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Overall hull girder nonlinear strength monitoring based on inclinometer sensor data

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A R T I C L E I N F O

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A B S T R A C T

It is announced a new procedure for the real-time overall hull response monitoring system depends on inclinometer sensor data. The procedure requires a few inclinometer sensors' data, located on the deck. Sensor data is used to obtain curvature values; and curvature values are used to find out displacements or relevant moment values according to pre-calculated moment-curvature diagrams. Numerical studies are demonstrated with reasonable accuracy for the pre-ultimate and the post-ultimate nonlinear behaviors. Elastic, inelastic, and post-collapse structural bending moment capacity determination of the hull has been presented. The proposed inverse engineering technique will be able to see the response of the hull in real-time with high accuracy to manage the course and speed when cruising or control the loading and the unloading process at the port.

1. Introduction

Hull girder longitudinal vertical bending moment is an important indicator to define structural strength conditions for the large ships. It is a traditional way to determine the ship's hull bending moment with the data from the loading scenario and the hydrodynamic analysis where sea waves are well defined. Unfortunately, when we consider a real-time situation, it is not easy to measure waves accurately in navigating. Therefore, there is uncertainty in the time-domain coming from dynamic sea state, and the human factor becomes very important at this stage on navigation. Real-time measured response of the structure not only guides to manage the course and speed of the sea-going vessel, and also guides dynamic control for the loading and the unloading process at the port.

This real-time measurement method on the hull girder is called Hull Response Monitoring System (HSMS), which has been taken part in the Classification Societies and International Maritime Organization (IMO). HRMS additionally assistances to show slamming safety and fatigue life predictions. HRMS employs sensor measurements for the analysis. The minimum requirement for HSMS in the Classification Societies is two strain gauges at amidships, an accelerometer, or pressure transducer in the bow (Phelps and Morris, 2013). Slamming pressures are obtaining with accelerometers and pressure transduces. Fatigue life is determined by the rain-flow counting method. Classification Societies well-defined regulations (ABS, 2020; DNV, 2020).

Monitoring with only a moment or stress data is not enough to be understood the overall structural condition of the hull. A few sensors usage in HSMS can only give a prediction only for amidships structural behavior as stress or strain, not for the overall structure. Overall monitoring is going to be much more convenient usage for the end-user. In this sense, the Inverse Finite Element Method (iFEM) has been adapted to the displacement and stress monitoring of the elastic hull girder overall response (Kefal and Oterkus, 2016). But, a great number of strain rosettes are required in the analysis to estimate the whole structure elastic behavior of the hull girder. Additionally, Thermal effects and calibration of the strain sensors highly affect the accuracy of the HSMS analysis (Storhaug et al., 2016; Xu and Haddara, 2001).

It is also possible to obtain monitoring without strain gauges. Employing rigid-body ship motion measurements in the time-domain strip theory method can figure out wave-induced ship hull longitudinal bending moment (Xu and Haddara, 2001; Moreira and Guedes Soares, 2020). Fourier transforms express the magnitude of bending moment as a function in rigid displacements, velocities, and accelerations. The main assumption of the approach is the rigid ship and the linear responses. We can have an estimation

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for the magnitude of the hull girder bending moment distribution (not limited to amidships) with this method, but not for the overall structure.

Some researchers think that hull bending deflection is more meaningful than stress or strain of the structural members for the captains (Takahashi et al., 1973). They have tried to measure the deflection with the use of a scanning laser-light and six photoelectric cells, where deflection is assumed to be straight between the photoelectric cells. The hull flexure is also proposed by another researcher to measure with Kalman filtered Inertial Measurement Units (IMUs) data where the ship is assumed to be rigid (Ma et al., 2017). Belak employs inclinometer data to calculate hull bending deformations where displacements assumed to be small, and hull deformation between two measuring points is a circular arc, not a straight line (Belak, 2004). The deflection curve is another good indicator as a hull bending moment, additionally; it will be also very useful at docking.

The strain measurement will become meaningless when yielding occurs. In case the hull deforms in the inelastic zone, the abovementioned methods will be unable to give an idea about its remaining capacity or existing condition. However, knowledge about the remaining strength will be of great importance to decide the safest operation afterward. According to all, a real-time tool providing the overall deflection curve and bending moment distribution of the hull girder will be fully operational. Assessments should not be limited to the elastic region. End-user should check the actual situation after buckling or yielding occurs. Moreover, sensors should be accurate, in a reasonable amount of numbers, and easily installed without time-consuming calibration procedures.

The author proposes a new concept to meet the needs in HSMS. The study is in two phases. Firstly, the hull deflection curve is going to be represented with the curvatures determined from inclinometers measurements. This hull deflection modeling problem has been discussed in kinematically in curvilinear coordinates to be regardless of forces. The evaluation will be verified with the simulated data and then the optimum number of sensor data will be defined. The second part is going to express usage of the curvature data to find out longitudinal bending moment distribution of the hull with the help of progressive collapse analysis.

2. Kinematic displacement theory for deflection modeling

Finding deflections from curvature distribution is a kinematic problem regardless of forces, and deflections can easily be generated (Kahraman and Tayyar, 2017; Tayyar et al., 2014).

A well-known method for the deflection curve of the hull girder is expressed by the integration of the curvature in the Cartesian Coordinate System under some assumptions. However, Elastica using curvilinear coordinates is one of the best nonlinear theories for finite strain calculations, where large deflection approach will be insufficient. Elastica gives a formulation for the deflection curve using inclines of the curve "θ" in radian as follows: where "s" denotes curvilinear length, "x" denotes longitudinal Cartesian displacement direction, "z" denotes upwards displacement Cartesian direction of the hull.

$$dz / ds = \sin \theta(s) \tag{1}$$

$$dx / ds = \cos \theta(s) \tag{2}$$

If we take the integration of Eq. (1) and Eq. (2), following expression for the displacement can be obtained as follows:

$$z(s+\Delta s) - z(s) = \int_{s}^{s+\Delta s} \sin \theta(\bar{s})\, d\bar{s} \tag{3}$$

$$x(s+\Delta s) - x(s) = \int_{s}^{s+\Delta s} \cos \theta(\bar{s})\, d\bar{s} \tag{4}$$

The expression for the curvature "K" or inverse of radius of curvature is given in the following relation:

$$\mathrm{K}(s) = d\theta / ds \tag{5}$$

The difference in the incline values Δθ of a segment can be calculated in terms of curvature values as given in Eq. (6). from Eq. (5) with the assumption that curvature is constant along Δs curvilinear length as shown in Fig. 1.

$$\Delta\theta = \theta(s+\Delta s) - \theta(s) = \mathrm{K}(s)\Delta s \tag{6}$$

The displacement formulations Eq. (7) and Eq. (8) can be obtained by submitting Eq. (6) into Eq. (3) and Eq. (4). as follows:

$$\Delta z(s) = -[\cos \theta(s+\Delta s) - \cos \theta(s)] / \mathrm{K}(s) \tag{7}$$

$$\Delta x(s) = [\sin \theta(s+\Delta s) - \sin \theta(s)] / \mathrm{K}(s) \tag{8}$$

If the incline is constant, it means that curvature equals to zero, and linear displacement formulations can be obtained from Eq. (1) and Eq. (2) as follows:

$$\Delta z(s) = \sin \theta(s)\Delta s \tag{9}$$

$$\Delta x(s) = \cos \theta(s)\Delta s \tag{10}$$

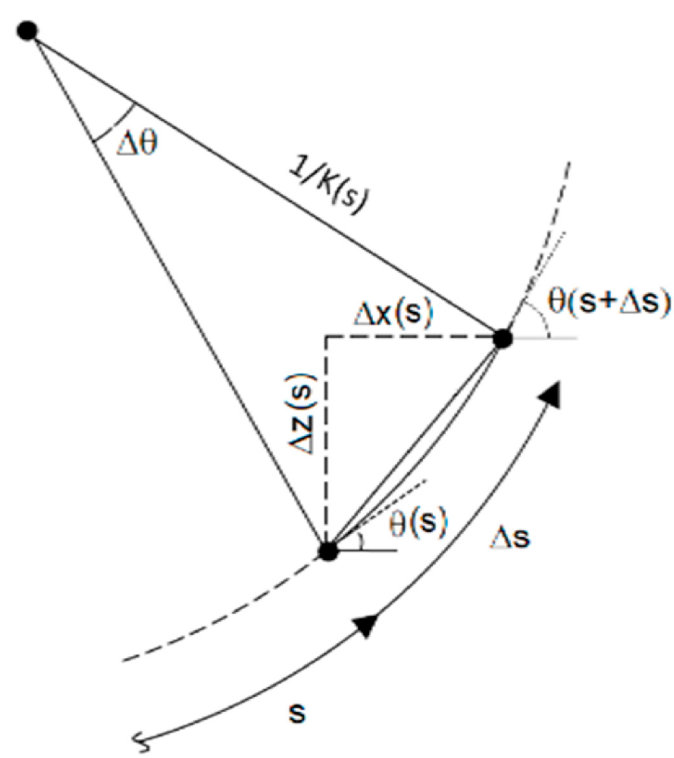

Fig. 1. Geometry of a segment displacement of a curve.

3. Procedure for monitoring

The procedure will be as follows for a hull girder monitoring: the structure has divided into segments longitudinally, and the inclines of each segment θm will be measured as the average curvilinear length s_{avr}. We can derive Eq. (6) to determine the average curvature values $K(s_{avr})$ of each segment. Deflections x and z can determine from Eq. (7) and Eq. (8) or Eq. (9) and Eq. (10). The procedure of the numerical analysis is summarized in the following figure as a flow chart, as shown in Fig. 2. This kinematic procedure is regardless of material properties, loading properties or boundary conditions, and able to determine curvature distribution or deflections by using incline values on specified nodes. This simple process can be run with Matlab or Excel.

Hull can be in a trimmed position with $\theta trim$. The algorithm can estimate the trimmed original curve or transform it into an untrimmed form. The untrimmed form transformation requires an extra correction iteration to satisfy the BC's as shown in Fig. 2.

3.1. Numerical study for the deflection curve monitoring

Two types of deflection curves are going to use in the validation of the method. The incline values of the curve will be read and use in the algorithm to demonstrate sensor readings. The first form is generated with a spline for the representation of the pre-ultimate inelastic behavior, the second form simulates post-collapse

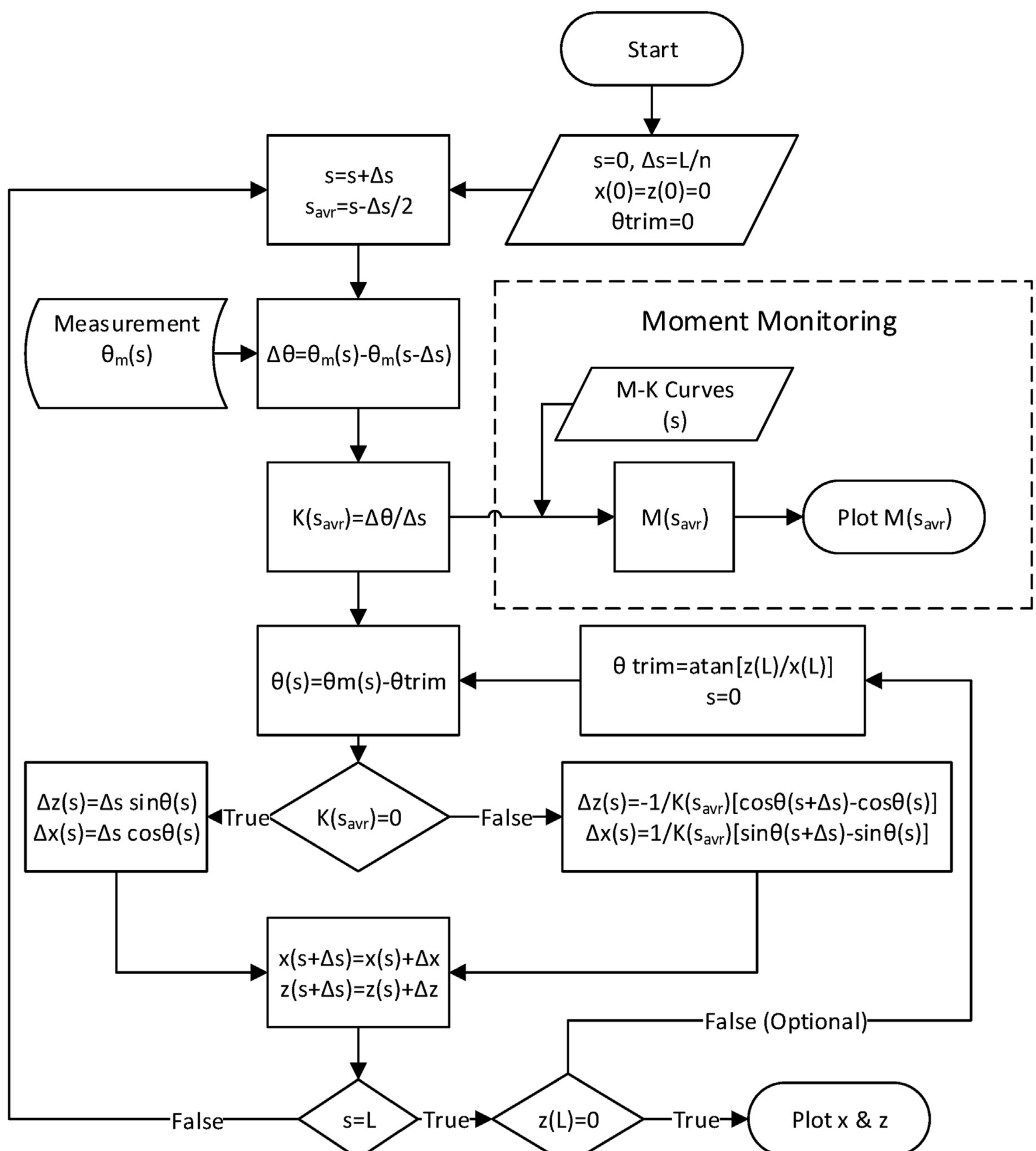

Fig. 2. Flow chart for deflection curve.

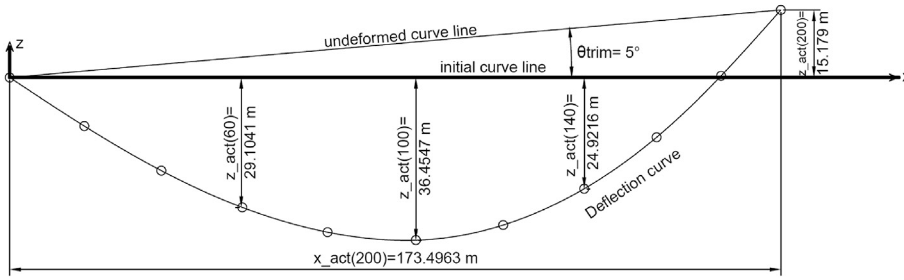

Fig. 3. Deflection curve.

behavior with a hinge formation. All deflections include a θ*trim* trim angle and magnitudes of the deflections are at a high level. The number of the reading points and accuracy of the sensor is going to study for the sensitivity analysis.

3.1.1. Numerical example #1

The deflection curve of the box type hull girder fitted with spline has been used in the analysis for validation of the procedure. The curve with severe displacement shown in Fig. 3 with 200 m curvilinear length has been divided into 10 segments and each node's incline has been measured for the numerical analysis. Numerical data of the procedure is given in Table 1 and compared with the actual values of the deflections *x_act* and *z_act*. Trim of the hull has been kept. The accuracy of the method is approximately 1.58% with 10 nodal reading.

3.1.2. Numerical example #2

One of the worst structural damage of a marine vessel is having a hinge formation at a post-collapse regime. Fig. 4 shows the failure of Very Large Crude Carrier, "Energy Concentration" in 1980. In the second numerical study, it was tried to show the hinge formation with a curve shown in Fig. 5.

The deflection curve of the hull girder is composed of curve fillet lines with a 4.5 m radius in the analysis for validation of the hinge scenario. The curve with severe displacement shown in Fig. 5 with 200 m curvilinear length has been divided into 10 segments and each node's incline has been measured for the numerical analysis. Numerical data of the procedure is given in Table 2 and compared with the actual values. Trim of the hull has been kept. The accuracy of the method is approximately 11.8% with 10 nodal readings for this deflection.

3.2. Sensitivity evaluation

Inclinometers within -+30° range can receive an accuracy of up to 0.0125° with 0.0007° precision for high-cost sensors, 0.025° with 0.001° precision for low-cost sensors. Measurements are going to be limited to the limitations of the low-cost sensors. The algorithm employs the difference between the inclinometer data between adjacent nodes, not the actual values. Therefore, the accuracy of the inclinometer is not effective on the results, the precision of the sensors is limiting the numerical accuracy.

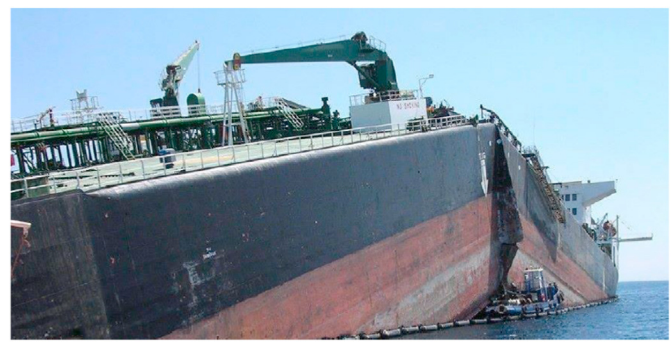

Fig. 4. Energy concentration (Ben-Amar, 2015).

The first numerical study error is approximately 1.58% and correlation is fine with 10 sensor data. If the number of sensors increased to 20, error reduces down to 0.87%. It is also possible to increase the accuracy of the numerical calculation by adding virtual sensor data generated from cubic interpolation. If the number of data is increased from 10 to 40 with cubic interpolation, the error reduces down to 0.52%. Therefore, it is not necessary to increase up the number of sensors for the pre-ultimate inelastic behaviors.

For the second study, error reaches 11.8% with 10 sensor data. Hinge formation mostly occurs near amidships if grounding is not considered. Therefore, increasing sensor concentration near amidships will be a powerful solution. Adding one more sensor

Table 1
Numerical calculation for example #1.

(m) s	(degree) θm(s)	(rad/m) K(s)	(m) Δx(s)	(m) Δz(s)	(m) x(s)	(m) z(s)	(m) x_act(s)	(m) z_act(s)	(%) Error z/z_{max}	(%) Error x/L
0	−33.41				0.00	0.00	0.00	0.00	0.00%	0.00%
20	−31.91	0.00131	16.84	−10.79	16.84	−10.79	16.79	−10.87	0.22%	0.02%
40	−27.53	0.00384	17.37	−9.91	34.21	−20.70	34.10	−20.87	0.48%	0.05%
60	−20.56	0.00602	18.25	−8.15	52.46	−28.84	52.31	−29.10	0.72%	0.08%
80	−11.12	0.00829	19.22	−5.46	71.68	−34.30	71.50	−34.68	1.05%	0.09%
100	1.94	0.01134	19.89	−1.60	91.57	−35.90	91.38	−36.45	1.52%	0.10%
120	17.73	0.01379	19.65	3.39	111.22	−32.51	111.02	−33.08	1.58%	0.10%
140	30.27	0.01100	18.23	8.12	129.45	−24.39	129.24	−24.92	1.47%	0.11%
160	40.14	0.00855	16.32	11.51	145.77	−12.87	145.54	−13.38	1.39%	0.12%
180	46.37	0.00550	14.56	13.70	160.33	0.82	160.04	0.39	1.19%	0.15%
200	48.40	0.00175	13.54	14.72	173.87	15.55	173.50	15.18	1.00%	0.19%

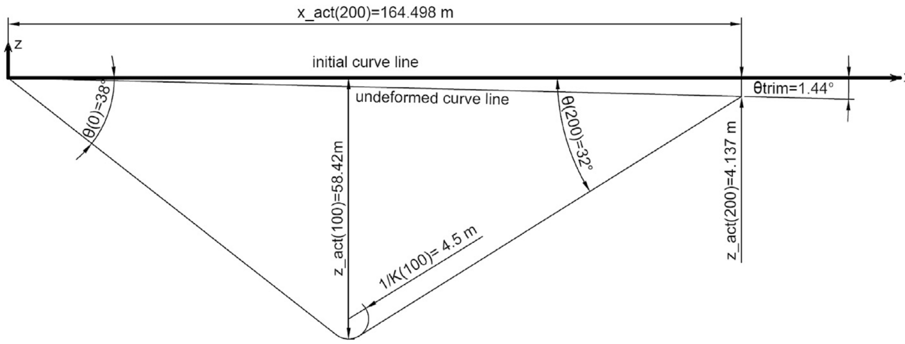

Fig. 5. Deflection curve for example #2.

Table 2
Numerical calculation for example #2.

(m) s	(degree) θm(s)	(rad/m) K(s)	(m) Δx(s)	(m) Δz(s)	(m) x(s)	(m) z(s)	(m) x_act(s)	(m) z_act(s)	(%) Error z/z_{max}	(%) Error x/L
0	−38.00				0.00	0.00	0.00	0.00	0.00%	0.00%
20	−38.00	0.00000	15.76	−12.31	15.76	−12.31	15.76	−12.31	−0.01%	0.00%
40	−38.00	0.00000	15.76	−12.31	31.52	−24.63	31.52	−24.63	0.01%	0.00%
60	−38.00	0.00000	15.76	−12.31	47.28	−36.94	47.28	−36.94	0.00%	0.00%
80	−38.00	0.00000	15.76	−12.31	63.04	−49.25	63.04	−49.25	0.00%	0.00%
100	32.00	0.06109	18.75	−0.98	81.79	−50.24	79.69	−57.13	11.80%	1.05%
120	32.00	0.00000	16.96	10.60	98.76	−39.64	96.65	−46.53	11.80%	1.05%
140	32.00	0.00000	16.96	10.60	115.72	−29.04	113.62	−35.93	11.80%	1.05%
160	32.00	0.00000	16.96	10.60	132.68	−18.44	130.58	−25.33	11.79%	1.05%
180	32.00	0.00000	16.96	10.60	149.64	−7.84	147.54	−14.74	11.81%	1.05%
200	32.00	0.00000	16.96	10.60	166.60	2.76	164.50	−4.14	11.80%	1.05%

near amidships reduces the error from 11.8% to 2.11%. Even though the error seems to be very large, it is reasonable for such catastrophic damage. Extending the data with Cubic or Bessel spline interpolation will not give a good response when straight lines exist. If the straight part is eliminated from the interpolation, extended data solution from 10 sensor data reaches 4.19%. It is clear the actual behavior of the straight part is going be slightly curved form due to gravity, not in straight form.

The actual performance of the sensor should be also tested within small deflections to see the accuracy is enough or not. To test this situation deflection curve is assumed to be a sine function given below

$$z(s) = \delta_{max} \sin(\pi s / L) \tag{11}$$

where δ_{max} denotes the maximum displacement at the amidships.

Sensors measurements can be defined with the differentiation of Eq. (11) as given below in Eq. (12):

$$\theta_m(s) = \pi \delta_{max} / L \sin(\pi s / L) \tag{12}$$

The effective number of the sensor should be determined for a hull strength monitoring system. Table 3 shows the results for the different quantity of sensors (n) where the resolution and accuracy of the sensor data are 0.001°.

Table 3
Sensitivity analysis results.

n	δmax/L						
	0.0001	0.00015	0.00025	0.000375	0.0005	0.001	0.0025
8	0.19%	1.46%	0.73%	1.10%	1.28%	1.33%	1.32%
10	−0.79%	0.23%	1.04%	0.40%	0.43%	0.65%	0.81%
12	−0.72%	0.86%	0.37%	0.71%	0.44%	0.48%	0.59%
14	0.58%	0.47%	−0.11%	0.27%	0.45%	0.49%	0.43%
16	−1.17%	1.28%	0.19%	0.23%	0.29%	0.27%	0.35%
18	−1.08%	−0.29%	0.61%	0.45%	−0.36%	0.20%	0.26%

3.3. Procedure for moment distribution

The previous procedure figures out modeling the deflection curve numerically with the usage of curvatures in curvilinear coordinates. The deflection curve divides into segments and each segment's incline of the cross-section is known. Determination of the moment distribution *M(s)* is going to obtain from progressive collapse analysis of the hull girder under vertical bending for the associated curvatures or inclines.

Progressive collapse analysis can be obtained from the Common Structural Rules (CSR) procedure based on the Smith Method. Alternatively, Nonlinear finite element Analysis (NFEA) with the tools such as ANSYS, Abaqus, LS-Dyna, or Patran; Idealized Structural Unit Method (ISUM) with the tool ALPS/HULL; Modified Paik-Mansour formula can be also chosen. Those methods are well studied and reviewed in the literature (Downes et al., 2017; ISSC, 2012; ISSC, 2015; Paik et al., 2013; Tuyen and Ping, 2018; Xu et al., 2017; Yao, 2003).

A full model of the hull is not necessary and a partial model will be enough for the evaluation. The main assumption of the analysis is plain sections remain plain on the boundary condition of the model. Under the external bending moments, it is expected that rigid plain planes will rotate on the neutral axis and balanced to an incline value as shown in Figs. 6 and 7. Each incline value of the cross-section has to be balanced with a moment value even post-collapse mechanism occurred. Eq. (5) shows the relation between the incline and the curvature. Therefore, the final product of the analysis is the moment-curvature curve for the hull model. The partial model length should be generated for the part of the hull

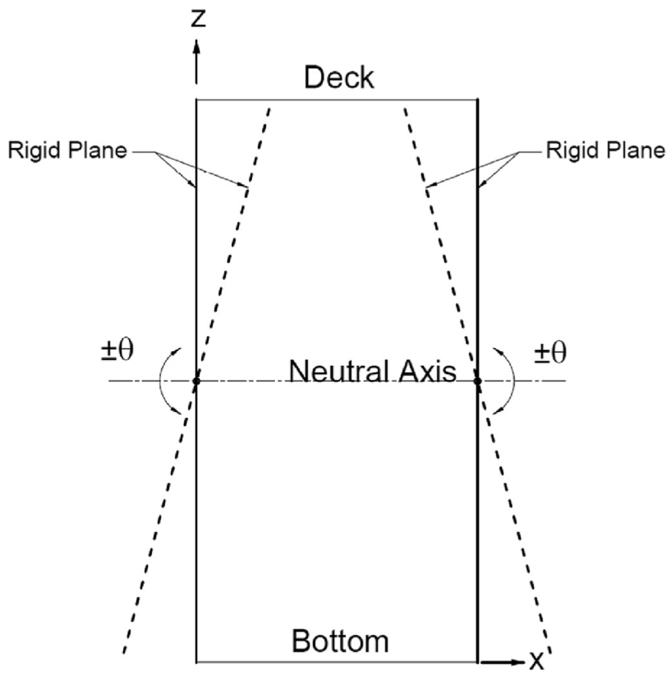

Fig. 6. Bending of a 2D block model.

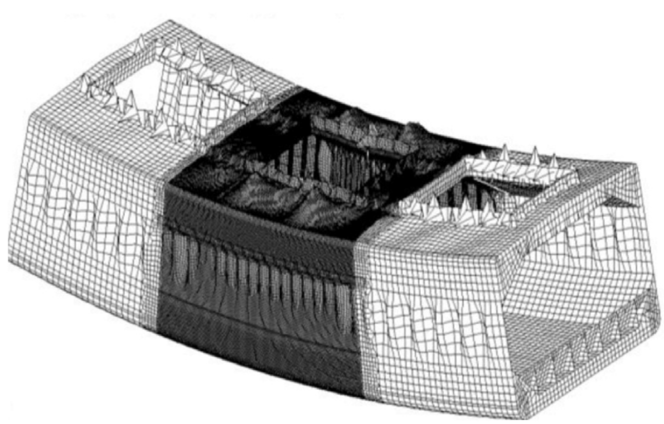

Fig. 7. Plane rotation of cross-sections in FEA (Alie et al., 2016).

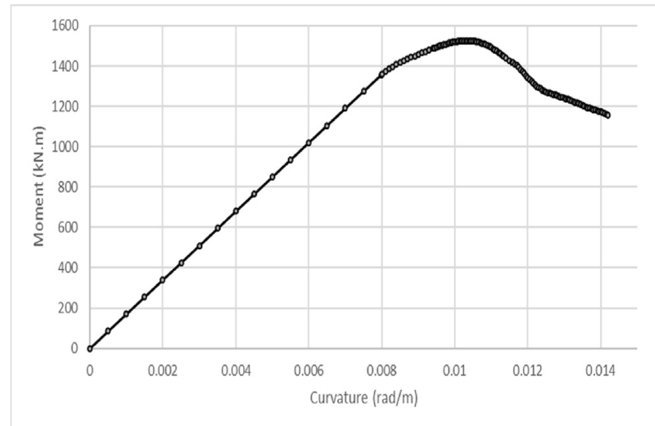

Fig. 9. Moment curvature diagram of a box girder.

between two adjacent sensors. The location of the sensors is very important; it should be away from local deformations and should satisfy the assumption of the plane section remains plane. But in this study and calibration procedure of the sensors kept for future tasks.

The main assumptions for the progressive collapse analysis are effects of shear force and torsional loading are neglected and plain sections remain plain. Lateral pressure effects, initial imperfection, welding residual stresses, material nonlinearities are all in the subject of Moment-Curvature (M-K) determination. This procedure is regardless of the M-K determination, just uses M-K diagrams for the estimation.

An example of a M-K diagram of a box girder in Fig. 8 is shown in Fig. 9, which has been experimentally and numerically studied in the literature (Gordo and Guedes Soares, 2004; ISSC, 2015; ISSC, 2018). This diagram is going to use in the numerical study of moment distribution determination.

The previous procedure already figures out the curvature distribution of the hull. Average moment values $M(s_{avr})$ of the segments should be interpolated from the M-K diagram for the relevant average curvature values of the analysis and plot as shown in Fig. 2.

3.3.1. A numerical example of the moment distribution procedure

M-K diagram in Fig. 9 is going to use in the numerical study. Relevant moment values have been obtained by cubic interpolation. Hull is considered to be in a 200 m parallel length. Table 4 represents the deflection and moment distribution from 10

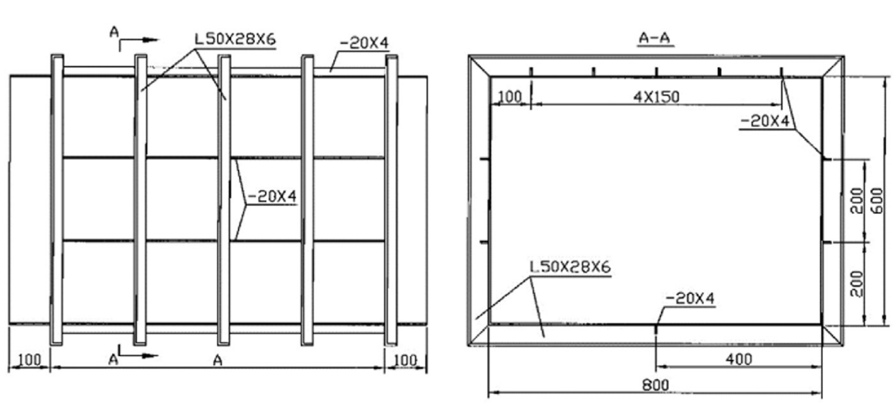

Fig. 8. Geometry of the box girder (Gordo and Guedes Soares, 2004).

Table 4
Numerical calculation example for moment monitoring.

(m) s	(m) s_{avr}	(rad) $\theta_m(s)$	((rad) $\Delta\theta$	(rad/m) $K(s_{avr})$	(kN.m) $M(s_{avr})$	(m) $\Delta x(s)$	(m) $\Delta z(s)$	(m) $x(s)$	(m) $z(s)$
0	0	0.9100			0			0.00	0.00
20	10	0.8655	−0.0445	0.00223	379	12.62	−15.51	12.62	−15.51
40	30	0.7362	−0.1293	0.00646	1099	13.91	−14.35	26.53	−29.86
60	50	0.5349	−0.2013	0.01007	1522	16.07	−11.85	42.60	−41.71
80	70	0.2812	−0.2537	0.01268	1260	18.31	−7.92	60.91	−49.63
100	90	0.0000	−0.2812	0.01406	1168	19.74	−2.79	80.65	−52.42
120	110	−0.2812	−0.2812	0.01406	1168	19.74	2.79	100.39	−49.63
140	130	−0.5349	−0.2537	0.01268	1260	18.31	7.92	118.70	−41.71
160	150	−0.7362	−0.2013	0.01007	1522	16.07	11.85	134.76	−29.86
180	170	−0.8655	−0.1293	0.00646	1099	13.91	14.35	148.68	−15.51
200	190	−0.9100	−0.0445	0.00223	379	12.62	15.51	161.30	0.00

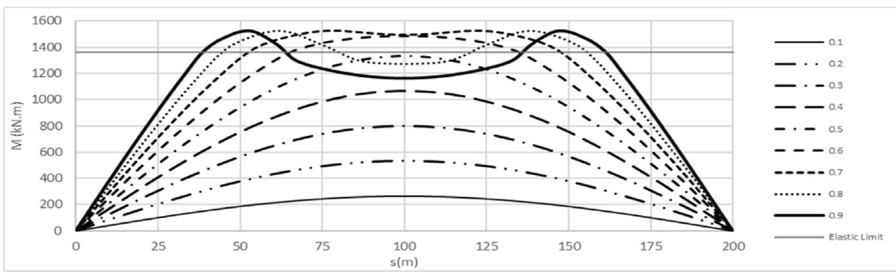

Fig. 10. Moment distribution for different loading conditions.

sensor data obtained from the cosine function of 0.91-radian amplitude.

Different loading amplitudes are also studied and summarized in Fig. 9. We can easily see the lost in the moment capacity from Fig. 10. When the amplitude of the incline function equals 0.6: the structure is in the pre-collapse region, but higher values of the amplitude make the structure to be in the post-collapse area.

4. Discussions

A new real-time procedure has been introduced to predict deflections, curvatures, and moment distributions of a hull based on inclinometer measurements. This simple inverse engineering technique has been represented in two parts. The first part is composed of curvature distribution determination and hull girder deflection calculation with the use of the curvature values. The second part is finding corresponding moment values of the curvature values.

Verification of the first procedures has been made by the deflection scenario of a hull. It is assumed that the incline values of the hull at specific nodes have been measured and used in the procedure. Finally, it was shown that the procedure can precisely estimate the deflection with a few sensor data. It is partially introduced some numerical methods to increase up the sensitivity. This simple technique can be run for linear response regime, pre-ultimate nonlinear response regime, or post-ultimate response regime. It is assumed that curve has the same magnitude of incline for fore and aft of a measurement node; with G1 type continuity. G0 type continuity has not been studied in the paper.

Defining the deflections can be very important data for a captain when facing a heavy sea condition, loading or unloading process, or trying to rest on blocks for docking. Another significant advantage of having accurate deflection information is on buckling assessment and progressive collapse analysis. This simple arithmetical procedure is extremely fast to get the response. Therefore, it can be a new perspective for hydroelasto-plasticiy approaches.

Curvature is not only used for the deflection calculations; it is also essential to determine moment distribution of the hull. This second procedure requires pre-calculated M-K diagrams. Moment values can be predicted with an interpolation method from M-K diagrams to provide the structural integrity of hull girder even for post-ultimate regime. Residual or remaining strength of the hull assessment has not been discussed in the study and kept for future tasks.

5. Conclusions

The author aims to show a new perspective on the usage of curvature. The author announced new procedures for the Real-time Hull Response Overall Monitoring System depend on inclinometer sensor data.

A real-time overall hull girder deflection curve modeling has been proposed. The procedure requires inclinometer sensors' data, located on the deck. Flow chart of the procedure explained and verified with the numerical studies. Numerical studies are demonstrated for the pre-ultimate and the post-ultimate nonlinear behaviors. It has been shown that 10 or 12 sensor data will be enough to represent the deflection curve. Sensitivity analysis showed that the system can measure accurately and stable when the magnitude of the deflection is greater than 0.05% of the hull length.

Ultimate strength assessments or progressive collapse analysis take an essential part in hull structural strength analysis where the final goal is to achieve actual moment-curvature (M-K) diagram. The procedure for the overall moment estimation depends on the M-K curve has been presented. A numerical example has been studied to demonstrate the analysis. Elastic, inelastic, and post-collapse structural bending moment capacity of the hull has been presented first time in the open literature.

The M-K diagrams are mostly obtained for the amidships section and used only as a limitation or criteria for the ultimate bending moment. With this study, it has been extended for the overall hull structure. Additionally, the balance of internal and external forces has been discretized from the analysis by pre-determined M-K diagrams. Consequently, the problem becomes a less computation time required kinematic determination, which can be easily run in real-time. It should be noticed that the accuracy of the bending moment estimation depends on the accuracy of the moment-curvature diagrams in the progressive collapse analysis.

If this system is applied to the hulls, it will be able to see the response of their hull in real-time with high accuracy to manage the course and speed when cruising or control the loading and the unloading process at the port.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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