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Loads on Structure and Waves in Ice (LS-WICE) project, Part 3: Ice-structure interaction under wave conditions

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ABSTRACT

A multi-group investigation was conducted at Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA) from Oct. 24 to Nov. 11, 2016 under the project: Loads on Structure and Waves in Ice (LS-WICE). There are three parts to this investigation: ice fracture under wave actions, wave attenuation/dispersion in broken ice covers, and ice-structure interaction under wave conditions. This paper focuses on the last part of the investigation in which a cylindrical structure was subjected to impact loads due to ice floes in regular waves.

The global loads from both only waves and combined ice/wave action were obtained. Waves with periods 1.5 s – 2.0 s and heights 25 mm – 75 mm were used in the tests. Two additional runs were performed with wave heights 100 mm and 200 mm and wave period 1.6 s; major fractures of the ice floes were observed in these test runs. All tests were well documented with help of pressure transducers, ultrasound sensors, accelerometers on the ice, load cells on the structure, an optical system and several cameras, which were covering the ice-structure interaction zone both above and under the water level.

KEY WORDS: Marginal Ice Zone; Waves; Loads on Structure; Model Tests.

INTRODUCTION

In the light of the observed climate change, Arctic marine structures may have to operate in Marginal Ice Zones (MIZ), in which the ice cover typically consists of individual ice floes formed by ocean waves penetrating into the ice field. Both vessel traffic and offshore structures may be subject to MIZ conditions, at least during a part of the ice season. Therefore, studying wave-ice interactions and their effects on a marine structure in such conditions is of practical importance.

A multi-group investigation was conducted at Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA) from Oct. 24 to Nov. 11, 2016 under the Hydralab+ Transnational Access project: Loads on Structure and Waves in Ice (LS-WICE). There are three parts to this investigation: ice fracture under wave actions, wave attenuation/dispersion in broken ice covers, and ice-structure interaction under wave conditions. This paper focuses only on the third part. Several accompanying papers at this conference present the other parts of the LS-WICE project (see Cheng et al., 2017; Herman et al., 2017; and Li et al., 2017).

DESCRIPTION OF THE EXPERIMENT

The experiment focused on studying combined wave and ice actions on a fixed structure represented by a cylinder with a diameter of 0.69 m. The structure was located approximately in the middle of the ice tank at 43.7 m from the wave maker as shown in Figure 1. The ice concentration near the structure was approximately 100%. Apart from the structure and the ice field, Figure 1 shows a number of sensors and video cameras that were used in the tests: 12 pressure sensors and 2 ultrasound sensors to measure wave height; Qualisys cameras and markers to monitor ice deflection; an Inertial Measurement Unit (IMU) to record the accelerations of an ice floe; video cameras on the ceiling, side walls, above the structure and under the water surface to monitor the ice cover and the ice-structure interaction area. A set of load cells that were installed inside the structure and fixed to a rigid carriage was used to measure loads on the structure. The IMU was installed at the centre of an ice floe adjacent to the structure to obtain the response in waves and impact accelerations (Figure 2).

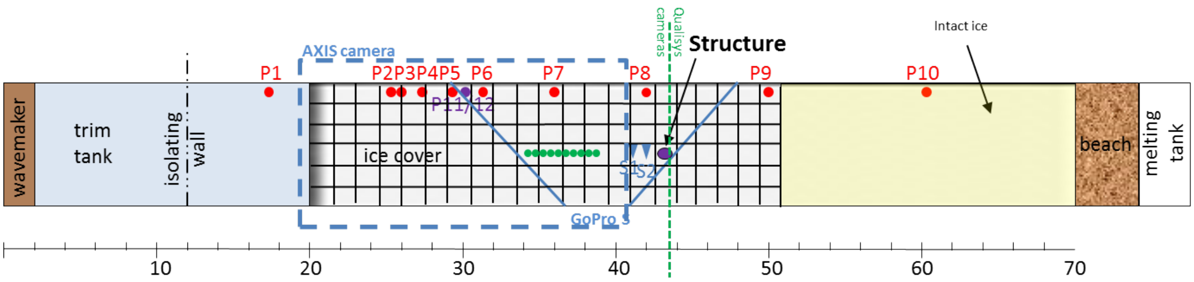

Figure 1. Layout of the wave tank and sensors. P1 – P10 are single pressure sensors, P11/12 – double pressure sensor, S1 and S2 – ultrasound sensors, continuous blue lines – fields of view of GoPro camera, dashed blue lines – field of view of the AXIS camera, continuous black lines – locations of longitudinal and transverse cuts (i.e., floe boundaries), yellow rectangle – a region, where no transverse cuts were done during the tests, green points – location of the Qualisys markers, dashed green line – approximate location of the Qualisys cameras and the IMU.

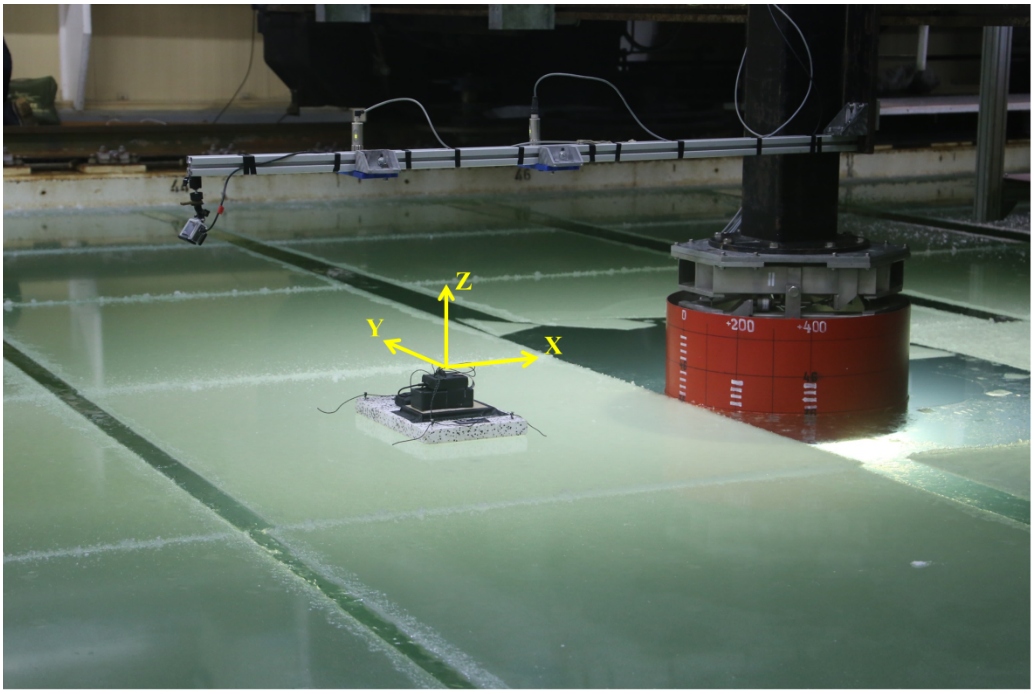

Figure 2. Structure and an adjacent ice floe equipped with an IMU. X shows the surge direction.

The procedure of producing the ice cover is described by Cheng et al. (2017). A level ice sheet was formed by seeding first to create a granular layer. Sustained cooling thickened this top layer by columnar growth until the whole sheet reaches about 0.035 m thickness. The Young's modulus, flexural strength, ice thickness, density and salinity were then obtained (Table 1). The choice of the ice properties was defined by the intention to have similar ice properties as in the tests of wave attenuation in broken ice (Cheng et al., 2017). The intact level ice was then cut longitudinally into six 1.6 m wide strips parallel to the wave tank wall. Transverse cuts were applied to create square floes of a uniform size.

Table 1. Ice properties.

Parameter	Unit	Mean Value
Thickness	m	0.035
Density	kg/m^3	924.8
Salinity	‰	4.0
Elastic Modulus	MPa	40.3
Flexural Strength	kPa	67.5
Compressive Strength*	kPa	200

* The compressive strength was not measured directly. It was obtained using a relationship between the flexural strength and the compressive strength for model ice as provided by HSVA.

Three test series were conducted with different wave periods between 1.5 – 2.0 s and three controlled wave heights between 25 and 75 mm at the wave maker. Two additional runs were performed with wave heights of 100 and 200 mm and a wave period of 1.6 s, during which major ice breaking was observed and therefore the IMU was removed. The water depth in the tank was 2.48 m (the deep-water section did not affect this experiment).

TEST SERIES AND RESULTS

This paper presents only a selected set of data obtained during the experiment. We mainly focus on the following parameters: the surge acceleration of the ice floe adjacent to the structure, a, and its oscillation amplitude due to waves, a_{amp}; additionally, the peak acceleration of the floe when it was impacting the structure, a_{peak}; the amplitude of the hydrodynamic wave force on the structure in the surge direction, F_{hd}; the surge force between the structure and the rigid carriage when the ice floe was impacting, R, and its peak value R_{peak}. The latter parameter is only used to indicate the impact load and cannot be directly interpreted as the total force on the structure due to waves and ice impacts; this is because the structure often responded to impacts at its natural frequency at approximately 10 Hz. This issue did not affect the measurements of F_{hd} as the wave frequencies were much below 10 Hz. Instead of using an inverse analysis of R to identify the actual impact force between the structure and the ice floe, this force was approximately calculated as $F_{imp} = -m^*a_{peak}$, where m is the mass of the ice floe. F_{imp} also includes the added-mass effects on the ice floe.

Table 2 summarises all parameters described above for the test series in which the ice floe adjacent to the structure remained intact, except for a small part of the floe crushed by the structure in the interaction zone. The controlled parameters in each test were the wave period T and the wave height at the wave maker. Instead of the latter, Table 2 presents the wave height H_{P8} which was measured by the pressure sensor located closest to the structure (see P8 in Figure 1); this is because of the fact that waves undergo attenuation in broken ice fields. Note that all parameters in Table 2 are related to the model scale.

Table 2. Controlled and measured parameters.

Run Number	**T [s]**	**H_{P8} [mm]**	**a_{amp} [m/s^2]**	**F_{imp} [N]**	**R_{peak} [N]**	**F_{hd} [N]**
4110	2.0	25	0.06	126	186	21
4120	1.8	22	0.2	122	169	20
4130	1.6	18	0.09	141	167	16
4140	1.5	16	0.14	110	159	21
4210	2.0	45	0.14	270	341	35
4220	1.8	40	0.13	289	360	35
4230	1.6	28	0.17	361	353	39
4240	1.5	27	0.26	379	276	41
4310	2.0	67	0.32	--	--	52
4320	1.8	55	0.26	319	438	55
4330	1.6	36	0.26	249	371	56

Typical time series of the forces obtained from the experiment are shown in Figures 3 and 4. The red curve is the surge force on the structure measured by the load cells, and the black force is the total force on the ice floe in the inverse surge direction, which was calculated as -

$m*a$. In these figures, the impact forces due to ice-structure collisions appear as long vertical spikes with positive peaks; spikes with negative peaks appear only on the black curves and are attributed to floe-floe collisions.

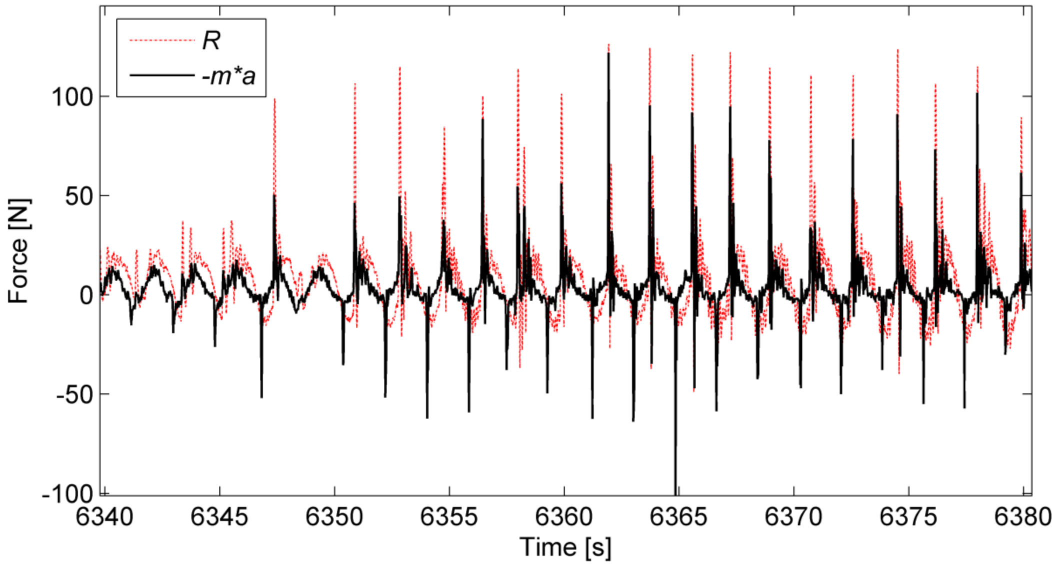

Figure 3. Time series of the surge force on the structure (red) and the inverse surge force on the ice floe (black) in Test 4120.

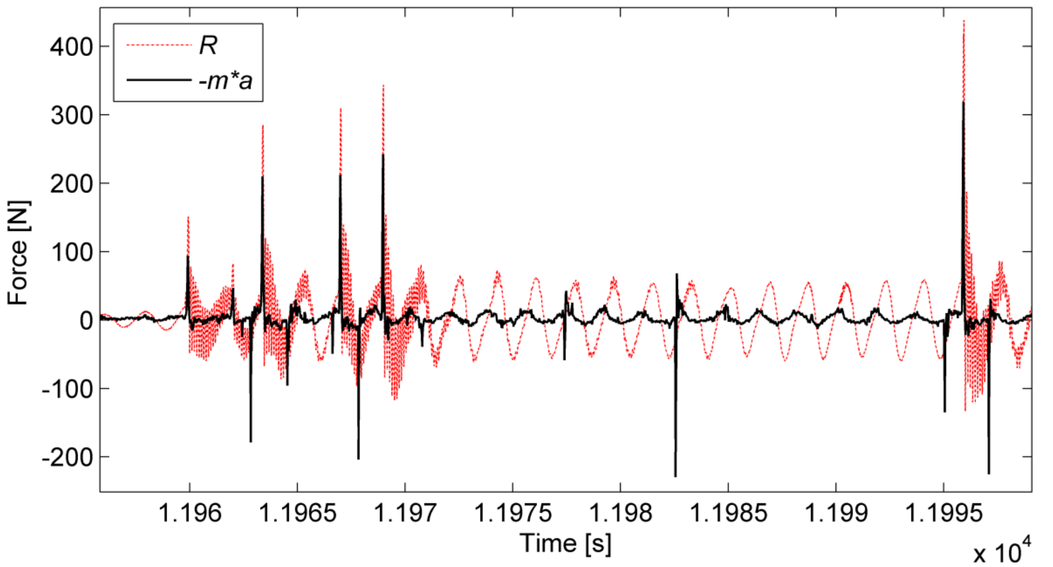

Figure 4. Time series of the surge force on the structure (red) and the inverse surge force on the ice floe (black) in Test 4320.

DISCUSSION ON THE FLOE RESPONSE NEAR THE STRUCTURE

The wave-induced motion of a floating body is usually presented in the form of non-dimensional response amplitude operators (RAO). The surge RAO of an ice floe is defined as

$x/(\frac{1}{2}H)$, where x is the floe motion amplitude in surge and H is the wave height. As the wave frequencies in the tests are known, x can be obtained by analytically integrating a_{amp} from Table 2. Figure 5 presents the calculated RAOs for the ice floe adjacent to the structure based on the acceleration data prior or between any collisions. The results are averaged for different wave heights and the bars show scatter around mean value.

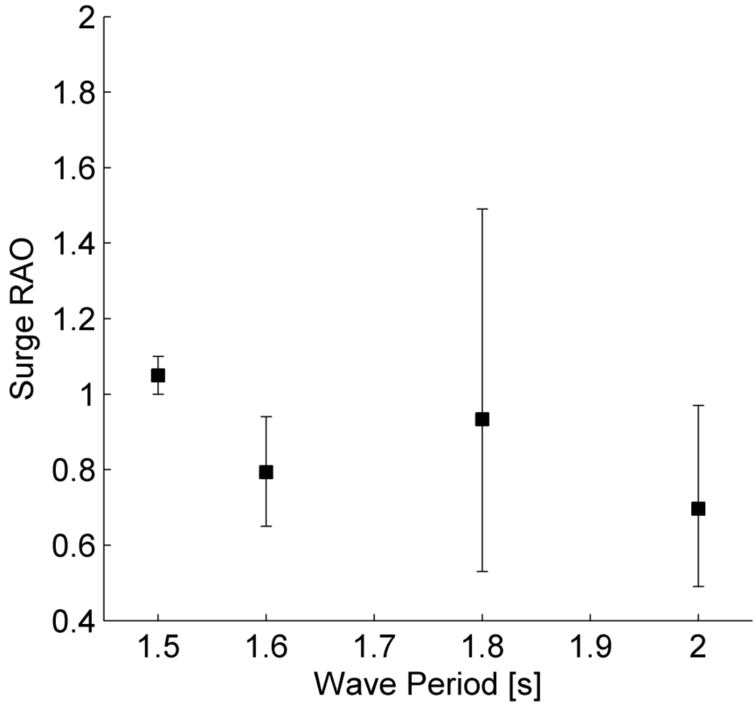

Figure 5. Surge RAO of the ice floe near the structure as a function of wave period.

According to Masson and LeBlond (1989), when the floe size is small compared to the wavelength, the floe tends to behave essentially as a fluid particle. For deep water waves, the water particle travels along closed circular orbits of radius $\frac{1}{2}H$, resulting in a surge RAO of 1. In our case, the obtained RAOs differ from unity because of several reasons: first, the wavelengths were only 2 – 4 times the floe size and therefore the long-wave assumption did not apply; second, the floe responses were also influenced by the presence of the structure due to the hydrodynamic interaction. The latter effect was thoroughly investigated by McGovern and Bai (2014) in a number of wave-tank experiments with a cylindrical structure and floes of different sizes and shapes. Their results showed that when an ice floe was in the vicinity of the structure, the floe's response in surge, regardless of whether there was an eventual impact, was markedly reduced compared to that in the far-field region. The surge RAO of the floe as it approached the cylinder decreased from 1.2 (in the far-field) to approximately 0.8 – 1 just before the impact. Similar results are also demonstrated in Figure 5 for the near-filed RAO.

DISCUSSION ON THE IMPACT FORCES

The experimental setup (Figure 2) ensured that all impacts of the upstream floe on the structure were nearly head-on. However, the impact occurrence in the experiment was not regular: in some tests impacts occurred almost at every wave cycle (e.g., Test 4120, see

Figure 3); in some tests impacts were rare (as shown in Figure 4 for Test 4320); in Test 4310 no impact was detected at all. As it was observed during the tests, impact occurrence seemed to be dependent on the initial separation distance between the floe and the structure and floe-floe interactions. No exact parametric dependence of impact occurrence was found.

As Table 2 presents, the impact forces F_{imp} were more than 5 times higher than the corresponding hydrodynamic forces F_{hd}. This was observed in all tests until the floe finally broke apart due to the wave action and impacts on the structure during Test 4330. There was a clear increase in F_{imp} with increasing wave height in all tests; however, the effect of wave period on F_{imp} is unclear. The increase in F_{imp} from Test 4210 to Test 4240 is most likely attributed to the increase of the interaction area between the floe and the structure due to crushing. Figure 6 shows how the crushed area was developing.

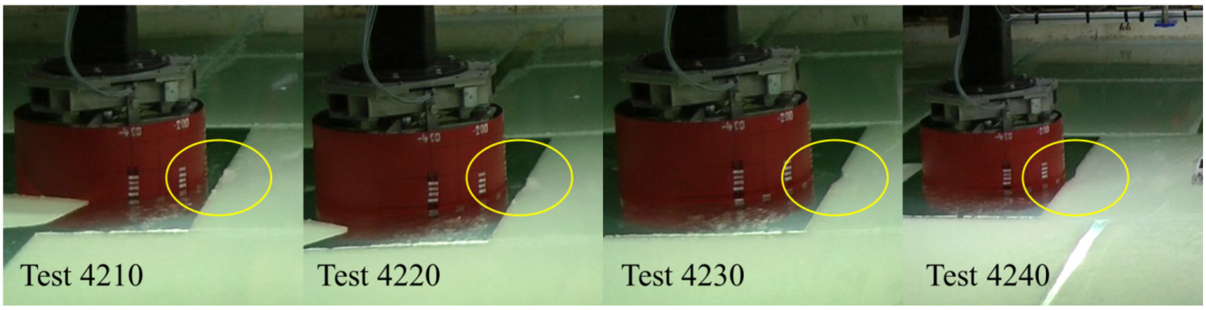

Figure 6. Increasing interaction area in subsequent tests.

As this paper presents only a preliminary analysis of the obtained data, no functional relationships were intended to be established between the impact force and the identified influencing parameters such as wave height and period, floe response in waves, floe-floe interaction prior to impact, penetration depth or interaction area. However, the range of data from the LS-WICE project allows a more thorough analysis that would result in such relationships.

CONCLUSIONS

A preliminary analysis of the LS-WICE data on wave-ice-structure interaction was presented. This analysis focused on both the response of a wave-driven ice floe near the structure and the forces on the structure due to both waves and ice impacts. Regarding the surge RAO of the ice floe, its mean values were not significantly different from 1 for all considered wavelengths. However, it was found that this RAO does not solely account for the variation of the impact forces on the structure and impact occurrence in the experiment. Floe-floe collisions seemed to affect impact occurrence as well.

Among the parameters influencing the impact force, we identified the following:

- wave height and period (also wavelength for shallow water);
- ice-floe kinematics in waves, including momentum exchange due to floe-floe interaction;
- interaction area between the structure and the ice floe.

The effect of ice properties was not assessed in this study. A major difference of this experiment compared to previous experiments on impacts of a wave-driven ice mass on a structure is the utilisation of a wave tank fully covered with ice floes instead of considering only one isolated ice mass and a structure. Full ice coverage ensures a better representation of MIZ conditions and allows taking into account floe-floe interactions and the wave dispersion effects in ice-covered water.

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