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Engine Component Design System Using Boundary Element Method

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ABSTRACT

Analyses through the application of the Finite Element Method (FEM) have been most widely utilized for the design and evaluation of engine parts. However, it requires a long time to produce models that have complicated three-dimensional profiles. Due to this disadvantage, it is difficult to use the FEM system in developmental stages.

We developed a new design system combining the Boundary Element Method (BEM) with a pre/post-processor. BEM needs a shorter period of time to produce models and is more flexible in making design modifications of the developed model. We modified the BEM analysis software to reduce memory and time needed for calculations for practical use. Also, we adopted an interactive pre/post-processor, which works in conjunction with the Computer Aided Design (CAD) system, and upgraded the user interface.

An example application of our system to the design of connecting rods was performed. This proved the accuracy of the system when applied to actual parts design. Furthermore, the system was successfully utilized to develop a lightweight connecting rod.

THE ADVENT OF HIGH SPEED, HIGH POWER ENGINES has recently made it necessary shorter periods of time. The improvements in performance, quality and development efficiency with the help of structural analysis using a computer have become indispensable to meet these requirements.

Unfortunately, there are few cases where engine designers have sufficient command of structural analysis in developmental stages. This is due to the fact that FEM, which is most often used for this purpose, requires a long time and special skills to produce. and modify engine parts models with complicated three-dimensional profiles (e.g. piston, connecting rod).

To reduce time required to produce models, specialized mesh generators of shape parameter input have been employed(1)(2)*. This approach is limited, however, since only a limited number of profiles can be treated and object profiles are not completely represented. Additionally, an FEM model consists of a tremendous amount of data and it is thus extremely difficult to modify the model.

To eliminate these difficulties, we developed a structural analysis system which can be used as a designing tool. In the development, we focused on the following criteria:

The system should

- be capable of analyzing arbitrary profile models
- allow a substantial reduction in time required to produce mesh models
- be reliable and easy to use throughout all the steps -- ranging from model production to evaluation

We applied BEM for this purpose, which has recently received attention as a method of engine parts analysis(3)(4). Also we developed a new user-friendly system through the application of a pre/post-processor interlinked with the CAD system. Thus, all steps from designing to evaluating results can be performed with ease using this system.

ANALYSIS SYSTEM

The BEM analysis system is composed of a CAD system, a pre/post-processor and BEM software. The outline of the system is shown in Figure 1. The particulars and functions of these components are described below.

ADVANTAGES OF BEM -- Since our BEM system has several advantages” over the FEM system, the application of the system to structural analysis has been increasing in our company. BEM analysis will become one of the major analysis methods for engine parts (5)(6).

The comparisons between BEM and FEM are shown in Table 1. One significant advantage is that BEM reduces time needed to produce and modify models, because it requires only surface element data and not internal element data. Figure 2 illustrates comparisons of required time to produce models with satisfactory calculation accuracy. It is particularly remarkable that pistons, crankshafts and other implicated profile parts can be produced in shorter periods of time when using BEM.

Figure 3 shows a crankshaft model made by our BEM system. The areas of high stress, such as the fillet-R and oil hole can be minutely divided. and more correctly reproduced. This shows that BEM allows the analysis of extremely complex configurations, which has been compromised in the FEM analysis. In addition to these advantages, BEM makes developing the automatic mesh generator easier than FEM, and improving substantially operational response.

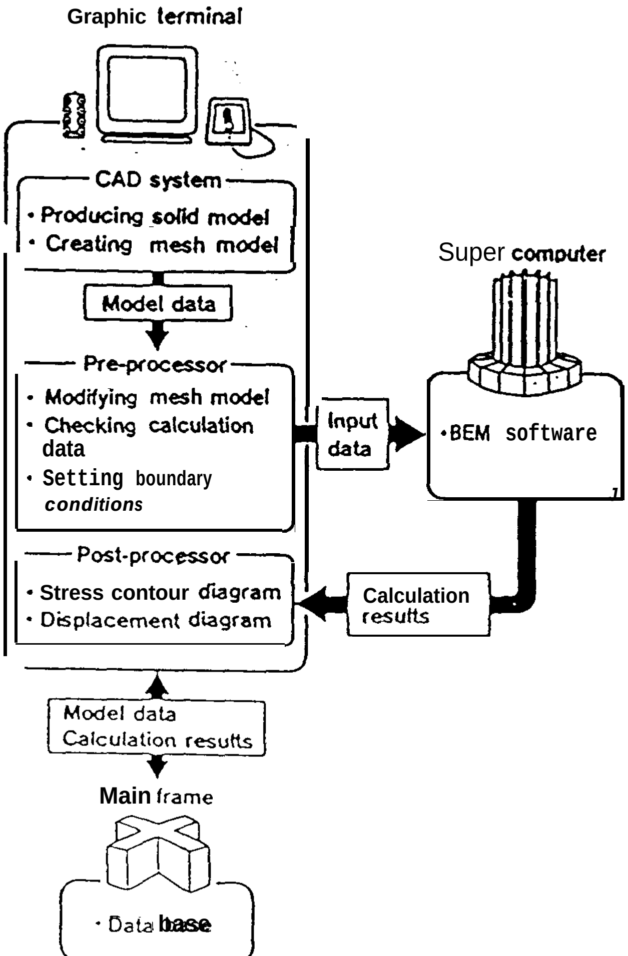


Table 1 Comparison between BEM and FEM

	BEM	FEM
Element	Boundary elements	Domain elements
Input data	Few, simple	Many, complicated
Matrix	Asymmetrical full matrix	Symmetrical band matrix
Calculation	Long time	Short time
Analysis area	Elasticity Infinite region	Elasto-plasticity Dynamic analysis
Application	Few	Many
Theory	Difficult	Easy

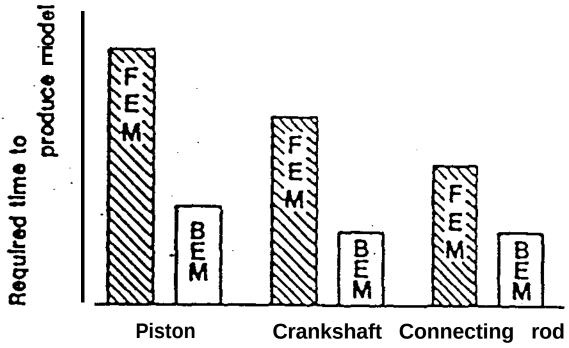
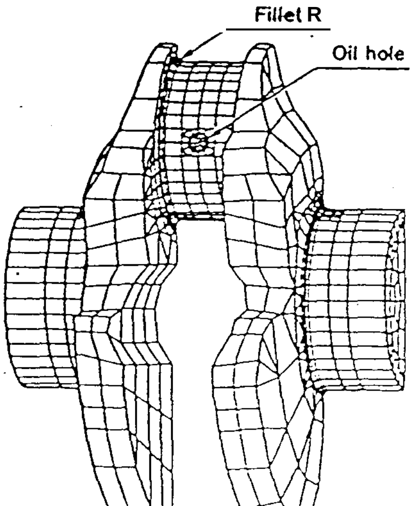


Fig. 2 Comparison of required time to produce models



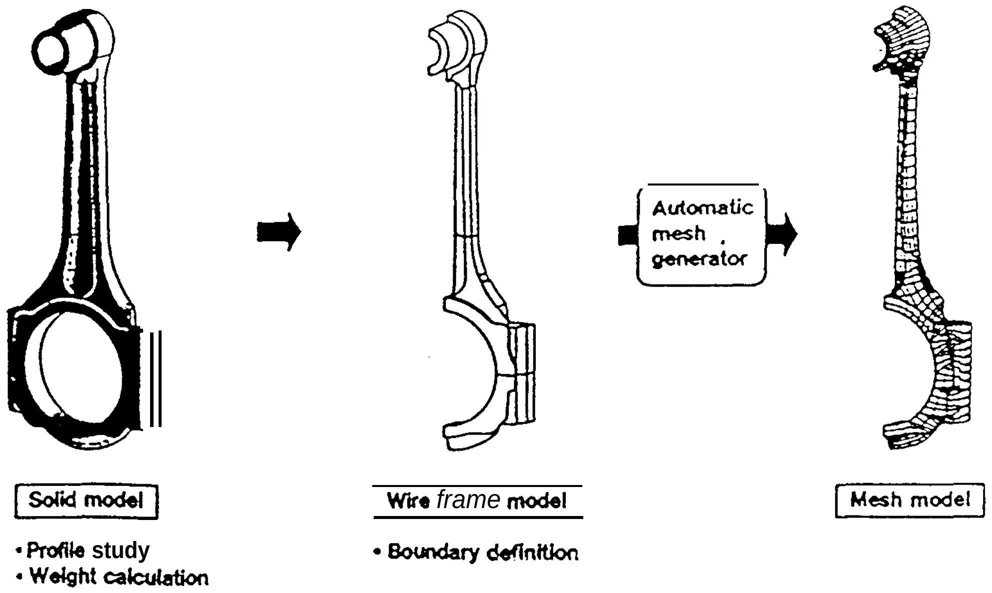


Fig. 4 Production process for BEM model

CAD SYSTEM -- Generally, most of the time to perform structural analysis is consumed in producing the model. Since the system is widely used in designing stages, it was advantageous to make it similar to the existing system which engine designers are familiar with. A system of this kind requires no further operation training for the designers.

In this respect, we decided to use CATIA as a base system (7). CATIA is a general-purpose CAD system for three-dimensional design and has a solid modeler function. Furthermore, we developed our original automatic mesh generator and incorporated it into CATIA, thus enhancing the mesh producing ability of the CAD system. As a result, we were able produce arbitrary three-dimensional profiles and ide the mesh by taking advantage of the interactive function while visually confirming the progress of the work. We could perform the analysis more efficiently since the data used is compatible to both the CAD and CAE systems.

Table 2 Functions of pre/post-processor

1. Pre-processor functions

Checking and modifying the model
- Aspect ratio
- Grading
- Normal vector
- Scaling

Setting the calculation conditions
- Loads
- Boundary conditions
- Material characteristics
- Division of the regions

2. Post-processor functions
- Display of surface stress
- Stress vector diagram
- Display of temperature distribution
- Display of displacement

Figure 4 shows an example of model production. Engine designers first produce a solid model evaluating the designed profile three-dimensionally displayed on the graphic terminal. At the same time, they assess weight and location of the center-of-gravity using the capability of CATIA. Next, the wire frame, which represents the contour, is made based upon the surface of this model. Finally, a mesh model is produced by generating boundary elements using the automatic mesh generator.

PRE/POST-PROCESSOR -- The pre/post-processor checks and modifies the mesh model made by the CAD system, determines the boundary conditions, compiles data for analysis, and assesses the calculated results. It plays an important role as a user interface and in part determines overall calculation accuracy. Thus, as shown in Table 2, this processor system was designed to make use of the analysis software characteristics and to satisfy demands of the engine designers.

When using the BEM software, where data is composed of surface elements, we first define the inside region of the model by directing the normal vector of each element outward. We also set a process of automatic checks and modifications of the vector. Next, in view of the substantial effects on the analysis accuracy, another automatic check and modification process was developed for the aspect ratio of the elements and comparisons of sizes between adjoining elements, known as grading.

Requirements to satisfy demands of the engine designers include operational ease by standardizing system operations as much as possible. By linking all the model data of nodal points, elements and boundary conditions, the basic operation procedures were the same as those of the CAD system. Consequently, all the operations were capable of being conducted by a single graphic terminal. Another requirement was the display Of the value of principal stress on the model surface for comparison with measurements obtained using a strain gauge.

ANALYSIS SOFTWARE -- The analysis software is one of the most important components of the system. We adopted BEASY(8), a BEM software developed by C.M.BEASY Ltd. The software analysis functions are listed in Table 3. However, there were several problems we had to resolve prior to applying it to our system. The BEM software, which usually requires a long time and large amount of memory for calculations, necessitates a computer appropriate for high speed processing and storage of huge quantities of data. Although we used a super computer for this reason, only small-scale models could be processed and the calculation time was long, making the system far from practical.

To tackle this problem, we collaborated with C. M.BEASY Ltd., concentrating on the following:

Table 3 Applicable areas of BEASY

1. Analysis types
    - Elastic stress analysis
    - Static heat conduction analysis
    - Thermal stress analysis
2. Calculation conditions
    - Stress analysis
        - Pressure load of arbitrary distribution
        - Acceleration and rotational force
        - Prescribed displacement
        - Sliding interface, spring interface
    - Heat conduction analysis
        - Boundary heat conduction
        - Temperature condition

- reduction in elapsed time by improved program I/O and utilization of computer buffer memory
- optimization of the use of memory and reduction in the amount of memories by diving the regions of the model

With the above modifications, the software became practical for design work.

EVALUATION OF APPLICATION RESULTS

To evaluate the system capability, we used it to analyze a connecting rod, focusing on the following:

1) static analysis
2) quasi-dynamic analysis with the consideration of inertia force
3) design of a lightweight connecting rod

When developing. a connecting rod, we normally go through the study of several profiles and perform preliminary tension and compression tests on each connecting rod to assess strength and stiffness. After these processes, we perform final durability tests on those which have passed the preliminary tests, incorporating them in the engine. We also followed the same procedures when conducting the BEM analysis.

Figure 5 provides the solid and mesh models used for analysis. The solid model precisely reproduced the actual profile with minimum weight error. The mesh model was made to a quarter model using two planes of symmetry. It correctly represented the oil jet hole and other detailed sections. The rod, cap, and bolts were integrated into one unit, whereas the piston-pin was defined as a separate region because of the interference of press-fitting to the small end.

STATIC ANALYSIS -- Figure 6 shows the boundary conditions when a tensile load is applied to a connecting rod:

- the piston-pin receives the force corresponding to the load from the piston and piston-rings under maximum inertia force

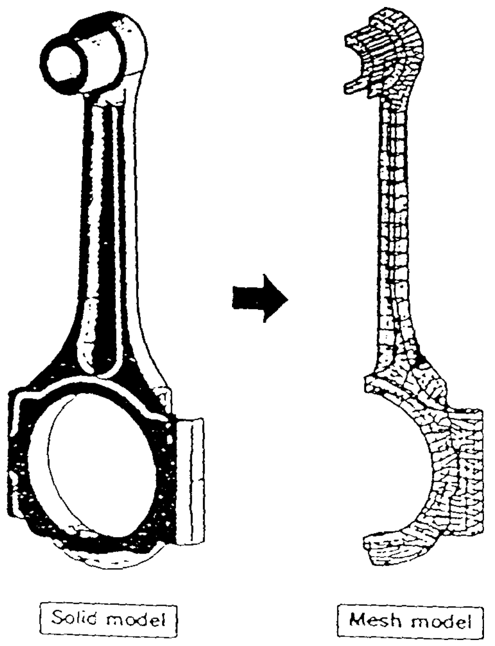


Fig. 5 Connecting rod analysis model

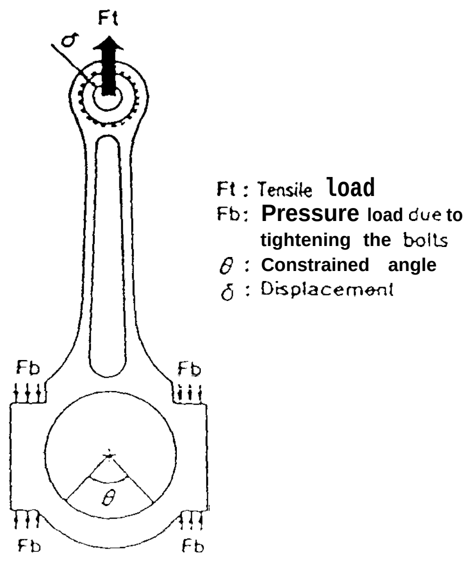


Fig. 6 Boundary conditions for static analysis

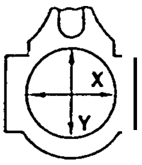
- the elements representing bolt and nut seats are loaded by tightening the bolts
- the area on the cap in contact with the crank-pin is constrained in consideration of bearing clearance
- the press-fit stress to the small end is reproduced by applying the piston-pin displacement identical to the press-fit interference

Figure 7 shows the distribution of the calculated maximum principal stress values and a comparison between calculated and measured stress values on various areas. It agrees well not only with the column and big end, but also with the stress concentration around the oil jet hole. Table 4 gives the amount of displacements in the big end diameter. The calculated values of these displacements, which have a significant effect on crank-pin lubrication, agree well with those actually measured.

Therefore, results indicate that the strength & stiffness of the connecting rod under static conditions could be precisely calculated using the BEM analysis.

Table 4 Comparison between calculated and measured displacements of big end diameter

	Displacement [μm]	
	X	Y
Calculated value	40	52
Measured value	41	56



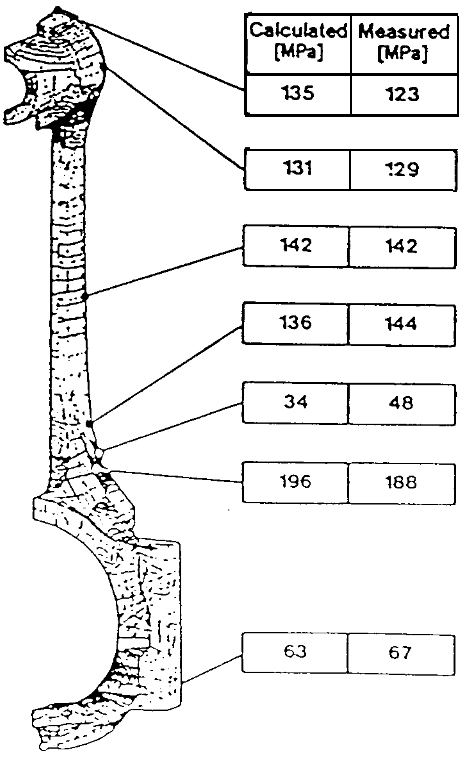


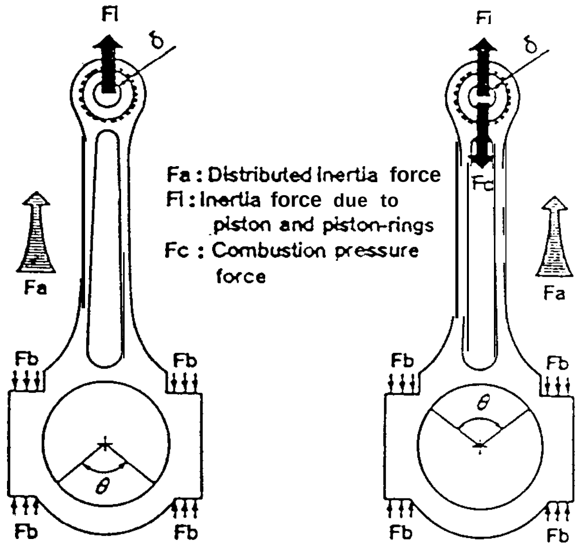
Fig.7 **Comparison** between **calculated and measured** stress **values in** static **analysis**

QUASI-DYNAMIC **ANALYSIS -- By** taking the **distributed inertia force** into **consideration in** the connecting rod, **we** were able to more closely simulate actual engine operating conditions. **Figure** 8 **shows the** boundary conditions:

- **the** piston-pin receives tension load **and** impression load at each engine speed
- the distributed inertia force is applied to the connecting rod
- either the rod-side (the upper portion of the big end) or the cap-side (the lower portion of the big end) is constrained

Under these conditions, we calculated the maximum stress amplitude (σa) and mean stress value (σm).

Using strain gauges, we measured stress *on* the connecting rod in an engine to compare them with calculated results. Signals from the engine in operation were picked up through **a link mechanism** shown in Figure 9. Engine specifications are given in Table 5.



Under inertia force

Under combustion pressure force

Fig. 8 Boundary conditions for quasi-dynamic analysis

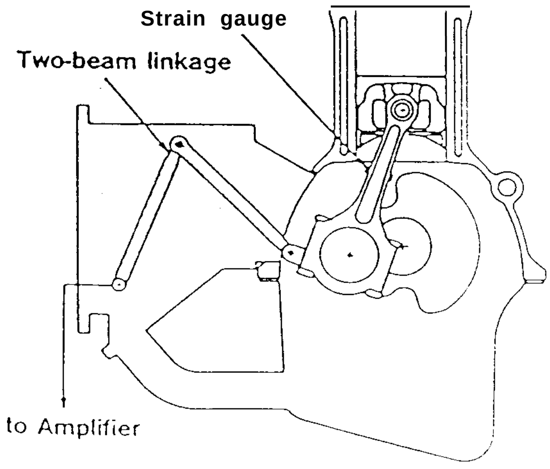


Fig.9 **Link mechanism for** measuring connecting **rod stress under** actual operating condition

Figure 10 shows a comparison between calculated and measured stress values. The figure contains the design limit line, which was obtained considering the fatigue limit of the material and a margin of safety. Except for the shoulder portions of the big end, where stress concentrates (almost reaching the design limit), stress on other points is comparatively low. Calculations agreed satisfactorily with measurements at all points.

Table 5 Specifications of test engine

Arrangement of cylinders	In-line 4-cylinder
Bore	81 mm
Stroke	95 mm
Displacement volume	1958 cm³
Maximum engine speed	6500 rpm
Weight of connecting rod	520 gram
Center-to-center dimension of the connecting rod	141.7mm

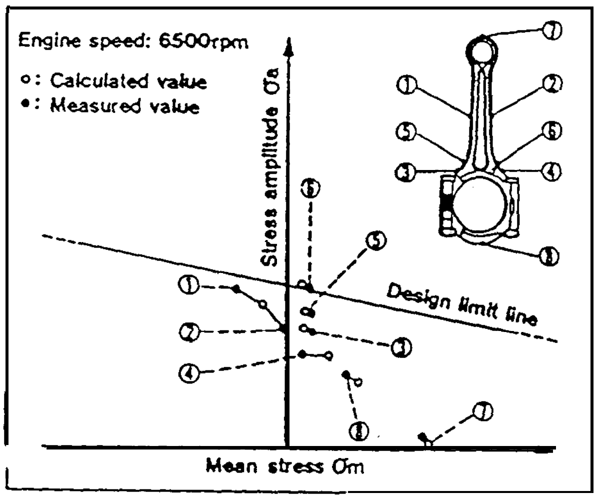


Fig.10 Comparison between calculated and measured stress values. in quasi-dynamic analysis

This proves that the quasi-dynamic analysis was effective in estimating the stress of the connecting rod under actual operating conditions.

LIGHTWEIGHT CONNECTING ROD -- To further enhance the utility of the system, we applied it to reduce the weight of the connecting rod. Taking advantage of the features of the system, we studied a large number of profiles.

Figure 11 illustrates two evaluated cases. Although a larger weight reduction was observed in Case 1, it was estimated that it had the risk of poor lubrication due to a larger deformation of the bearing holding surface when loaded. We determined that Case 2 should be adopted despite its smaller weight reduction than Case 1, because it does not lead to such profile deformation.

Figure 12 shows a lightweight connecting rod actually designed and produced based upon Case 2. By incorporating a thin I-shaped section column and adopting the two rib design to the big end, we successfully reduced the weight by approximately 20%.

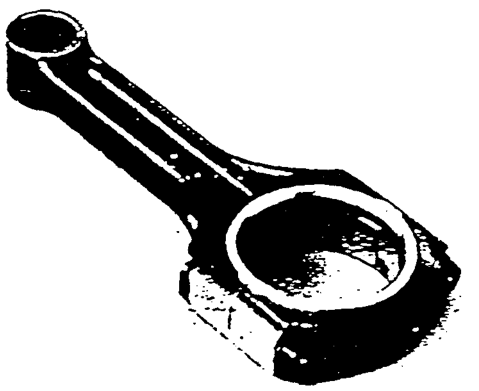
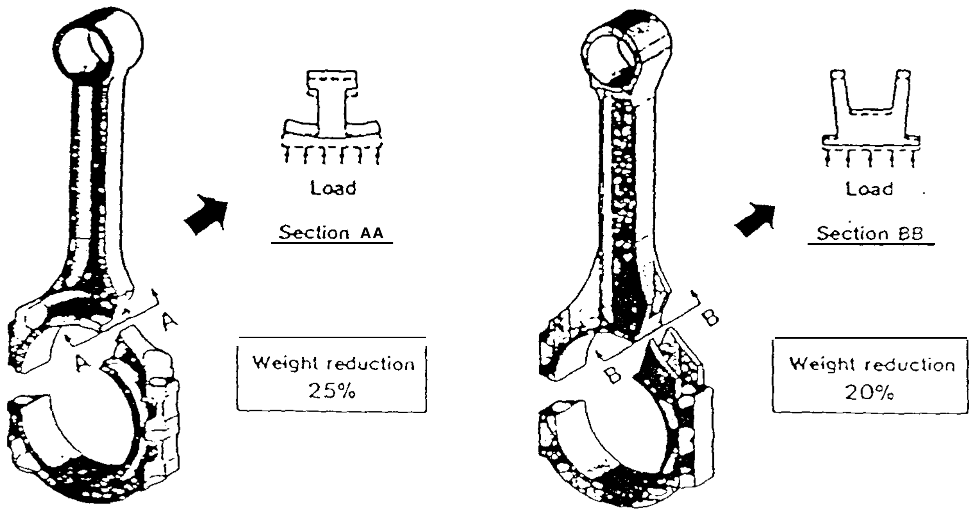


Fig.12 Lightweight connecting rod



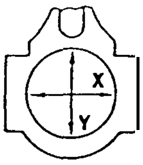
Case 1

Case 2

Fig. 11 Profile study of lightweight connecting rods

Table 6 **Calculated displacements of big end diameter for lightweight connecting rod**

	Displacement [μm]	
	X	Y
Lightweight connecting rod	43	53
Original connecting rod	40	52



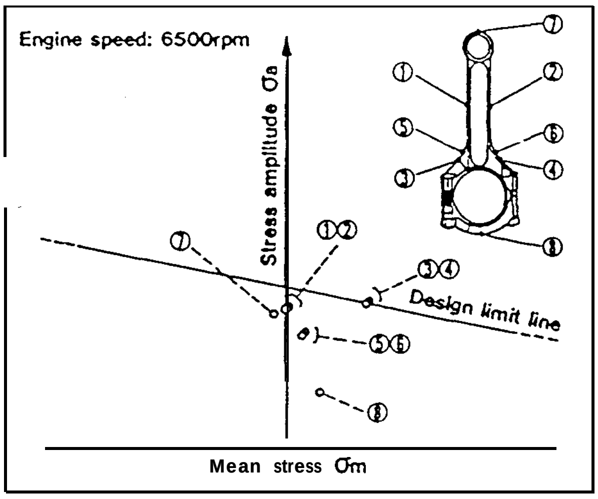


Fig. 13 **Calculated stress** values of lightweight connecting rod

Table 6 **lists the calculated displacements of** the big end diameter. Weight reduction resulted in nearly the same amount of deformation as that of the original connecting rod. This fact suggested that the profile modification complemented stiffness rioration due to weight reduction.

Figure 13 shows the evacuation of calculated stress values based upon the design limit line to review durability of an actual engine. Due to profile modifications, the values of each calculation point were below the design limit line even though the weight reduction was implemented.

We assembled the lightweight connecting rod in an actual engine to perform a durability test, and there has been no problem detected. This endorses the validity of the evaluation.

The analysis results verified that it is **possible to estimate stress distribution of** the **connecting rod under actual operating** conditions. We **also confirmed that the system is effective** in **weight reduction and allows-more flexible design** analysis.

CONCLUSION

1) **Through the use** of BEM, **we developed a structural analysis** system **that proved to be effective as a tool for engine** designers. The system enables three-dimensional modeling of engine parts with complicated profiles in shorter periods of time.
2) We applied the system to connecting rod analysis. The calculated and measured values were compared, demonstrating that the system provides a satisfactory level of analysis accuracy.
3) We proved the effectiveness of the system by achieving a 20% weight reduction of **the** connecting rod.

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