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Development of a Small Tsunami Shelter and Its Sea Experiment of Towing and Drifting

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ABSTRACT: We developed a small Tsunami shelter. The design characteristics of this shelter are, its floater keeps the shelter floating even if the cabin space is fully flooded, the shelter can be self-recovered from the upside down situation when it rolls in the sea. When the shelter is washed away from the shore, it starts drifting. In that case, passengers might have to stay in the small cabin for several days. The length of the shelter is around 2m, which is much less than a typical life boat. So we carried out the first sea experiment using a real shelter with riding 8 passengers. In this paper, we'll show the experimental results of motion sensor, towing force, as well as lessons learnt.

1 INTRODUCTION

1.1 *The Tsunami on 3.11*

The 2011 off the Pacific coast of Tohoku Earthquake occurred on 11th March in 2011. Its magnitude was 9.0 and it caused a massive disaster of tsunami. From the report of the ministry of land, infrastructure and transport (Mlit report 2011), the tsunami height from the normal tide level was more than 20m in many areas along the Sanriku coast line, and in some areas, it was more than 30m up to 40m. The death toll was more than 15,000. It is said more than 90% of the toll was death by drowning due to the tsunami.

From the report by the Weather News Company in September 2011 (Wethernews 2011), they conducted a hearing investigation soon after the earthquake from those who survived in the tsunami disaster area from May 18th to June 12th. From this report, the average evacuation time which means the time when one started evacuation from when the earthquake occurred was 19 minutes for those who survived, whereas 21 minutes for those who deceased. This means only a few minutes earlier action can save many lives. It is said that most of the people there thought the tsunami wouldn't come as usual because they experienced big earthquake several times before with tsunami waning every time but no tsunami hadn't come before. So it is no wonder that they thought the warning was just a routine work of the news program like before and evacuation starting was possible to be late. In addition, from this report we can find several reasons to prevent people from evacuating to the supposed safe place. The main reason was there were so many obstacles on the road like traffic jams or landslides that they cannot move smoothly (Fujiu et al. 2016). The tsunami speed was faster than their walking speed, so many were not able to reach the safe place. Another main reason was some of them went back to a dangerous area because they were going to help others like the aged people or their family (Mikami 2014).

Considering these data, we think if there is a safe shelter in the garden or the parking lot in the house or a small company, we can overcome those bad factors mentioned above. They can just go into the shelter as soon as a big earthquake occurs whether the tsunami is coming or not. It will take less than 10 minutes. A family can be in the same place. If they can be in the shelter, they don't need to use a car for evacuation so that the traffic jam will be alleviated.

On the other hand, there have been many projects that were supported by Japanese government or municipal governments like building Tsunami evacuation towers, building a long seawall along the coastline where is supposed the next Tsunami coming (Kihara et al.2014). But it is difficult to cover all area, so individual effort to prepare for the disaster by oneself is important.

Many concepts of Tsunami shelter have been proposed by many house makers or venture companies. Most of these shelters are designed as a temporary evacuation capsule to prevent people from drowning at encountering the first Tsunami, however few of them are designed considering the situation of surviving when the shelter starts floating on the sea after being washed away by the first or second Tsunami. So we developed a small lifeboat type.

2 THE TSUNAMI SHELTER

2.1 *Background of design concept of the shelter*

The shelter is designed reflecting some lessons learnt from the 3.11 earthquake. The massive flow of tsunami includes everything on the ground like crashed houses, cars, debris from factories or shops, and even big ships from near ports. If one can drift with these debris, the external force exerted to a drifter seemed endurable and the possibility of survival can be increased. Actually, there were some people who were on a floatable debris survived drifting with the flow. On the other hand, at one community center where was designated as an evacuation place when a big earthquake occurs, many elderly people gathered were drowned because tsunami was not supposed to come at that time. In this case, one of the authors heard soon after the tragedy from a student from the area that the victims were not only drowning. The aged people were whirled up to the beams of the roof of the community hall when the hall had filled with sea water. As the water ebbed rapidly while they were holding the beams that they had to hang down from the beam and fallen down from several meters high.

Considering these lessons, we decided to design the shelter can be floatable and should be strong while its drifting enough to protect people from the debris which can hurt human body like a sharp edged debris of metal or glass and so on.

Another lesson was prevention from hyperthermia and store provisions and necessities. Most of the evacuee lost not only their own house but also any community center by being washed away by the tsunami. More than 118,822 houses were totally broken. More than 184,615 houses were half broken. More than 386,000 of people had to spend several nights without any shelter under the condition that all route had shut down.

So our shelter is designed as a kind of small life raft and also to be habitable as a temporary house.

2.2 *The shelter*

The shelter is designed as follows.

- The buoyancy must be always positive even when the space inside is fully flooded, which means it never sinks.
- The shape is round not to stack a structure like a building or a bridge column while it is being flowed by the tsunami flow.
- It is watertight even if it submerges under 20m.
- If the shelter turns upside down, it recovers by itself. This is important because there is a very high chance of rolling on the ground while being washed away with the strong current.
- It has enough space for 8 passengers including provisions like water and food.

Considering above requirements, the principal dimensions is set as Table 1 and the final design are as shown from Figure 1 to Figure 4.

Table 1. Principal dimensions of the shelter.

Length	2.55 m
Breadth	2.14 m
Height	2.01 m
Number of passengers	8
Weight in air	4900 N

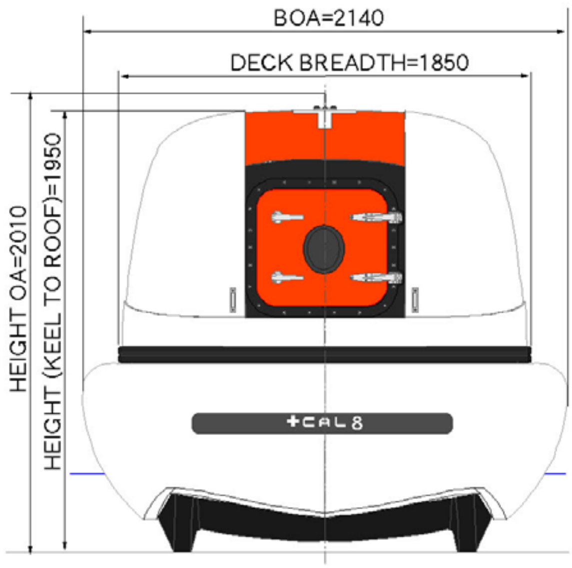

Figure 1. Front view of the shelter

Figure 2. Side view of the shelter

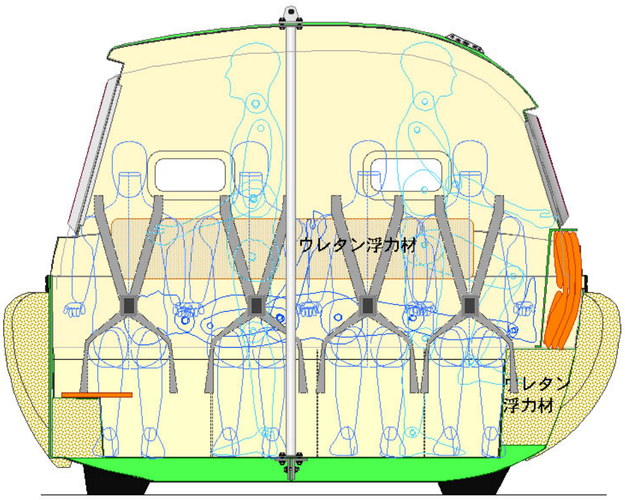

Figure 3. Passenger arrangement (side view)

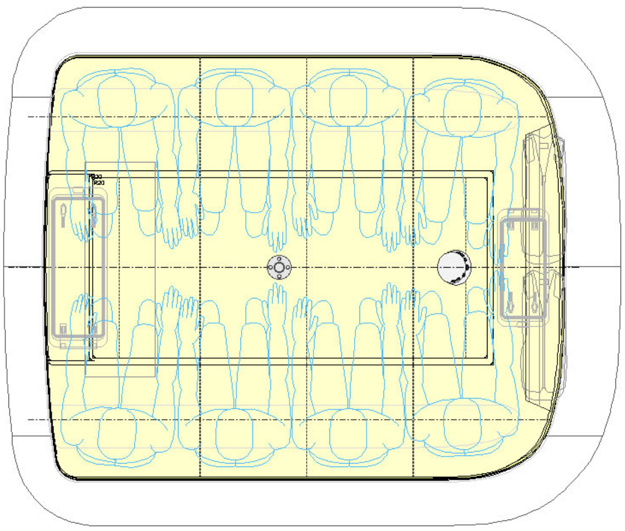

Figure 4. Passenger arrangement (top view)

The cabin is made of FRP. The lower overhanging part is made of urethane which yields enough buoyancy even when the cabin is fully flooded. There are two water tight hatches where the evacuees get onboard at front side and back side. A hatch can open and close both from outside or inside. For air ventilation, each hatch has a ventilating opening which can be closed from inside. It is possible that the evacuees get off the shelter on the sea to get on the rescue ship of the coast guard or defense force. So the hatch position is determined to avoid flooding while it is opened.

As shown in Figure 3, maximum eight passengers can get onboard. There are two benches inside and eight seatbelts are installed. The bench has a lid and it is used as a storage. The survival kit that includes water, emergency provisions, fishing tools etc. is settled in the bench. There are also a set of paddle inside the bench and the hull has two holes for paddling that can be closed from inside, so we can thrust the shelter manually using these paddles.

The hull was fabricated in a Chinese company which makes SOLAS adapted lifeboats. The wall thickness is almost twice as thick as a normal lifeboat. We designed the wall stronger than a life boat because the shelter is possible to contact with many obstacles like a floating car, destroyed houses or a column of a bridge while it is being washed away by the tsunami current.

The strength of the shelter body must be tested especially from the viewpoint of impact force exerted during tsunami. This is our future work.

3 THE SEA EXPERIMENT

3.1 *The purpose of experiments*

The shelter is designed to be able to survive in the tsunami current. So we believe the evacuee in the shelter can be much safer compared to the situation of 3.11 tsunami. The best story supposed is the shelter is transported to the higher place by tsunami current and it runs aground somewhere. The evacuee can live there for the time being.

However, if the shelter is flowed off the coast with the strong back wash, the evacuee in the shelter must drift on the sea until a rescue ship comes to tow them to the shore. As the size of the shelter is around 2 m, sea sickness might be a big issue. In addition, as the cabin is very narrow so psychological situation of the people in the cabin might be an issue. Furthermore, if many shelters are on the sea, a rescue ship has to tow several shelters and how many shelters can be towed at one time might be estimated to make a plan of collecting shelters in an appropriate period.

So the purposes of the sea experiment in this research are set as,

1 Evaluating roll, pitch motion in the sea.
2 Estimation of towing force for one shelter.
3 How do the evacuees feel in the shelter while drifting.
4 Temperature difference measurement between inside and outside.

The experiment was carried out on 16th January in 2019 in the Suruga Bay. The weather was fine but windy and around 1~1.5m swell was observed. It is towed by Tokai University's research ship "HOKUTO". We made a motion and position recording unit. The GARMINE GPS 18x 5Hz receiver is used as a GPS receiver. The roll, pitch and yaw acceleration, velocity, and angle are recorded with the GPS position. The GPS antenna is attached on the top of the shelter as shown in Figure 5. The radar reflector is also attached as shown in Figure 5.

Figure 5. GPS antenna and a radar reflector

Figure 6. Trajectory record in the experiment

The trajectory recorded in the experiment is shown in Figure 6. We confirmed the shelter can be found from more than 4 miles by radar.

Before sea trial, we measured how many seconds it takes for eight passengers to get into the shelter. When we get onboard using only one hatch, the average was about 55 seconds. If we use both hatches, the average was 35 seconds. As we tried several times, the time becomes shorter.

3.2 *The temperature comparison*

The temperature and air ventilation are very important for the shelter habitability. As mentioned earlier, more than 386,000 people spent a week outside in the cold air. To provide a shelter which protect people inside from cold wind or rain is very important. To know heat retaining property of the shelter, we measured both outside and inside temperature. Figure 7 shows the position of the thermo sensor inside of the shelter. Outside thermo sensor is attached adjacent to the GPS antenna.

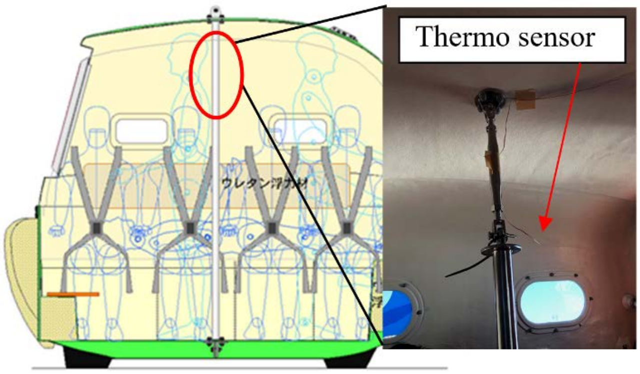

Figure 7. Thermo sensor arrangement inside

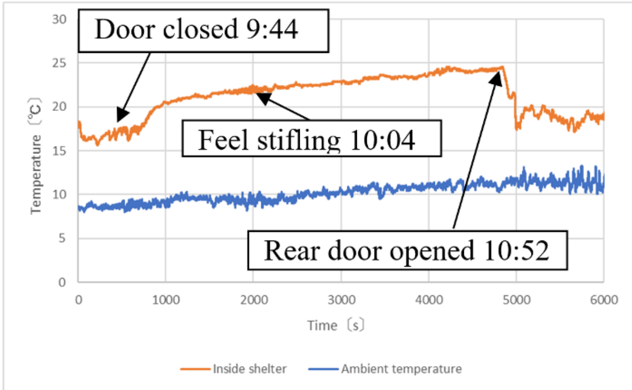

Figure 8. Temperature record of first 100 minutes

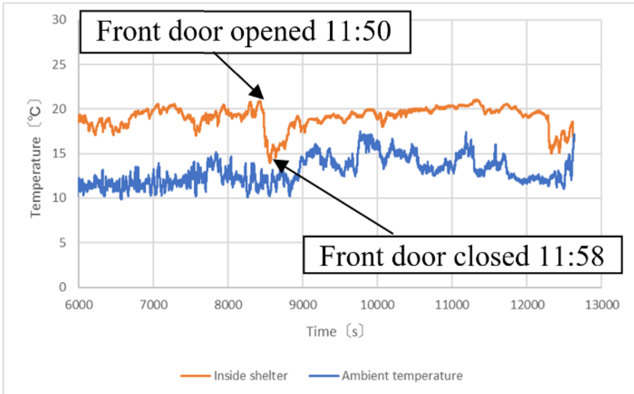

Figure 9. Temperature record of next 100 minutes

Figure 8 and Figure 9 are a series of temperature data. The orange line is the inside temperature. The blue line is the outside temperature. Eight passengers were onboard.

As shown is the Figure 8, we closed both hatches at 9:44 and started towing. After 20 minutes, around 10:04, everyone felt stifling. As the hatches have an air ventilation hole, we regarded ventilation would be enough and we would not feel stifling before this experiment started. However, we all felt bad air condition in around 20 minutes. The hole is small to be able to be closed easily to make it watertight. At 10:52, we all felt the inside air was endurable so we agreed to open the rear hatch. When hatch opened we all felt the air rapidly refreshed. From this experiment, we found the ventilation hole should be larger. As for heat retaining property, we found it satisfactory. As the Figures show, the inside temperature was kept around 20℃ regardless outside temperature was less than 15℃ in addition to the sea temperature was low in winter. When both hatches were closed, the inside temperature increased around 25℃. This is due to it was sunny on the day of experiment and eight men were inside.

As shown in Figure 9 if both hatches were opened

the temperature drops around the outside temperature in about 8 minutes. This also means the air inside can be ventilated within 10 minutes if we open both hatches.

From this experiment we confirmed that this shelter can be useful not only protecting evacuees from drowning or crashing in debris but also providing them with a warm and rain-sealed shelter. As the shelter stores at least minimum emergency food and water, it will keep evacuees from hyperthermia as well as dehydration.

3.3 *Motion characteristics while drifting on the sea*

The size of the shelter is determined as it can be placed in one's garden or a parking lot with keeping eight passengers. As a result, the size became as shown in Table 1.

This size around 2 m is so small that its motion on the sea is supposed to be relatively large. This will cause evacuees seasickness. The priority of this shelter is to survive from tsunami. So ride quality must be sacrificed. However, while waiting on the sea until the rescue ship from the coast guard is coming, the evacuees must drift freely on the sea.

So we conducted the free drift experiment and recorded motion data. For this experiment, we made a motion recording unit as shown in Figure 10. The motion sensor is AMU light 9 axis MEMS of Silicon sensing Japan Inc. All data were recorded in 5 Hz. The module was set around the middle of the shelter as shown in Figure 11. We can monitor whether the sensor and GPS are working from outside PC.

Figures 12-14 are roll, pitch and yaw angles while drifting. As Figure 12 and Figure 13 show, both roll and pitch amplitude angles were around 10 degrees. Those motion periods were from around 2 seconds to 4 seconds from FFT analysis. Figure 14 shows yaw angle. We can see it kept rotated. The combined motion made everyone feel sick. To improve its ride quality, we need to evaluate RAOs and compare it with our experimental results. This is our important future work.

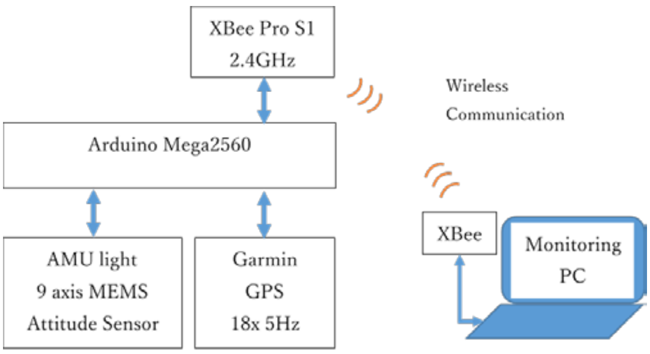

Figure 10. Sensor module architecture

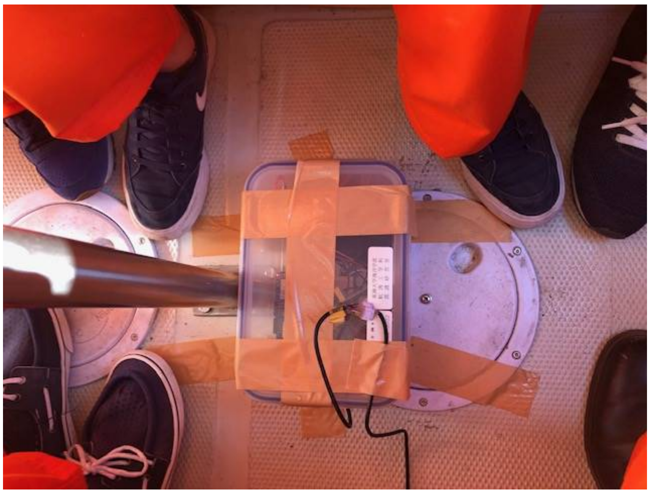

Figure 11. Motion recording unit setting

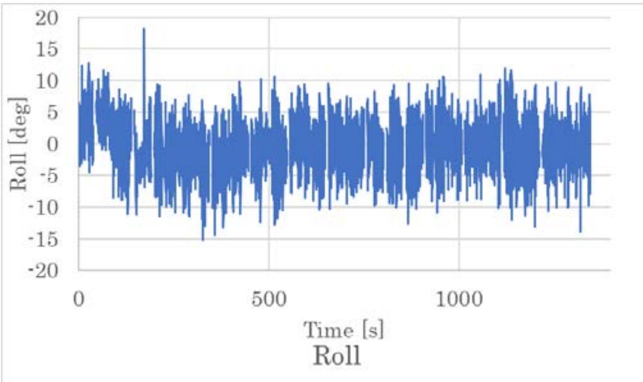

Figure 12. Roll angle while drifting

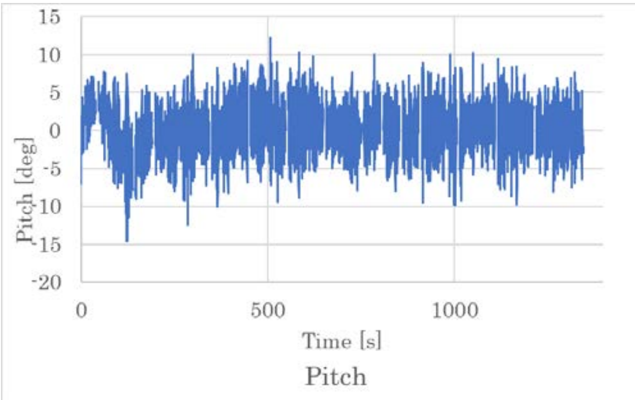

Figure 13. Pitch angle while drifting

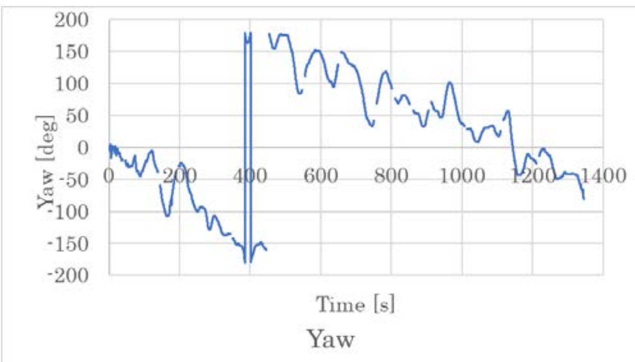

Figure 14. Yaw angle while drifting

Figure 15. Students feeling sick while drifting

3.4 *Towing force measurement*

The shelter must be recovered as soon as possible after a disaster ends. If many shelters are on the sea, how to collect them is an important agenda for a government. One possible story is gathering several shelters together and tows them by a ship from the coast guard or defense force. Towing force estimation is important for this story. So we measured the towing force while our shelter was towed as shown in Figure 16. The towing force was measured by a force sensor as shown in Figure 17. We read the sensor value every 600 seconds with the speed of the boat. The measured result is shown in Figure 18. The towing speed was kept constant around 1.5 m/s to 2.0 m/s. However, we measured fluctuation of the towing force, especially when the towing ship turned or the shelter front plunged into the water. To estimate the typical drag force coefficient of the shelter, we assumed the representative towing force can be estimated by the next simple drag force equation.

$$F_{towing} \equiv \frac{1}{2} \rho C_d A u^2 \quad (1)$$

where, ρ kg/m^3 is water density, u m/s is towing speed, A m^2 is a representative area, breadth*draft.

Figure 16. Towing experiment

Figure 17. Relation of towing speed and force

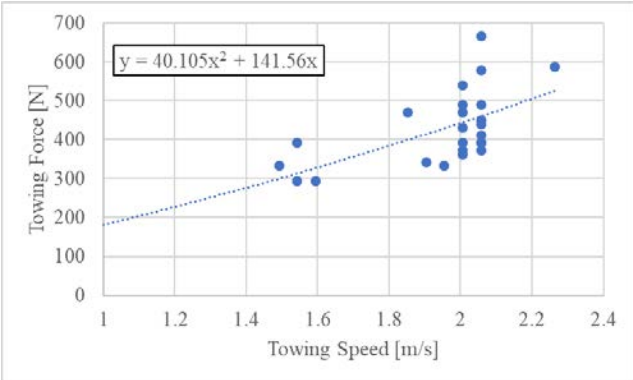

Figure 18. Towing force and speed measured

By using the approximate polynominal in Figure 18, we evaluated the typical towing force was 314 N at 1.5 m/s and 461 N at 2.0 m/s.

The weight of shelter itself is 4900 N and total passenger weight was around 6860 N. So we calculated the draft as 0.3m, then the submerged area was around 0.6 m^2. From equation (1) and the estimated typical towing force values above, we estimated the representative Cd value around 0.4 or 0.5. From this experiment, it turned out that the estimated Cd value of the shelter was much lower than we supposed.

When the towing speed was faster than 2.0 m/s, we in the shelter observed the front of the shelter sometimes plunged into the water. This seemed to increase the exerted area A in equation (1) so that the drag force becomes more than twice of the typical value. As the estimation here is very simplified one, so further investigation including 6 DOF simulation and experimental data accumulation should be our future work. As a primary study, we found the towing force was not excessive and a rescue ship can tow many shelters to the shore simultaneously with gathering shelters drifting on the ocean.

3.5 *Upside down test*

We can easily suppose that the first tsunami water might roll over the shelter and the shelter rolls several times on the ground before it is afloat. Personal safety inside is very important. As shown in Figure 19, eight seatbelts are implemented in the shelter. We planned the roll-over experiment in the shallow rapid river, but permission has not authorized yet.

Figure 19. Passenger seatbelts in the shelter

Figure 20. Upside down test in the pier

Instead, we carried out several upside-down tests in the pier. We suspended the shelter from a crane and rolled it over. While this test, we sat inside the shelter with seatbelts fastened. As the shelter was designed to be able to recover by itself on the sea, we were not able to turn it down 180 degrees because it somehow rolled back. However, we confirmed we managed to bear the upside down rolling situation inside without falling down from the head.

We realize more accelerated rolling situation should be investigated further. It is a little bit dangerous for us to ride on the rolling shelter, so we need to use dummy dolls to collect data exerted on a human body. This is also our important future work.

4 CONCLUSION AND FUTURE WORK

We conducted a sea experiment using the real tsunami shelter. It turned out that the shelter drag force is small enough, it can keep inside temperature higher than outside air in winter. The rolling and pitching motion were relatively large but we managed to bear. We also confirmed that its self-recovery from upside-down rolling situation. The hatch height seemed high for the elderly, so we need to modify it. Through the experiments in this study, we confirmed basic function of the shelter and it seems it will be helpful for protecting people from supposed tsunami.

This is our primary study and we found several important future work agendas as follows. Impact force test should be carried out to confirm its structural strength. RAO evaluation and motion simulation in various sea conditions should be studied. Fluid dynamical parameters like a drag coefficient should be investigated further to estimate its 6DoF motion and towing force. Inertial force applied to a human body while the shelter is rolling or smashed should be estimated by experiments.

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