Support for restoration following the Kumamoto Earthquake in 2016 -Setting up laboratories at disaster recovery sites

1. Outline of Studies and Activities

Table 1 Major events related to the restoration of the 2016 Kumamoto Earthquake implemented under the authority of the national government.

April 14 and 16, 2016	Onset of the Kumamoto earthquake (observed two earthquakes that measured level 7 on the Japanese seismic scale)
May 9, 2016	The restoration of the Aso Bridge on National Road No. 325 was decided to be carried out as a project under the authority of the national government in accordance with the Road Traffic Act.
May 13, 2016	Prefectural Road No. 28 Kumamoto-Takamori line (approximately 10 km section) and village road Tochinoki-Tateno line (approximately 3 km section) were decided to be restored under the authority of the national government based on the Large-Scale Disaster Reconstruction Act.
July 01, 2016	Establishment of the Kumamoto Earthquake Disaster Management Office in the Kyushu Regional Development Bureau (The NILIM officials also participated in this process.)
December 24, 2016	The Tawarayama Tunnel Route (Prefectural Road No. 28 Kumamoto-Takamori Line) opened with a detour through a portion of the old road to avoid the bridge section, which required time for restoration.
April 1, 2017	Establishment of the Kumamoto Earthquake Recovery Division, Research Center for Infrastructure Management, at the disaster site (Minamiaso Village, Aso County, Kumamoto Prefecture) Start of operations in the same building as the Kyushu Regional Development Bureau's Kumamoto Reconstruction Project Office, which was established on the same day and was in charge of the restoration work (established as a temporary organization for five years until March 31, 2022)
August 27, 2017	Completion of the restoration and reopening of the Choyo Bridge route (village road Tochinoki-Tateno Line) (Emergency restoration of the Aso Choyo Bridge and Toshita Bridge)
December 14, 2017	Partial reopening of the Tawarayama Tunnel Route in the Toriko area (Restoration of the Oginosaka Bridge and Susukinohara Bridge)
July 20, 2018	Completion of restoration and reopening of the Kuwatsuru Bridge on the Tawarayama Tunnel Route
August 03, 2019	Completion of restoration and reopening of the Tawarayama Bridge on the Tawarayama Tunnel Route
September 14, 2019	Completion of the restoration of the Tawarayama Tunnel Route and reopening of the entire route at the original location (restoration of the Okirihata Bridge)
October 03, 2020	Opening of the National Route No. 57 North Restoration Route (conducted by Kumamoto Office of Rivers and National Highways) and reopening of the current road section
March 07, 2021	Completion and reopening of the New Aso Bridge on the Aso Ohashi Route (Route 325)

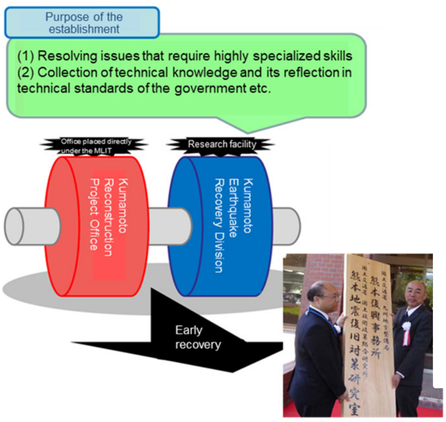


Figure 1 Purpose of establishing the Kumamoto Earthquake Recovery Division

Table 2 Major research subjects and results of the Kumamoto Earthquake Recovery Division

Topics of research	Main results (reflected in restoration)
Minimizing the impact of ground deformation on bridges	Proposal of a damage control method (failure type and design method) for failure-proof fulcrum member that contributes to the early recovery of road functions and prevents falling bridges (Reflected in the restoration of Okirihata Bridge, New Aso Bridge, etc.)
Evaluation of load-bearing capacity and durability of cables	Accumulation of knowledge on the load-bearing capacity of cables, proposal for methods of repairing cable sheathing and verification methods of water resistance (Reflected in the restoration of Kuwazuru Bridge)
How to confirm the effect of repairing bridges that were restored after an earthquake	Proposal for a monitoring method for confirming repair effectiveness in earthquake restoration work using ICT technology (Reflected in the restoration of Aso Choyo Bridge)
Information to be obtained during earthquake restoration work that will be useful for maintenance and management and how to use it	Proposal for methods of utilizing information obtained from earthquake restoration work for maintenance and management, and methods of recording and storing the information.
Advancement of methods for investigating foundation damage	Proposal on how to use the high-frequency impact survey method in foundation damage investigations Accumulation of knowledge on the influence of the foundation structure type and topographical conditions on foundation damage

The Kumamoto Earthquake occurred in April 2016. In this earthquake, a foreshock (magnitude 6.5) was recorded around 21:26, April 14, followed by the main shock (magnitude 7.3) around 01:25, April 16. These earthquakes resulted in many casualties and collapsed houses mainly in Kumamoto and Oita prefectures. This series of earthquakes caused damage to many road structures, including the collapse of National Route 57 located in front of a large slope collapse in the Tateno District of Minamiaso Village, the collapse of the Aso Bridge on National Route 325, damage to bridges and tunnels on Prefectural Road 28, Kumamoto-Takamori Line, and the fall of the bridge over Kyushu Expressway.

To respond to the damage among the road networks connecting Kumamoto City and the Aso region, restoration work was to be conducted under the authority of the national government in accordance with the Act on Reconstruction from Large-Scale Disasters at the following sites: an approximately 10 km section of Prefectural Road No. 28, Kumamoto-Takamori Line (Komori, Nishihara Village to Kain: Tawarayama Tunnel Route) and an approximately 3 km section from Village Road Tochinoki to Tateno Line (Kawayo, Minamiaso Village to Tateno: Choyo Bridge Route). The reconstruction of the Aso Bridge on National Route 325 (Aso Bridge Route) was also to be carried out under the Road Traffic Act. The national government also decided to implement restoration work for the large-scale slope collapse in areas near the Aso Bridge as an emergency response to a landslide disaster. Of these, this was the first case in Japan that the national government was acting on its own authority to restore roads in accordance with the Act on Reconstruction from Large-Scale Disasters.

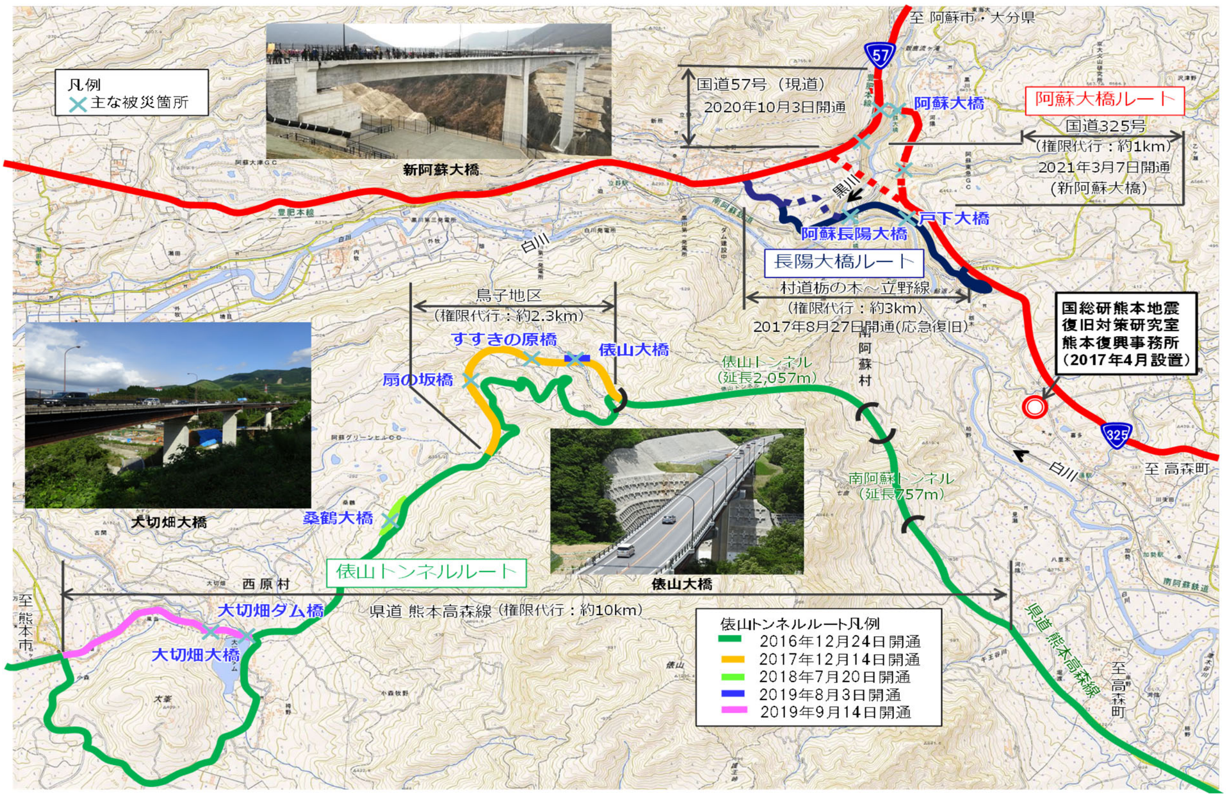


Figure 2 Sites of restoration projects conducted under the authority of the national government

In FY 2016, the first year of the restoration project, the Kumamoto Office of Rivers and National Highways of the Kyushu Regional Development Bureau, the Tateno Dam Construction Office, and the Kumamoto Earthquake Disaster Management Office, which was established on July 1, 2016, within the same Regional Development Bureau, started the restoration activities. Among them, six members of the NILIM participated in the Kumamoto Earthquake Disaster Management Office and took on the roles of technical supervisor and road, erosion control, and river specialists. Since the technical support covers a wide variety of aspects, the support was provided jointly with the NILIM departments related to road structures, such as the Road Structure Department, that has technical knowledge, Center for Advanced Engineering Structural Assessment and Research (CAESAR) of the Public Works Research Institute (RWRI), and other departments, such as the Geology and Ground Research Group. Since the damage to road structures was extensive and unique, the technical support required advanced technical capabilities. Thus, project teams consisting of experts from research institutes and other organizations and government officials were established for each of the earthworks, tunnels, and bridges.

The teams then worked on the restoration work while conducting technical studies to expedite restoration in cooperation between research facilities and those conducting the fieldwork.

In the following fiscal year, April 2017, the Kumamoto Reconstruction Project Office of the Kyushu Regional Development Bureau was newly established in Minamiaso Village, Aso County, Kumamoto Prefecture, near the disaster restoration site to centrally carry out restoration work on damaged roads and landslide sites as an authorized project. At the same time, in order to accelerate the restoration and reconstruction of civil engineering structures damaged by the Kumamoto Earthquake, the Kumamoto Earthquake Recovery Division, Research Center for Infrastructure Management of the NILIM (hereinafter referred to as "the Recovery Division") was newly established as a five-year time-limited organization. The Recovery Division was assigned to activities to accelerate restoration jointly with the Kumamoto Reconstruction Project Office located within the same building. This was the first time that a NILIM division was set up at a disaster restoration site outside of Tsukuba and Yokosuka.

The purpose of the Recovery Division was to swiftly solve problems in road restoration that require advanced technical capabilities and support early recovery and to gather technical knowledge through the restoration work and engage in research to reflect the gained knowledge on national technical standards and so forth. In addition to these activities, the team is also taking advantage of the regional nature of being located in Kyushu to improve local technical capabilities in addition to engaging in earthquake restoration.

In August 2017, one year and four months after the earthquake, emergency restoration of the Aso Choyo Bridge and Toshita Bridge along the Choyo Bridge Route was completed, and the route was reopened. In addition, the entire Tawarayama Tunnel Route was reopened in September 2019. In October 2020, the restoration of the large-scale landslide was completed, and the current National Route 57 was reopened. In March 2021, the New Aso Bridge reopened. With the completion of these projects, all the damaged national roads and prefectural roads were reopened.

2. Main Research Results

(1) Resolving issues that require highly specialized skills

This section presents some of the characteristics of the highly specialized technologies employed in the restoration projects that were realized by the Recovery Division and the Reconstruction Office in cooperation with the relevant departments of the NILIM and the PWRI.

1) Restoration of Kuwatsuru Bridge

The Kuwatsuru Bridge, a cable-stayed bridge with unequal longitudinal slope, suffered a failure of its bearing that had resisted vertical upward and horizontal forces with the same member, causing the girder ends to lift up and hindering the early recovery of roadway functions. As a countermeasure to prevent serious damage due to the lifting of the girder ends, the NILIM proposed that the members resisting vertical upward forces be independent of the members resisting horizontal forces and that members of a different system be installed to prevent the girder ends from lifting easily even if these members should fail (Figure 3).

In addition, tests to obtain cable tension and the natural frequencies of the rehabilitated bridge were conducted at the on-site briefing held prior to the reopening of the bridge to hand over the bridge to Kumamoto Prefecture, which will be the administrator of the bridge. This process was held so that they could identify changes in the condition of the bridge in the event of another major earthquake while they are in charge of maintaining and administering the bridge after the reopening. This process was also done with an eye toward the fact that the local government, not the national government, which did the rehabilitation work, would be in charge of road administration. In order to facilitate the use of the test results in maintenance management, the test was designed to be as simple as possible in obtaining results so that the tests would not be a heavy burden on maintenance management. During the on-site briefing, the vibration characteristics of the bridge were explained, tests were conducted, and an explanation of how to use the test data for maintenance and management was provided (Figure 4).

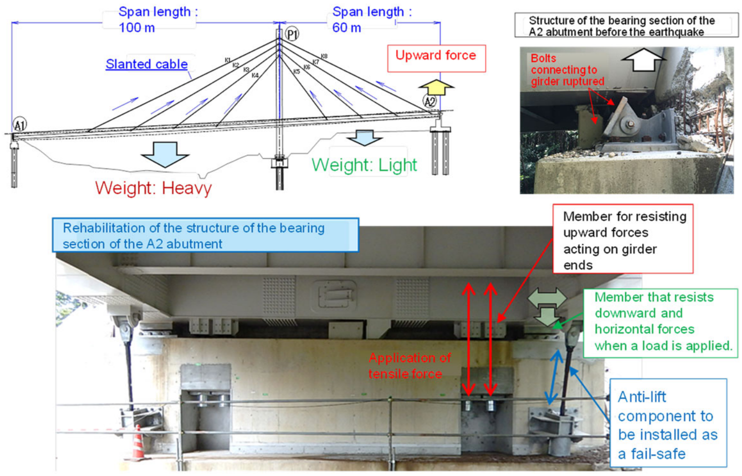


Figure 3 Structure of the fulcrum that prevents the girder end from

(1) Status of cable tension verification testing

(2) Explanation to administrators regarding the use of data acquired during the construction phase for maintenance and management

Figure 4 On-site briefing session at the Kuwatsuru Bridge for the administrator (Kumamoto Prefecture)

2) Restoration of Okirihata Bridge

In the case of the Okirihata Bridge, a five-span continuous non-composite curved plate girder bridge, all but one of the bearings were damaged, causing the superstructure to shift and the main girder to buckle in the interstitial section. This kind of damage had never been observed in past earthquakes. The rehabilitation was conducted based on the basic policy of restoring the bridge as a whole to the same load-bearing capacity as before the disaster. From the viewpoint of recovering the load-bearing capacity of the superstructure, a strategy was devised to install a new girder and cross-frame within the damaged section, leaving the buckled main girder in place (Figure 5). The load sharing by the newly added girder was confirmed by monitoring the stress (strain) generated in the girder because the load acting on the superstructure changes from changes in the fulcrum conditions during the construction process and vehicle loading after completion.

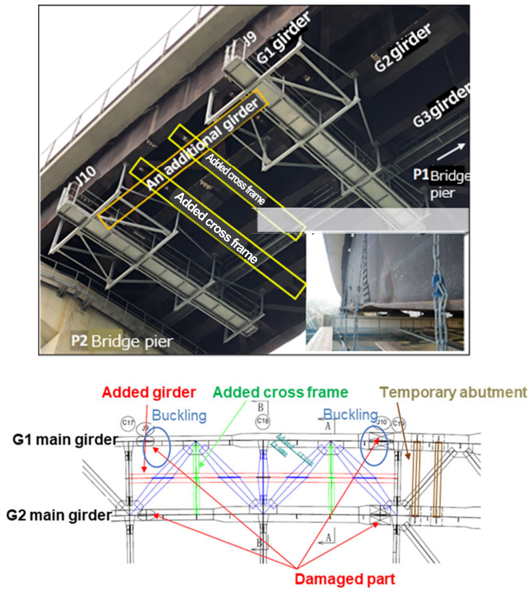
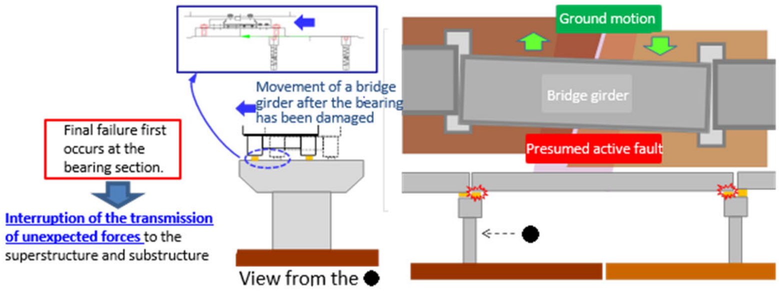


Figure 5 The Okirihata Bridge repaired to recover the load-bearing capacity of the entire superstructure

3) Restoration of Aso Bridge (Construction of New Aso Bridge)

The New Aso Bridge was constructed approximately 600 meters downstream from the Aso Bridge (arch bridge) that collapsed because of the earthquake. In constructing the New Aso Bridge, the NILIM proposed various technical considerations at each stage of planning, design, and construction based on the lessons learned from the damage caused by the Kumamoto earthquake. For the crossing section, a bridge type (PC rigid-frame structure with cantilevered erection) was adopted so that the superstructure could stand on its own even if the substructure at the girder ends moved or settled from ground deformation (Figure 6). In addition, the section that straddles the fault where lateral displacement is anticipated is a single-diameter steel girder bridge, so that even if the girder moves due to movement of the substructure caused by displacement of the fault, it will not interfere with the superstructure of the adjacent section. The NILIM also proposed technical considerations for the span that crosses the fault line to make it more difficult for the bridge to fall and also to restore the road function as soon as possible. Details of the proposals are as follows: to design with differential load-bearing capacity at the bearings and their attachments so that the failure of the bridge is guided to the bearings when relative displacement occurs in the upper and lower structures due to ground deformation caused by faulting activities, to provide enough width of the pier top edge so that the bridge does not immediately fall from the top edge of the substructure if the bearing section were to fail (Figure 7), to secure space at the top end of the piers to facilitate temporary support of the girder if it were to move, and to arrange reinforcement within the top

Figure 6 The New Aso Bridge where the bridge girders remain without falling off even when the ends of the girders are not on the bridge piers (under construction) (Photo provided by the Kumamoto Reconstruction Project Office)



The tops of the piers are widened to make it more difficult for the superstructure to fall off.

Hierarchical load-bearing capacity to absorb deformation caused by fault displacement

Figure 7 Structural plan to let go of fault displacement without resisting it by force (New Aso Bridge)

edge assuming the installation of anchor bolts in advance. In addition, the bridge has hollow piers at the crossing that reach 97 meters at their highest point. Therefore, the suggestion included installing inserts for rope access at the construction stage and creating inspection holes in the column heads to check inside the hollow section. These suggestions were to make it easy to monitor the bridge condition before damage occurs (Figure 8).

(2) Evaluation of load-bearing capacity and durability of cables

In the Kuwatsuru Bridge, which is a cable-stayed bridge, the earthquake caused cables to kink and the sheathing to be damaged from contact with lighting columns (Figure 9). A study of the cable integrity was conducted to contribute to future inspections and diagnostics utilizing the removed cables that had been replaced because of external deformities observed during repairs. Tensile tests were conducted on the steel strands of the cables used in this bridge for about 20 years. Findings from the tests were then obtained regarding corrosion protection, external deformation, and tensile strength. A method to check the humidity and other conditions inside the cable sheath, a method to repair the high-density polyethylene sheath, and a method to verify the water resistance were proposed. These were reflected in the restoration work (Figure 10).

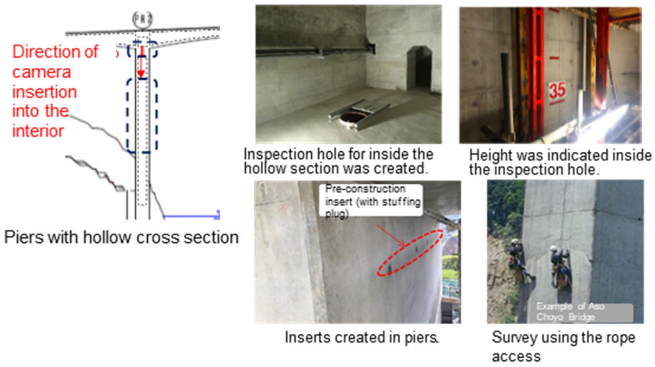
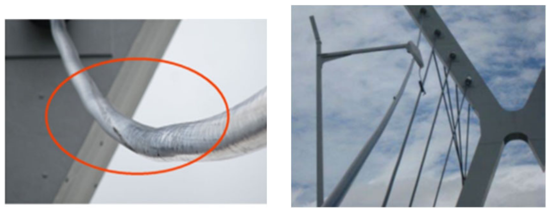


Figure 8 Considerations in maintenance to make bridge inspections easy
(Photo provided by the Kumamoto Reconstruction Project Office)

(3) Utilization of data obtained in the restoration process

1) Confirmation of repair effectiveness through monitoring using ICT technology

At the Aso Choyo Bridge, where resistance was reduced because of cracks penetrating the cross-section of the reinforced concrete piers with the hollow section, the hollow section was filled with concrete to regain resistance. Noting that the way the bridge shakes changes if this method is appropriate and effective, we proposed and implemented a method to confirm the effect of the repair by conducting a vibration test in conjunction with concrete filling and measuring the difference in the way the bridge shakes before and after the repair using an accelerometer (Figure 11).



(1) Cable kink

(2) Damage to PE sheath due to buffering with lighting column

Figure 9 Deformation of cables identified during visual inspection of the Kuwatsuru Bridge

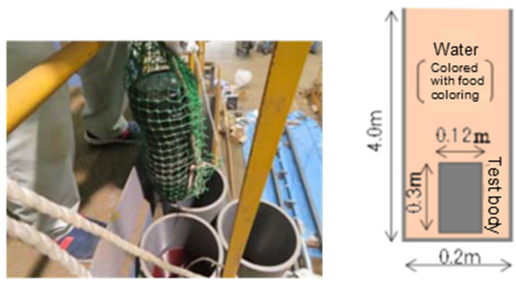
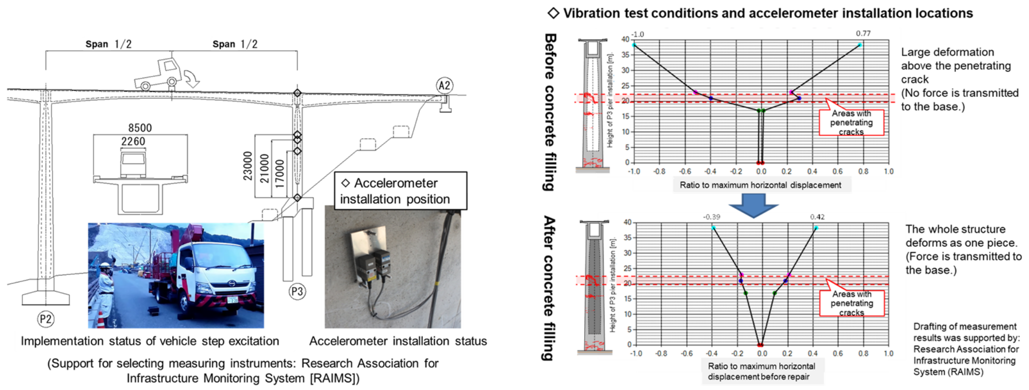


Figure 10 Water resistance verification test of cable sheath repaired by the proposed method (Condition in which a cable specimen is put into water with food coloring)



(1) Vibration test conditions and accelerometer installation locations

(2) Comparison of horizontal response of piers before and after concrete filling

Figure 11 Confirmation of repair effectiveness of the Aso Choyo Bridge using ICT technology

2) Acquisition, recording, and storage of construction data with consideration for use in the maintenance and management of bridges restored after the earthquake

The maintenance and management of bridges that have been rehabilitated after an earthquake must take into account the various uncertainties that are not present in newly constructed bridges. Therefore, based on the damage caused by the earthquake, the characteristics of the type of repair work to be conducted and the concerns anticipated after the repair, information that should be obtained during the construction phase is extracted, taking into consideration how to utilize the information during the maintenance and management phase. In addition, we continue to research more versatile methods of recording and storing the data based on the experience gained through the Kumamoto earthquake restoration work. Among these, regarding the method of recording and storing information necessary for maintenance and management of rehabilitated bridges, we are researching methods that can be effectively used for maintenance and management by utilizing 3D models, taking into consideration the development of BIM/CIM in the maintenance and management phase (Figure 12).

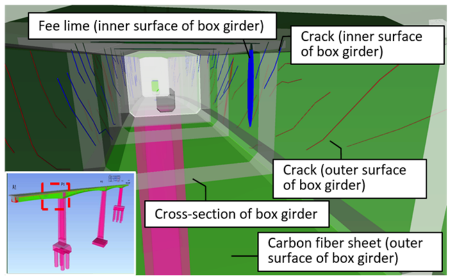


Figure 12 Prototype example of a method for recording and storing information required for maintenance and management using a 3D model (Superstructure with cracks repaired and fiber sheeting applied)

3. List of related reports and technical documents

1) F. Miyahara, T. Imamura, H. Nishida, and J. Hoshikuma. "Proposal of Rehabilitation Measures for a Cable-Stayed Bridge Damaged in the Kumamoto Earthquake and a Method for Understanding the Condition Change after the Rehabilitation." *Journal of JSCE,* A1, Vol. 76, No. 4, pp. 461-471, 2020.9

2) F. Miyahara, T. Imamura, S. Suzuki, H. Nishida, and J. Hoshikuma. "Repair Design of Steel Superstructure Focusing on Recovery of Load Carrying Capacity - Rehabilitation of Okirihata Bridge Damaged by the Kumamoto Earthquake -." *Civil Engineering Journal,* Vol. 62 No. 8, pp. 46-49. 2020.8.

3) F. Miyahara, T. Imamura, S. Suzuki, H. Nishida, and J. Hoshikuma. "Selection of Steel Superstructure Repair Method According to Structural Characteristics and Damage Conditions – Rehabilitation of Okirihata Bridge Damaged by the Kumamoto Earthquake -." *Civil Engineering Journal,* Vol. 62 No. 7, pp. 8-13, 2020.7.

4) H. Nishida, T. Imamura, K. Takimoto, T. Tamakoshi, and J. Hoshikuma. "Study on Condition Assessment and Repair Method of Cable Members with Damaged Polyethylene Sheath." *Journal of Structural Engineering,* A 66A pp. 617-628, 2020.4.

5) J. Hoshikuma, T. Imamura, and H. Nishida. "Consideration of the Influence of Ground Deformation in the Planning and Design of the Aso Bridge (tentative name)." Compilation of Lectures from the 22nd Symposium on Seismic Design of Bridges, pp. 85-90, 2019.7.

6) M. Sawada, T. Imamura, R. Nakagawa, and J. Hoshikuma. "Rehabilitation of PC Rigid-Frame Bridges Damaged by the Kumamoto Earthquake and Utilization of Monitoring." *Civil Engineering Journal,* Vol. 60 No. 2, pp. 36-39, 2018.2.

4. Future Outlook

Technical knowledge obtained at the restoration site should be passed on to the administrator (Kumamoto Prefecture, etc.) so that it can be used for maintenance and management of the restored road structures. Further study is also needed for creating standards for reflecting the knowledge on technical standards and other references.