Cyclic Mechanical and Fatigue Properties of OCTG Materials

Much of the design for well structures subjected to high-amplitude cyclic loading is based on material assumptions that extrapolate strength properties from uniaxial, monotonic tests to conditions where cyclic, multiaxial stresses are imposed. The full-length paper presents results from cyclic testing on common oil-country tubular goods (OCTG) materials and shows the difference between physical behavior measured under cyclic-loading conditions and theoretical behavior extrapolated by numerical modeling. Modeling theories for plastic deformation are discussed, including their limitations and relevance in a cyclic-loading environment.

Introduction

Most thermal-recovery oil wells in western Canada operate by use of cyclic steam stimulation (CSS) or steam-assisted gravity drainage. Both methods impose thermal cycles on well structures, particularly the intermediate casing. Thermal expansion is constrained by the formation and cement, producing loads that exceed tubular yield strength when the well is heated. Localization mechanisms amplify strain magnitude, imposing additional plastic-fatigue loads at discrete locations in the well.

Thermal-well casing designs have evolved through more than 30 years of operating experience, and much of the computer modeling that describes casing performance is based on uniaxial material properties, extrapolated to multidimensional and cyclic behavior through engineering models.

Cyclic material-properties data are very sparse, particularly in the temperature range common in thermal-recovery wells. Furthermore, plastic-fatigue-life information for materials commonly used in well construction is difficult to obtain. Such information, however, is required to make reliable predictions of certain deformation mechanisms and associated fatigue life for wells exposed to cyclic, thermally imposed deformations.

A test program for characterizing cyclic material properties was undertaken to evaluate both cyclic mechanical properties and low-cycle fatigue life. Test results demonstrate consistency indicative of reliable material characterization that can be applied in analysis models and component life assessments. The observed cyclic behavior also demonstrates material characteristics significantly different from those predicted through engineering models using uniaxial, monotonic material properties for input. This has important implications for selection of steels used in thermal-well designs and for implementing techniques to mitigate casing-deformation effects.

Background

Post-Yield Plasticity. Much of the work to characterize metal post-yield behavior was developed to support structural analysis under conditions where the load exceeds that required to yield some components. Material properties usually are determined from uniaxial coupon tests that give elastic modulus, yield strength, and post-yield strengthening or hardening. Structural modeling, whether analytic or numeric, requires that behavior measured in one dimension be extended into a multidimensional stress state. Furthermore, plastic behavior is load-path dependent (i.e., the stress state is not defined uniquely by the strain, but rather depends on the history of plastic deformation).

The most common plastic-analysis modeling approach for structures is the finite-element-analysis (FEA) method. It is understood that metal plasticity is independent of static stress and that plastic deformations can occur without volumetric change. This simplifies many aspects of material characterization and mathematical-modeling requirements.

Associated Flow With Isotropic Hardening. The most basic plasticity model used in analysis uses the von Mises effective-stress function, the associated flow rule, and an isotropic hardening model. This model works well in many situations, particularly where the loading is proportional and monotonic. Hardening is correlated to the accumulated effective plastic strain, which is a mathematical consolidation of the multidimensional incremental plastic strain components into a single variable representative of the plastic strain from a material-coupon test. The predicted uniaxial-elastic-strain range starts at twice the elastic limit and increases with plastic deformation.

Associated Flow With Kinematic Hardening. In applications where loading is not monotonic or proportional, other material aspects can become important. One material characteristic observed under cyclic-loading conditions is a reduction in yield strength in one direction when the material is hardened in the reverse direction. This commonly is known as the Bauschinger effect. A simple approach for capturing this analytically is with the common kinematic-hardening model, which keeps the same stress range by translating the yield "surface" rather than expanding it as is done in the isotropic-hardening model. The uniaxial-elastic-stress range starts at twice the initial elastic limit and remains constant.

Mróz Plasticity Model. Measurements of stress response to cyclic deformations demonstrate more-complex behavior than is captured by models that characterize hardening behavior with a single accumulated-plastic-deformation variable. Typically, the elastic range in a stress reversal following plastic deformation in one direction is substantially smaller than twice the elastic strength, typically no larger than the elastic limit, and often even smaller than that.

*This article, written by Assistant Technology Editor Karen Bybee, contains highlights of paper SPE 97775, "Cyclic Mechanical and Fatigue Properties for OCTG Materials," by **T.M.V. Kaiser,** SPE, and **V.Y.B. Yung,** SPE, Noetic Engineering Inc., and **R.M. Bacon,** Imperial Oil Resources, prepared for the 2005 SPE International Thermal Operations and Heavy Oil Symposium, Calgary, 1–3 November.*

Mróz plasticity models track plastic deformation through tensor, rather than scalar, functions, allowing cyclic behavior to be modeled in much greater detail. While the effectiveness of these models is widely demonstrated in the literature, the complexity of such models can be difficult to implement in numerical-modeling strategies.

Fatigue Failure. It is well known that a structure able to withstand initial loading without failure might fail if the loading is removed (or reversed) and reapplied repeatedly. This phenomenon, known as fatigue failure, has been studied extensively and normally must be determined experimentally.

Material Behavior

Because material behavior usually is temperature dependent, thermal sensitivity of material properties should be considered when designing wells for thermal applications.

Physical Material Behavior. Materials used for OCTG show a complex stress/strain response when subjected to large plastic deformations. Empirical data presented in the full-length paper demonstrate some of these complexities. Material test coupons were taken from a single tubular of 178-mm, 34.3-kg/m L80 casing commonly used in OCTG applications, and tests were conducted at room temperature (i.e., 20°C).

Mechanical Behavior. **Fig. 1** shows the measured response of a uniaxial test coupon loaded monotonically in tension to 3.3% strain (solid line), and then cyclically with a strain amplitude of 2.8% (dashed line). The monotonic loading starts with an elastic response. A stress peak is observed at the initial yield point, followed by a stress plateau. Many metals exhibit such behavior during monotonic loading. However, following load reversal in subsequent cyclic loading, the materials often exhibit a gradual transition from elastic to plastic deformation (a "round-house" curve). In addition, yielding in reverse and subsequent cyclic loading occurs at a lower stress magnitude than during the initial monotonic loading (the Bauschinger effect). The results demonstrate that the observed cyclic elastic-stress/-strain range is less than the value predicted by the kinematic-hardening assumption. When modeling material response, it often is necessary to treat the different monotonic- and cyclic-loading responses of the material separately. In this example, the elastic range is shown to be approximately equal to the current yield strength in the initial monotonic loading.

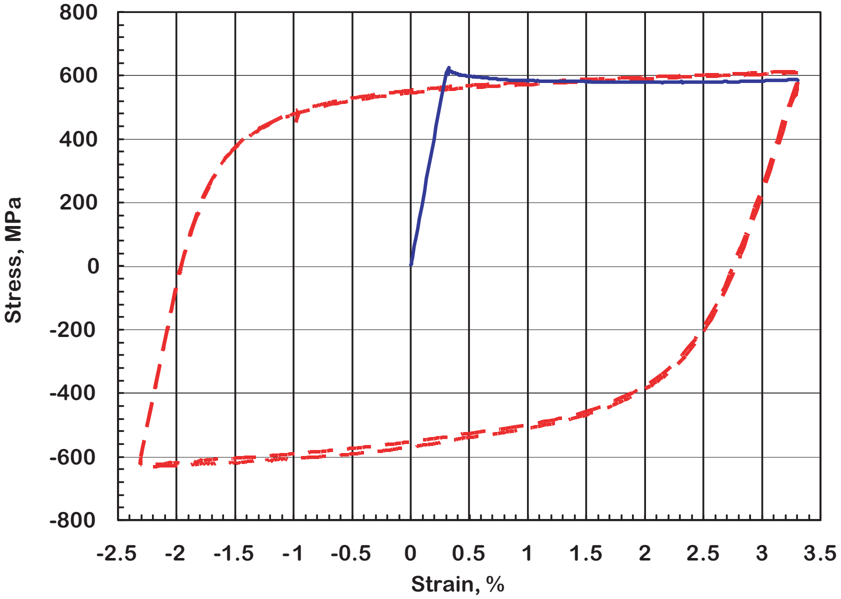

Fig. 1—Measured stress/strain response.

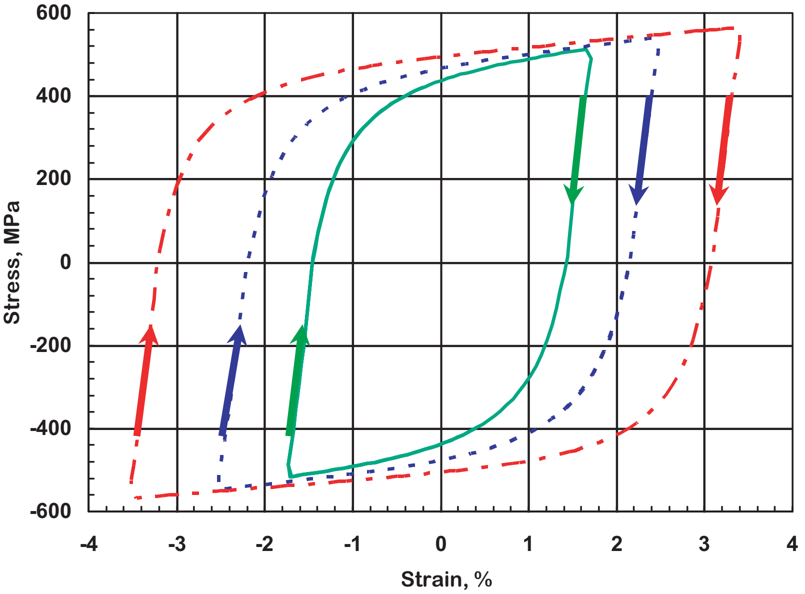

Fig. 2—Measured cyclic stress/strain for three strain amplitudes.

Fatigue Behavior. Low-cycle fatigue-life tests also were conducted on coupons of the same OCTG steel at three different strain amplitudes. The characteristic stress/strain curves shown in **Fig. 2** were obtained at the half-life cycle for each coupon. The data demonstrate that stress amplitude under cyclic loading is a nonlinear function of strain amplitude. The nonlinearity is most pronounced for strain amplitudes less than 1%, where the round-house yield has greatest influence.

Structures in thermal wells may experience temperature changes of approximately 310°C. Thermal expansion constrained by the formation results in a global, total mechanical strain of approximately 0.45%. Using L80-grade casing, the results of material-fatigue tests indicate a well life of more than 1000 cycles at this strain level. By these results, the current design basis for thermal wells is more than adequate when the design assumptions are satisfied.

Higher-than-expected strain levels can occur locally within a well because of strain localization and formation movement, as commonly occurs at the top of the producing reservoir. These higher strain levels can lead to fatigue failure within a few cycles. Strain localization occurs where a part of the well structure has reduced stiffness relative to the surrounding structure, as a result either of variations in manufactured product or of damage introduced by other loads. Under thermal loading, this part will experience more strain than the surrounding structure.

Modeled Behavior. Structural response predicted by FEA is dependent on the material model used in the analysis. To be of practical use, mathematical models used to predict material behavior are idealized and simplified. However, models must capture essential material characteristics to make reasonably accurate predictions under conditions that cause material deformation.

Coupon tests provide information on material response under uniaxial loading conditions. To predict the behavior of well structures, the FEA model must predict material response to general, multiaxial loading. Hardening rules relate post-yield response under multiaxial or cyclic loading to the post-yield response under monotonic, uniaxial loading. FEA software typically provides isotropic-, kinematic-, and mixed isotropic-/kinematic-hardening rules in its material models. The full-length paper contains a detailed discussion of these hardening rules.

Applications

Industry-Recommended Practice (IRP) for Thermal-Well Design. The Petroleum Industry Training Service in Alberta, Canada, maintains an IRP document for heavy-oil and oil-sands operations. Included in the recommendations is an approach for designing wells for thermal operations to accommodate cyclic thermal loads. An appendix includes descriptions of casing response to thermal and cyclic loads for a variety of materials and indicates that the casing material will "harden," or increase in yield strength when the thermal-strain range exceeds the elastic range of the material. These conclusions are based on computer simulations of material response extrapolated from uniaxial physical material tests. Multisurface constitutive models with thermal dependence were not available when work for the IRP was performed. With only uniaxial coupon test data available, the plasticity models were the only means available to perform the parametric assessment of various materials that was required for the IRP. Recognizing that isotropic- and kinematic-hardening models do not capture reliably some aspects of cyclic behavior, particularly hardening behavior, some cyclic hardening conclusions of the IRP should be revisited.

There is some physical evidence that cyclic thermal loads do not always produce the round-house behavior indicated by the test results presented, and that the total elastic range is closer to the full range modeled by kinematic-hardening assumptions. This could be a result of not considering any localization behavior in the constrained total strain in the tests that produced the data. Also, the testing included a limited number of thermal cycles and small plastic-strain amplitudes and did not validate the conclusion of material hardening under cyclic loads.

Fatigue Predictions of Deformed Casing and Mitigation Options. Casing deformation has been observed in some wells used in CSS operations in western Canada. Workover difficulties indicate possible deformations, and multisensor caliper logs and interpretation techniques are available to quantify the deformation. Well casing is remarkably tolerant of moderate lateral deformations. While such deformations may appear severe, modest additional cyclic plastic strain associated with the deformation corresponds to a relatively long fatigue life. Serviceability often becomes an issue before pressure integrity. Consequently, monitoring programs have been implemented to track deformation progression in such wells from cycle to cycle, and decisions regarding continued well operation are made on the basis of that progression.

The decision-making process to determine continued well serviceability could be improved if a quantitative basis could be developed. Furthermore, such a quantitative basis also could be used to assess the mitigation-option effectiveness for extending the life of deformed casing. Reliable cyclic mechanical and fatigue properties are a key component of any predictive approaches to providing such assessments.

An FEA model has been developed to simulate the behavior of deformed casing under cyclic thermal conditions. The model was calibrated with results from a physical test program to demonstrate a deformation mode that approximates that observed downhole through caliper-log imaging. The calibration exercise revealed a number of modeling issues that needed to be resolved, particularly material-modeling aspects. For example, material behavior in the first compressive loading was substantially different from that indicated during cyclic loading. Consequently, model adjustments were required to allow the material properties to be changed after the first half-cycle. These results also confirmed that the path-dependent material behavior indicated by material coupons also applies to full-scale applications. The result of this "discovery" was a requirement for better deformation control and monitoring during the first half-cycle of all tests.

Summary and Conclusions

Both mechanical and fatigue properties for the L80-casing material were measured at ambient temperature. The results indicate that the cyclic elastic range of casing material is significantly smaller than usually is determined under common industry design assumptions (i.e., the kinematic-hardening rule). However, low-carbon steels similar to the tested material generally offer substantial fatigue life, which results in a conservative design basis under moderate cyclic plastic-strain loads. The conclusion drawn from these observations is that a strain-based approach provides a more suitable design basis for constrained thermal wells. Under this design approach, alternative grades of material can be considered for these wells to offer increased flexibility in well design to satisfy other demands, provided that good fatigue life can be demonstrated.

A review of commonly available mathematical models for simulating material behavior in structural analysis was provided in the context of cyclic material response. While most of these models offer good value for the majority of structural analyses, some modeling issues were raised for applications with cyclic deformations. The most common isotropic-hardening models were shown to indicate artificial hardening in the material with cyclic plasticity. The kinematic-hardening model was indicated to demonstrate reduced strength with accumulation of plastic strain. The multisurface Mróz-type models show the most promise for accurately modeling cyclic deformation behavior, but successful implementations of these models are sparse in the analysis industry. As analysis methods are increasingly applied to problems in the thermal-production area of the oil industry in conjunction with strain-based design methodologies, development and implementation of a reliable Mróz-type multisurface model will be an important step for supporting this type of design. The most useful approach to achieving this goal will be to implement the model as a user subroutine in one or more of the major multipurpose finite-element codes. JPT