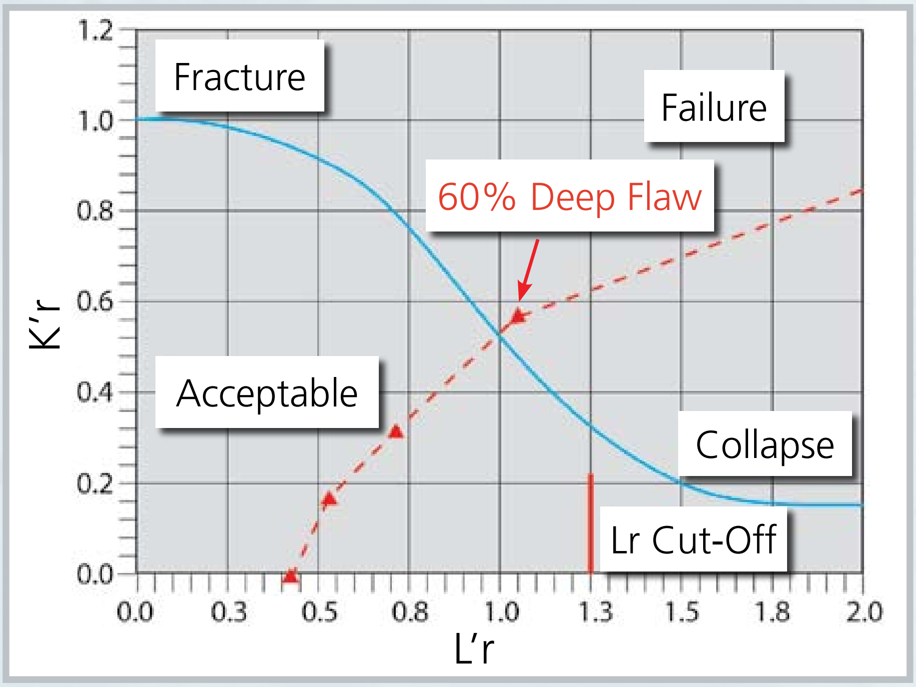


Figure 6: Failure assessment diagram showing the assessment points for a longitudinally oriented surface flaw in a cylinder subjected to internal pressure and bending stress

In-Service Monitoring: Regardless of the outcome from an FFS assessment, it is important that in-service monitoring programs be implemented to ensure the suitability of the structure for its intended function. Such monitoring is performed to: verify assumptions made in the FFS assessment, assess the rate of crack growth or continued corrosion-induced deterioration, identify new cracking or corrosion damage before it becomes critical in nature, make certain that changes in recommended operating procedures are being carried out, and identify significant changes in the operating environment.

Evaluating Steel Structures with Crack-Like Flaws

FFS evaluation of steel structures with crack-like flaws is most reliably accomplished using fracture mechanics. Crack-like flaws are structural discontinuities that are planar in nature such as cracks, sharp notches and weld discontinuities (undercut, incomplete fusion and penetration).

Since crack-like flaws induce local stress fields which are not readily characterized by customary stress analysis techniques, fracture mechanics has evolved as the only acceptable methodology for predicting their behavior. Within the fracture mechanics framework, the failure assessment diagram (FAD) is the most comprehensive approach. This method accounts for the interaction of rapid-unstable fracture, ductile tearing and/or plastic collapse. A typical FAD failure locus, shown in Figure 6, is described by the following relationship in terms of the brittle fracture ratio (K_r) and ductile (reference) stress ratio (L_r).

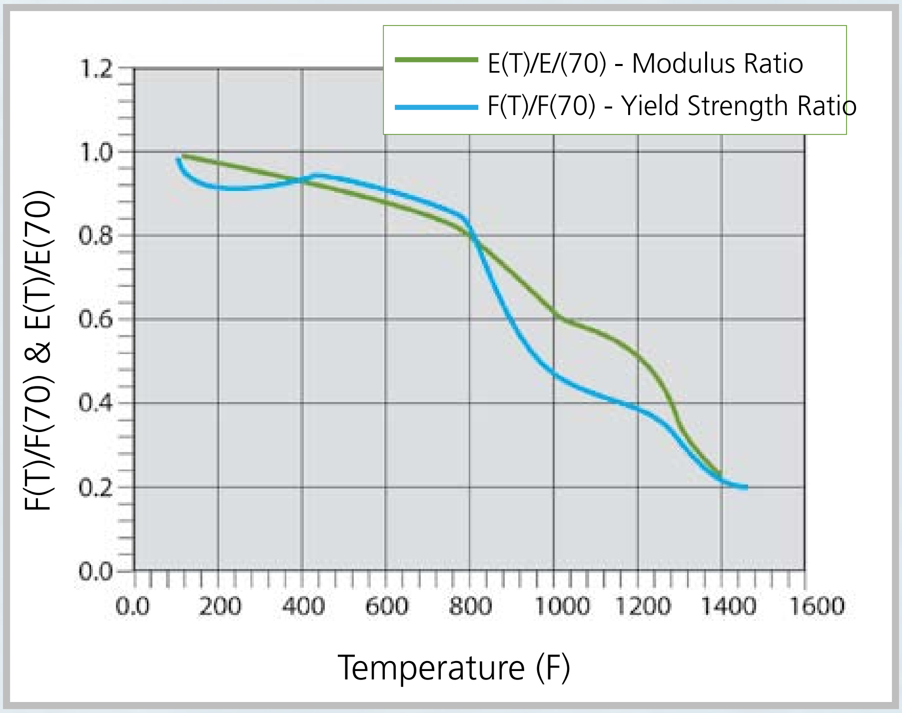
$$K_r = \left(1.0 - 0.14(L_r)^2\right)\left(0.3 + 0.7\exp\left[-0.65(L_r)^6\right]\right) \text{ for } L_r \geq L_{r(max)}$$

Equation (1)

where $L_{r(max)}$ is the ductile fracture cut-off limit and varies from 1.25 to 1.80.

A FAD analysis requires the calculation of the crack-like flaw assessment point, $L'_r - K'_r$, where L'_r is the ratio of the applied stress to the corresponding stress at the limit load and K'_r is the ratio of the applied stress intensity factor (K) to the fracture toughness (K_{1c}). Failure is indicated when the assessment points, $L'_r - K'_r$, intersects or exceeds the FAD failure locus (*Figure 6*). Margins of safety are also easily incorporated and allow for the consequence of a failure, the importance of various failure modes, and variations in material properties.

For a cracked structure, stress intensity factor (K_r) and reference stress solutions (L_r) can be obtained from existing compilations or derived using the finite element method. Fracture toughness and tensile properties for the structure are required. While tensile testing is relatively inexpensive and tensile properties are only secondarily dependent upon temperature, fracture toughness testing is considerably more expensive and is strongly dependent on temperature. An alternative and significantly less expensive methodology for determining fracture toughness is the estimation of fracture toughness from small specimen Charpy V-notch impact test results.



Assessment of Corrosion Damaged Structures

As with most FFS assessments, the initial stage of a corrosion damage assessment is a triage-type analysis. Accordingly, more advanced corrosion damage is given more rigorous treatment, when the consequence of failure is severe. Less severe corrosion damage can be assessed with simpler analyses. However, the simpler analyses incorporate a notable safety margin that can result in excessive conservatism. The most in-depth analyses typically require detailed modeling of the actual geometry, service loading and material properties. API 579 provides an excellent methodology for the assessment of corrosion damage.

A simplified corrosion assessment can be performed if the consequences of failure are low. This approach assumes the maximum metal loss measured during inspection occurs over the entire component. Hence, future thickness (t) as a function of time in future service (T) is estimated using the current minimum measured thickness (t_c), maximum attack found in inspection (Δt_{max}) and the time (T_o) over which Δt_{max} occurs:

$$t = t_c - (\Delta t_{max}/T_o)(T) \qquad \textit{Equation (2)}$$

Remaining life is based on the maximum corrosion rate and the minimum design thickness, and assumes the original design loading is still valid. When a simple analysis proves to be too conservative, corrosion damage can be modeled using more rigorous analytical techniques, such as FEA (see API 579 Appendix B).

Assessment of Fire Damage

Common structural steel members (e.g., beams, columns. and plates) are generally fabricated from plain low carbon steel and furnished in the hot rolled or normalized condition with a ferrite-pearlite microstructure. Accordingly, the strength of these steels does not change significantly when exposed to temperatures up to approximately 800°F. On the other hand, structural steels exhibit a dramatic loss in strength and modulus at temperatures above 1000 to 1200°F, as shown in *Figure 7*. More importantly, the tensile properties of these steels change only marginally after cooling if the steels had been heated to less than approximately 1200°F for a short time (i.e., several hours). Therefore, typical structural steels exposed to fire, do not exhibit significant changes in tensile properties following the fire.

In contrast, high strength carbon and alloy heat-treated steels used in fasteners are susceptible to metallurgical degradation when exposed to the heat of a fire. High strength fasteners (ASTM A325 and A490) are usually fabricated by quenching and tempering in the range of 800 to 1200°F. Hence, a substantial reduction in strength occurs following exposure to temperatures above about 800°F.

Assessment of damaged structural steel members following a fire is most effectively performed using a multi-level approach. Assessment is performed in steps such that the extent of damage is categorized according to overall distortion, followed by subsequent detailed evaluations, as necessary. Initial visual examination should document the extent of global distortion such as camber and sweep and the extent of local deformation such as stiffener or flange buckling.

A site evaluation of a fire-damaged structure should be performed as quickly after the fire as possible to facilitate the identification of the most highly heated locations. In this regard, fire-induced temperatures at various locations can be visually appraised based on the following damaged material characteristics:

- Wood and paper ignite at approximately 450°F, plastics melt or burn between 180 and 350°F;
- Concrete changes color at approximately 550°F and becomes deep red at 1100°F;
- Coatings, markers and paints usually change color, blister or spall above 600°F.
- Steel mill scale starts to spall with the associated development of coarse surface texture above 1200°F.

More often than not, the most severe damage generally sustained by structural steel members exposed to fire is excessive distortion. It is common practice, therefore, to sort fire exposed structural steel into three categories based on the extent of distortion, as follows:

- Visually unaffected,
- Somewhat deformed and economically repairable, and
- Severely deformed and replacement is required.

It should be noted that the existing pre-tension force in bolts might also be lowered as a result of relaxation if the bolts are heated to temperatures above approximately 950°F. Distortion of the steel members during the fire can also cause overloading and plastic deformation of the bolts with a loss of pre-tension even if the bolts had not been heated.

Once it has been determined that distortion is not excessive, it is often desirable to verify that the heat of a fire has not significantly affected steel strength. If it is suspected that excessive heating (>1200°F) has occurred without accompanying distortion, then the in-place strength of steel members can be estimated by hardness testing. Steel hardness correlates reasonably well with its tensile strength. However, the hardness and, therefore, the strength of high strength bolts can be significantly reduced below the required level when heated above the tempering temperature (800-1000°F). Alternatively, coupons can be removed for tensile testing in order to determine yield and tensile strength, as well as ductility. However, care must be taken when removing coupons so as to avoid adversely affecting the load carrying capacity of the member and inducing any stress concentrating effects due to cutting the member.

Conclusion

Condition or fitness-for-service assessment plays a fundamental role in ensuring the integrity of steel structures. This article has described the failure modes of steel structures and several ways cracked or damaged structures can be successfully evaluated and restored to service.▪

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Structural Condition Assessment (Ratay) can be purchased through the American Society of Civil Engineers' (ASCE) Bookstore (**www.pubs.asce.org/books2.html**) or directly from John Wiley & Sons (**www.wiley.com**).

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