Technical Topic

Experimental Technologies and Facilities to Clarify Structural Mechanisms

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Abstract

Under the carbon neutrality policy, more challenging structural development is required. Nippon Steel Corporation has developed experimental technologies for new structures ranging from large-scale facilities to specialized equipment. We will introduce them with the aim of contributing to the development of the construction market.

1. Introduction

To offer safe and practical steel structure to the construction market, it is essential to pursue structural practicality through clarification of the structural mechanism. Under the Japanese government's policy toward a carbon-neutral society, the demands for structural practicality continue to increase. Although the advancement of calculators accelerates numerical simulation technologies, experiments are inevitable to realize new technologies and challenging structure and verify their safety. Therefore, the results of appropriately performed experiments will validate numerical simulation technologies. The Nippon Steel group owns large-scale facilities, such as tensile testing machines for which the maximum appliable load is as high as 80 MN and reaction floors whose length can reach up to 40 m, and multiple specialized facilities. We also constructed a new facility to reproduce a heavy rainfall disaster at a levee. Thus, we have been improving the technologies to innovate new structure. This paper introduces experimental technologies of the Nippon Steel group with the aim of contributing to further expansion of the construction market.

2. Outline of Experimental Technologies

Figure 1 summarizes experimental technologies in the construction sector. Basic technologies are related to tension (a), compression (b), flexure (c), and shear (d). In multiple loading (e) in which multiple such loads are applied, a single type of material, such as shaped steel and steel pipe, or partial structure, such as a cross-frame and T-frame, are tested. Other experimental technologies are used for: Shaking experiments (f) in which seismic force is applied; impact (falling weight) (g) in which impact force is applied; and experiments in which soil pressure (h) or water pressure (i) is applied.

Most of these experimental facilities are located at two centers: RE Center in Futtsu City, Chiba, (hereinafter, "Futtsu center") and Hasaki Research and Development Center in Kamisu City, Ibaraki (hereinafter, "Hasaki center"). **Figure 2** outlines the locations of the main testing facilities/equipment and reaction walls at the two centers. The Hasaki center has a large L-shaped reaction wall (Fig. 2-R1) and extra-long reaction floor (Fig. 2-R2). The Hasaki center mainly assesses and analyzes properties of full-scale structures and is used to pursue and study new experimental methods. The Futtsu center has specialized equipment that can be used to evaluate improved ideas, which are formed based on the study results obtained at the Hasaki center using full-scale facilities/equipment, on a parametric basis and that are used to perform scaled-down experiments promptly. The Futtsu center also has a new Geo Lab and that has specialized equipment (e.g., water disaster simulator) designated for the study of in-soil structures.

3. Specific Experimental Technologies and Facilities/Equipment

Specific experimental technologies are described below according to the classifications in Fig. 1 along with the facilities/equipment involved. Please see **Table 1** that shows the outline. Note that, in this paper, general material tensile tests and Charpy tests are omitted.

3.1 Structural experiments

(a) Tension

One main mechanical property of steel materials is tensile strength, so naturally we have many tensile testing machines. The maximum appliable load is as high as 80 MN. In the construction

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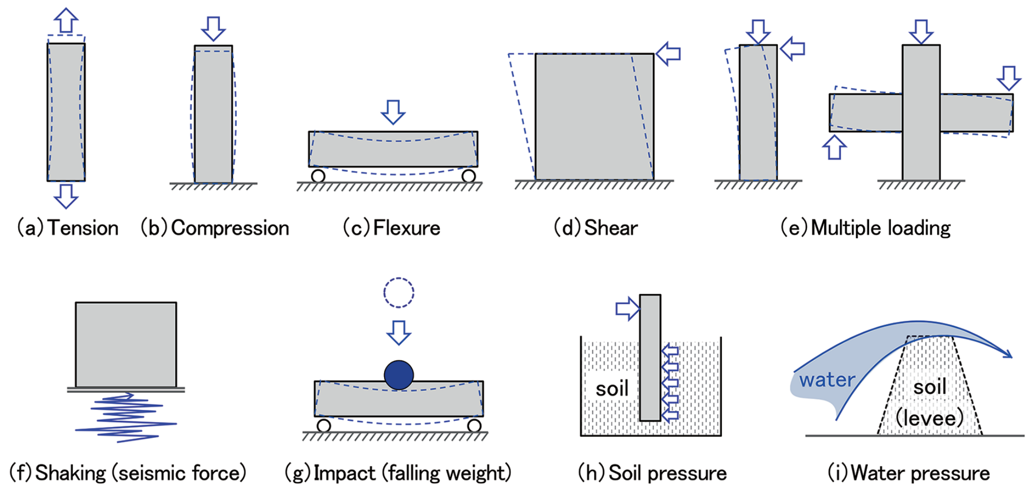
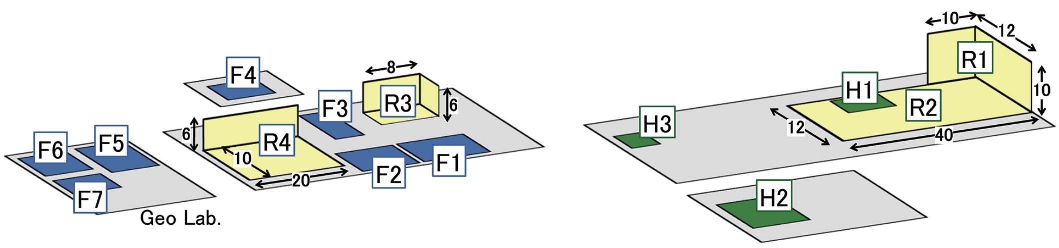


Fig. 1 Types of structural experiments



(a) Research & Engineering Center (Futtsu) (b) Hasaki Research & Development Center
R1 to R4 indicate reaction floors and walls. Other symbols indicate the location of the test equipment.

Fig. 2 Layout of testing facilities

sector, the performance of sections joined by welding or bolts needs to be correctly evaluated, in addition to the tensile strength of materials. Example experiment targets are welds between H-beam flange ends and a column (**Fig. 3**) and a high-strength bolted friction joint (**Fig. 4**).

(b) Compression

As a characteristic of structural experiments in the construction sector, the properties of structures, i.e., shaped steel materials, need to be evaluated, in addition to steel materials. **Figure 5** shows a compression test of lightweight gauge members. When the structural performance of members consisting of such thin steel plates is evaluated, expertise to reinforce them such that they will not break at small points (loading points and support points) determines success or failure of the tests.

(c) Flexure

Products used in the construction sector, such as footings, piles, columns, beams, floors, roofs, and walls, are long and thereby high bending stress works on them due to self-weights, earthquakes, winds, soil pressure, and water pressure, etc. We perform various types of flexural tests to reproduce such conditions.

When the working load is 150 kN or smaller, for example, in the case of small-diameter steel pipes used for lighting poles and thin and lightweight channel steel, the equipment shown in **Fig. 6** is used. The support span of a test specimen is 4 m and a panel-shaped test specimen with a width of up to 1.8 m can be tested. The equipment can also perform fatigue tests at the loading speed of up to 1 Hz.

To evaluate large products among steel pipes and shaped steel, the equipment that can apply a load up to 5 MN shown in **Fig. 7** is used. This equipment has a test bed that can move in the longitudinal direction of a material and it is easy to place a long product under the loading jack. This equipment can test a test specimen for which the support span is up to 6 m and the width is up to 1 m.

When longer products are tested, reaction floors and walls are used. **Figure 8**(a) shows a flexural test at the Hasaki center using the reaction floor (Fig. 2-R2) targeting a steel pipe pile for which the diameter was 1.6 m and the distance between the support points was 16 m. Even the flexure performance of three connected steel sheet piles can be evaluated using this reaction floor (Fig. 8(b)).

Long stroke (1.2 m) cyclic flexural experiments can be performed at a load of up to 10 MN. In the flexural experiment shown in **Fig. 9**, long-stroke bending stress was repeatedly applied to a large H-beam to check the structural performance of a weld provided at the center of the test specimen. The fracture mode in the end can be observed, which makes it possible to set an appropriate safety factor and also to improve products boldly.

As a special flexural test, **Fig. 10** shows loading method using a water pressure bag.[*1] For composite segments that form tunnel walls as composite structure consisting of steel shells and concrete, if a concentrated load is applied, the inner concrete may be partially broken, which makes it impossible to check actual phenomena. The method in which force is applied to the test specimen via a water pressure bag can properly reproduce soil pressure.

[*1] Property of Nippon Steel Eco-Tech Corporation.

Table 1 Experimental techniques and equipment

Fig. No.	Experimental Technologies		Experimental category										Research Site	
			Main action force (◎), possible action force (○)									work-abilty	Futtsu	Hasaki
		Facilities	(a) tension	(b) com-pression	(c) flexure	(d) shear	(e) multiple loading	(f) shak-ing	(g) impact	(h) soil pres-sure	(i) water pres-sure			
3	Tensile test of welds between beam ends and column	General-purpose larger testing equipment (20 MN, 80 MN)	◎										○	
4	Tensile test of a high-strength bolted friction joint	General-purpose testing equipment (4 MN)	◎	○									○	
5	Compression test of lightweight gauge members	General-purpose testing equipment (2 MN)	○	◎										H3
6	Cyclic flexural test of small diameter pipe	General-purpose smaller testing equipment (150 kN)		◎	◎		○						F4	
7	Flexural test of single sheet pile	General-purpose testing equipment (5 MN)		◎	◎		○						F1	
8 (a)	Flexural test of long steel pipe pile	Long reaction floor (Total length 40 m)			◎		○							R2
8 (b)	Flexural tests on connected steel sheet pile wall	Long reaction floor (Total length 40 m)			◎		○							R2
9	Cyclic bending test of full-scale members	Long stroke cyclic flexural experiment (10 MN)		○	◎		○							H1
10	Tunnel segment flexure test using a water pressure bag	Water pressure bag-loading equipment			◎					○			*1	
11	Wall panel shear test	Panel testing equipment (300 kN)				◎							F3	
12	Combined loading test of steel pile	Large L-shaped reaction wall	○	○	○		◎							R1
13	Cross-frame loading test of column-beam joint structure	Cross-frame load testing equipment (10 MN)		○	○		◎						F2	
14	Cross-frame loading test of column-beam joint structure	Large L-shaped reaction wall	○	○	○		◎							R1
15	T-frame loading test of column-beam joint structure	Large L-shaped reaction wall	○	○	○		◎							R1
16	Flexural test of building floor substructures	Long reaction floor (Total length 40 m)			○		◎							R2
17	Seismic shaking tests of a reservoir levee	Biaxial shaking table testing equipment						◎		○	○			H2
18	Falling weight test of rockfall protection wire mesh	Falling weight test equipment							◎				*2	
19	Compound loading tests on steel pipe piles	Pile in soil behavior simulator		○	○		◎			◎			F7	
20	Overflow and scour test of river levee	Water disaster simulator								○	◎		F5	
21	Steel pipe pile driving test	Pile installation simulator		○								◎	F6	
22	Experiments to evaluate bearing strength of steel pipe piles	Full-scale test yard at RE Center	○	○	○							◎	○	
23	Performance evaluation test of seismic isolation devices	Seismic isolation device testing equipment		○	○	○	◎						*3	
24	Loading test ensuring load straightness	Horizontal testing equipment with rails		◎	◎		○						*4	
25	Acoustic visualization test	Acoustic visualization camera system	other										mobile	
26	Vibration visualization test	Scanning laser-doppler vibrometer	other										mobile	

Properties of *1 Nippon Steel Eco-Tech Corporation, *2 Nippon Steel Metal Products Co., Ltd., *3 Nippon Steel Engineering Co., Ltd., *4 Nippon Steel Technology Co., Ltd.

(d) Shear

Various technologies use the walls of structures to absorb seismic force. As a technology for low-rise houses, we have been developing lightweight, high-earthquake-resistance wall structure by processing thin steel plates. **Figure 11** shows specialized equipment for it. The equipment can apply cyclic shear force of up to 300 kN to a horizontally-placed wall. It has a pantograph to reproduce actual force and it can apply vertical force to the wall at the same time.

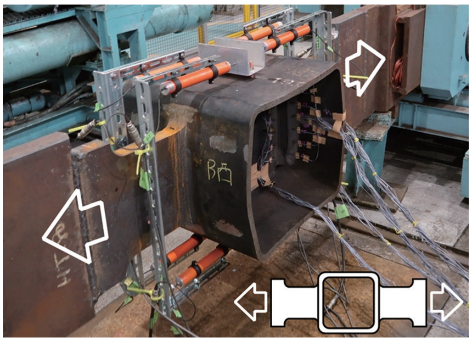


Fig. 3 Tensile test of welds between beam ends and column

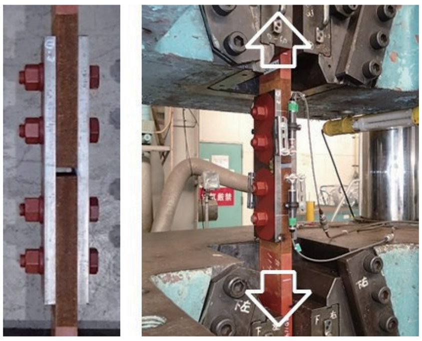
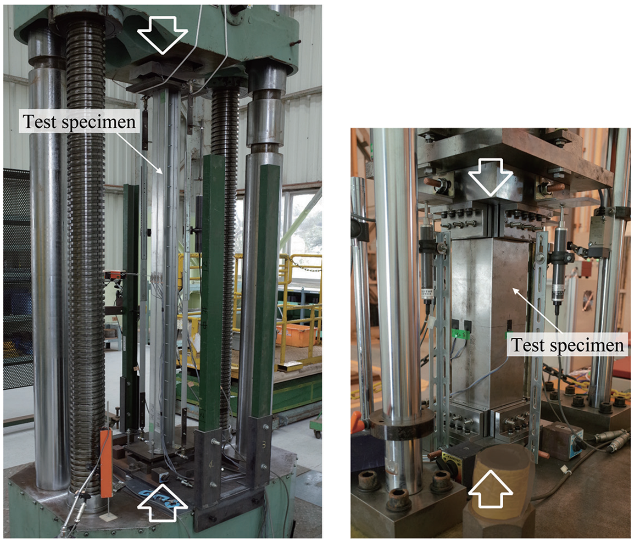


Fig. 4 Tensile test of a high-strength bolted friction joint



(a) Long column compression test (b) Stub column test

Fig. 5 Compression test of lightweight gauge members

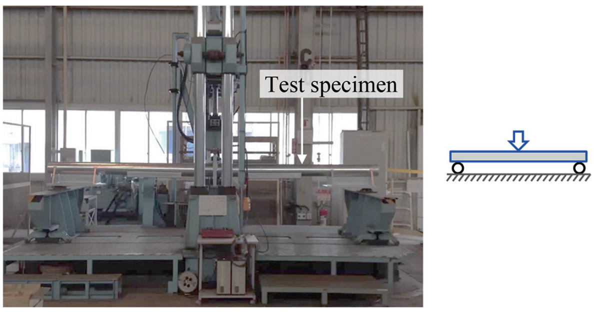


Fig. 6 Cyclic flexural test of small diameter pipe

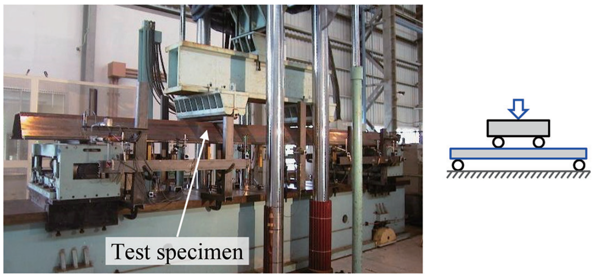
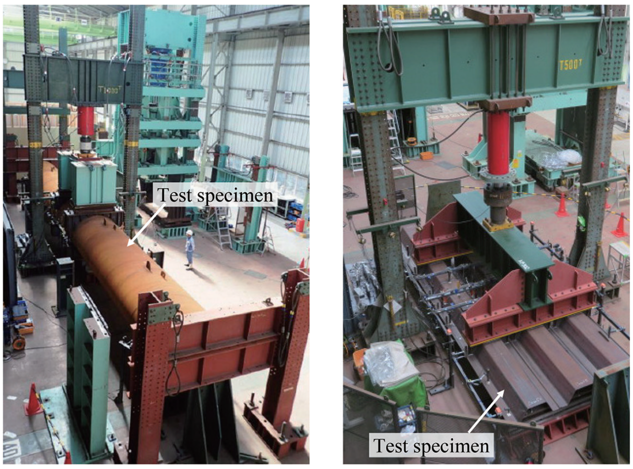


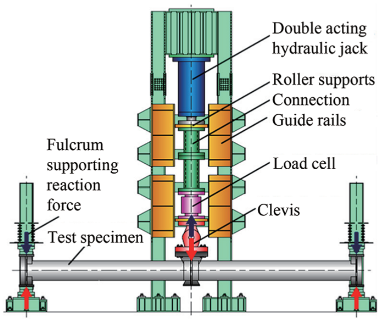
Fig. 7 Flexural test of single sheet pile



(a) Steel pipe pile (φ1.6 m, L=16 m) (b) Hat-type steel sheet pile (3 sheets connected)

Fig. 8 Flexural test on long reaction floor

(a) Testing equipment



(b) Equipment configuration

Fig. 9 Long stroke cyclic flexural experiment

(e) Multiple loading

The sections above introduced the experimental technologies to apply a single type of external force. Multiple external forces work on actual structures simultaneously as shown in Fig. 1 (e). Experimental technologies to reproduce such forces appropriately are described below.

Figure 12 shows a combined loading test targeting the head of a pile using the reaction wall (Fig. 2-R1). To reproduce an actual phenomenon, the structure was installed upside down on the reaction floor.

Figure 13 shows specialized equipment that tests the cross-frame of column-beam joint structure. The equipment can apply axial force of 10 MN to the column and bending stress of 3 MN to the beam at the same time. Cyclic loading that reproduces seismic force statically is possible and the results of such tests show structural properties as shown in Fig. 13 (b). To test larger structure that this equipment cannot accommodate, the reaction wall (Fig. 2-R1), etc. are used. **Figure 14** shows a loading test of the cross-frame of a column-beam joint structure and **Fig. 15** shows loading to the T-frame.

Needs for full-scale tests are growing. **Figure 16** shows the reproduction of loads to a building floor substructure (Fig. 16 (a)) using multiple jacks (Fig. 16 (b)). Because the test specimen was as large as 12 m, concrete was poured on the reaction floor (Fig. 2-R2) to complete the test specimen (Fig. 16 (c)) and then loads were applied as the test processes.

(f) Seismic shaking

Figure 17 (a) shows seismic shaking for a 1/25 levee model using a shaking table with two actuators for the horizontal and vertical axes. The size of the shaking table is 2 m × 3 m and the horizontal excitation is applied in the long-side direction. The equipment with a water supply and drainage function can reproduce earthquake damages when the reservoir becomes full. The seismic waves observed at Kobe after the Great Hanshin and Awaji Earthquake and at Kamaishi after the Great East Japan Earthquake, etc. can be input (Fig. 17 (b), etc.)

(g) Impact force

To evaluate impact force, such as impacts by falling stones, etc.

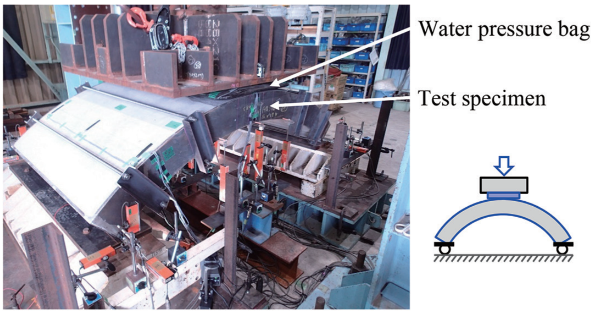
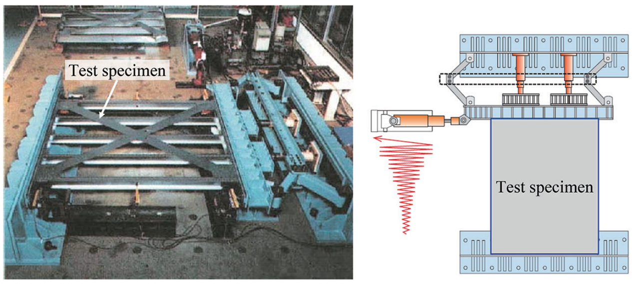
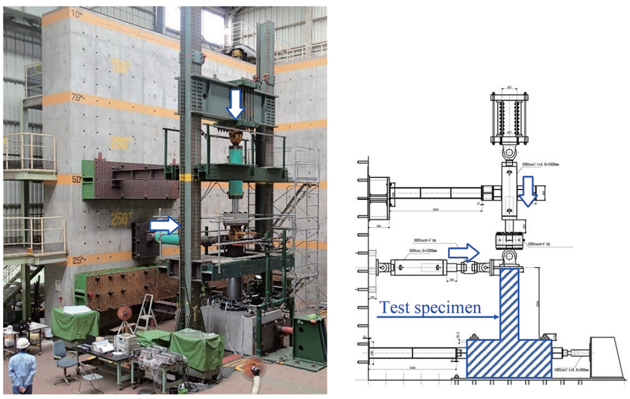


Fig. 10 Tunnel segment flexure test using a water pressure bag[*1]



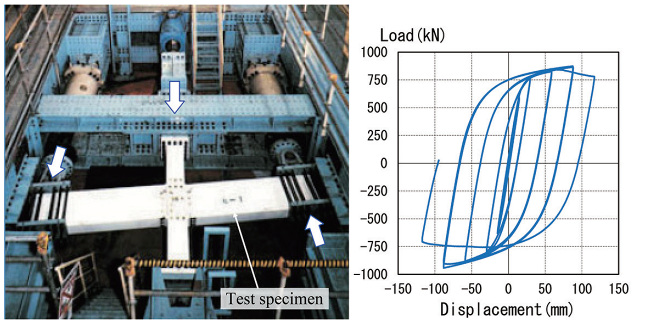
(a) Testing equipment **(b) Loading conditions**

Fig. 11 Wall panel shear test



(a) Testing equipment **(b) Loading conditions**

Fig. 12 Combined loading test of steel pile (installed upside down)



(a) Testing equipment **(b) Example of experimental results**

Fig. 13 Cross-frame loading test of column-beam joint structure

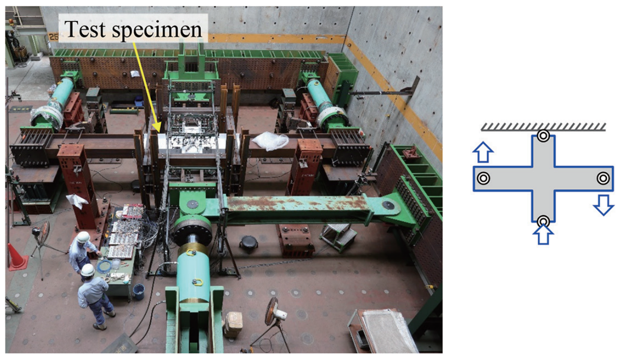


Fig. 14 Cross-frame test

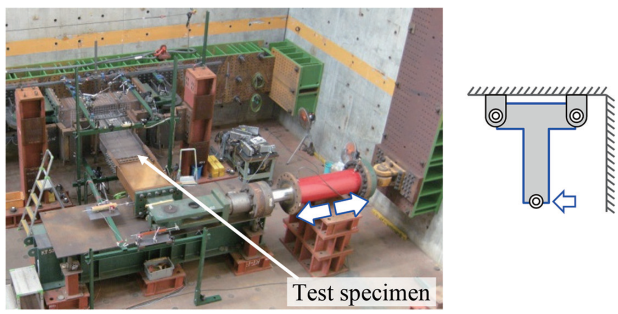
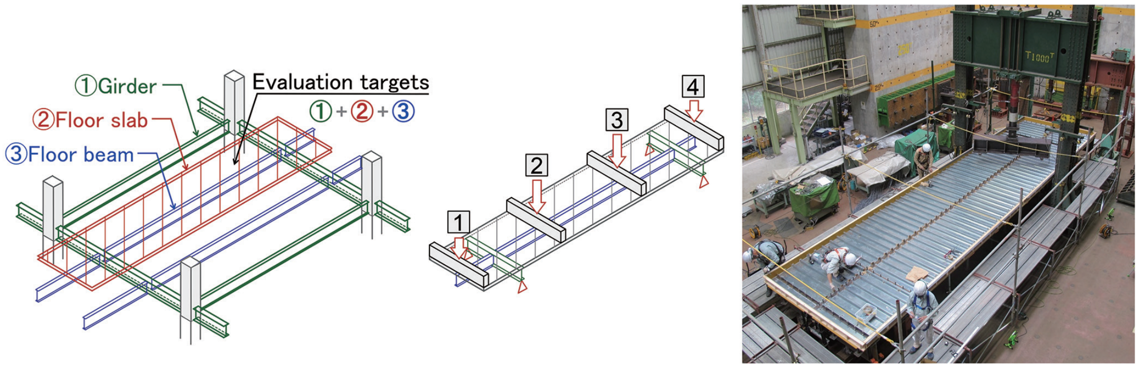
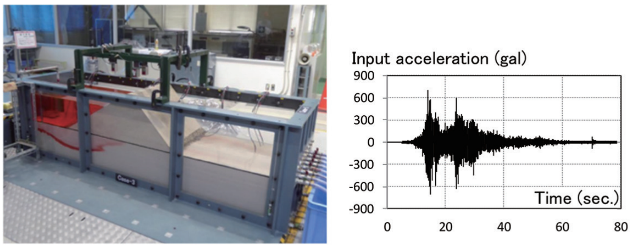


Fig. 15 T-frame test



(a) Evaluation targets (b) Loading condition (c) Test specimen construction

Fig. 16 Flexural test of building floor substructures



(a) Testing equipment (b) Example of input seismic wave

Fig. 17 Seismic shaking tests of a reservoir levee

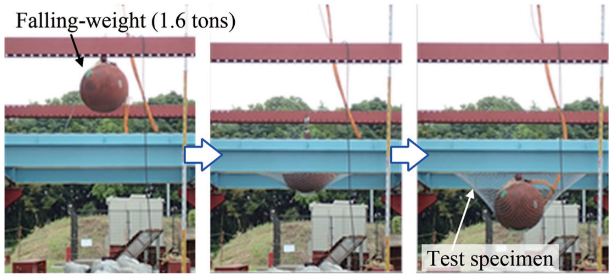
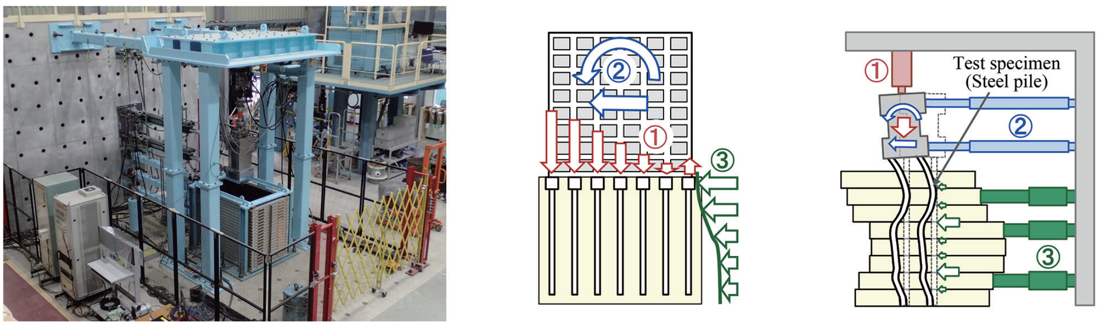


Fig. 18 Falling weight test of rockfall protection wire mesh[*2]



(a) Testing equipment (b) Loading condition (c) Replication of earthquake loading

①Vertical force caused by the building's own weight and inclination, ②Horizontal force and rotational moment caused by building mass inertia, ③Shear force caused by ground deformation

Fig. 19 Pile in soil behavior simulator

or by vehicle crashes, to be applied to structures, falling weight tests in which a weight is dropped from above are performed. **Figure 18** shows a test in which a 1.6-ton weight assuming that of a falling rock was dropped from a height of 3.8 m onto a wire mesh.[*2]

(h) Soil pressure

The 2016 Kumamoto earthquakes revealed invisible damage to foundation piles. Considering such new damage to buildings, we developed specialized equipment to simulate pile in soil behavior (**Fig. 19**(a)) in order to pursue phenomena occurring in piles during severe earthquakes. Ground deformation during an earthquake (Fig. 19(b)) is reproduced using three horizontal jacks and at the same time three forces in the vertical, horizontal, and rotational directions can be freely applied to the pile head (Fig. 19(c)). This equipment can reproduce any stress and deformation condition occurring on a foundation pile during a severe earthquake.

(i) Water pressure

Typhoon Hagibis in 2019 wreaked terrible damage due to breaches of the Chikuma and Abukuma river levees. To demonstrate river levee collapse and study effective reinforcement methods, we developed a water disaster simulator (**Fig. 20**) as specialized equipment. The water level on the back of an approximately 1/15 levee model is increased to observe levee breach behavior at the time of overflow from the side (Fig. 20(b)). In addition, two levees can be constructed side-by-side for comparison tests to see the effect of reinforcement, influence by differences in reinforcement types, and other factors (Fig. 20(c)). The water circulation system can continue supplying water at 1.2 m^3/min at maximum. The equipment can reproduce various phenomena that may occur on rivers comprehensively for short- to long-terms using the levee model.

[*2] Property of Nippon Steel Metal Products Co., Ltd. A weight of up to 2 tons can be dropped from a height of 8 m.

3.2 Constructability experiments

Construction methods applied to construction sites are also important targets of our research and development. For underground structures, such as steel pipe piles and steel sheet piles, in particular, the workability greatly varies depending on the ground type, so the workability needs to be checked. As specialized equipment for that purpose, we developed a pile installation simulator (**Fig. 21**). The relationship between the insertion pressure/running torque when a pile is placed and the bearing force after the placement can be evaluated. In addition, by combining an acrylic earth tank and the particle image velocimetry (PIV) technique, the influence of a pile on the ground can be visually analyzed.

To verify improvement ideas studied using reduced-scale model, full-scale test are required. The Futtsu center has an outdoor yard on the north side and construction tests of steel pipe piles and steel sheet piles and full-scale bearing force tests (**Fig. 22**) can be performed.

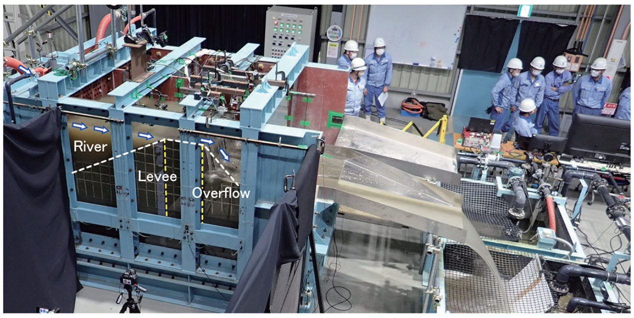
3.3 Other experiments

3.3.1 Technology to evaluate the performance of seismic isolation and vibration damping devices

Figure 23[*3] shows testing equipment to develop seismic isolation and vibration damping devices, such as equipment to prevent ground shaking during earthquakes from directly working on buildings and dampers for absorbing seismic energy. The equipment has a large vertical jack and a horizontal jack. The vertical jack reproduces the axial force of a column and the horizontal jack reproduces seismic force while retaining the axial force. The equipment can reproduce the axial force of a column of large distribution warehouses with four or so stories and can evaluate the performance of a full-scale seismic isolation and vibration damping device.

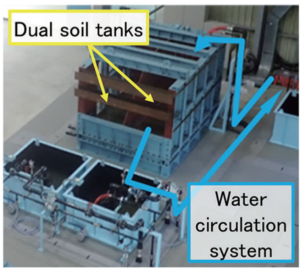
3.3.2 Loading experiment in which the straightness of external force was improved

The testing equipment[*4] shown in **Fig. 24** can apply horizontal



(a) Overflow experiment

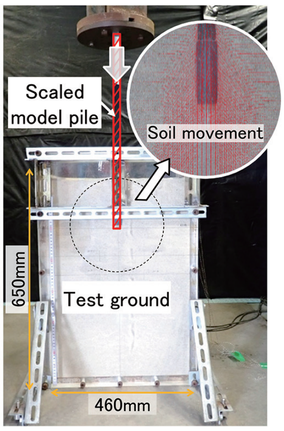
(b) Loss of levee due to flooding (Observed from the side of the levee)



(c) Dual soil tanks and water circulation system

Fig. 20 Water disaster simulator

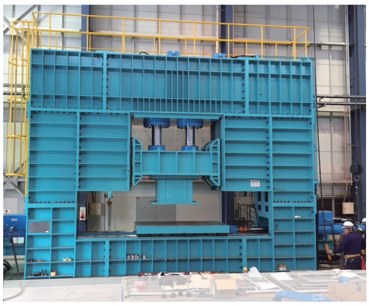
(a) Testing equipment



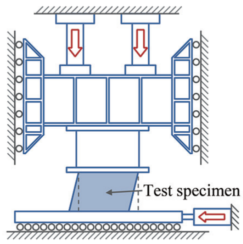
(b) Visualization tests

Fig. 21 Pile installation simulator

Fig. 22 Full-scale test yard at RE Center (Futtsu)



(a) Overall view of the equipment



(b) Schematic drawing of loading test

Fig. 23 Performance evaluation of seismic isolation devices[*3]

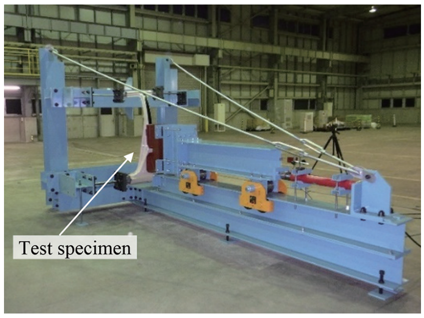


Fig. 24 Straight-line compression/flexural test equipment[*4]

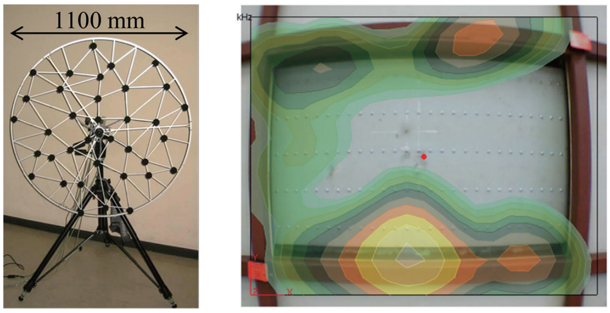
[*3] Property of Nippon Steel Engineering Co., Ltd.
[*4] Property of Nippon Steel Technology Co., Ltd.

force for which the straightness was improved. Although, for the testing equipment, the evaluation case of an automotive part is shown, construction structure can be evaluated when it is placed horizontally and the load is 200 kN or smaller.

3.3.3 Technology to visualize sound and vibration

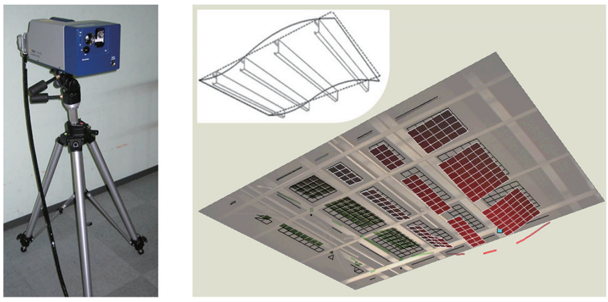
In the residential building sector, there are high needs for measures to combat sound and vibration. To satisfy such needs, we have been working to establish technologies by using technologies that are used in the automobile sector. **Figure 25** shows measuring equipment to visualize sound. By analyzing acoustic data measured by the randomly arranged 38 microphones (Fig. 25 (a)), the sources of the sounds at each frequency can be visualized. Figure 25 (b) shows measurement results that show 500-Hz sounds are being released from the gap between the flooring and floor beam.

Figure 26 shows measuring equipment to visualize vibration. The mechanism is the same as that of laser Doppler vibrometers. The equipment can measure (scan) planar vibration of the measurement target. Figure 26 (b) shows the measured vibration mode of the floor of a low-rise house under construction. The result shows that the 63-Hz mode, which poses a problem as heavy-weight impact sound, comes from the vibration in the direction perpendicular to the floor beam.



(a) Microphones **(b) Example of result (500 Hz)**

Fig. 25 Acoustic visualization technology



(a) Laser head **(b) Example of result (63 Hz)**

Fig. 26 Vibration visualization technology

4. Conclusion

Advancement of calculators and software has made it possible for numerical simulation technologies (computer-aided education (CAE)) to take part in structural experiments and the trend may accelerate also in the future. To obtain accurate results by CAE, the results of properly performed experiments are required. Needs for high-level experimental technologies may increase further in the future. In addition, the U.S. and Europe demand near-full-scale structural experiments to verify the safety of new technologies in some cases, so the scales of experiments may further expand. The Nippon Steel group will contribute to further advancement of the global construction markets including Japan through further improvement of technologies by drawing on our strengths of being able to use structural experimental technologies in other sectors, such as the automobile, energy, and shipping sectors.

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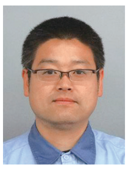

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