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Error in strain gauge location affecting load estimation

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ABSTRACT

A common method for determining ice induced load on ship hulls is indirectly via shear strain measurements. This methodology includes determining load-strain relation, usually done using Finite Element (FE) Analysis, and described with Influence Coefficient (IC). The FE model used to create the IC should be accurate representation of the structure instrumented with shear strain gauges, but requiring absolute accuracy for the FE model would be inefficient. FE models usually correspond to structural drawings of the actual structures fairly accurately. Actual structures differ from the structural drawings within allowed building tolerances. Also, location of installed strain gauges may have some deviation from the planned location. Therefore, location and orientation of shear strain measurement points should be modelled on the FE model based on measurements of the structure and not on the planned drawings. This paper studies how error in location and position of measurement points in the FE model used to create the IC transfers errors to the final result i.e., ice load magnitude and tries to answer what should be acceptable level of inaccuracy between location and position of strain gauges and measurement points in full scale structures and FE model, respectively.

KEY WORDS Ice load monitoring; Shear strain measurements; Measurement error; Finite Element Analysis

NOMENCLATURE
FEA (Finite Element Analysis); FE (Finite Element); IC (Influence Coefficient); NA (Neutral Axis)

INTRODUCTION

Indirect measurements, where load is determined via strain response of the structures, is a commonly used method in full-scale ice load measuring solutions. Installing strain gauges on the frames or shell plate doesn't require any modifications of the surrounding structures and can be long lasting solution when installed correctly. One popular way of determining ice loads on ship structures via strain measurements is measuring shear strain difference between two ends of ice frames. This has been in use in several ships already from 1970's till recent years (Suominen, 2018). This paper considers Shear strain difference measurements.

To determine ice loads from shear strain difference, load-strain relation must be known. In the application presented in this paper the load-strain relation is described using Influence Coefficient. IC is created using finite element analysis (FEA) and discussed further in Methods sections.

The FE model should be detailed enough, especially around the instrumented frames, to accurately determine load strain relation of the structures, but too detailed model increases modelling and analysis time inefficiently high. The level of detail for idealization provided by class guidelines (DNV, 2022) is a good starting point.

FE models are created based on structural drawings, and details such as steel plate thickness variance within acceptable tolerances and welding deformations (IACS, 2010) would be very difficult to implement to the model. Dimensions of precut plates of primary structures might not always be exactly as drawn in plans, but within the tolerances. In a such occasion shipbuilders must force the plates where they are planned to be. Therefore, span of a frame can differ from the planned. This may have a further effect e.g., a bulkhead being some distance off its planned location, which is being used as a reference point for a strain gauge, resulting in information about strain gauge location being off too.

Especially in high ice-class ships in ice belt region, which are interesting for instrumentation, the structure can be very constricted and hard to reach, making installation work difficult and laborious. It is important that teams installing the gauges and creating the FE models communicate with each other. In some instances, gauges cannot be installed on the planned location due to unexpected structural constrain such as large welding seam or an additional bracket. Also, human errors can occur during the installation. The best effort should be used installing the gauges on the structures as drawn. After installation, the true location of the gauges should be re-measured, and the measurement points should be modelled on the FE model based on these re-measured true locations.

The issue of measurement accuracy has been recently approached from effects of load location and type of frame instrumentation (1-sided vs. 2-sided instrumentation). Böhm et al. (2021) with numerical analysis, and Valtonen et al. (2025) with semi-scale experiment confirmed theory of Suominen et al. (2017) about effect of frame rotation to the measurement accuracy. This paper aims to learn how inaccuracies in FE model used to create IC transfers to final results of indirect ice load sensing i.e., load magnitude. The inaccuracies are modelled in longitudinal direction of the frame (along the hull) and orientation. The inaccuracy in direction of frame height (normal to the hull) is left out from this study and should studied in the future.

FEA is efficient and cheap option compared to experimental calibration of ice load sensing systems. Understanding sources of error in verification via FEA helps to deduce the extent of possible error in results and if it is even viable tool in calibrating ice load sensing systems.

MODEL

A simplified 3D model of typical heavy icebreaker, with Polar Class (PC) 2 ice class (IACS, 2019), is modelled in NAPA Designer 2024.2. The 3D model, from which the FE model is created, is three decks high, 6 m in total, and three web frame spacings long, 9.6 m in total, and 3.7 m wide (Figure 1). The decks are equally high and the web frame spacings are equally long. The three decks and web frame spacings allow boundary conditions being sufficiently far, when middle frame is loaded in FEA. The double hull is 2.5 m from the shell. The shell is 45 mm thick in the “icebelt” (two lowest decks). Frame spacing is 0.4 m and deck beams are on every other frame, except on the highest deck on every frame. Ice frames are flat bars 400 mm high and 40 mm thick. Brackets on the ice frames are 300 mm x 300 mm and 20 mm thick.

The lowest and highest planes, “decks”, are only to help modelling and are deleted after meshing (Figure 1).

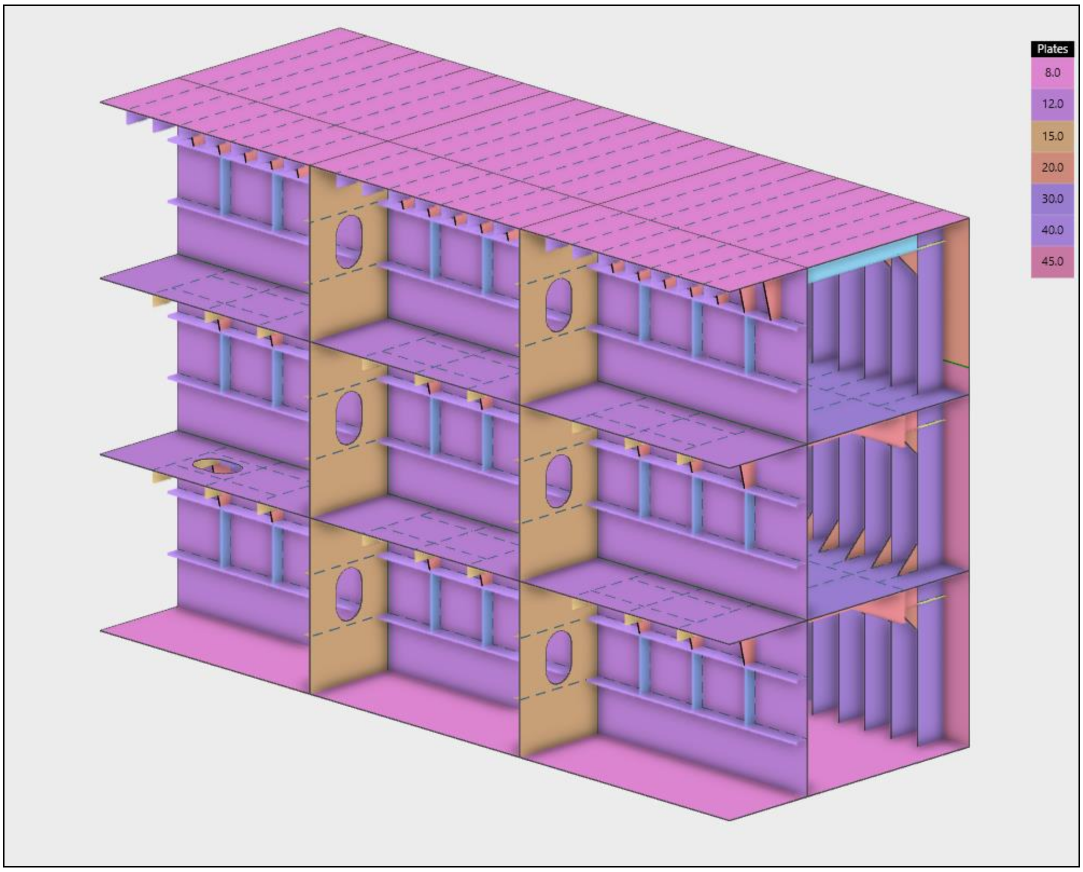

Figure 1. A simplified 3D model of typical heavy icebreaker in NAPA Designer.

METHODS

Influence Coefficient

Solving ice loads from measured strain response of the structure is an inverse problem, where input (load) is determined when output (strain response) and the system (steel structure) are known. The load-strain relation of the instrumented structure is described using IC, which is relatively simple to construct for a configuration that utilizes shear strain difference as the strain response of the structure. Commonly for these types of solutions single frames have been instrumented with two shear gauges, one on lower end and one on upper end of the frame. Shear strain difference is calculated between these two gauges per frame. The configuration studied in this paper has two gauges, upper and lower, on the same side of the frame.

IC is formed using FEA. A single frame is loaded with unit pressure load and strain response is measured from both ends of the frame. A load patch is located middle of the frame span measured from the ends of brackets connected to the frame. The load patch is one frame span wide and 50 mm high (Figure 2). In her study Adams showed the line-like nature of ice load and that height of ship-ice contact is mostly below 50 mm (Adams, 2018). Unit load used is 1 MPa.

Ice induced load, *F*, is determined as product of inverse of IC, ***Z***, and strain response, $\Delta\gamma$ (Equation 1):

$$F = Z^{-1} * \Delta\gamma. \quad (1)$$

IC is solved from Equation 2:

$$Z = f^{-1} * \Delta\gamma \quad (2)$$

, where *f* is the unit pressure applied on the frame and $\Delta\gamma$ is the strain response measured from the frame. (Romppanen, 2008).

Finite Element Analysis

Mesh for the FE model was created in NAPA Designer 2024.2. The FE model was then finalised in Abaqus/CAE 2025. The model consists of quadrilateral and triangular elements. Quadrilateral elements were preferred but triangular elements were used when geometry of the model required it. The mesh size was 25 x 25 mm, except around the measurement points and the load patch the mesh was denser. Around the measurement points the mesh was 1 mm x 1 mm, changing further to 2.5 mm x 2.5 mm, changing to 5 mm x 5 mm, changing to 10 mm x 10 mm and finally to 25 mm x 25 mm (Figure 2). The strain measurement points were modelled as nodes in the FE model. The strain measurement point locations are given Gauge Location and Orientation Error -section. The FE model was pinned by its boundaries. The boundary conditions and unit load patch are shown in (Figure 3). The FEA was solved linearly using Abaqus/Standard.

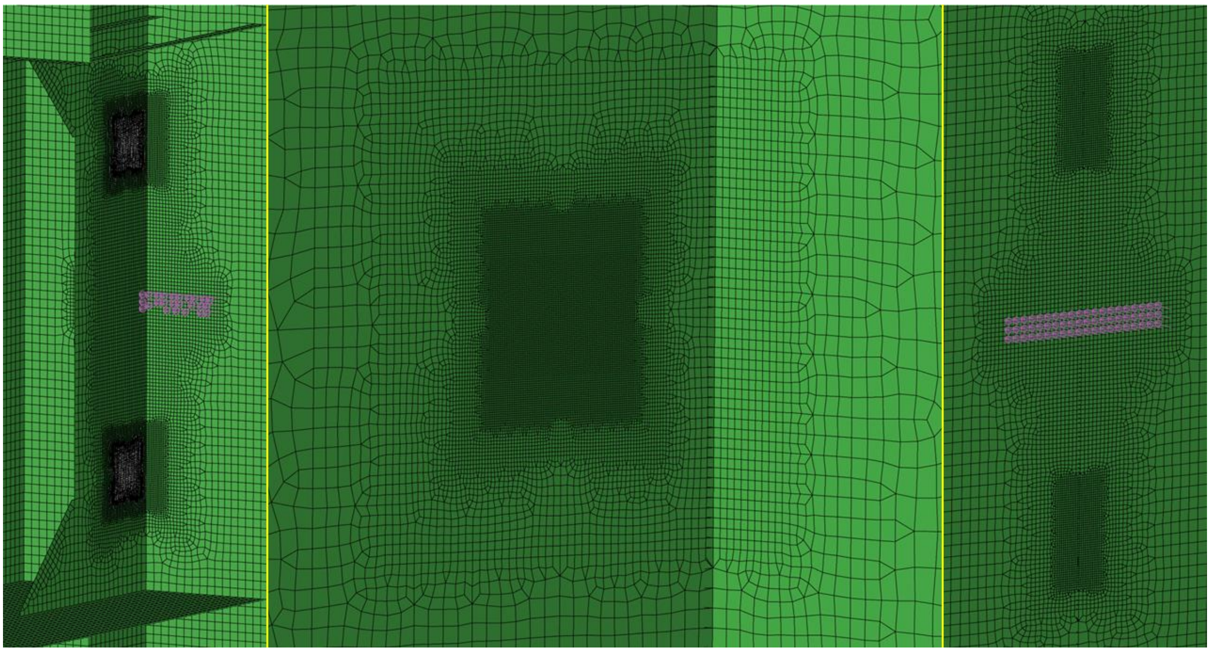

Figure 2. From left to right: the frame which is loaded; mesh around the measurement points changing from 1 mm x 1 mm to 25 mm x 25 mm; load patch (purple arrows) and mesh of the shell.

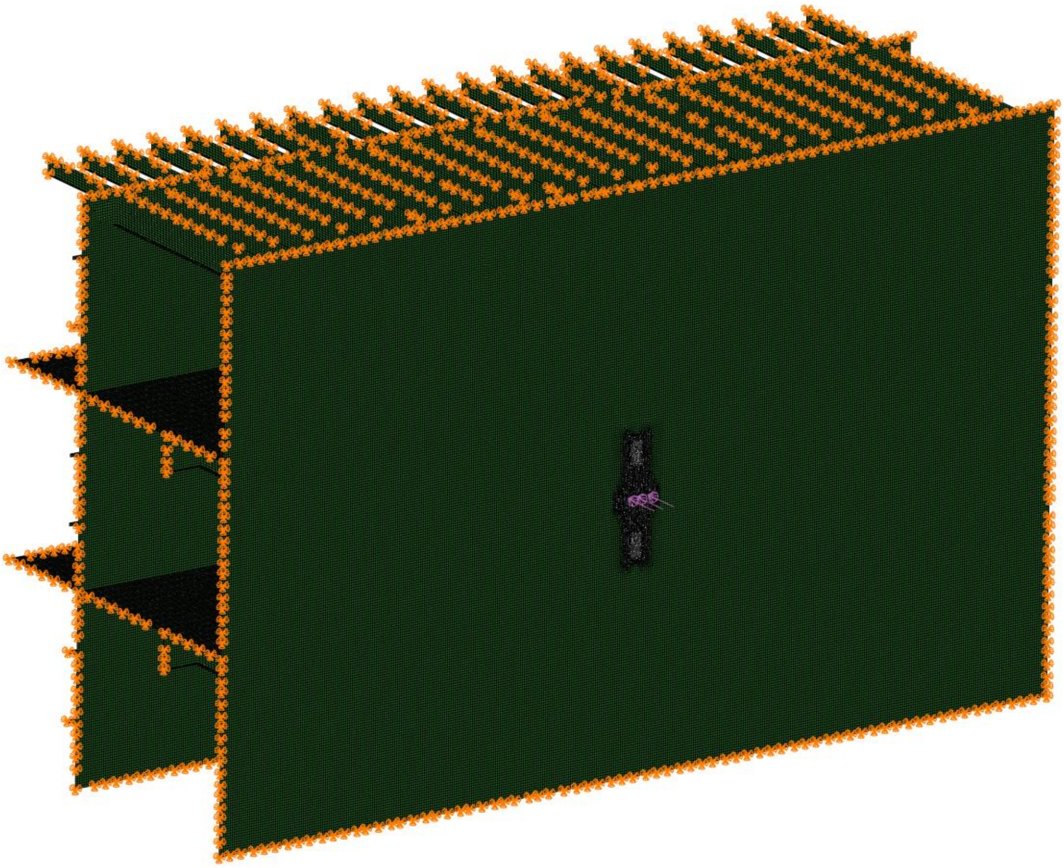

Figure 3. Boundary conditions and load in Abaqus/CAE.

GAUGE LOCATION AND ORIENTATION ERROR

Measurement Point Location and Orientation

The correct location of the measurement points in FE model should match with the shear strain gauge locations in the full scale structure. Gauges are generally installed on the neutral axis (NA) of the frame where the highest shear stress occurs. In this study the correct measurement point is on the NA of the frame and 50 mm from the end of brackets towards middle of the frame. The error of measurement point location is modelled as a distance along neutral axis of the frame from the correct location as shown in Figure 4. The location error, d_{err}, is studied from 1 mm to 10 mm to both directions from the measurement point.

Strain response is also measured with incorrect angles. The strain response with the angle error is measured from the correct measurement point (Figure 4). The angle error, θ_{err}, is studied from 1 deg to 10 deg to both directions.

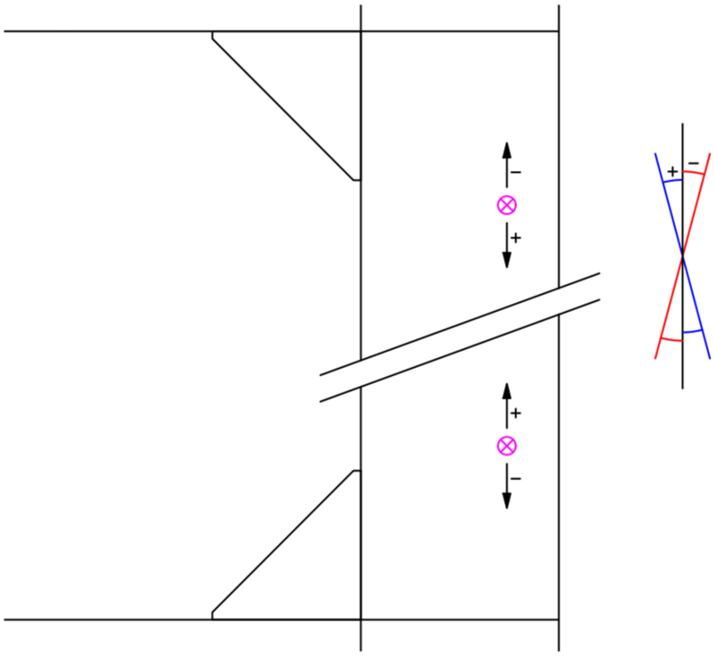

Figure 4. Diagram of how error in measurement point location and orientation is modelled.

Error in Determined Load Magnitude

Shear difference, $\Delta\gamma_{l,u}$, is calculated for each pair of measurement locations in d_{err} and orientation θ_{err}. l and u are location or orientation error in the lower and upper measurement points, respectively. IC, $Z_{l,u}$, is calculated for the planned location and orientation using Equation 2. Then force, $F_{l,u}$, is determined for each location and orientation pair using Equation 1, where $Z_{l,u}$ is $Z_{0,0}$ and $\Delta\gamma_{l,u}$ is shear difference of corresponding location and orientation pair. This configuration describes a situation, where Z is already determined based on planned location, but gauges are installed off from the planned location by d_{err} or θ_{err}. Finally error in the determined load magnitude is calculated as $F_{l,u}/F_{0,0} - 1$. $F_{0,0}$ is a force determined using $Z_{0,0}$ i.e., with no location or orientation error.

Allowed Tolerance

Acceptable error caused by mislocating or misorientating the gauges should be smaller than error caused by parameters that are not dependent on the installation of the gauges. As discussed in Introduction, the full-scale structures may differ slightly from the drawings. One easily defined parameter would be thickness of the ice frames, which may differ in tolerance defined in rules or standard. For this paper tolerances of standard EN 10029:2010 are used. For the frames of the example model the minus tolerance and plus tolerance are 0.3 mm and 2.3 mm, respectively. The FEA is rerun with frames being 0.3 mm thinner and 2.3 thicker, after which forces $F_{-0.3mm}$ and $F_{+2.3mm}$ are determined with Equation 1 but using shear differences $\Delta\gamma_{-0.3mm}$ and $\Delta\gamma_{+2.3mm}$ on the correct location and orientation. The error from the minus tolerance, $F_{-0.3mm}/F_{0,0} - 1$, is 0.690 %, which will be used as allowed tolerance for results from mislocated and misorientated measurement points. The error from plus tolerance is -4.945 %.

RESULTS

Location Error

The error in determined load magnitude, $F_{l,u}$, from every measurement location pair is combined to Table 1. Suffixes lo and up are lower and upper measurement point of the frame, respectively. Positive direction in both ends is towards middle of the frame (Figure 4). Errors larger than allowed tolerance, 0.690 %, are bolded in yellow.

Table 1.Error in determined load magnitude when the measurement point is mislocated. Values are in percentages.

[mm]	lo+10	lo+9	lo+8	lo+7	lo+6	lo+5	lo+4	lo+3	lo+2	lo+1	lo+0	lo-1	lo-2	lo-3	lo-4	lo-5	lo-6	lo-7	lo-8	lo-9	lo-10
up+10	**1.06**	**1.00**	**0.94**	**0.88**	**0.82**	**0.76**	**0.70**	0.64	0.57	0.51	0.45	0.39	0.32	0.26	0.19	0.13	0.06	0.00	-0.07	-0.13	-0.20
up+9	**1.02**	**0.96**	**0.90**	**0.84**	**0.78**	**0.72**	0.66	0.59	0.53	0.47	0.40	0.34	0.28	0.21	0.15	0.08	0.02	-0.05	-0.11	-0.18	-0.24
up+8	**0.98**	**0.92**	**0.86**	**0.80**	**0.73**	0.67	0.61	0.55	0.49	0.42	0.36	0.30	0.23	0.17	0.11	0.04	-0.02	-0.09	-0.16	-0.22	-0.29
up+7	**0.93**	**0.87**	**0.81**	**0.75**	**0.69**	0.63	0.57	0.50	0.44	0.38	0.32	0.25	0.19	0.13	0.06	0.00	-0.07	-0.13	-0.20	-0.27	-0.33
up+6	**0.89**	**0.83**	**0.77**	**0.71**	0.65	0.58	0.52	0.46	0.40	0.34	0.27	0.21	0.15	0.08	0.02	-0.05	-0.11	-0.18	-0.24	-0.31	-0.38
up+5	**0.84**	**0.78**	**0.72**	0.66	0.60	0.54	0.48	0.42	0.35	0.29	0.23	0.16	0.10	0.04	-0.03	-0.09	-0.16	-0.22	-0.29	-0.36	-0.42
up+4	**0.80**	**0.74**	0.68	0.62	0.56	0.49	0.43	0.37	0.31	0.25	0.18	0.12	0.06	-0.01	-0.07	-0.14	-0.20	-0.27	-0.33	-0.40	-0.47
up+3	**0.75**	**0.69**	0.63	0.57	0.51	0.45	0.39	0.33	0.26	0.20	0.14	0.07	0.01	-0.05	-0.12	-0.18	-0.25	-0.31	-0.38	-0.45	-0.51
up+2	**0.71**	0.65	0.59	0.53	0.47	0.40	0.34	0.28	0.22	0.15	0.09	0.03	-0.04	-0.10	-0.16	-0.23	-0.29	-0.36	-0.42	-0.49	-0.56
up+1	0.66	0.60	0.54	0.48	0.42	0.36	0.30	0.23	0.17	0.11	0.05	-0.02	-0.08	-0.15	-0.21	-0.27	-0.34	-0.40	-0.47	-0.54	-0.60
up+0	0.62	0.56	0.50	0.43	0.37	0.31	0.25	0.19	0.13	0.06	0.00	-0.06	-0.13	-0.19	-0.26	-0.32	-0.39	-0.45	-0.52	-0.58	-0.65
up-1	0.57	0.51	0.45	0.39	0.33	0.27	0.20	0.14	0.08	0.02	-0.05	-0.11	-0.17	-0.24	-0.30	-0.37	-0.43	-0.50	-0.56	-0.63	**-0.70**
up-2	0.52	0.46	0.40	0.34	0.28	0.22	0.16	0.10	0.03	-0.03	-0.09	-0.16	-0.22	-0.28	-0.35	-0.41	-0.48	-0.54	-0.61	-0.68	**-0.74**
up-3	0.48	0.42	0.36	0.29	0.23	0.17	0.11	0.05	-0.01	-0.08	-0.14	-0.20	-0.27	-0.33	-0.40	-0.46	-0.53	-0.59	-0.66	**-0.72**	**-0.79**
up-4	0.43	0.37	0.31	0.25	0.19	0.12	0.06	0.00	-0.06	-0.12	-0.19	-0.25	-0.31	-0.38	-0.44	-0.51	-0.57	-0.64	**-0.70**	**-0.77**	**-0.84**
up-5	0.38	0.32	0.26	0.20	0.14	0.08	0.02	-0.05	-0.11	-0.17	-0.23	-0.30	-0.36	-0.43	-0.49	-0.55	-0.62	-0.69	**-0.75**	**-0.82**	**-0.88**
up-6	0.33	0.27	0.21	0.15	0.09	0.03	-0.03	-0.09	-0.16	-0.22	-0.28	-0.35	-0.41	-0.47	-0.54	-0.60	-0.67	**-0.73**	**-0.80**	**-0.87**	**-0.93**
up-7	0.29	0.23	0.16	0.10	0.04	-0.02	-0.08	-0.14	-0.20	-0.27	-0.33	-0.39	-0.46	-0.52	-0.59	-0.65	**-0.72**	**-0.78**	**-0.85**	**-0.91**	**-0.98**
up-8	0.24	0.18	0.12	0.06	-0.01	-0.07	-0.13	-0.19	-0.25	-0.32	-0.38	-0.44	-0.51	-0.57	-0.63	**-0.70**	**-0.76**	**-0.83**	**-0.90**	**-0.96**	**-1.03**
up-9	0.19	0.13	0.07	0.01	-0.05	-0.12	-0.18	-0.24	-0.30	-0.36	-0.43	-0.49	-0.55	-0.62	-0.68	**-0.75**	**-0.81**	**-0.88**	**-0.94**	**-1.01**	**-1.08**
up-10	0.14	0.08	0.02	-0.04	-0.10	-0.16	-0.23	-0.29	-0.35	-0.41	-0.48	-0.54	-0.60	-0.67	**-0.73**	**-0.80**	**-0.86**	**-0.93**	**-0.99**	**-1.06**	**-1.13**

Orientation Error

The error in determined load magnitude, $F_{l,u}$, from every measurement orientation pair is combined to Table 2. Suffixes lo and up are lower and upper measurement point of the frame, respectively. Positive direction of both ends is shown in Figure 4. Errors larger than allowed tolerance, 0.690 %, are bolded in red.

Table 2. Error in determined load magnitude when the measurement point is misorientated. Values are in percentages.

[deg]	lo+10	lo+9	lo+8	lo+7	lo+6	lo+5	lo+4	lo+3	lo+2	lo+1	lo+0	lo-1	lo-2	lo-3	lo-4	lo-5	lo-6	lo-7	lo-8	lo-9	lo-10
up+10	-6.64	-5.96	-5.33	-4.76	-4.26	-3.82	-3.44	-3.13	-2.88	-2.70	-2.58	-2.53	-2.54	-2.62	-2.76	-2.96	-3.24	-3.57	-3.97	-4.43	-4.96
up+9	-6.13	-5.45	-4.82	-4.26	-3.75	-3.31	-2.94	-2.62	-2.38	-2.19	-2.07	-2.02	-2.03	-2.11	-2.25	-2.46	-2.73	-3.06	-3.46	-3.92	-4.45
up+8	-5.68	-4.99	-4.37	-3.80	-3.30	-2.86	-2.48	-2.17	-1.92	-1.74	-1.62	-1.57	-1.58	-1.66	-1.80	-2.00	-2.27	-2.61	-3.01	-3.47	-3.99
up+7	-5.28	-4.59	-3.97	-3.40	-2.90	-2.46	-2.08	-1.77	-1.52	-1.34	-1.22	-1.17	-1.18	-1.26	-1.40	-1.60	-1.88	-2.21	-2.61	-3.07	-3.60
up+6	-4.94	-4.25	-3.62	-3.06	-2.56	-2.12	-1.74	-1.43	-1.18	-1.00	-0.88	-0.83	-0.84	-0.91	-1.05	-1.26	-1.53	-1.87	-2.27	-2.73	-3.25
up+5	-4.65	-3.96	-3.34	-2.77	-2.27	-1.83	-1.45	-1.14	-0.89	-0.71	-0.59	-0.54	-0.55	-0.63	-0.77	-0.97	-1.24	-1.58	-1.98	-2.44	-2.96
up+4	-4.42	-3.73	-3.11	-2.54	-2.04	-1.60	-1.22	-0.91	-0.66	-0.48	-0.36	-0.31	-0.32	-0.39	-0.54	-0.74	-1.01	-1.35	-1.75	-2.21	-2.73
up+3	-4.24	-3.56	-2.93	-2.37	-1.86	-1.42	-1.05	-0.73	-0.49	-0.30	-0.18	-0.13	-0.14	-0.22	-0.36	-0.57	-0.84	-1.17	-1.57	-2.03	-2.56
up+2	-4.13	-3.44	-2.81	-2.25	-1.74	-1.30	-0.93	-0.62	-0.37	-0.19	-0.07	-0.01	-0.02	-0.10	-0.24	-0.45	-0.72	-1.05	-1.45	-1.91	-2.44
up+1	-4.06	-3.38	-2.75	-2.19	-1.68	-1.24	-0.87	-0.55	-0.31	-0.12	0.00	0.05	0.04	-0.04	-0.18	-0.39	-0.66	-0.99	-1.39	-1.85	-2.38
up+0	-4.06	-3.37	-2.75	-2.18	-1.68	-1.24	-0.86	-0.55	-0.30	-0.12	0.00	0.05	0.04	-0.03	-0.18	-0.38	-0.65	-0.99	-1.39	-1.85	-2.37
up-1	-4.11	-3.42	-2.80	-2.23	-1.73	-1.29	-0.91	-0.60	-0.35	-0.17	-0.05	0.00	-0.01	-0.09	-0.23	-0.43	-0.70	-1.04	-1.44	-1.90	-2.43
up-2	-4.22	-3.53	-2.91	-2.34	-1.84	-1.40	-1.02	-0.71	-0.46	-0.28	-0.16	-0.11	-0.12	-0.20	-0.34	-0.54	-0.81	-1.15	-1.55	-2.01	-2.53
up-3	-4.39	-3.70	-3.07	-2.51	-2.00	-1.56	-1.19	-0.88	-0.63	-0.44	-0.33	-0.27	-0.28	-0.36	-0.50	-0.71	-0.98	-1.31	-1.71	-2.17	-2.70
up-4	-4.61	-3.92	-3.29	-2.73	-2.23	-1.79	-1.41	-1.10	-0.85	-0.67	-0.55	-0.49	-0.51	-0.58	-0.72	-0.93	-1.20	-1.54	-1.93	-2.40	-2.92
up-5	-4.89	-4.20	-3.57	-3.01	-2.50	-2.06	-1.69	-1.38	-1.13	-0.95	-0.83	-0.77	-0.78	-0.86	-1.00	-1.21	-1.48	-1.81	-2.21	-2.67	-3.20
up-6	-5.22	-4.53	-3.91	-3.34	-2.84	-2.40	-2.02	-1.71	-1.46	-1.28	-1.16	-1.11	-1.12	-1.19	-1.34	-1.54	-1.81	-2.15	-2.55	-3.01	-3.53
up-7	-5.61	-4.92	-4.30	-3.73	-3.23	-2.79	-2.41	-2.10	-1.85	-1.67	-1.55	-1.50	-1.51	-1.58	-1.73	-1.93	-2.20	-2.54	-2.94	-3.40	-3.92
up-8	-6.05	-5.37	-4.74	-4.18	-3.67	-3.23	-2.86	-2.54	-2.30	-2.11	-1.99	-1.94	-1.95	-2.03	-2.17	-2.38	-2.65	-2.98	-3.38	-3.84	-4.37
up-9	-6.55	-5.87	-5.24	-4.67	-4.17	-3.73	-3.36	-3.04	-2.79	-2.61	-2.49	-2.44	-2.45	-2.53	-2.67	-2.88	-3.15	-3.48	-3.88	-4.34	-4.87
up-10	-7.11	-6.42	-5.79	-5.23	-4.72	-4.28	-3.91	-3.60	-3.35	-3.16	-3.05	-2.99	-3.00	-3.08	-3.22	-3.43	-3.70	-4.03	-4.43	-4.89	-5.42

DISCUSSION

Table 1 shows that when only one measurement point has location error it can be over 1 cm off along the NA of the frame and still the error in final results is less than allowed tolerance. 1 cm is already a lot when installing gauges, that can be about 1 cm in diameter. Other notable quality is how error is closest to zero when measurement points move to same direction, but not in equal distances. This is likely to do with frame boundaries and differences in their stiffness.

If installation site is especially cramped and the installation team must work in difficult positions, location error might be 0-2 mm, so well within tolerances. A typical new building and repair tolerance for structures is 8 mm (IACS, 2010). Error due building tolerances is usually acceptably small.

Table 2 shows that orientating the gauges to the right angle is more critical than locating it to the planned location. Already 4 degrees of orientating error in one end can cause error in final result to exceed allowed tolerance. Similar to location error also orientating error in different ends affects differently to error of load magnitude, implying stiffness differences in frame boundaries. This makes error in final results within allowed tolerance 'asymmetrical'.

CONCLUSIONS

The effect of the location and orientation errors of the measurement points in the FE model have to the load magnitude in basic ice load monitoring system was shown for an example frame. For a relatively large frame orientating the measurement point seems to be far more critical than locating. Required accuracy is still something that human eye can detect, and installation can be done manually without advanced tools or systems. Also allowed tolerance was proposed to be linked in thickness tolerance of the instrumented frames. This way installation tolerances are linked to existing rules. With several sources of error, that either have increasing or decreasing effect on the determined ice load, the errors can reduce or amplify each other.

This has been a quite short glance to the effects of location and orientation of strain gauge installation. This paper studied only one example frame to point out effects of mislocating and orientating the measurement points. Further studies of these effects should be conducted to learn more universal tolerances. Following further work is recommended:

1. Effect of location error in normal to hull
2. Combined effect of location and orientation error
3. Effect of frame boundaries
4. Unitless tolerance based on frame size
5. Full scale data with known exact gauge location

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