# Application of Structural Strength Evaluation Technology in the Development of Reciprocating Engines

**TODA Yasuko** : Fundamental Technology, Research & Development, Engineering & Technology Center, Niigata Power Systems Co., Ltd.
**SAITO Toshiyuki** : Fundamental Technology, Research & Development, Engineering & Technology Center, Niigata Power Systems Co., Ltd.
**WATANABE Yasuhide** : Fundamental Technology, Research & Development, Engineering & Technology Center, Niigata Power Systems Co., Ltd.
**KATO Shoji** : DE Development, Design & Development, Engineering & Technology Center, Niigata Power Systems Co., Ltd.
**GOTO Satoru** : Dr. Engineering, Executive Officer, General Manager, Engineering & Technology Center, Niigata Power Systems Co., Ltd.

Engine development in recent years must be able to address the severe demands of the market. Therefore, CAE (Computer Aided Engineering), including structural strength evaluation using FEM (Finite Element Method) and CFD (Computational Fluid Dynamics), is a clearly important part of a design for the realization of lightweight and reliable engines. Niigata Power Systems has applied structural strength analysis using FEM to various engine components in consideration of complex physical phenomena during the assembly of components and engine operation to achieve optimized design, fast development and lower costs. This paper reports on certain aspects of the structural analysis of main engine components performed during the development of the 28AHX, which is a high-performance and eco-friendly engine.

## 1. Introduction

To contribute to solution in global environmental problems, engines with less environmental impact are required. Desired characteristics include not only lower fuel consumption and exhaust emissions, but also higher output, compact size, light weight and high reliability. To develop such high-performance engines, computer-aided simulation is essential.

Simulation technologies such as structural calculations based on the Finite Element Method (FEM) and calculation of thermal conditions with Computational Fluid Dynamics (CFD) are often used in the engine development process. The use of such Computer Aided Engineering (CAE) tools during the preliminary study prior to the design process can significantly reduce both the development period and the cost of experiments and prototypes, while achieving the optimal design. As high-performance computers have become more available in recent years, simulations may be extended from simple static stress to dynamic calculations involving detailed physical phenomena.

Niigata Power Systems (NPS) used CAE for the engineering process to develop its high-performance eco-friendly AHX engine series, which are characterized by both high efficiency and high output. This paper describes the strength engineering process for the main components during development of the 28AHX, a medium-speed marine engine. **Figure 1** shows the appearance of a 6-cylinder 28AHX and **Table 1** lists the main specifications of the 28AHX series.

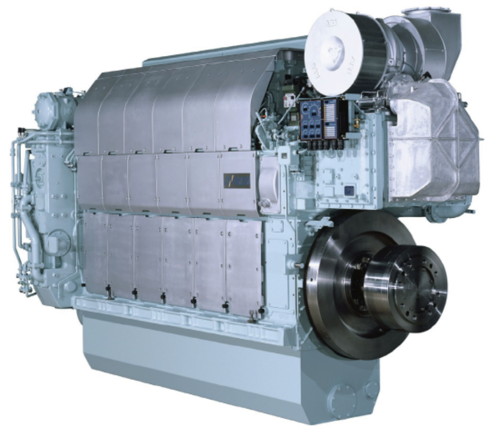


**Fig. 1** External appearance of 28AHX

**Table 1** 28AHX main specifications

| Engine model | | | 28AHX | |
|---|---|---|---|---|
| Cylinder bore | mm | | 280 | |
| Piston stroke | mm | | 390 | |
| Engine speed | $min^{-1}$ | | 800 | 750 |
| Maximum continuous rating | kW | 6 cylinder | 2 220 | 2 070 |
| | | 8 cylinder | 2 960 | 2 760 |
| | | 9 cylinder | 3 330 | 3 105 |
| Mean effective pressure | MPa | | 2.31 | 2.30 |
| Mean piston speed | m/s | | 10.40 | 9.75 |
| Maximum combustion pressure | MPa | | 18.0 | |

## 2. Cylinder block

The cylinder block is a major component of an engine, accounting for roughly one fourth of its entire weight. The structure of the cylinder block determines the structure of the engine. It protects the engine from the inertial forces generated by moving components and combustion pressure.

### 2.1 Calculation model

The stresses of the cylinder block were calculated with the following load conditions considering actual operation:

(1) Metal crush of the main bearing
(2) Bolt tightening during assembly
(3) Temperature rise
(4) Combustion pressure

**Figure 2** shows the calculation model of the cylinder block. In order to the calculation for a single cylinder, the calculation model consists of one cylinder block wall, a main bearing cap and two cylinder liners.

### 2.2 Structural analysis

The cylinder block was evaluated by stress analysis, followed by safety factor evaluations based on High Cycle Fatigue (HCF) analysis. **Figure 3** shows the distribution of the HCF safety factor.

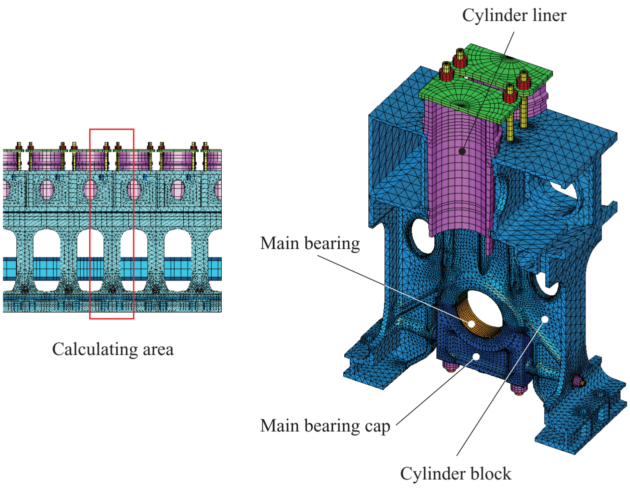



**Fig. 2** Calculation model for cylinder block

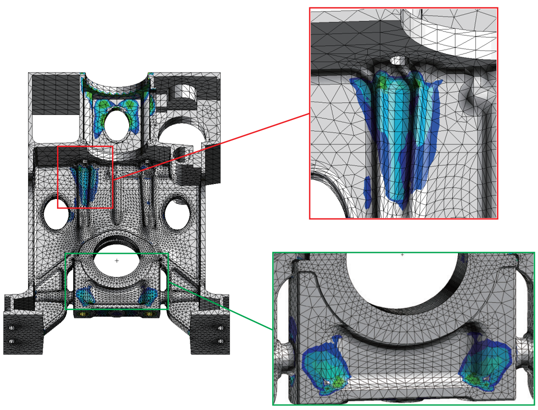


**Fig. 3** HCF safety factor for cylinder block

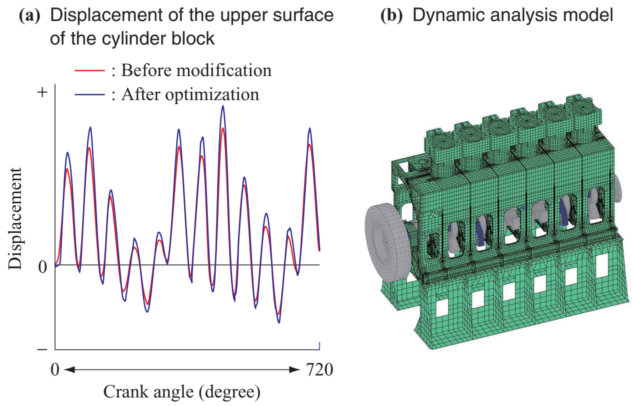



**Fig. 4** Calculation model for cylinder block

The main bearing walls and bearing caps are important for the strength of the cylinder block. These sections are modified to reduce weight and their shapes are optimized to keep the HCF safety factor at the required level based on the analysis results.

In addition, the dynamic rigidity of the cylinder block must be evaluated to avoid vibration problems. **Figure 4** shows an example of a dynamic analysis model and the resulting fluctuation in the vertical displacement of the top section of the cylinder block. The dynamic analysis is calculated based on the response resulting from fluctuations in combustion pressure and fluctuations in loads generated by moving parts, including the crankshaft and connecting rods.

The results show the safety factor and stiffness needed to attain the required material strength of the cylinder block and to design a shape that is lighter than conventional engines.

As described above, the cylinder block of the 28AHX was designed to provide the required HCF safety factor and rigidity based on the results of static and dynamic analyses. These analysis results were compared with stress measurements for an actual cylinder block, and the results showed good agreement. An endurance test performed with an actual product also confirmed that it had sufficient durability and rigidity.

## 3. Connecting rods

The connecting rods transmit combustion loads to the crankshaft and are subjected to extremely harsh conditions. When analyzing the connecting rod structure, the following must be considered:

(1) Deformation of the bearing housing
(2) Strength of the rod shank
(3) Buckling
(4) HCF in various parts

### 3.1 Calculation model

**Figure 5** shows the computational model used for the structural analysis of the connecting rod. The model includes various components, such as the piston pin, crank pin, and other accessory parts.

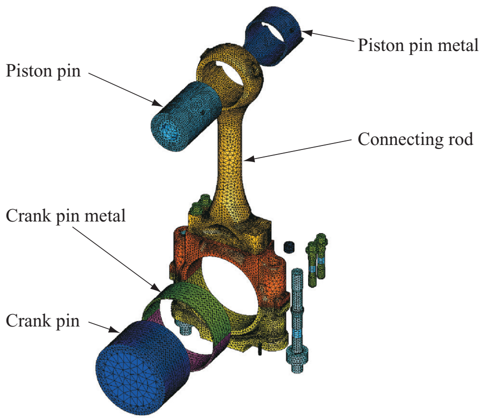



Fig. 5 Calculation model for connecting rod

### 3.2 Loading conditions

The following loads are considered in the structural analysis of the connecting rod:

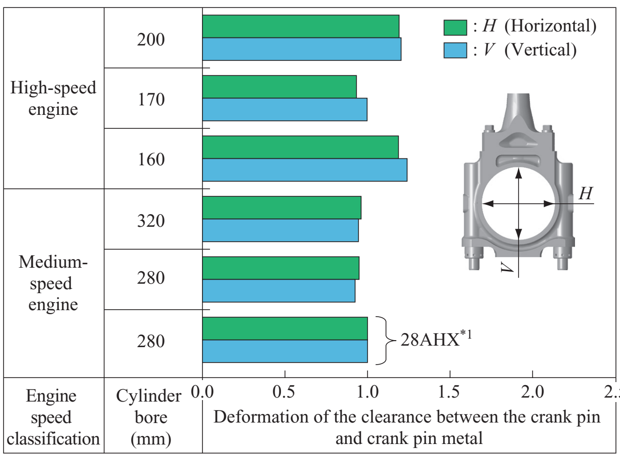
(1) Metal crush
(2) Bolt tightening during assembly
(3) Loads generated during operation (combustion load and inertial load)

When the engine operates, the connecting rods are subject to combustion load and inertial load resulting from the reciprocating motion of the pistons. These loads fluctuate intricately during a single cycle, and the combined force of these loads was used as a loading condition in the structural analysis.

### 3.3 Calculation results

#### 3.3.1 Deformation of bearing housing

Since deformation of bearing housing results in serious damage such as shaft seizure, it must be evaluated. **Figure 6** compares the deformation of the connecting rod housing of the 28AHX to that of another NPS model with a proven track record. The extent of deformation of the 28AHX housing is roughly the same as that of another model with a good track record, showing that the 28AHX housing has adequate soundness.




(Note) *1: The value for the 28AHX is standardized as 1.0.

Fig. 6 Big-end housing deformation

#### 3.3.2 Safety factor evaluation

To assess the safety factor of the connecting rod, HCF was evaluated based on load fluctuations occurring during operations due to the stress generated by fluctuating loads and the stress resulting from inertial loads. **Figure 7** illustrates an example of the distribution of HCF safety factor. The 28AHX connecting rod is designed to provide the required HCF safety factor at the section which often causes problems, based on fatigue assessment results. The soundness of the connecting rod was confirmed in an endurance test performed with an actual engine.

#### 3.3.3 Reduction of component weight

**Figure 8** shows the connecting rods of NPS's engines with a bore diameter of 280 mm. **Table 2** lists the ratio of weight to maximum combustion pressure for each connecting rod shown in **Fig. 8**.

As indicated in **Table 2**, the ratio of weight to maximum cylinder pressure of the connecting rod of the 28AHX is less than that of all previous models with a cylinder bore of 280 mm. The detailed evaluations described above are based on structural calculations using 3D models that take into account the various conditions. The optimized structure results in more rigid and lighter connecting rods for the 28AHX.

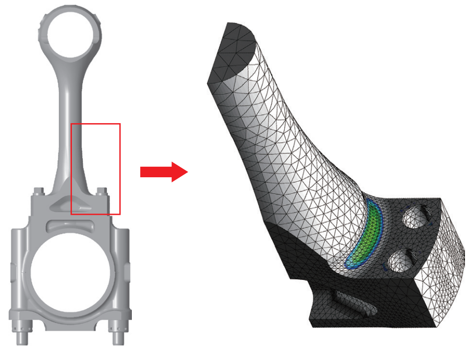


Fig. 7 HCF safety factor of connecting rod

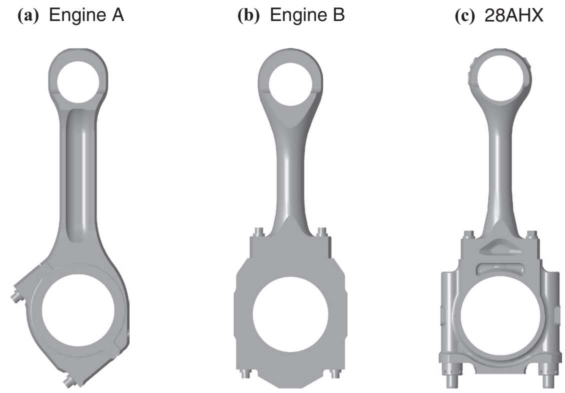



Fig. 8 Connecting rod 3D model for cylinder bore 280 mm engine series at NPS

Table 2 Connecting rod weight

| NPS's engines with $\phi$280 mm bore | Engine A | Engine B | 28AHX |
|---|---|---|---|
| Mass/maximum combustion pressure | 1.1 | 1.4 | 1.0 *1 |
| Shipped since | 1988 | 1998 | 2010 |

(Note) *1: The value for the 28AHX is standardized as 1.0.

## 4. Pistons

Since pistons are exposed to high temperatures, it is necessary to consider both mechanical loads and thermal loads, and to estimate the temperature distribution. The evaluation of pistons takes the following into consideration:

(1) Piston temperature
(2) High-cycle fatigue
(3) Deformation of piston-ring groove
(4) Contact surface pressure between piston and cylinder liner

### 4.1 Calculation model

**Figure 9** shows the calculation model used for structural analysis of the piston. The model consists of a piston, piston pin, connecting rod, and cylinder liner.

### 4.2 Load conditions

The structural analysis of the piston took the following loads into account:

(1) Loads applied during operation (combustion load/ inertial load)
(2) Side force
(3) Thermal load during operation

During engine operation, the piston is subjected to combustion load and inertial load. The load applied to the piston fluctuates during the cycle, as in the case of the connecting rod. Therefore, loading conditions are determined as appropriate load values.

To receive the distribution of piston temperature, the results of combustion CFD and lubricating oil CFD are used as thermal conditions in piston heat transfer calculations. The material strength of piston is dramatically deteriorated when its temperature exceeds a certain level, underscoring the importance of analyzing the temperatures to which the top section of the piston is exposed. **Figure 10** shows the piston temperature distribution of the 28AHX.

### 4.3 Calculation results

For the piston, HCF analysis is carried out by using the combination of the stress generated by mechanical and thermal load in accordance with the temperature distribution. **Figure 11** shows the distribution of HCF safety factor obtained by the fatigue analysis. Although the HCF safety factor tends to decrease at the piston top section and inside the cooling gallery or other places, that required by the piston is maintained. The soundness and temperature level of the piston were also confirmed in the endurance test with an actual engine.

**Figure 12** shows one of the calculation results of the contact surface pressure between the piston and cylinder liner. It was confirmed that there were no problems with the sliding movement of the piston during operation.

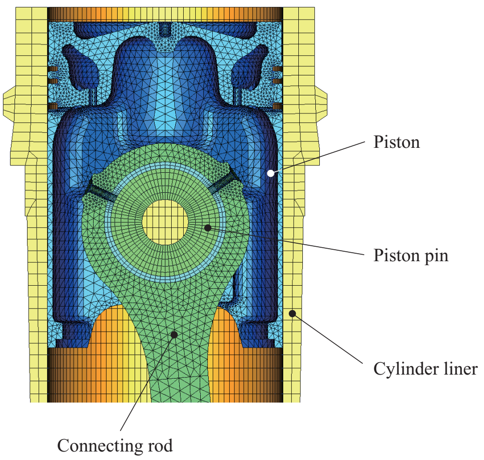



**Fig. 9** Calculation model of piston

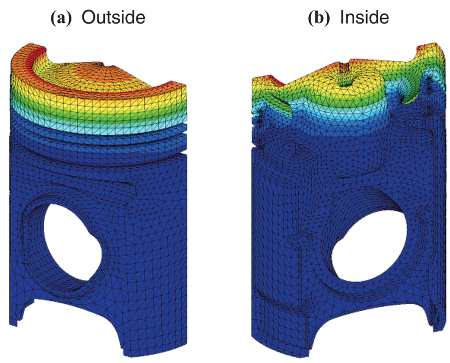



**Fig. 10** Temperature distribution of piston

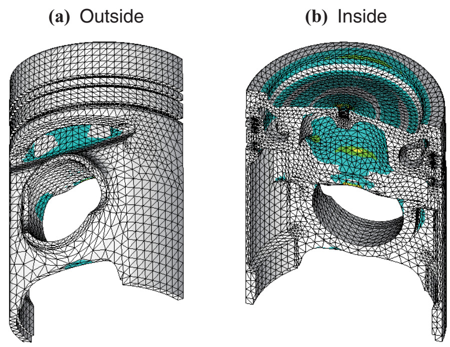



**Fig. 11** HCF safety factor distribution piston

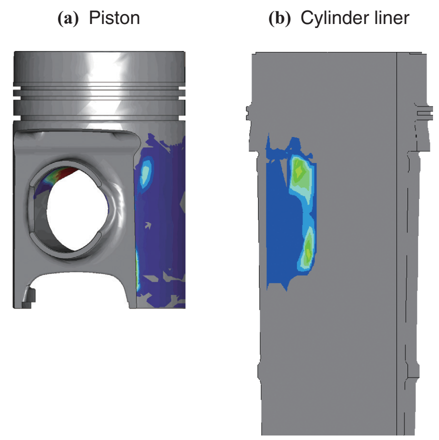



**Fig. 12** Piston – cylinder liner contact pressure

## 5. Validation of calculation results

Stress and temperature of an actual engine were measured in order to validate the simulation results. The measured values agreed well with the calculated values. Soundness and sufficient reliability were also verified by endurance testing for more than 1 800 hours and overhaul inspection of the actual engine.

## 6. Conclusion

This paper introduced an example of CAE structural analysis of engine components performed by NPS. In the process of developing the new 28AHX medium-speed marine diesel engine, CAE structural analysis was performed to significantly reduce the weight of the connecting rod compared to previous models, an ideal balance of lower weight and higher durability was achieved, and the soundness of the components was confirmed in an endurance test of an actual product.

In addition, structural analysis helped to achieve high fuel efficiency and compliance with the IMO NOx Tier II regulation while increasing output and reducing engine weight. The same approach was applied to the development of the 17AHX series, a new small medium-speed diesel marine engine, which was released in 2011.

The authors continue to develop the analytical technologies to contribute the short term engine development with high specification.