Journal of
Ship&Ocean
Technology
©DECEMBER 2004

SOTECH Vol. 8, No. 4, pp. 17 ~ 25, 2004

Two-plane Hull Girder Stress Monitoring System for Container Ship

Jae-Woong Choi[1] and Yun-Tae Kang[1]

[1] Shipbuilding/plant Research Institute, Samsung Heavy Industries, Gyungnam, Korea; E-mail: jaewng.choi@samsung.com

Abstract

Hull girder stress monitoring system for container ship uses four long-base-strain-gages at mid-ship to monitor the resultant stresses and the applied moment components of horizontal, vertical and torsional moments. The bending moments are estimated by using the conventional strain-moment relations, however, the torsional moment related to the warping strain requires the assumption of the shape of torsional moments over the hull girder. Though this shape could be a sine function with an adequate period, it largely depends upon certain empirical formulas.

This paper introduces additional four long-base-strain-gages at mid-ship to derive the longitudinal slope of the warping strain because this slope is directly related to the torsional moment by Bi-moment concept. An open-channel-type cantilever beam has been selected as a simplified model for container ship and the result has proved that the suggested concepts can estimate the torsional component accurately. Finally this method can become reliable technique to derive all external moments in hull girder stress monitoring system for container ships.

Keywords: two-plane measurement, strain decomposition, hull girder stress monitoring system, container ship, LBSG(long-base-strain-gage)

1 Introduction

Hull girder stress monitoring systems are being used to monitor the structural safety of hull girder during navigation and loading/unloading of cargos in real time since the hull girders of some ships have collapsed due to severe wave conditions. Hence, the conventional hull girder stress monitoring systems have been monitored the resultant stresses and the related moment components of the vertical bending moment, the horizontal bending moment and the torsional moment, with respect to the permissible values defined in Class Rules.

Besides, container ship whose top of hold area is opened should be designed to sustain severe torsional moment due to wave excitation and loading/unloading policies. However, torsional component in container ship has not been estimated in these systems because the component cannot be formulated in a simple way. Choi and Kang(2003) have suggested a strain decomposition method to derive those bending and torsional components based on the measured strains from the four LBSGs within one cross-section. In this derivation, the shape of torsional moment was assumed to formulate the moment as a function of warping strain at measured cross-section. The shape might have a sinusoidal function (Kim et al 2000) with period of hull length or opened-top length, and some empirical function (NK 2003). These assumptions are the reasons for an inaccurate estimation of torsional moment.

This paper introduces two-plane hull girder stress monitoring system to derive the true torsional moment according to the warping strain. In the suggested system, additional four LBSGs are located at a cross-section with a suitable distance from the cross-section of conventional system. Then the strain decomposition algorithm (Choi and Kang 2003) is applied to these sections, independently. The warping strains from two cross-sections are used to obtain the slope of the warping strains. Finally the torsional moment related to the warping strain can be estimated by using the relation of Bi-moment.

An open-channel-type cantilever beam under a torsional moment at free-end is chosen to prove the validity of this theory. The estimated torsional moment shows the same value as the applied one. This application could be regarded as a confirmation to the real container ship.

2 The relations between strains and moments

Figure 1 illustrates a simplified LBSG arrangement of a conventional hull girder stress monitoring system at the mid ship of a container ship. The external moments are horizontal and vertical bending moments, and the torsional components consists of warping and St. Venant strains. Though detailed graphical notations for those components can be found in Choi and Kang(2003), more rigorous derivation for the torsional moments except bending components will be described in this paper to show the theoretical background of two-plane hull girder stress monitoring system. This paper will also provide the correction to the symbolic notation of warping function and the revised form of the relation between St. Venant strain and pure torsional moment.

2.1 Governing equation of torsional component

Strains due to torsional moment can be divided into warping strain having cross-sectional distortion and St. Venant strain keeping plane cross-section. So the governing equation for this can be described as the following. (Kim et al 2000, Fujitani 1990)

$$EJ_w\theta''''-GJ\theta''=m_z \tag{1}$$

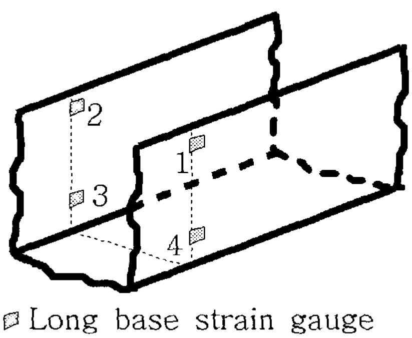

Figure 1: A conventional arrangement of gages at the mid ship of container vessel.

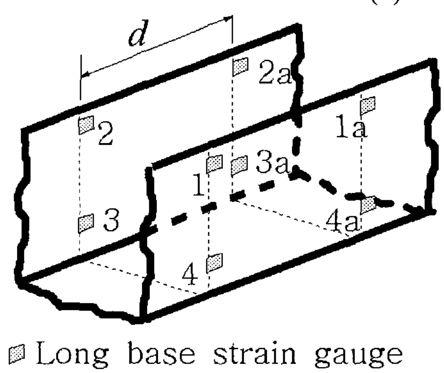

Figure 2: A new arrangement of two-plane strain decomposition.

Here, E and J_w stands for Young's modulus and the second moment of cross-section at shear center, respectively. The G and J represent the shear modulus and polar moment of inertia at centroid, respectively. The first and second terms in the left hand side represent warping and St. Venant components, respectively. The right hand side stands for the torsional moment per unit length. Hence, the torsional moment can be rewritten by the integration with respect to the longitudinal variable.

$$T = GJ\theta' - EJ_W\theta''' \quad (2)$$

2.1.1 Warping component

Distortion of cross-section is described by warping variable w that is the slope of twisting angle with respect to longitudinal direction.

$$w = \frac{d\theta}{dx} \quad (3)$$

Then the warping normal strain ε_w and stress σ_w can also be described as following.

$$\varepsilon_w = U\frac{dw}{dx} \quad (4)$$

$$\sigma_w = EU\frac{dw}{dx} \quad (5)$$

Here, U stands for warping function and can be obtained by the finite element modeling (Fujitani1990) for complex geometry and by simple formulas (Kim et al 2000) for simple geometry. Then the torsional moment related to warping strain can be rewritten by using Bi-moment Bi. (Kim et al 2000)

$$T_w = -\frac{dBi}{dx} = -\Gamma\frac{d^2w}{dx^2} \quad (6)$$

Here, Γ is the torsional constant and multiplication of Young's modulus and the second moment of cross-section at shear center.

$$\Gamma = EJ_w \quad (7)$$

$$J_w = \int_\xi U^2 t d\xi \quad (8)$$

$$\frac{d^2w}{dx^2} = \frac{d(\varepsilon_w/U)}{dx} \cong \frac{(\varepsilon_{aw}/U_a - \varepsilon_w/U)}{d} \quad (9)$$

That is, the warping strain ε_{aw} at an adjacent cross-section is required to obtain the torsional moment. To obtain this relation, this paper suggests two-plane measurement using the eight LBSGs.

The torsional moment in previous work (Choi and Kang 2003) was expressed in terms of warping strain and constant coefficient describing the assumed shape of torsional moment over the hull opening length L_H.

$$T_w = K_w |\varepsilon_w| \tag{10}$$

$$K_w = \frac{\Gamma}{U(L_H/\pi)\tan(\pi z/L_H)} \tag{11}$$

However, the opening length can become the distance between forward perpendicular and the front of accommodation or the distance between forward and backward perpendiculars. (Paik et al 2001, Lee 1981) Moreover, the assumed torsional shape could also get rather complex. (NK 2003) That is the reason why the equation (6) should be implemented in hull girder stress monitoring system.

2.1.2 St. Venant component

This strain for a beam-like structure due to the pure torsional component depends on the boundary conditions. For fixed-fixed boundary conditions, the distance of two pre-defined positions is deformed by the external torsions. However, the distance will be kept in case of free-fixed or free-free boundary conditions. Figures 3 and 4 illustrate all these phenomena according to torsional moments at one end, including the original and deformed shapes. These interpretations conclude that LBSGs only measure the deformation due to the fixed-fixed component because the gages are sensitive to the axial deformation.

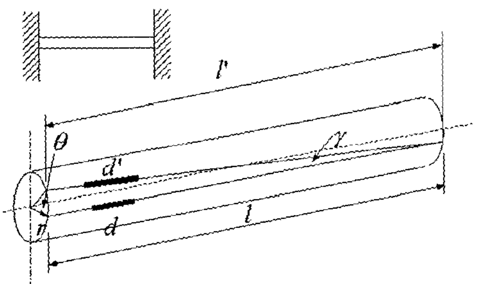

Figure 3: An example of cantilever beam with fixed-fixed boundary conditions.

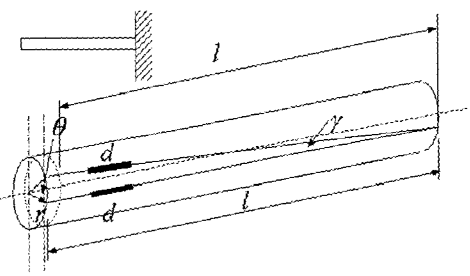

Figure 4: An example of cantilever beam with fixed-free boundary conditions.

Let's consider the fixed-fixed conditions in detail. By the definition of distance r_{sc} between shear center and the sensor position, the mathematical relation between pure torsional moment and St. Venant strain becomes,

$$\begin{aligned} T_p &= GJ\theta' \\ &= GJ\theta / l \\ &= \sqrt{2\varepsilon_T}\, GJ/r_{sc} \end{aligned} \tag{12}$$

Here,

$$\begin{aligned} \varepsilon_T &= \frac{l-l'}{l} \\ &\approx 1-\cos\gamma \\ &= (\theta/l)^2 r_{sc}^2/2 \end{aligned} \tag{13}$$

Then the axial stress can also be defined as the following.

$$\sigma_T = E\varepsilon_T \tag{14}$$

Moreover, Lee(1981) described that the boundary condition of hold area of a container ship can be a combination of fixed and free conditions. Henceforth, hull girder stress monitoring system might lose the torsional component due to the free-fixed and/or free-free boundary conditions.

However, Paik et al(2001) described that the boundary conditions could be partially restrained warping conditions for hold area of a container ship and warping strain is the main contribution in torsional moment at about mid-ship area. Therefore, this decomposition can be considered as suitable in hull girder stress monitoring system.

2.2 Horizontal moment

Horizontal strain occurs by waves, winds and currents etc. and the related stress and moment can be introduced by using the Young's modulus E and the second moment of cross-section Z_{yy}.

$$M_y = EZ_{yy}\varepsilon_y \tag{15}$$

$$\sigma_y = E\varepsilon_y \tag{16}$$

2.3 Vertical moment

Vertical strain is induced by the loading distribution over the longitudinal direction and pitching motions of hull and bow slamming phenomena etc., and the related stress and moment can be expressed by using the Young's modulus E and the second moment of cross-section Z_{yy}.

$$M_z = EZ_{zz}\varepsilon_z \tag{17}$$

$$\sigma_z = E\varepsilon_z \tag{18}$$

3 Implementation of two-plane hull stress monitoring system

Decomposed strain vector $\bar{\varepsilon}$ can be obtained by the following corrected equation of strain decomposition method (Choi and Kang 2003) based on the measured strain vector $\bar{\varepsilon}_m$.

$$\bar{\varepsilon}_m = \bar{A}\,\bar{\varepsilon} \tag{19}$$

Here,

$$\bar{\varepsilon}_m = \begin{bmatrix} \varepsilon_1 & \varepsilon_2 & \varepsilon_3 & \varepsilon_4 \end{bmatrix}^T \tag{20}$$

$$\overline{A} = \begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ y_B/y_T & -z_B/z_T & U_3/U_1 & \left(r_{3sc}/r_{1sc}\right)^2 \\ -y_B/y_T & -z_B/z_T & -U_3/U_1 & \left(r_{3sc}/r_{1sc}\right)^2 \end{bmatrix} \tag{21}$$

$$\overline{\varepsilon} = \begin{bmatrix} \varepsilon_y & \varepsilon_z & \varepsilon_w & \varepsilon_T \end{bmatrix}^T \tag{22}$$

The decomposed strain component vector is defined as the following, with respect to the strain at the 1st sensor.

Strain due to horizontal moment: $\varepsilon_{1y} = -\varepsilon_y$ (23)

Strain due to vertical moment: $\varepsilon_{1z} = \varepsilon_z$ (24)

Warping strain due to torsional moment: $\varepsilon_{1w} = \varepsilon_w$ (25)

St. Venant strain due to torsional moment: $\varepsilon_{1T} = \varepsilon_T$ (26)

The similar results can be obtained at an adjacent plane with subscript a and having a distance of d, and then the subtraction of the two equations can be expressed as

$$\Delta\overline{\varepsilon}_m = \overline{A}\Delta\overline{\varepsilon} \tag{27}$$

Here,

$$\Delta\overline{\varepsilon}_m = \begin{bmatrix} \varepsilon_{1a} - \varepsilon_1 & \varepsilon_{2a} - \varepsilon_2 & \varepsilon_{3a} - \varepsilon_3 & \varepsilon_{4a} - \varepsilon_4 \end{bmatrix}^T \tag{28}$$

$$\Delta\overline{\varepsilon} = \begin{bmatrix} \varepsilon_{ay} - \varepsilon_y & \varepsilon_{az} - \varepsilon_z & \varepsilon_{aw} - \varepsilon_w & \varepsilon_{aT} - \varepsilon_T \end{bmatrix}^T \tag{29}$$

The transformation matrix $\overline{A}$ will be the same, because the two planes will be located at the plane having the same cross-sectional properties. Finally, the torsional component due to warping can easily be obtained by the following.

$$\begin{aligned} T_w &= -\Gamma \frac{d^2 w}{dx^2} \\ &\approx -\Gamma \frac{\varepsilon_{aw} - \varepsilon_w}{U_1 d} \end{aligned} \tag{30}$$

4 Simulation

4.1 Application to a cantilever model

Figure 5 shows a cantilever beam with open top cross-section with torsional moment of $500Nm$ at the free end and Table 1 represents all geometrical properties. This model is meshed by square shapes with $0.02m$ mesh size. Conventional NASTRAN solver was used to solve the deformed shape illustrated in Figure 6 and the solved and decomposed strains are tabulated in Table 2.

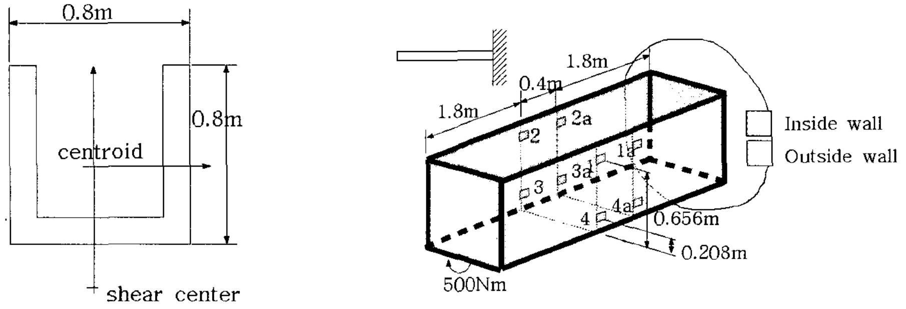

Figure 5: A graphical illustration of a cantilever beam with open top in case of torsional moment. (Thickness of wall is 0.002m)

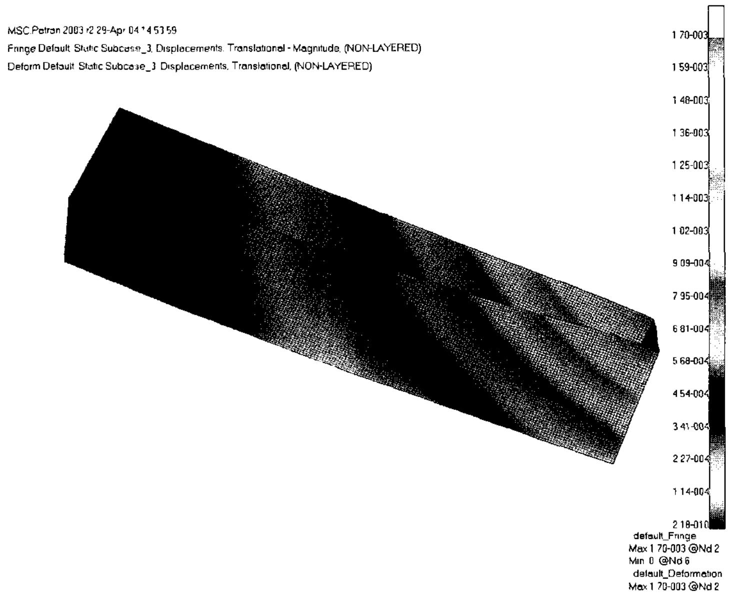

Figure 6: Deformed shape of the cantilever beam with torsional moment of $500Nm$

Table 1: Geometrical parameters of the cantilever beam.

Variable	Value	Remark
z_B/z_T	$0.0594m/0.3887m$	
y_B/y_T	$0.40m/0.40m$	
J_w	$3.901e^{-5}m^6$	Second moment of cross-section
Centroid	$0.2674m$	
Shear center	$-0.3415m$	
r_{1sc}/r_{3sc}	$1.0747m/0.6797m$	
U_1	$0.1258m^2$	
U_3	$0.0534m^2$	

Table 2: Estimated and decomposed strains by using NASTRAN solver.

Cross-section	Estimated strain	Decomposed strain
Cross-section (1, 2, 3, 4)	$\varepsilon_1 = -0.1440e^{-4}$ $\varepsilon_2 = 0.1462e^{-4}$ $\varepsilon_3 = -0.0621e^{-4}$ $\varepsilon_4 = 0.0629e^{-4}$	$\varepsilon_y = -0.0006e^{-4}$ $\varepsilon_z = 0.0000e^{-4}$ $\varepsilon_w = -0.1457e^{-4}$ $\varepsilon_T = 0.0010e^{-4}$
Cross-section (1a, 2a, 3a, 4a)	$\varepsilon_1 = -0.1764e^{-4}$ $\varepsilon_2 = 0.1780e^{-4}$ $\varepsilon_3 = -0.0760e^{-4}$ $\varepsilon_4 = 0.0766e^{-4}$	$\varepsilon_y = -0.0008e^{-4}$ $\varepsilon_z = 0.0000e^{-4}$ $\varepsilon_w = -0.1780e^{-4}$ $\varepsilon_T = 0.0008e^{-4}$

Finally, the torsional moment can be estimated by using the equation (30), the geometrical properties are shown in Table 1 and the decomposed strains in Table 2.

$$\begin{aligned} T_w &= -\Gamma \frac{\varepsilon_{aw} - \varepsilon_w}{U_1 d} \\ &\approx -\left(200e^9\right)\left(3.901e^{-5}\right)\frac{-0.1780 + 0.1457}{(0.1258)(0.4)} \\ &\approx 499.7Nm \end{aligned} \tag{31}$$

This torsional moment is quite the same as the applied torsional moment of $500Nm$, and therefore this two-plane hull girder stress monitoring system can be concluded to an effective technique to estimate warping component in real container ship.

4.2 Parameters to considered

The distance between two-plane could be the parameter of torsional moment and can be rewritten as

$$d = \left| \frac{\varepsilon_{aw} - \varepsilon_w}{U_1 T_w} \right| \tag{32}$$

This equation shows that the distance has to be significant to recognize the strain difference between two planes. The large distance leads to big difference of the strains but nonlinear behaviors of the slope cannot be avoidable.

5 Concluding remarks

Two plane hull stress monitoring system is suggested in this paper. The system has eight measured strains at two planes with finite distance and has the same geometrical properties. The warping torsional moment is also interpreted by the combination of the slope of warping strain and geometrical properties. This formulation deletes the assumption of torsional moment shape that is largely depends upon certain empirical formulas.

A cantilever beam with open top cross-section has been chosen to be a simplified container ship model. To verify the performance for estimation of warping component, a torsional moment was applied to the free-end of the model. The strain components were estimated by using finite element analysis and the proposed decomposition method was applied. The estimated torsional moment illustrates the same quantity as the applied torsional moment causing warping strain. Hence, one can conclude that the proposed method can be an effective tool to estimate the external moments in real container ships.

References

Choi J.W. and Y.T. Kang. 2003. Strain decomposition method in hull stress monitoring system for container ship. The Society of Naval Architects of Korea, **7**, **3**, 56~65.

ClassNK. 2003. Guidelines for Container Carrier Structures.

Fujitani, Y. 1990. Thin-Walled Beam Structural Analysis. Baihukan Book Company. (in Japanese)

Kim, K.S., K.S. Kim, J.W. Lee, I.T. Kim and H.S. Bang. 2000. Mechanics of Ship Structures. Inha University Press, in Korean Translation Version, Chapter 5. (in Korean, Original book: Yamamoto, Y., H. Ohira, Y. Sumi and M. Hujino. 1997. Mechanics of Ship Structures. Seizando Shoten, in Japanese)

Lee J.S. 1981. Ship Structural Mechanics. Korea Maritime Research Institute. (in Korean)

Paik, J.K., A.K. Thayamballi, P.T. Pedersen and Y.I. Park. 2001. Ultimate strength of ship hulls under torsion. Ocean Engineering, **28**, 1097-1133.