# A comprehensive methodology for the modeling of diesel four-stroke engine pistons for variable engine speed conditions

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**Abstract**

There are pistons that meet safety requirements according to predictions of the current finite element piston modeling methodology but fail on experimental engine tests. In this work a new methodology is proposed for modeling the behavior of diesel pistons during the thermal transient. In addition to the thermal loading, we need also to model the purely mechanical loading. However, it is not only a question of adding such mechanical loading to the analysis. Since the pressure loading is cyclic and plasticity effects are to be taken into account, how to introduce the mechanical loading together with the thermal transient is an important modeling issue. The modeling methodology proposed depends very much on this loading strategy. Selected results that show the usefulness of the methodology are reported.

*Keywords:* Modeling; Diesel piston; Finite elements; Thermo-transient analysis; Variable engine speed conditions; Thermo-mechanical analysis; Thermo-elastic constitutive model; Thermo-elasto-plastic constitutive model

## 1. Introduction

Nowadays finite element modeling of pistons is routinely used in industry. The procedures used have already attained a considerable degree of sophistication since the models already take into account some of the complexity of the physical problem. The evolution of computer hardware and software makes it possible to solve models that consider the load history and use very refined finite element meshes. Nevertheless, there are pistons that meet safety requirements according to the predictions of the current finite element piston modeling methodology but fail on experimental engine tests. In this work a new methodology is proposed for modeling the behavior of the piston during the thermal transient that is not considered in the traditional modeling methodology. As reported in [1], during the thermal transient the temperature gradients induce stress peaks in the piston that are not predicted by current methodologies. In order to take into account these peak stress predictions in fatigue analysis, we need also to model the purely mechanical loadings that are relevant for diesel pistons, the gas pressure being the most important one. However, it is not only a question of adding such mechanical loading to the analysis. Since the pressure loading is cyclic and plasticity effects are to be taken into account, an important modeling issue is how to introduce the mechanical loadings together with the thermal transient. Of course, the modeling of the mechanical load in each cycle during the transient period is not possible due to the enormous number of cycles that would be required.

The main objective of this work is to propose a methodology to model the piston thermo-mechanical behavior under variable engine conditions. The stresses due to the thermal transient and mechanical loadings are the primary variables to be predicted. Of course, the ultimate objective is to arrive at stress predictions that, through fatigue analysis, could explain some cracks that appear in experimental observations but are not anticipated by current methodologies.

## 2. Modeling the thermo-mechanical conditions

We performed the thermo-mechanical analysis of a

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*Computational Fluid and Solid Mechanics 2005*
K.J. Bathe (Editor)

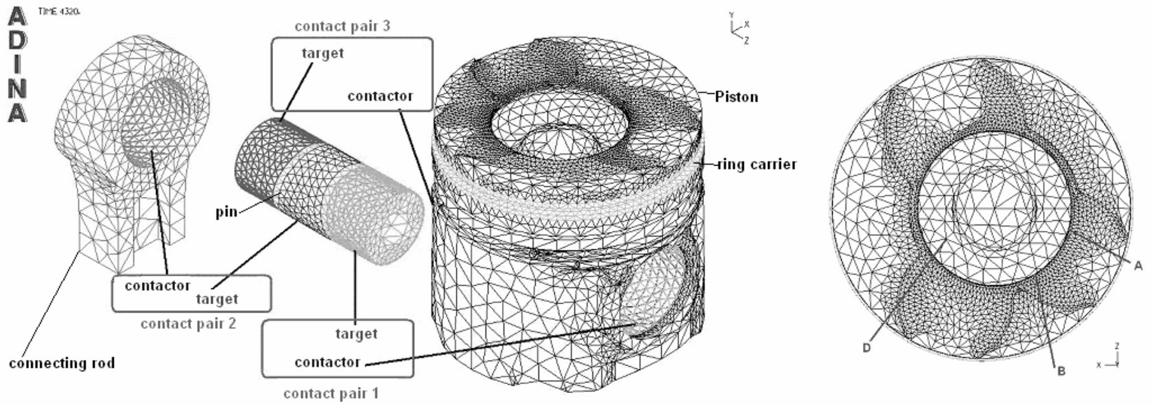


Fig. 1. Finite element model and location of points A and D.

high speed aluminum alloy piston using the ADINA program [2]. The thermal load was applied through temperature histories obtained from thermo-transient analysis for each node of the mesh. In order to obtain accurate boundary conditions for the piston, the solid model contains not only the piston but also the pin and the upper portion of the connecting rod. The contact conditions between them are modeled using the constraint function method [3]. The finite element model used is shown in Fig. 1.

Both thermo-elastic and thermo-elasto-plastic analyses were undertaken. A thermo-elasto-plastic multilinear kinematic hardening model [4] was adopted for the piston. The constitutive model parameters were obtained from experimental low fatigue cycle tests, using a methodology described in [4]. All the other components are modeled as being of thermo-elastic material.

In Fig. 2 we present the strategy used for the loading. Actually the modeling methodology proposed depends very much on this loading strategy. The piston is supposed to be at room temperature when we start the analysis. Then the low idle engine condition (900 rpm) is introduced and after the temperature distribution stabilizes the rated power engine condition (3500 rpm) is imposed until new thermal stabilization. The details and the specifications of the loading strategy can be found in [1]. We summarize the most important facts below. In the top of the graph the thermal loading for the transient analysis is given. In the middle graph a typical temperature of a point in the piston is reported. We recall that the thermal loading is introduced as nodal temperatures obtained from the transient analysis. In the bottom graph the assumptions for the gas pressure loading are described. We note that for the transient time periods the gas pressure is kept constant. After each temperature stabilization some cycling of the gas pressure is introduced as guided by a previous study [4], which shows that the plastic deformations almost do not change after one and half cycles (until the maximum load). We note that during the transient periods the unit of time of our incremental analysis is real time. However, after the temperature stabilizes we use as time unit one degree of crank angle since the real time becomes irrelevant for this part of the analysis.

To obtain extreme stress conditions for the fatigue analysis, it is necessary to model two load conditions, since it was not possible to consider the gas pressure cycle during the thermal transient period (the initial 158 s of each engine condition). In both analyses presented the thermal load is modeled. However, in one we model the gas pressure, while for the other we do not.

## 3. Numerical results of the thermo-mechanical analyses

We present in Fig. 3 the elastic and elasto-plastic principal compressive stress history for point A (a bowl rim node representing one of the most critical regions of the piston) for the models with and without gas pressure. At low idle condition this point presents the temperature of 190 °C and at rated power 372 °C. We see that during the thermal transient time stress peaks occur in all models. For both regimes, we can also see that, after the maximum load of the second combustion cycle occurs, the stress history is repeated in the following cycle.

We present in Fig. 4 the elastic and elasto-plastic principal tensile stress history for point D (bowl ground node) for the models with and without gas pressure. At low idle condition this point presents the temperature of 165 °C and in at rated power 290 °C. It is important to note that for both stabilized temperature distribution conditions this point presents a compressive stress state, but in the beginning of both thermal transient periods tensile stresses occur when the gas pressure is applied.

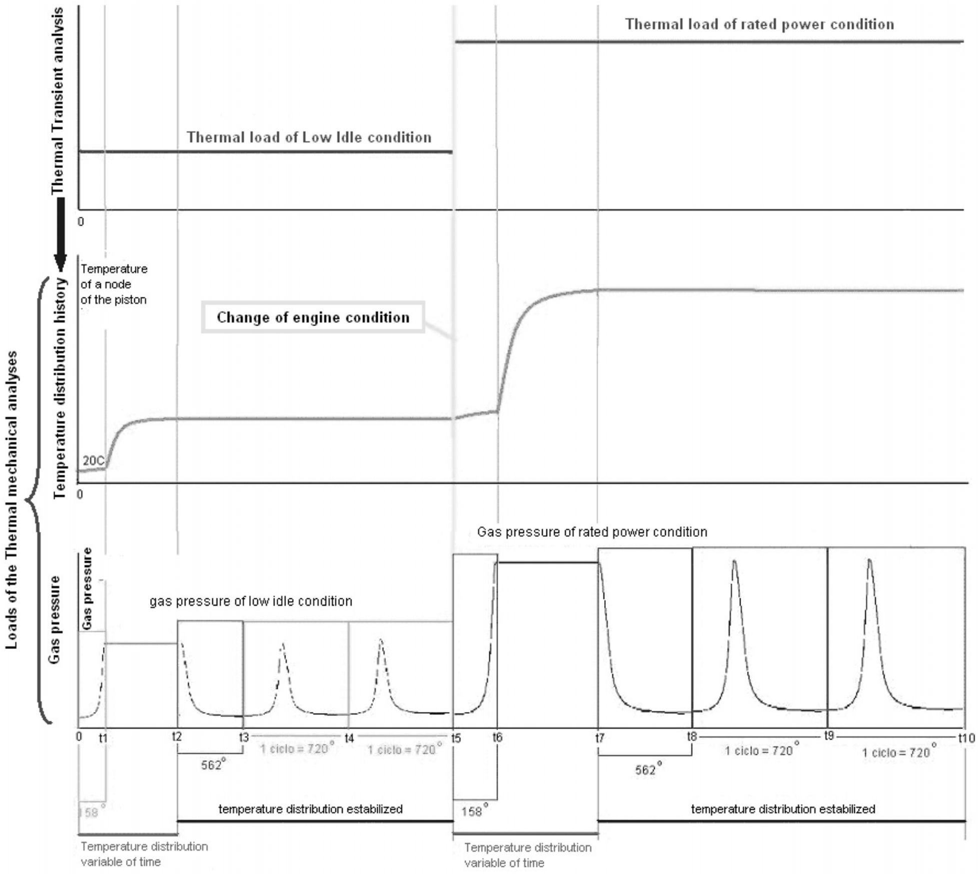


Fig. 2. Thermal and load mechanical application strategy.

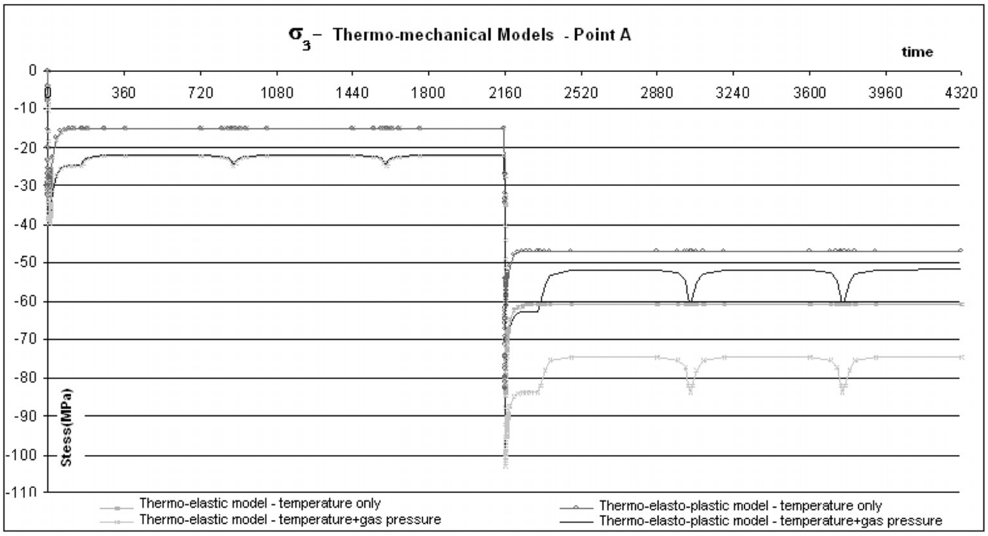


Fig. 3. Principal stress $\sigma_3$ history of point A.

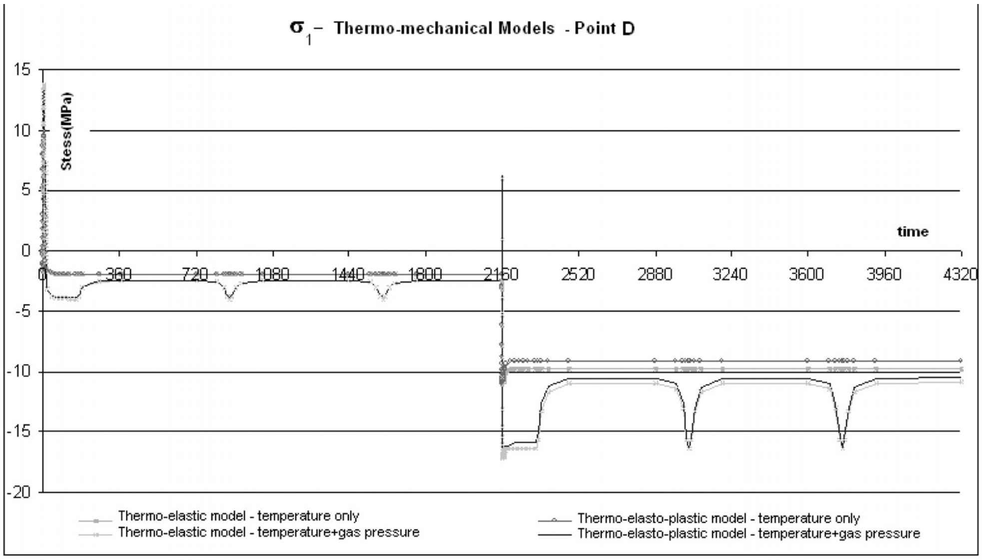


Fig. 4. Principal stress $\sigma_1$ history of point D.

These results are very important since only they can explain some cracks on the bowl ground. In the model with only the thermal load, stress compressive peaks are predicted.

We can verify that the consideration of the plastic behavior of the material decreases the stress peaks and stress stabilized values when compared with the elastic results.

## 4. Conclusions

The proposed methodology for performing thermo-mechanical modeling of pistons under variable engine conditions considering the effects of the thermal transient can capture phenomena that are not predicted by current methodologies. Therefore the modeling of the thermal transient is necessary. The stress and strain histories can be very useful for improving the lifetime fatigue analysis predictions. The tensile stress condition verified on the bowl ground nodes may explain some cracks that the current methodology is not able to.

It is important to remark that the modeling methodology developed can be applied considering many other constitutive models.

## Acknowledgment

The support of the Fundação de Amparo à Pesquisa do Estado de São Paulo is gratefully acknowledged.

## References

[1] Bueno EMR. On methodologies for the structural modeling of pistons: plasticity and contact (in Portuguese). Doctoral Thesis, Escola Politécnica da Universidade de São Paulo, 2004.

[2] ADINA R&D, Inc. Automatic Dynamic Incremental Nonlinear Analysis. ADINA System, 2004.

[3] Eterovic AL, Bathe KJ. On the treatment of inequality constraints arising from contact conditions in finite element analysis. Comput Struct 1991;40:203–209.

[4] Bueno EMR, Bucalem ML, Furukawa C, Zabeu CB, Lopez LMV. Thermo-elasto-plastic finite element modeling of an Otto four stroke engine piston for consecutive load cycles. In: Proc of the 2nd MIT Conference on Computational and Solid Mechanics, Cambridge, 14–17 June, 2003, pp. 149–153.