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Field application of elasto-magnetic stress sensors for monitoring of cable tension force in cable-stayed bridges

Jinsuk Yim[1], Ming L. Wang[2], Sung Woo Shin[*3], Chung-Bang Yun[4], Hyung-Jo Jung[5], Jeong-Tae Kim[6] and Seung-Hyun Eem[5]

[1]Samsung C & T Company, 1321 Seocho-dong, Seocho-gu, Seoul 137-857, Korea
[2]Department of Civil and Environmental Engineering, Northeastern University, 360 Huntington Ave., Boston, MA02115, USA
[3]Department of Safety Engineering, Pukyong National University, 100 Yongdang-dong, Nam-gu, Busan 608-739, Korea
[4]School of Urban and Environmental Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Eonyang-eup, Ulsan 689-798, Korea
[5]Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Korea
[6]Department of Ocean Engineering, Pukyong National University, 599-1 Daeyeon-dong, Nam-gu, Busan 608-737, Korea

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Abstract. Recently, a novel stress sensor, which utilizes the elasto-magnetic (EM) effect of ferromagnetic materials, has been developed to measure stress in steel cables and wires. In this study, the effectiveness of this EM based stress sensors for monitoring of the cable tension force of a real scale cable-stayed bridge was investigated. Two EM stress sensors were installed on two selected multi-strand cables in Hwa-Myung Bridge, Busan, South Korea. Conventional lift-off test was conducted to obtain reference cable tension forces of two test cables. The reference forces were used to calibrate and validate cable tension force measurements from the EM sensors. Tension force variations of two test cables during the second tensioning work on Hwa-Myung Bridge were monitored using the EM sensors. Numerical simulations were conducted to compare and verify the monitoring results. Based on the results, the effectiveness of EM sensors for accurate field monitoring of the cable tension force of cable-stayed bridge is discussed.

Keywords: stress sensing; elasto-magnetic sensor; cable tension force monitoring; cable-stayed bridge; structural health monitoring

1. Introduction

Since the cable is one of primary structural elements in a cable stayed-bridge, the tension force of a cable in the bridge is very important parameter to be measured during construction and even in-service for assessing the safety and integrity of the cable bridges. In practice, vibration based method is commonly used to estimate the cable tension force in cable-stayed bridges due to its

∗Corresponding author, Associate Professor, E-mail: shinsw@pknu.ac.kr

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simplicity in test procedures (Zui *et al*. 1996, Russell and Lardner 1998). However, although the vibration based method is very practical and cost effective, it has some limitations in accurate measurements of the cable tension force in real bridges. One such problem is the uncertainties of essential parameters such as length and mass of the cable in real bridges. Uncertainties of those parameters often lead to an erroneous result in the estimation of the cable tension force in field (Kim and Park 2007, Triantafyllou and Grinfogel 1986). For this reason, many research efforts have been devoted to develop nondestructive methods for cable tension force measurements as an alternative to the vibration based method.

It is well known that the magnetic properties of ferromagnetic materials such as steel vary with the state of stress in the materials (Cullity and Graham 2008). This is so-called elasto-magnetic (EM) effect. The EM based stress sensor, which has recently been developed for measurement of stress in steel cables, utilizes the EM effect of ferromagnetic materials (Wang *et al*. 2000, 2001, Chen 2000). The EM stress sensor has been applied for various types of cables such as wires and strands and successfully shown its effectiveness in stress measurements (Wang and Wang 2004, Wang 2006). Recently, the EM stress sensor has also been applied to monitor stress loss of tendons in pre-stressed concrete beams and earth anchors (Sumitro *et al*. 2005). Compared to the vibration method for cable tension force measurements, the great advantage of the EM stress sensor is that it does not be affected by the length and mass of the cable in the estimation of the cable tension force since it only depends on magnetic properties of steel cables.

In this study, EM stress sensor is applied to a real cable-stayed bridge (Hwa-Myung Bridge) to investigate its effectiveness in measurements of cable tension force in field. Sensing principle and installation procedure of EM stress sensor are introduced. Conventional lift-off test is conducted to obtain reference cable tension forces of the test cables in Hwa-Myung Bridge. The reference forces are used to calibrate and validate cable tension force measurements from the installed EM stress sensors. Cable tension force measurements using EM stress sensor are carried out and the results are compared with both actual and numerically calculated forces. Finally, the effectiveness of the EM sensor for accurate field monitoring of the cable tension force is discussed.

2. EM based stress sensing principle

The sensing principle of EM stress sensor is based on the EM effect, i.e., stress dependence on magnetic properties of ferromagnetic materials. When external magnetic field is applied around a ferromagnetic material (e.g., steel), the resulting magnetic flux is produced inside the ferromagnetic material, which is called magnetization. Each ferromagnetic material has a unique relationship (called as the magnetization curve) between the applied magnetic field strength (H) and the resulting magnetic flux density (B). The magnetic permeability (μ), which is a characteristic value of magnetic materials, can be obtained from the magnetization curve as

$$B = \mu H \tag{1-a}$$

Normally, since the magnetization curve of ferromagnetic materials is nonlinear and hysteretic, the magnetic permeability for ferromagnetic materials is preferably defined as

$$\Delta B = \mu \Delta H \tag{1-b}$$

It should be noted that μ is not the slope of the magnetization curve, but simply represents the ratio B/H or $\Delta B/\Delta H$ (Bertotti 1998). Therefore, if the magnetization curve is nonlinear and hysteretic, μ may have different value according to the point at which it is measured. The magnetization curve of a ferromagnetic material can be modified due to its stress dependency (Cullity and Graham 2008, Bertotti 1998). Therefore, the permeability is also changed with respect to the state of stress in the material. The EM stress sensor utilizes this stress dependency of the magnetic permeability to estimate the stress in steel cables (Wang *et al*. 2000, 2001, Chen 2000).

In order to measure the permeability of steel cable, two solenoid coils, the primary (charging) and the secondary (sensing) coils, are wound on steel cable as shown in Fig. 1. The interrogation unit charges the primary coil to apply a magnetic field H to the cable. Then, the resulting magnetic flux density B in the cable produces a current in the secondary coil due to electromagnetic induction. According to Faraday's law, an electromotive force (ε_{out}) induced in the secondary coil (N turns) is proportional to a time change in magnetic flux ϕ inside the solenoid. If a steel cable with cross-section A_s is inserted in the coil, ε_{out} can be expressed using Faraday's law as

$$\varepsilon_{out} = -N\frac{d\phi}{dt} = -N\left[\mu_0 \frac{d}{dt}\int_{A_c - A_s} H(t)dA + \frac{d}{dt}\int_{A_s} B(t)dA\right] \tag{2}$$

where μ_0 is the permeability of air, A_c is the area inside the secondary coil and t is time. The first term in the right-hand side of Eq. (2) is a magnetic flux through an air gap between the coil and the steel cable, and the second one is a magnetic flux through the steel cable. Assuming a constant magnetic field inside the solenoid the integrated output voltage in the secondary coil will be

$$V_c = -\frac{1}{RC}\int_{t_1}^{t_2} \varepsilon_{out} dt = \frac{N}{RC}\left[(A_c - A_s)\mu_0 \Delta H + A_s \Delta B\right] \tag{3}$$

where R and C are the resistance and capacitance of the secondary coil, ΔH and ΔB are total amount of changes (from time t_1 to t_2) of the applied magnetic strength and the resulting magnetic flux density in the cable, respectively. In the same way, the integrated output voltage without steel cable is

$$V_0 = \frac{N}{RC} A_c \mu_0 \Delta H \tag{4}$$

Using Eqs. (3) and (4), we have the ratio of two integrated output voltages as

$$\frac{V_c}{V_0} = 1 + \frac{A_s}{A_c}\left(\frac{\mu}{\mu_0} - 1\right) \tag{5}$$

Eq. (5) can be re-written using the relative permeability μ_r (=μ/μ_0) as

$$\mu_r = 1 + \frac{A_s}{A_c}\left(\frac{V_c}{V_0} - 1\right) \tag{6}$$

Since V_0, A_c and A_s are constants, V_c becomes a sole variable of μ_r (Wang *et al*. 2000). Therefore, when V_c is measured, stress in steel cable can be determined using pre-established relationship between stress and the relative permeability of steel cable. Note, as shown in Eqs. (3) and (4), the output voltage is an integrated voltage within an effective time from t_1 to t_2. The integrated voltage is not the peak voltage of the output.

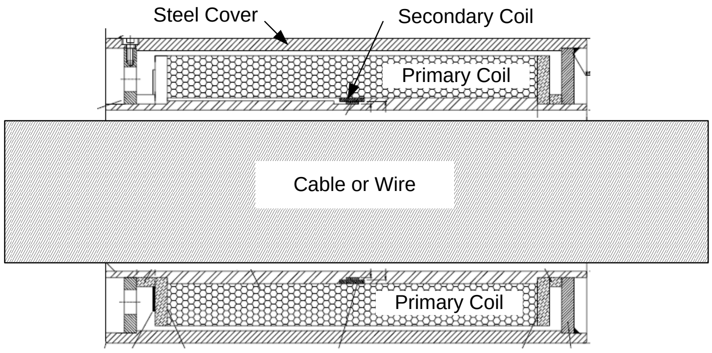


Fig. 1 Two solenoid coils for stress sensing of steel cable

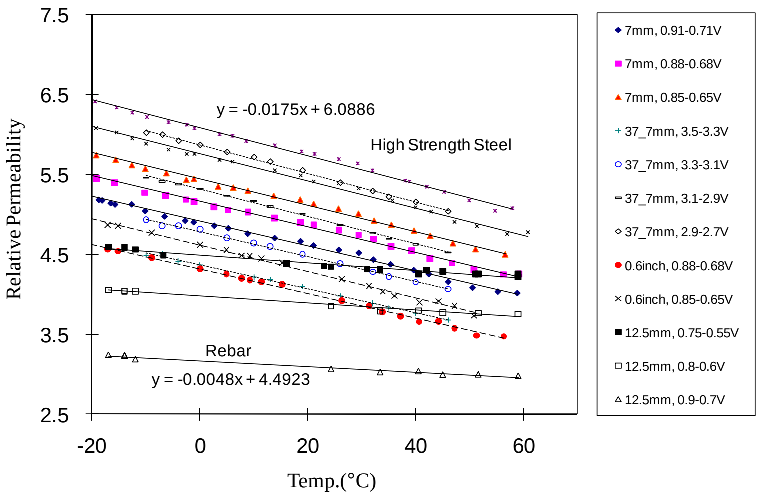


Fig. 2 Relationship between temperature and relative permeability for various strands and rebar

On the other hand, the magnetic permeability depends not only on stress (σ) but also on temperature (T) as shown in Fig. 2 (Lloyd *et al.* 2002). Therefore, temperature effect on permeability measurement should be considered for practical use of EM stress sensor. Temperature effect can be removed using temperature coefficient. The relative permeability varies linearly with temperature under the same stress condition (Chen 2000). Therefore, under zero stress condition ($\sigma = 0$), the relative permeability of ferromagnetic material with respect to temperature (T) has a following relationship.

$$\mu_r(0,T) - \mu_r(0,T_0) = \alpha(T - T_0) \tag{7}$$

where T_0 are reference temperature and α is temperature coefficient which is the slope in Fig.

2 and only depends on the type of material (Chen 2000, Lloyd 2002).

As described, a pre-established relationship between stress and the relative permeability of steel cable is used to measure stress of steel cable. In order to establish the relationship considering temperature effect, the effective relative permeability ($\bar{\mu}$) is defined based on the fact that the permeability-stress relation is parallel over the same temperature condition.

$$\bar{\mu}(\sigma,T) = \mu_r(\sigma,T) - \mu_r(0,T) \tag{8}$$

Using Eqs. (6) to (8), a final relationship between stress and the effective relative permeability of steel cable can be obtained as

$$\bar{\mu}\left(\sigma,T\right) = \mu_r(\sigma,T) - \mu_r(0,T_0) - \alpha(T-T_0) = \frac{A_c}{A_s}\left[\frac{V_c(\sigma,T) - V_c(0,T_0)}{V_0}\right] - \alpha(T-T_0) \tag{9}$$

Once this relation is established through calibration process, stress in the tested steel cable can be monitored by measuring temperature (T) and output voltage of the secondary coil (V_c).

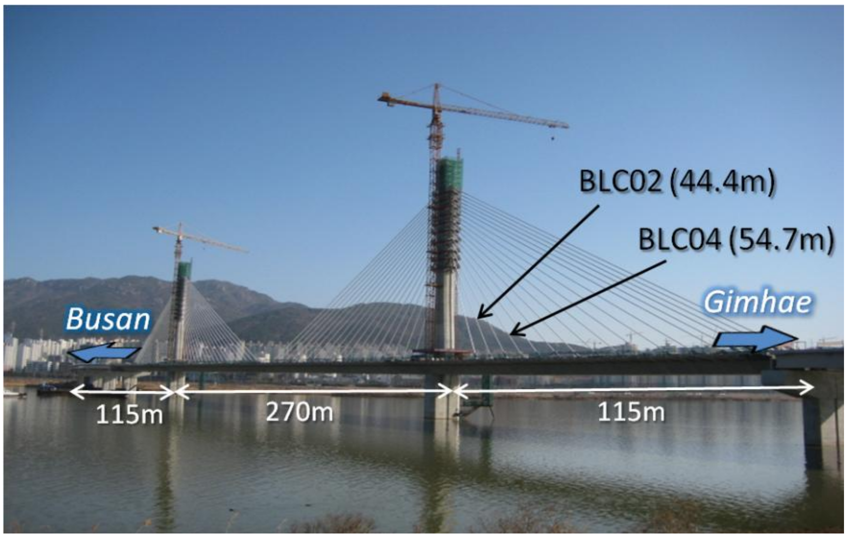


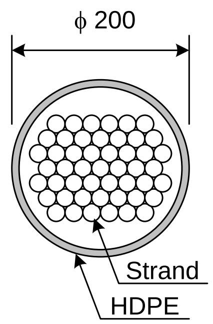
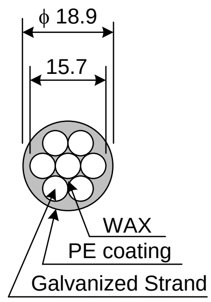
Fig. 3 Hwa-Myung Bridge and test cables (BLC02 and BLC04)

3. Filed test plan

3.1 Test bridge and setup

A cable-stayed bridge, Hwa-Myung Bridge (see Fig. 3), was selected as a test bridge. Hwa-Myung Bridge is the longest cable-stayed pre-stressed concrete (PSC) box girder bridge in South Korea, connecting Busan and Gimhae cities across Nakdong River. The total length of the bridge is 500 m (270 m for main span and 115 m for each side span). PSC box girder is hung with 72 cables in a single plane. Multi-strands (MS) type cables are used due to their easy maintenance such as replacement and re-tensioning. Each strand in an MS cable is galvanized and coated with polyethylene (PE) and each MS cable is covered with a high-density polyethylene (HDPE) duct on which helical strips are attached to mitigate rain-wind induced vibration. Among 72 cables of Hwa-Myung Bridge, two short cables (BLC02 and BLC04 indicated in Fig. 3) at a side span toward Gimhae city were selected for the test. The cross-sectional dimensions of two test cables are identical but the lengths are different (44.4 m for BLC02 and 54.7 m for BLC04). The individual MS cable has 49 strands inside the duct. The detailed specifications for the selected two cables are listed in Table 1.

Table 1 Specification of test cables

Properties	MS cable (BLC02 and BLC04)		Individual strand	
Nominal area (mm^2)	7,350		150	
Tensile strength (kN)	13,671		279	
Elastic modulus (kN/mm^2)	195		195	
Unit weight (N/m)	661.89		12.74	
Number of strand	49		-	

At the time of test (20-25 December 2010), Hwa-Myung Bridge was under construction (just after the construction of key segment). The cable tensioning work on Hwa-Myung Bridge consists of 3 stages. The first tensioning work was conducted to hold cantilevered girder segments at the pylons. The second tensioning was conducted for shape control right after installation of the key segment. The final tensioning work was conducted for fine-tuning of cable tensions. After this final tensioning stage, all cable tensions fit into a design range and the whole structure also becomes geometrically stable. This fine-tuning work, however, is not necessary for all cables in the bridge. If developed tension of a certain cable after the second tensioning work satisfy the design value, the fine-tuning for this cable is not necessary. The field test was conducted during the second tensioning stage. More details on the test schedule during the second tensioning work will be described in a later section.

Before the second tensioning work, two EM stress sensors were installed on the test cables as shown in Fig. 4. The inner and outer diameters and the length of each sensor are 224 mm, 294 mm, and 455 mm, respectively. The area A_c is 39,388 mm^2 and A_s is 7350 mm^2. The integrated output voltage in solenoid without cable (V_0) was set to be 2,600 volts. The number of turns of primary coil and the integrated output voltage without cable are the design parameters of the EM sensor and those are depending on the size of steel cable and the degree of the magnetic saturation as desired. Details of the determination of the design parameters of the sensor are discussed in the references (Wang *et al*. 2000, 2001, Chen 2000, Wang and Wang 2004, Wang *et al*. 2006). Sensor installation procedure is shown in Fig. 5. Temperature gauge was also attached to EM sensor to measure the temperatures of test cables. Two EM sensors are operated with an interrogation unit (PowerEM$^{\text{TM}}$ manufactured by IIS Systems Inc.). Main functions of the unit are (1) provision of large current pulse signals (up to 500 V) to a primary coil to magnetize the steel cable and (2) reception of the analog signals from the sensing coil. The interrogation unit has an AC to DC converter and a high voltage capacitor. When the capacitor in the unit has been charged to a prescribed level, then it discharges to produce current pulse signal to magnetize the steel cable. PowerEM$^{\text{TM}}$ unit has an embedded signal processing circuitry, thereby the input and output signals are automatically processed to calculate the relative permeability of the test cables.

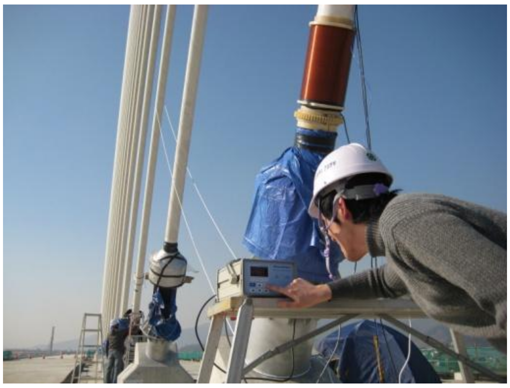


Fig. 4 Installed EM sensor and interrogation unit (BLC02)

1. Secondary Coil

2. Primary Coil

3. Temperature Gauge

4. Protection

5. Covering

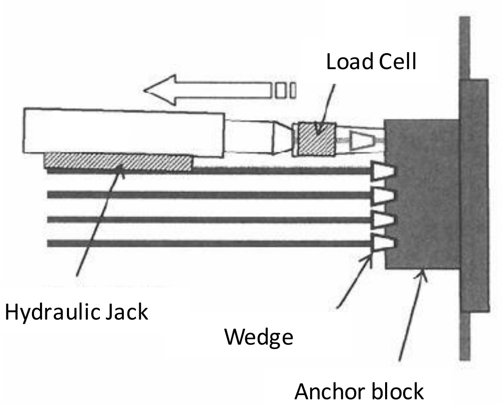
6. Completion

Fig. 5 EM Sensor installation procedures

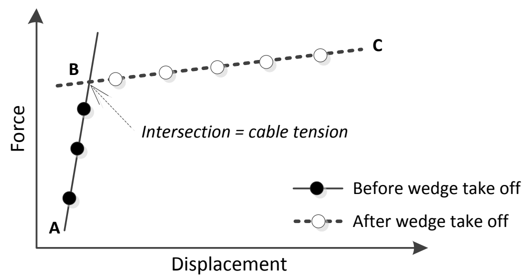
3.2 Lift-off test

For measurements of the cable tension force using EM sensors, a relationship between the stress of the test cable and corresponding relative permeability of the cable must be established. Normally this calibration process is done in laboratory prior to field application. However, laboratory calibration may not be available if the cable has already been installed in real bridges.

Therefore, to use EM stress sensor for the cable installed in a real bridge, a test which can obtain the reference force must be conducted for in-field calibration of EM sensors. In this study, among available test methods to measure cable tension force, conventional lift-off test is employed to obtain the reference force for calibration since the measurement accuracy of EM sensors greatly depends on the force used for calibration. The lift-off test is an accepted mechanical method useful to obtain accurate cable tension force in field. Test setup for the lift-off test consists of a load-cell, a hydraulic jack, and a displacement sensor such as LVDT. Fig. 6(a) shows the setup of lift-off test. In the lift off test, a strand wedged at the anchor block is slowly pulled by hydraulic jack. In the initial pulling stage, the strand out of the wedge resists the jacking force so that the force-displacement relationship is very steep as A-B of Fig. 6(b). However, if the jacking force reaches to a critical force that the wedge can hold, the wedge is lifted up from the anchor block. When the wedge is lifted up, the jacking force is transferred to the whole length of strand so that the displacement rapidly increases as the jacking force increases. At this stage, the force-displacement relationship changes gentle as B-C of Fig. 6(b). The intersection of two linear-regression lines is considered as the cable tension force in the lift-off test. For MS type cables, the lift-off test is generally carried out for several selected strands in the cable and their average force is multiplied by the total number of strands in the cable to obtain the cable tension force.



(a) Test setup



(b) Determination of tension force

Fig. 6 Lift-off test

3.3 Field Test Schedule

The field test was conducted during the second tensioning work of Hwa-Myung Bridge. The second tensioning work was done from 20th to 24th December 2010. EM sensors were installed before the second tensioning work. The tensioning work was executed in the late night (after 8 PM) to minimize the temperature difference among materials, such as cable, concrete girder, and pylon on the cables. The field test of EM sensors consists of 3 stages. The first stage, which was done during the second tensioning work on two test cables (late night of 20 December), is for calibration of EM sensors to construct the relationship (Eq. (9)) between the effective permeability and stress of each test cable. The second stage, which was done during the second tensioning work on other cables in the bridge (21 to 24 December), is for monitoring of cable tension force using EM sensors. The final stage, which was done after finishing the second tensioning work of Hwa-Myung Bridge (25 December), is for validation of tension force measurement. The detailed test schedule is described in Table 2.

The lift-off test was conducted 3 times for each test cable (two for calibration and one for validation). The first two lift-off tests for calibration were done during the second tensioning work on two test cables (20 December) and the validation test was done after finishing the second tensioning work on all other cables of Hwa-Myung Bridge (25 December). Tension force variations of the test cables during the second tensioning work on other cables were monitored only by EM sensors.

Table 2 Test Schedules

Stages	Dates	Second tensioning work	BLC02		BLC04	
			Lift-off	EM Sensor	Lift-off	EM Sensor
Calibration	20 Dec	Before Tensioning on BLC02	**O**	**O**	-	-
		Tensioning on BLC02	-	**O**	-	-
		After Tensioning on BLC02	**O**	**O**	-	-
		Before Tensioning on BLC04	-	-	**O**	**O**
		Tensioning on BLC04	-	-	-	**O**
		After Tensioning BLC04	-	-	**O**	**O**
Monitoring	21 Dec	Tensioning on the other cables	-	**O**	-	**O**
	22 Dec		-	**O**	-	**O**
	23 Dec		-	**O**	-	**O**
	24 Dec		-	**O**	-	**O**
Validation	25 Dec	-	**O**	**O**	**O**	**O**

4. Test results and discussions

4.1 Calibration and validation of EM sensors

The second tensioning work on the test cables (BLC02 and BLC04) was conducted at late night of 20 December 2010. The second tensioning of the BLC04 cable started at 8:40 PM on 20 December and tensioning on BLC02 was then started at 02:35 AM on 21 December. Total numbers of strands in BLC02 and BLC04 are identical (49 strands). In the test, each of 49 strands was pulled by hydraulic jack up to a designed force as shown in Fig. 7. A pulling sequence number was assigned for each strand in the cable as shown in Fig. 8. The EM sensor measured the output voltage whenever the jack moved to the next strand so that in total of 49 measurements were conducted in parallel with strand jacking. It is noted that the jacking step for BLC04 was 98 since each strand of BLC04 was jacked two times (50 % of the target force was jacked at the first time).

Fig. 7 Cable tensioning work

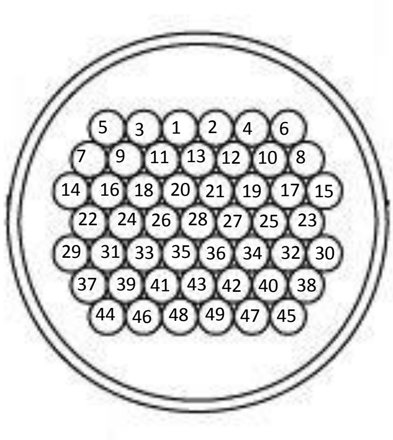


Fig. 8 Pulling sequences of strands in test cable

Figs. 9(a) and 9(b) show the measured voltages, $V_c(\sigma, T)$, during the second tensioning work for BLC02 and BLC04, respectively. As the number of jacking step increases, the measured voltage increases almost linearly. This result suggests that the EM sensor can sensitively detect the stress change in the cable and the stress and the voltage (i.e., relative permeability of cable) have a linear relationship. An interesting observation is that EM sensor detects the changes of stress in the cable with the sense of average. Stress distribution in the test cable during tensioning work should be uneven since the strand in the cable was jacked one by one. However, the voltage was linearly increased for this one-by-one jacking, and which confirms the EM sensor detects the average stress change in the cable.

Before and after the second tensioning work on each test cable, lift-off test were conducted to obtain the reference cable tension force which will be used for the calibration. In the test, 5 out of

49 strands were selected to obtain average tension force of strands in the test cable. Measured tension forces for the selected strands are shown in Table 3. It is seen that the variation of tension forces of the strand was less than 0.1 %, and which suggests that tension force was equally distributed in the test cables. Cable tension force was calculated by multiplying the average tension force of the strands with the total number of the strands in the test cables. The force changes before and after tensioning were around 1500 kN and 1800 kN for BLC02 and BLC04, respectively.

Table 3 Lift-off test results

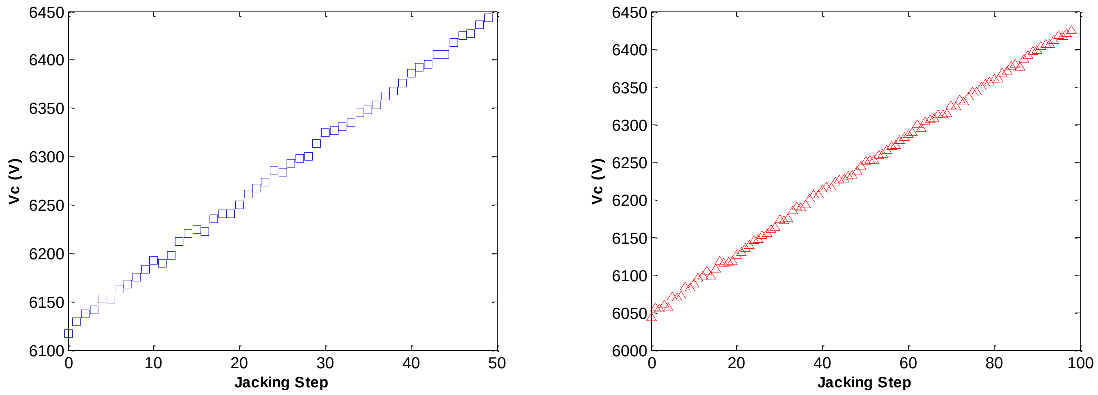
Lift-off Test for BLC04 (Cable Temperature : 3°C)				Lift-off Test for BLC02 (Cable Temperature : 0°C)			
Before Tensioning (8:40 PM 20 December)		After Tensioning (11:35 PM 20 December)		Before Tensioning (2:35 AM 21 December)		After Tensioning (4:12 AM 21 December)	
Strand #	Force (kN)	Strand #	Force (kN)	Strand #	Force (kN)	Strand #	Force (kN)
1	66.89	1	104.5	1	63.45	1	94.7
6	66.96	8	103.7	8	64.80	8	94.9
14	65.82	14	103.9	23	65.39	23	96.1
30	65.70	18	102.8	30	65.66	30	96.5
49	65.74	49	103.2	46	65.78	46	96.6
Average	66.22	Average	103.6	Average	65.02	Average	95.8
Cable Tension Force	**3244.9**	Cable Tension Force	**5077.4**	Cable Tension Force	**3185.8**	Cable Tension Force	**4692.6**

Using two reference forces (before and after tensioning) for each cable, the jacking step in Fig. 9 can be converted into corresponding cable tension force (i.e., jacking step 0 to be the cable tension force before tensioning while the final step to be that after tensioning). Fig. 10 shows linear best-fit lines between the cable tension force and measured voltage for two test cables. Extrapolated zero stress voltages, $V_c(0, T_0)$, are 5448 volts for BLC02 and 5381 volts for BLC04.

Even though the cross-sectional dimension and the materials are identical for BLC02 and BLC04, it is seen that the voltages for the same cable tension force are different. As described, this is mainly due to temperature dependence of magnetic permeability. At the time of lift-off test, measured (reference) temperatures (T_0) were 3°C for BLC 04 and 0°C for BLC02.

Using Eq. (6), the relative permeability can be calculated using measured output voltage and measurement constants. Then we can obtain the relationship between the effective relative permeability and corresponding cable tension force based on Eq. (9). Measurement constants for calculation of μ_r and $\bar{\mu}$ are listed in Table 4. It should be noted that since reference temperature (T_0) is equal to T at the calibration, the term for temperature compensation $\alpha(T_o\text{-}T)$ in Eq. (9) is zero at the calibration stage. It is also noted that according to Eq. (9) $\bar{\mu}(0,T_0)$ should be zero at the calibration stage. As shown in Fig. 11, the calibrated linear best-fit relationship between cable tension force (F) and the effective relative permeability ($\bar{\mu}$) were obtained as F=2289$\bar{\mu}$ for BLC02 and F=2346$\bar{\mu}$ for BLC04. The unit for force is kN.

For validation of the obtained relationship, the lift-off test was conducted at 25 December which was just after the second tensioning work of Hwa-Myung Bridge. The result is shown in Table 5. The measured cable tension force from the lift-off test was 4620 kN for BLC02 and 4959 kN for BLC04. The estimated cable tension force from the EM sensor was 4690 kN for BLC02 and 4935 kN for BLC04. The difference is negligibly small (less than 1.5%) and which verifies the effective of the EM sensor for cable tension measurements.



(a) BLC02 (b) BLC04

Fig. 9 Senor output voltages during pulling of strands

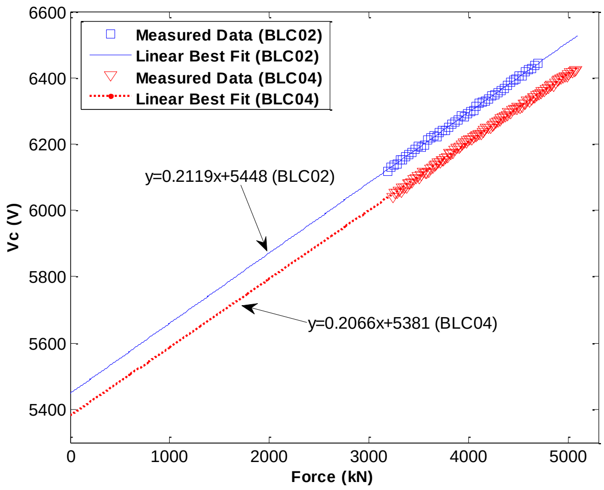


Fig. 10 Relationship between sensor output voltages and tension forces of test cables

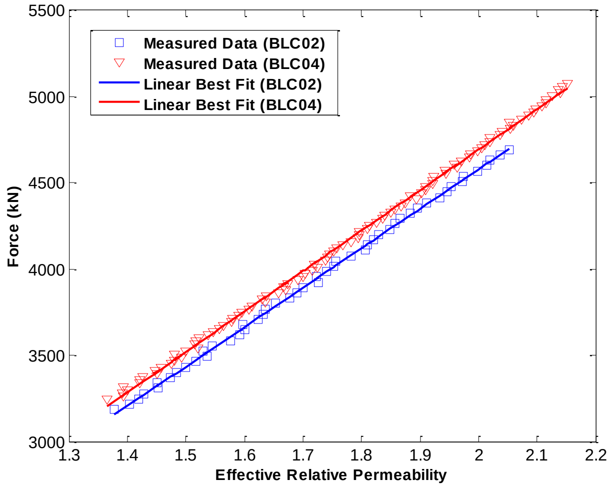


Fig. 11 Relationships between effective relative permeability and tension force of test cables

Table 4 Measurement constants

	T_0 (°C)	$V_c(0,T_0)$	$\mu_r(0,T_0)$	A_s (mm^2)	A_c (mm^2)	α (1/°C)	V_0 (V)
BLC02	0	5447.7	11.226	7350	39388	0.0175	2600
BLC04	3	5379.8	11.086				

Table 5 Comparison of tension forces measured by EM sensor and lift-off test

	BLC02					BLC04				
	V_c (V)	μ_r	$T-T_0$ (°C)	$\bar{\mu}$	F (kN)	V_c (V)	μ_r	$T-T_0$ (°C)	$\bar{\mu}$	F (kN)
EM Sensor	6459	13.31	2	2.049	**4690**	6443	13.277	5	2.1035	**4935**
Lift-off Test			-		**4620**			-		**4959**
Difference (%)			-		70 (1.5%)			-		24 (-0.5%)

4.2 Tension redistribution monitoring

Before the second tensioning work, the lift-off tests were conducted for all cables in the bridge to select cables needed to be re-tensioned. Based on the lift-off test results for all cables in the bridge, 18 out of 72 cables in the bridge were selected for the second tensioning work. The second tensioning work on the selected cables was conducted during 20-24 December 2010. Tensioning schedule for the selected cables is shown in Fig. 12. After the tensioning work, the lift-off tests for all cables were conducted again to confirm the fitness of the developed tension forces. Fig. 13

shows the lift-off test results before and after the second tensioning work. It is seen that the developed tension forces fit into the design forces. It is also seen that most cables showed large force changes due to the second tensioning work. Especially forces of the tensioned cables were increased, while those of the non-tensioned cables were decreased.

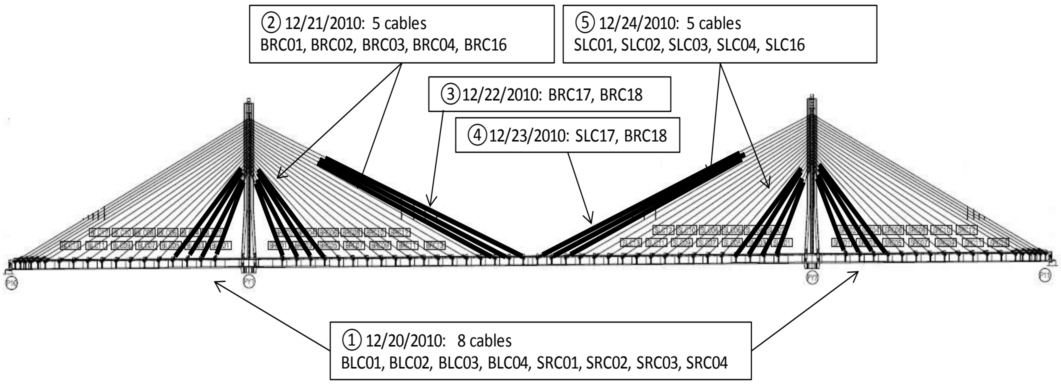


Fig. 12 Schedule of second tensioning work of Hwa-Myung Bridge

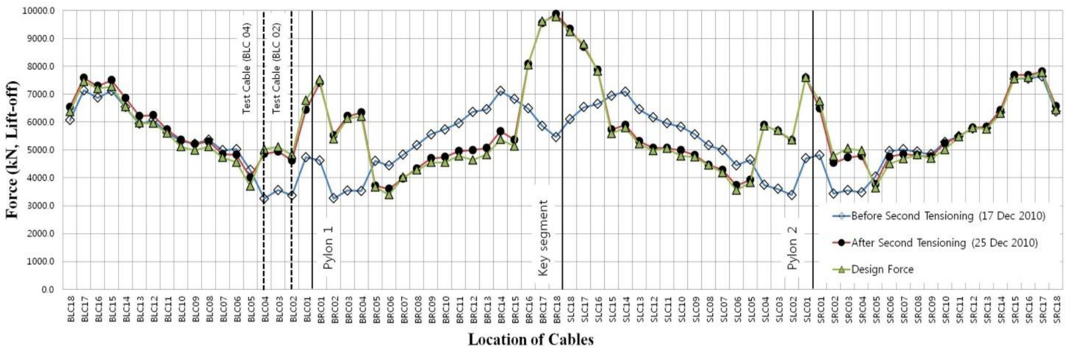


Fig. 13 Tension force history of all cables in Hwa-Myung Bridge

Cable tension forces of BLC02 and BLC04 can be changed due to tensioning work on other cables in the bridge. Tension force variations of BLC02 and BLC04 due to the tensioning work on other cables in the bridge were monitored by EM sensors. Measured tension forces for BLC02 and BLC04 during the second tensioning work are shown in Table 6 and Fig. 14. The results show that the seating force of the cable was decreased as much as 230 kN to 300 kN (around 5%) during the tensioning work on other cables. However, the final tension forces after completion of the second tensioning work almost recovered the original seating forces of BLC02 and BLC04. Many factors such as temperature change affect tension forces of the test cables. However, it is believed that the tension force changes of BLC02 and BLC04 are mainly due to the tension redistribution effect of other tensioned cables. This will be proved in the subsequent section.

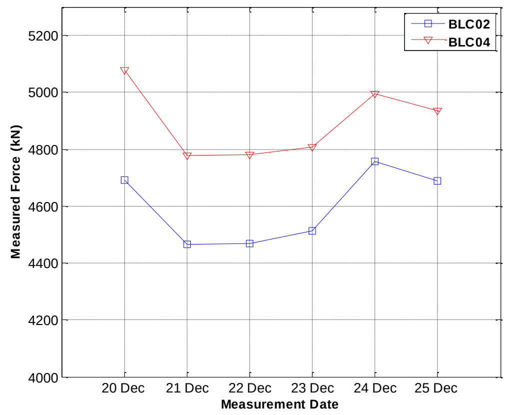


Fig. 14 Measured tension forces of test cables during second tensioning work on other cables

Table 6 Tension forces of test cables monitored by EM sensors

Dates	BLC02 ($T_0 = 0$ °C)					BLC04 ($T_0 = 3$ °C)				
	V_c (V)	μ_r	$T - T_0$ (°C)	$\bar{\mu}$	F (kN)	V_c (V)	μ_r	$T - T_0$ (°C)	$\bar{\mu}$	F (kN)
20 Dec (after Tensioning)	6443	13.278	0	2.052	**4693**	6424	13.239	0	2.152	**5077**
21 Dec	6366	13.118	-3.3	1.9507	**4465**	6366	13.118	-0.3	2.0373	**4779**
22 Dec	6330	13.045	-7.5	1.9525	**4469**	6330	13.044	-4.5	2.0381	**4781**
23 Dec	6361	13.107	-5.1	1.9718	**4513**	6356	13.098	-2.1	2.0494	**4808**
24 Dec	6456	13.304	0	2.078	**4756**	6439	13.268	3	2.1286	**4994**
25 Dec	6459	13.31	2	2.049	**4690**	6443	13.277	5	2.1035	**4935**

4.3 Numerical verification of tension force monitoring

In order to verify tension force monitoring results of EM sensors, numerical simulation was performed. A commercial finite element (FE) analysis package, MIDAS/Civil®, was used for simulation. Fig. 15 shows the FE model of Hwa-Myung Bridge, which consists of 120 beam elements and 72 truss elements. Truss elements were used for modeling cables. Lift-off test results for all cables in Hwa-Myung Bridge, which were obtained before the second tensioning work, were used for initial cable tension forces in FE model. Design tension forces (see Fig. 13) for the selected cables, which were tensioned in the second tensioning work, were used as inputs to calculate cable tension forces of BLC02 and BLC04.

Simulation results for each date are shown in Table 7 and Figs. 16(a) and 16(b). Since design tension forces were used as inputs for simulations, predicted forces can be different with the measured forces. However, it is observed that overall trend of the predicted force history is very similar with the monitoring results. This result proves that the EM sensor accurately monitored the cable tension forces during the second tensioning work of Hwa-Myung Bridge and thus verifies the effectiveness and practicality of EM sensors for monitoring of cable tension force in real cable-stayed bridge. Moreover, since temperature effect was not considered in FE simulations, the changes of tension forces for BLC02 and BLC04 are only due to tensioning of other cables in FE model. This verifies that the changes of tension forces of BLC02 and BLC04 during the second tensioning work are mainly due to the tension redistribution effect of other tensioned cables.

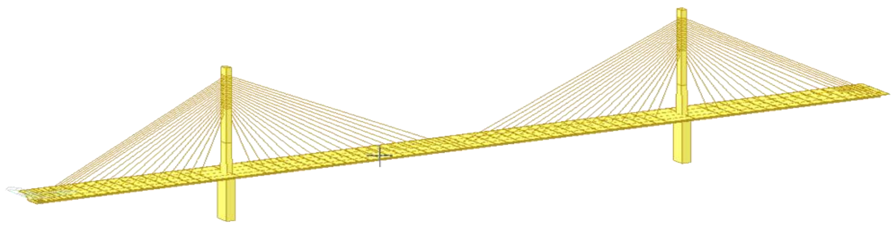
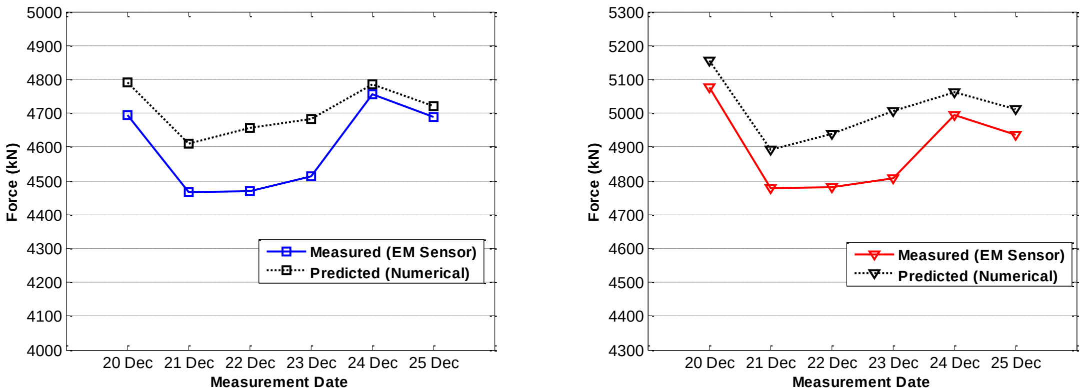


Fig. 15 Finite element model of Hwa-Myung Bridge



(a) BLC02 (b) BLC04

Fig. 16 Tension force variations of test cables

Table 7 Comparison of tension forces of the test cables obtained from EM sensors and numerical simulations

Dates	BLC02			BLC04		
	EM Sensor	Numerical	Lift-off	EM Sensor	Numerical	Lift-off
20 Dec (after Tensioning)	4693	4791.1	4693	5077	5154.3	5077
21 Dec.	4465	4609.9	-	4779	4891.8	-
22 Dec.	4469	4656.8	-	4781	4937.5	-
23 Dec.	4513	4683.5	-	4808	5007.5	-
24 Dec.	4756	4786.2	-	4994	5061.3	-
25 Dec.	**4690**	4722.1	**4620**	**4935**	5012.2	**4959**

5. Conclusions

In this study, EM stress sensors were installed on two MS cables in a real scale cable-stayed bridge (Hwa-Myung Bridge) and the tension forces of those two cables were measured during the second tensioning work of Hwa-Myung Bridge. Calibration and validation tests for the installed EM sensors were carried out. Numerical simulations of cable tension force variation were conducted and the results were compared. The findings from this study can be summarized as follows.

(1) The relative permeability of MS cable linearly increased as stress of the cable increased. This result indicates that the relative permeability and the stress of cable have a linear relationship and verifies that the EM sensor can sensitively detect average stress changes in cables.

(2) The measured permeability of two test cables under the same stress condition was different even though the cross-sectional properties (dimensions and materials) of two test cables were identical. This is mainly due to temperature dependency of relative permeability. Therefore, temperature effect on the relative permeability should be considered for accurate cable tension force measurement in field.

(3) Tension force of the test cable (estimated by a calibrated relationship between the effective relative permeability and tension force of the test cable) was matched well with both the actual forces measured by conventional lift-off test (less than 1.5% error) and predicted forces calculated from numerical simulations. This proves that EM sensors can be effectively used for accurate measurement of cable tension force in field.

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