Numerical Simulation and Life Prediction of Stepped Shaft Under Biaxial Fatigue Loading

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Abstract:

The fatigue analysis have been applied to uniaxial and biaxial loading conditions for geometrically stepped shaft. The present work studied numerically simulation analysis of the fatigue behavior of stepped shaft made of Carbon steel SAE 1045_390_QT under a biaxial loading (torsion-bending moment) and uniaxial loading (only bending moment case), (only torsion case). This work included the complete analysis of stepped shaft by using ANSYSWORKBENCH 14.5 and the fatigue analysis using nCode Design Life 14.5®.the numerical results showed how important is the effect of biaxial loading on fatigue life where was results for biaxial loading ($2.039 * 10^4$) cycles while for uniaxial loading only bending case ($1.013 * 10^5$) cycles and in only torsion case it was ($4.756 * 10^7$) cycles.

Keywords: Biaxial Fatigue, nCode, Numerical Analysis.

Introduction:

Fatigue is a form of failure that occurs in structures subjected to dynamic and fluctuating stresses, under these circumstances it is possible for failure to occur at a stress level considerably lower than the tensile or yield strength for a static load. The term “fatigue” is used because this type of failure normally occurs after a lengthy period of repeated stress or strain cycling. Fatigue is important inasmuch as it is the single largest cause of failure in metals, estimated to comprise approximately 90% of all metallic failures; polymers and ceramics (except for glasses) are also susceptible to this type of failure. Furthermore, fatigue is catastrophic and insidious, occurring very suddenly and without warning. Fatigue failure is brittle like in nature even in normally ductile metals, in that there is very little, if any, gross plastic deformation associated with failure. The process occurs by the initiation and propagation of cracks, and ordinarily the fracture surface is perpendicular to the direction of an applied tensile stress. [1]

Literature Review:

Developing a fatigue-safe structural component is probably one of the critical ingredients of manufacture of durable products in automotive and related industries. Considering rigorous cost and time restrictions on vehicle development programs today, automotive engineers have to implement reliable and efficient computational methodologies to ensure a fatigue-safe component design earlier in the computerized engineering phase [2].

The validation practice of automotive parts is commonly based on component sign-off tests that the fatigue failure is assumed to occur when a measurable crack is detected under a given service or simulated loading conditions even for cases where the structural integrity may still be preserved on the component level. Therefore, the crack initiation concept plays a crucial role in durability assessment of automotive components, and local stress/strain approaches based on critical plane concept become a convenient technique for fatigue life analysis in this context [3].

Numerical techniques such Finite element (FE) or Boundary element (BE) methods can efficiently be applied for multiaxial stress and strain analysis within elastic deformation regime. Their use with nonlinear incremental plasticity has been largely pro-habited because of the high computational costs required for relatively long duration fatigue loadings. Instead, simplified notch analysis methods have been introduced as an alternative to calculate elastic plastic stress and strain components at a single material point by approximations from elasticity solutions for the same point in early studies, monotonic loading conditions leading to uniaxial stress and strain cases were investigated [4]. Neuter's rule [5] and equivalent strain energy density (ESED) concept [6] have been established to be appropriate methods for plane stress and plane strain deformation conditions, respectively [7,8]. More recent studies in literature have been focused on extending uniaxial simplified methods for cases where notch deformations are multiaxial and elastic plastic. Hoffmann [9] proposed a multiaxial extension of Neuter's rule by replacing the uniaxial stress-strain quantities with the corresponding equivalent stress and strain measures. Barkey [10] introduced the anisotropic yield surface concept in order to describe the multi-axial elastic plastic strains in terms of nominal notch stress components via a plasticity flow rule. Moftakhar [11] developed multiaxial generalizations of Neuter's rule and ESED method for proportional loading conditions. Koettgen [12] proposed the use of a cyclic plasticity model in conjunction with a structural yield surface. Buczynski and Glinka [13] developed a multiaxial notch analysis method based on the incremental relationships between the fictitious elastic and elastic—plastic strain energy densities at the notch tip and the Mroz-Guard plasticity model was employed in calculating the material cyclic stress—strain behavior. In a recent study, Sethuraman and Gupta [14] pointed out that a fraction of the total elastic strain energy density at the notch root is conserved due to relaxation and stress redistribution during multiaxial loading and introduced the proportionality function concept to include this effect in the material stress—strain response at the notch root. Their notch analysis model was based on the multiaxial generalization of Neuter's rule and used von Mises plasticity in conjunction with the multiline strain hardening rule. Ye and his coworkers [15] derived a unified expression for the strain energy densities considering the stored and dissipated energies at the notch root. Their notch analysis model combines Neuter's rule and Mon ski-Glinka's energy criterion in an energy balance expression and employs three incremental strain ratio expressions following Moftakhar's approach [16]. An investigation of the recent research shows that the simplified methods give results with good accuracy in comparison to the results obtained using nonlinear FEM analysis. Simplified methods have been also devised for fatigue analysis in many engineering applications and good results were also reported in recent literature [17-20]. In this paper, a notch analysis method is presented for numerical modeling of elastic plastic notch deformations under cyclic loadings. An incremental algorithm is developed on the basis of total strain energy density equations and integrated with Chaboche's cyclic plasticity model [21]. The linear elastic FE analyses are used in computing local fictitious stress and strain tensors. The calculated stress-strain histories are employed in fatigue analysis using Smith—Watson-Topper and Fatemi Socie critical-plane damage parameters. The developed numerical tool is integrated with ANSYS FE software [22] and applied to simulate combined bending-torsion fatigue of SAE 1045 notched shaft [23]. The predicted test cycles and critical fatigue locations were compared with experimental results from SAE test program.

Multiaxial Fatigue Analysis:

The actual stress and strain responses at the notch root of a notched specimen were determined using the analytical modeling approach described in the previous section. Once stress and strain components are determined for the notched component using the approximate analytical approach, the stress and strain components need to be transformed on potential material planes to evaluate fatigue damage on various planes. The fatigue damage is evaluated all potential planes and fatigue failure is assumed to occur on the critical plane with the largest amount of fatigue damage.

It is well known that the local strain approach has been well adapted as a practical engineering method in fatigue assessment of mechanical components. A fatigue damage parameter, which quantifies the fatigue damage as a function of certain stress and strain variables such as normal strain, maximum stress and etc., relates the fatigue damage to fatigue life cycles. In past few decades, a significant number of fatigue damage parameters have been developed and no universal consensus has been reached on the best approach to multiaxial fatigue problem. However, these damage parameters have limitations taking into account mean stress effects, non-proportional hardening, and requirement for additional material constants to characterize the fatigue damage. It has been well known that stress-based damage parameters well define fatigue damage of materials at high-cycle fatigue regimes while the strain-based damage parameters show better fatigue damage estimations at low-cycle fatigue regimes. In order to overcome short comings of the existing damage parameters, Inca [44] proposed an original multiaxial fatigue damage parameter based on the maximum damage plane. The proposed damage parameter can be expressed in form of generalized strain amplitude,

$$\frac{\Delta\varepsilon^{*}_{gen}}{2} = \left(\frac{\tau_{\max}}{\tau'_f}\frac{\Delta\gamma^{e}}{2} + \frac{\Delta\gamma^{p}}{2} + \frac{\sigma_{n,\max}}{\sigma'_f}\frac{\Delta\varepsilon^{e}_{n}}{2} + \frac{\Delta\varepsilon^{p}_{n}}{2} \right)_{\max} = f\left(N_f\right)$$

Implementation of the proposed multiaxial fatigue analysis methodology, which incorporates the proposed fatigue damage parameter based on the generalized strain amplitude and the elastic-plastic stress-strain model is suitable for the design evaluation of notched components used in general engineering applications, especially ground vehicles.

Simulation of Combined Bending and Torsion Fatigue of SAE Notched Shaft:

The computational methodology presented in previous two sections is coded into a computer program with C programming language, and given material parameters and the pseudo-stress tensor history; the developed program calculates the local material stress-strain response and performs fatigue damage assessment. The calculation of pseudo-stress tensors as inputs to the program and processing of fatigue results at a given material point are performed using [modeling, solution and post-processing capabilities of ANSYS FE program. Both software are integrated by means of ANSYS Parametric Design Language [24]. The developed simulation tool is applied for computer modeling of combined bending and torsion fatigue of a notched specimen under in-phase and out-of-phase cyclic loading conditions figure (1). The notched specimens were tested under constant-amplitude bending and torsion moments applied cyclically in a hydraulic load-controlled test rig. The fatigue test results are collected on the basis of number of loading cycles for the initiation of a "1.0 mm" fatigue crack and the number of loading cycles for complete specimen separation. The details of fatigue testing procedures and complete description of the research program can be found in a special SAE publication. [25].

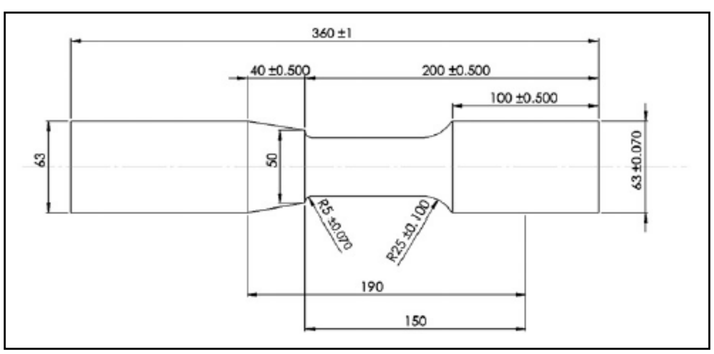

Figure (1) The SAE notched shaft specimen.

Project Flow Chart into Workbench:

The project consist of three types as shown in figure (2) each type is connected with the same geometry modeler. The geometry of shaft that was used in the analysis is shown in figure (3). All parts are simulated using static structural modeler. Part one consider the condition where both bending and torsion are applied to the shaft, as shown in figure (4) this type of loading is done by introduction a step time condition to include both loadings and the sketched shape. Bending only loading is considered in part two of the analysis as can be shown in figure (5). Finally the torsion only loading was considered in part three of the analysis as can be shown in figure (6). The next step in the analysis is carried out by connecting the static analysis results to a specialized fatigue analysis software (ANSYS nCode Design Life 14.5 ®) which will perform a low cycle fatigue analysis using the initial solution from workbench and introduction the real loading conditions.

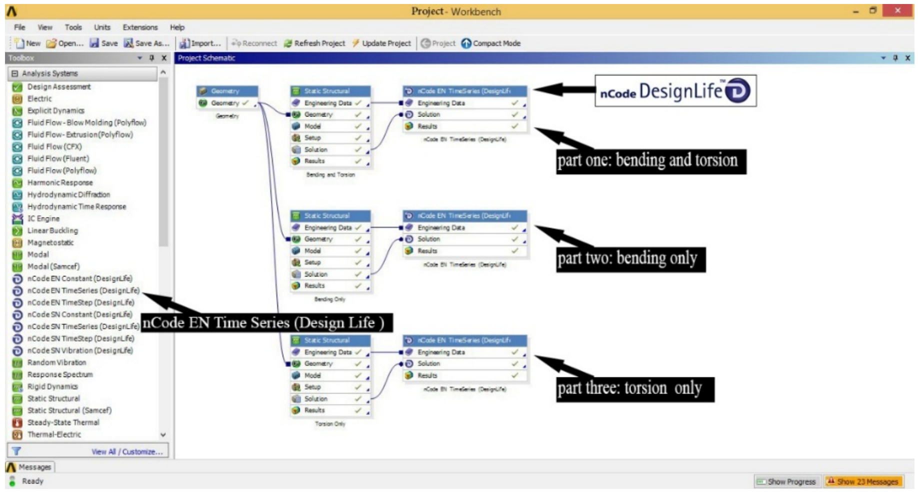

Figure (2) Project Flow Chart into Workbench.

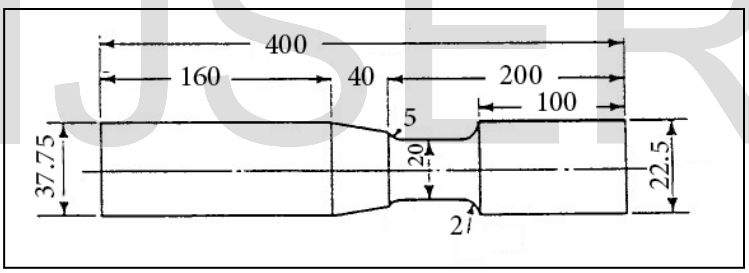

Figure (3) the geometry of shaft.

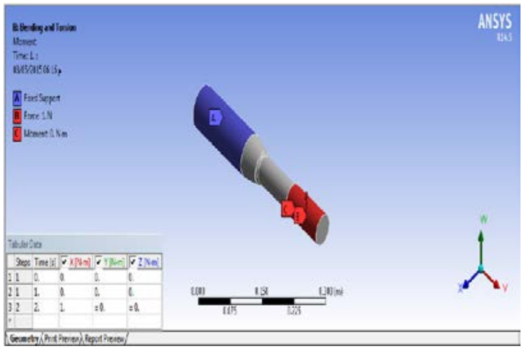

Figure (4) the condition where both bending and torsion are applied to the shaft

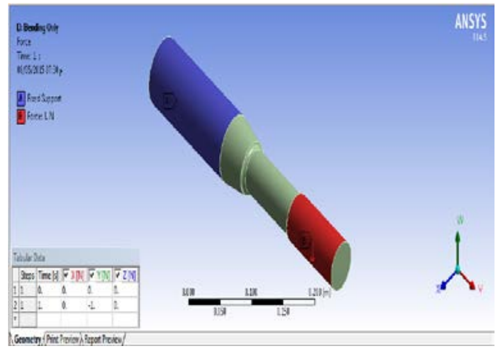

Figure (5) part two of the analysis bending only.

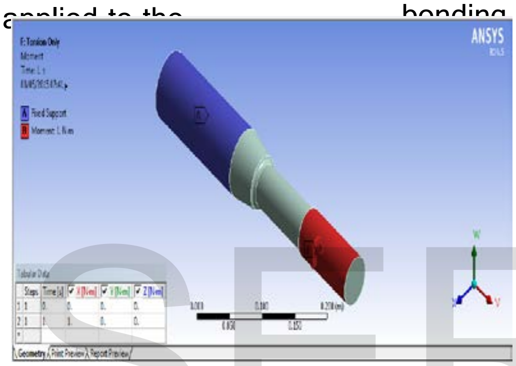

Figure (6) part three of the analysis

For an initial design, a mesh can often be generated in batch with an initial solution run to locate regions of interest. Further refinement can then be made to the mesh to improve the accuracy of the solution. There are physics preferences for structural, fluid, explicit and electromagnetic simulations. By setting physics preferences, the software adapts to more logical defaults in the meshing process for better solution accuracy the geometry after applying mesh process as shown in figure (7) and details of mesh as shown in table (1).

Table (1) Details of Mesh

Statistics	
Nodes	6142
Elements	3359

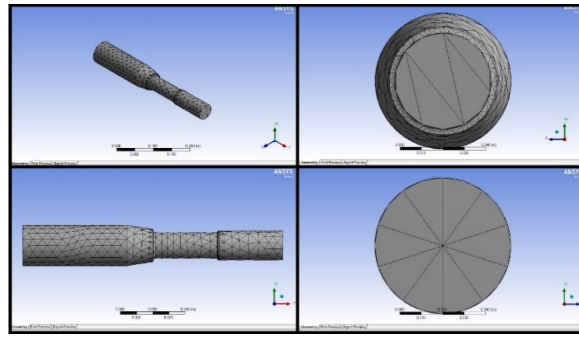

Figure (7) Specimen Mesh.

Project Flow Chart into

ANSYS nCode Design Life ®

Model was used as an input simulation model into the nCode DesignLife ® as shown in figure (8). This model were subjected to the actual fatigue loading that was obtained in the experimental work as shown in figure (9). Figure (10) shown flow process into the nCode DesignLife ®.

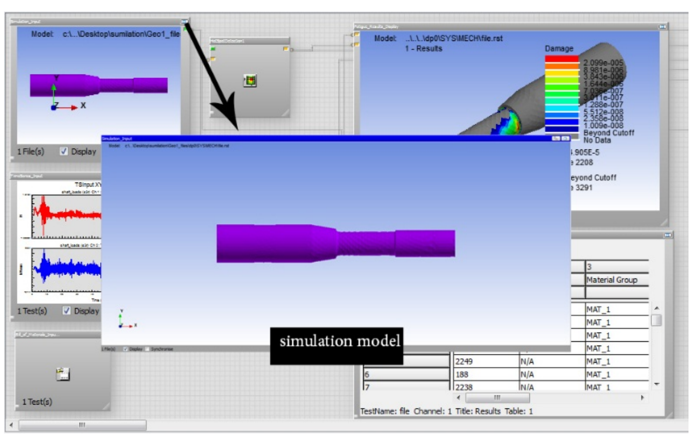

Figure (8) input simulation model into the nCode

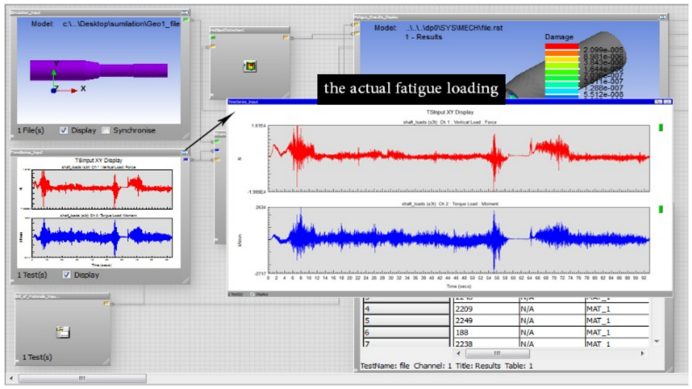

Figure (9) the actual fatigue loading.

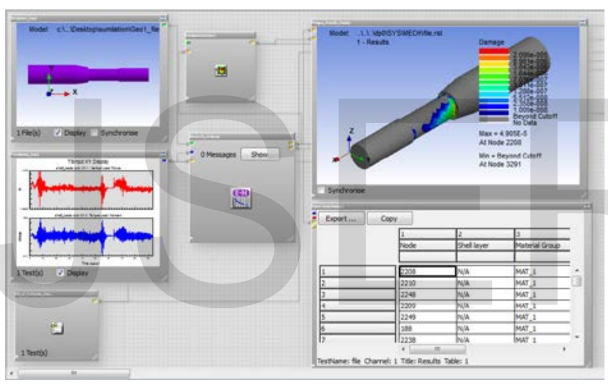

Figure (10) shown flow process into the nCode

DesignLife ®

Numerical Results of Fatigue Life:

From simulation analysis into ANSYS nCode DesignLife ®, fatigue life result shown in figures (11), (12), (13) and table (2) showsMin and location (Nodes) results.

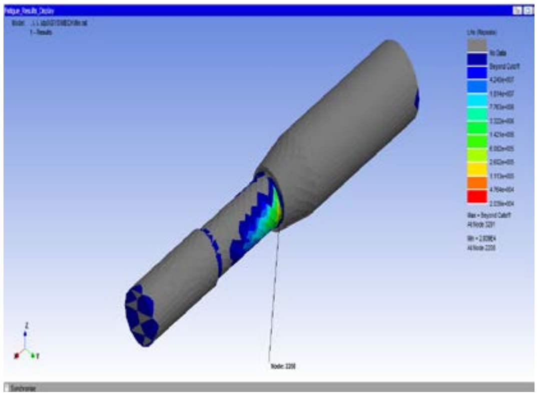

Figure (11) fatigue life result for bending and torsion

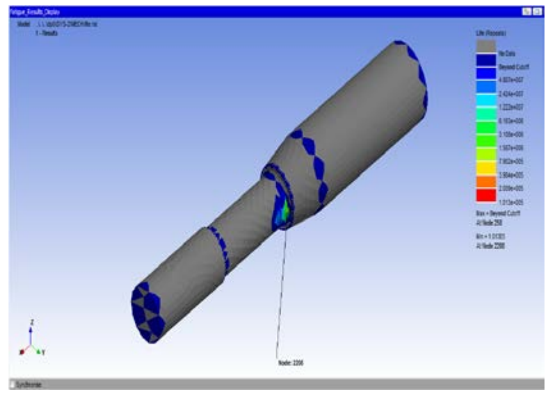

Figure (12) fatigue life result for only bending

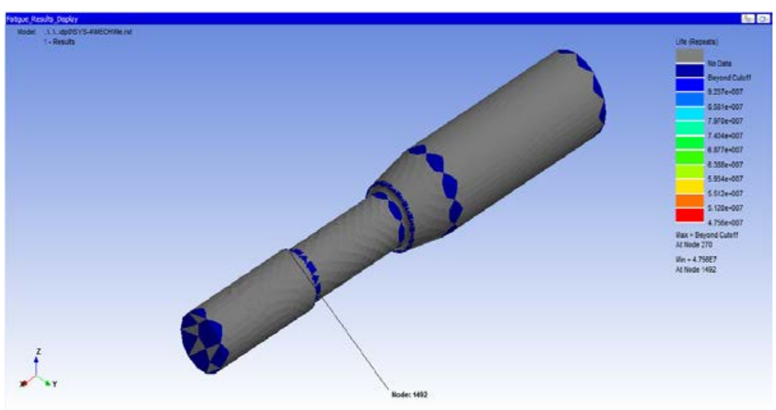

Figure (13) fatigue life result for only torsion

Table (2) Minimum and location (Node) fatigue life results

Type	Min	Node
Bending and torsion	$2.039 * 10^4$	2208
Bending	$1.013 * 10^5$	2208
Torsion	$4.756 * 10^7$	1492

Fatigue life in case biaxial loading (fatigue life = $2.039 * 10^4$ cycles at Node 2208) smaller than fatigue life in case uniaxial loading (fatigue life for only bending = $1.013 * 10^5$ cycles at Node 2208), (fatigue life for only torsion = $4.756 * 10^7$ cycles at Node 1492).From this conclude that in the case shaft under the influence of biaxial loading the analysis must be done by dependence of biaxial loading real because it effects on the fatigue life significantly.as can see from figures (11), (12), (13) and table (2) the location of Min fatigue life is the same for biaxial loading and uniaxial loading (case only bending) which it be at Node 2208 and it differ from the only torsion case which it be at Node 1492 ,the reason for this different is the bending loading effect more than torsion for the fatigue life location. The location must be consider in design.

Conclusion:

1. Since the fatigue life under biaxial loading conditions much lower than that of uniaxial loading, the fatigue analysis of mechanical parts which loaded by multi axial loadings must consider biaxial fatigue analysis.

2. Location of minimum fatigue life differs according to the loading type as can be seen from the results which indicates the importance of knowing the type of loading and not only its value.

3. The effect of torque on the minimum fatigue life location is more than that of the bending, since the torque only condition gives difference location of the fatigue life.

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