

Failure Mode Effects and Fatigue Data Analyses of Welded Vehicle Exhaust Components and Its Applications in Product Validation

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ABSTRACT

Vehicle exhaust components and systems under fatigue loading often show multiple failure modes, which should be treated, at least theoretically, with rigorous advanced bi-modal and multi-modal statistical theories and approaches. These advanced methods are usually applied to mission-critical engineering applications such as nuclear and aerospace, in which large amounts of test data are often available. In the automotive industry, however, the sample size adopted in the product validation is usually small, thus the bi-modal and multi-modal phenomena cannot be distinguished with certainty.

The purpose of this paper is two-fold: (1) a large amount of historical fatigue data of several types of welded exhaust components belonging to several diverse programs are collected and statistically analyzed; the similarities and differences in the data patterns, the standard deviation of the cycles to failure in particular, of the different groups of the data are examined, and (2) with the statistical information obtained from the historical data and a previously developed Bayesian statistics approach, examples in design limit/curve construction are provided to demonstrate the values of the historical data in product validation.

CITATION: Wei, Z., Zhu, G., Gao, L., and Luo, L., "Failure Mode Effects and Fatigue Data Analyses of Welded Vehicle Exhaust Components and Its Applications in Product Validation," *SAE Int. J. Mater. Manf.* 9(3):2016, doi:10.4271/2016-01-0374.

1. INTRODUCTION

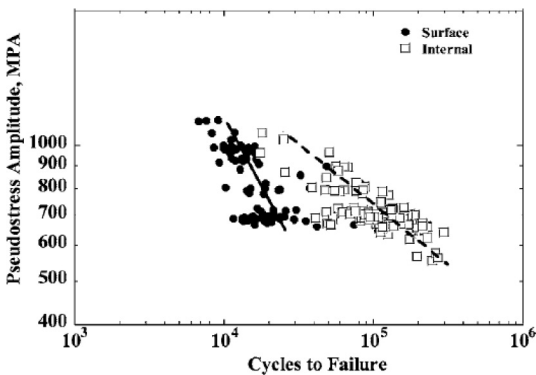
Durability and reliability performance is a major concern for vehicle components, and life testing (or test-to-failure) is the most commonly used testing method in product durability and reliability validation [1,2]. The life testing method tests a component to the occurrence of failure under a specified loading. Fatigue test data usually shows significant scatter and therefore repeated tests are often required to capture the uncertainty, scatter, and failure probability of the test data. Lognormal and Weibull continuous probability density functions (PDFs) and cumulative distribution functions (CDFs) are often used for characterizing the scattered fatigue life data [3]. Based on test data, several statistical parameters, such as the mean, standard deviation, and particular failure probabilities for a lognormal distribution can be estimated. The uncertainty caused by sample size effects is quantitatively described using the concept of "Confidence". In product validation, design criteria of R90C90 (i.e. 90% in reliability and 90% in confidence) and R99C50 are commonly used to guarantee that a certain amount of the data fall above the *RC* bound with a certain failure probability *R* and a specified confidence level *C* [1]. The *RC* criterion is now already a common practice in the automotive industry. However, several potential improvements can be made towards better understanding the fundamentals and more cost-effective testing strategies in the product validation procedure. Among several possible improvements, two prominent issues will be addressed in this paper, and all of them are related to the collection and analysis of the historical fatigue data: failure modes and the Bayesian statistics approach.

First, in product validation, how to treat data with two or more failure modes is still a controversial issue. Generally, there are two conflicting opinions:

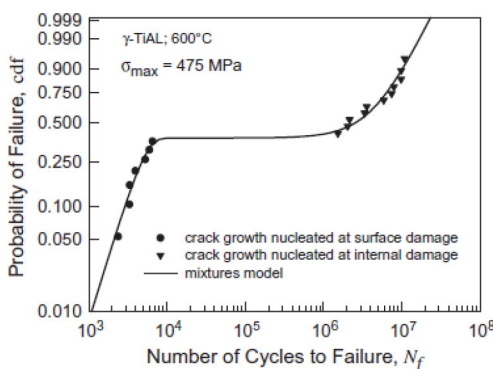
1. all tested data should be considered as samples from a single population, so that a single probabilistic function can be used to interpret the data. The main reasoning behind this opinion is that knowing the different failure modes will not be very helpful because the tests are conducted with a very limited sample size anyway. More tests and efforts can reveal more failure modes and more data for statistical analysis, but the data may never be large enough. Additionally, more complicated methods might not guarantee higher quality of the analysis and more useful information in decision making because these models could bring more uncertainties, such as the model uncertainty.
2. data with different failure modes should be treated separately because different failure modes lead to different data patterns, which may result in very different conclusions from those obtained without failure mode separation.

Indeed, a variety of materials have exhibited bi-modal or multi-modal failure behavior. Some fatigue test data can be even divided into two or more distinct subgroups with different features [4,5,6,7,8,9,10]. Examples with bi-modal failure modes are given in Fig. 1(a) and (b). Fig.1 (a) shows the separation of the data with two failure modes: Surface Failure and Internal Failure. Fig.1 (b) shows the Smith failure mode separation phenomenon for a material at a given

temperature and a stress level. If a uni-modal or mono-modal model was used for these types of data, a very misleading results could be obtained [9]. Several statistical modeling methodologies for bi-modal and multi-modal models have been developed. Generally, the bi-modal and multi-modal data can be closely represented by a probabilistic function resulting from the superposition of the probabilistic functions of two or more individual mechanisms [4,5,6,7,8,9]. These models include mixture models, competing risks models, dominant mode models, and combined (nested) methods [8]. It should be noted that the bimodal failure phenomenon is usually observed in superalloys and some steels with a large amount of test data. An early preliminary investigation shows that the bi-modal and the multi-modal behavior of the vehicle exhaust component fatigue data is not very obvious [11, 12]. In order to completely reveal the failure modes and their effects on fatigue life and confirm previous observations, significant amounts of repeated tests should be conducted for data analysis, although this is typically not the normal practice in the automotive industry, particularly at the component and system levels. In this paper, a different approach is adopted: a significant amount of historical fatigue life data with 6 samples for each test are collected and analyzed, then the effect of the failure modes that are hidden deep in the data can be indirectly revealed.



a.



b.

Fig. 1. (a) Fatigue S-N curve of René 95 with bi-modal failure modes [9]; (b) bi-modal distribution of fatigue life at a stress level for γ -TiAl alloy [8]

Secondly, although the current product validation procedure based on probability plot is routinely used, new approaches, which can reduce sample size and the associated test cost/time and increase assessment accuracy, are also intensely investigated. Recently, several Bayesian statistics based design curve construction methods have been

developed to serve these purposes. Bayesian statistics [13] generates posteriori distribution by updating prior distribution based on the historical data and a few new test data. Among all of these methods, a Monte Carlo simulation based resampling method [14, 15] developed by the authors of this paper is of particular importance. The method is based on historical fatigue test data, i.e. the probabilistic distributions of the mean and standard deviation of the failure cycles, and an advanced acceptance-rejection resampling algorithm. Two types of Bayesian analysis approaches have been developed:

1. Bayesian-V1[14], which requires finite element analysis (FEA) methods for calculating the nodal forces at the points of interest and then a special stress recovery technique, i.e. the Verity method [16], to convert the nodal forces to structural stresses in order to comply with the associated master S-N curve. The distributions of both mean and standard deviation are required from the historical data. However, it is applicable only to thin-walled welded structures, such as Pipe-to-Pipe and other 360° Welds, in which the structural stress can be estimated.
2. Bayesian-V2[15], which requires neither FEA nor stress recovery techniques. The fatigue cycle information for any load measures such as force or torque can be directly used. The only historical information required for Bayesian-V2 is the distribution of the standard deviation of the cycles to failure, which are already available for 360° Welds [14]. The distribution of the mean is calculated from the new test data and the Central Limit Theorem, which could make Bayesian-V2 even more accurate and reliable than Bayesian-V1 [15].

With these Bayesian statistic approaches, a design limit or curve can be constructed with sample sizes of 3, 2, and even 1, which is much smaller than the current 6 samples at each stress/load level, eventually leading to the achievement of cost savings [14, 15]. However, the historical data collected previously [14, 15] are only limited to 360° Welds, which is just one of many types of welded structures in the vehicle exhaust systems. More data collection is needed for other failure modes so that a systematical life assessment for an exhaust can be conducted.

In this paper, fatigue load-cycle (S-N) test data with one, two, and multiple failure modes are randomly selected from the component bench fatigue test database and analyzed to investigate the data patterns. The hanger rod, which shows a wide variety of failure modes such as Rod Bend, Rod-to-Rod, and Rod-to-Pipe, is the specific target of this paper. The fatigue data of 360° Welds previously collected [14] are also included and compared to find the common data patterns. The emphasis of this research is on the differences and similarities among different failure modes. Finally, the fit parameters as obtained from the historical data are used in design limit/curve construction.

2. FAILURE MECHANISMS AND MODES IN EXHAUST COMPONENTS AND SYSTEMS

The automotive exhaust system serves both emission control and noise reduction purposes [17]. During vehicle operation, the high temperature exhaust gas generated inside the engine flows into exhaust

manifolds, through the exhaust system, and is finally discharged out the tailpipe. Vehicle exhaust components and systems are almost invariably subjected to static and cyclic loadings due to engine and road vibrations [17]. Fig.2 schematically shows the overall structure of a vehicle exhaust system, which consists of several exhaust components, such as manifolds, downpipe, catalytic converter, flexible coupling, extension pipe, resonator, muffler, and tailpipe.

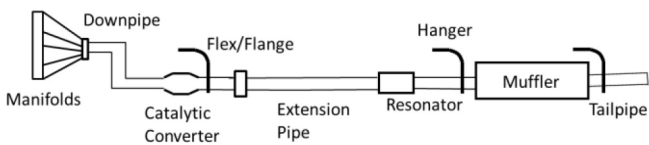
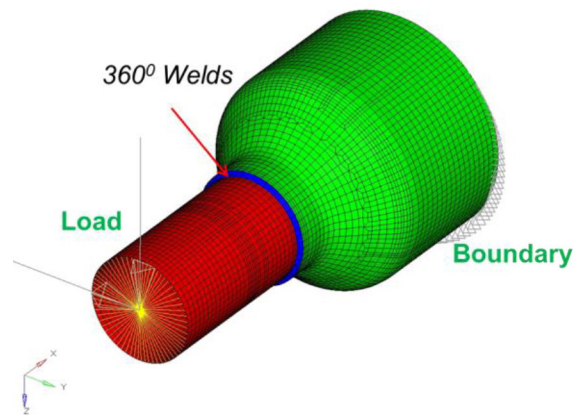


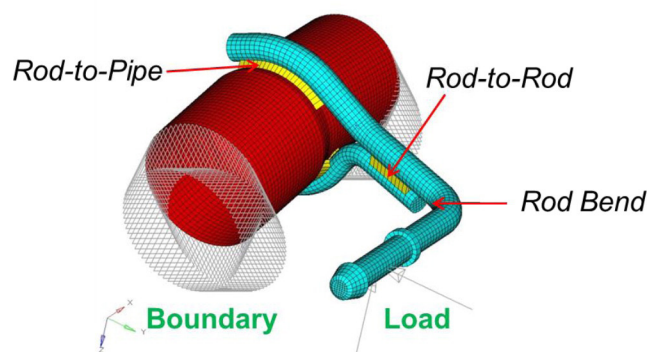
Fig. 2. Schematic of a vehicle exhaust system.

To achieve emission and noise reduction performance requirements and structural integrity, these exhaust components must be properly connected to form an exhaust system. Additionally, the exhaust systems must be properly attached to the vehicle body. Welding is the common joining method for the exhaust systems. Fig.3 (a) shows the Pipe-to-Converter connection with welds, in which welding is conducted around the circumferential direction with 360° . Pipe-to-Pipe and Pipe-to-Flange are another 360° welds. Hangers are often used to connect the vehicle exhaust systems to the vehicle body through the isolators made of rubbers on the body side and welds on the exhaust side. Fig.3 (b) shows the two typical weld locations: Rod-to-Rod and Rod-to-Pipe. Years of experience has shown that the prevailing failure modes in exhaust systems are cracked welds at joints between pipes and mufflers/resonators/converters, such as the 360° weld shown in Fig.3(a), cracked hanger-to-pipe welds (Rod-to-Pipe in Fig.3 (b)), and broken hanger rods (Rod-to-Rod and Rod Bend shown in Fig.3(b) [17]. It should be noted that the Rod Bend is a non-welded location. Multiple fatigue failure modes can occur in exhaust components and systems under fatigue loading. These failure modes can be caused by several different failure mechanisms [17] depending on material, loading amplitude, and operating temperature and environments. At room or low operating temperatures, the fatigue failure is usually the dominant failure mechanism.

Fig. 4 (a) shows a set of fatigue failure data with a single failure mode at two stress levels. Fig. 4 (b) shows a set of test data with two failure modes, Failure mode-A and Failure mode-B for short. Fig. 4 (c) shows a set of fatigue data with three failure modes: Failure mode-A, Failure mode-B, and Failure mode-C. The mean curves are also plotted in these figures. In Fig.4 (b), failure mode-A appears on the right side at the upper stress level while on the left side at the lower stress level. In Fig.4(c), failure mode-A, -B, and -C all appear at the upper stress level. However, there is no clear evidence to support the hypothesis of subpopulation separation caused by the multi-modal mechanism, and the data can be well described with a single distribution function, though the data shows three different failure modes. Furthermore, only Failure mode-A appears at the lower stress level, and it is interesting to note that although only one failure mode is operating, the goodness-of-fit is not good in terms of AD statistic [11].



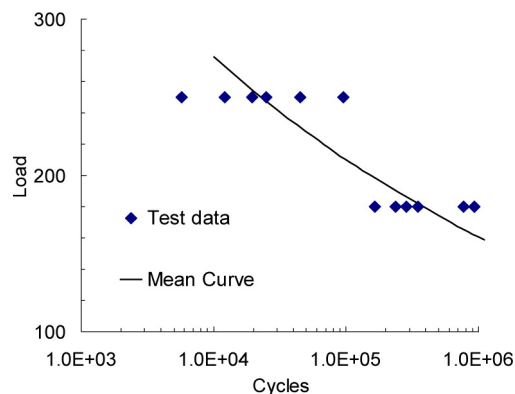
a.



b.

Fig. 3. Possible failure modes at (a) 360° welds, (b) hanger rods

From Fig.4 it can be seen that it is more convenient in engineering applications to treat the multiple failure mode data with a single distribution function, i.e. uni-modal analysis model. There is no clear benefit to use a bi- or multi-modal model to describe the fatigue behavior of tests with small sample size. However, the separation of subpopulation of test data caused by the bi- or multi-modal mechanisms could be concealed by the uncertainty caused by small sample size.



a.

Fig. 4. (a) Fatigue S-N test data with a single failure mode, (b) two failure modes, and (c) three failure modes.

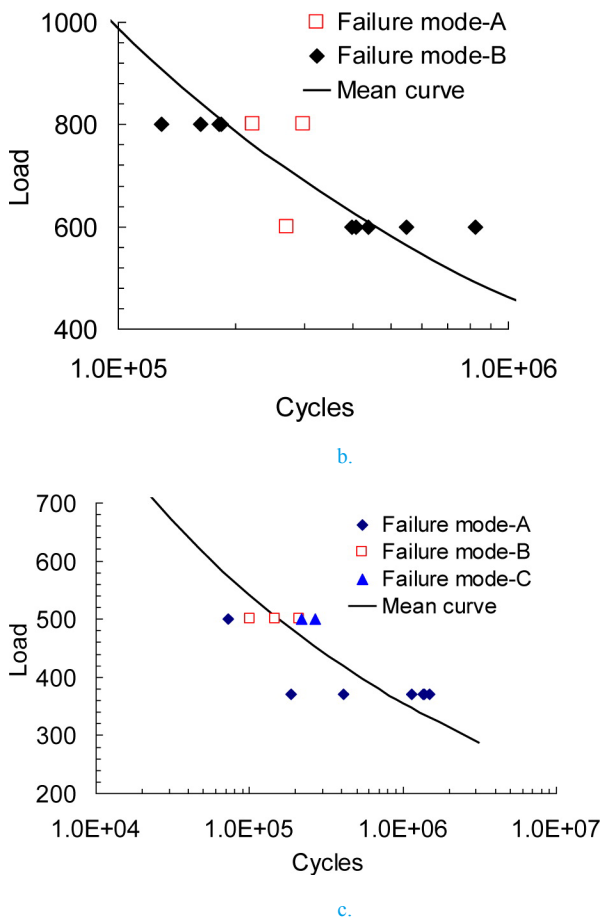


Fig. 4. (cont.) (a) Fatigue S-N test data with a single failure mode, (b) two failure modes, and (c) three failure modes.

With the consideration of multi-modal mechanism, the product validation process could be adversely impacted. Finally, it would be very interesting to see whether the single distribution function can fit multiple failure modes. Clearly, more data collection and in depth analysis is required. [Section 3](#) provides the new development in this direction.

3. ANALYSIS OF FATIGUE LIFE DATA OF VEHICLE EXHAUST COMPONENTS

3.1. Data Collection and Analysis Approach

The fatigue data were collected from the fatigue database for several programs, which account for a significant amount of the ground vehicle applications. The 360° Weld data have been collected and analyzed [14, 15]. The hanger rod data were collected with this effort and analyzed based on the failure modes which consists of Rod Bend, Rod-to-Rod, and Rod-to-Pipe. The failure modes at the hanger rod is more complex in testing, analysis, and simulation. For example, 360° Welds have closed weld ends so that the distribution of stress is relatively smooth and even. By contrast, welds at hanger rod such as Rod-to-Rod and Rod-to-Pipe are open welds indicating there is stress risers at the end of the welds. The ends of the welds cause stress concentration and eventually failure initiation during service. Rod Bends are made of base materials, however, it is also a common failure because of the defects introduced by tool marks and residual

stress during bending operation and manufacturing. Welding quality is often not very consistent at the hanger rods because of complex geometry, limited space etc. Hanger rods are more complex to analyze in terms of structural stress analysis, which is supposed to be applicable for thin walled structures. Hanger rods are even more difficult in simulation, in particular finite element analysis (FEA), because the results are mesh sensitive. Too much or too less elements across the welds all cause issues. In practice, a row of elements (Hex) are often used to represent the real welds for simplicity. Clearly, this practice is not representative of real welds. More elements could provide higher resolution, however, the uncertainty in the welding process can shadow the numerical accuracy. Overall, current analysis and simulation tools have not shown their capability to satisfactorily predict the fatigue life at hanger rods with welds. Testing is therefore the most reliable approach for product validation, and further data collection and analysis could provide more insight into the structures and patterns of the data.

The data collections are based on the following steps and criteria:

1. Data were selected from three major programs;
2. Data were randomly selected from the database, which was generated over a period of several years;
3. Solid rod only. Data for hollow rods are excluded;
4. Rod materials are stainless steels, and data for rods made of other materials such as aluminum were excluded;
5. Failure modes were checked with pictures, and the data with ambiguities were not included
6. Data with single failure mode were selected only when a failure mode was clearly defined. Oftentimes, some failures were caused by both Rod Bend and Rod-to-Rod. In this case, the data were either excluded or included in the category of multiple failure modes.

3.2. Continuous Fatigue Life Distributions

Both two-parameter and three-parameter Weibull distribution functions were used to fit the failure data collected. The Weibull pdf and cdf are shown in [Eq.\(1\)](#) and [Eq.\(2\)](#)

$$f(x) = \frac{\beta}{\eta} \left(\frac{x-\gamma}{\eta} \right)^{\beta-1} \exp \left[- \left(\frac{x-\gamma}{\eta} \right)^{\beta} \right]; \quad x \geq 0, \eta > 0, \beta > 0, x > \gamma \quad (1)$$

$$F(x) = 1 - \exp \left[- \left(\frac{x-\gamma}{\eta} \right)^{\beta} \right]; \quad x \geq 0, \eta > 0, \beta > 0, x > \gamma \quad (2)$$

where η , β and γ are the scale, shape, and location or shift or threshold parameters, respectively. When $\gamma = 0$, the three-parameter Weibull functions are the two-parameter Weibull distributions. The threshold parameter γ gives the lower bound of the Weibull cdf. As the name implies, the threshold parameter locates the cdf along the abscissa. Changing the value of γ has the effect of "sliding" the cdf.