

# Prediction of Life Distribution and Design Robustness of Converter Joint Durability Using CAE Techniques

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## ABSTRACT

A variety of parameters influence the durability of a converter to pipe joint of an automotive exhaust system. Some of the parameters are design variables and some factors are related to manufacturing. The design parameters include the thickness of the components, diameter of the pipe, sleeve length of the cone etc. While the variables like the weld penetration and the fit-up of the joint are related to manufacturing. Traditional durability simulations utilizing computer aided engineering (CAE) methods are conducted using nominal values of the design and manufacturing variables. In reality scatter and randomness in parameters are present due to the tolerance in components and limitations of the manufacturing process. In this paper a CAE based stochastic approach to determine the life distribution for a converter joint of an automotive exhaust system is presented. During the first step of the study, design of experiments (DOE) using finite element analysis (FEA) were conducted to identify the critical parameters and interactions. Results from the DOE study were utilized to generate the response surface model to predict the durability of the joint. Finally, the response surface model was used to conduct Monte Carlo simulation and six sigma analysis to understand the robustness and reliability of the design. Correlation between the life of the converter joint predicted from this approach and life distribution obtained from physical tests are also presented. The main advantage of this approach is that the joint life is predicted using probabilistic distributions instead of the mean life.

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## INTRODUCTION

Reliability of a product carries prime importance during its design. It is a big challenge to design robust products taking into account the variability in both design and manufacturing variables considering the cost implications. It is important to identify the variability and sensitivity of all critical factors, related to both design and manufacturing, early in the design stage to minimize their effects so that fatigue life distribution of the joint meets the durability requirements.

A typical converter to pipe joint used in an automotive exhaust system and the section view of the joint is shown in [figure-1](#). The joint consists of an outer cone, inner cone and pipe welded together.

The primary load acting on the converter joint is the bending moment at the weld seam. It is the standard practice in exhaust system engineering to conduct bench testing of converter joints in order to establish their life distribution and reliability. A typical test setup of a converter joint is shown in [figure-2](#). As shown in [figure-2](#), the component is held rigidly at the converter body and loading induces bending moment at the weld seam of the converter joint. [Table-1](#) shows the loads and cycles to failure for a converter joint. As shown in [table-1](#), for the same load there is wide scatter in the cycles to failure of the part. The

scatter in the results could be due to the tolerances in design parameters like thickness of the components, diameter of the pipe, length of the sleeve, etc. Additionally, it could be induced due to the variability of the welding process or it is affected by the variations in the fit-up of various components.

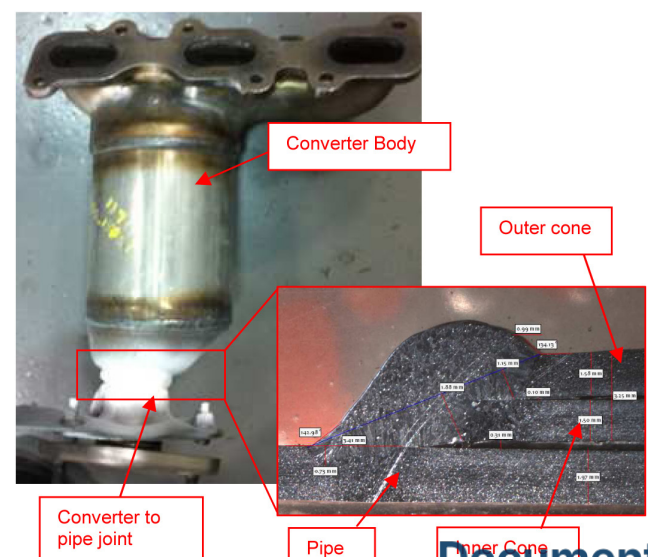


Figure-1. A typical Converter to pipe joint and section view.

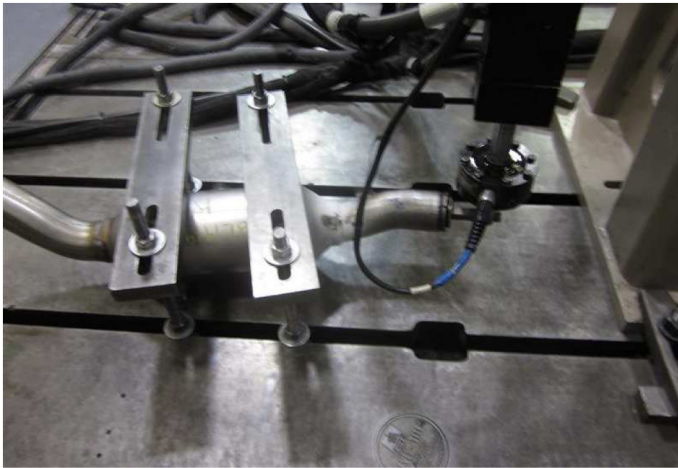


Figure-2. Test setup for bench testing of converter joints

Table-1. Results from bench test of part shown in figure-1

| Component # | Moment Load applied at the Weld Seam (load range N-m) | Cycles to Failure |
|-------------|-------------------------------------------------------|-------------------|
| Part-1      | 655.3                                                 | 47479             |
| Part-2      | 655.3                                                 | 90152             |
| Part-3      | 655.3                                                 | 275497            |
| Part-4      | 655.3                                                 | 111208            |
| Part-5      | 655.3                                                 | 72400             |
| Part-6      | 655.3                                                 | 95920             |

Computer aided engineering (CAE) analysis is also widely used in exhaust system development to design converter joints. Traditional CAE techniques use nominal parameters to generate finite element (FE) models. The deterministic approach cannot address the variability seen in the durability of the joint as shown in [table-1](#). In this paper, a CAE based method is outlined to understand the reasons for scatter in life and keep its effect within acceptable limits so that the design is robust enough to meet the durability requirements of the joint [1]. The method presented here looks at utilizing FEA based design of experiments (DOE) studies using both design and manufacturing variables with Monte Carlo simulation to obtain the life distribution of a converter joint [2].

## ANALYSIS PROCEDURE

A converter joint is essentially a pipe subjected to a bending load at its weld seam. The stress for a pipe in bending can be calculated with the following equation [3]

$$PipeStress = Kt * \left( \frac{BendingStress}{2} + \sqrt{\frac{BendingStress^2}{4} + ShearStress^2} \right) \quad (1)$$

$$BendingStress = \frac{32 \times Force \times Length \times OD}{\pi \times (OD^4 - ID^4)} \quad (2)$$

$$ShearStress = \frac{4 \times Force}{\pi \times (OD^2 - ID^2)} \quad (3)$$

Where  $OD$  is the outer diameter of the pipe,  $ID$  is the inner diameter of the pipe,  $Length$  is length of the moment arm and  $K_t$  is the stress concentration factor. The only unknown in the above equation is the stress concentration factors  $K_t$ . The stress concentration factor for any location depends on the geometric shape of the joint. The geometry near the joint is determined by design variables and the factors introduced during manufacturing of the joint. Once  $K_t$  for a given joint is determined, the stress at the joint can be evaluated by [equation-1](#). The life of the joint is then calculated with appropriate SN curve using the stress calculated from [equation-1](#) [4].

So the most critical step in determining the stress at the converter joint is to establish the  $K_t$  of the joint. Both design and manufacturing variables influence  $K_t$ . During the first step of the study, all the critical design and manufacturing variables were identified and the range of each parameter was established. A DOE with all the factors was conducted to determine the critical factors influencing  $K_t$  of the joint. The results from the DOE were used to generate a response surface model for  $K_t$ . The response surface model obtained from the DOE studies were combined with [equation-1](#) to determine the stress/life of the converter joint. Finally, Six Sigma analysis with Monte Carlo method using the tolerance on each design and manufacturing variable was carried out to obtain a life distribution for a given converter joint configuration [5]. The life distribution predicted by this method was compared with the distribution obtained from physical tests in order to understand the validity of the procedure.

## CALCULATION METHOD FOR $K_t$

Stress concentration factor for various types of geometries are available in many standard design handbooks [6]. However, they are valid for only very simple geometries. The welded joint considered in this study is more complex and involves interaction between many variables. So FEA was used in this study to establish the stress concentration factor of the converter joint. The concentration factor is calculated by the following equation

$$Kt = FEA\_stress / \left( \frac{BendingStress}{2} + \sqrt{\frac{BendingStress^2}{4} + ShearStress^2} \right) \quad (4)$$

Where  $FEA\_stress$  is the stress at joint obtained from Finite Element Analysis and  $BendingStress$  and  $ShearStress$  are obtained from equations 2 and 3

Typical failure locations of converter joints are shown in figure-3. As shown in figure-3, the failure of the joint invariably occurs near the weld, either on the cone or the pipe depending on the geometry. Since failure can occur either at the pipe or the cone,  $K_t$  on both the converter cone and pipe were calculated. Stress/life calculations were done at both sides of the joint and the minimum life was determined to be the life of the joint.

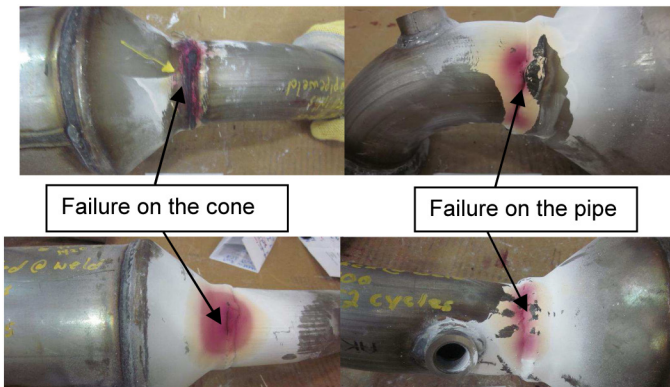


Figure-3. Typical failure locations of converter joints during the physical test

## VARIABLES INFLUENCING STRESS CONCENTRATION FACTOR: $K_t$

As explained before, the first step of determining the stress concentration factor is to identify the critical design and manufacturing variables that influence the geometric shape of the converter joint.

### Design Variables

The design variables are the factors that are controllable by the design engineers. For a converter joint, they include the thickness of components, diameter of the pipe, length of the sleeve, etc. The various design factors for a typical converter joint is shown in figure-4. The ranges of each factor were established from design drawings of converter joints used for various applications. The design factors and ranges used in this study are as follows

Converter outer cone thickness: 1.2 mm to 2 mm

Pipe Thickness: 1.2 mm to 2 mm

Pipe Diameter: 54 mm to 70 mm

Sleeve Length: 8.5 mm to 15 mm

Cone Length: 24 mm to 70 mm

Fillet Radius: 2 mm to 7 mm

The inner cone is used for heat insulation and it is not a load bearing part. So the thickness of the inner cone was considered not important and was not included in the DOE study. The converter body diameter was always maintained at 2 times the pipe diameter, which is also typical for converter designs.

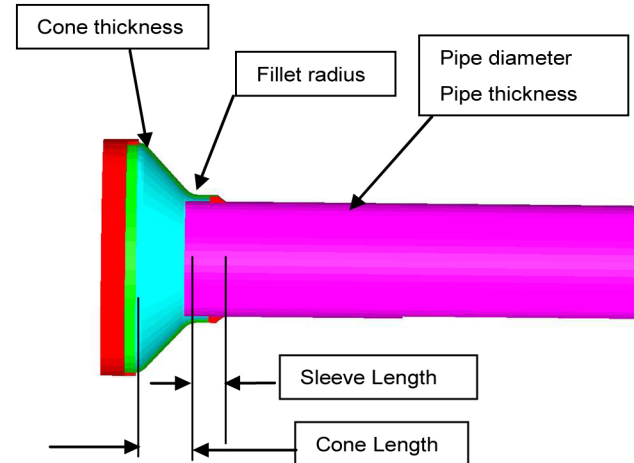


Figure-4. Design variables for a converter joint

### Manufacturing Variables

The manufacturing factors include the weld parameters and the fit-up of the components that make up the joint. The section view of a typical converter joint is shown in figure-5

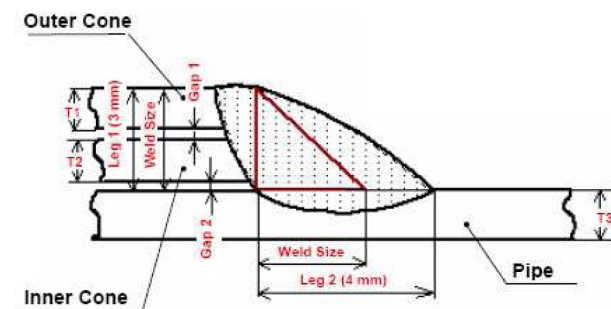


Figure-5. Section view of a typical converter joint

The leg of the weld (weld length) is the weld factor and the gap between the components (Gap 1 and Gap 2) is the factor influenced by the fit-up of the components. Weld length and gap between the components were identified as the most important manufacturing variables for this study.

Weld length and gap between the components are influenced by a wide range factors like the weld method, the welding process, the tolerance of different components that make up the joint, etc. It is extremely difficult to empirically determine the weld length and gap for a given converter joint configuration. So for this study, metallurgical sections were made for a number of typical converter joints and the weld lengths, gaps between components were measured. Figure-6 shows a typical