Crankshaft reliability by integrated design, simulation and testing

This testing method is proven and beneficial for the design and development of the crankshaft and could be applied to other critical engine components, thereby extending to system reliability.

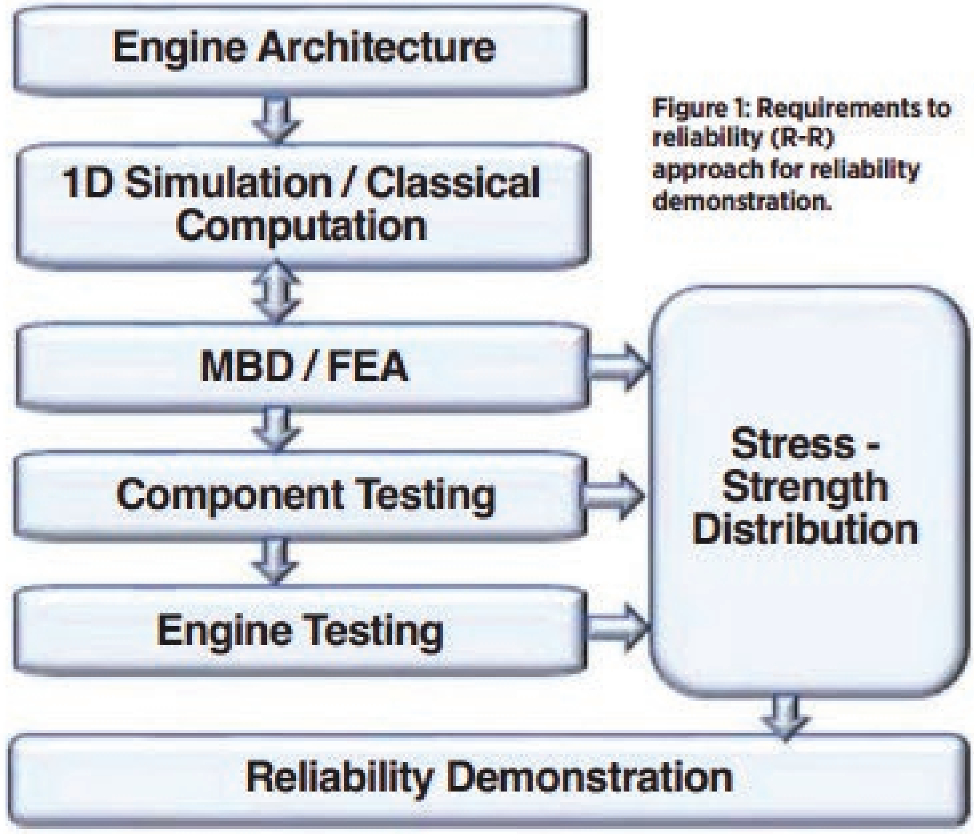

Figure 1: Requirements to reliability (R-R) approach for reliability demonstration.

With the crankshaft being one of the key components in engine development, it draws outsized attention from powertrain developers seeking to ascertain its reliability. Crankshaft reliability depends on a number of parameters such as general engine architecture, material property variations and manufacturing process variations.

Reliability is defined as the ability of a system or component to perform its required functions under stated conditions for a specified period of time. The concept of reliability, however, is quickly evolving from component and engine validation to simulation and verification at the early stages of engine design. Reliable crankshafts provide assured performance and scalable design for future engine families.

Methodology

Figure 1 illustrates the overall reliability methodology for crankshaft design. In the current scenario, misperceptions exist among engineers as where to begin the design for reliability (DFR) process—should it be from benchmarking data or engine architecture to validate a reliable design. This paper attempts to clarify the approach required for Requirements to Reliable (R-R) design as shown in Figure 1.

Our study result and approach is based on the stress-strength method, where the design

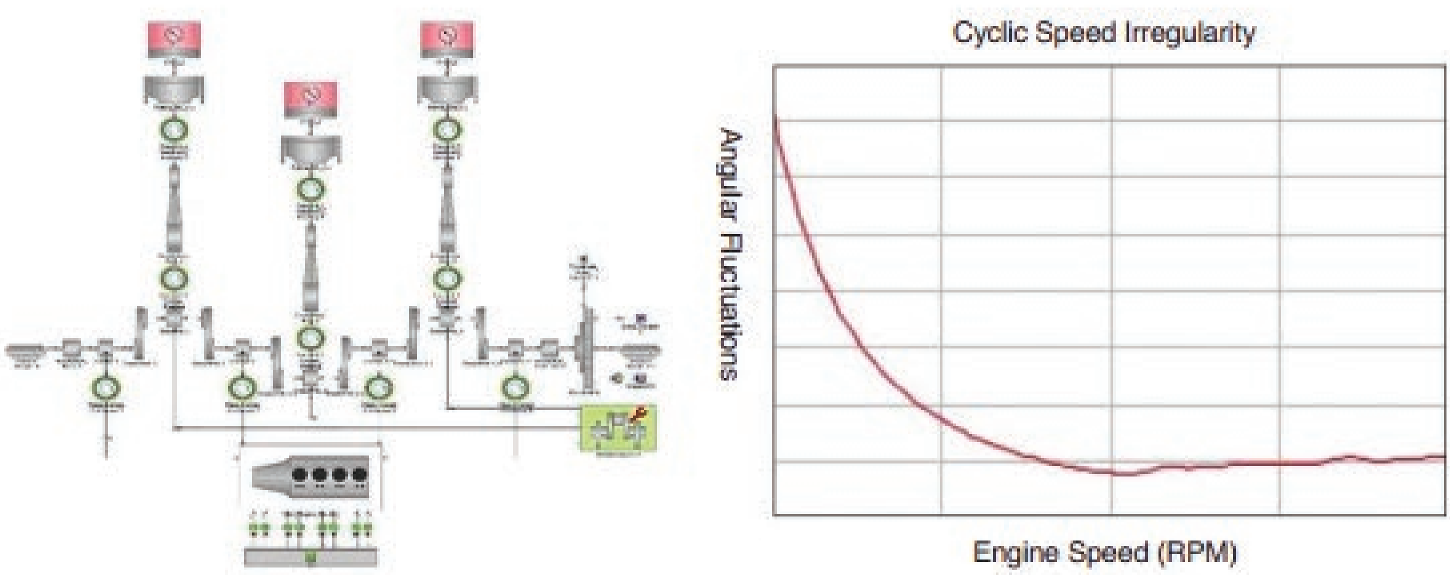

Figure 2: 1-D cranktrain model and its typical output.

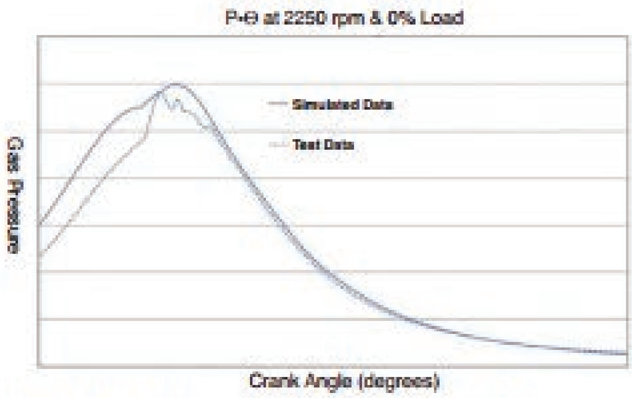

Figure 3: Peak pressure prediction in-cylinder combustion simulation.

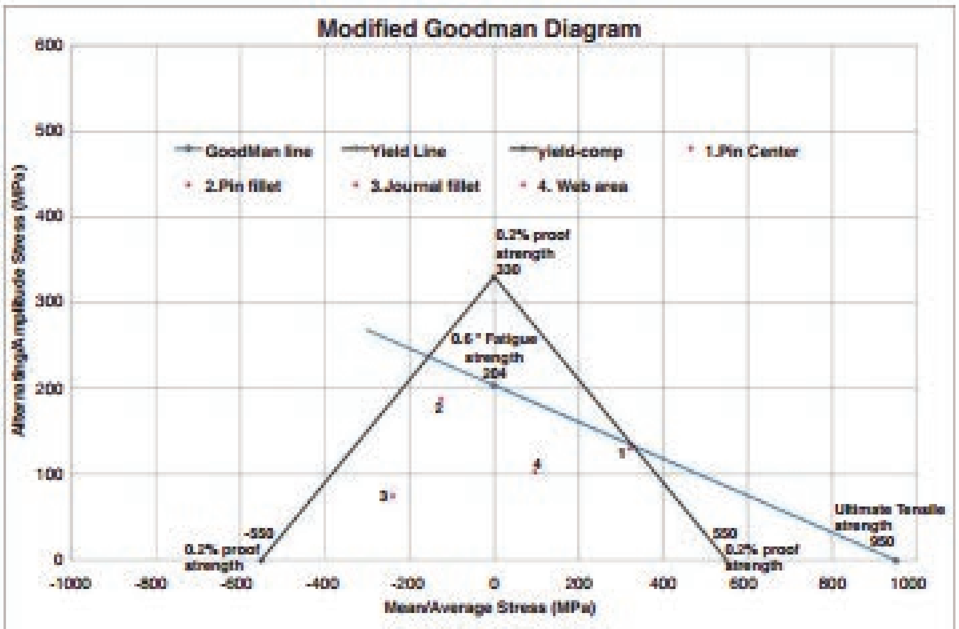

Figure 4: Sample Modified Goodman Diagram

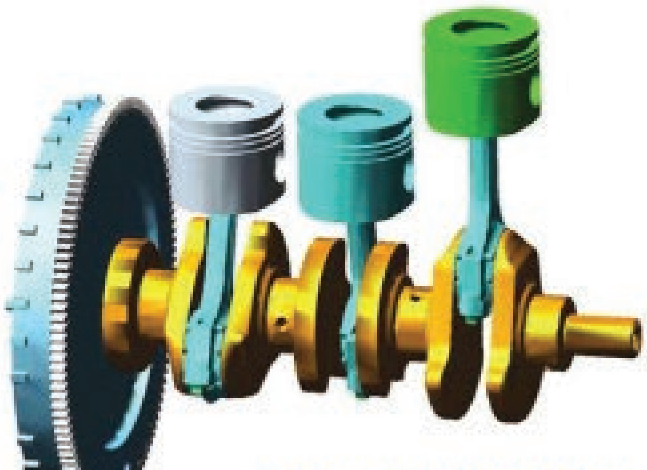

Figure 5: Typical MBD model for simulation.

TABLE 1: MULTIBODY DYNAMICS MODEL - JOINTS DEFINITION		
COMPONENT 1	COMPONENT 2	JOINT TYPE
Piston	Ground	Translation
Piston	Piston Pin	Fixed
Piston Pin	Connecting Rod	Revolute
Connecting Rod	Crankshaft	Revolute
Crankshaft	Ground	Force component

TABLE 2: SIMULATION/TESTING - INPUTS & OUTPUTS		
SIMULATION/TESTING	INPUT	OUTPUT
Classical computation	Engine architecture	Critical CAD dimensions
1-D simulation	CAD dimensions	Crank fluctuations, bearing forces, crank mass balancing
IC engine combustion simulation	CAD, flow measurements	Peak pressure (Pmax), heat-release rate
FEA / MBD	CAD, pressure-crank angle, bearing reaction forces	Stress, strain at pin/journal fillet, pin center
Component fatigue testing	Test load cycles/time, Strain gauging	No. of cycles to failure, strain measurement
Physical testing	Test load cycles/time	No. of cycles to failure

is carried out to 99.97% reliability with 90% statistical confidence to prove reliability via component and engine testing.

Engine architecture and simulation

This work explains the advanced engineering approach to the design of a crankshaft from requirements and engine architecture. Engine architecture requirements were 250,000 kilometers (155,350 miles) of engineering life, flat torque in a mid-rpm range and best brake specific fuel consumption (BSFC) and fuel efficiency (FE) with an engineering target for emissions. Based on that requirement, bore, stroke and other critical engine dimensions were finalized.

Classical computational models were used to arrive at crankshaft critical dimensions and generate a preliminary computer aided design (CAD) model.

1-D simulation tools use inputs from common computations such crankshaft dimensions, balance masses, etc. Typical outputs from the 1-D simulation tool are crank fluctuations, main bearing reactions and crankshaft mass balancing. Figure 2 shows 1-D cranktrain model and its outputs.

Correlation of 1D-simulation results with field measurement was carried out to ensure model robustness. The pressure-crank angle inputs for multi body dynamics (MBD) was taken from in-cylinder combustion simulation. Figure 3 shows the correlation of combustion peak pressure simulation and test results.

A Modified Goodman diagram (Figure 4) is plotted from inputs from finite element analysis (FEA) to find design factor of safety.

The objective of MBD is to simulate crankshaft behavior under varying speeds and loads and understand the stress variation for a given Indian Driving Cycle (IDC). The MBD model uses IDC and pressure-crank angle as primary inputs separate from geometry inputs from CAD. Joint definitions in MBD are shown in Table 1.

The simulation was run for one full duty cycle and the stress history at the pin center and pin/journal fillets were obtained. Stress history,

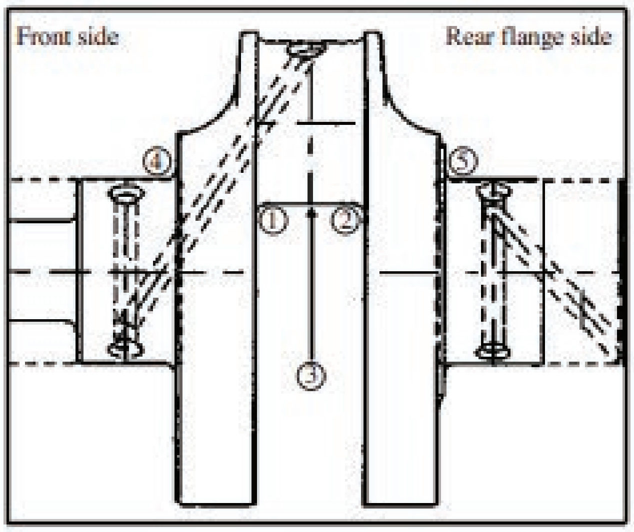

Figure 6: Strain gauge locations in crankshaft.

Figure 7: Crankshaft test setup (courtesy Ametek & Sumitomo Metal Corp.)

TABLE 3: FATIGUE TEST PARAMETERS

PARAMETER	VALUE
Sample Tested	8
Excitation Source	electric Shaker @50Hz
Strain Ratio	-1
Test Nature	HALT (highly accelerated list test)
Strain gauging areas	refer figure 6

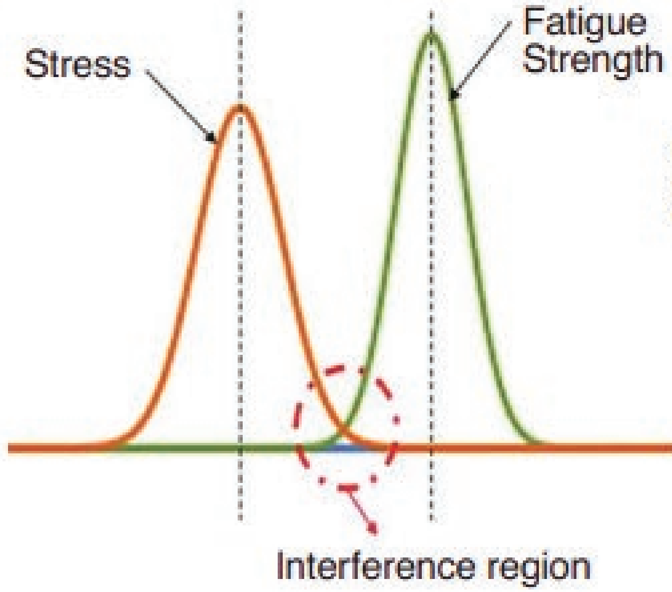

Figure 8: Stress-strength approach for crankshaft reliability.

along with duty cycle, is used in MSC fatigue software to estimate cycles to failure for the design. Table 2 provides a summary of simulation inputs and outputs. Figure 5 shows a typical MBD model bound for simulation.

Component fatigue test

Crankshaft fatigue evaluation was done through the resonance bending method. Table 3 gives the test condition summary.

The component validation provided outputs such as stress concentration factor, strains at critical locations, fatigue strength and failure region identification. Magnetic particle inspection was carried out to confirm crack initiation.

Engine validation

The crankshaft was validated through several engine metrics such as the resonance durability, cyclic durability, piston scuff, high-speed-no-load and deep thermal shock tests.

Accelerated testing was carried out for all durability testing. Tested crankshafts were inspected for wear, surface and sub-surface cracks (via magnetic particle inspection), change in hardness and fatigue strength.

Statistical tools in reliability demonstration

Reliability calculations were carried out using in-house tools based on the stress-strength approach. Stress variation (from FEA) and material strength variation (from testing) are input to the tool. The standard deviation and covariance are calculated at 3σ levels.

Interference region in Figure 8 provided the 99.997% reliability with 90% engineering confidence.

Summary

The stated approach helped to develop crankshaft by requirements-reliability with due correlation with part development and validation test data. The integration of 1D, MBD & FEA gave a complete understanding of stress distribution. Test Results (fatigue/engine testing) provided strength distribution and failure area with engineering confidence. The reliability tool is capable of understanding variations and mean shift and effectively produce a reliability (≥6σ) for the crankshaft. This approach is proven and beneficial for design and development of the crankshaft and could be applied to other critical components, thereby extending to system reliability. ■

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