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ICE LOAD MEASUREMENT BY TACTILE SENSOR IN MODEL SCALE TEST IN RELATION TO RUBBLE ICE TRANSPORT ON ARCTIC OFFSHORE STRUCTURES **(RITAS)**

BY KARL-ULRICH EVERS & WENJUN LU

Ice is a rather brittle material, strong in compression but weak in tension. The magnitude of ice load largely depends on the corresponding ice feature's dominant failure modes and failure processes. Studying ice-structure interactions or icebreaking processes of icebreaking vessels require a good understanding on ice mechanics and ice failure processes.

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Physical experiments and numerical simulations are executed in ice tanks with focus on the spatial distribution of ice loads acting on offshore structures located in arctic or sub arctic regions. When designing arctic offshore structures or icebreaking vessels not only the global ice load acting on the structure is of relevance but also the spatial distribution of ice load (local ice pressure) is of interest for a safe and economic design.

When ice encounters sloping sided offshore structures it fails sequentially from breaking, rotating to submerging. Current offshore structure design practice does not differentiate such failure process in a procedural manner. Instead, all the ice load contributions from these failure processes are conservatively added up together to yield the final design load (*API_RP2, 1995; ISO/FDIS/19906, 2010*).

In the framework of the I3 Hydralab-IV contract a transnational access project "Rubble Ice Transport on Arctic Structures (RITAS) was executed in the Large Ice Tank at the Hamburg

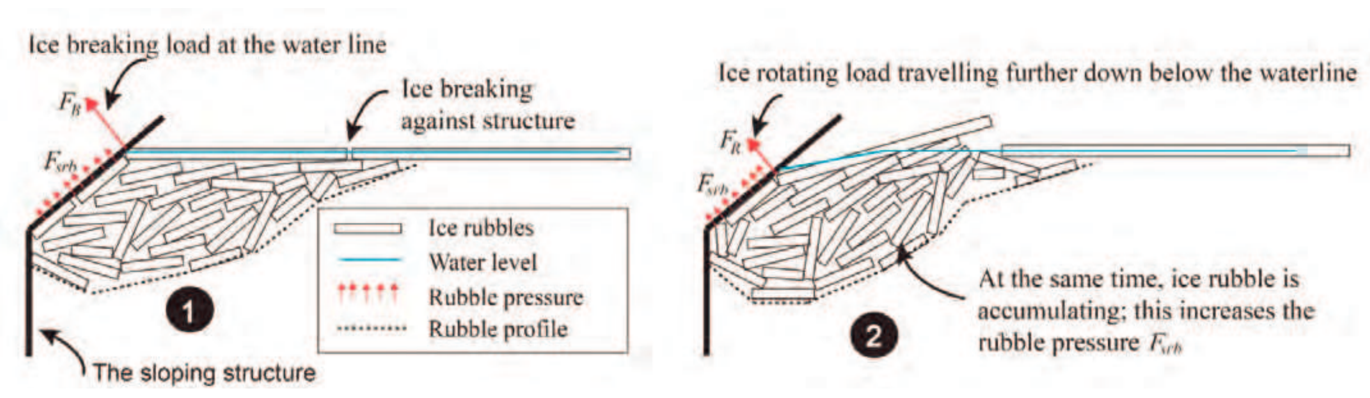

Figure 1 - Schematic diagram of interaction mechanisms between level ice and a wide sloping structure

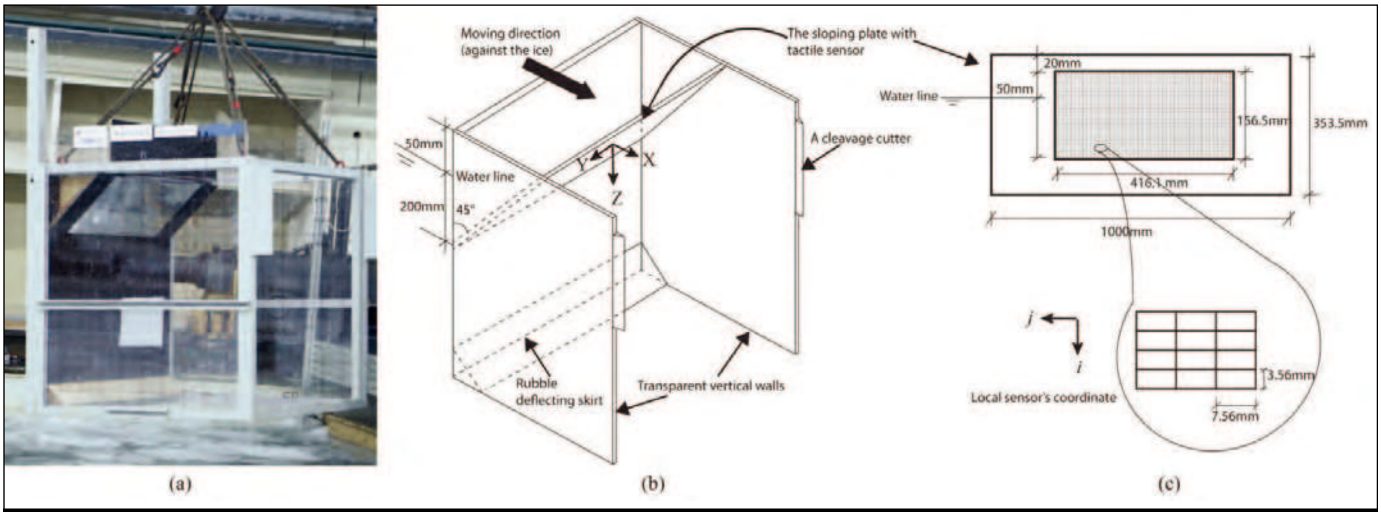

Figure 2 - Buoyancy box (a), schematic diagram of test set-up (b), tactile sensor mat (c)

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Ship Model Basin (HSVA) in Hamburg, Germany.

The objective of the study was to investigate the temporal and spatial distribution of ice loads on a wide inclined structure with the presence of ice rubble accumulation by application of tactile sensors.

Interaction mechanisms

Wide sloping structures have many applications in ice covered waters. Due to the relatively limited ice clearing capability of a wide sloping structure, the presence of ice rubble greatly influences the whole interaction mechanism *(Serré et al., 2013)*. The interaction mechanism between level ice and wide sloping structure could be categorised into three different stages *(Lu et al., 2014)*. A brief interaction mechanism is shown in *Figure 1*.

The first stage is the ice breaking stage (*Figure 1* ❶). In this stage, the incoming ice fails against the structure and a large ice breaking load is expected to be detected at the waterline.

The second stage is the ice rotating stage see (*Figure 1* ❷). As the broken ice fragment is travelling downwards, the corresponding ice rotating load is supposed to be measured below the waterline. The third stage is the rubble accumulation stage which occurs simultaneously with the previous two stages and is shown in both *Figure 1* ❶ and ❷.

The questions for the current problem are:

(1) Where exactly are these loads spatially located?

(2) What are the comparative values of these loads?

(3) How would these loads evolve with time?

A tactile sensor mat (sensor type #5513) produced by *I-Scan™ Tekscan Inc*. was installed on a sloping surface of a structure confined by two transparent Lexan™ plates. The geometry of the test set-up and the location where the tactile sensor mat is mounted are shown in *Figure 2*.

The operating temperature ranges from -9°C to 60°C; the pressure measuring range is within 0 to 175 MPa. This specific sensor has a rather long tail that ensures that the handle which connects the tail to the computer can be positioned far away from the water.

This sloping structure has been tested in different ice conditions with different ice thickness and different interaction speeds. The application of tactile sensor in all these tests follows generally three important steps which are described below:

Installation of tactile sensor (step 1)

During the installation, great attention has been paid to make sure that the tactile sensor is waterproof and protected against ice abrasion. To achieve this, the sensor was first put in between two plastic films adhered by silicone gel so as to make it waterproof. Afterwards, a metallic adhesive layer was applied above the sensor serving as the abrasion protection. This step is finished in the very beginning of the tests and no further repetition was made as long as the tactile sensor worked properly.

Calibration of tactile sensor (step 2)

Due to the complexity of ice-structure interactions, the ice pressure covers a very wide range of possible values. In the current tests, based on the chosen sensitivity and saturation pressure, tactile sensor tends to capture the ice pressure that repeats most often, saying the pressure that would be around the mean ice pressure. However, for extreme values, the sensor is prone to underestimate the extreme values. Even though, the merits of using tactile sensor in the current test should not be degraded. Tactile sensor will anyhow produce the contact area (i.e. the load's spatial variation) and comparative pressure irrespective of possible errors within its measured maximum values. The pertinent choice on tactile sensor's sensitivity and saturation pressure are made in the literature *(Lu et al., 2013b)*.

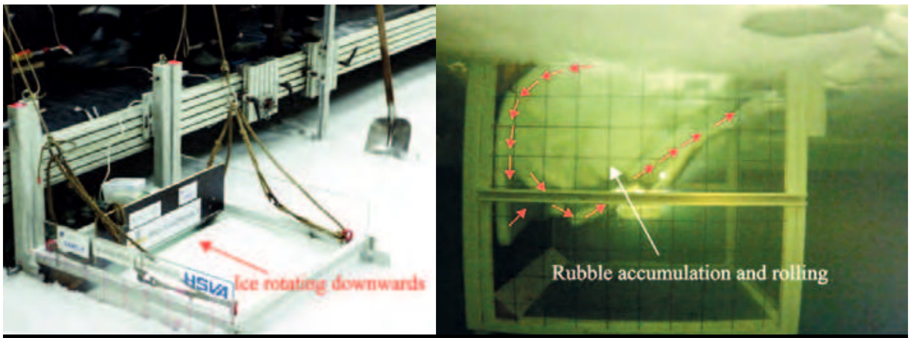

Figure 3 - Sloping structure pushed through level ice (a), the ice failed into fragments along the inclined plate and rotated downwards (left)

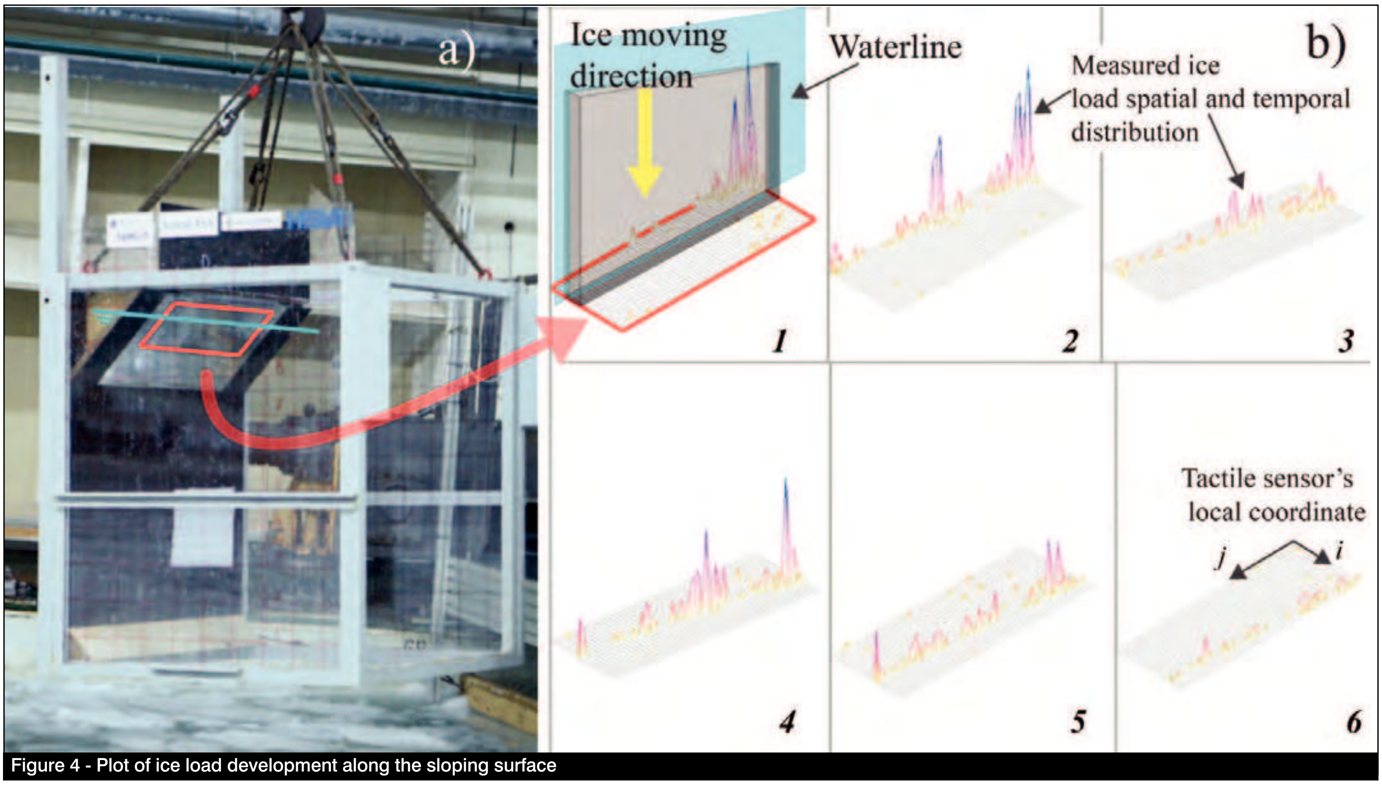

Figure 4 - Plot of ice load development along the sloping surface

Validation of tactile sensor in each test (step 3)
Before each test, the tactile sensor is again validated against several known weights so as to confirm its functionality (calibration check). In all the validations, errors between the measured results and the known weights were all within 15%. With all these three steps implemented, tactile sensor was successfully utilised in measuring the ice load (at least its spatial distribution).

Measurement visualisation

During different tests, the sloping structure in Figure 3 was pushed through level ice sheets in the ice tank. The ice failed into fragments along the inclined plate and rotated downwards *(Figure 3 b)*.
The spatial and temporal variation of the ice load is recorded by the installed tactile sensor. A real time ice load evolution can be exemplified as in *Figure 4* (different colours represent different pressure magnitude). This measurement illustrates one circle of the ice load development, i.e. the ice breaks at the waterline and rotates downwards. It takes approximately 3 seconds for such cycle to develop in *Test 1210*. It can be seen that, after the initial breaking of the incoming ice, the local pressure did not diminish instantly. Instead, the pressure keeps travelling down at a relatively smaller yet comparable magnitude.

Ice load's spatial variation

With the measured data as presented in Figure 5, it is possible to study how the ice load is distributed in the vertical direction (i.e., Z-direction or the short edge's direction of the panel in *Figure 4*).
Summing all the load recordings along the long edge's direction in *Figure 4*, we are able to present the time averaged ice load's spatial distribution as in *Figure 5(a)* and the maximum ice load's spatial distribution as in *Figure 5(b)*.

Since both the elastic foundation beam and plate theory suggest that the tip deflection at flexural failure is minimal comparing to the thickness of the ice, it would be reasonable to assume the ice breaking load (i.e. the load required to bend the incoming intact ice) is within the un-deformed level ice's thickness region (i.e. the shaded area in Figure 5). Note that inside this region, other interaction mechanisms such as the initial ice rotating and rubble effect also exist (Lu et al., 2014). As shown in Figure 5 (b) the maximum loads are mainly found within such shaded area. This agrees with our common sense and previous research assumptions that the ice breaking load is one of the decisive components of the ice load. However, as it is shown in the theoretical model (Lu et al., 2014; Lu et al., 2013a), the ice rotating load would also become decisive when there is sufficient rubble accumulated in front of the structure. For the time being, it can be simply concluded that based on tactile sensor's measurement, the maximum load often takes place around the un-deformed level ice's thickness region. The numerical simulation conducted by *Paavilainen and Tuhkuri (2013)* also detected the maximum ice load slightly below the waterline for gentle slope angles.

Ice load's spatial and temporal variation

Among all important findings based on the measurements from tactile sensor, it is interesting to illustrate the ice load's spatial and temporal variation as shown in *Figure 6*.
It can be seen from *Figure 6* that generally most of the recorded loads in the vertical direction increase with time. This underlines the importance of rubble accumulation. Moreover, below the un-deformed level ice's thickness region, i.e. below bin number 3 and 4, the recorded ice load also increases with time and may become even more significant than the process that occur within the un-deformed level ice's thickness region. This further strengthens the point that the accumulated rubble together with the ice rotating process intensifies the ice load under the un-deformed level ice's thickness region.

Though *Figure 5* and *6* are presented with absolute values of the ice load, caution should be made on the reliability of tactile sensor's measurement since it does not have the same accuracy in all the measuring range. In this test campaign, the tactile sensor was calibrated to capture the mean ice load with a higher accuracy than the maximum ice load. Therefore, the measured absolute value of the mean ice load can be assigned a higher confidence. Furthermore, tactile sensor's capability in measuring the ice load's spatial distribution as in *Figure 5* and *6* supplied valuable information in investigating the pertinent questions regarding spatially load distribution and load evolution with time.

Regarding the sensitivity of measurements with the loading area size, this test campaign was not able to avoid this problem. However, considering the fact that most of the time, the effective ice load behaves a 'line-like' distribution as shown in *Figure 5*. Significant variation in contact area is not expected. Therefore, we can have a higher confidence in the measured value irrespective of this unsolved disadvantage of tactile sensor.

In a further analysis of the measured data in the RITAS project (Lu et al., 2014), we have utilised load cells' measurement to compensate the inaccuracy of tactile sensor's measurement in the maximum ice load range. From experiences made we recommend to use a combination of both measuring techniques in order to obtain most reliable results.

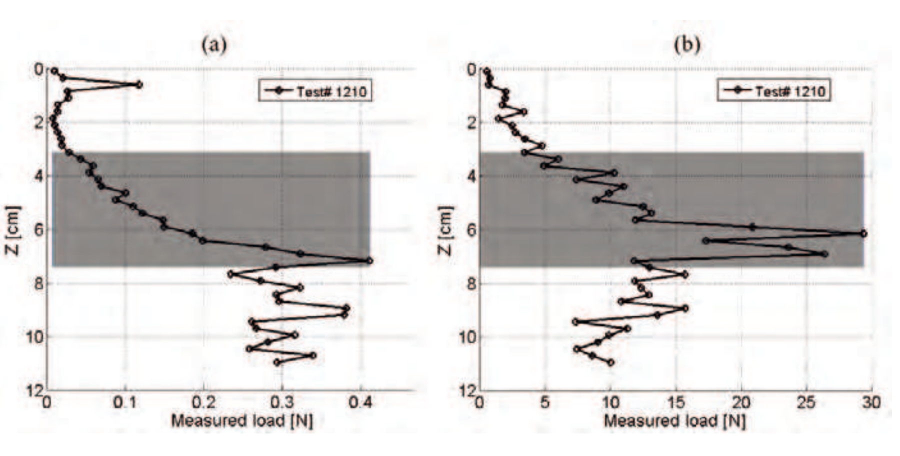

Figure 5 - Time averaged ice load (a) and time history of maximum ice load variation in vertical direction of sensor (b), shaded area is the location of un-deformed level ice

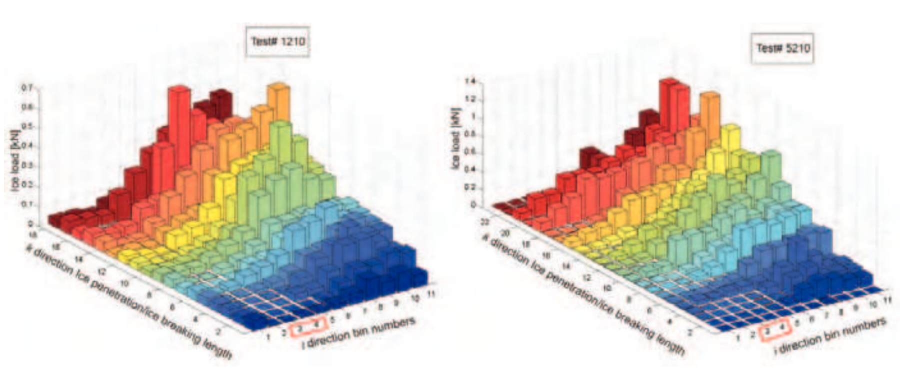

Figure 6 - Vertically spatial and temporal ice load distribution (bins 3 and 4 in the red square indicates approximately the location of un-deformed level ice)

Conclusion

In the study carried out tactile sensors were used to investigate the interaction mechanism between level ice and a wide sloping structure in particular the temporal and spatial distributions for different test scenarios.

Based on these physical experiments we can conclude:

- During the interaction, after the breaking of initially intact ice, the recorded ice load does not diminish instantly. Instead, the ice moves continuously downward with a relatively lower load magnitude (see Figure 4). This is considered due to the effect of ice rotating load in combination of the accumulated rubble effects.
- Based on the mean ice load's (i.e., averaged in time) vertical variation, it is found out that equally large ice load can be detected beneath the un-deformed level ice's thickness region (see Figure 6a). As discussed above, the contribution of this large ice load is mainly due to the combined effects of ice rotating load and the rubble accumulation;
- Generally the recorded maximum load acts at the un-deformed level ice's thickness region (see Figure 6b). The ice breaking occurs mainly at the waterline region. This is in line with previous experiments and assumptions that the ice breaking load is one of the decisive loads regarding design.

With respect to the utilisation of tactile sensor in this test campaign, it can be concluded that tactile sensor is beneficial in displaying ice load's relative spatial distribution while its magnitude should be treated with caution. A measurement system which combines both tactile sensor and the conventional measuring technique (e.g., measuring by load cell) tends to offer a better understanding on the ice load's spatial and temporal variation.

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