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FULL-SCALE EXPERIMENT AND NUMERICAL SIMULATION OF TSUNAMI-BORNE FRP BOAT IMPACT

Toru Kuriyama[1], Sota Fukumoto[2], Yuudai Koike[3], Makoto Toyoda[4], and Hideki Kaida[5]

[1] Office of Civil Engineering and Architecture, Kansai Electric Power Company, Osaka, Japan (kuriyama.toru@c3.kepco.co.jp)
[2] Leader, Office of Civil Engineering and Architecture, Kansai Electric Power Company, Osaka, Japan (fukumoto.sota@b3.kepco.co.jp)
[3] Office of Civil Engineering and Architecture, Kansai Electric Power Company, Osaka, Japan (koike.yuudai@c3.kepco.co.jp)
[4] Manager, IHI Corporation, Yokohama, Japan (toyoda2836@ihi-g.com)
[5] Research Scientist, Nuclear Risk Research Center, Central Research Institute of Electric Power Industry, Chiba, Japan (h-kaida@criepi.denken.or.jp)

ABSTRACT

The issue of evaluating the impact load of tsunami-borne fishing boats made of FRP (Fiberglass Reinforced Plastic) on seawalls has been drawing increased attention over recent years. Nevertheless, research related to this topic remains limited. To address this, a research project on the evaluation of the impact load of tsunami-borne FRP boats was conducted by Japanese electric power companies operating nuclear power plants, including discussions held by a working group from the Japan Society of Civil Engineers. This project explored evaluation methods for the impact load of FRP boats through full-scale experiments and associated reproduction analysis. As a result, characteristics of FRP boat collisions were clarified and the effectiveness of impact analysis as a means of estimating the impact load was demonstrated.

INTRODUCTION

A tsunami is a natural phenomenon that must be considered in the design or risk assessment of nuclear power plants, especially those located in coastal areas. One of the effects of a tsunami is the loss of the functions of tsunami protection facilities such as breakwaters and seawalls due to colliding debris from the tsunami. It is important to maintain their functions against tsunami-borne debris in order to ensure the safety of nuclear power plants, and a great deal of research has been conducted about impact due to collision from wood, containers, vehicles, and large-size ships (e.g., Aghl et al. (2014); Kaida et al. (2018); Arita (1988)). There have been many previous studies evaluating the collision force of a variety of debris, and these studies have been used in practice. Although the evaluation of the impact load of small FRP fishing vessels is important, there is little research related to tsunami-borne fishing boats of less than 20 gross tonnage in size, which have the possibility of colliding with facilities at nuclear plants in Japan; many of these boats are made of FRP (Fiberglass Reinforced Plastic). Use of FRP boats is widespread. They are lighter than conventional steel boats and have higher durability and rust resistance, accounting for 97% of all vessels in Japan.

In order to establish a methodology for evaluating the integrity of tsunami protection facilities against collisions with tsunami-borne FRP boats, a research project was started by Japanese electric power companies operating nuclear power plants. As part of this project, a full-scale collision experiment with the actual FRP boat was conducted and impact analysis of the FRP boat was performed using results from the experiment. Outcomes from the project were discussed by a working group at the Japan Society of Civil Engineering from 2019 to 2021 (referred to as the “WG” hereinafter). This paper summarizes the current status of the evaluation of the impact load of tsunami-borne debris and reports on the efforts of this project, including discussion within the WG.

REVIEW OF THE ESTIMATION METHODS FOR IMPACT FROM TSUNAMI-BORNE DEBRIS

To evaluate the impact load of tsunami-borne debris, various estimation methods have been utilized for each type of debris. Most of them are written as follows:

$$F = CV^{l}K^{m}M^{n} \tag{1}$$

where F is the debris impact load, C is the coefficient, V is the impact velocity of the debris, K is the stiffness of the debris, and M is the mass of the debris. l, m and n are power numbers. The stiffness is frequently used here as the effective stiffness, which considers interaction between the impactor and the impacted object.

Haehnel and Daly (2002) modelled the collision of logs with rigid structures as a one-degree-of-freedom system, and described the maximum impact load with the following equation:

$$F = u\sqrt{\hat{k}m} \tag{2}$$

In this formula, F represents the maximum impact load, u is the impact velocity of the debris, $\hat{k}$ is the effective axial stiffness, and m is the mass of the debris. Here, equation (2) is based on the assumption that the mass and stiffness of the impacted object is significantly larger than that of the impactor and the collision time is short enough to ignore damping.

In FEMA P-646 (2012), considering the importance of structures with which debris collides and the influence of fluid in motion with the debris in equation (2), the impact load is represented by

$$F = 1.3u\sqrt{\hat{k}m(1+c)} \tag{3}$$

where 1.3 is the importance coefficient and c is the hydrodynamic mass coefficient. In FEMA P-646 (2012), the approximate values of m, c, and $\hat{k}$ for common lumber, wood logs, and standard shipping containers are listed for use in equation (3). In addition, it should be noted that FEMA P646 (2012) was updated in 2019. In FEMA P-646 (2019), the evaluation of the impact load of debris is referred to ASCE7 (the latest version was published in 2022), where the impact load based on equation (2) is used.

Arikawa et al. (2010) conducted experiments in which driftwood was made to collide with a concrete wall, and demonstrated that it is possible to determine the degree to which the concrete wall would be damaged using the estimation formula for collision load based on Hertz's elastic contact theory, as shown below:

$$F = \gamma_p \chi^{2/5}\left(\frac{5}{4}m\right)^{3/5}u^{6/5}, \chi = \frac{4\sqrt{a}}{3}\frac{E}{1-\nu^2} \tag{4}$$

γ_p is the coefficient related to the energy attenuation effect due to plasticity, a represents half the radius of the impact surface between driftwood and a concrete wall, E is Young's modulus of driftwood, and ν is Poisson's ratio for driftwood.

The estimation formulas mentioned above are designed for debris with simple structures, such as logs and containers. On the other hand, for vehicles and ships that are assumed to become debris and collide, due to their complex structure it is difficult to evaluate the impact load using estimation formulas that take into account the effect of rigidity. Takabatake et al. (2015) conducted static loading and collision experiments using real cars, and demonstrated that axial stiffness changes in stages according to the components (e.g., bumper, side member) or structures from the derived load-displacement curve. It was suggested that through due consideration of the changes in this axial stiffness in Equation (1), it is possible to estimate the impact load in a simple and reasonable manner.

Arita (1988) [6] conducted model experiments simulating bow collision on ships with a gross tonnage of 500 and 4,000 tons (equivalent to mid-distance ferries, small cargo ships, etc.). It was shown that until compressive failure is reached, the load increases at a constant proportion (i.e., axial stiffness), and thereafter, it transitions to a constant value (compressive failure load). Arita proposed that this compressive failure load can be approximated with the component of the buckling load of the ship's side outer plates (equivalent to a combination of two steel plates) in the direction of the collision.

In addition to experiments, analytical approaches are effective in estimating the impact load and deformation of debris with complex structures. The National Crash Analysis Center (NCAC) at George Washington University conducted a reproduction analysis of the collision experiments on the Toyota Yaris. These experiments were originally performed by MGA Research Corporation as part of a New Car Assessment Program conducted by The National Highway Traffic Safety Administration (NHTSA). From this analysis, NCAC created a finite element model (FEM) of a Toyota Yaris that could be used to numerically estimate impact loads and behavior in terms of destruction. Given that FRP boats vary in size and shape depending on their use, and their structures are complex, it is not practical to conduct experiments on each one to evaluate the effect of impact when they become debris. Therefore, it would be desirable to first establish a method that can analytically estimate impact loads and destructive behavior, similar to that used for vehicles.

PROBLEMS IN EVALUATING THE IMPACT LOAD OF TSUNAMI-BORNE FRP BOATS

As nuclear power plants in Japan are located in coastal areas, it is necessary to assess their integrity against impact from tsunami-borne debris. In this process, operators initially survey the marine areas surrounding the plants and identify objects that may potentially drift, including FRP boats. Subsequently, they conduct impact evaluation on the debris that is believed to potentially have the most significant impact on the nuclear power plant facilities in the event of a collision, taking into account the weight and approach speed of the debris. When evaluating impact from FRP boats, formulas for impact force, which are applied to materials like timber or containers, have been utilized under conservative conditions due to limited knowledge about the impact load.

The formula potentially applicable for evaluating collisions with small boats such as FRP boats is Equation (3). This equation facilitates a straightforward calculation of impact load, provided that the parameters specific to the type of debris are known. FEMA P-646 (2012) provides values for mass, hydrodynamic mass coefficient, and effective axial stiffness for driftwood, 20-ft containers, and 40-ft containers. The values for the hydrodynamic mass coefficient and effective axial stiffness for FRP boats remain unknown, however. For the hydrodynamic mass coefficient, it may be possible to apply a value of 1.0, corresponding to the case of the container oriented transverse to flow as indicated in FEMA P-646 (2012), given that the conditions of water entrained by the debris during collision are relatively similar. Nevertheless, further study is necessary to determine the appropriate value. In terms of effective axial stiffness, a method that calculates this value based on the buckling load derived in viewing the bow structure of a large ship as a combination of two plates, as suggested by Arita (1988), can be taken into consideration. Applying this to FRP boats, however, which are different from larger ships in scale, structure, and material, is challenging. Moreover, even with the same types of FRP boats, differences in size and detailed structure suggest that effective axial stiffness may vary for each boat, and there are no established methods for accurately estimating these parameters. Therefore, estimating the impact load while considering the destructiveness of FRP boats during a collision remains a significant challenge for evaluators, particularly in terms of the method of setting values for effective axial stiffness.

Against this backdrop, Japanese electric power companies operating nuclear power plants have initiated a research project on methods to evaluate FRP boat impact. Results from this project were deliberated within the "Tsunami-borne Debris Collision Evaluation Working Group," established by the Japan Society of Civil Engineers from 2019 to 2021. This WG consisted of experts from various fields such as coastal engineering, impact engineering, and materials science. The following chapters will present an overview of the full-scale collision experiments and impact analysis of FRP boats discussed in this WG.

FULL-SCALE COLLISION EXPERIMENT WITH FRP BOAT

In order to properly assess the impact of FRP boats that have become floating objects and collide with nuclear power plant facilities, it is crucial to understand the nature of the destruction and fluctuations in impact load according to the progression of destruction when the collision occurs at tsunami flow speed, using an actual boat. Therefore, in this project, we obtained a representative type of FRP ship operating around Japanese nuclear power plants and conducted a full-scale experiment where it was made to collide at a speed equivalent to tsunami flow. Details regarding this experiment can be found in Toyoda et al. (2022).

In Japan, FRP boats that operate around nuclear power plants are often either a type with an engine positioned in the center of the hull that rotates the propeller with power transmitted by a shaft (shaft-type boat) or a type with an inboard/outboard motor attached to the rear of the hull (drive-type boat). The shaft-type boat is partitioned with large-rigidity strength members such as frames and bulkheads to secure space for engine rooms and fish holds, and these are covered with side and bottom plates. As a result, in areas where strength members are located, the impact load is considered to increase due to their resistance when destruction takes place. Therefore, the collision experiment utilized a shaft-type boat. Figure 1 (a) shows the FRP boat used in the collision experiment.

The collision experiment was conducted using a free-fall method as a way to reliably transmit the collision load to the load cell at a collision speed equivalent to tsunami flow speed. Other methods were considered, such as loading the boat onto a cart and causing it to collide horizontally with the load cell. This method, however, presented concerns about the difficulty of properly separating the cart and the boat at the moment of collision, even though this collision posture guaranteed a degree of stability. As a result, this approach was not used, due to the potential for inaccurate impact load measurement.

Figure 1 (b) shows the collision experiment itself. In the free-fall collision experiment, the attitude of the boat at the moment of impact could lead to significant rotation and sliding of the hull, potentially hindering adequate transmission of the impact load to the load cell. To address this issue, the stern of the vessel was lifted using a crane, taking into consideration its posture during the collision. The collision experiment setup was positioned at a height of 5.1m from the load cell, assuming that the boat would be driven by a tsunami and collide at a velocity of 10m/s.

(a) The FRP boat used in the collision experiment

(b) Appearance of the Full-scale collision experiment

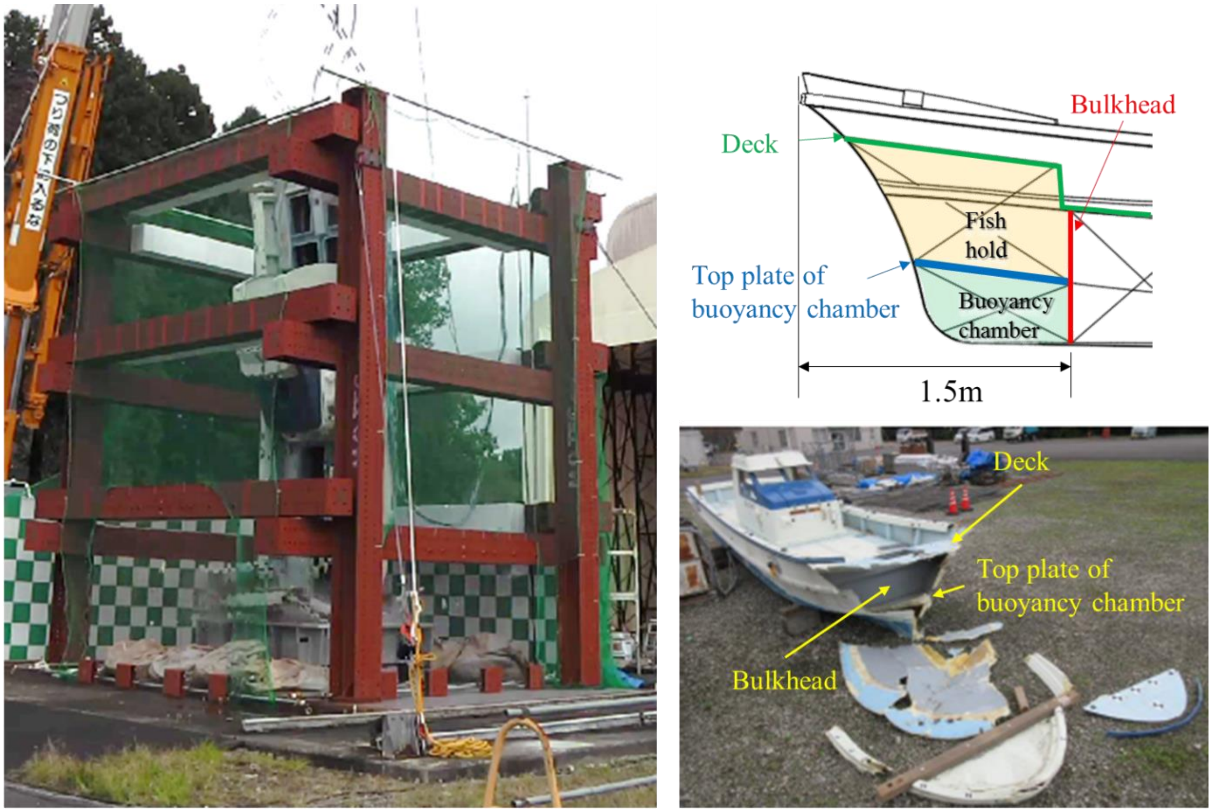
Figure 1. Overview of the full-scale collision experiment using actual FRP boat

The main measurement items in the collision experiment are shown in Table 1. In the collision experiments, high-speed cameras were used to capture the exact speed of the FRP boat during the collision, and high-definition cameras were used to observe the posture of the hull during collision and to acquire the displacement. Furthermore, action cameras were installed inside and outside the FRP boat to observe its local behavior. In addition, the load cell was made of steel and designed to measure the impact load based on the measurement values of the strain gauges attached to the columns.

The collision experiment was conducted under weather conditions with minimal wind effects to minimize the influence on the attitude of the FRP boat during the collision. The boat was dropped onto the load cell and maintained its posture and destruction progressed until the end of the collision. After terminating the collision, it leaned towards the deck. The initial velocity at the start of the collision was 9.9 m/s. Figure 2 shows the post-collision condition of the FRP boat.

Table 1. The Main Measurement Items of the Collision Experiment

Measurement item	Equipment	Purpose
Velocity	High speed camera	Measuring speed during the collision
Overall behavior & Displacement	H-D camera	Observation of the posture of the FRP boat & Measuring displacement
Local behavior	Action camera	Observation of local damage behavior inside and outside the FRP boat.
Impact load	Load cell	Measuring the load during the collision



(a) Situation immediately after the collision experiment (b) Destruction situation of the FRP boat

Figure 2. Post-collision condition and destroyed area of the FRP boat

For confirmation of the attitude of the FRP boat during collision, the time series of the center of gravity was focused on. Figure 3 shows the time history of center of gravity displacement from the start of the collision. The vertical displacement of the center of gravity increased up to about 1,300mm as the destruction progressed, considering downward as the positive direction. Horizontal displacement of the center of gravity remained below 100mm, suggesting that horizontal movement was not significant, considering the bottom of the boat as the positive direction. Furthermore, as the displacement converged in both directions after the collision ended, it can be inferred that the boat collided with the load cell while maintaining posture during collision and the impact load was transmitted without dispersion.

A destruction situation of the FRP boat is presented. As shown in Figure 4, the destruction of the FRP boat progressed from the bow to the fish hold, the buoyancy chamber, and up to just in front of the bulkhead. In addition, focusing on the mode of destruction of the FRP boat, it can be observed that the major components such as the deck and side plates predominantly undergo bending-induced destruction during collision.

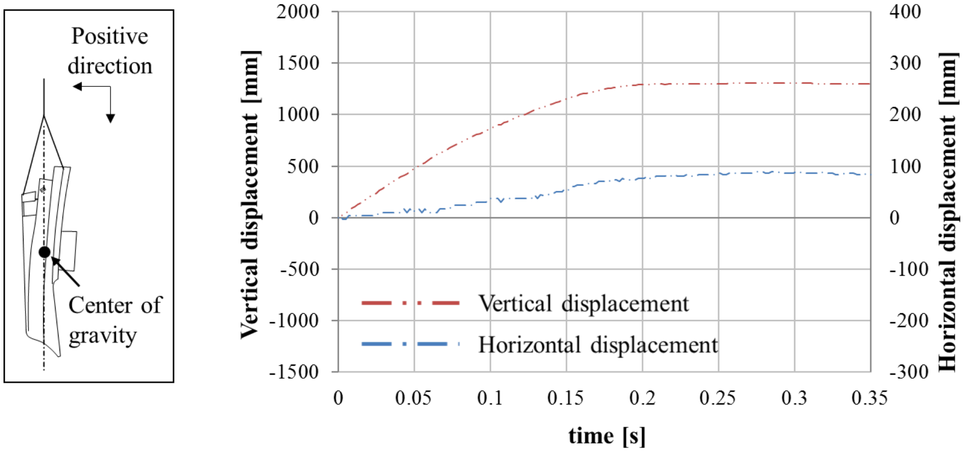


Figure 3. Time series for center of gravity displacement

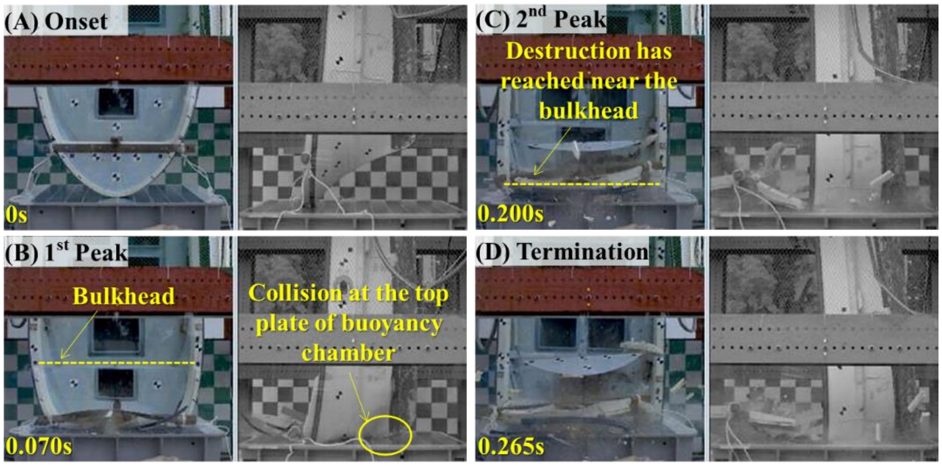


Figure 4. Deformation on the FRP boat

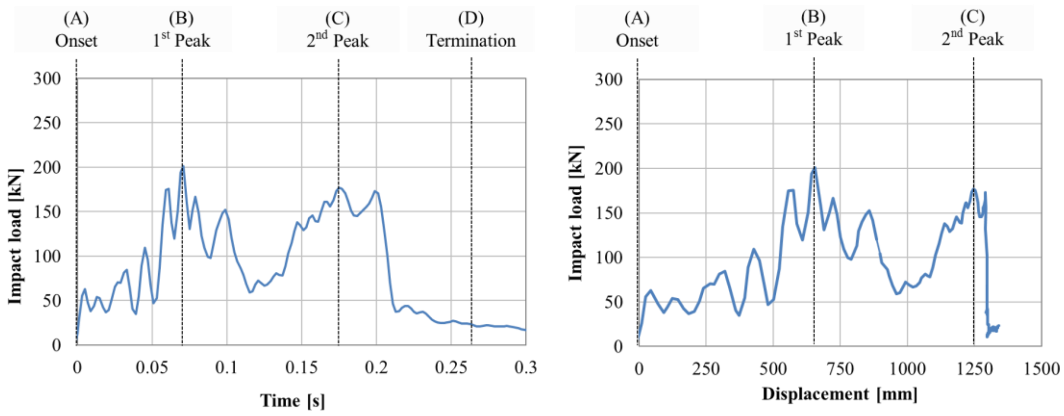


Figure 5. Impact load-time history (left) and load-displacement relationship (right) in the FRP boat collision experiment

Attention is focused on the bow structure of the FRP boat, and the relationship between the progress of destruction and the impact load is examined. The graph on the left side of Figure 5 shows the history of impact load and the right side illustrates the relationship between impact load and displacement, which means crushing amount from the bow of the FRP boat. The labels (A), (B), (C), and (D) in the figure each represent: (A) the onset of collision; (B) the occurrence of the first peak load; (C) the occurrence of the second peak; and (D) the termination of the collision, corresponding to the destruction states of the FRP boat at each time, as shown in the graph on the right side of Figure 5. The FRP boat reached the first peak when the destruction reached near the top plate of the buoyancy chamber, and the collision ended when the second peak occurred, when destruction reached the location just before the bulkhead. As these components are positioned to resist collision, it is inferred that their resistance led to the peaks in impact load.

Consequently, based on this collision experiment, in estimating the collision velocity of FRP fishing boats, destruction in relation to the complex structure of the boat should be given consideration.

IMPACT NUMERICAL ANALYSIS OF FRP BOAT

The characteristics of the impact load of FRP boats were clarified in the previous chapter. However, considering that the scale and shape of an FRP boat can vary depending on its usage, the results from the previous chapter cannot be used directly as the input load for evaluating the integrity of the facilities. Therefore, a method is necessary to analytically estimate the impact load of FRP boats that can be expected to collide with a facility. In this project, the validity of evaluating the impact load of FRP boats through collision analysis was discussed using reproduction analysis from the collision experiment conducted in this project.

In the reproduction analysis, we conducted a collision simulation using a finite element model with LS-DYNA and carried out a time-history response analysis by explicit method. The primary components, made of FRP material etc., were modelled using shell elements, based on the design drawings and the observation results of the FRP boat used in the experiment. For the boat’s weight, in addition to the weight of the components modelled by shell elements, the weights of the engine and measuring instruments included in the weight of the FRP boat in the collision experiment were considered as a concentrated mass and placed at a position that matched the center of gravity position in the collision experiment. It should be noted that the concentrated mass was placed far enough away from the bow of the ship and was not affected by the destruction of the ship. The load cell was set to steel material properties. The analysis model is shown in Figure 6.

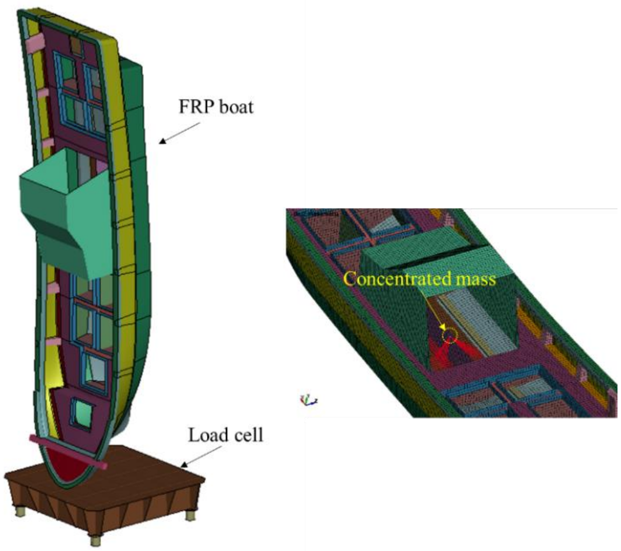


Figure 6. Analysis model of the FRP boat

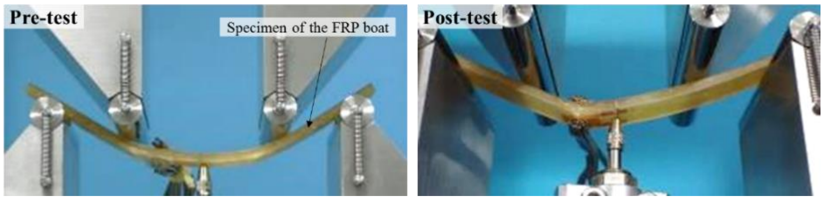


Figure 7. Overview of the 4-point bending test for specimens obtained from the FRP boat

In setting material properties for the FRP, it was taken into account that bending-induced destruction was predominant in the collision experiment. Several specimens were obtained from the area of the FRP boat that were not affected by the destruction in the collision experiment. The material properties of FRP were determined based on the results obtained from the 4-point bending tests on these specimens in compliance with the ASTM D7264 standard, as shown in Figure 7.

Using the aforementioned analysis model, a preliminary analysis was conducted considering gravitational acceleration at a collision speed of 9.9 m/s, similar to the collision experiment. It was found that the setting of the friction coefficient between the FRP material and the load cell tends to affect the inclination of the boat hull during collision, as shown in Figure 8. This is indicated to be due to the ever-changing parts in contact with the load cell in response to the complex progression of destruction during collision. As the aim of this study is to accurately predict collision phenomena through analysis, the method of setting the friction coefficient will be left for future consideration. An appropriate friction coefficient was set within the possible range for the FRP material to ensure that the collision posture generally matches the collision experiment. Comparisons of the conditions of destruction and changes in load will be covered subsequently.

The results of the reproduction analysis conducted with the above-mentioned settings and the comparison with the collision experiment results carried out in the previous chapter are shown as the load-time history and load-displacement relationship in Figure 9, and the destruction situation at key timing intervals is shown in Figure 10. The analysis successfully reproduced two peaks corresponding to the structure of the FRP boat, a characteristic in its collision, and matched particularly well at the first peak, which is the maximum collision load. In addition, the conditions of destruction were approximately similar in both. These results show that FRP boat collision process can be evaluated through numerical analysis.

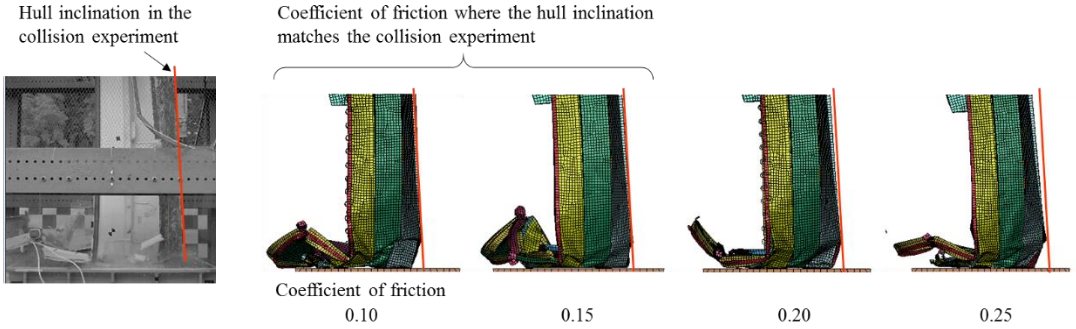


Figure 8. Comparison of hull inclination in the collision experiment and reproduction analysis due to differences in coefficient friction

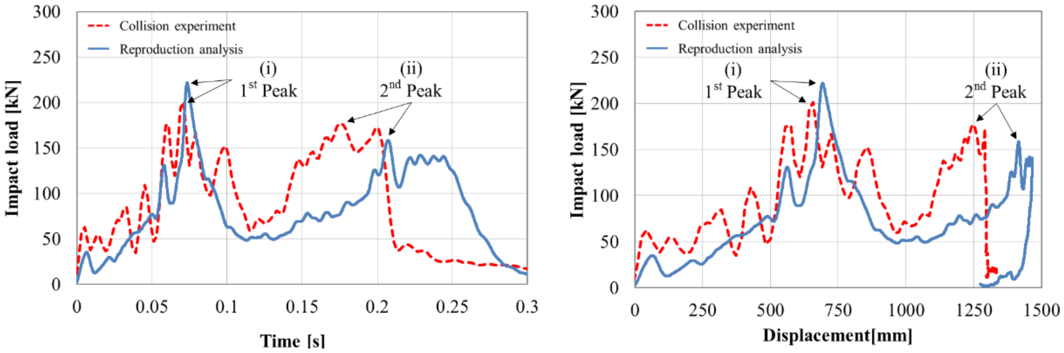


Figure 9. Comparison of load-time history and load-displacement relationship between the reproduction analysis and the collision experiment

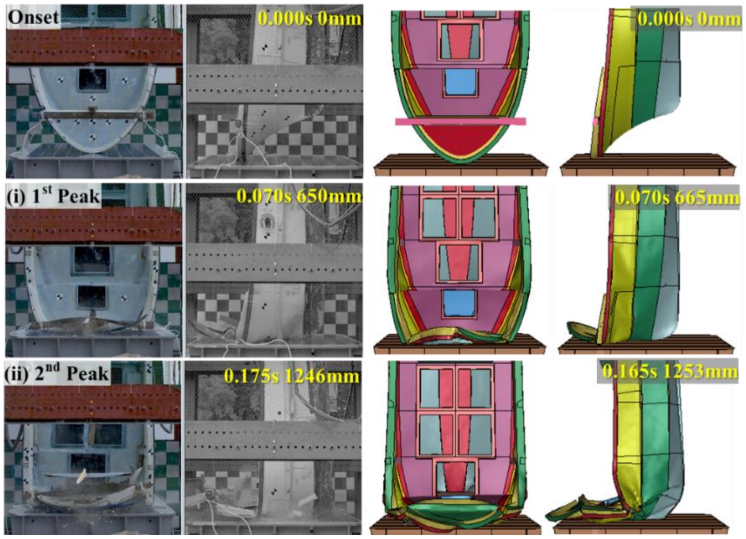


Figure 10. Comparison of deformation between the reproduction analysis and the collision experiment

CONCLUSION

In this paper, after organizing the current status and outlining the challenges of assessing tsunami-borne object collision, a study on the collision evaluation of FRP boats through a full-scale falling collision experiment using an actual FRP boat and reproduction analysis of this were overviewed. The time series of impact load, including the peak load, and deformation for the collision of FRP boats were confirmed to agree well between the results of the collision experiment and the reproduction analysis. This can be said to demonstrate the effectiveness of impact analysis as a means of estimating the impact load of FRP boats that vary in scales and sizes depending on their use. For more detailed information on the FRP boat collision experiment and the reproduction analysis, please refer to Toyoda et al. (2022). It is hoped that there will be an increase in the application of the FRP boat collision analysis method introduced in this paper. We believe that focusing on the response assessment of nuclear power plant facilities such as seawalls hit by FRP boats and improving the evaluation method accordingly will help develop an integrity evaluation method for nuclear power plant facilities against collisions with tsunami-borne objects, including FRP boats.

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