Experiment, Analysis and Evaluation Techniques to Protect Structures from Windstorms and Massive Earthquakes

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Wind-resistant and anti-seismic designs have been applied to structures for years. Technologies to evaluate aerodynamic stability and seismic resistance, as well as to prevent problems, have been further advanced on a daily basis because of the more complex and larger structures and larger earthquakes we have to consider. In aerodynamic stability evaluations, a hybrid technique of wind tunnel testing, CFD analyses and simple aerodynamic stability evaluation is promoted. In seismic resistance evaluations, vibration control devices that take advantage of the elasto-plastic characteristics of steel have been developed, and application to real structures has been promoted as a vibration control design that can endure massive earthquakes. This report will outline examples of experiments, analyses and evaluation technologies, as well as applications to real structures.

1. Introduction

For aerodynamic stability evaluations, MHI has the techniques of wind tunnel testing, analysis such as CFD (Computational Fluid Dynamics) and vibration control measures. For seismic resistance evaluations, MHI has the techniques of testing (static/dynamic) and analysis, in addition vibration control measures. MHI has been evaluating aerodynamic stability and seismic resistance for large-scale structures such as bridges, stacks and the supporting steel-frames of plant equipment by using these techniques to improve the safety and reliability of these products. Recently, MHI has been promoting the development of more reasonable evaluation methods and design techniques. For aerodynamic stability, we developed a hybrid technique utilizing wind tunnel test techniques, CFD analytical techniques and simple aerodynamic stability study methods. Research on anti-seismic techniques has rapidly accelerated after the Great Hanshin Earthquake. MHI developed vibration control devices and tested the performance of the products to develop more reasonable anti-seismic structures. Considering the damage caused by the 2011 Great East Japan Earthquake, anti-seismic design has become more important.

2. Aerodynamic stability evaluation technology

What is essential in the economical and reasonable construction of safe and secure structures is aerodynamically stable design that is comprehensively quick, inexpensive and accurate, without omitting any of these factors. MHI has used its techniques of wind tunnel testing, vibration control measures and vibration response monitoring accumulated through long-span bridge construction projects such as the Honshu-Shikoku Bridge. In addition, as shown in **Figure 1** of an aerodynamic stability evaluation flow, MHI has used CFD analysis and aerodynamic stability studies using simple wind tunnel testing (S-VFD: Super-Visualized Fluid Dynamics)[1] before large-scale wind tunnel testing to pursue higher reliability and lower cost of aerodynamic stability evaluations. Our evaluation technology is outlined below with some examples from recent projects.

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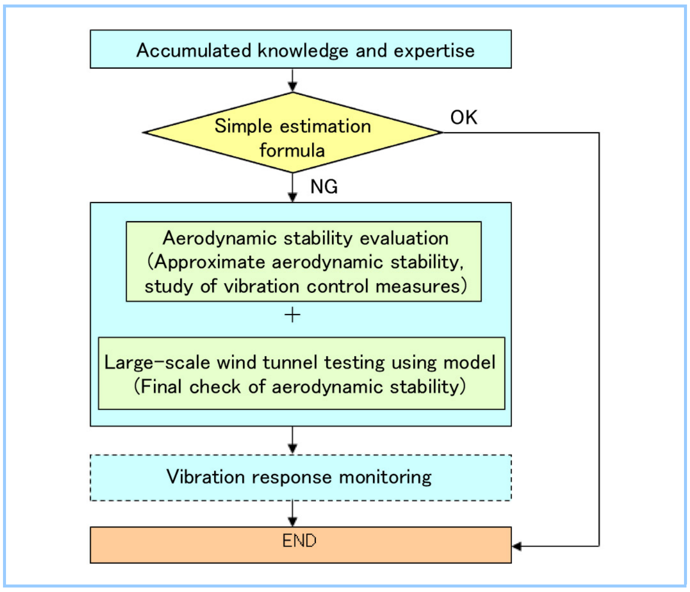


Figure 1 Wind-resistance evaluation flow
We pursue higher reliability and lower cost by integrating large-scale wind tunnel testing, S-VFD and CFD.

2.1 Bridges

In Japan, long-span bridge construction projects have reached a point of pause and the focus has shifted to isolated island bridge projects. Many of the island bridges are narrow box girder bridges with single lanes. These bridges have a specific geometry of a high slenderness ratio in the axial direction (i.e., the span/width of girder) and a low cross-section ratio of girders (i.e., the width of girder/height of girder). Wind-resistant design is critical for such bridges because they may be subject to vertical self-induced vibrations known as galloping, even at lower wind velocities.

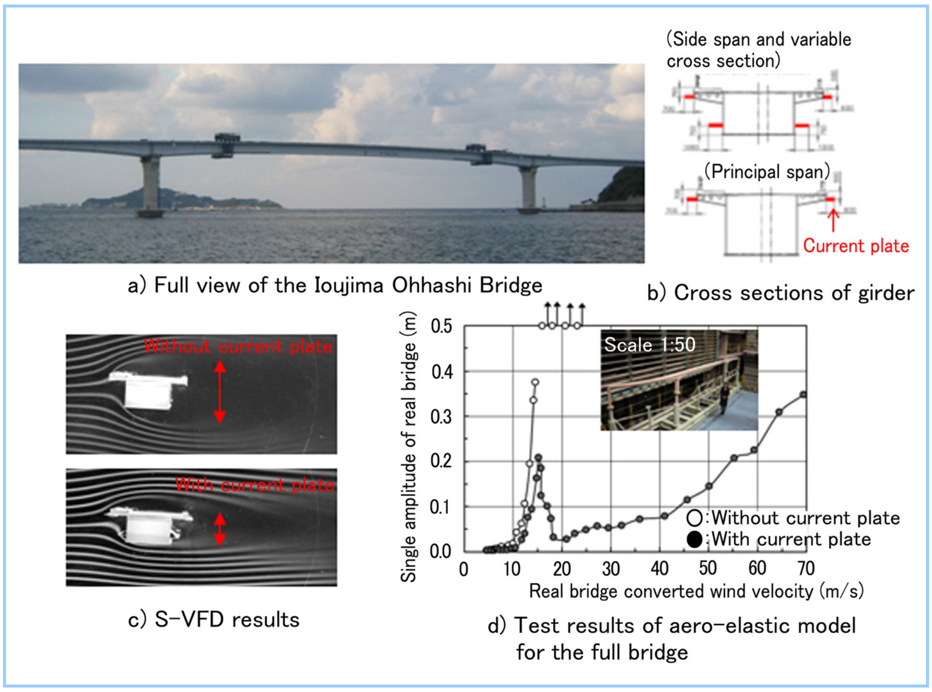


Figure 2 Aerodynamic stability evaluation of the Ioujima Ohhashi Bridge
a) Full view, b) Ultimately adopted girder cross-section diagrams, c) Installation of current plates can reduce the vortex and improve aerodynamic stability, d) The effect of the current plates was verified quantitatively.

One example of an isolated island bridge project is the Ioujima Ohhashi Bridge (240 m span) shown in **Figure 2**a)[2]. In this project, the total cost of the aerodynamic stability study could be reduced by omitting the 2D model test conducted in the conventional procedure based on past vibration countermeasures. Specifically, the installation positions of the current plates were identified based on past records, then the airflow around the girder sections was visualized by

S-VFD as shown in Figure 2c) to determine the most effective installation positions of the plates. Next, the vibration response was measured through testing using the aero-elastic model for the full bridge shown in Figure 2d) to evaluate the quantitative aerodynamic stability. The wind velocities and vibrations were monitored during the construction stage. Vibrations projected by the wind tunnel testing occurred, but the aerodynamic stability of the bridge was acceptable.

In overseas trends, there is a rush to construct social infrastructure in China, and there are strait bridge construction projects planned in East Asia and Europe. MHI's aerodynamic stability evaluation technology accumulated in Japan will be used in bridge projects worldwide. **Figure 3** shows an example of MHI's evaluation technology used in the construction of the Nanjing 3rd Bridge in China.[3,4] The photo on the left shows the test using the aero-elastic model for the full bridge, where aerodynamic stability during and after construction was tested by simulating the wind around the installation points in a wind tunnel. The photo on the right shows the wind tunnel test during the main tower construction. At the construction stage of the main towers, the towers were in a cantilever condition with a fixed base, and were structurally flaccid. In addition, the positions of the scaffolding and cranes for construction had an effect on the aerodynamic stability. Detailed models of the construction equipment were duplicated to test the aerodynamic stability and the results were applied to the construction engineering of the real bridge. This bridge is the first long-span bridge with steel main towers in China, and the aerodynamic stability was carefully studied. MHI's test data were selected for the final design after comparison with test data from Chinese universities. In this manner, based on the budget, wind risks and ROI, we can select appropriate test methods from our abundant study lineup of aerodynamic stability projects accumulated in Japan.

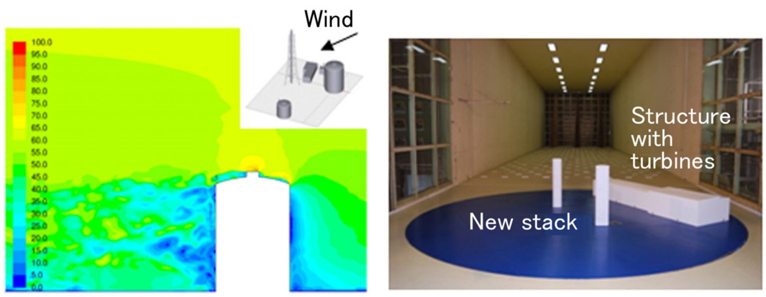
Figure 3 Example of wind tunnel test for overseas bridge construction （Nanjing 3rd Bridge in China）

2.2 Smokestacks

Smokestacks higher than 60 m must be certified by the Minister of Land, Infrastructure and transportation. Particular stacks, such as aesthetic stacks with peculiar figures or stacks to be constructed in parallel with others within narrow areas, are not covered by the regulations or guidelines. These stacks need to be verified for aerodynamic stability in wind tunnel testing. **Figure 4**a) shows a CFD example for a preliminary study of the impact of the turbulent airflow generated near the gas tank on the aerodynamic stability of the newly constructed smokestack. Figure 4b) shows an example of wind tunnel testing to verify the aerodynamic stability of an aesthetic stack constructed in parallel with another stack.[5] With these steps, the cost of the aerodynamic stability study can be reduced without sacrificing the reliability by identifying concerns by CFD before ultimately confirming them in testing.

2.3 Cranes

As shown in **Figure 5**a), jib cranes consist of slender components, which could result in the generation of vibrations, even at typical lower wind velocities. Even small vibrations, if numerous, can cause cracks at the weld zones as shown in Figure 5b), resulting in concerns about serviceability. Figure 5c) shows an example of prevention, where a spiral rope is wrapped around the component. The wind velocity and vibration monitoring ultimately showed that no harmful vibrations had occurred.



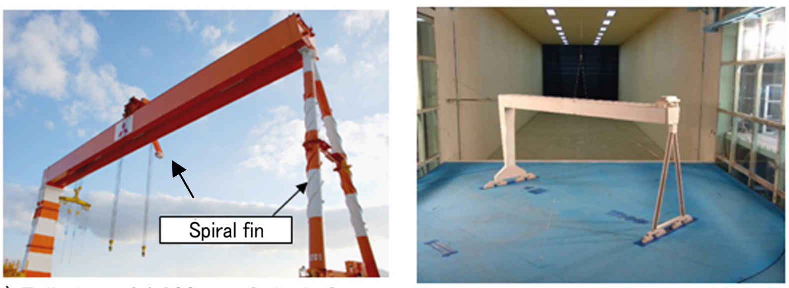
a) CFD (preliminary study example)   b) wind tunnel test (Final check example)

Figure 4 Aerodynamic stability evaluation considering the impact of structures near smokestack
a) Study example of impact of turbulent airflow caused by a nearby gas tank on the smokestack, b) Example of wind tunnel test to evaluate aerodynamic stability if new smokestack is constructed in parallel.

a) Full view of jib crane   b) Crack occurrence   c) An example of vibration control measures

Figure 5 Vibrations of jib crane components

For large-scale equipment such as cranes, wind-load design as well as wind-resistant design is essential because aerodynamic vibrations could be generated at lower wind velocities than the design wind velocity due to the bulky components. One example of an aerodynamic stability evaluation for a large-scale crane is the 1,200 ton Goliath Crane shown in **Figure 6**a), which began operation in 2008 at MHI's Kouyagi Shipyard in Nagasaki. The crane consists mainly of a girder, a square support and cylinder supports. At the design phase, the generation of various vibrations at each component was predicted. MHI then studied the aerodynamic stability with a whole 3D model and vibration control measures, and evaluated the quantitative effects of the measures (Figure 6b). The results were introduced in the vibration control design. In addition, MHI ensured the safety of the crane through real wind response monitoring and confirmed the effectiveness of the vibration control measures.



a) Full view of 1,200 ton Goliath Crane at MHI's Kouyagi Shipyard.   b) Wind tunnel test with aero-elastic model for the full crane

Figure 6 Example of aerodynamic stability evaluation of Goliath Crane

2.4 Other

Figure 7 shows an example of wind-resistant design for the world's highest Ferris wheel (165 m height) in Singapore.[6] We conducted a close investigation of the wind loads through wind tunnel testing using a sectional model of the Ferris wheel, because wind loads are the dominant concern for structures in Singapore, which is free from large earthquakes. This helped to cut the steel weight by reducing the wind loads by 25% from the design value estimated by the conventional guidelines, meeting both economic and safety demands.

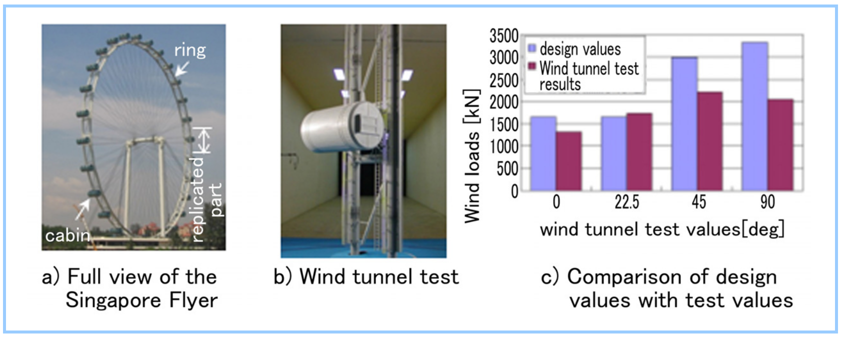


Figure 7 Example of wind-resistant design of Ferris wheel
a) Full view, b) Wind tunnel test, c) Wind loads could be cut by 25% (90-deg wind direction) from the initial design value by using the wind tunnel test results.

3. Seismic resistance evaluation technology

After the Great Hanshin Earthquake, MHI developed reasonable design techniques to improve a structure's seismic resistance, while maintaining the robustness of the main components. For mid- to long-span arch and truss bridges and support frames for heavy structures such as plants, components with energy absorption ability (vibration control devices that can absorb energy) are installed apart from the main components of the whole structure system. In this section, test results showing the stable hysteretic property of this vibration control device (an axial-yield type buckling-restrained brace, referred to as a damper brace hereinafter) and the vibration control effects of being installed to a whole structural system are mentioned below.

3.1 Overview of damper braces

Damper braces are hysteresis dampers that take advantage of the elasto-plastic characteristics of steel. Damper braces are commonly installed instead of braces on truss structures. Damper braces consist of a core member that can absorb elasto-plastic energy by axially yielding to axial force (cruciform section: low yield point steel with yield stress σy = 225 MPa (LY225)), a restrained member (rectangular steel pipe) placed next to the core member with space to restrain lateral buckling and twist buckling of the core member due to compression force after the yield and an intermediate member (circular steel pipe) that links damper members composed of the core member and restrained pipe at both ends of the brace (see **Figure 8**a).

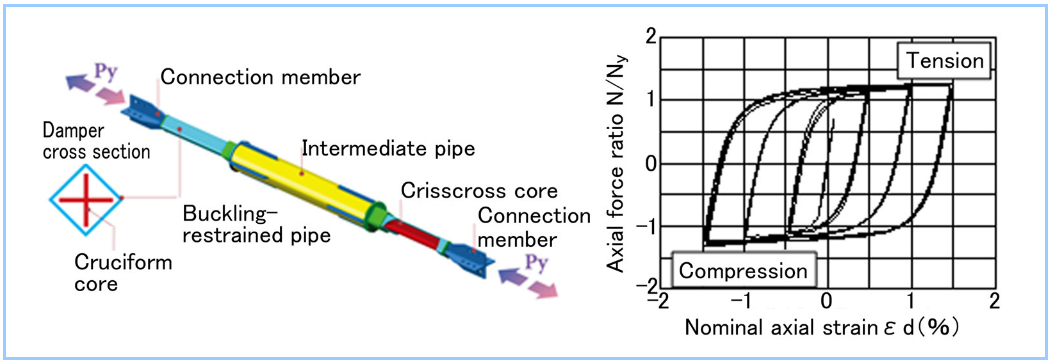


Figure 8 Overview of the damper brace structure and hysteresis property
a) A damper brace consists of a cruciform core member, a buckling-restrained pipe, an intermediate member and a connection member. b) The cruciform core shows axial-yielding, but the buckling is restrained by the stiffening effect of the buckling-restrained pipe under compression force, showing similar elasto-plastic behavior under tension force.

The stable plastic deformation characteristics and energy absorption performance (cyclic plastic deformation capacity) of the damper was confirmed by static load testing as shown in Figure 8b)[7] and seismic-response vibration testing using a scaled specimen and shaking table as shown in **Figure 9**[8]. In the dynamic vibration testing, the performance was compared with a specimen with a conventional H-shape brace. The conventional design showed unstable behavior due to the buckling of the H-shape brace, but the vibration control design with the damper braces showed stable energy absorption performance in cyclic elasto-plastic regions during earthquakes.

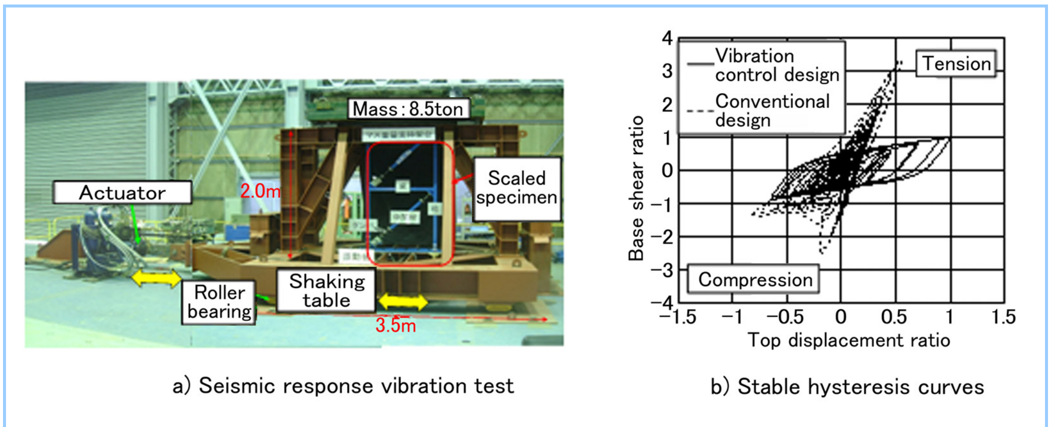


Figure 9 Seismic response vibration test with scaled specimen
a) Seismic response vibration test with scaled specimen. A frame test specimen and mass were placed on a shaking table and vibrated by an actuator to apply seismic vibrations, b) The vertical axis is the ratio of the maximum base shear of the vibration control design, and the horizontal axis is the ratio of the maximum displacement of mass.

3.2 Reasonable design for real bridges with damper braces

The target was a medium-span upper-deck type steel arch bridge with a length of 140 m (span: 20＋100＋20 m), a main truss distance of 7.35 m and a height of 20 m as shown in **Figure 10**a). The damper braces were placed at the brace positions of the vertical truss surfaces as X-directional (bridge axis direction) vibration control countermeasures indicated as bold lines in Figure 10a), on the end piers and on the bottom truss surfaces parallel to the arch ribs as Y-directional (vertical to the bridge axis) countermeasures. Figure 10b) shows a comparison of the stress ratios (= applied stress / allowable stress; if stress ratio > 1.0, stress verification result is fail) of the girders, arch ribs and end piers in the elasto-plastic seismic response analysis. The results show the successful rationalization of anti-seismic design because the stress ratio of each element due to the damper braces is less than 1.0, where the stress verification result was a failure under the conventional design.

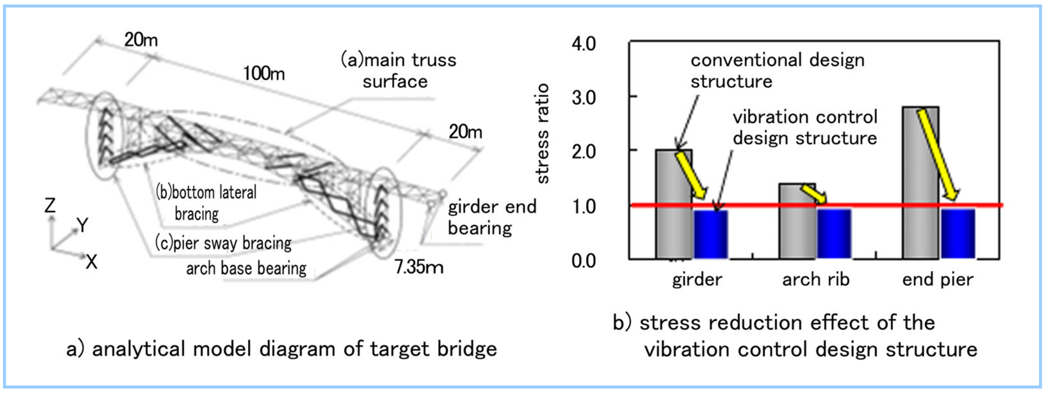


Figure 10 Confirmation of vibration control effect through elasto-plastic seismic response analysis
a) Damper brace installation positions are indicated as bold lines, b) The vibration control design shows a significant response reduction effect. Components with a stress ratio > 1.0 under the conventional design showed < 1.0 under this vibration control design, passing the stress verification test.

4. Conclusion

To ensure aerodynamic safety and the anti-seismic safety of structures, MHI has used CFD and other analytical methods, in addition to various tests using large models and evaluation techniques to improve the reliability of aerodynamic stability evaluations, to develop vibration control technology and to apply the results to real machines for aerodynamic stability evaluations. Similarly, MHI has developed vibration control devices that take advantage of the elasto-plastic characteristics of steel and has identified seismic-response characteristics for seismic resistance evaluation technology. With these tests and analytical technologies, MHI has developed vibration control measures that can deal with massive earthquakes. Damage investigations concluded that some damper braces installed on plant supports seemed to have prevented damage during the Great East Japan Earthquake

In the midst of the further promotion of the rationalization of aerodynamic stability and anti-seismic and changing levels of external forces, MHI will improve the reliability of the aerodynamic stability and seismic resistance of structures to be built not only in Japan, but also worldwide, and will continue to conduct technical development to protect structures from natural external forces such as windstorms and massive earthquakes.

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