ABSTRACT

Material properties, loading, geometry and manufacturing processes are considered as the major elements in fatigue design problems. The effect of geometry has always been one of the challenging issues for designers to face with. The methodologies to transfer material properties obtained from specimen fatigue tests to fatigue behavior of real components, where neither a nominal stress nor a notch factor could be defined, have not been completely accurate or reliable. Therefore, direct component testing, though time consuming and expensive, is often a necessity in fatigue design and optimization. A limited number of accurate component tests to verify and complement analytical techniques, reduces the number of component tests and saves time and cost. Contrary to specimen testing, which numerous standards have been developed for, component testing is more a matter of designer’s practice. Various parameters such as simulation of the actual service condition, collecting useful data, and correspondence of the test results to analytical predictions determine the correctness and applicability of the conducted test. This article intends to provide a step-by-step guideline to conduct fatigue testing, with a focus on automotive parts. Essential pre-test, during-the-test, and post-test details are discussed. The guideline is implemented on sample steering knuckles as example parts, and the challenges and shortcomings for each test are investigated.

Introduction

In fatigue design process of a component [1], input data including geometry, loading history, material properties, and environmental parameters are collected. Implementing the design criteria, the designer selects the configuration, material and manufacturing processes of the component. Stress and strain analyses enable evaluating the critical locations of the designed component under the assigned loading condition. Generally, four fatigue life analysis models are commonly used; the nominal stress-life (S-N) model, the local strain-life (ε-N) model, the fatigue crack growth (da/dN-ΔK) model, and the two-stage model, which combines the second and third models to incorporate both macroscopic fatigue crack formation (nucleation) and fatigue crack growth. The load history of a component in actual applications is typically variable amplitude and, for instance in the case of automotive suspension components, complex load spectrums exist. Choosing a proper damage model is, therefore, the next step in fatigue design that accounts for the cumulative effects of the cycles. The fatigue life calculated for the component is verified in the next step by component or in-service tests and subsequently, the component’s configuration, material and manufacturing processes are modified in an iterative process to achieve the optimum design. The methods for component durability assessment could be categorized into experimental and analytical-numerical procedures. While historically, the numerical pre-dimensioning was followed by experimental optimization of particular components and experimental proof-out of a system consisting of different components, the present industrial trend interacts these phases of product development with each other by simultaneous engineering in order to reduce time and cost. This procedure can deliver a reliable design only if the numerical assessment considers service experience and is accompanied by experimental verification [2]. Component tests and more importantly, the accuracy of the tests, therefore, could not be ignored and should rather play a very significant role in this process. In literature, numerous studies pointed to different aspects of component testing (for example refer to [3 - 8]).

In this study, it is attempted to develop a guideline to prepare for, perform and analyze a fatigue component test with adequate accuracy. The flowchart of the developed guideline is illustrated in Figure 1 and is comprised of five major stages, as described in detail for the cases studied in this work. This guideline is implemented to two automotive parts from different manufacturing processes; forged steel and cast aluminum steering knuckles, safety-critical suspension components that are regularly subject to large-amplitude load fluctuations. The emphasis of this work is on elaborating the importance of performing the accurate test by following a comprehensive guideline that incorporates all the necessary experimental details. Service condition identification, analytical evaluation, numerical simulation, test apparatus preparation, and test monitoring are among
the major steps pursued in detail for the variety of components and service conditions. Finite element simulation of the component in real-life service is recommended as a main tool to predict the critical locations as well as to configure the proper fixtures and constraints in the test arrangement. Load-control tests are found to be sufficient testing modes if accompanied by strain measurements to guarantee the accuracy of the test. The test progress should be monitored for changes in displacement amplitude to detect crack initiation, growth rate and failure. The results of this work will help component designers in both design and optimization stages to limit the number of component tests by obtaining reliable fatigue performance data for in-service or to-be-designed components.

![Diagram](image.png)

Figure 1. The developed flowchart for fatigue component testing

**Identifying the Component and Its Service Conditions**

The comprehensive guideline developed is applied to the studied components by initiating stage I (Figure 1). The suspension systems of the vehicle, which the steering knuckles belong to, were identified and the loading and attachment conditions were investigated. The forged steel (11V37) steering knuckle belongs to the rear suspension system of a four-cylinder sedan vehicle. It is a symmetric component with one plane of symmetry. The cast aluminum (A356-T6) steering knuckle belongs to the front suspension of a six-cylinder minivan. Figure 2 shows the forged steel and cast aluminum steering knuckles as installed in the suspension system of the vehicles. For the case of the forged steel steering knuckle, the strut mounting holes are connected to the strut joints, the front and rear lateral links connect to the chassis and the tension strut joint is attached to the tension strut that is fixed to the chassis bracket. The hub and bearing assembly mount on the spindle. The hub bearing sits on the spindle middle step. The inner part of the hub attaches to the mounting holes, while the outer part connects to the wheel and is free to rotate. For the case of the cast aluminum steering knuckle, the strut mounts on the steering knuckle vertical arm, and the control arm and the stabilizer bar attach to the horizontal arm and lower body. The body also attaches to the caliper from its two outer bolt holes and to the wheel hub from the four mounting holes.

The primary loading conditions for the forged steel and cast aluminum steering knuckles were simulated as shown in Figure 3. For the forged steel steering knuckle, because of the symmetrical round geometry of the spindle, the forces and moment in the y or z directions result in a uniaxial stress along the spindle direction and a failure location at the second step of the spindle. Therefore, the loading could be simplified to a single moment applied to the spindle in the y or z direction. The torsional moment and axial force in the x direction are minor due to the presence of bearings on the spindle. In addition, attaching the hub assembly to the steering knuckle mounting holes prevents the transfer of these loads to the body. For the cast aluminum steering knuckle, the primary loading is in the form of a moment applied in the y direction to the arm, while the body is fixed through its four bolt holes.
Figure 2. (a) Forged steel steering knuckle within the rear suspension system of a 4-cylinder sedan, and (b) cast aluminum steering knuckle within the front suspension system of a 6-cylinder minivan

Figure 3. Simulated primary loading and restraints on (a) forged steel and (b) cast aluminum steering knuckles for testing.

**Fixture Assembly Design and Preparation**

Prior to preparing the fixture parts and along with stage I of the flowchart of Figure 1, finite element models of the simulated loading conditions were analyzed in order to determine and verify the critical locations and the loading and restraint arrangements. The critical points of highest stress in the components for the primary loading conditions discussed above were detected from the stress analysis as shown in Figure 4 and discussed in detail in reference [9]. These critical points were spindle fillet and hub bolt holes for the forged steel and cast aluminum steering knuckles, respectively. Accordingly, specific test fixtures for each one of the two steering knuckles were designed and machined, according the stage II of the procedure of Figure 1. The fixture assembly is shown in Figure 5. For the forged steel knuckle, the spindle was fixed by a 2-piece block where threaded rods tightened the block to the spindle. A pair of L-shaped moment arms transferred the load from the testing machine loading actuator to the spindle blocks in the form of bending load. The strut and suspension connections on the steering knuckle body were fixed to the bench using round and square blocks. For the cast aluminum knuckle, a two-strut-attachment test was conducted. In this arrangement, the strut attachment of the arm was connected from both sides to a pair of moment arms. The moment arms transferred the bending load from the loading actuator to the steering knuckle. The four hub bolt holes were fixed to the bench.
Figure 4. Contours of von Mises stress at the highest moment levels for (a) forged steel \( M_{\text{max}} = 1515 \, \text{N.m} \), and (b) cast aluminum \( M_{\text{max}} = 2230 \, \text{N.m} \) steering knuckles. The stress values of the color bar are in MPa. [9]

Figure 5. Schematic drawing for (a) forged steel and (b) cast aluminum knuckle test arrangements. [9]

Pre-Test Data Analysis

A number of points were considered to ensure accuracy of the tests to satisfy stage III of the guideline. Strain gages were positioned on the components and the strain readings were compared to analytical values and finite element analysis (FEA) results [9]. To validate the test setups, values of strains as measured by strain gages in component testing and as predicted using FEA were compared, and are listed in Table 1. The strain gages for the forged steel steering knuckle were positioned at the vicinity of the spindle root and the first step fillets, and for the cast aluminum steering knuckle two gages were positioned at the goose neck of the strut arm and two at the hub bolt holes where crack initiation was observed during component testing. These locations are identified in Table 1. Depending on the location of the gage, the proper component of the strain obtained from the FEA was selected for comparison. The differences between measured and predicted strains obtained for the two steering knuckles were less than 18% and were considered reasonable for the complex steering knuckle geometries. The error can be attributed to: 1) difficulty in matching the exact corresponding node on the FEA model to the strain gage location, 2) difference in boundary conditions between FEA and actual test setup, 3) the unwanted friction force that exists between the point of load application and the moment arms in test (although this was reduced significantly by using roller bearings), and 4) measurement errors related to strain gage averaging particularly for cast aluminum steering knuckle due to high strain gradient at the strain gage locations. The measured strains also confirmed the symmetry of and linear variations with elastic loading.

For the forged steel steering knuckle, which has a relatively simpler geometry, results of strain calculations from analytical equations are also listed in Table 1. These results are mostly in between the measured and FEA-predicted strains. It should be noted that the position of the strain gages and the magnitudes of the applied loads were such that all measured strains were in the elastic range. In addition, it was confirmed that change of the gripped spindle length for the forged steel steering knuckle does not affect the strain reading at the locations close to the spindle step. For the cast aluminum steering knuckle, the bolt pretension and the accompanied compressive stress on the engaged area of the component was estimated for a bolt torque of
13.6 N.m (applied to the bolt during the component tests) and a bolt having major thread diameter of 12.7 mm to be 5.4 kN and 14 MPa (2 ksi), respectively. The stress value was negligible compared to the stresses generated due to the experiment loading and were not considered in subsequent stress analysis and predictions.

A closed-loop servo-controlled hydraulic 100 kN axial load frame was used to conduct the tests. The calibration of the system was verified prior to the beginning of the tests. A rod end bearing joint was used to apply the load from the actuator to the moment arms, in order to avoid any out of plane bending. Due to relative rigidity of the fixtures, the effect of horizontal friction force was found to be significant at the joint-fixture contact point. Therefore, a needle roller bearing was installed on each side of the pin of the bearing, allowing the moment arm to roll horizontally to minimize friction force. Care was taken to ensure symmetry of the bending load transferred from the two moment arms. All fixture bolts and nuts were tightened with identical torque values to maintain consistency.

Table 2 lists the maximum moment, moment amplitude, ratio of maximum to minimum moments, and test frequencies. The moment levels were determined based on stress analysis results, the true stress-true strain curve of the materials, and standard load cases. The actual load cases for these specific components were not available, but two standard load cases, Lotus load condition used in Daewoo Motors [10] and ULSAS standard load cases [11] were examined. The primary load of 3g acting on the wheel is the vertical bump for both of the load cases, where g is the acceleration of gravity. Based on component weights of 1195 kg (2635 lb) and 1983 kg (4372 lb), and the wheel hub moment arms (from the center of the wheel bearings to the critical location of the components) of 21.9 mm and 25.4 mm, maximum moments of 1000 N.m and 2000 N.m were obtained for the forged steel and cast aluminum steering knuckles, respectively. The highest maximum moment levels in the component test were specified to be 1515 N.m and 2230 N.m for the forged steel and cast aluminum steering knuckles, respectively. A minimum moment of 75 N.m was used in all tests, corresponding to an R-ratio \((M_{min}/M_{max})\) of less than 0.08.

Although the loading in real-life service conditions of such a component falls below zero, an approximate \(R=0\) value was selected to simplify the experimentation procedure, since the compressive part of the load does not contribute to the damage underwent by the component and the \(R=0\) condition resembles the service loading condition accurately. A total of seven component tests at four moment levels with amplitudes between 380 N.m and 720 N.m for the forged steel steering knuckle, and a total of six tests at four moment levels with amplitudes between 560 N.m and 1075 N.m for the cast aluminum steering knuckle were conducted. The frequency of the tests ranged from 0.5 Hz for higher moment levels, to 5 Hz for lower moment levels. The moment levels chosen resulted in fatigue lives between \(10^6\) and \(2\times10^6\) cycles.

Table 1. Measured and predicted strain values at 680 N.m static moment. Locations of the gages are also shown. [9]
Table 2. Component test data of forged steel and cast aluminum steering knuckles investigated.

<table>
<thead>
<tr>
<th></th>
<th>$M_{\text{max}}$ (Nm)</th>
<th>$M_a$ (Nm)</th>
<th>R-Ratio</th>
<th>$N_f$, Crack Nucleation (cycle)</th>
<th>$N_f$, Fracture (cycle)</th>
<th>Test Freq. (Hz)</th>
<th>Remarks</th>
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1. There was no marked difference between crack nucleation and fracture lives of the forged steel steering knuckle.
2. These parts broke at a location other than the critical location due to fixture part breaking, therefore they were considered as run-out tests.

Collecting Test Data

The progress of the test should be carefully monitored and useful data should be collected as indicated in stage IV of the guideline of Figure 1. Displacement amplitude versus cycle data of the components during each test were monitored in order to record macro-crack nucleation (i.e. a crack on the order of several millimeters), growth, and fracture stages. Due to the nature of the loading and restraints on both steering knuckles, the locations of crack initiation could not be reached to enable detecting crack nucleation. Therefore, a marked displacement amplitude increase during the test was considered as the crack nucleation point, and a sudden increase as the final fracture. Variations of displacement amplitude versus cycles for two typical tests of the forged steel and cast aluminum steering knuckles are shown in Figure 6. As can be observed from this figure, for the forged steel steering knuckle the displacement amplitude was nearly constant until about the end of the test. This indicates that the time lag between macro-crack nucleation and fracture was a small fraction of the total life. On the other hand, for the cast aluminum steering knuckle the crack growth portion of the life was significant. The crack lengths of the cast aluminum steering knuckles were also visually observed and recorded. For the typical cast aluminum steering knuckle data in Figure 6, the crack lengths were 8 mm, 13 mm, 20 mm and 27 mm at $N/N_f$ equal to 0.3, 0.5, 0.7 and 0.9, respectively, where crack grew with an approximately linear trend versus number of cycles. The lives to failure used in latter comparisons for the cast aluminum steering knuckle were considered to be those of macro-crack nucleation.

![Figure 6. Displacement amplitude versus normalized cycles for typical forged steel and cast aluminum knuckles. [9]](image-url)
Post-Test Analysis

Following the termination of the tests, a number of analysis are required to interpret the collected data, as indicated in stage V of the guideline of Figure 1. Table 2 presents the component test data and Figure 7 shows the applied moment amplitude versus fatigue life curves for the two components. Although a plateau was observed for the forged steel steering knuckle as could be seen in Figure 7, the cast aluminum steering knuckle did not exhibit this behavior at the selected lower moment amplitude levels. The stress amplitude versus fatigue life curves of the two steering knuckles are superimposed in Figure 8. The stresses in this chart are the local von Mises stresses at the critical locations of the components obtained from nonlinear FEA [9]. For the cast aluminum steering knuckle S-N lines based on failure defined as either macro-crack nucleation or fracture are shown. On the average, about 50% of the cast aluminum steering knuckle life is spent on macro-crack growth. This figure also shows that the forged steel steering knuckle results in about two orders of magnitude longer life than the cast aluminum steering knuckle, for the same stress amplitude level. This occurs at both short as well as long lives. Note that the difference can be even larger at long lives, due to the run-out data points for the forged steel steering knuckle. It could also be seen from this figure that the highest load levels provided life in the range of $10^5 \text{ to } 5 \times 10^4 \text{ cycles}$. Moment levels corresponding to this life range could be considered as representative of overload conditions for suspension components, such as a steering knuckle, in service. Fatigue life of the components could also be predicted and verified with the experimental results as discussed elsewhere [12].

Different fracture surface characteristics were observed for the forged steel and cast aluminum steering knuckles. As could be seen in Figure 9 for a typical steering knuckle, the failed forged steel steering knuckles had a typical ductile material fatigue failure surface including crack initiation, smooth crack growth and rough fracture sections. The failed cast aluminum in Figure 9 could be seen with a relatively longer crack growth portion (as observed in the displacement monitoring curve), as compared to the crack growth portion of the forged steel steering knuckle.

![Figure 7](image1.png)

(a) (b)

Figure 7. Applied moment amplitude versus fatigue life curves for (a) forged steel and (b) cast aluminum steering knuckles.

![Figure 8](image2.png)

Figure 8. Superimposed stress amplitude versus fatigue life curves for forged steel and cast aluminum steering knuckles. [9]
Summary

In order to attribute to the purpose of undertaking accurate fatigue component tests, a guideline is developed and implemented to two automotive suspension components as typical cases. Five major stages are designated and followed to accomplish the goal of a reliable fatigue component test. The necessary data required to design the tests are specified as well as the assumptions and limitations. Careful monitoring of the test progress as well as precise analyses of the test outputs are also elaborated. It is emphasized that a reliable fatigue design process of a component suffers a major deficiency without the results of accurate component tests. On the other hand, availability of reliable component test data will contribute to analytical and numerical design and optimization tools and will result in more robust and less expensive products. The accurate results of a limited number of component tests, if used as the means of verification of analyses, will save considerable amount of time and cost on the way to obtain the finalized design of the component, compared to numerous tests conducted on components conventionally in design and optimization stages.

Acknowledgments

Part of this research was sponsored by Forging Institute Educational and Research Foundation (FIERF) and American Iron and Steel Institute (AISI). The authors appreciate their participation.

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