Designing Cylinder Head Gaskets for New Generation Powertrains

Rohit Ramkumar, Jason M. Tyrus, Paul M. Fatora and Harald Rebien

Dana Incorporated

***Abstract**: The past decade has seen transformative changes in internal combustion engine technology. Revolutionary technological advances of powertrains include the replacement of traditional gasoline internal combustion engines with smaller displacement engines, the use of turbocharging to make smaller displacement engines more powerful and efficient, and the use of lightweight materials in both vehicle bodies and engines. Furthermore, the federal government's CAFE standards mandate that OEMs develop more fuel-efficient vehicles with lower emissions. To keep pace with the radical advances in powertrain technology, advanced cylinder head gaskets (CHG) are needed to achieve higher performance expectations by accommodating higher temperature exposure, the use of aluminum alloy hardware instead of traditional cast iron hardware, and extended warranty guidelines from the OEMs. Along with technological advances, time to market and first time right initiatives are pushing the development of CHG to utilize new levels of simulation and optimization processes. Increased use of Isight for optimization of forming processes and stopper height along with improved analysis techniques for fatigue prediction enable the design of more robust CHG. This paper demonstrates how simulation is driving the complex development of technologically advanced CHG.*

***Keywords**: Powertrains, MLS Gaskets, Optimization, Metal Forming, Gasket Behavior, Sealing, Heat Transfer, Fatigue, Residual Stress and DOE.*

1. Introduction

To meet increasing demands for better fuel economy and emissions from smaller engines without sacrificing power, technologies from niche and premium markets have been brought into mainstream applications. Some of the approaches include:

1. Turbocharging systems
2. Direct gasoline (petrol) injection
3. Higher pressure diesel injection
4. All aluminum hardware with cylinder spray bore
5. Combined head, exhaust manifold & turbocharger
6. Cylinder deactivation
7. Exhaust gas recirculation (EGR)

Higher cylinder pressures are being used in modern powertrain designs to generate the same power output in smaller engines. Gasoline engines operate up to 17 MPa, and diesel engines up to 22 MPa for passenger car applications. This causes increased peak temperatures and temperature gradients, which adds more complexity to the cooling and lubrication strategy. These aspects, plus the use of light weight alloys and thinner structures, create a challenge to seal the modern powertrain with higher reliability.

2. Cylinder Head Gasket Technology

For automotive applications, the main gasket technology used to seal internal combustion engines is Multi-Layer Steel (MLS). The MLS cylinder head gasket consists of multiple layers of metal as shown in Figure 1. Macro sealing is accomplished with embossed sealing “beads” that are formed in a thin layer of hardened steel. An elastomeric coating is applied to seal the surface roughness present in the engine hardware due to machining (see Figure 2).

The gasket contains several types of sealing beads. The combustion beads seal the cylinder bore and the backland beads seal coolant and oil passages. The combustion seal can be a combination of a “stopper,” which creates the first sealing line, and the “full bead,” which defines the second sealing line of the combustion seal. The backland seal is usually created with “half beads.”

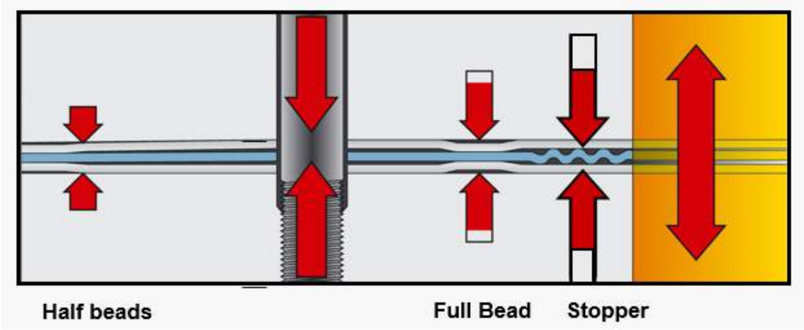

Figure 1. Gasket section

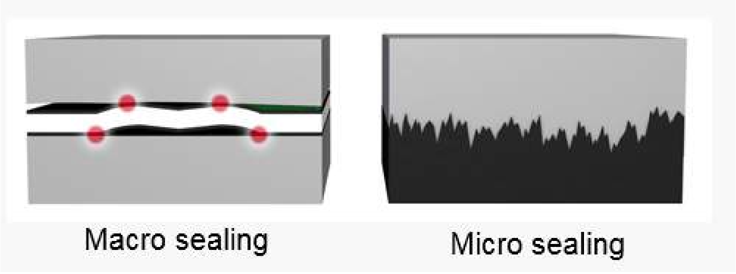

Figure 2. Two sealing functions of the gasket

The stopper element maintains a higher operating thickness, which raises the local sealing pressure and modifies the compression characteristics of the sealing bead. The stopper can be either a separate layer in series with the sealing bead, or an adjacent feature that is loaded in parallel with the sealing bead. Some typical combustion seal designs are shown in Figure 3.

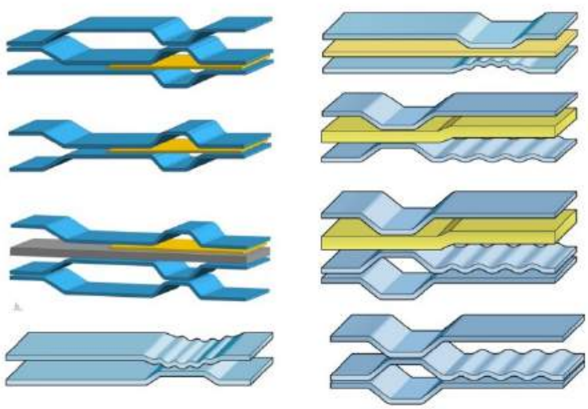

Figure 3. Multi-layer gasket design options

3. "First-Time Right" Gasket Design

Typical finite element analysis is performed on each design with an Abaqus gasket element model, as shown in Figure 4. Gasket elements have uniaxial mechanical behavior that is limited to contact pressure versus thickness (N-type gasket elements). The gasket is assembled with the cylinder head, cylinder block, cylinder liners, bolts, exhaust seats, intake seats and valve guides. In some cases, other components such as the intake manifold, exhaust manifold, or turbo model are added to get better prediction of cylinder head gasket sealing performance. To duplicate engine operating conditions, results from heat transfer analysis of an engine test condition or a set of temperature profiles from an engine validation test are included to study the thermo-mechanical stresses on the hardware and resultant effects on the gasket performance. Primary design criteria for the gasket beads are the sealing pressure and high cycle vertical motion, known as "lift-off," which is a primary factor that affects fatigue life. Based on the initial set of results, further design optimization is studied. In the past, the usual practice was to run the optimization loops manually. This tedious practice takes time to make model changes and to re-run the analysis cases one by one. With improvements in software capability and optimization software integration, features of the gasket design can be immediately adjusted and robust designs can be achieved at a much faster pace.

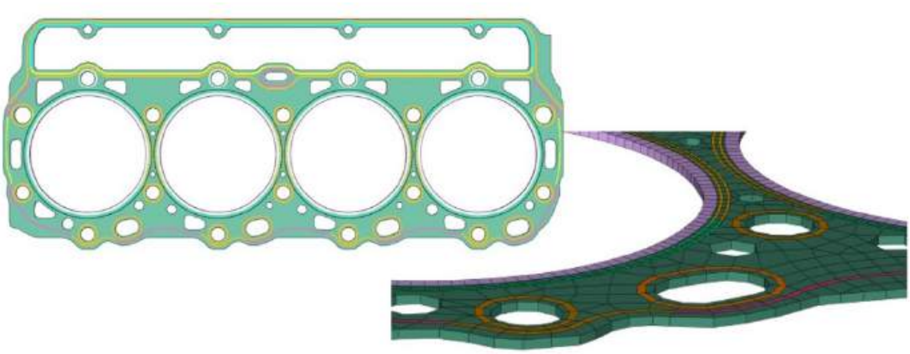

Figure 4. Model with gasket elements

3.1 Optimization of Stopper Height

The Wave-Stopper™ is a versatile gasket feature that offers design advantages. This feature consists of a series of low, stiff embossments as shown in Figure 5. The stiffness of the stopper can be varied by adjusting the height and width to obtain the best load distribution for the application. In the following example, the height of the stopper was studied to improve the minimum sealing pressure without exceeding the hardware stress limits. The range of heights for the stopper was based on design and manufacturing limits.

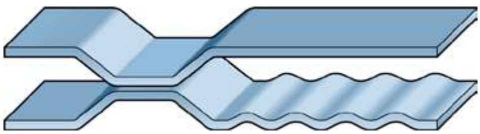

Figure 5. Wave-Stopper™ combustion seal

Isight was used to optimize the overall minimum sealing pressure on the Wave-Stopper™. Figure 6 shows the Isight sim-flow.

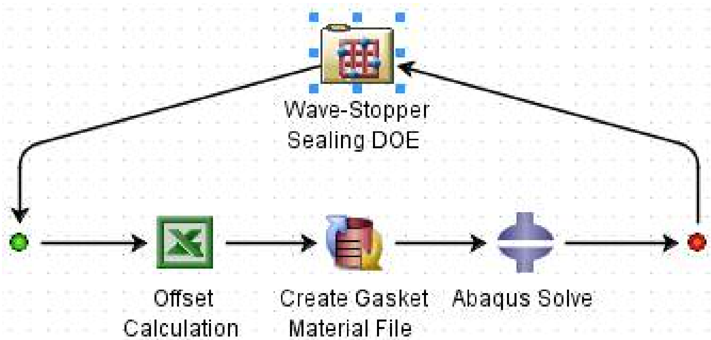

Figure 6. Wave-Stopper™ sealing pressure DOE sim-flow

The Isight root level was set to a Design of Experiments (DOE) component which executed all possible stopper height values specified as the primary input parameter to determine the height value that results in the greatest overall minimum sealing pressure on the stopper.

The subflow of the Isight process automatically executed the steps required in the DOE and managed the data. The steps within the subflow consisted of the following:

- Excel component: configured to use the specified values of Wave-Stopper™ height to compute the offset of the Wave-Stopper™ elements relative to the other components in the gasket
- Data Exchanger component: configured to use the offset value computed by the Excel component to create a unique gasket input file
- Abaqus component: configured to submit an Abaqus run using the unique gasket file in the 3D powertrain model, extract the minimum sealing pressure on the Wave-Stopper™ elements over the specified analysis steps, and return the values as the output parameter of the root level DOE.

Figure 7 shows the variation in Wave-Stopper™ sealing pressure results for the DOE.

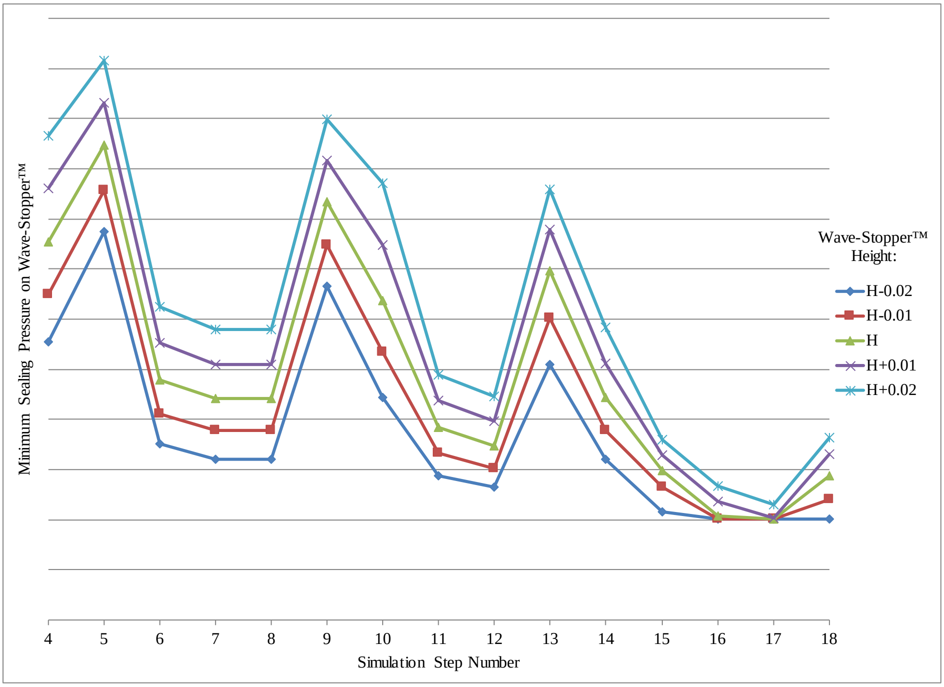

Figure 7. Wave-Stopper™ sealing pressure results

3.2 Optimizing Stopper Topography

In many cases, a uniform height stopper is not sufficient. Hardware characteristics such as temperature, structure, and bolt pattern result in non-uniform pressure distribution around the cylinder bore (see Figure 8). The load distribution affects the bending of the hardware, which could result in higher hardware stress, thereby causing damage to the hardware. Therefore, it is important to design a gasket which not only meets the gasket performance requirements, but also minimizes the hardware stresses. The stiffness of the stopper can be varied by varying the stopper height or width around the bore to achieve:

- Uniform sealing stress distribution around the bore
- Reduced bore distortion
- Increased minimum overall sealing pressure on the stopper
- Improved load distribution and lower dynamics at the cylinder bore.

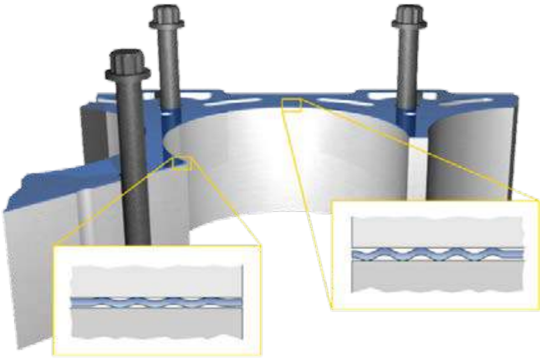

Figure 8. Varying stiffness behavior of the Wave-Stopper™

In the following example, Isight was utilized to evaluate the influence of stopper topography on the maximum principal stress in the engine liner. In this study, each section of the stopper in the 3D gasket element model was modeled with a different element set having different load deflection behavior. Figure 9 shows the Isight dataflow.

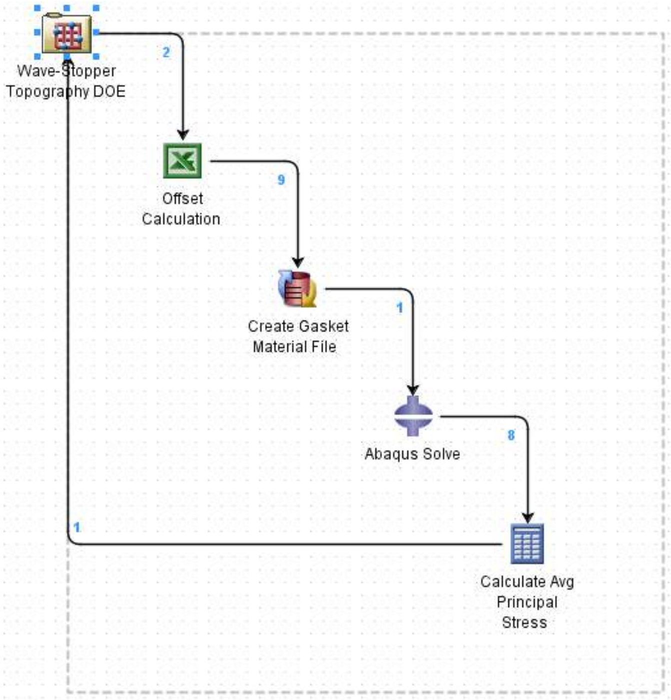

Figure 9. Stopper topography DOE dataflow

The Isight root level was set to a DOE component which executed all combinations of maximum and minimum Wave-Stopper™ height values within the given limits specified as the primary input parameters. The combination of stopper heights that resulted in the lowest value of maximum principal stress on the liner was determined.
The subflow of the Isight process consisted of the following:

- Excel component: configured to use the minimum and maximum values of Wave-Stopper™ height to compute the offset of the Wave-Stopper™ elements in the gasket relative to the other components in the gasket. Computed the offset of the maximum and minimum areas as well as the offsets for 7 defined transition elements between the minimum and maximum values in each section of the gasket.
- Data Exchanger component: configured to use the 9 offset values computed by the Excel component to create a unique gasket input file
- Abaqus component: configured to submit an Abaqus run using the unique gasket file in the 3D powertrain model and extract the maximum principal stress at each of 8 integration points for the liner element of interest
- Calculator component: configured to compute the average principal stress over the 8 integration points at the element of interest and return the value as the output parameter of the root level DOE.

By calculating the principal stress in the liner (shown in Figure 10) over a series of steps, the gasket design was optimized to reduce stress in the engine liner.

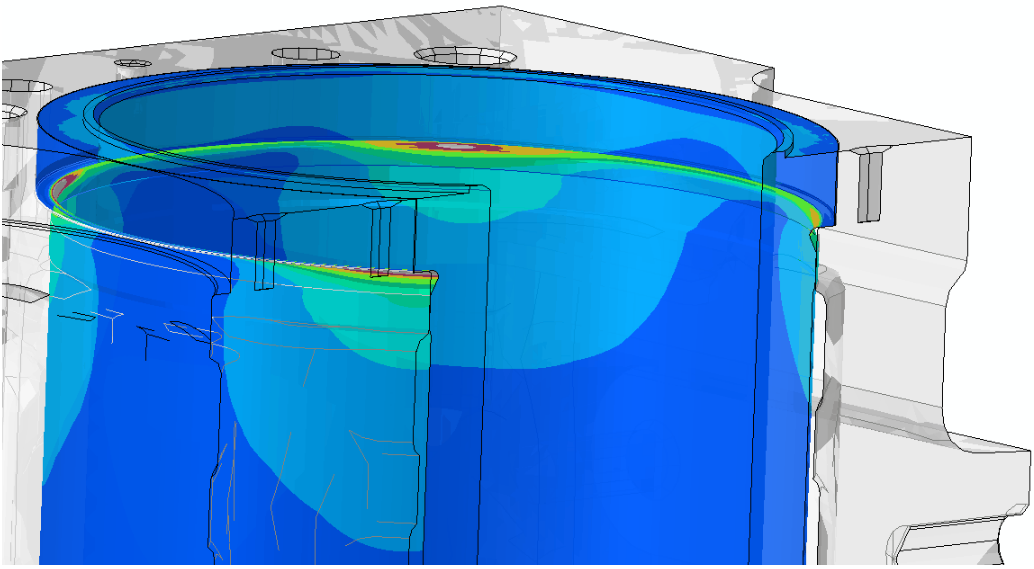

Figure 10. Liner principal stress

3.3 Fatigue Analysis Method

Finite element analysis of gaskets was performed with continuum elements in Abaqus. Most models were 2D axisymmetric configurations of a critical section, as shown in Figure 11.

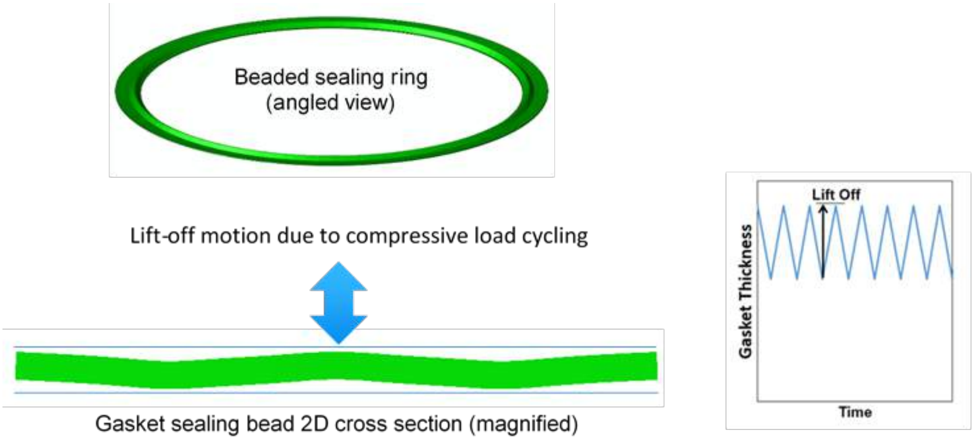

Figure 11. Gasket fatigue test configuration

The gasket layer was defined with elastic-plastic mechanical properties. The thin coating was included (which broadens the contact pressure distribution). The coating was defined with hyperelastic mechanical properties.

The FEA loading steps included the following stages (see Figure 12):

- Gasket forming
- Gasket compression between engine surfaces
- Lift-off during cylinder pressurization

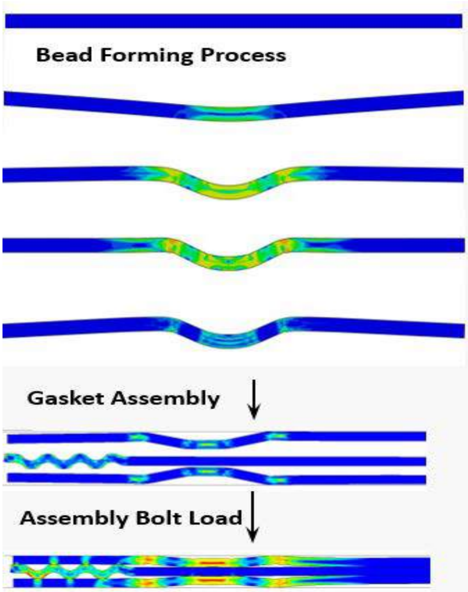

Figure 12. Loading steps for fatigue analysis

Elastic-plastic FEA provided the as-formed shape with residual stresses. Constant amplitude lift-off (steady state) was used for gasket FEA design comparisons.

For most 2D models, the gasket compressive load and thickness changes were obtained from a 3D FEA model of the engine, using gasket elements. The loading and thickness changes were applied in most 2D models through rigid surfaces. Coating thinning effects were included in the 3D model.

In a limited number of cases, a 3D gasket model was created with continuum elements. This enabled fatigue calculations over the entire gasket without the need for 2D sections. Tradeoffs include a considerable longer time to set up and solve the model, with more convergence difficulties and a coarser mesh.

The FEA results were post-processed with fe-safe fatigue analysis software using the critical plane method. A stress-life algorithm with a mean-stress correction was fit to the results from beaded sealing ring samples (single layer) tested in cyclic compression. The endurance limit for crack initiation was defined at 10 million cycles. Fatigue amplitude results for a single gasket layer are plotted in Figure 13. Stress amplitude versus mean stress results are shown in Figure 14 for a test that exceeded the endurance limit.

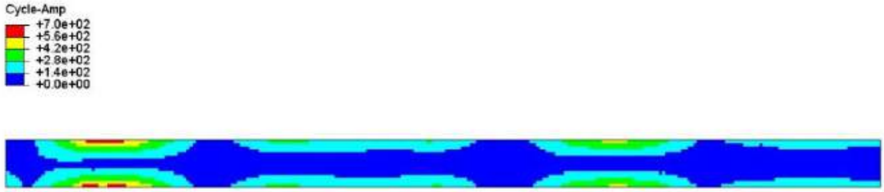

Figure 13. Fatigue amplitude (plotted on the undeformed gasket layer)

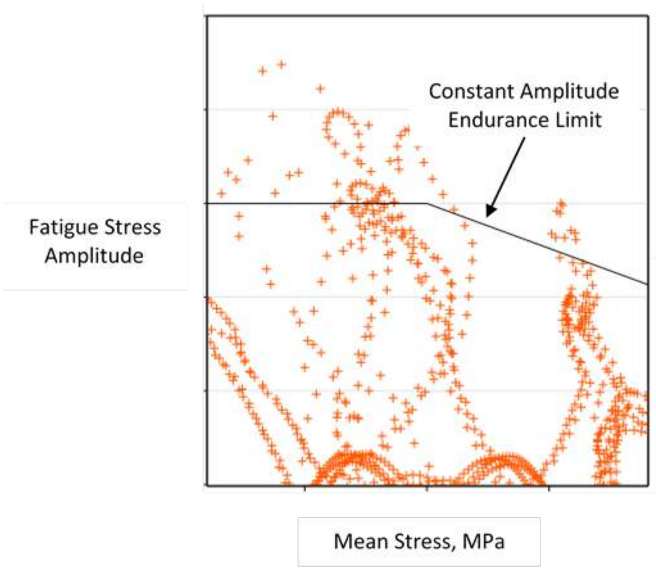

Figure 14. Stress amplitude versus mean stress plot (Haigh Diagram)

3.4 Variable Amplitude Fatigue Study

Engine temperature and thermal expansion varies with location and time, from cold start through power and rpm cycling. Thus, the fatigue stress amplitude changes during engine operating conditions. A “Pulsator” rig test was developed at Dana to verify fatigue life of head gaskets in variable amplitude conditions that were more severe than steady state engine operation.

The Pulsator test was set up with a gasket bolted between a modified head and block. The valve seats and cylinder bore were sealed with metal disks. Coolant was circulated between the coolant jacket and heat exchangers, which cycled between hot and cold limits. Connections were added to admit high pressure hydraulic oil in two combustion chambers, which were alternately pressurized at engine firing frequency (see Figure 15).

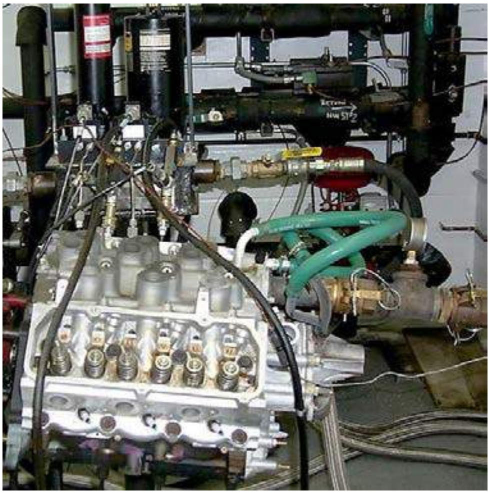

Figure 15. Pulsator test configuration

A transient thermal model of the Pulsator test cycle was created using fluid structure interaction methodology. STAR-CCM+ was used to calculate the heat flux from the coolant and oil domains, paired with Abaqus calculations of the temperature in the engine, using Co-Simulation methodology. The model inputs were the fluid temperature, pressure and flow. Correlation was verified with thermocouple data from the engine.

3D structural FEA of the gasket was performed with the resulting thermal model at regular time intervals. Variable lift-off (and fatigue stress) resulted, as shown in Figure 16.

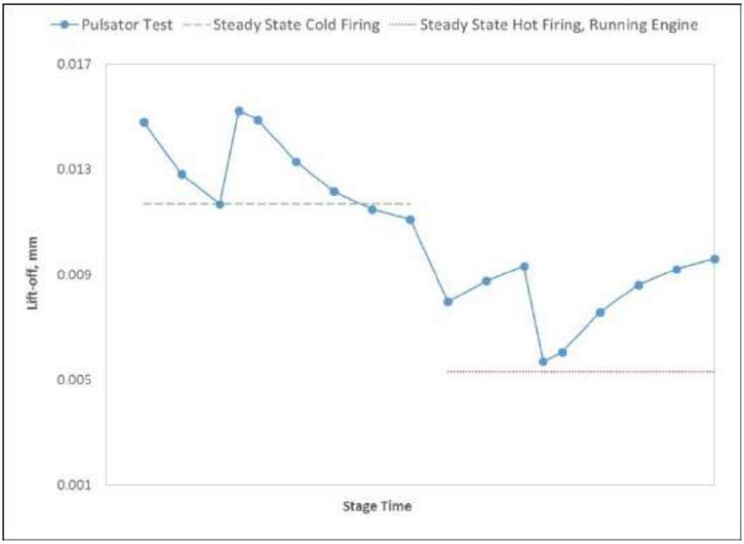

Figure 16. Lift-off results from the Pulsator test versus steady state thermals

The lift-off in the Pulsator test was generally higher than the results with steady state thermals. The highest vertical motion and fatigue stresses occurred near the start of the cold stage of the test. The fatigue calculations indicated that the gasket could withstand 30% test pressure increase before crack initiation. The amplitude results are shown in Figure 13 and Figure 14.

4. Conclusions

The technological advances in powertrains coupled with more severe operating conditions require new levels of simulation to drive the complex development of advanced CHG. Techniques such as optimization, DOE, and fatigue prediction are essential to develop “first-time right” CHG in a shorter timeframe than ever before. Advances in simulation techniques enable the design of more robust CHG that can withstand the transformative changes in internal combustion engines.

5. References

1. Abaqus Users Manual, Version 6.14-1, Dassault Systémes Simulia Corp., Johnston, RI.