Development of improved fatigue design procedure for nuclear/non-nuclear materials subjected to simple/complex cyclic loads

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Abstract

The piping/ vessel components of Indian Nuclear Power Plants (NPPs) are subjected to complex multiaxial cyclic conditions. These components are designed for envisaged cyclic conditions using standard codes. The current design procedures under complex multiaxial cyclic loading conditions do not adequately account for fatigue damage. Therefore, such design procedures result in inaccurate fatigue life assessments. In this regard, extensive fatigue tests have been conducted to determine the extent of fatigue damage under complex multiaxial conditions vis-à-vis simple uniaxial cycling. A new procedure has been developed which predicts fatigue crack initiation life and crack orientation plane reasonably well. The developed procedure has been validated for various materials used for nuclear and non-nuclear applications.

Keywords: Fatigue crack initiation life, multiaxial, cyclic plasticity, critical plane models, crack initiation plane

Introduction

Almost all structural components used for nuclear and non-nuclear applications are subjected to cyclic loads during their design life. The fatigue failures may occur in material even if it is subjected to load amplitudes lesser than the yield strength of material. Therefore, the conventional fatigue design procedure differs from that under static (or non-cyclic) load conditions.

A very large factor of safety, typically 20 on number of cycles or 2 on stress amplitude, whichever is conservative, is adopted in fatigue design codes unlike 1.5 on yield strength or 3 on ultimate tensile strength, for the design against static loads. Despite this large factor of safety for cyclic loading, various fatigue related failures have been cited by International Atomic Energy Agency (IAEA) for various components of Light Water Reactors (LWRs) ([1],[2]). This indicates that either the conventional design procedure does not adequately quantify the fatigue damage or even a large safety factor of 20 on number of cycles is inadequate.

This mismatch in realistic fatigue damage and that as quantified using design code, is primarily due to the use of material fatigue life curve determined under pure axial cyclic conditions for benign air environment. However, the real component of NPP is subjected to multiaxial state of cyclic stresses/ strains under comparatively harsh coolant environment. These major key points of multiaxial cyclic stress state and synergistic damage under corrosion-fatigue are not accounted in the present design explicitly.

To overcome this shortcoming, it is required to understand the fatigue damage under complex multiaxial stress state vis-à-vis pure axial conditions and quantify the variable safety factors (in-spite of fixed factor of 20) for various operating coolant conditions w.r.t. air at room temperature. For this purpose, the present study investigated the first key reason of stress multiaxiality. Extensive test investigations have been performed on primary piping material of Pressurized Heavy Water Reactor (PHWR) under simple uniaxial and complex multiaxial cyclic conditions. The actual fatigue life under such conditions has been determined and compared with that predicted using present fatigue design procedure. The popular critical plane models, as available in literature, have also been explored. The predicted fatigue life using existing code procedure/ popular critical plane models is found to be higher than that observed in many multiaxial fatigue tests.

A new simple-to-use critical plane model has been developed which results in accurate fatigue life assessments for PHWR piping material. The validity of the developed model has been confirmed w.r.t. 17 different ferrous/ non-ferrous alloys used for various engineering applications and subjected to wide variety of simple/ complex multiaxial cyclic conditions.

Uniaxial and multiaxial fatigue tests: Determination of fatigue life

Extensive uniaxial and multiaxial fatigue test data have been generated on Primary Heat Transport (PHT) piping material (low carbon steel) of PHWR ([3], [4]). The duration of each fatigue test typically varies from few days to several weeks depending on the applied loading conditions. Typical multiaxial test set up
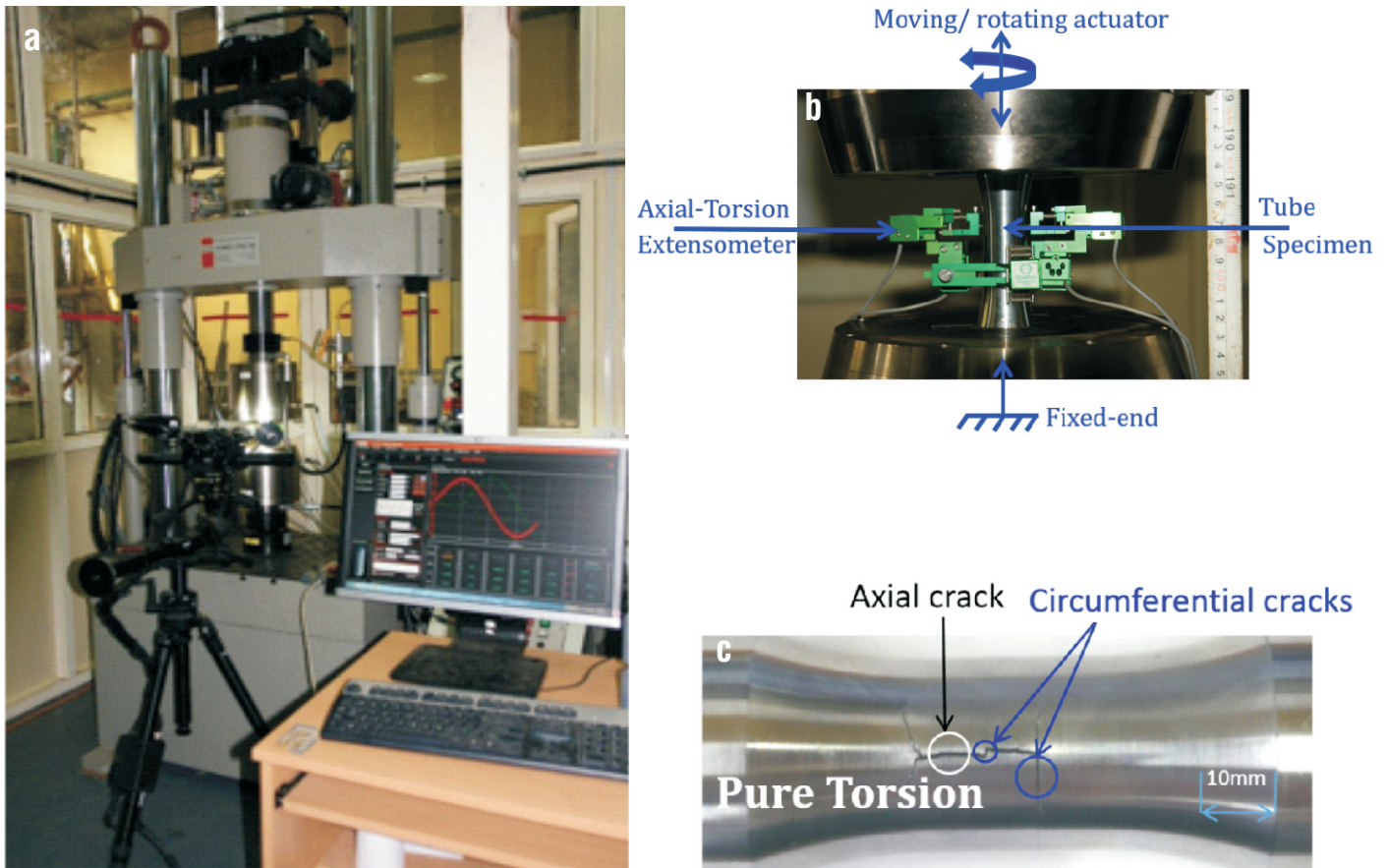
Fig. 1: (a) Multiaxial fatigue testing machine, (b) Tube sample mounted with biaxial extensometer and (c) Cracked tube after fatigue test

showing a tube (representative material of PHWR piping component) along with necessary instrumentation, has been shown in Fig. 1.

A wide variety of multiaxial loading conditions simulating different service transients, have been investigated. These multiaxial loadings can be in-phase or out-of-phase with each other. Test observations have brought out that carbon steel material shows significantly higher fatigue damage under out-of-phase loading conditions than corresponding in-phase scenario. Therefore, the observed fatigue life under out-of-phase conditions is significantly shorter than the corresponding in-phase condition. Fig. 2 indicates the higher fatigue damage in terms of higher equivalent stress amplitude (material response) for out-of-phase multiaxial conditions than in-phase condition for a given equivalent strain amplitude (measure of controlled variables). The equivalent stress amplitude under in-phase condition has been observed comparable to corresponding pure axial and pure torsion conditions (Fig. 2).

Standard code design procedure for fatigue life assessment

The section III of American Society of Mechanical Engineers (ASME),Boiler and Pressure Vessel (B&PV) code is referred for the design of pressure vessels/ piping components[5] of nuclear facilities. This code is based on maximum shear stress/ maximum distortion energy failure criteria. These criteria have been adopted for evaluation of fatigue damage along with stress analysis based on linear elastic material considerations. Though, there exists two different design procedures for in-phase and out-of-phase loading scenarios in code, yet, these procedures do not account for additional damage taking place under out-of-phase multiaxial conditions, as observed in test studies. Due to this reason, the code procedure results in over-estimation of fatigue life for out-of-phase conditions. The comparisons between fatigue damage (in terms of alternating stress intensity amplitude, Salt) and test fatigue life (Ni) for pure axial, pure torsion, in-phase axial-torsion and out-of-phase axial-torsion are shown in Fig. 3.This

figure shows that best fit curve as determined under pure axial conditions on PHT piping material of PHWR is close to ASME median fit curve for carbon steel material. A factor of two on median fatigue life is a well-established band to account for material intrinsic variability. This band has been considered for assessing the goodness of different fatigue life assessment procedures. Fig. 3 shows that fatigue damage assessed(in terms of Salt) using ASME procedure results in over-estimation of fatigue life mostly for out-of-phase conditions. However, pure axial, pure torsion and in-phase loading cases fall within the material intrinsic data scatter band.

A new critical plane methodology: Developed for improved fatigue assessments

A new methodology [6] has been developed for accurate assessment of fatigue life of nuclear structural components. In this methodology, elastic-plastic finite element analysis is first performed for simulation of multiaxial stress-strain behavior. The accurate
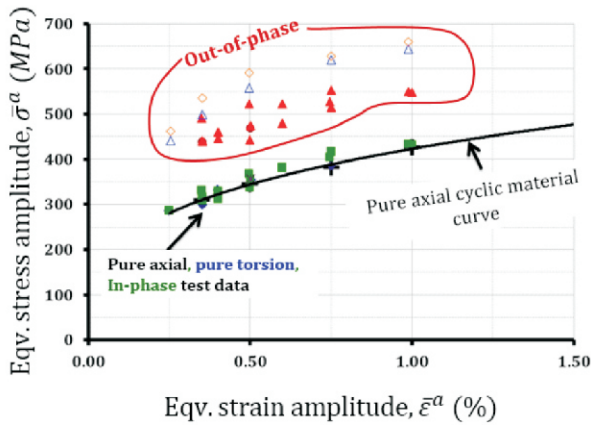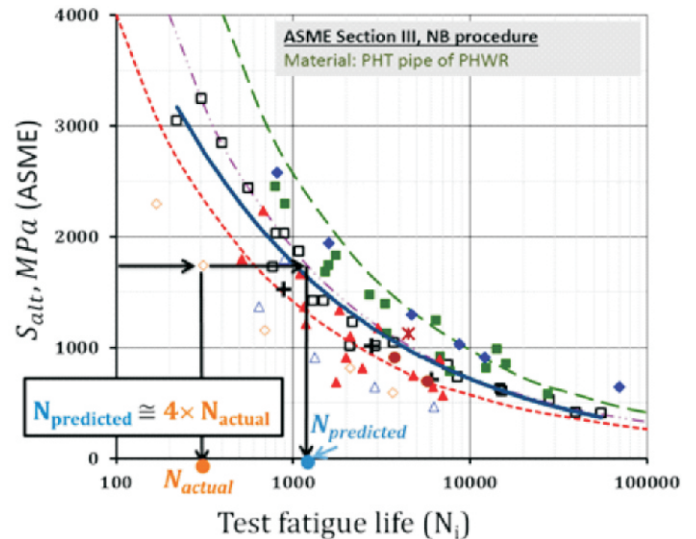
Fig. 2 (above): Cyclic stress-strain material diagram showing pure axial, pure torsion, in-phase axial-torsion and out-of-phase axial-torsion test data points.

Fig. 3 (right): Alternating stress intensity amplitude (Salt, code measure of fatigue damage) versus test fatigue life curve for PHT piping of PHWR.

Fig. 4 (below): Typical comparison between test and simulated axial hysteresis loop (axial stress-versus-plastic axial strain).
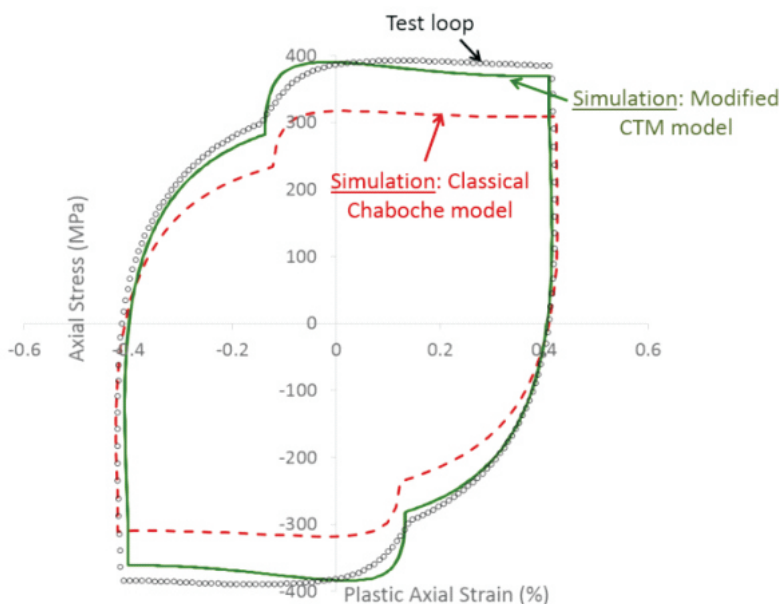

information of simulated stress-strain response is used as input for fatigue life assessment model. Therefore, the information of higher hardening under out-of-phase conditions is used for fatigue life assessments. Due to this reason, critical plane models are expected to produce improved assessments. Although, there exists several critical plane models ([7]-[10]) in the open literature, however, these models have been validated for limited class/ grades of materials. Also, nearly all these models ([8]-[10]) are associated with the subjectivity in calculations of resultant shear component on an oblique material plane. The newly developed model has eliminated this subjectivity and is simple-to-use[6]. Further, the new model uses a material parameter (k) in fatigue damage to quantify the relative extent of shear (or normal) strain energy w.r.t. total strain energy. Therefore, model with such material parameter is expected to produce reasonably accurate fatigue life assessments for materials failing in both shear mode (highly ductile materials) and normal energy mode (relatively high strength and less ductile materials).

a. Modeling of cyclic stress-strain response

The first step towards fatigue life assessment is to simulate cyclic stress-strain behavior of material in the form of cyclic hysteresis loops accurately. For this purpose, commercial Finite Element (FE) softwares are available with various classical cyclic plasticity material models. These models perform reasonably well for uniaxial/ in-phase loading scenarios. However, the stress response is significantly under-estimated for out-of-
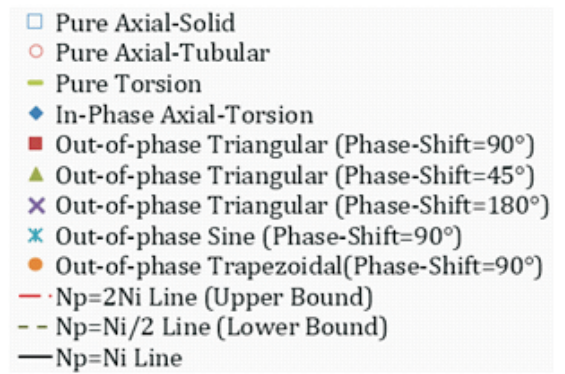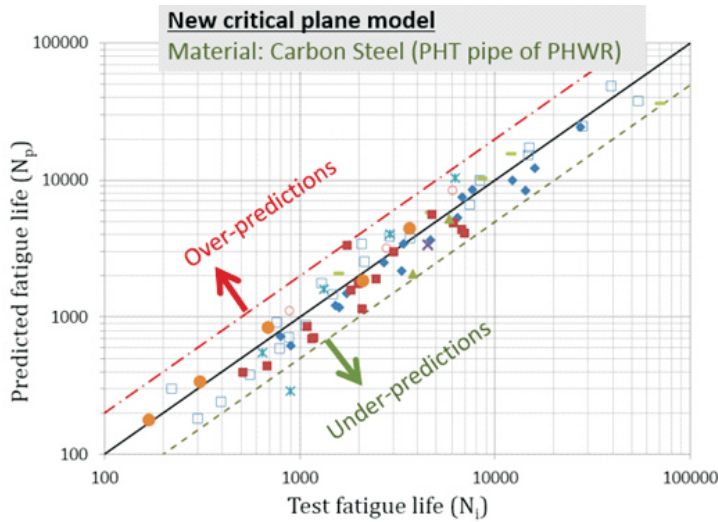
Fig. 5: Comparison of predicted (using new critical plane model) and test fatigue life for simple uniaxial and complex multiaxial load cycling for the tests carried out on PHT piping material of PHWR.
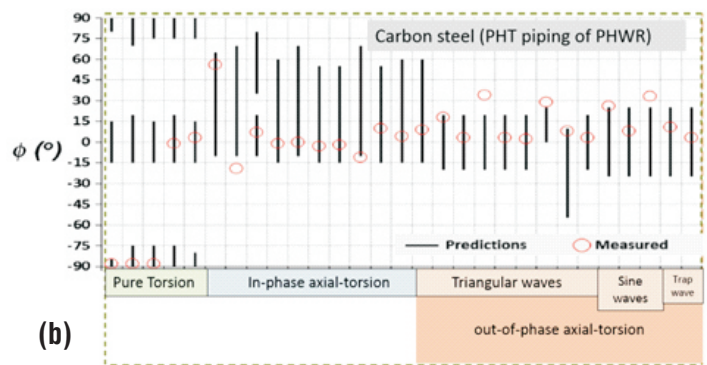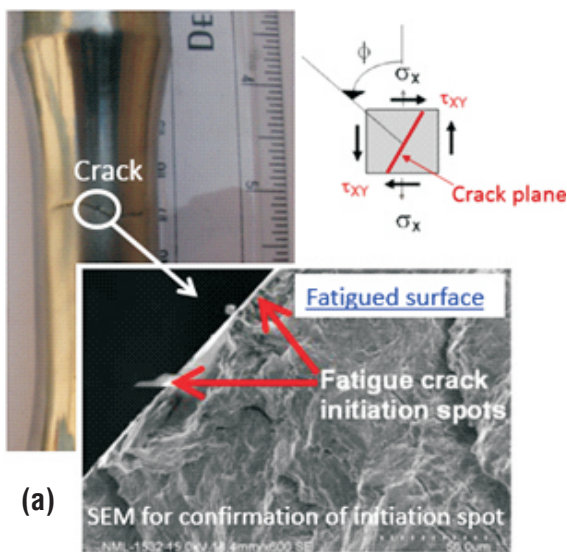

(a)

(b)

Fig. 6. (a) Fatigue tested specimen showing crack on outer surface of tube and SEM image to confirm crack initiation location, (b) comparison for predicted cracking plane range with measured crack angles

phase conditions [11]. Some of the advanced cyclic plasticity material models are available in literature ([12]-[14]). However, these models have been hardly included on commercial FE platforms. In this view, an in-house FE code has been developed for accurate simulation of material response under simple and complex cyclic conditions. This code is based on incremental plasticity theory at continuum length scale and includes von-Mises yield criterion, Prandtl-Reuss flow rule, linear / non-linear kinematic hardening rules and isotropic hardening rule. The code has been benchmarked for various loading conditions and material considerations. This FE code includes classical cyclic plasticity material model of Chaboche and few advanced material models, such as Chaboche-Tanaka-Meggiolaro (CTM) and in-house developed modified-CTM [11]. The modified-CTM material model results in accurate simulation for uniaxial, in-phase and out-of-phase loading conditions. A typical comparison between test and simulated hysteresis loops is shown in Fig. 4 for out-of-phase condition using classical Chaboche (commercial FE software) and modified-CTM (in-house FE code) models.

b. Fatigue life assessments: Predicted-versus-test fatigue life

The simulated hysteresis response is input to newly developed critical plane model under various uniaxial and multiaxial conditions. Fig. 5 shows the comparison between predicted and test fatigue life for various tests conducted under pure axial, pure torsion, in-phase axial-torsion and out-of-phase axial-torsion conditions with various phase shift angles such as 45⁰, 90⁰ and 180⁰ with different loading waveforms (triangular, sine, trapezoidal). The comparison shows that predicted and test fatigue life under all

such loading scenarios are in close agreement with each other and the test data are mostly contained in material intrinsic acceptable data scatter band of two.

c. Orientation of crack initiation plane: predictions-versus-measurements

Since the critical plane theory is associated with the material plane experiencing maximum fatigue damage, therefore, the crack plane orientations can also be predicted using critical plane model. The actual cracking angles have been measured using post image analyses of fatigued tube specimens [3]. The location of crack initiation spot has been confirmed using Scanning Electron Microscopy (SEM) as shown in Fig. 6 (a). The material planes experiencing fatigue damage higher than 90% of the maximum damage value are the probable cracking plane orientations. Fig. 6 (b) shows that new critical plane methodology also results
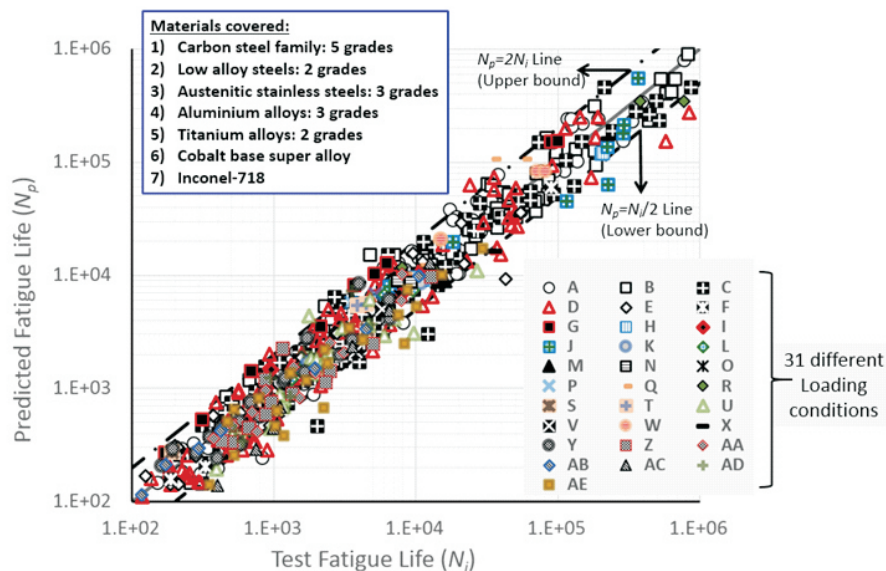
Fig. 7. Comparisons between predicted fatigue life (using new critical plane model) and test fatigue life for 10 numbers of ferrous alloys and 7 numbers of non-ferrous alloys

in accurate predictions of cracking planes under nearly all loading scenarios.

Extensive validation of developed model for various ferrous/ non-ferrous alloys

Although a large number of critical plane models are available in literature, yet scarcely a model exists which has been validated w.r.t. wide variety of engineering materials and large sets of multiaxial test data. With this viewpoint, a large set of uniaxial/ multiaxial tests data on 17 different grades of ferrous/ non-ferrous alloys has been collected from literature.

The ferrous alloys, typically used as PHWR, LWR piping/ vessel materials, cover different grades of mild/ carbon steel, low alloy steels, austenitic stainless steel and non-ferrous alloys include various grades of aluminum alloys, titanium and its alloys, cobalt base super-alloy and nickel alloy.

The yield strength of these materials/ alloys varies from 191.5 MPa to 1160 MPa and ultimate tensile strength ranges from 229 MPa to 1420 MPa. Thirty one different uniaxial and complex multiaxial loading conditions have been considered for this validation exercise. The test fatigue life typically ranges between ~100 cycles and ~10^6 cycles covering low to high cycle fatigue regimes. Fig. 7 shows reasonably accurate comparisons between predicted fatigue life using new critical plane methodology and test fatigue life for various ferrous and non-ferrous alloys. This validation for fatigue life assessments

on 17 numbers of widely different engineering materials subjected to 31 loading conditions with more than 800 fatigue life comparisons, further strengthens the applicability of the newly developed critical plane model ([6],[15]). Hence, this model can be used for realistic fatigue life assessment of wide range of metals (both ferrous and non-ferrous) under simple as well as complex multiaxial loading cases.

Conclusions

The uniaxial/ multiaxial test studies carried out on Primary Heat Transport (PHT) piping material of Indian PHWR and fatigue life assessments using current design code procedures vis-à-vis new methodology are summarized below,

- PHT piping material showed higher material hardening under out-of-phase axial-torsion conditions than corresponding in-phase and uniaxial cases. This higher hardening resulted in reduction of fatigue life for out-of-phase multiaxial conditions.

- The current ASME section III, NB procedure for fatigue life assessments results in over-prediction of fatigue life mostly for out-of-phase conditions.

- A new simple-to-use critical plane based fatigue life assessments model has been developed. This model predicts both fatigue crack initiation life and crack orientations accurately.

- The developed model has been extensively validated for various materials and loading conditions. This model may be used for improved fatigue assessment of mechanical components.

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