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Conference Article

Reliability Assessment of the Casted Steel Function Block in Gasoline Fuel Rails

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Abstract

In this study, the reliability of the casted function block, a critical component of the fuel rail assembly (FRA), is examined under the pressure and thermal loads typically encountered in an engine compartment. The function block serves a dual purpose: it acts as a holder for the fuel rail, securing it to the cylinder head (CH), and it includes the injector cup, which connects the injectors to the rail. This component is manufactured as a single piece using casting methods.

To assess the stress experienced by the function block, Finite Element Analysis (FEA) techniques are employed. Additionally, a specialized mechanical pulse test is developed to determine the fatigue limits of the casted function block. This testing is crucial for understanding how the component will perform under cyclic loading conditions.

The failure probability of the function block is quantified by generating S-N (stress-cycle) curves based on the results from the mechanical pulse tests. These curves illustrate the relationship between the applied stress and the number of cycles to failure, allowing for a comprehensive analysis of the component's durability.

Ultimately, the study demonstrates that the failure probability of the casted function block is estimated to be less than 1 ppm (parts per million) for serial production. This finding confirms that the function block meets the stringent reliability requirements necessary for automotive *applications, ensuring its performance and safety in the demanding environment of an engine compartment.*

Keywords: Fatigue, Mechanical Pulse Tests, Stress, Strength, Casted manufacturing, Gasoline Fuel Rails,

1. Introduction

a. Schematic of the Gasoline Injection System

Internal combustion engines (ICE) convert chemical energy into mechanical energy by burning gasoline fuel within the combustion chamber. This process involves a series of components that work together to ensure efficient fuel delivery and combustion. In this engine layout, we focus on an internal combustion engine equipped with a high-pressure fuel injection system.

In this system, gasoline fuel is initially drawn from the fuel tank and transferred to a low-pressure pump, which is driven by an electric motor. This low-pressure pump is responsible for moving the fuel to the high-pressure pump. Once the fuel reaches the high-pressure pump, it is pressurized to approximately 350 bar, depending on the specific requirements of the engine and the fuel injection system.

The high-pressure fuel, now at 350 bar, is then directed to the forged fuel rail, which serves as a distribution point for the fuel to the injectors. The fuel rail is designed to withstand the high pressures involved and ensures that the fuel is delivered evenly to each injector, allowing for precise control of the fuel-air mixture entering the combustion chamber.

This high-pressure fuel injection system enhances the efficiency and performance of the internal combustion engine by enabling better atomization of the fuel, leading to more complete combustion and reduced emissions. The design and reliability of components such as the fuel rail and function block are critical to the overall performance and longevity of the engine.

(Figure 1) would typically illustrate the layout of the fuel system, showing the flow of fuel from the tank through the pumps and into the fuel rail.

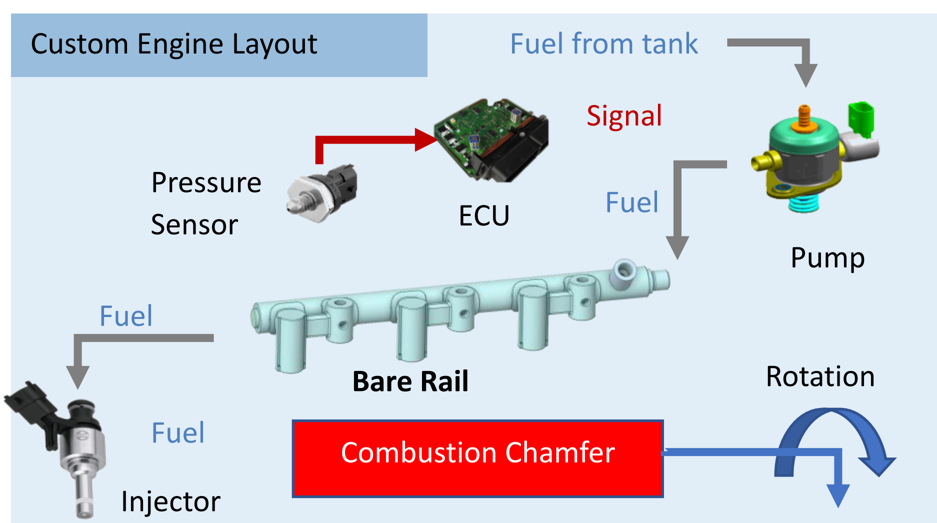

Figure 1. Internal Combustion Engine (ICE) Schematic View

b. Function of FRA and Motivation of The Strength Detection

The main function of the bare rail (Figure 2) is to store high pressured fuel inside of the rail and to be tight during the service life of the product. Another function of the bare rail together with injectors that is called as fuel rail assembly (FRA) is to transfer required amount of fuel in desired time and in desired volumes to the combustion chamber.

Given that gasoline is a highly flammable liquid, any leakage in the engine compartment poses a significant fire risk. Therefore, it is crucial to assess the strength and reliability of the casted function block under various environmental loads, including pressure, temperature, and vibration. This study aims to evaluate the structural integrity of the function block to prevent crack formation that could lead to fuel leakage.

The casting method is currently favoured for production due to its ability to provide greater design flexibility, particularly concerning the placement of the holders and injector cups. However, this flexibility necessitates a thorough examination of potential critical design elements to ensure safety and reliability.

To meet reliability requirements, the outer surface of the casted function block is rigorously tested to confirm the tightness of the rail under environmental loads. Validation activities are conducted to assess the block's performance against pressure, temperature, stresses. Understanding the strength (loadability or load capability) of the outer surface of the casted function block is essential, especially since it is critical to identify any early crack initiation points in these areas. By ensuring that the casted function block can withstand the operational stresses without compromising its integrity, the study aims to enhance the overall reliability of the fuel rail assembly, thereby reducing the risk of fuel leaks and potential fire hazards in the engine compartment.

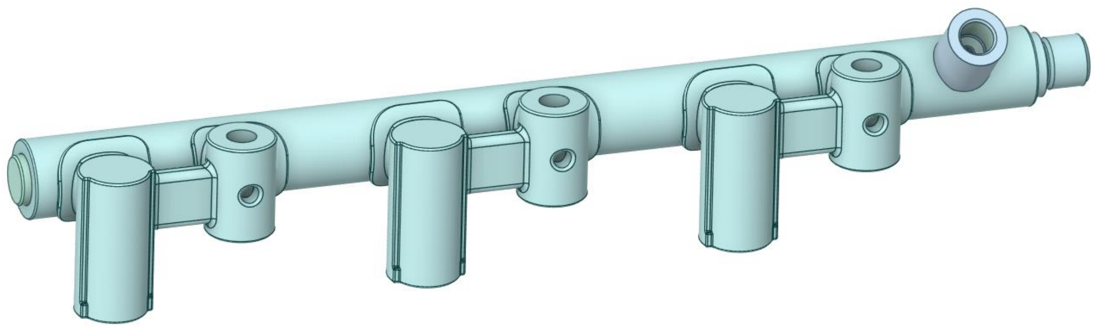

Figure 2. Bare Rail Overview

In reliability perspective, strength of the design elements must be known by the validation methods and more common way to create the Wohler curves of the design element by using hydro pulse or mechanical pulse devices under variable loading. Force-cycles curves will be created after running mechanical pulse tests in this study for the potential critical areas of the Casted Function Block (Figure 3).

FEA methods are also important activity for this study. Because as an output of mechanical pulse test, Wohler curve will be created as Force-cycle curve and it must be converted to Stress-cycle (SN) curve to get a universal representation of this test and SN curve is a load independent curve and can be used to perform assessments with different loads such as pressure, temperature, and vibration or in their combinations.

After getting SN curves and load spectrum from vehicle measurements, fatigue assessments must be performed to ensure the failure probability of the design element must be less than 1 ppm during the service life of the product.

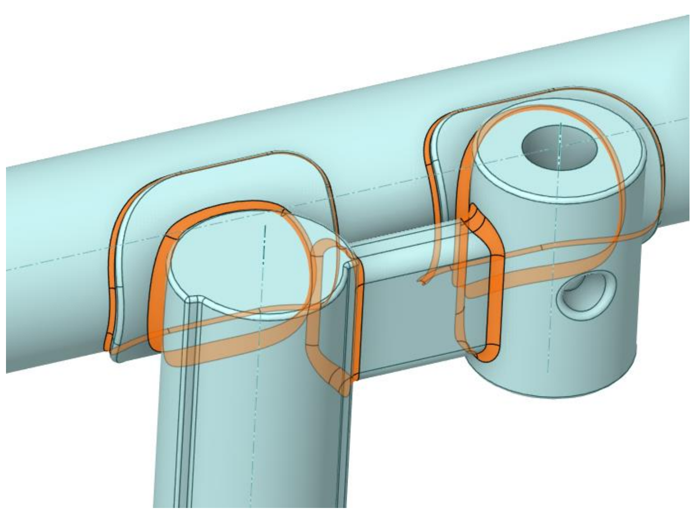

Figure 3. Potential Critical Areas under Environmental Loads

2. Reliability Requirements for The Casted Function Block

Rail design must fulfil reliability requirements during project phase. Since rail is a part which stores fuel and supplies it to the injectors required amount of fuel, therefore leakage is not allowed as a safety relevant requirement. Rail should withstand loads during lifetime. Rail is evaluated by finite life fatigue approach which is considering load collective from the field therefore failure probability must be less than 1 ppm.

Strength data is required for focused area to complete fatigue assessment. When a new project is started, strength data (Wohler curves) is not known as shown in Figure 4, and it should be conducted by mechanical pulse tests.

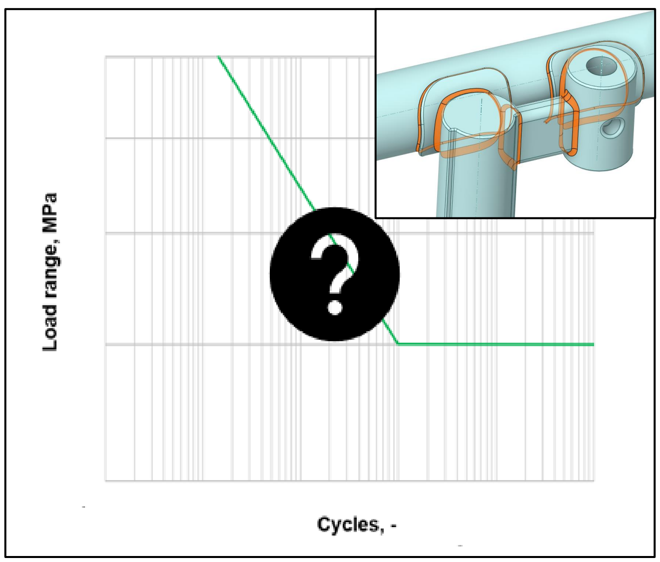

Figure 4. Unknown Strength Data of new design surfaces (Illustrative Data)

3. Simulation Studies

Simulations are performed to evaluate and to improve the design against environmental loads. Initial simulation considers operational loads which are mounting, pressure and

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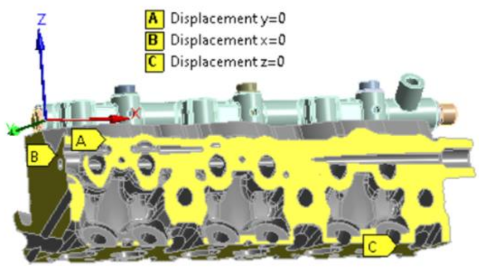
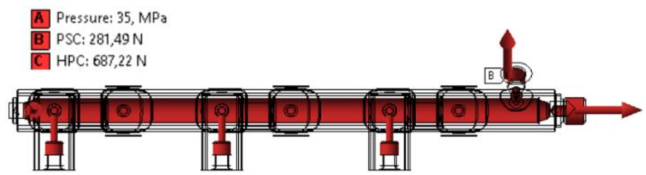
temperature loads. Boundary conditions represent engine working conditions. If stress results are higher, design optimization studies are done.

Simulations are performed to see the stress status on the potential critical areas under pressure, temperature loads.

In figure 5, boundary conditions are shown for different simulation types. Stress calculation includes mounting load, system pressure to fuel area and temperature load for all components. It's also called as operational loads.





Step	LS	Description	Mounting Load		Operational Load	
			Fv [N]	NHE [N]	pi [bar]	Temp. [°C]
1	**LS11**	Fv Bolt Pretension	**14197**	-	-	20
2	**LS12**	LS11 + NHE Force	14197	**480**	-	20
3	**LS13**	LS12 + 350 bar	14197	480	**350**	20
4	**LS14**	LS13 + 130°C	14197	480	350	**130**

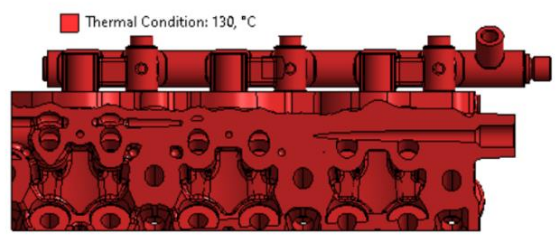


Figure 5. Boundary Conditions Overview

4. Mesh

Fine mesh is created on focused area to have accurate stress result. Mesh distribution and elements are seen in Figure 6. Areas in which have fine mesh distribution and smaller element size are used. Tetrahedral element type is preferred to have better transition between locations. FE model has nodes number around 7.000.000.

Figure 6. Mesh Distribution

5. Material Model

In Figure 7, material models are seen. Steel is used for Rail and Bolts. Aluminium is used for engine.

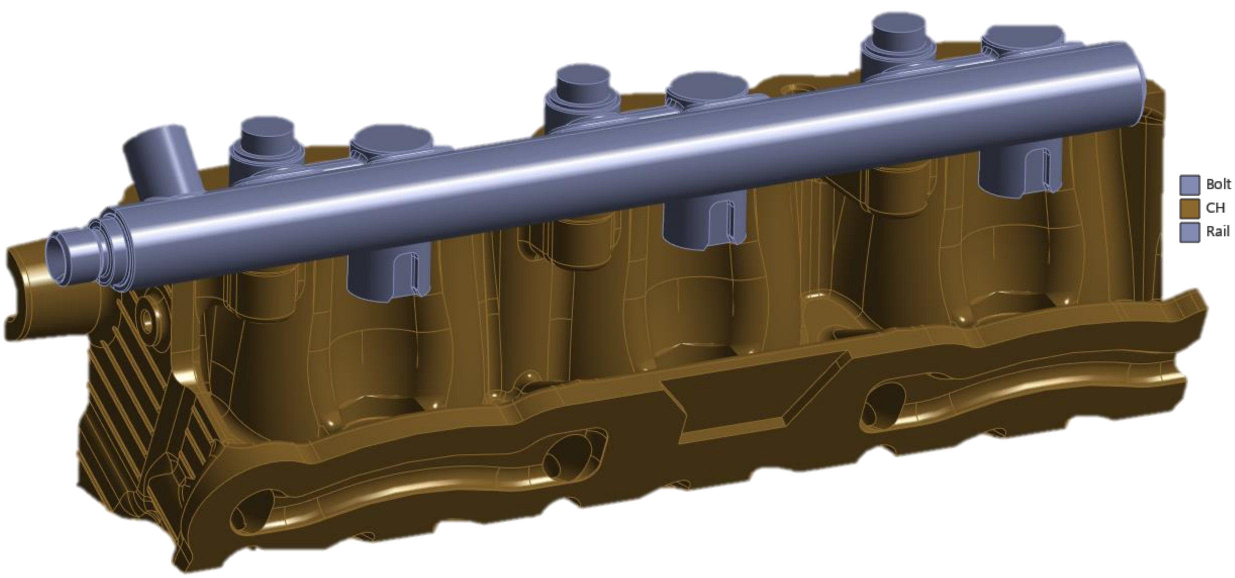


Figure 7. Materials

6. Simulation Result: Under Operational Load

The stress calculation results under operational loads are illustrated in Figure 8. In this figure, the coloured areas represent varying levels of stress experienced by the component. The red regions indicate maximum stress levels, while the blue areas signify minimum stress levels.

The analysis reveals that the maximum stress concentration occurs at the bridge between the injector cup and the holder. This area is particularly critical because it is a free end, which causes the injector cup to bend upward in response to the internal pressure exerted by the fuel. This bending action contributes significantly to the stress experienced in this region.

Additionally, the stress levels in this area are further exacerbated by thermal expansions that occur during engine operation. As the temperature fluctuates, the materials expand and contract, leading to additional stress that compounds the bending effects caused by the internal pressure.

Understanding these stress distributions is crucial for assessing the structural integrity and reliability of the component. The findings highlight the need for careful design considerations in this region to mitigate the risk of failure due to high stress levels, particularly under the combined effects of pressure and thermal loads.

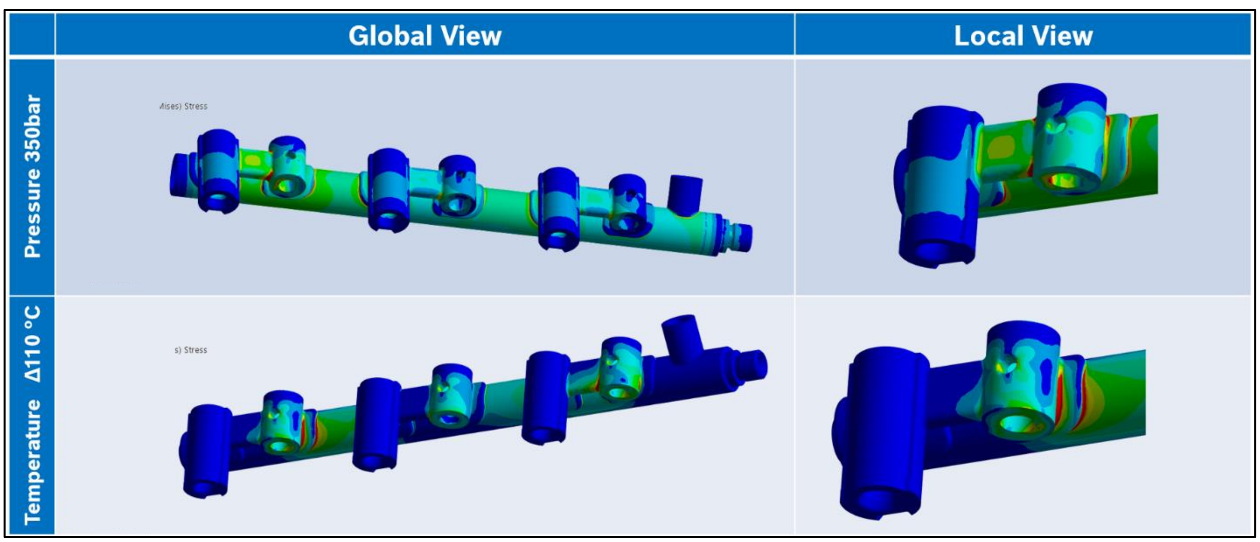


Figure 8. Stress Distribution under Pressure & Temperature Load

7. Validation Activities

a. Mechanical Pulse Test Set-up with FEA

To evaluate the strength status of potential critical regions on the casted function block, mechanical pulse tests are conducted. These tests are designed to simulate operational conditions and assess the component's strength (load capability) response to cyclic loading.

To ensure accurate results, Finite Element Analysis (FEA) studies are performed in conjunction with the mechanical pulse tests (Figure 09). The FEA simulations with fixtures of the test device provide valuable insights into the stress points within the function block under mechanical pulses. This analysis focuses on identifying both the locations of maximum stress and the directions of the stress tensors, which are crucial for understanding the stress and its direction must be similar between operational conditions and test device environment.

By correlating the data obtained from the mechanical pulse tests with the FEA results, a comprehensive understanding of the strength characteristics of the casted function block can be achieved.

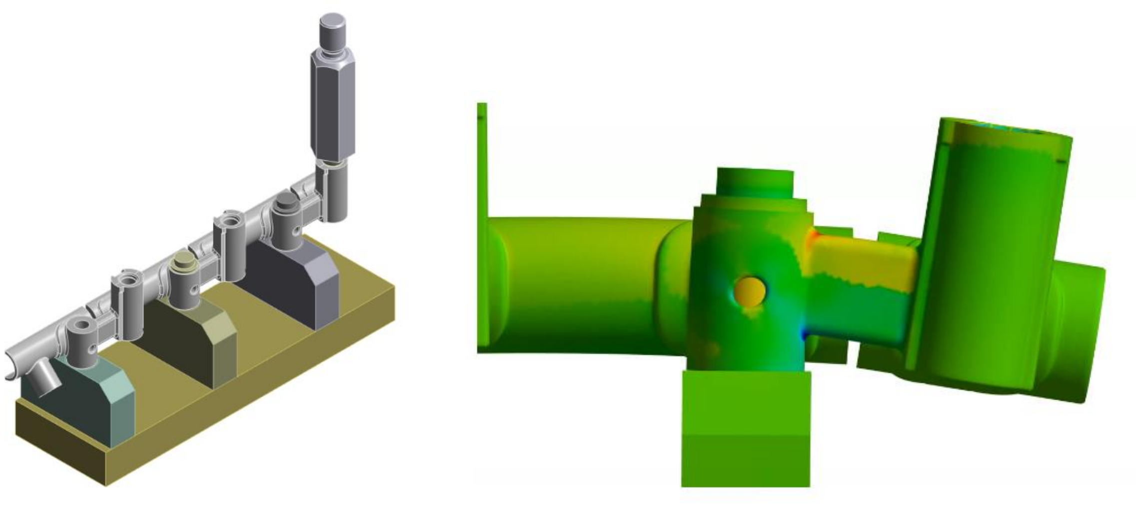


Figure 09. Mechanical Pulse Test Set Up & its FEA Results.

8. Result

a. Observation of the Test Result & Strength

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Mechanical Pulse tests are performed in 4 load levels. These 4 load levels are identified by checking the FEA results in respect to material strength.
As seen the Figure 10, load levels in Newton (N) with max and min load definitions are seen. Based on these different load levels, failed parts and non-failed parts are recorded. Non-failed parts are specified based on maximum 10 million cycles criteria. The parts that reach to 10 million cycles are assumed as success run.

Load Level	Min. Comp. Force [N]	Max. Comp. Force [N]	Range (ΔForce) [N]	Tested Parts	Failed Parts	Test Region
1	200	3325	3125	5	2	Infinite
2		3950	3750	5	5	Finite
3		4700	4500	5	5	Finite
4		5285	5085	5	5	Finite

Figure 10. Mechanical Pulse Test Results & Failure

b. Observation of the Strength (Load Capability)

All data is transferred into the Wohler Curve (SN Chart) to represent the strength state of the potential critical region (Figure 11).

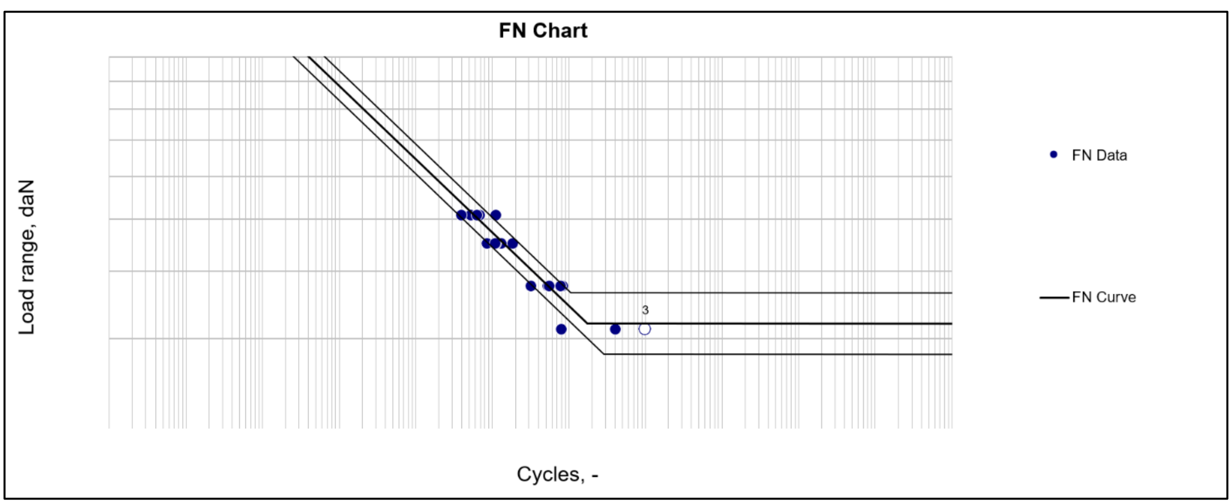
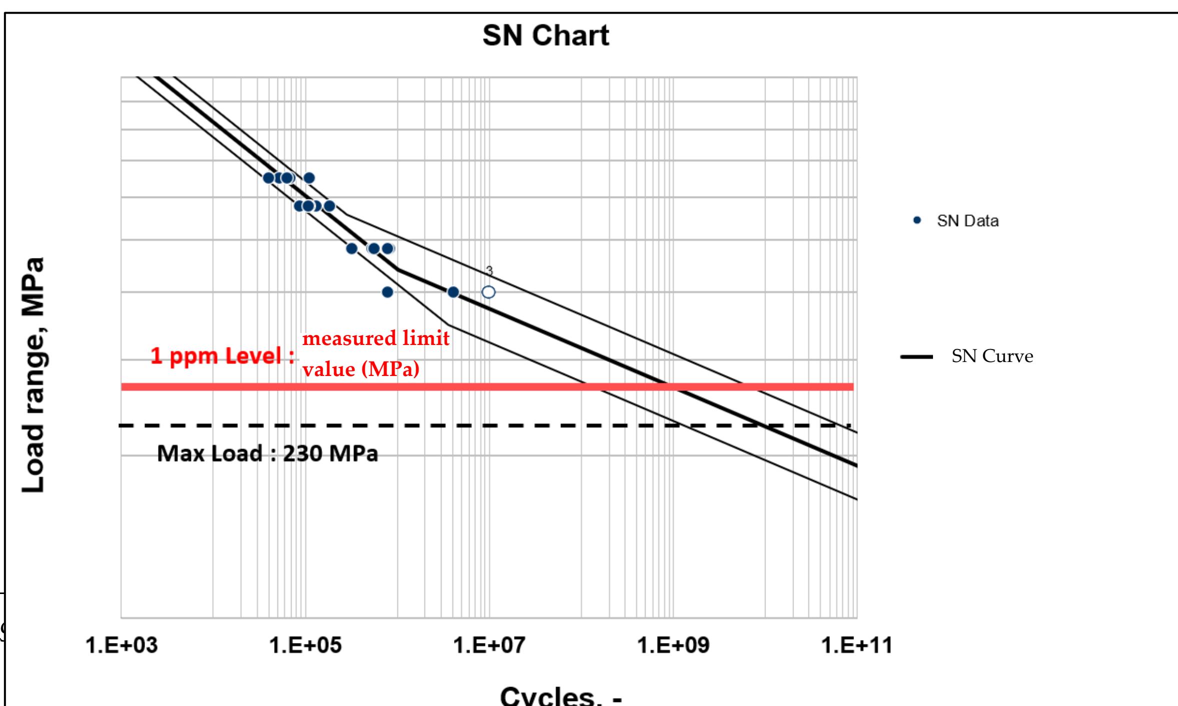


Figure 11. Wohler curve

a. Reliability Assessment & Conclusion

After completing the Mechanical Pulse tests and deriving the Wohler curve, the final step is to assess the reliability of the part in relation to its failure probability during its service life of 240,000 km (or 15 years). The reliability requirement mandates that the failure probability must be less than 1 ppm (parts per million) throughout this period. A 1 ppm strength line can be established on the Wohler curve through a statistical evaluation based on the Gaussian normal distribution of strength values on the Y-axis (refer to Figure 12). It has been determined that the 1 ppm strength line corresponds to a stress level of *measured limit value (MPa)* for this critical region.

To ensure a reliable design in the field, the stresses resulting from operational conditions must remain below the *measured limit value (MPa)* threshold. If this condition is met, we can conclude that the design satisfies the safety and reliability requirements, resulting in a failure probability of less than 1 ppm. Upon evaluating the operating loads, it is found that the maximum stress, arising from the most extreme pressure and temperature scenarios, is *calculated stress level (MPa)*. Since this *calculated stress level (MPa)* is less than *measured limit value (MPa)*, the design successfully meets the reliability requirements.



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Calculated stress
level (MPa)

Figure 12. Reliability Assessment

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