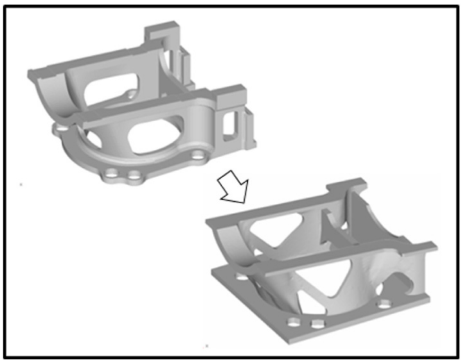
Innovation of Design and Development Process using Structure Optimization Technology



YASUHARU CHUMAN[*1] HIROSHI KATSUURA[*2]

TAKASHI OKAFUJI[*3]

With the increase in the capabilities of computers in recent years, the technology for optimizing a structural shape by automatically repeating FEM analysis several times is approaching practical application. So far, Mitsubishi Heavy Industries, Ltd. (MHI) has established expertise on structural optimization that can be adapted to its various products, loading conditions and manufacturing conditions, and has been promoting the development of original tools. By applying structure optimization technology, the optimum structure can be determined at the initial stage of design, and a design and development process in which there is no starting over can be established. In addition, entirely new structural concepts can often be devised and substantial reductions in weight can be expected.

1. Introduction

In conventional product development design operations, as shown on the left in **Figure 1**, the process starts with the planning of basic structure from actual results and rule of thumb and proceeds to detailed design and the study of productivity/economic efficiency repeatedly. Stress analysis by FEM is conducted, but FEM analysis is a tool for analyzing the shape of a given object and cannot be used for directly deriving new shapes.

With the increase in the capabilities of computers in recent years, FEM analysis can be repeatedly conducted, and structural optimization technologies with FEM at the core have been approaching practical application. In addition, optimization can be made not only by repeated calculations with different dimensions and shapes, but also with consideration given to complicated constraints such as production restrictions.

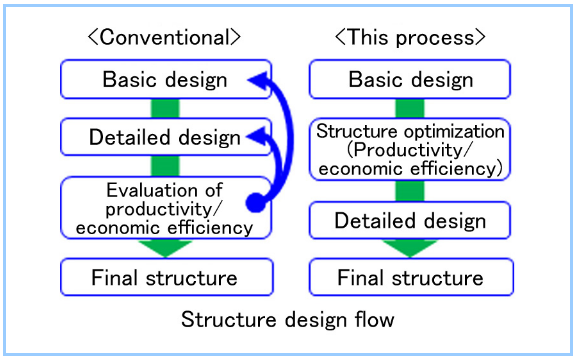


Figure 1 Structure design flow using the structure optimization method

By applying structural optimization technologies, the optimum structure can be determined at the initial stage of design as shown on the right side of Figure 1, and a design development process in which there is no starting over can be established. Entirely new structural concepts can often be

*1 Director, Strength Research Department, Research & Innovation Center, Technology & Innovation Headquarters
*2 Chief Staff Manager, Strength Research Department, Research & Innovation Center, Technology & Innovation Headquarters
*3 Strength Research Department, Research & Innovation Center, Technology & Innovation Headquarters

devised, and substantial reductions in weight and performance enhancement can be expected.

We have been making efforts to establish analysis expertise and new analysis methods which can be adapted to MHI's various product lines, loading/environmental conditions, and production methods. The parts of products are broadly classified into three structures: solid structure, shell structure and beam structure. The structural optimization technologies that correspond to the respective structures are topology optimization, topography optimization and dimension optimization. We have been studying the respective application methods and developing applications to actual product design.

There are many cases, however, where it is difficult to realize optimization by just using commercially available tools for structural optimization. There are many problems in cases where a number of members are included in a structure such as a plant steel frame, where fatigue strength at multiple positions and under complex loading conditions is set as an objective function, etc. In this article, the application examples of structural optimization technologies are described and an outline of MHI's proprietary structural optimization technology for expanding the scope of application and its application examples are introduced.

2. Structural optimization

Structural optimization is a technology for coming closer to a structural target by automatically changing FEM mesh models in FEM analysis. The optimization of all structures cannot be achieved through just a single method, and the various optimization methods that depend on the structural characteristics have been developed. Structures are broadly classified as thick-walled structures such as castings and machined products (solid structure), thin-plate structures such as plate press-worked products (shell structure) and structures with beams such as steel frames (beam structure). The following methods for the structural optimization of the respective structures have been developed, which also allow analysis with commercially available tools.

(1) Topology optimization

Topology optimization is a method leading to the optimum structure by determining whether FEM elements in the initial design region are required. Compared with other optimization methods, it has a large degree of freedom and it can lead to new shapes that are completely different from those of existing products. Accordingly, substantial improvement can be expected with this method.

In the method, the degree of contribution to rigidity of each element is calculated, and elements with a low degree of contribution are selected for elimination as structurally unnecessary elements. In calculation, they are treated as virtually nonexistent elements by reducing the Young's modulus/density (weight) of the element.

When topology optimization is simply implemented, perforated structures or unfeasible shapes may be formed. Recently, however, the directivity for reducing the thickness and the minimum thickness can be set as detailed constraint conditions, and optimization calculation in consideration of castability and processability is possible. The setting of these constraint conditions requires expertise, and through application to various products, this expertise has been accumulated.

Figure 2 shows an example of topology optimization. Figure 2-(1) is an example of application to the nacelle base of a wind turbine. In this optimization, the initial design space as shown in the figure was set, and then the constraint conditions such as directivity for reducing the thickness, minimum R and minimum thickness were set in consideration of various loading conditions and castability, and the minimization of weight was set as the objective function. In consideration of the occurrence frequency of various wind loads, optimum structures were synthesized and the final structure was determined. Compared with existing structures, the optimum structure has a smaller maximum stress and a 20% reduction in weight was achieved. Figure 2-(2) is an example of the optimization of a component of a machine. The existing structure was a cross rib structure. As the optimum structure, a V-shaped rib structure was derived and a 20% reduction in weight was achieved.

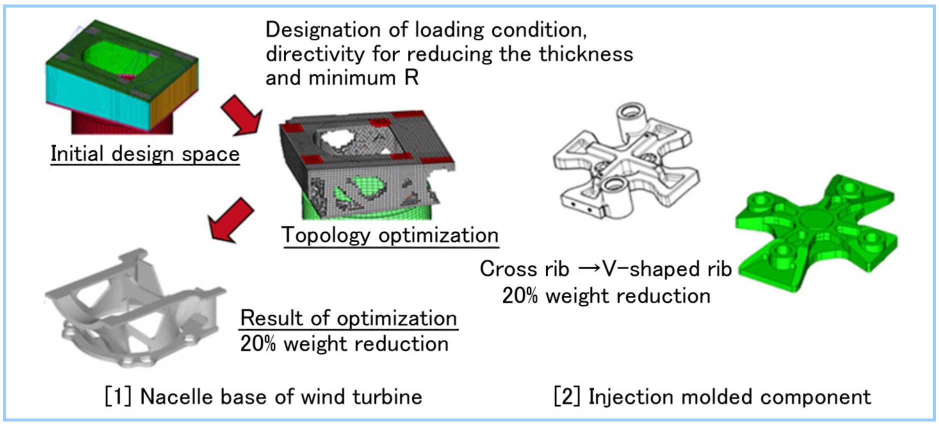


Figure 2 Example of topology optimization

(2) Topography optimization

There are structures with dents and bumps of beads or embossing formed by press working, etc., in order to increase the rigidity of thin-plate material. The method for optimizing the dents and bumps of plate material is topography optimization. In topography optimization, rigidity, displacement, natural frequency, etc., may be set as the objective functions, the limit depth of the dents and bumps and R shape in press working may be set as constraint conditions, and the linearity, symmetry, cycle, etc., may be designated as the functional convex and concave pattern. **Figure 3** shows an example of topography optimization, which is applied to exterior sheet metal components. The resulting exterior sheet metal is superior in rigidity and vibration property compared with the existing one, and the thickness was reduced by 20% or more.

(3) Beam structural optimization

Beam structures are used in plant support steel frames, bridges, etc. In this structure, weight is a direct function of cost, and a reduction in weight is necessary. On the other hand, strict restrictions of anti-seismic standards are imposed. Beam structures have the lowest degree of freedom in members, but several thousands of steel frame members are used in an entire plant. Thus, it is a design issue requiring the handling of many parameters, and there is the constraint condition that components must be selected from conforming materials. To address these issues, MHI has developed the steel frame cross-section minimization method, M-FRAME (Mitsubishi－Frame weight Reduction Algorithm for Multiple Elements)(1). Using this method, the dimensions of each member enabling the minimization of the overall weight can be calculated while satisfying the anti-seismic design standards and giving consideration to conformance/nonconformance of materials, the productivity of joint portions, etc.

Figure 4 shows an optimization application model of a plant steel frame structure.

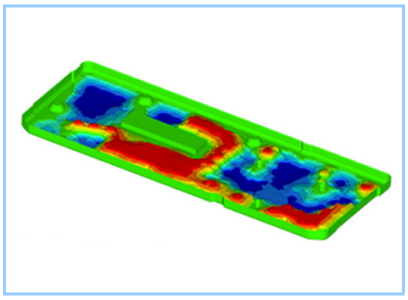


Figure 3 Example of topography optimization
Exterior sheet metal components
Red shows bumps and blue shows dents.

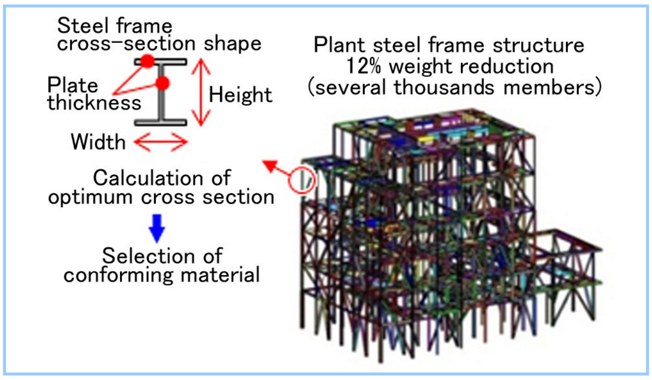


Figure 4 Example of optimization of steel frame structure

3. Minimization of fatigue damage at multiple points

To obtain the R shape that maximizes the fatigue life (≒minimizing stress concentration) in stress concentration parts, human systems are studied at present, which constitutes a cause of increases in weight and extended study time. Therefore, in order to improve the design efficiency of stress concentration parts at multiple regions (over 20 regions) and with complex loading conditions (over 10 conditions), an optimization method using mesh morphing has been developed.

(1) Optimization using mesh morphing

Through the mesh morphing method in which the surface nodal point of the FEM model is moved to change the shape, the peak stress at the stress concentration part can be calculated somewhat accurately compared with the topology optimization method, so it is considered to be suitable for the optimization of local shape. Optimization for a single shape and a single load using mesh morphing can be relatively easy to achieve by commercially available optimization software, but in actual design, fatigue strength optimization at multiple regions and under complex loading conditions is required. Therefore, the function for that purpose has been developed as an external routine.

As the method of representing the local shape, rather than an R shape with a single curvature radius, and R shape with a free curve as shown in **Figure 5** was considered. Multiple shape functions are combined so that a smooth R shape is always obtained by mesh morphing. The opening has deformation constraints inside and outside so that it does not interfere with the window sash and frame.

An optimization example of a common shape at multiple regions is shown in **Figure 6**. When optimization is applied to only one corner which has the largest stress (2), the stress at the other corners increases. Therefore, calculation for the simultaneous optimization of all corners with a common shape (3) is effective. The fatigue strength optimization function has also been incorporated with consideration given to the occurrence frequency of fatigue load.

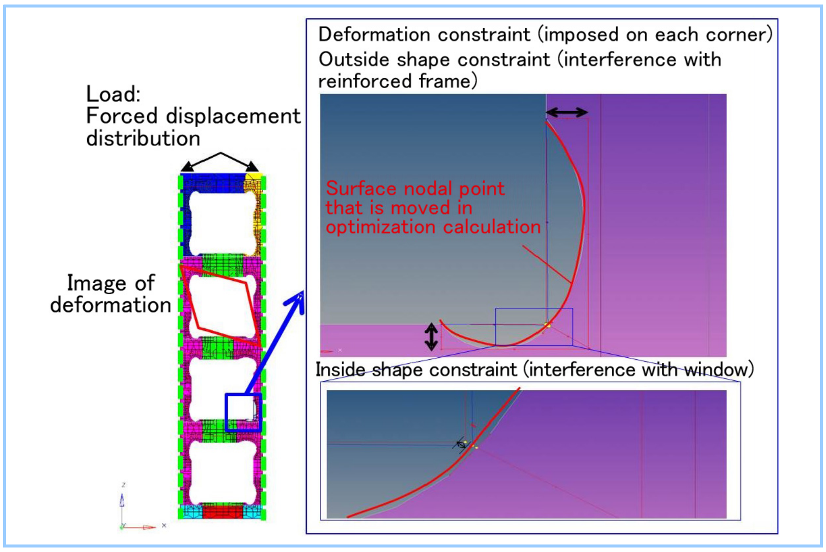


Figure 5 Optimization model for multiple corner R parts using mesh morphing

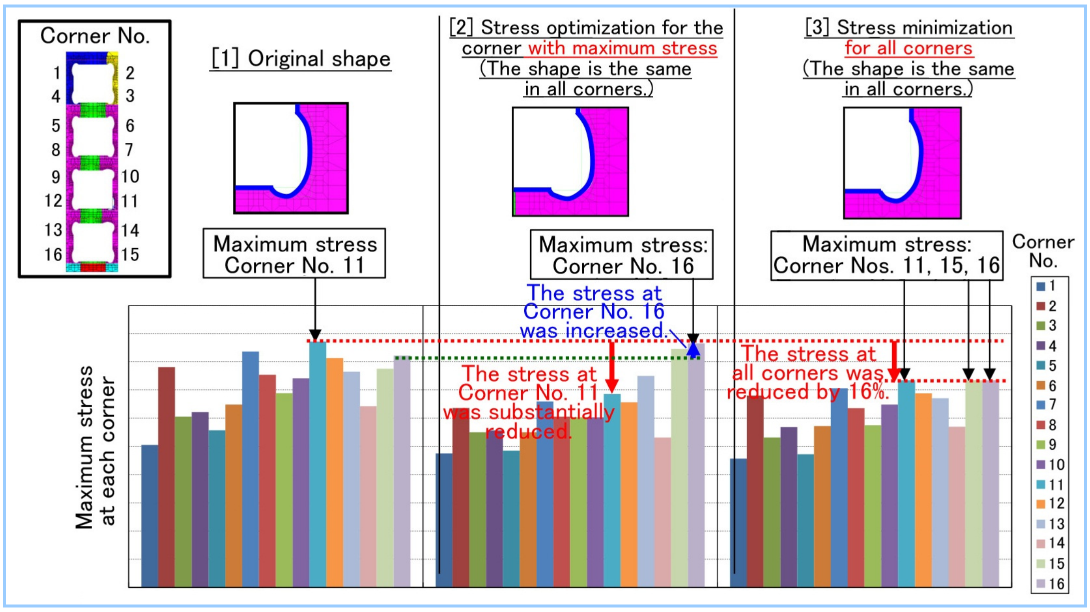


Figure 6 Result of optimization for multiple corner R parts using mesh morphing

(2) Example of application to passenger ship opening

For a passenger ship, the optimization calculation of the R shape of multiple openings was conducted. **Figure 7** shows the analysis model. There are 56 corners and the shape constraints at each corner are the same as Figure 5.

The analysis results are shown in **Figure 8**. The maximum stress was reduced by 30%. This corresponds to an improvement of more than 10% improvement in fatigue life.

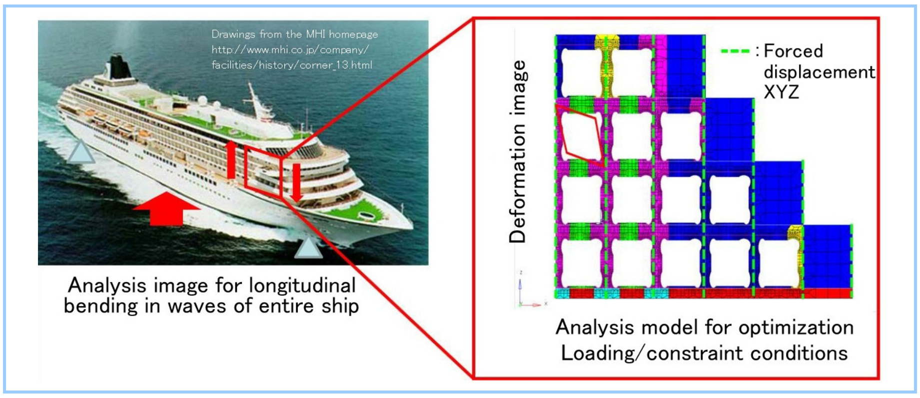


Figure 7 Optimization of window frame shape of a passenger ship

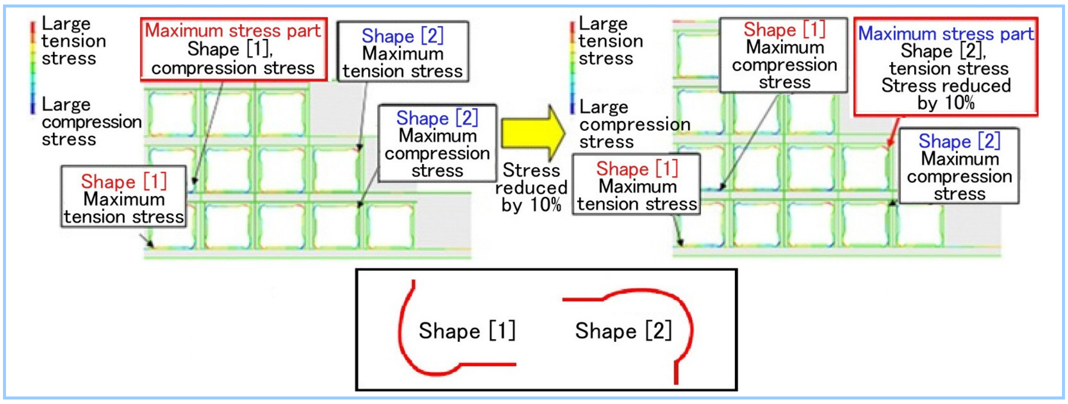


Figure 8 Optimization for multiple corner R parts using mesh morphing

4. Conclusion

Conventionally, it has been regarded as matter of course that product reliability and economic efficiency are gradually improved through the maturing of a product and with experience over many years after a product is first launched. There is a possibility that structural optimization technologies could drastically change the maturing process of products, and it is expected that the optimum structure can be selected at the initial stage of development, and products with higher reliability and economic efficiency can be provided. The example described in this paper showed that the application of optimization technologies achieved a reduction in weight of approximately 20% compared with the existing structures.

However, structural optimization cannot be easily calculated. Depending on the setting of the objective function and constraint conditions, the results calculated as being optimum become significantly different. As such, it required a significant amount of expertise. MHI has many product lines and must meet various structure and design standards, limit environments, loading conditions and manufacturing/processing conditions. It is necessary to share optimization technologies and expertise and establish a design system where the optimization method is customized for each product.

In order to provide products with high reliability for customers faster and cheaper, we will make further efforts to develop structural optimization technologies.

References

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