Multi-Layer Steel Head Gasket Durability Analysis using Stacked GASKET Element Model

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Abstract: In order to accurately calculate the stresses in Multi-Layer Steel (MLS) head gasket durability analysis, the normal and relative shear motions between cylinder head and gasket, gasket and block, as well as between gasket layers have to be comprehended in the analytical model. In this study, an analytical method was developed to effectively calculate the MLS head gasket stresses during engine operating condition. In the analysis model, each layer of the MLS head gasket is modeled using GASKET element, developed by ABAQUS, and the GASKET element layers were stacked together according to the configuration of the head gasket. The stiffness of a particular embossment section in this model was represented by combining the load-deflection curve for each composed gasket layer as a series of springs. Due to the physical modeling of each gasket layer in the stacked GASKET element model, the relative shear motion between gasket layers can be accurately predicted from the system level analysis, and the gasket stress can be calculated from the gasket sub model analysis where the formed geometry for each gasket layer is modeled using continuum elements. This study was also done using continuum elements to model each gasket layer in the system level analysis, but it used significant amount of CPU and took twice the time to run compared to stacked GASKET element model and the calculated head gasket normal and shear deformation between cylinder head and block as well as between gasket layers from these two approaches were very comparable.

Keywords: Stacked gasket, relative slip, line load, gap amplitude, durability, global analysis, sub modeling, interlayer friction

1. Introduction

Multi-Layer Steel (MLS) head gasket is widely used in automotive industry because it is more durable than the composite graphite head gasket. However, MLS head gaskets sometime crack around stopper, function bead, coolant hole and dowel hole areas during engine operating condition. These failures could be due to over compression of beads, excessive head lift off, or fretting between head and gasket, gasket and block.

Traditionally, one-layer GASKET elements (shown in Figure 1a) developed by ABAQUS are used to model the MLS head gasket in the thermal/structural analysis of the head-gasket-block engine system. In this model, the stiffness of the MLS head gasket in the normal direction is represented through the load-deflection curves for each embossment section in the gasket, and the stiffness in the transverse direction is modeled through the shear and membrane stiffness. However, the stiffness in the normal and transverse direction is decoupled in this element model.

The one-layer GASKET element model is adequate for head bolt load transfer across head gasket between cylinder head and block to calculate head gasket sealing pressure, cylinder block and head distortions and stresses during engine thermal cycle. However it may not be accurate enough to calculate the head gasket detailed stress for fatigue analysis. This is because the physical part of each gasket layer is not modeled in the global analysis and hence the relative motion between different gasket layers can not be comprehended from this analysis. It is found that the relative motion between head gasket layers has significant effect on head gasket stress distribution within each gasket layer from both experimental observation and numerical simulation.

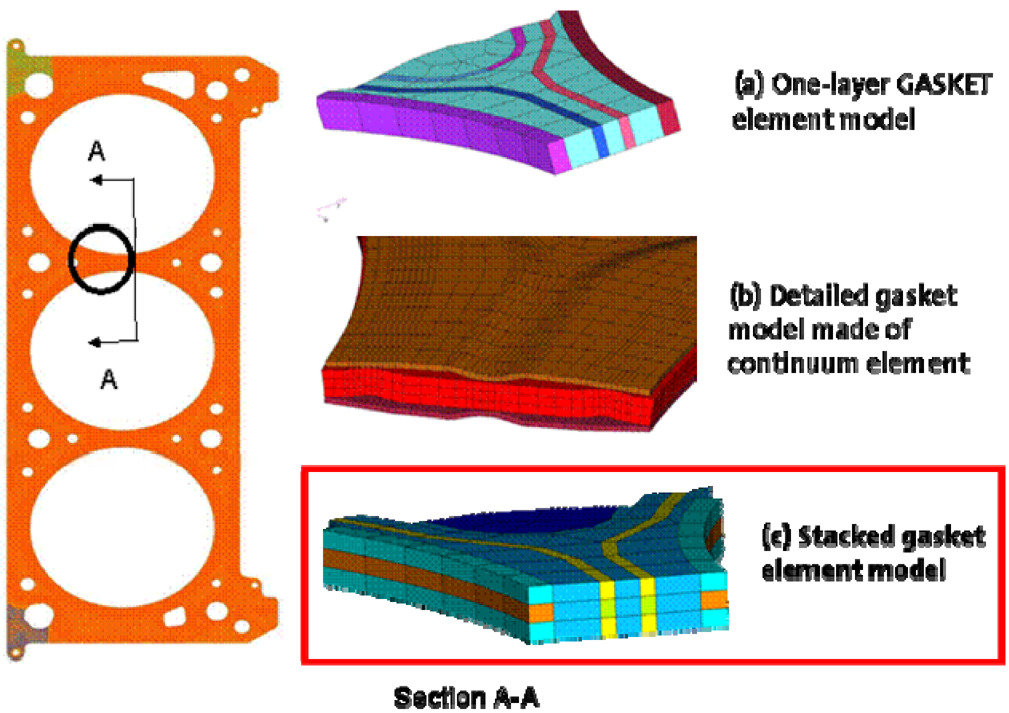


Figure 1: MLS head gasket finite element modeling

One way to improve the head gasket modeling in getting accurate gasket normal and transverse motion as well as gasket stress is to model each gasket layer in detail using the continuum element model (shown in Figure 1b). In this model, the embossments from formed geometry for each gasket layer are modeled in detail using finer mesh and then they are incorporated in the head-gasket-block system model for analysis. Although this model can comprehend both load transfer for head gasket sealing and gasket interlayer shear motions for gasket stress analysis, the computation becomes very intense due to the larger degrees of freedom in the gasket model and the additional contact relationship between gasket layers. This time consuming analysis process using detail head gasket modeling is not effective particularly in the early design phase of the engine program to evaluate head gasket durability.

In this study, an analytical method was developed to effectively calculate the Multi-Layer Steel (MLS) head gasket normal and shear motion between cylinder head and block as well as between different gasket layers during engine operating condition. In the global analysis which includes cylinder head, head gasket and engine block, each layer of the MLS head gasket was modeled by the one-layer GASKET element and they were stacked together according to the number of layers in the gasket (as shown in Figure 1c). Due to the presence of each gasket layer in the stacked GASKET element model, the gasket interlayer shear effect was comprehended in the analysis. As a result, the stacked GASKET element model was able to predict more accurate head gasket normal and shear displacement fields from the global analysis compared to the one-layer GASKET element model. On the other hand, the displacement fields calculated from the stacked GASKET model were found to be comparable with those calculated from the detailed gasket model using continuum element but with much less CPU time. The resulting displacement field from the stacked GASKET element global analysis was used in the gasket sub modeling analysis to calculate the detailed stress in each layer for head gasket durability assessment.

2. Head gasket durability analysis

To study the head gasket durability analytically in engine design, a global-local analysis approach is required in general. In the global analysis, an engine assembly model consists of cylinder head, head gasket, cylinder block, valve seat, valve guide, liner, and main bearing cap, head bolts, are required. These components are made of 3-D continuum element with coarser mesh. Figure 2 shows a typical engine assembly model, which is one-bank of a V6 engine, used for head gasket durability analysis. The loading conditions in the global analysis are engine assembly load, thermal load and firing load to simulate engine durability test. From the global analysis, the displacement of the head-gasket-block engine system is calculated under various loading conditions. These displacement fields can then be used to run gasket sub model, which consists of a portion of the head gasket made of finer mesh, to calculate the gasket stresses for fatigue analysis.

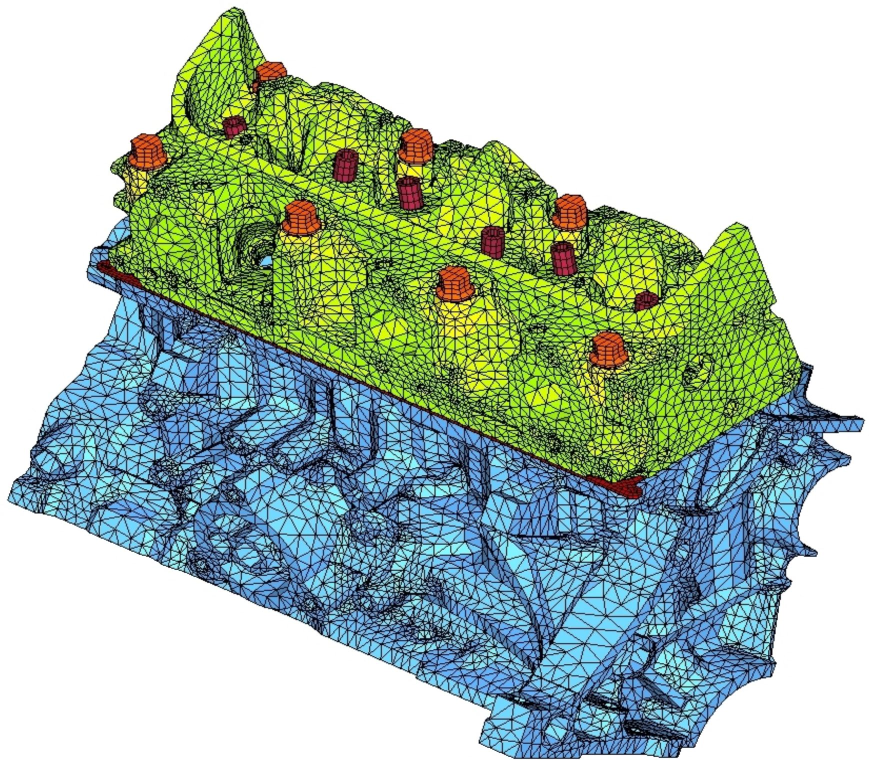


Figure 2: Typical engine assembly model used for head gasket durability analysis

Figure 3 shows the different head gasket modeling schemes used in the global and sub modeling analysis for head gasket durability analysis. In the global model, the MLS head gasket can be modeled using either one of the following element, i.e. one-layer GASKET element, multi-layer gasket using continuum element and multi-layer stacked GASKET element. From the global analysis, the head gasket sealing pressure, relative slip between head and block, and the gap amplitude or head lift-off at the fire ring due to maximum combustion firing pressure can be calculated. The head gasket sealing pressure, relative slip and gap amplitude calculated from the global analysis can be used to pinpoint the potential gasket failure location by comparing the calculated data with the design target provided by the gasket suppliers. This is followed by the sub modeling analysis to calculate the detailed stresses of the head gasket at the potential failure locations using various head gasket local modeling approaches.

As shown in Figure 3, the head gasket sub modeling can be done using (1) 2-D section model consists of multiple gasket layers at a specific bead section (2) one-layer of head gasket which can be active layer or stopper layer (3) 3-dimensional multi-layer head gasket made of continuum element following the gasket formed geometry. For the 2-D section sub modeling, the displacements calculated at the head and block deck faces from the global analysis at the specific sectional area are imposed on the top and bottom of the 2-D gasket section model via two rigid lines and calculate the gasket stress. For the one-layer head gasket sub modeling usually included the dowel pin in the model, the maximum relative slip between head and block deck surfaces calculated from the global analysis can be imposed on one end of the gasket layer with the other end fixed. This is to simulate the pull test due to maximum gasket in-plane shear motion to calculate the gasket stresses particularly around the coolant hole and dowel hole areas. For the 3-dimensional multi-layer head gasket sub modeling, a portion of head and block model near the fire deck areas should be included in the sub modeling, and the displacement fields at the cut boundary of head and block sub models are driven from the global analysis results. Then calculate detailed head gasket stresses in each gasket layer.

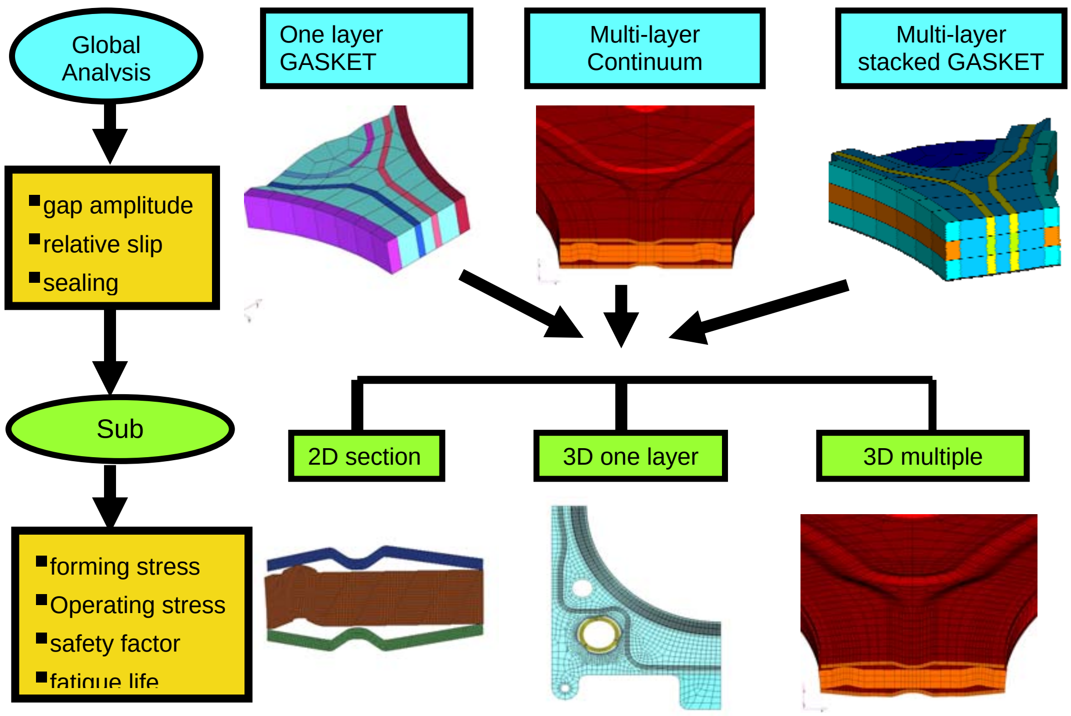
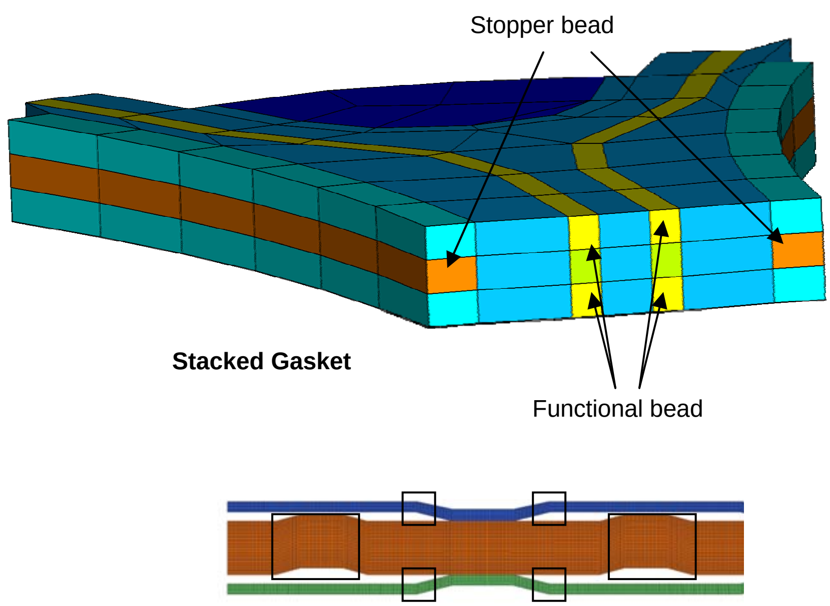


Figure 3: Different modeling schemes in head gasket global-local analysis

2.1 Stacked head gasket modeling

Figure 4 illustrates the stacked GASKET element model used in the global analysis for head gasket durability analysis. The following are the steps to construct the stacked GASKET element model

- Create all layers using gasket elements
- If 1 layer gasket model already exists, split it into as many layers as needed
- Identify bead elements in functional and spacer layers and create element sets for each individual layer.



3 Layer continuum gasket

Figure 4: Construction of stacked gasket element model

2.2 Stacked head gasket stiffness

The pressure closure curves and the initial gaps from 1-layer gasket need to be adjusted for stacked gasket model in all the functional beads, backland beads, and flat areas of gasket. The curves are adjusted assuming layers are like springs in series. The transverse stiffness is described based on the membrane and shear stiffness and is assumed constant for all layers.

2.3 Global results

The displacement fields calculated from the engine global analysis using stacked GASKET element model are compared with those calculated using one-layer GASKET element as well as multi-layer continuum element gasket model. The results are compared at the functional bead for combustion seal in front cylinder of a one-bank V6 engine under hot assembly condition. This is illustrated in Figure 5.

1. Relative slip between head and block

The relative slip calculated between cylinder head and block fire decks (Figure 5a and 5b) indicate that the relative slips along both crack axis direction and cross axis direction are comparable between one-layer GASKET element, multi-layer continuum element and the stacked GASKET element model when coefficient of friction 0.2 is used at interface between gasket and head, gasket and block, as well as at gasket interlayer. However, when the coefficient of friction is changed from 0.2 to 0.05 in the gasket interlayer, the relative slips calculated from stacked GASKET model still match well with multi-layer continuum element gasket model but not with the one-layer GASKET element model.

2. Line load (sealing pressure)

The line load calculated at the combustion seal region (Figure 5c) from stacked GASKET element model is comparable with those calculated from the one-layer GASKET element model as well as multi-layer continuum element gasket model. This is essential to ensure consistent load transfer in the three models. It is also found that unlike the relative slips between head and block deck faces, the coefficient of friction used at the gasket interlayer does not have significant effect on line load distribution at the combustion seal region.

3. Gap amplitude

The gap amplitude (head lift-off) at the function bead in combustion seal due to maximum combustion pressure (Figure 5d) is also comparable among these three approaches. The magnitude of the gap amplitude predicted from the stacked GASKET element is within 1 micron difference.

4. CPU time

Finally, the CPU time required to run global analysis to calculate head gasket displacement field due to engine assembly load, thermal and firing load, was 3 days using one-layer GASKET element model, 10 days using multi-layer continuum element gasket model, but 5 days using stacked GASKET element gasket model. Timings are for 8 cpu's on IBM AIX. It should be noted that the one-layer GASKET element model could not predict accurate relative slip between head and block deck faces because the friction of coefficient at the head gasket interlayer could not be comprehended.

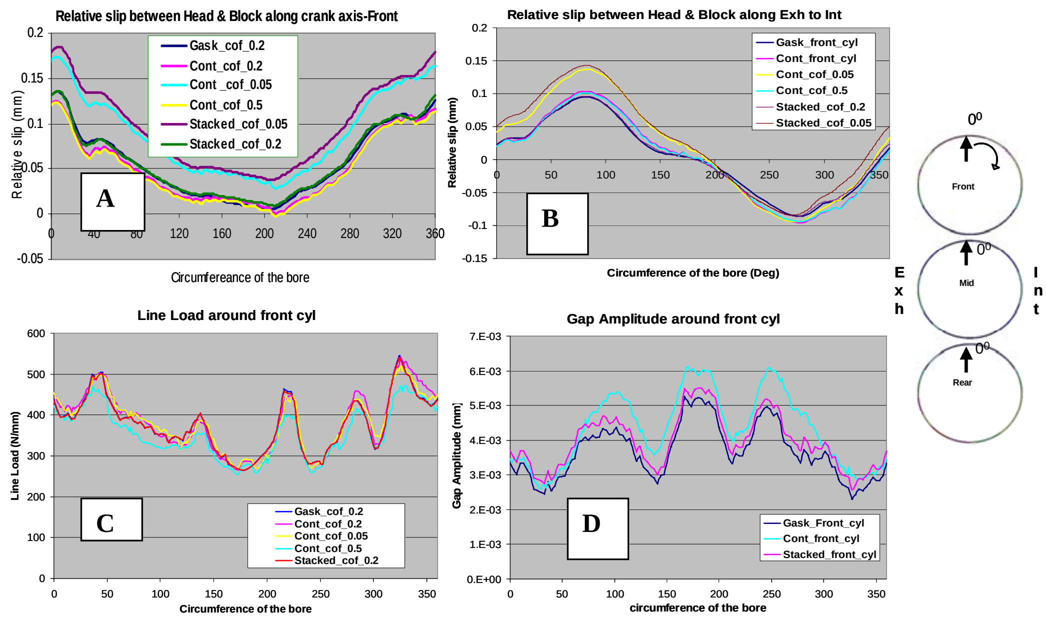


Figure 5: Correlation of displacements from different head gasket modeling

2.4 Head gasket stresses from Sub model analysis

From the global analysis using one-layer GASKET element, multi-layer continuum element, and stacked GASKET element models as described in the previous section, the displacement fields of cylinder head and engine block, as well as MLS head gasket at both normal and in-plane shear directions, are predicted. Based on the calculated displacements, a local head gasket model made of finer mesh, using either 2-D plane strain element or 3-D continuum element following the gasket formed geometry, is used to calculate the detail stress of the head gasket to assess head gasket durability. Figure 6a compares the 2-D head gasket cross section stresses at combustion seal region from the gasket sub modeling analysis. The sub modeling is driven by the displacements calculated from the global analysis using stacked GASKET element model and multi-layer continuum element gasket model.   Similarly, Figure 6b compares the head gasket stress at the dowel hole regions from the sub modeling analysis. It was concluded that the gasket stress calculated from the global analysis using stacked GASKET element model was very comparable with that from the multi-layer continuum element model.

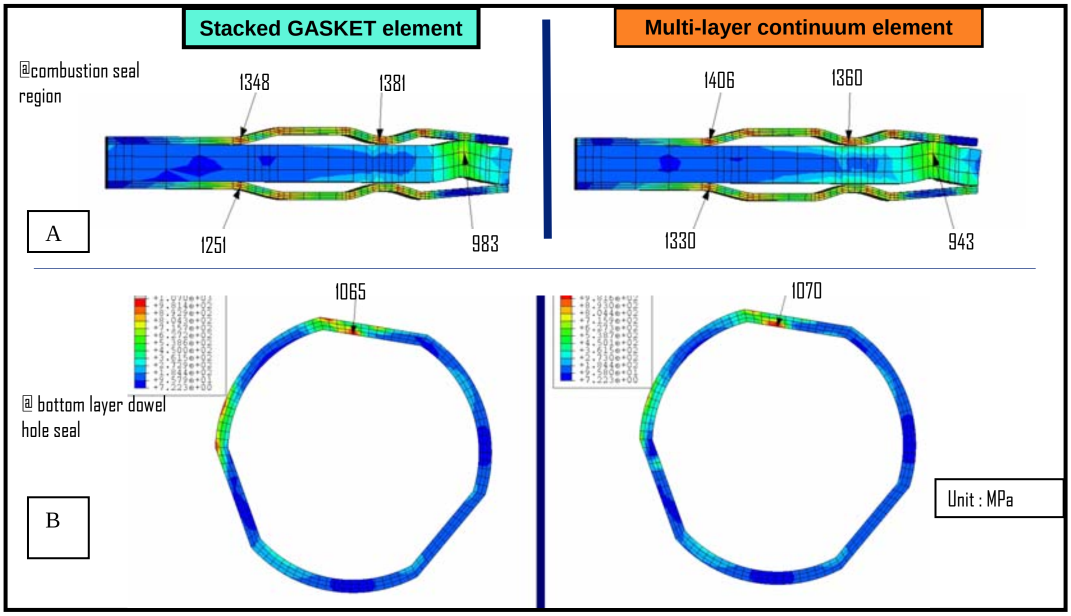


Figure 6: Comparison of head gasket stress from sub modeling driven by different head gasket global models

Figure 7 illustrates the effect of head gasket interlayer friction on gasket stress at the dowel hole of the bottom active layer. With coefficient of friction 0.2 applied at interface between head and gasket, gasket and block, as well as at gasket interlayer in the stacked GASKET element model, the calculated stresses from the global-local analysis at the gasket dowel hole area were comparable with those calculated using one-layer GASKET element in the global model.

However, by changing the coefficient of friction from 0.2 to 0.05 at the gasket interlayer in the stacked GASKET element model, it significantly changes the stress distribution at the dowel hole area. This effect of the interlayer friction on gasket stress can not be comprehended in the gasket durability analysis using one-layer GASKET element model.

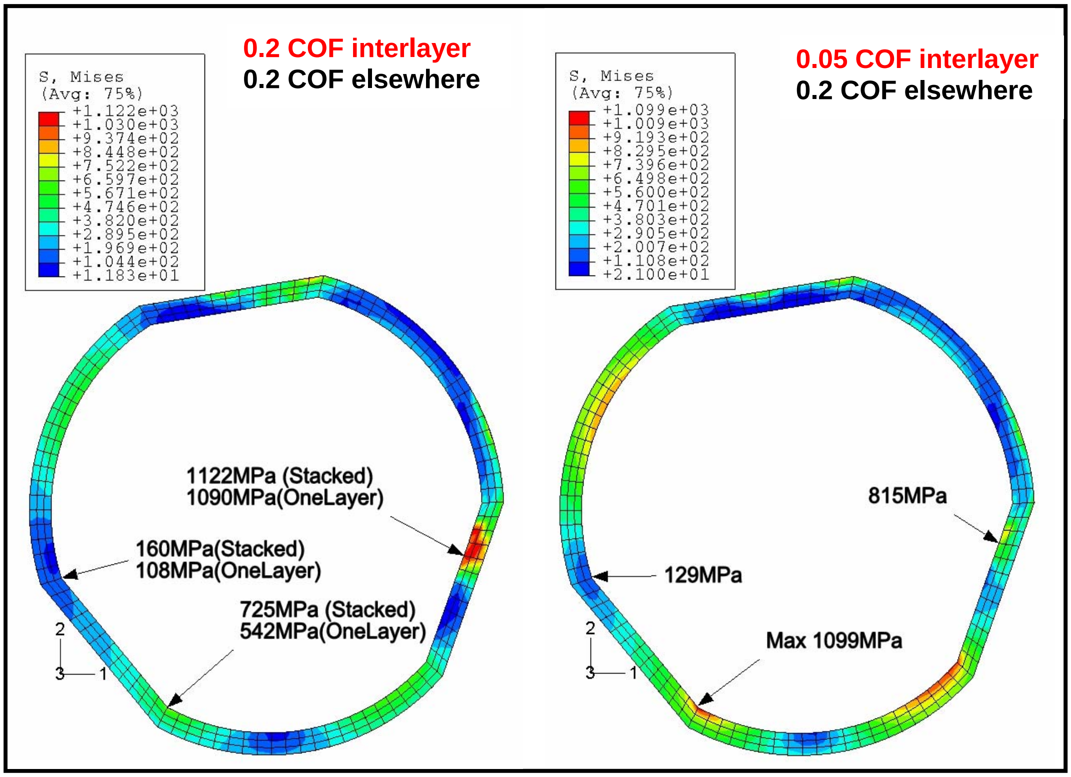


Figure 7: Effect of gasket interlayer friction on gasket stress

3. Application of stacked GASKET element method for head gasket durability

The stacked GASKET element developed from this study was applied to investigate the head gasket cracks in the coolant hole and dowel hole in the gasket active layer. Following the global analysis using stacked GASKET element model, gasket sub modeling analysis was carried out to calculate the detailed head gasket stresses. Figure 8 compares gasket stress calculated in the dowel hole between the original design and the modified design. Also shown in Figure 8 is the picture of the dowel hole crack. By modifying the dowel hole from triangular shape to a round shape along with slightly larger dowel pin/hole clearance significantly reduced the stress. Figure 9 shows the gasket stress calculated in the coolant hole near the rear end of the head gasket and the actual crack location. The cracks observed at the sharp corners of the coolant hole was due to not only the shape of the coolant hole but also the larger relative in-plane shear motion between the aluminum cylinder head and iron engine block particularly near the two ends of the head gasket. Again, by making the sharp corner smoother, it reduced the maximum gasket stress at the coolant hole significantly.

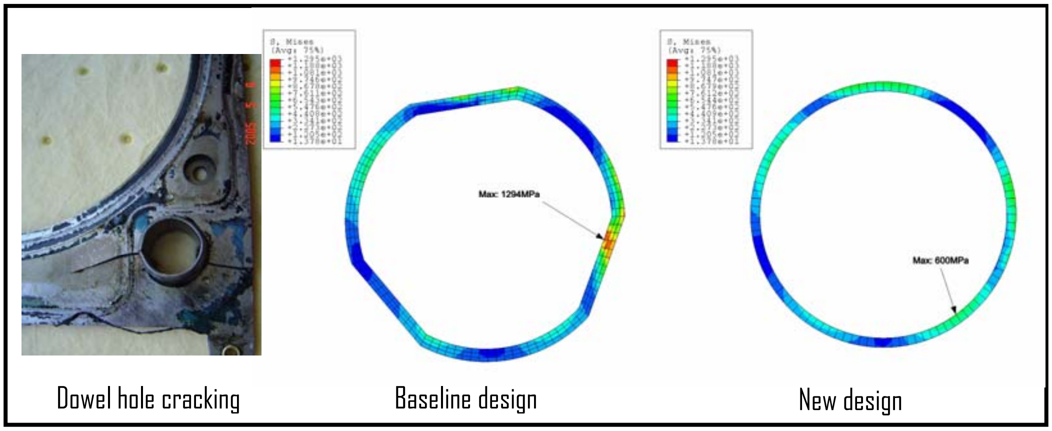


Figure 8: MLS head gasket durability analysis – dowel hole cracking and predicted stresses

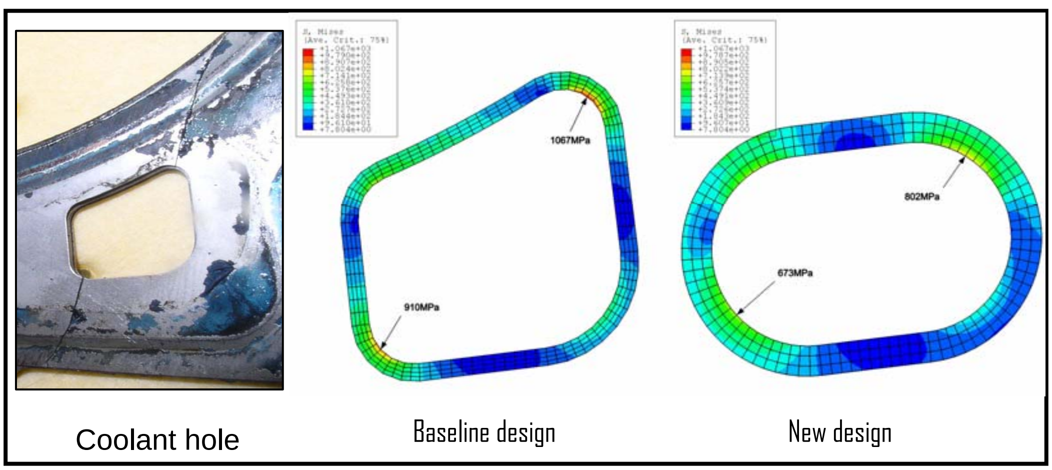


Figure 9: MLS head gasket durability analysis – coolant hole cracking and predicted stresses

4. Conclusions

This paper illustrates the development of stacked GASKET element model used for head gasket durability analysis. Unlike the conventional one-layer GASKET element, the stacked GASKET element is able to comprehend the gasket interlayer shear effect, which is critical in predicting the relative slip between head and block and the detail gasket stress within each gasket layer accurately for gasket fatigue analysis. Even though stacked gasket model and detailed continuum model showed very similar stress results, the CPU required to run the global analysis using stacked GASKET element is much less than the continuum element gasket model. Also, the stacked GASKET element model has much lower no. of degrees of freedom and is mush easier to build the model compared to detailed continuum gasket model since stacked gasket model does not need to follow the gasket formed geometry.

The application of the stacked GASKET element model to investigate the head gasket durability in a bimetallic engine has shown good correlation between the analysis predicted gasket stress and the actual gasket crack location during engine durability test. The use of stacked GASKET element model in the global analysis along with detail gasket sub modeling to calculate gasket deformation and gasket stresses should be an effective analytical tool to evaluate head gasket design in the early design phase.

5. Acknowledgements

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6. References

ABAQUS user’s manuals