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Three-Dimensional Shape Sensing of a Representative Ship-Hull Cross-Section Based on Inverse Finite Element Method

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Abstract: Marine structures are usually exposed to harsh environmental conditions such as wave strikes and severe hurricanes, which can lead to damage/failure of the structure. Therefore, the implementation of a reliable Structural Health Monitoring (SHM) system is crucial to reduce the economic cost and improve the predictive maintenance plan. As an important part of SHM, shape sensing reconstructs the displacement field using in-situ strain sensors. The inverse finite element method (iFEM) is a powerful technique for tracking the static and dynamic response of structural components in three dimensions in real time. For this purpose, iFEM uses strain data collected from a discrete number of on-board/embedded sensors. The main objective of this study is to monitor the deformation of a ship hull structure under representative loads due to hydrostatic pressure and water wave impacts using the iFEM method. A robust inverse shell element, called iQS4, is used to estimate the iFEM capability in three-dimensional shape sensing of a ship hull structure with only a number of sensors on board. A direct Finite Element Analysis (FEM) is performed to simulate the strain information required for the iFEM analysis. The obtained reference result is compared with the iFEM analysis to prove the efficiency and accuracy of the iFEM method in predicting the full-field deformation of such complex structures with only a few sensor paths. In addition, the accuracy of iFEM approach is also assessed for broken/damaged sensors among other sensors.

Keywords: Marine Structures, Ship-Hull, Shape Sensing, Inverse Finite Element Method, Sensors

1. INTRODUCTION

Ships operate in harsh conditions because the marine environment can lead to structural failure due to extreme wave and/or wind loads. This harsh situation can cause structural failure and cause serious accidents resulting in loss of life, pollution of the marine environment, and very expensive maintenance/repair cost. Therefore, it is necessary to ensure the safety of the ship's entire structures in order to avoid serious accidents. The ship-hull is the most conspicuous structural unit of the ship. The ship-hull is the watertight shell of the ship that protects the cargo, machinery, and accommodation spaces of the ship from the effects of weather, flooding, and structural damage. To detect such probable failures in these structures, a proper structural health monitoring (SHM) system must be installed on-board the structure. The reconstruction of the displacement field from in-situ sensors in real-time is called "shape sensing" and is an important part of the SHM process.

The inverse finite element method (iFEM) is a powerful shape sensing technique introduced by Tessler and Spangler [1] that can be useful for the SHM of plate/shell structures. The iFEM is a sensor-based method which performs shape capture by minimizing a weighted least squares function that aims to match experimental strain measurements with their theoretical counterparts. Several robust inverse elements based on the iFEM formulation have been developed in the literature [2-4]. Abdollahzadeh et al [5] conducted a comparison study between existing inverse shell elements (i.e., iMIN3, iQS4, and iCS8). The iQS4 element is a four-node quadrilateral inverse shell element first introduced by Kefal et al [3]. The kinematic relations of the iFEM-iQS4 formulation are based on Mindlin's plate theory. The iFEM-iQS4 analyses have been widely used for shape and stress monitoring of various engineering applications with different geometric topologies including marine, and offshore structures [6-10]. However, to the best of the authors' knowledge, there are no studies in the literature to evaluate the capability of iFEM-iQS4 for the three-dimensional shape detection of a representative ship-hull cross-section.

The aforementioned problem is addressed in the present study by performing numerical shape sensing analyses on a representative ship-hull cross-section using the iFEM-iQS4 methodology. For this purpose, a FEM analysis is performed using ANSYS-APDL. This FEM analysis is used first to obtain simulated strain data required to be given in iFEM formulation and second to be considered as a reliable reference solution for comparison with iFEM results. The obtained full-field displacement contours and related quantitative results show a high consistency between iFEM and FEM solutions. Since some of the sensors might be broken or damaged due to tough operational situations of the marine environment, the efficiency and accuracy of the iFEM approach are reevaluated considering some broken/damaged sensors among other sensors. It is shown that iFEM can provide a reliable 3D shape reconstruction even if some sensors fail.

2. MATHEMTICAL FORMULATION

iQS4 is a four-node quadrilateral inverse plate/shell element with six degrees of freedom (DOF) per node as shown in Fig. 1(a). The main advantage of using iQS4 is the inclusion of the drilling rotations which enables superior shape-sensing of different applications with complex geometries.

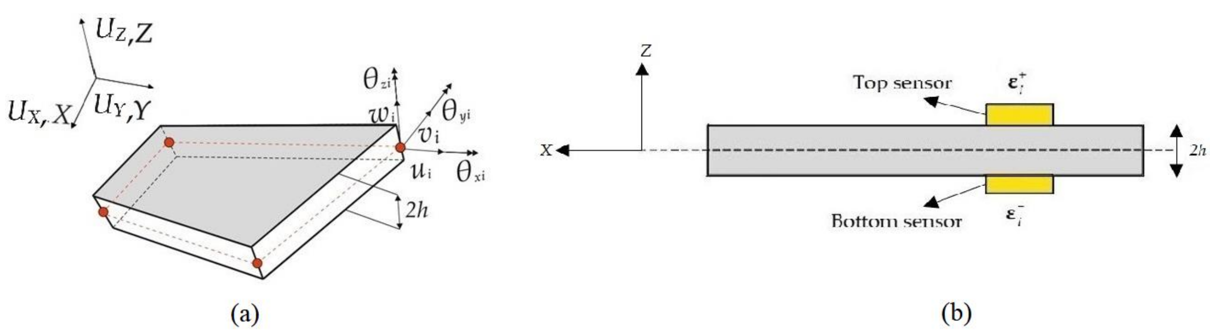

Fig. 1. *(a) Geometry of iQS4 inverse shell element with related global and local coordinate systems, (b) Position of the strain sensors at top and bottom of the element's surface.*

The detailed formulation of the shape functions, displacement vectors and displacement-strain relationships are provided in [3]. The analytical strain components can be calculated in terms of the nodal displacement vector, $\mathbf{u}^e$, as

$$\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{Bmatrix} = \mathbf{e}(\mathbf{u}^e) + z\boldsymbol{\kappa}(\mathbf{u}^e) = \mathbf{B}^m\mathbf{u}^e + z\mathbf{B}^k\mathbf{u}^e \tag{1a}$$

$$\begin{Bmatrix} \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} = \mathbf{g}(\mathbf{u}^e) = \mathbf{B}^s\mathbf{u}^e \tag{1b}$$

where $\mathbf{e}$, $\boldsymbol{\kappa}$, and $\mathbf{g}$ represent the analytical membrane, bending, and transverse shear strains respectively and $\mathbf{B}^s$, $\mathbf{B}^m$ and $\mathbf{B}^k$ are the matrices containing derivatives of the iQS4 shape functions. The explicit forms of these matrices can be found in [3]. To calculate the experimental counterparts of the numerical section strains, strain rosettes should be located on top and bottom surfaces of each iQS4 element as depicted in Figure 1(b). Using these in-situ strain measures, one can easily calculate the experimental section strains as:

$$\begin{bmatrix}\mathbf{e}_{\mathrm{i}}^{\varepsilon} & \boldsymbol{\kappa}_{\mathrm{i}}^{\varepsilon}\end{bmatrix} \equiv \begin{bmatrix}\frac{1}{2}(\boldsymbol{\varepsilon}_i^{+}+\boldsymbol{\varepsilon}_i^{-}) & \frac{1}{2h}(\boldsymbol{\varepsilon}_i^{+}-\boldsymbol{\varepsilon}_i^{-})\end{bmatrix} \quad (i=1,2,...,n_s) \tag{2}$$

where $\mathrm{e}_{\mathrm{i}}^{\varepsilon}$ and $\kappa_{\mathrm{i}}^{\varepsilon}$ show the experimental counterparts of the membrane and bending strains for n_s number of discrete sensors, respectively. The experimental transverse shear strain $\mathrm{g}_{\mathrm{i}}^{\varepsilon}$ cannot be directly extracted from the obtained strain measurements. Nevertheless, the contribution of this shear strain for shape sensing of slender structures can be safely omitted due to its minor effect among other strains. The weighted least-square functional can be defined based on the numerical and experimental section strains as follows:

$$\boldsymbol{\Phi}(\mathbf{u}^e) = \mathbf{w}_e \left\|\mathbf{e}(\mathbf{u}^e)-\mathbf{e}^{\varepsilon}\right\|^2 + \mathbf{w}_k \left\|\boldsymbol{\kappa}(\mathbf{u}^e)-\boldsymbol{\kappa}^{\varepsilon}\right\|^2 + \mathbf{w}_g \left\|\mathbf{g}(\mathbf{u}^e)-\mathbf{g}^{\varepsilon}\right\|^2 \tag{3}$$

where the weighting constants of individual section strains w_e , w_k, and w_g are related to membrane, bending, and transverse shear section strains, respectively. If any of the experimental section strain data is missing, then the related weighting constants are set to a small positive value such as $\mathrm{w}_e = \mathrm{w}_k = \mathrm{w}_g = 10^{-4}$. Otherwise, they are assumed to be equal to unity. Minimizing the Φ functional with respect to the nodal displacement vector results in an equation in the form below:

$$\frac{\partial\Phi(\mathbf{u}^e)}{\partial\mathbf{u}^e} = \mathbf{k}^e\mathbf{u}^e - \mathbf{f}^e = 0 \Rightarrow \mathbf{k}^e\mathbf{u}^e = \mathbf{f}^e \tag{4}$$

where the $\mathbf{k}^e$ and $\mathbf{f}^e$ are analytical shape matrix and experimental shape vector in the local coordinate system, respectively. These local quantities can be transformed into a global coordinate system by using an appropriate transformation matrix, $\mathbf{T}^e$ as:

$$\mathbf{KU} = \mathbf{F} \tag{5a}$$

$$\mathbf{K} = \bigcup_{e=1}^{N_{el}}\left[(\mathbf{T}^e)^T\mathbf{k}^e\mathbf{T}^e\right],\ \mathbf{F} = \bigcup_{e=1}^{N_{el}}\left[(\mathbf{T}^e)^T\mathbf{f}^e\right],\ \mathbf{U} = \bigcup_{e=1}^{N_{el}}\left[(\mathbf{T}^e)^T\mathbf{u}^e\right] \tag{5b}$$

where the $\bigcup$ operator denotes assembly process of the finite element method, and the $\mathbf{U}$, $\mathbf{F}$, and $\mathbf{K}$ represent the shape matrix, displacement vector, and experimental shape vector, in global coordinate system in the given order. In this study, the accuracy and efficiency of the iFEM element are assessed by computing the percent difference for the maximum values of the total displacement between iFEM and FEM analyses as

$$\text{Percent Difference}(\%) = \left|\frac{\delta^{\mathrm{iFEM}}-\delta^{\mathrm{FEM}}}{\delta^{\mathrm{FEM}}}\right| \times 100 \tag{6}$$

where the parameter δ corresponds to total translational deformations.

3. NUMERICAL IMPLEENTATION

A representative cross-section of a small ship-hull is considered to be shape estimated using the iFEM method. The cross-section of this ship-hull has a width of 5m, a height of 2.5 m, and a depth of 2 m as demonstrated in Fig. 2. The hull is stiffened laterally and longitudinally using girders with 0.2 m width as shown in Fig. 2. All components of this hull are made of 5 mm thick sheets of AISI type 304 stainless steel. It is presumed that 1.5 m of the hull becomes under the water subjected to hydrostatic pressure. Moreover, the right and left panels of the hull are exposed to water wave strikes of maximum a 6 KPa pressure. Moreover, all the cross-sectional edges are considered to be fully clamped.

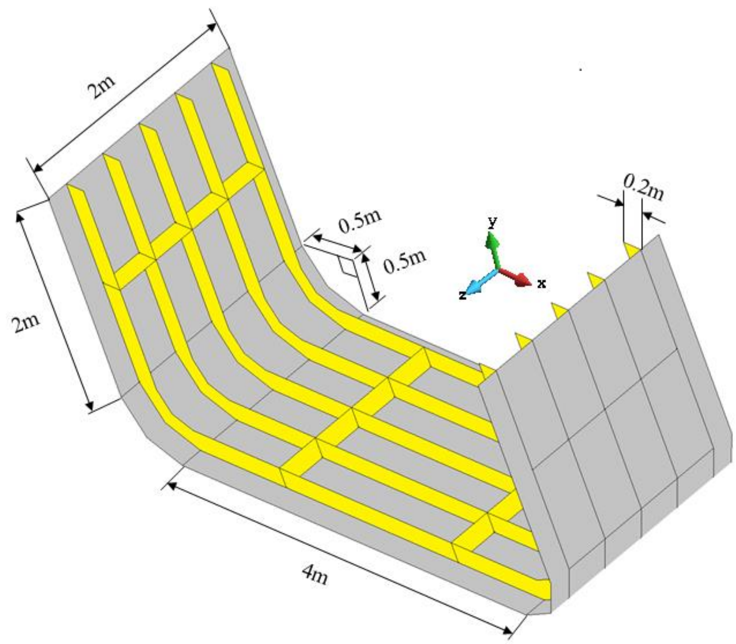

Fig. 2*. Dimensions of the stiffened ship-hull.*

The most important part of the iFEM analyses is the acquisition of the experimental strain measurements on the top and bottom of the structural components. Before installing the sensor network experimentally on the structure, you must create an accurate layout for the location of the sensors. The required experimental strain data can be obtained either by in-situ strain measurement systems (e.g., strain gauges, rosettes and FBGs) or simulated by a FEM analysis, which can be used as discrete strain data in the iFEM formulation. Moreover, the FEM analysis is used as a reliable reference solution that can be compared with the iFEM results. In the current study, the iFEM model consist of 148 elements which 48 of them are accommodated with strain rosettes as shown in Fig 3(a). The weighting constants corresponding to the membrane and bending strains of the elements that have a sensor in the center were set to unity. However, for the elements without sensors, these constants were defined with a very small value (i.e., 10^{-8}). The weighting coefficient of the transverse shear strains was set to $\mathbf{w}_g = 10^{-5}$ for all iQS4 elements.

In most engineering applications, damage or loss of the sensors is almost inevitable under difficult manufacturing and/or operating conditions. Therefore, to illustrate the practical efficiency and accuracy of the iFEM approach, some damaged/broken sensors were randomly simulated among other sensors. For this purpose, one-sixth of the total sensors (i.e., eight sensors) are assumed to be out of service, as shown in Fig. 3(b). The symbol 'iFEM_D' is used to represent the iFEM analyses with damaged/defective sensors.

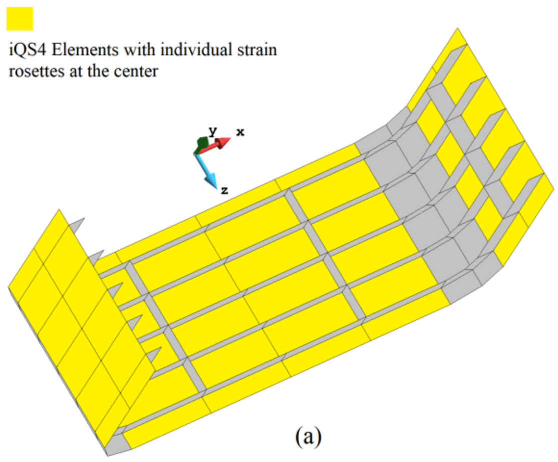

***Fig**. **3** Sensor deployment used for (a) iFEM, and b) iFEM_D analyses.*

4. RESULTS & DISCUSSION

In this section, the results of the iFEM and FEM analyses are compared and discussed in detail to verify the predictive shape detection capability of the iQS4 element. Fig. 4 shows the deformed shapes of the preventative ship-hull cross section obtained from both FEM and iFEM analyses. Note that the deformation values for both solutions are magnified by the same factor 4000. Observing Fig. 4, one can easily understand that iFEM has reasonable potential to reconstruct the 3D full-field deformations compared to the results obtained by FEM. This proves the practical suitability of iFEM-iQS4 as a reliable system for shape acquisition.

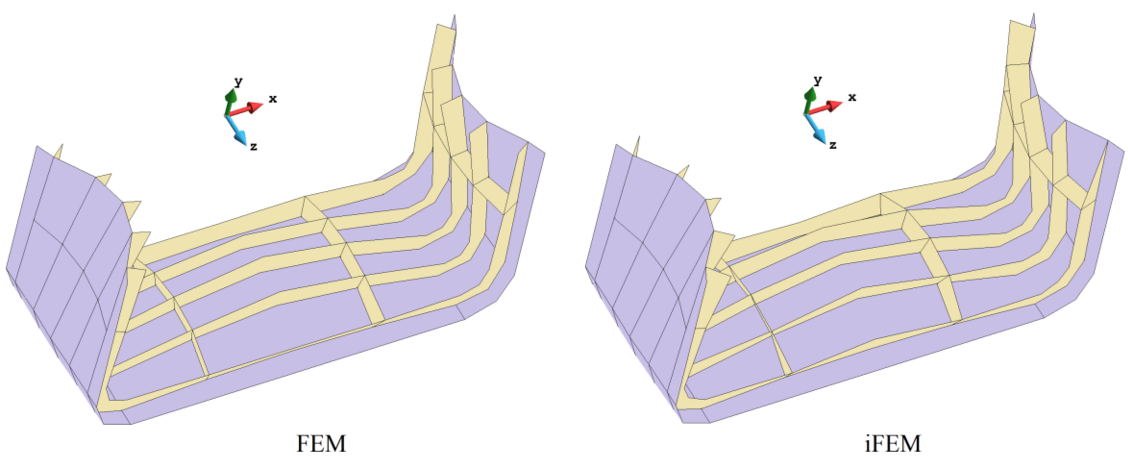

***Fig. 4.** The FEM and iFEM deformed shapes (with same magnitude factor of 4000).*

As for the quantitative results in Fig. 5, the percentage differences between the maximum total displacement of iFEM, iFEM_D and the reference solution FEM are about 0.6% and 3.4%, respectively. Moreover, the total displacement contours obtained from the iFEM analyses show a superior similarity between FEM and iFEM analyses. Overall, the quantitative contour results and the reconstructed deformed shapes show that the iFEM approach can be easily used to predict high-precision full-field displacements, even in the case of an on-board sensor network with multiple defective/damaged sensors. Therefore, for monitoring the structural health of various marine components iFEM can be classified as one of the most robust and accurate shape detection and real-time monitoring systems.

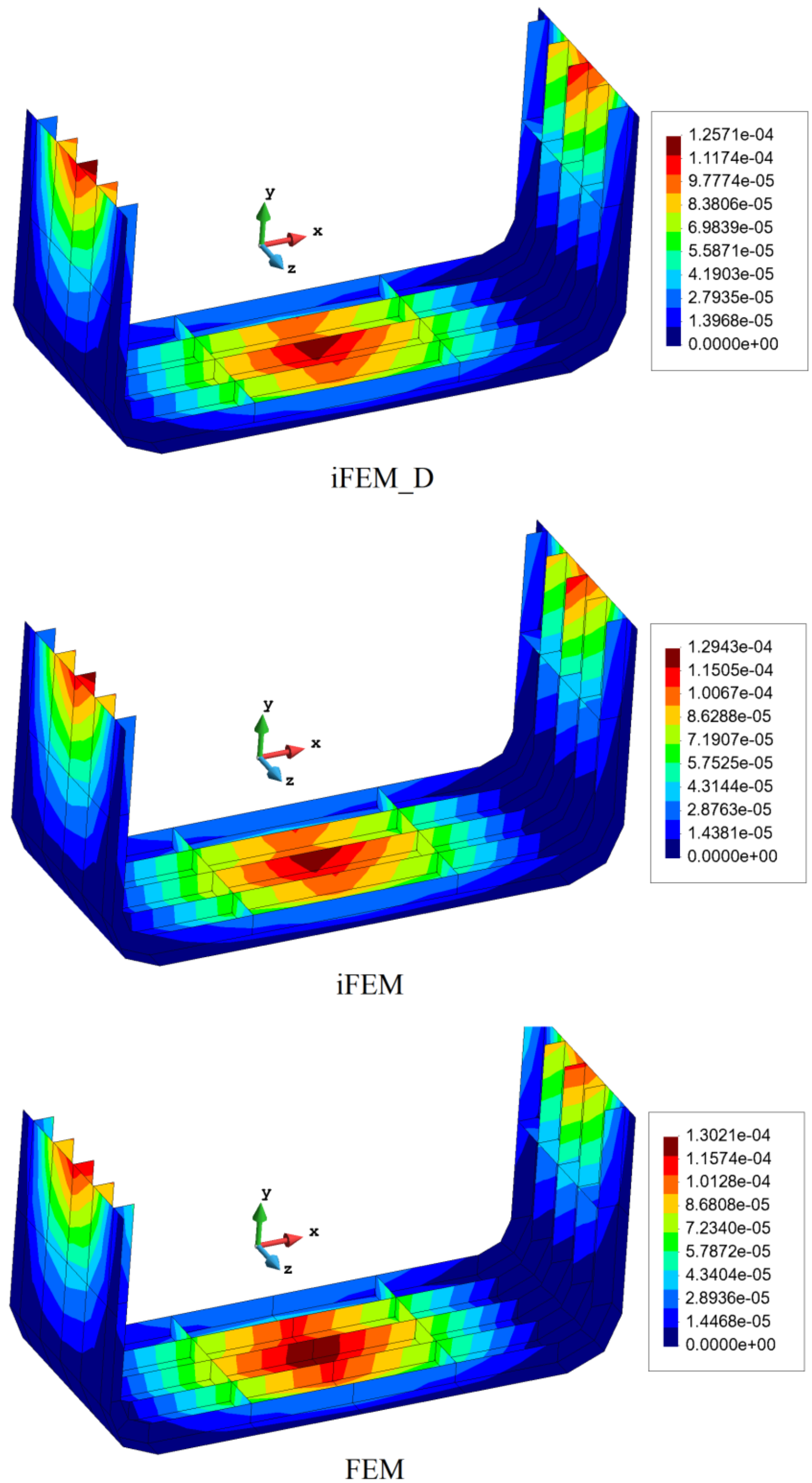

Fig. 4 *Total displacement fields obtained by FEM, iFEM, and iFEM_D analyses.*

5. CONCLUSSION

The shape estimation of a representative cross-section of a ship-hull is carried out using a new sensor-based approach called iFEM. The obtained results clearly show that this method is robust enough to reconstruct the translational fields and is able to predict quantitative results with a small deviation from the FEM reference solution, even when some of the sensors are out of service due to operational and application situations. The knowledge gained from this study may lead to the expansion of shape capture studies using this technique to other marine and sub-marine components in the future.

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