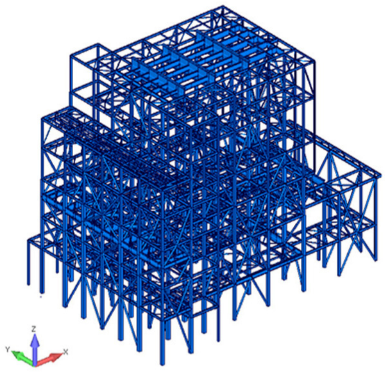
Development of Rational Design Technique for Frame Steel Structure Combining Seismic Resistance and Economic Performance



MOTOKI KATO*1 KUNIHIRO MORISHITA*2
MASAKI SHIMONO*3 YASUHARU CHUMAN*4
TAKASHI OKAFUJI*5 TOSHIAKI MONAKA*6

Anti-seismic designs have been applied to plant support steel frames for years. Today, a rational structure that further improves seismic resistance and ensures economic performance is required in response to an increase of seismic load on the assumption of predicted future massive earthquakes. For satisfying this requirement, a steel frame design method that combines a steel frame weight minimizing method, which enables economic design through simultaneous minimization of multiple steel frame materials, and a seismic response control design technology that improves seismic resistance has been established. Its application in the design of real structures has been promoted. This paper gives an overview of this design technology and presents design examples to which this design technology is applied.

1. Introduction

Mitsubishi Heavy Industries, Ltd. (MHI) has numerous plant products and there are various sized steel frames to support them.

The performance of these plant support steel frames is to reliably support plant equipment, and they are required to withstand natural disturbances such as earthquakes and violent winds while ensuring safety and reliability. In particular, Japan is an earthquake-prone nation and MHI has been enhancing the seismic resistance of plant support steel frames while following changes of aseismic design codes. On the other hand, the level of seismic load considered in the design phase is on the increase and further enhancement of seismic resistance has been demanded in the wake of the Great East Japan Earthquake in 2011 and the predicted occurrence of giant earthquakes including the Nankai Trough Earthquake. Naturally, economic efficiency is a necessary factor for a product, and therefore, designers are now proceeding with designs in consideration of both seismic resistance and economic efficiency through trial and error. However, there is a limit on the manually performed design of steel frames consisting of thousands of members as described above, so a rational design technology that simultaneously realizes the contradicting performance factors of seismic resistance and economic efficiency is required.

2. Overview of plant support steel frame design

In Japan, the seismic resistance of plant support steel frames is designed mostly according to the Building Standards Law, and primary design and secondary design are undertaken in consideration of a level 1 earthquake, which is assumed to rarely occur, and a level 2 earthquake, which is assumed to very rarely occur, respectively. **Figure 1** shows a schematic diagram of the design flow. In the primary design, plant support steel frames are designed so that the seismic force

*1 Hiroshima Research & Development Center, Technology & Innovation Headquarters
*2 Manager, Hiroshima Research & Development Center, Technology & Innovation Headquarters
*3 Hiroshima Research & Development Center, Technology & Innovation Headquarters
*4 Chief Staff Manager, Nagasaki Research & Development Center, Technology & Innovation Headquarters
*5 Nagasaki Research & Development Center, Technology & Innovation Headquarters
*6 Manager, ICT Solution Center, ICT Solution Headquarters

does not exceed the allowable stress for temporary loading of all steel frame members and the story drift (horizontal relative displacement between the lower floor and the upper floor) does not fall below the allowable value of 1/200. In the secondary design, on the other hand, seismic control design using seismic control devices that can efficiently absorb seismic energy and reduce seismic response has increasingly been applied in recent years because the conventional design method sometimes results in an irrational design with enlarged steel frame members due to an increased seismic load.

This paper presents a case example where a rational design with excellent seismic resistance and economic efficiency is established by applying to the primary design a steel frame weight minimizing method that satisfies design evaluation while meeting various constraint conditions, not by trial and error as shown in Chapter 3, and by applying to the secondary design a seismic response control design that effectively utilizes seismic response control devices described in Chapter 4.

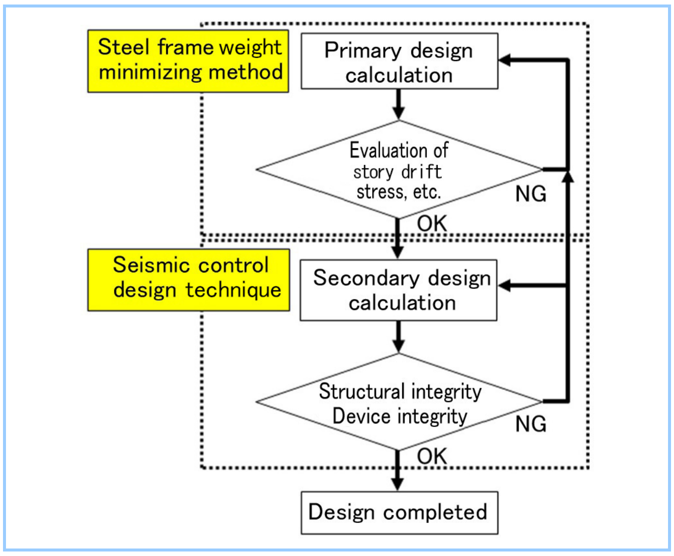


Figure 1 Plant steel frame design flow
Primary design and secondary design are performed in consideration of earthquakes that occur rarely and very rarely, respectively.

3. Steel frame weight minimizing method

As described in the preceding chapter, the M-FRAME (Mitsubishi Frame weight Reduction Algorithm for Multiple Elements) steel frame cross section minimizing method that can simultaneously minimize the weight of many members forming the plant support steel frame is applied to the primary design of plant support steel frames. **Figure 2** shows the outline flow of this method. Each phase of this method is explained as below.

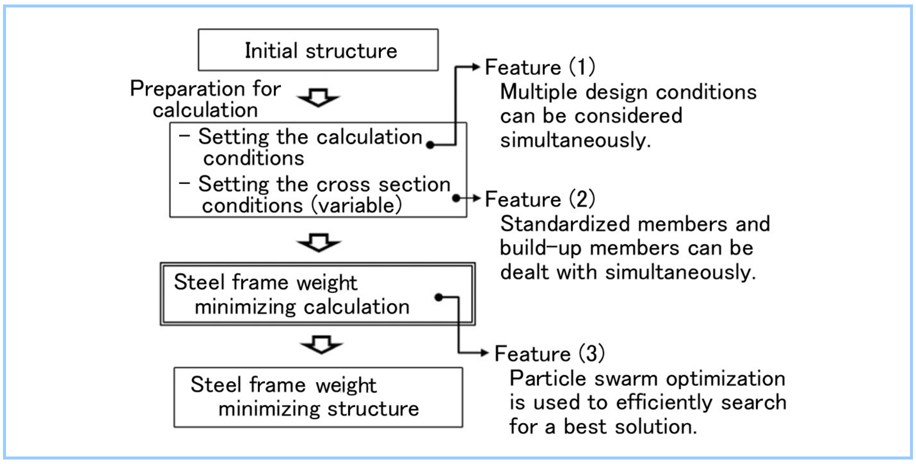


Figure 2 Steel frame weight minimizing design flow
In the steel frame weight minimizing calculation, various design conditions and cross section conditions can be considered simultaneously in order to deal with all structures. A particle swarm optimization method is used to efficiently search for a solution.

(1) Calculation conditions

The steel frame weight minimizing method performs calculation so that the evaluation value of the weight of the entire structure is minimized in order to attain the economic efficiency of the entire structure. Steel frames need to be designed to enable various allowable values such as generated stress and story drift to be satisfied as described above. Therefore, this method established a system that can consider these design conditions as constraint conditions, and realized simultaneous minimization of weight of multiple members under multiple design conditions. As a result, the appropriate cross section of multiple members can be selected automatically; otherwise it is normally selected by trial and error. **Figure 3** shows the change of the relationship between the stress ratio (ratio of the generated stress to the allowable stress) and the number of members resulting from application of this method. As shown in the figure, the weight of the entire structure is reduced by making smaller the cross sectional area of members with the lower stress ratio that are relatively strong enough within the constraint conditions (allowable stress ratio of 1.0 or less, allowable story drift of 1/200 or less, etc.).

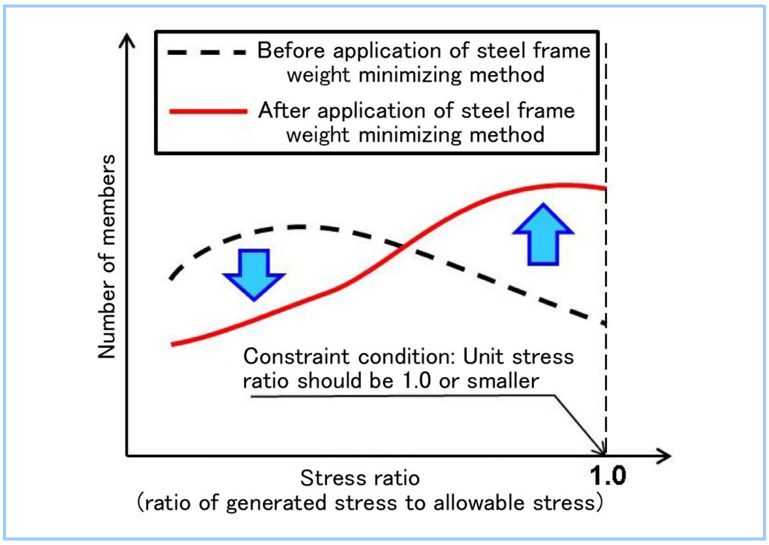


Figure 3 Change in relation between stress ratio and number of members

With the steel frame weight minimizing method, the weight of the entire structure is reduced by making smaller the cross sectional area of members with the lower stress ratio that are relatively strong enough within the constraint conditions. As a result, the number of members with smaller stress ratio decreases and the number of members with larger stress ratio increases.

(2) Setting the conditions of the cross sectional shape

Plant support steel frames of MHI products have various cross section sizes. For structures consisting of members with relatively small cross sections such as small and medium-scale structures, shaped steel members typified by JIS-shaped steels, are used in many cases. On the other hand, for large-scale structures that resist a great load such as large boiler support steel frames, build-up members (components manufactured in a factory by assembling steel pieces cut from a steel sheet) and shaped steel members are used in a mix because necessary performance cannot be attained by shaped steel members in some points. The cross section minimizing method has the ability to deal with the cross sections of both shaped steel members and build-up members in order to handle all structures of any scale. Specifically, discrete values and continuous values can be calculated simultaneously. When shaped steel members are used, an appropriate cross section is selected from a list prepared in advance (for dealing with discrete values). When build-up members are used, a cross section property that attains the goal of weight minimization is obtained by continuously changing the cross section property such as the cross-sectional area and the moment of inertia (for dealing with continuous values).

(3) Calculation algorithm

The steel frame minimizing method uses particle swarm optimization (PSO) as a calculation algorithm. **Figure 4** shows an image of this algorithm. This method imitates the intelligence of a swarm of insects, fish, or birds that allows all swarm members to exchange information when one of the swarm members finds a goal, such as food, and to move toward it no matter where they are. Specifically, the final best solution is obtained as shown in Figure 4 by updating the position of each individual based on three kinds of information: [1] the best solution for the swarm, [2] the best solution for each individual, and [3] the current moving direction (inertia) seen from the previous position of each individual. Because the steel frame weight minimizing method handles both shaped steel members and build-up members as described above, the calculation is performed as a mixed integer optimization problem that deals with discrete variables and continuous variables. This method allows each individual to search for a solution while holding the best solution for itself and the best solution for the swarm, and therefore, can obtain a solution that efficiently attains a goal.

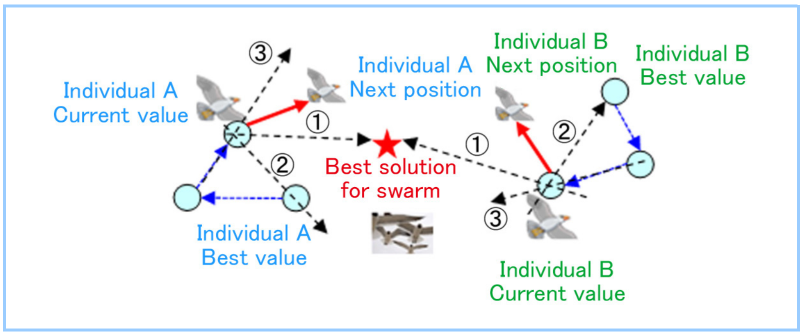


Figure 4 Overview of particle swarm optimization
The particle swarm optimization method searches for a solution based on three kinds of information: [1] the best solution for the swarm, [2] the best solution for each individual, and [3] the current moving direction (inertia) seen from the previous position of each individual.

4. Seismic response control device

The adopted seismic response control device is a hysteresis damper that is inserted in the diagonal member part of a truss structure. This hysteresis damper has an energy absorption mechanism using the elasto-plastic characteristics of a steel material, not using a mechanical feature such as friction or oil. The hysteresis damper used here (hereinafter referred to as a damper brace) is an axial yielding-type buckling-restrained brace that can be used for a long member with a length of 10 meters or more.

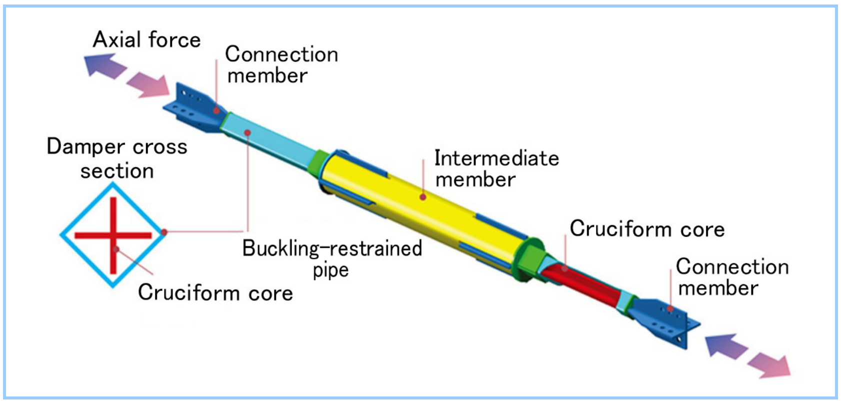


Figure 5 Overview of damper brace structure
The damper brace consists of cruciform core, buckling-restrained pipes, an intermediate member, and connection members.

Figure 5 shows an overview of the damper brace structure. The damper brace consists of the cruciform core (having a cross-shaped cross section) that absorb elasto-plastic energy by yielding axially against an acting axial force, buckling-restrained pipes (rectangular steel pipes) that restrain the core member from lateral buckling and twist buckling after yielding when a compression force is applied, and an intermediate member that connects damper components (the cruciform core and the buckling-restrained pipes) positioned on both ends of the brace. This structure can adjust the yielding axial force and the axial stiffness separately with the cruciform core and the intermediate member, respectively, and therefore, the optimum characteristics of the brace can be set. When an axial force acts on the brace, the cruciform core yields against the compression force and then begins a buckling deformation, but the buckling-restrained pipe restrains the buckling deformation of the core member.

As a result, elasto-plastic behavior similar to that occurring in the tensile side also occurs when a compression force is applied.

Figure 6 shows the result of an experiment where load was repeatedly applied to the damper brace. The vertical axis represents the mean axial stress σd, and the horizontal axis represents the mean axial strain εd. This result indicates that a very stable elasto-plastic energy absorption effect was generated.

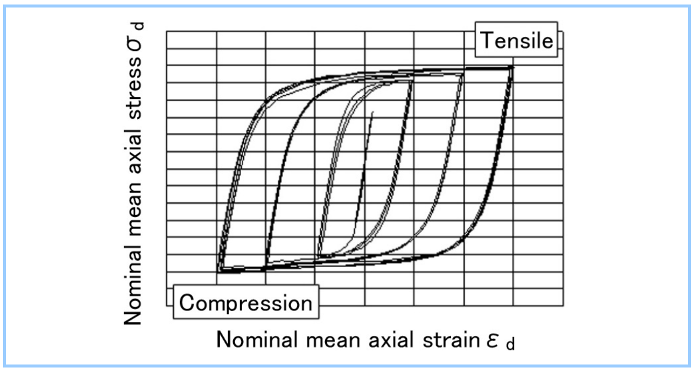


Figure 6 Damper brace hysteresis characteristics
The cruciform core yields axially, but the effect of the buckling-restrained pipe restrains the buckling deformation of the core member. As a result, elasto-plastic behavior similar to tensile yielding occurs. This figure shows the result of an experiment where the static load of compression and tension was applied alternately. This result indicates that behavior similar to the tensile side was also generated for the compression force (minus side).

5. Case example of plant support steel frame anti-seismic design

This chapter presents a case example to which the above described combination of the steel frame weight minimizing method and the seismic response control design was applied.

(1) Object structure

Figure 7 shows a model diagram of the object structure. The object structure was a boiler support steel frame, and a large structure consisting of approximately 2,000 members. The red lines in the diagram are the positions where the damper brace was installed.

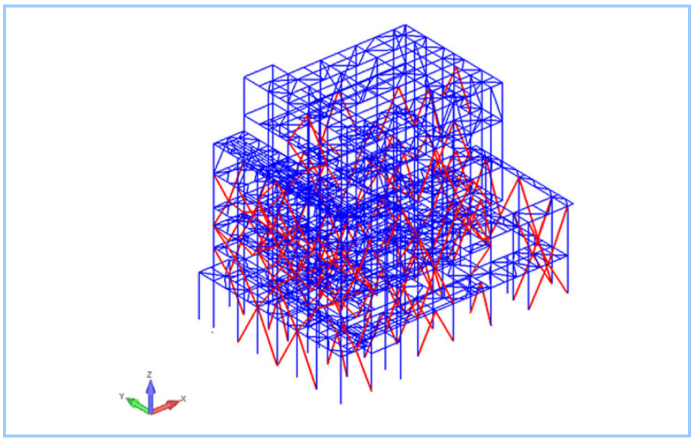


Figure 7 Object structure (model drawing)
The object structure was a boiler support steel frame (consisting of approximately 2,000 members). The red lines are the positions where the damper brace was installed.

(2) Design method

The structure was designed according to the procedures shown in Figure 1. The primary design used the steel frame weight minimizing method, and the secondary design used the seismic response control design. The level of the external force of an earthquake for the secondary design was twice as much as that for the primary design.

(3) Result of design

Figure 8 shows the weight reduction effect obtained by the design. This figure compares the designed weight with the weight to which the steel frame weight minimizing method is not applied (excluding the weight reduction due to seismic control design). As shown in this figure, weight reduction of several percent to more than ten percent could be attained due to the efficient design of the steel frame weight minimizing method.

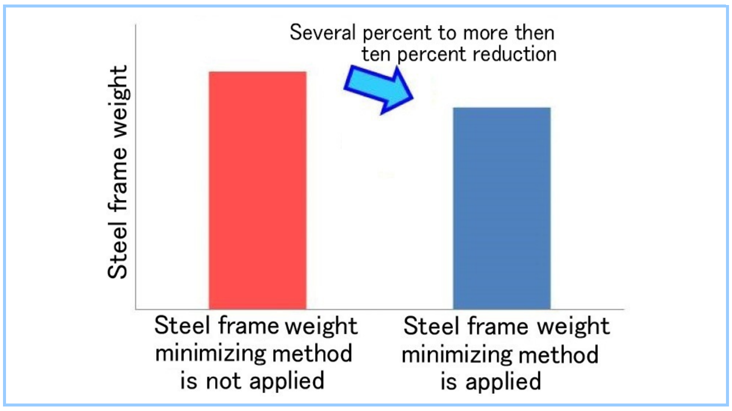


Figure 8 Weight reduction
A weight reduction of several percent to more than ten percent was attained due to the application of the steel frame weight minimizing method (excluding the weight reduction due to seismic control design).

Figure 9 shows the change of the number of members with the stress ratio (ratio of the generated stress to the allowable stress, which is set at less than 1.0 in the design) of 0.8 to 1.0 in the primary design as a result of the steel frame weight minimizing method. As shown in this figure, the application of the steel frame weight minimizing method resulted in a three-fold increase in the number of members with a stress ratio of 0.8 to 1.0. This verifies the fact that an efficient design was attained due to the steel frame weight minimizing method.

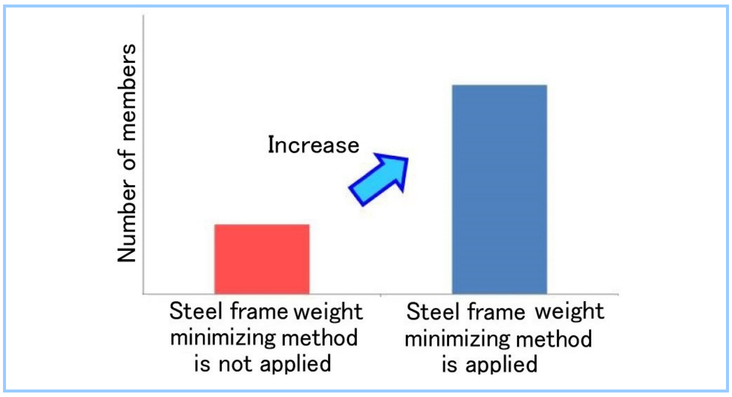


Figure 9 Change of unit stress ratio
This figure shows the change of the number of members having a stress ratio (ratio of the generated stress to the allowable stress) of 0.8 to 1.0. Application of the steel frame weight minimizing method resulted in a three-fold increase in the number of members having a stress ratio of 0.8 to 1.0.

Figure 10 shows a distribution chart of the story shear force in the secondary design (analysis of seismic response). This chart compares cases in which the damper brace was applied and not applied and the vertical axis represents the height of the structure and the horizontal axis represents the story shear force (indicated while using the story shear force at the base in the case in which the damper brace was not applied as 1). As shown in this figure, the story shear force was reduced throughout the height of the structure when the damper brace was applied. In particular, a reduction by 20 to 30% was attained at the base. This reduction was due to the above-mentioned seismic response control effect of the damper brace. In this way, an efficient anti-seismic design was realized by the installation of the damper brace, which significantly reduced the seismic response. In this result, all the generated stress of steel frame members excluding damper braces was less than the allowable stress in the secondary design.

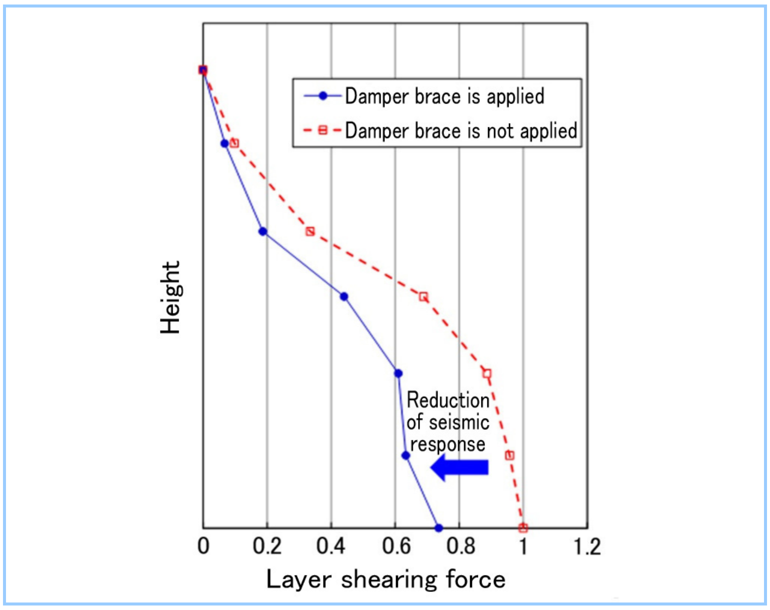


Figure 10　Distribution of story shear force in secondary design
This chart represents the distribution of the story shear force of the structure in analysis of seismic response of the secondary design (indicated while using the story shear force at the base in the case in which the damper brace was not applied as 1). The story shear force was reduced all over the height of the structure due to the seismic response control effect of the damper brace.

6. Conclusion

For steel structures such as plant support structures, MHI has established a design method combining a steel frame weight minimizing method that can simultaneously minimize the weight of many steel frame members with a seismic response control design technology that attains a significant reduction of the seismic response using seismic response control devices having a seismic energy absorption effect. The application of this design method allows rationalization of the plant support steel frame and also reduction in the scale of the foundation structure that supports the steel frames due to the seismic response reducing effect. In this way, the rational design of whole structure including the steel frames and the foundation that simultaneously realizes both seismic resistance and economic efficiency is attained and an environmentally friendly design also becomes possible due to the reduction of material usage for the steel frames and foundation. MHI is willing to extend the application of this design technology to other products in the future.