An innovative method to speed up the Finite Element Analysis of critical engine components

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ABSTRACT

This paper introduces a method to simplify a non linear problem in order to use linear finite element analysis. This approach improves calculation time by two orders of magnitude. It is then possible to optimize the geometry of the components even without supercomputers. In this paper the method is applied to a very critical component: the aluminium alloy piston of a modern common rail diesel engine. The method consists in the subdivision of the component, in this case the piston, in several volumes, that have approximately a constant temperature. These volumes are then assembled through congruence constraints. To each volume a proper material is then assigned. It is assumed that material behaviour depends on average temperature, stress magnitude and stress gradient. This assumption is valid since temperatures varies slowly when compared to pressure (load & stress). In fact pressure propagates with the speed of sound. The method is validated by direct comparison with non linear simulation of the same component, the piston, taken as an example. In general, experimental tests have confirmed the cost-effectiveness of this approach.

Keywords: Optimization, Simulation, CAD, geometry, FEA

1.1 MATERIAL PROPERTIES OF THE CRITICAL COMPONENT

A good knowledge of the material properties is fundamental for any simulation. In this case he piston is made of the well known aluminum alloy 390-T5. This alloy is commonly used in high performance turbocharged diesel engines [1][2][3]. The 390-T5 chemical and mechanical properties are summarized in table 1 and 2. Quasi static Young modulus and yield stress dependency to temperature are depicted in fig. 1 and 2:

Chemical composition	
Component	**Weight. %**
Al	78
Cu	4 – 5
Fe	Max 1.3
Mg	0.45 – 0.65
Mn	16 – 18
Ti	Max 0.2
Zn	Max 0.1

Table 1: A390 data

Mechanical and physical properties	
Hardness	125 HB
Ultimate tensile stress	295 MPa
Yield tensile stress	260 MPa
Young Modulus	81.35 MPa
Melting temperature	648.88 °C
Thermal capacity	0.962kJ/kg°C
Density	0.0157 kg/m^3

Table 2: A390 properties

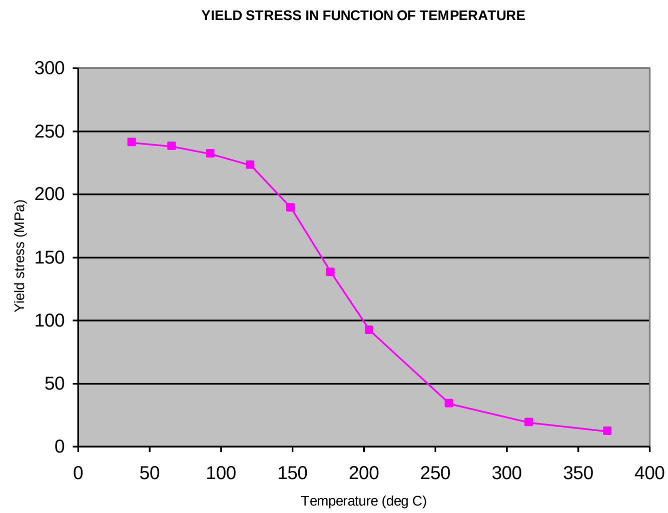

Figure 2: The static yield stress in function of the temperature

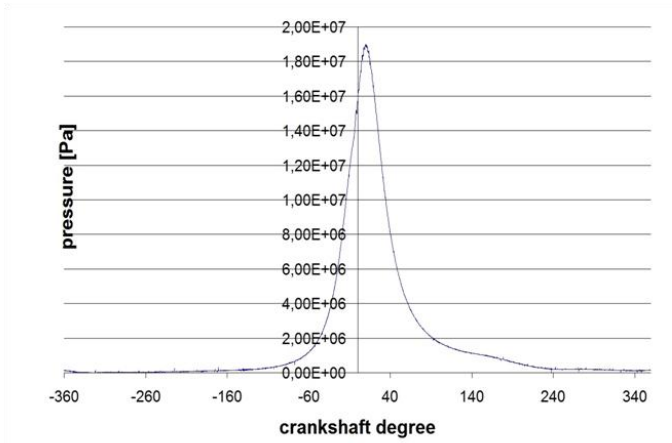

Figure 2a indicator diagram

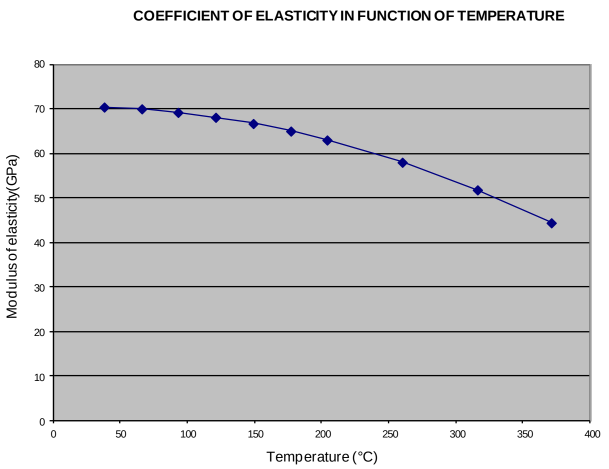

Figure 1: The static modulus of elasticity in function of temperature

1.2 MATERIAL PROPERTIES AND VELOCITY OF APPLICATION OF LOADS

Loads are applied on the piston at very high velocity and acceleration (see Figure 3, indicator diagram). In this condition, both Young modulus and ultimate tensile stress are sensibly higher than quasi-static values. However in diesel common rail engines pressure gradient is very steep, with values that may easily arrive up to 1.3×10^8 [bar/s], At room temperature yield stress tends to approach ultimate tensile stress, and the material tends to lose its ductility. Since the crystals that constitute the material do not have the time to modify their properties and the dynamic modulus of elasticity is incremented nearly up to the values of room temperature. For this particular alloy this relationship is kept up to 550°C. Practically, a hardening process takes places inside the material, that deforms plastically, keeping the mechanical properties typical of much lower temperatures.
The low of plastic flux is the following:

$$\sigma = C\,(d\varepsilon/dt)^m$$

where σ [psi] is the stress and ε is the deformation [-], while C and m are material constants. C and m for the Aluminum alloy 390.0-T5 are summarized in table 3.

Temperature (˚C)	C (ksi)	m [-]
200	11,6	0,066
400	4,4	0,115
500	2,1	0,211

Table 3: Aluminum alloy 390.0 T5 a constants

Table 3 shows that m increases four folds with the temperature that varies from 200 a 500 ˚C and this numbers confirm that the modulus of elasticity does not vary significantly.
Following this approach it is possible to extrapolate the data of table 4.

Temperature [°C]	Modulus of Elasticity [MPa]	Yield stress [MPa]	Ultimate stress [MPa]
497	48,000	65	80
483	48,000	63	82
412	60,000	70	100
330	62,000	75	105
314	68,000	80	110
292	68,000	82	110
263	68,000	130	200
256	68,000	130	200
233	70,000	130	200
208	70,000	135	208

Table 4: A390 T5 alloy material properties with a combustion chamber pressure gradient of 1.3x108 [bar/s]

2. THE THERMAL ANALYSIS OF THE PISTON

The thermal analysis of the piston is finalized to calculate or measure the temperature field inside the piston. In our case the analysis starts from experimental data with lower power loads. This makes it possible to tune the simulation model and to upgrade it to the required power level.

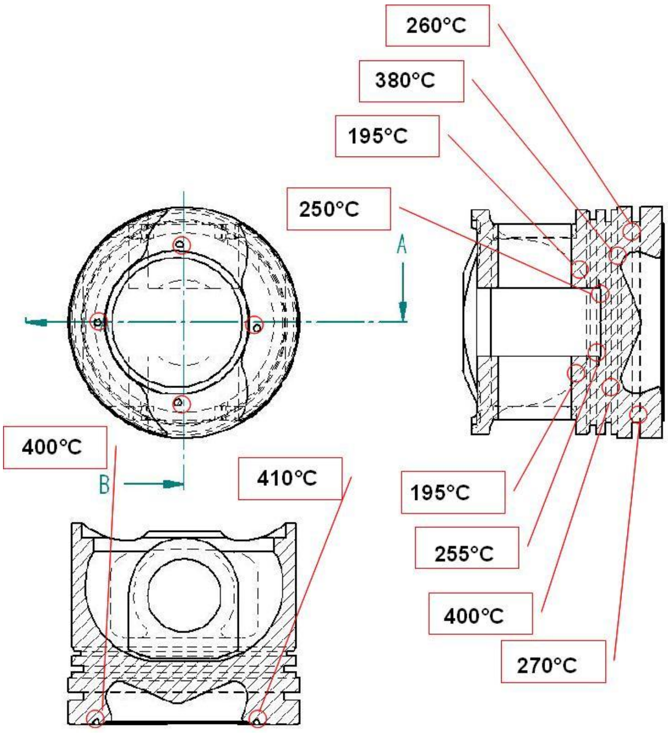

Fig. 3 experimental temperature measured on piston with the original (reduced) thermal load

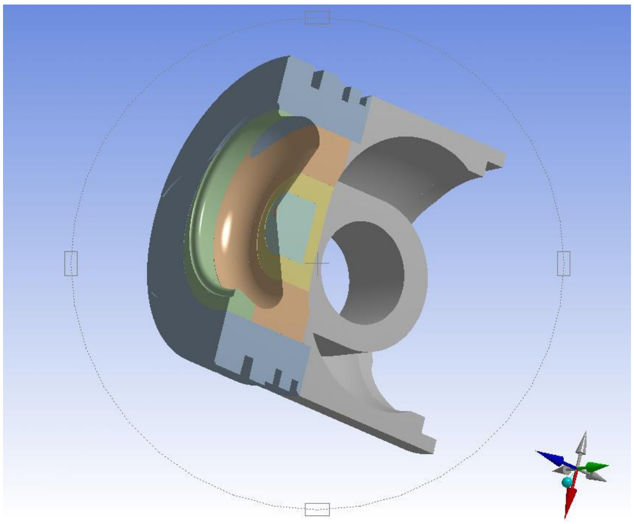

Fig. 4 different volumes with different temperatures

In figure 4 the different volumes for different temperatures are depicted. The software considers these volumes as perfectly adherent, so congruence of displacements is automatically imposed on boundary surfaces.

3. COMPUTING

3.1 Linear FEA mesh

Figure 5 shows the FEA mesh with the due refinement.

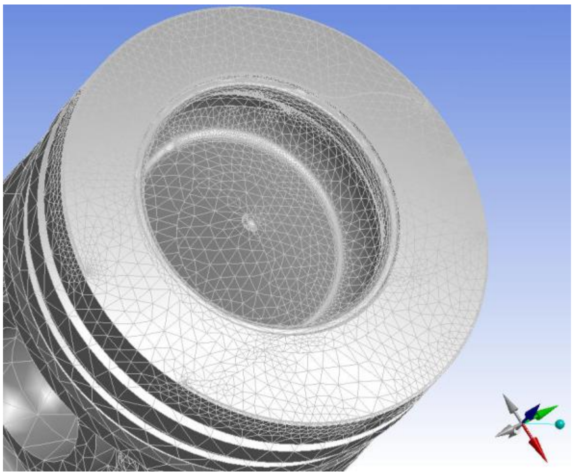

Figure 5: Mesh for linear solution

The mesh generators takes the volumes as perfectly adherent and "generates" the mesh. Due refinement is then manually added on fillet and geometrically "difficult" points.

3.2 Constraints

The piston should slide in the cylinder and for this purpose it has been considered the constraint through the rings. The piston can also freely rotate around the piston pin. Figures 6 and 7 show the constraint on FE model.

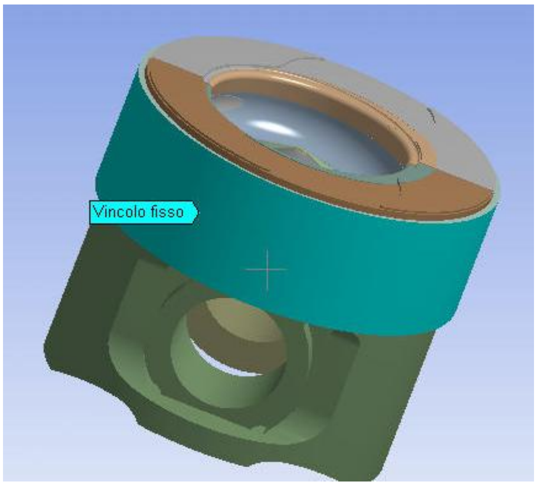

Figure 6 Ring constraint that simulates cylinder wall

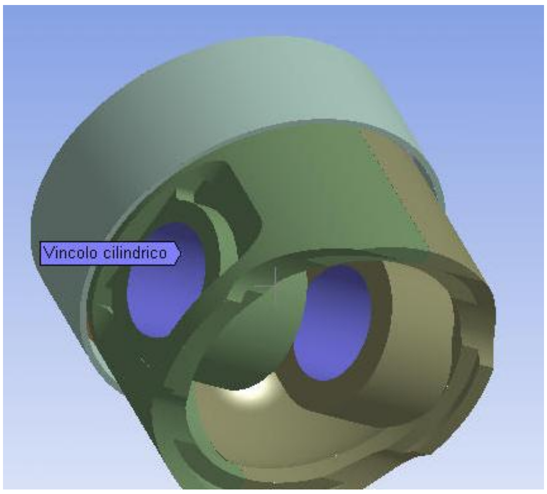

Figure 7 Cylindrical constraint that simulates the pin

3.3 Loads

The total load that affects the piston is composed by a the pressure load and by the thermal load.
The thermal load is already embedded in the model through volumes with different material properties.
The pressure load is simulated by the application of different pressures on different piston top surfaces. The different pressure values have been evaluated through the simplified method of [1]. Average values of 160 bar inside the combustion chamber (bowl) and of 140 bar on the remaining piston surface have been applied. These pressure values are applied on the FEA (Finite Element Analysis) model both for the non linear and linear analysis.

3.4 Results of the simplified analysis

The figures 8 and 9 summarize the stress on the piston top for a pressure load of 180 bar in the combustion chamber and of 160 bar on the piston top.

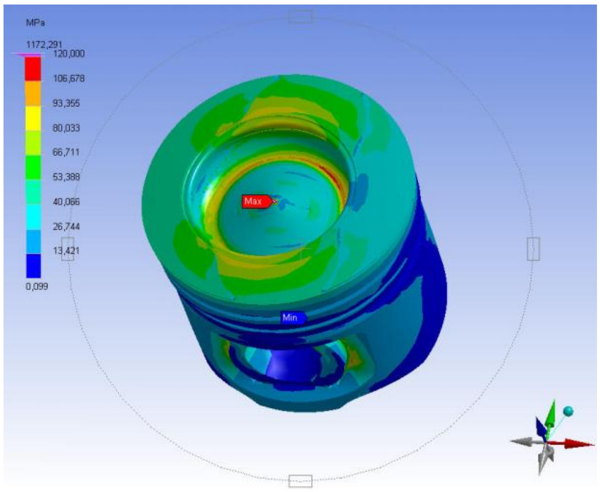

Figure 8: Pressure 160-180 bar

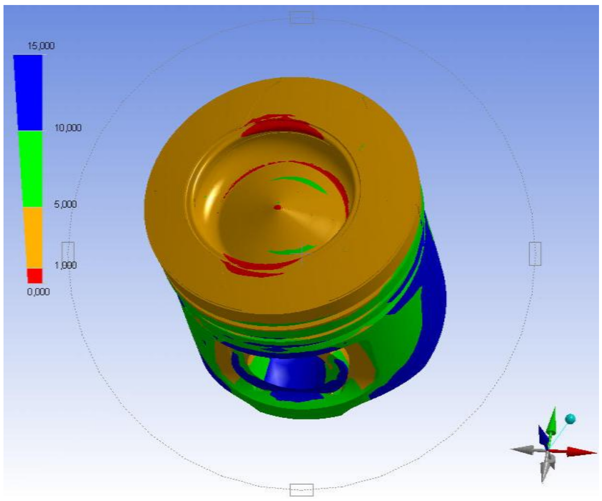

Figure 9: safety factor at 160-180 bar

In figure 9 it can be seen that the piston does not resist in the internal fillet of the combustion chamber bowl (red line). The only feasible solution is to change piston geometry, by increasing the fillet radius or by expanding the combustion chamber inside the piston. In this case a flatter and less profound combustion chamber is obtained; another possible solution is to improve piston cooling through a duct inside the piston. The larger fillet radius is introduced in figure 10. This solution makes it possible to increase significantly the safety factor.

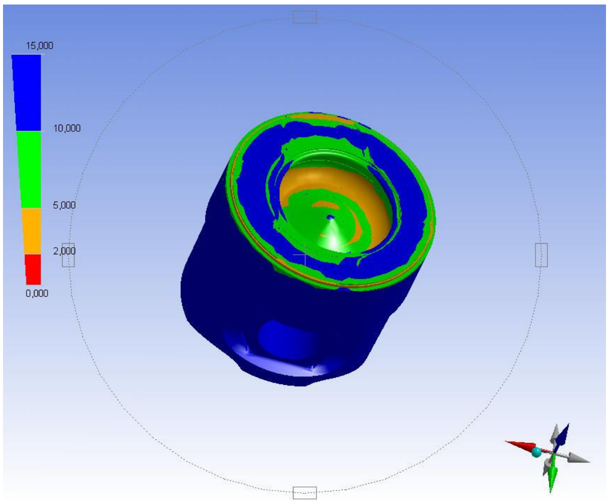

Figure 10: Pressure 140-160 bar

3.5 Non-linear FEA mesh

A traditional non linear model has been implemented in order to compare the simplified linear approach with the traditional non linear solution. Only half of the piston has been considered in order to reduce the computer time. For this purpose 10-nodes tetrahedral elements have been used. Figure 11 shows the non linear mesh.

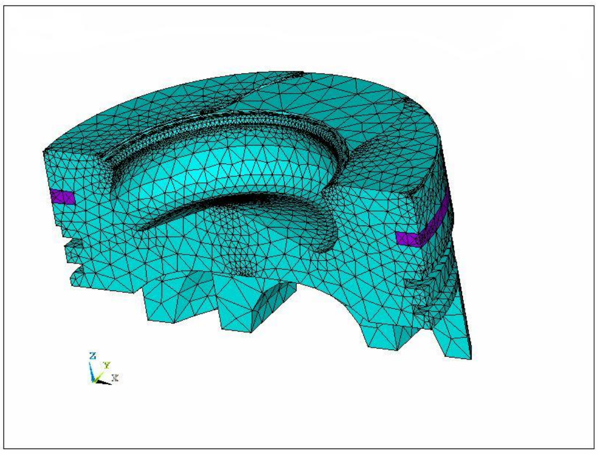
Figure 11: Non linear mesh

3.6 Non liner analysis

The thermal flow value and the faces(walls) exchange coefficients have considered as following:

- Adiabatic faces(side walls) of the piston;
- Thermal flow consequently found;
- Material characteristics, constraint system and thermal and structural loads as in linear analysis.

Figures 11, 12 and 13 show the thermal and pressure loads and the constraint system.

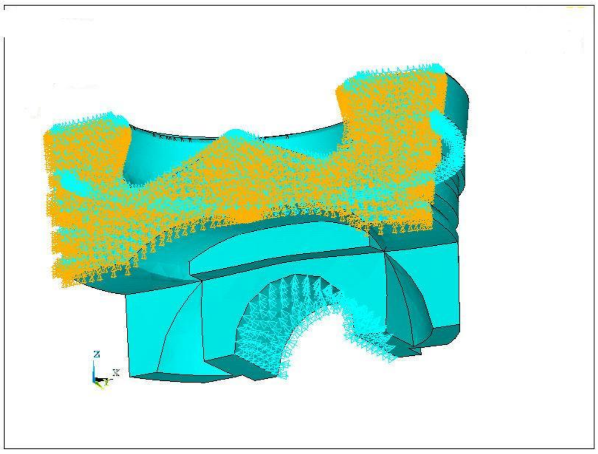
Figure 11:Constraints

It has been necessary to impose the symmetrical constraint in order to analyze only an half of the piston(yellow arrows in figure 11). Cylindrical constraints were also added in the piston-pin contact area. A radial boundary condition was added to simulate piston rings.
The temperature application field goes from a maximum of 400 ˚C on the top (red) to 208 ˚C (green) at the bottom of the piston, as it can be seen in figure 12.

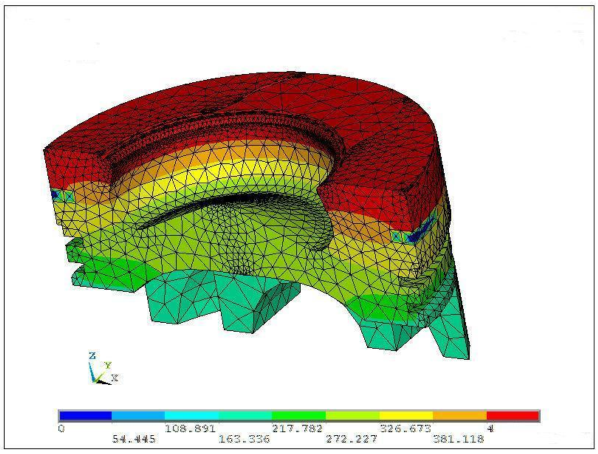

Figure 12: Temperature distribution

The results depicted in figure 13 show that the original piston cannot bear a maximum pressure of 160 bar, the combustion chamber fillet(red) is again the critical point. This result corresponds perfectly with the one obtained with the linear analysis.

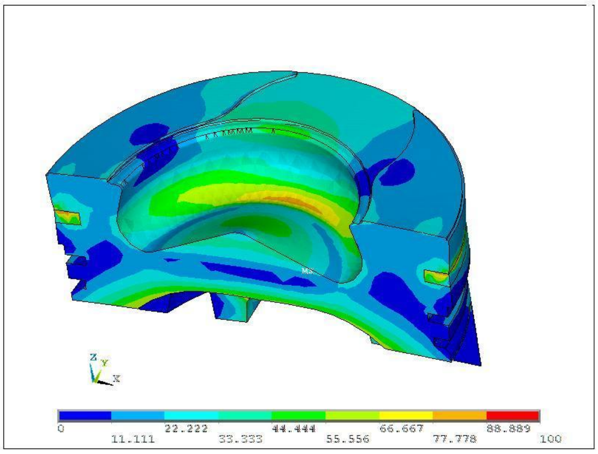

Figure 13: Non linear FEA results on the original piston with a peak pressure of 180 bar

4. CONCLUSIONS

The linear analysis gives the same results even on a very "difficult" component like an aluminum-alloy-diesel-direct-injection piston. This validates the method at least for aluminum alloy components, similar analysis have been performed on high temperatures alloys with even better accordance between linear and non linear analysis. The components have then been tested on the engines with increased performance. No experimental data were collected on the upgraded parts with the new higher power level. However the new part run without problems.

The linear method, with its very reduced computer time, makes it possible to optimize the component, operation that is not possible with non linear analysis even with modern computers.

5. REFERENCES

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