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A SYSTEM TO MEASURE ICE ACCRETION MASS

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ABSTRACT

Marine icing is ice accumulation on vessels and offshore constructions which endanger marine operations. To avoid or reduce icing it is important to understand this physical phenomenon and to be able to forecast it. However, measurements of marine icing are scarce and most of them were done manually with poor time resolution. There are no standardized sensors for marine icing measurements. A new system consisting of load cells was developed and applied in a field experiment. The system made it possible to measure spray flux and mass increase of the ice accretion with a time resolution of less than a second and high precision. This paper presents this system and the results obtained in the field. It also suggests a further modification of the system which can be used for autonomous measurements of ice accretion rates on vessels or offshore constructions.

INTRODUCTION

A number of methods exist to measure droplet size and liquid water content for atmospheric icing ranging from simple systems such as Multi-cylinders (Makkonen, 1992) to expensive tools (http://www.dropletmeasurement.com/products/airborne) which are designed to be used on airplanes. The small droplet size and relatively low density of spray makes the task simpler compared with the measurements of sea spray icing. Main complications associated with sea spray measurements are high spray density, larger droplet size (approximately 0.5-6 mm, see Ryerson (1995)), corrosion caused by salt, and vessel movement. In addition, it is desired to have an automatic system which excludes manual and costly offshore operations. Certain attempts were made to perform measurements using napkins, cameras and spray collectors (Jørgensen, 1985; Ryerson and Gow, 2000; Ryerson and Longo, 1992). Similar equipment was recently developed by Sintef but no measurements were performed offshore (Leirvik and Daae, 2010). To date, there is no standard technique or equipment for the measurements of the sea spray. The ice thickness was also measured only visually or manually.

It is also important to note that some researches raise the problem of unknown ice density and its variability. Even though the variation is small and within 15% from the mean value of 805 kg m^{-3}, i.e., 690 – 920 kg m^{-3} (Ryerson and Gow, 2000), the direct measurements of mass are preferable. It is the mass and not the thickness which causes ice load. In addition, heat balance equations and icing model predicts the ice accretion mass, which is later recalculated into thickness. Therefore, it is more valuable for model validation to measure ice mass.

The idea to measure ice mass is not new. An attempt to measure the ice accretion by measuring its load is described in Lozowski et al. (2002). However, the measurements were not very successful. The system could not register light or moderate icing events. Only one sever icing event was measured because the system was designed to tolerate significant ice load caused by ice thicknesses up-to 50 cm. The load cells were connected to heavy metal plates which required significant capacity from the load cells. In addition, no precautions were made to avoid ice bridge build-ups between the stationary and moving parts which may have obscured the mass measurements.

This paper presents a system successfully used in field experiments on Spitsbergen to measure ice accretion mass in real-time. The following section presents a suggestion of the mass measurement system to be applied offshore and it is followed by a summary.

REAL-TIME MEASUREMENTS IN THE FIELD EXPERIMENTS

The system presented below was used in field experiments performed in Spitsbergen at a range of wind speeds up to 10 m s^{-1} and an air temperature down to -25°C, see Kulyakhtin (2014) and Kulyakhtin (2013) for details. The mass measurement system is shown in Figure 1. Ice accretion was measured on horizontal cylinders with lengths of 300 mm and diameters of 20, 40 and 100 mm exposed to freezing saline spray. A cylindrical structure was used for the measurements because the airflow and the heat transfer around cylinders are well studied. The ends of the cylinders were attached to metal rods with diameters of 10 mm. The ends of the rods were placed on plastic arms connected to load cells, which continuously measured the mass of the cylinder including the accreted ice and unfrozen water (Figure 1). A shield concealed the load cells (ice protection cover in Figure 1) from the spray to prevent icing of the load cells. Only the cylinder and 15 mm of the rods on each side of the cylinder were exposed to the spray. The gap between the cylinder and the shield was sufficient to prevent the ice on the cylinder from coming into contact with the shield. In addition, the ice on the front part of the shield was removed every 20 min to avoid bridging between the shield and the cylinder.

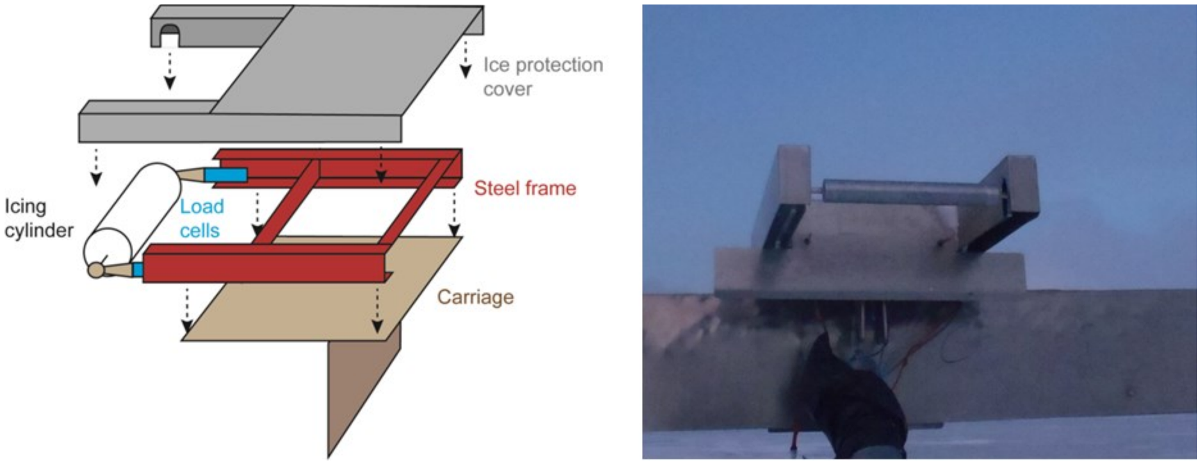

Figure 1. Sketch and photograph of the system for the real time mass measurements.

The mass on the cylinder was measured by HBM (Hottinger Baldwin Messtechnik) SP4MC3MR/1kg load cells designed for a maximal load of 1 kg. Each load cell has an accuracy of 0.3 g. For high accuracy mass measurements reliable and accurate electronics is essential. Initially a Campbell CR1000 data logger was used for data recording. However, it did not give the desired accuracy, and thus, an HBM setup was used. The HBM setup consisted of an amplifier MX440 and a data recorder CX22-W. The load was recorded with a 20 Hz frequency and the combined accuracy of two load cells was 0.7 g. After the end of each experiment the cylinder with ice mass was removed and weighed separately to verify the accuracy of the load cells.

Figure 2 provides an example of the time series of the accretion mass (water + ice mass) on the cylinder measured by the load cells for 3 spray periods. Such measurements can be used to validate the time-dependent models of sea spray icing. The data for each single spray period can be analysed separately. The steps distinctly correspond to an increase in mass due to the spray flux. The monotonic decrease after each step corresponds to the water run-off.

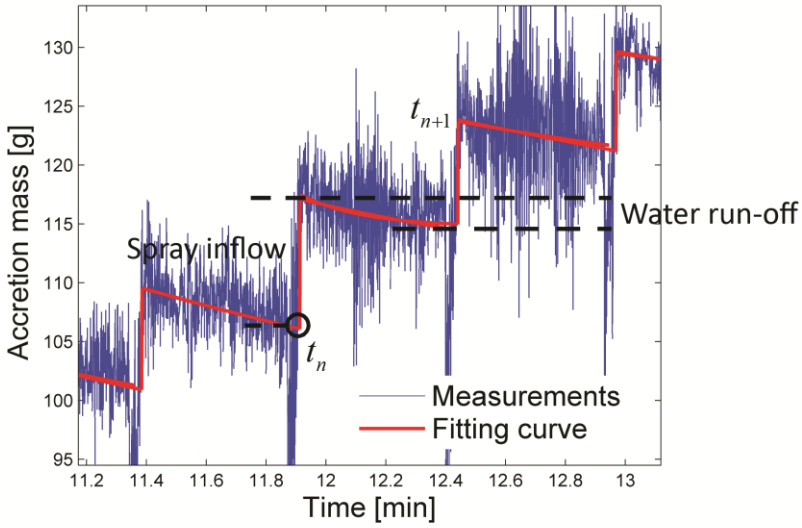

Figure 2. Measured signal and curve fitted to illustrate different processes during the ice accretion in Test 60.

The signal fluctuation was induced by the impinging spray, motion of the carriage along the rail (see Kulyakhtin (2014) for details), and lift force due to the wind. The fluctuating lift force on the cylinder can be calculated as follows (Zdravkovich, 1997):

$$F_L = 0.5 C_L \rho_a U^2 DL \qquad (1)$$

where C_L is the lift coefficient, ρ_a is the air density, U is the wind speed, D is the cylinder diameter, and L is the cylinder length. Most of the experiments were performed in the Reynolds number range from 10^4 to 10^5 where the lift force coefficient unfortunately takes its maximal value of 0.1 – 0.8 (Zdravkovich, 1997). In the case of a 100 mm diameter cylinder and a wind speed of 3.8 m s^{-1} (conditions of Test 60) calculations give values of 4 – 34 g for the amplitude of the lift force, which are similar to the observed values (Figure 2). This shows that the measured noise is actually wind induced vibrations.

For the rest of Reynolds number range, the lift coefficient is significantly lower and as a consequence the produced noise is lower too. Variation of lift coefficient may be considered in the design of the system for offshore measurements. A vertical orientation of the cylinder may reduce wind induced vibrations as well.

Fortunately, the mean lift force is zero and therefore, it is easy to filter out these oscillations. Figure 3 shows the measured signal after application of a median filter. It may seem that the mass measurement system allows observations of exact spray inflow in addition to the measurements of the accretion rate per each spray event. However, this system only shows the maximal water amount which stays on the cylinder during the spray event. This amount is always lower than the actual spray inflow. This is because part of the water runs off the cylinder before the end of the spray event. The actual spray inflow is only measured when the run-off is zero. That happens during the first spray events when the surface of the cylinder is clean from the ice and all incoming spray rapidly freezes due to the heat absorption of the cold cylinder (see Figure 3).

Table 1. Conditions under which the experiments presented here were performed.

	Test 60 (Figure 2)	Test 56 (Figure 3)
Air temperature [°C]	-11.5	-11.2
Cylinder diameter [mm]	100	40
Average wind speed [m s^{-1}]	3.8	2.6
Reynolds number	29000	8000
Relative humidity [%]	74	71
Interval between starts of sequential spray events [s]	31.7	31.7
Duration of spray events [s]	1.9	1.9
Approximate spray inflow per spray event [g]	10 – 20	10 – 20

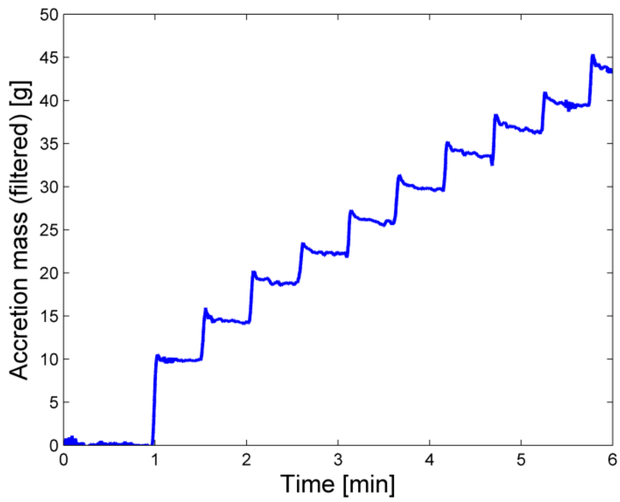

Figure 3. Measured mass of the ice accretion in Test 56 after application of median filter.

SUGGESTION FOR OFFSHORE APPLICATIONS

The main problem of the system used in the experiments is that it required to be cleaned every 20 – 30 minutes. Otherwise the cylinder would freeze to the shield. A slightly modified version of the system could be used offshore. The sketch of the system is shown in Figure 4. The main difference is that the cylinder is oriented vertically and can be cleaned automatically by heating.

The system is designed to measure ice accretion mass only on the cylinder, which is marked with a red label (Figure 4). The actual size of the system may vary depending on the location on the vessel or rig and on the expected spray flux. Approximate dimensions are given here in order to discuss objectively the factors that need to be taken into consideration. An approximate diameter of the cylinder is 80 mm and only 350 mm of the total length of 520 mm are exposed to icing. The rest of the cylinder is hidden by the shield. A distance of 120 mm between the lower edge of the shield and the lower part of the support is to assure that no icing occurs between the support and the cylinder. Any ice build-up between the support and the cylinder would cause error in mass measurements. 120 mm distance is rather large but it is important to keep it large to assure that no droplets will reach the support. This is also achieved by keeping the gap between the cylinder and the shield small, only 30 mm, thus, reducing any possible air circulation between the shield and the cylinder. However, the lower limit of the gap size is set by the requirement that potential icicles from the shield would not come into contact with the cylinder.

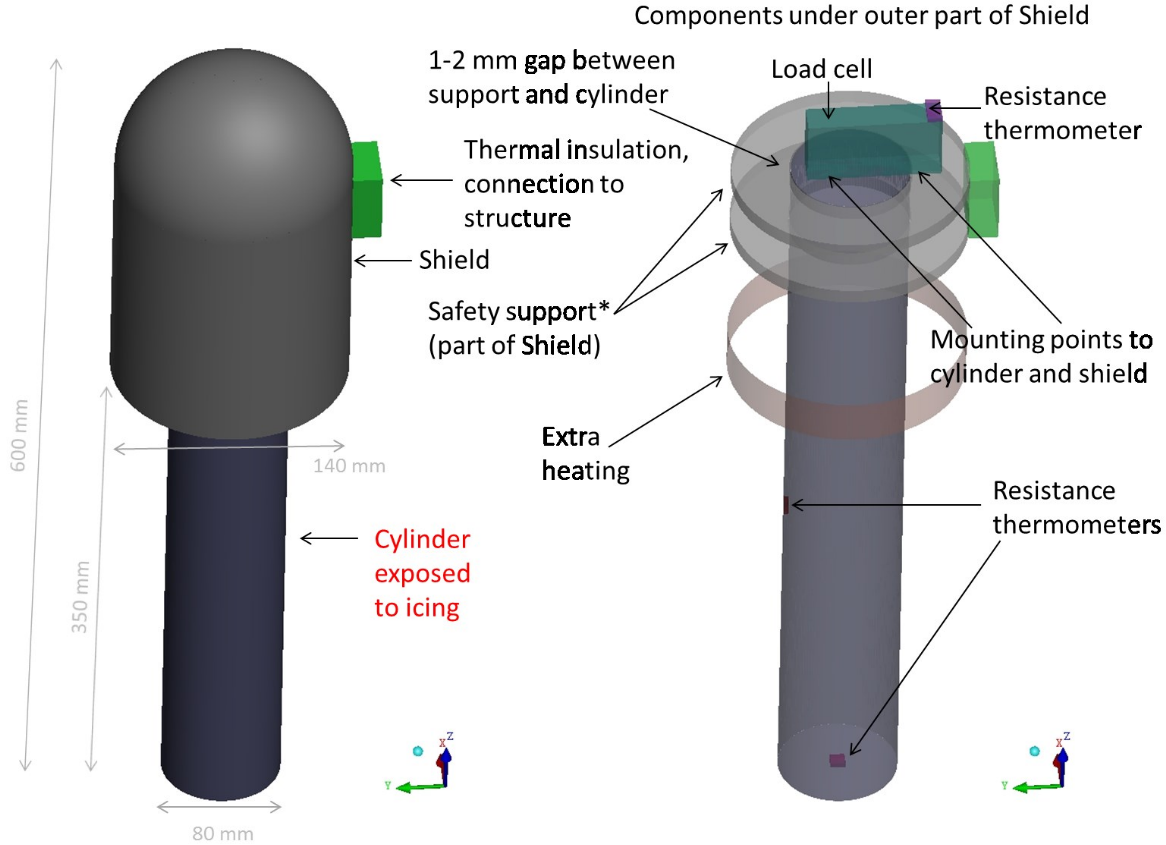

Figure 4. Sketch of a system for ice accretion measurements in offshore conditions.*The safety support is connected to the shield which is removed from the right picture. The shield protects the load cell from the ice.

The mass of the cylinder sets limitation on the resolution of the system. A hollow cylinder with the described dimensions may be made of aluminium and the total mass of such a cylinder can be less than 1 kg. We design the system to measure a maximum ice load of 1 kg (which corresponds to approximately 1.1 cm thick ice uniformly distributed on the circumference of the cylinder, i.e., one third of the gap size). A typical load cell with a C3 class of accuracy and a maximal load of 2 kg can measure mass with an accuracy of 0.7 g (corresponds to an ice thickness of approximately 0.01 mm) and will yield a high resolution of the ice growth process over time.

An ice load higher than 1 kg should not be measured, due to potential creation of icicles on the cylinder. The icicles change the geometry of the cylinder and over complicated physics of the ice build-up for future model validations. In addition, the load should be restricted to avoid building of bridges between the shield and the cylinder.

Two supports surrounding the cylinder are designed to protect the load cell from the force caused by any massive water splashes coming in the direction normal to the cylinder surface, which may potentially overstrain the load cell. Therefore, the gap between the supports and the cylinder is only 1-2 mm which is less than the strain of the load cell under the load of the cylinder.

The high resolution of the system sets the limits on the maximal load as was described before. To avoid building of the ice mass above a given load (e.g., 0.8 kg), the system is periodically cleaned from the ice by heating elements which are installed inside the cylinder and on the inner surface of the shield. Extra heating is applied on the lower edge of the shield to remove icicles and to keep that area free from any ice bridges. The cleaning of the rest of the cylinder or the shield is less important.

Powerful heating elements are to be used in order to rapidly clean the system by creating a thin layer of melted water between the cylinder and the ice. In this case, the ice will fall from the cylinder before melting completely. To avoid heat loss to the structure, a thermal insulator is installed between the system and the structure. Any type of mounting can be used including clamping to the rails.

Three resistance thermometers are applied. Two thermometers installed inside the cylinder are used to measure the cylinder temperature to have a control over the conductive heat flux during the ice growth and the freezing temperature. The thermometer mounted on the load cell is used to control heating and to avoid exceeding the maximal storage temperature of the load cell, which, for example, for some HBM load cells is 70 °C.

The heating elements should be supplied by power periodically, independent of the ice growth and when the ice mass on the cylinder exceeds 0.8 kg. The heating should be paused when the temperature of the load cell reaches 70 °C and should be stopped completely when the ice and water mass on the cylinder approaches zero. Therefore, a data processing unit will be required for the system to operate.

To evaluate sensitivity of the described system we compare the maximal design load and system resolution with available data of spray inflow. There are several equations describing spray inflow on different structures. For example, a several orders of magnitude difference is predicted by RIGICE04 (Forest et al., 2005) and ICEMOD (Horjen, 1990) icing models (Figure 5), see Appendix F in Kulyakhtin (2014) for details.

Let us consider a spray flux of the RIGICE04 model which is in the range from 10 to 10^4 kg m^{-2} hr^{-1} for elevations of 5 – 35 m, depending on the wind speed and that all incoming spray freezes. The ice will likely grow only on one side of the cylinder, and thus, effectively the cylinder will collect ice as a rectangle with dimensions of 0.08 x 0.35 m. The increase of the ice mass on the cylinder therefore will vary from 0.28 to 280 kg hr^{-1}. Approximately once an hour or less often heating of the cylinder is reasonable otherwise the growth rate will be highly affected by the heating or cooling of the cylinder. In general, frequent heating is also a controllable condition in subsequent modelling and the data collected even in such case will still be valuable. This conservative estimate for the spray flux shows that the mass measurement system can be used at elevations above 20 – 25 m, which is similar to the elevation of the main deck of a rig (see for example offshore rigs considered in Jones and Andreas (2012), and Kulyakhtin and Tsarau (2014)). In contrast, when applying spray flux computations from ICEMOD, the system presented here can be used for any elevations.

Therefore, it is better to use a system designed for lower spray inflow which will be able to register minor icing events.

On the other hand the spray flux is always higher than the ice growth rate. Observed icing events on offshore rigs typically produce ice with a maximal thickness of less than 10 cm (Brown and Mitten, 1988) and the typical duration of the icing event is 15 hours with a standard deviation of 13 hours (Brown and Agnew, 1985). Thus, for a typical icing even only one cleaning per hour is sufficient, and therefore, the suggested sizes seem suitable.

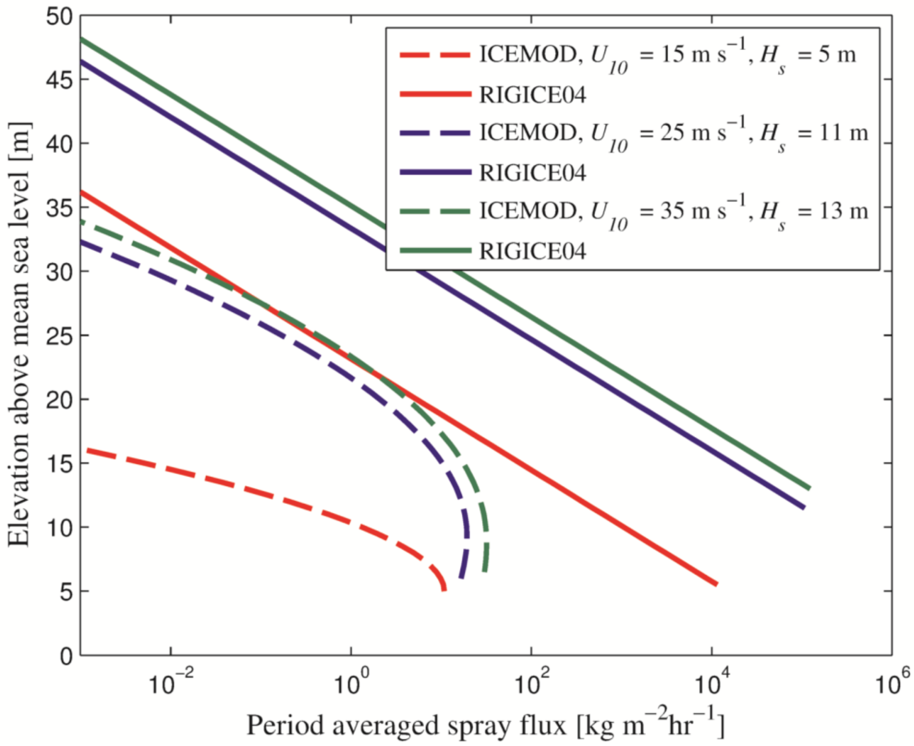

Figure 5. Typical values of the spray flux used in icing models.

In general, the size of the system or the capacity of the load cells can be easily varied to fulfil the criteria for any given elevation. The only way to find suitable parameters is to test such a system offshore, which is a relatively inexpensive operation considering that the components of the system are cheap and the operation of the system can be fully automatic.

The system described above can be used on board of any rig or vessel where water spray flows in horizontal or downward oriented direction. It cannot be installed on the rig parts where the spray flies upwards after interaction with the structure. To be applied there, the orientation of the system would have to be changed to almost horizontal with the outer shield pointing away from the structure. In addition, following the multi-cylinder approach by Makkonen (1992) used in atmospheric icing, different size cylinders can be used for collection of droplets of different size.

To use the measured ice growth for the validation of an icing model, the system should be accompanied with the measurements of weather conditions such as wind speed and direction, air temperature, and air humidity. In the case of offshore conditions it should also include measurements of wave parameters and vessel movement including acceleration with high time resolution. The latter is also required for the data analysis of mass measurements to exclude the noise induced by the vessel movement. In addition, as it is explained in Kulyakhtin (2014) the heat conduction and heat capacity of the icing object are important factors in the case of the ice growth caused by periodic sea spray. Therefore, the temperature of the icing object must be measured too. It can be argued that a material with low heat conductivity may resolve this problem. However, as soon as a certain amount of ice will appear on the cylinder, its heat capacity will affect the ice growth. Therefore, the measurement of the ice accretion temperature is a must and it is easier to measure it if the icing object is made of the material with high thermal conductivity and the mass of it is known.

SUMMARY

The paper focuses on a method to measure ice growth caused by sea spray icing with possible offshore applications. The paper presents a system used to study the ice accretion growth in field experiments. The system allowed to measure the ice accretion mass and observe increments of the ice and water mass on the cylinder for each individual spray event. The accuracy of measurements was 0.7 g and was defined by the load cells. Additional noise is caused by the wind induced vibrations and movements of the system.

A similar system can be used offshore on rigs or vessels and a sketch of a slightly modified and fully automated system is presented. Details and important parameters of the system are discussed considering the known typical icing conditions. The system is based on applications of single point load cells. This technique of mass measurements is well established and inexpensive load cells have an accuracy better than 0.1% of the maximum design load.

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