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Application of vibration method for estimating tension force of stay cables in 2002 World-cup stadiums in Korea

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Abstract

This study is to consider the character of cables in six World-Cup stadiums constructed in 2002 and to inspect problems on measurement natural frequencies interpretation and application of existing theory. Because stay cable structures should be controlled by the tension force of cable under the construction, and managed to maintain geometric balance without loss of the tension force after construction. it is very important to develop the method which is able to measure the tension force easily, quickly and reliably in the field. The result of experiment shows it is possible to determine the tension force with an accuracy of 8% by taking the cable bending stiffness. However, if single mode of vibration is used, the tension force of the real cables could be overestimated, and the estimated tension force with experimental results would not be reliable.

Keywords: stay cable, cable tension, vibration method, bending stiffness

1. Introduction

Cable structure is used very effectively in the various cable stayed structures for example cable stayed bridge, guy tower, mast, as well as spatial structure such as World-Cup stadiums due to the character of cables which is high strength and light weight. These structures used tension cables should be controled by the tension force of cable under the construction, and managed to maintain geometric balance without loss of the tension force after construction. It is very important to develop the method which is able to measure the tension force easily, quickly and reliably in the field.

Vibration method of the previous study is to calculate indirectly the tension force with the relationships between the cable tensions and their corresponding natural frequencies. Though this method gets ahead theoretically about the relationship between the cable tension and their corresponding natural frequencies, the experimental verification on presented theory is not sufficient actually. Moreover, because most of the experimental verification have been developed by civil engineering structures like a bridge, the application of the spatial structure is uncertain.

This study is to consider the character of cables in six World-Cup stadiums constructed in 2002, Korea and to inspect problems on measuring location on the cable, natural frequencies interpretation and application of existing theory. Especially, the effect of bending stiffness of cable would be focused. This is because most cables of six World-Cup stadiums ranges over negligible in the deflection effect ($\lambda^2 \leq 0.17$) and mainly controlled under bending stiffness($15 \leq \xi \leq 100$) (Fig. 1). Also the reliability of the proposed methods using single and multiple modes of vibration would be reevaluated in view of practical application.

2. Experiment

2.1 Specimens

Fig.1 illustrates range of nondimensional parameters reflecting effect on bending stiffness and deflection of cables of World Cup stadiums in Korea as well as experiment range of some previous studies. The figure shows that cables of six World-Cup stadiums is mostly under the area for which have not been experimented yet by previous researchers and also is distributed in the area where the effect by bending stiffness is dominant with no necessity to consider the effect of deflection(shaded part).

Table 1 shows the list of specimens. Specimens were scaled down first to be available of the experiment for considering range of nondimensional parameters and then modelled to divide the whole effective range in three parts. The specimens were named first as A, B by length to recognize the range of study easily and then named as ‘1’, ‘2’, ‘3’ in order of specimens with from lower to higher bending stiffness index. This means that ‘1’ is the specimen with the bending stiffness index within range of 15~20, ‘2’ within 45~55 and ‘3’ within 100~110. The sectional shape of specimens is to made with 6 strands on the outside and 1 strand on the center as 1x7 PC steel wire strands. Specimens are uniform as 0.015m in diameter, 1.413E-04 m^2 in cross section, 1.78E-09 m^4 in moment of inertia, 0.0111kN/m in unit weight and 2.08E+08 kN/m^2 in Young’s Modulus.

2.2 Method of experiment

Fig. 2 shows how specimens were installed. One end of the stay cable was fixed to the steel frame in use of special-made hinge and anchor systems and another end is tensioned by oil jack at diffenent levels fron 2.58kN to 74.4kN. The applied cable tension forces are measured by a load cell.

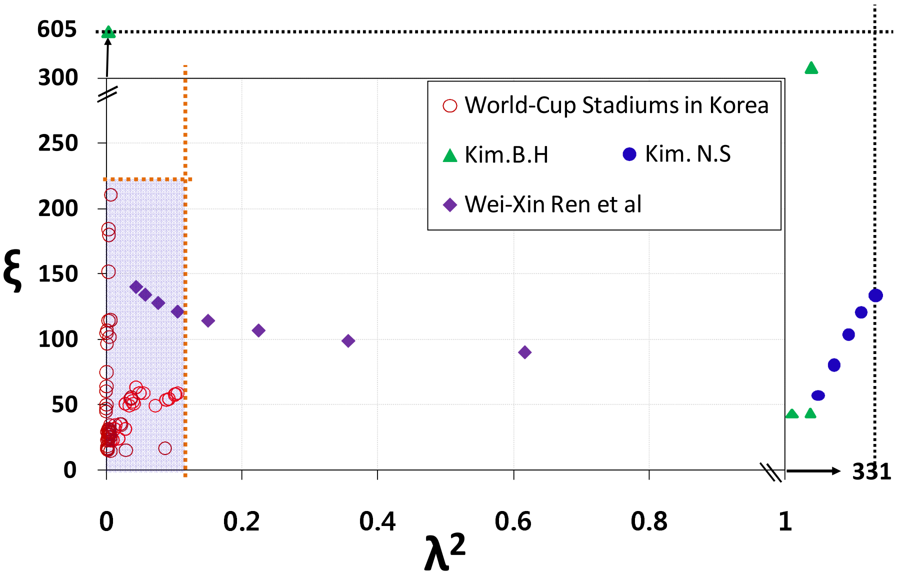


Figure 1 : Comparison of ξ & λ^2 in 2002 World-cup stadium cables

Table 1 : List of specimens

Specimen name	length (m)	Elastic moduls (kN/m^2)	Ultimated load (kN)	Sectional Area (m^2)	Moment of inertia (m^4)	Unit weight (KN/m)	Applied Tension (KN)	ξ	λ^2
PC-A1	3.55	2.08E+08	273	1.413E-04	1.780E-09	0.0111	8.93	17.4	8.6E-02
PC-A2	3.55	2.08E+08	273	1.413E-04	1.780E-09	0.0111	74.4	50.3	1.5E-04
PC-B1	7.65	2.08E+08	273	1.413E-04	1.780E-09	0.0111	2.58	20.2	1.6E+01
PC-B2	7.65	2.08E+08	273	1.413E-04	1.780E-09	0.0111	19.77	55.9	3.7E-02
PC-B3	7.65	2.08E+08	273	1.413E-04	1.780E-09	0.0111	72.31	106.9	7.5E-04

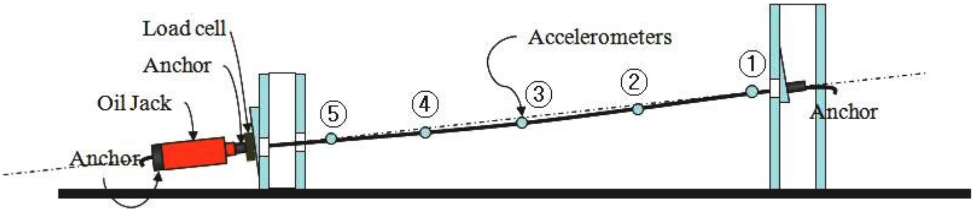


Figure 2 : Installation of specimens

Specimens were checked to maintain the inclination of cable from installation of specimens to application of tension in use of digital goniometer in each processing step of experiment. To gain the natural frequencies of cable, the acceleration was measured first on 5 points with 5 accelerometers installed in longitudinal direction of cable at regular intervals as shown in Fig.2. The accelerating force in experiment was made in use of impact hammer and the experiment was done repeatedly until valid signal can be gained and after gaining at least 3 valid time records, power spectrum was calculated from the records to decide on the natural frequency on the average of them. At this time, we analyzed the natural frequency together with mode shape using 5 points of signal information.

2.3 Results

Firstly, measured and designed tension were compared and it was shown in Fig.3. Since stiffness of cable changes sensitively according to the applied tension force, it must be important above all to guarantee reliability of applied tension for correct reflection of characteristics of cable. As Fig. 3 shows less than 1% error in comparison between measured and designed tension, we can say that enough reliability was secured as per the planned intension for this experiment. Table 2 shows the natural frequencies measured in each specimen. As FRF(Frequency Response Function) of acceleration record measured on 5 points showed the peak mostly on the same position, it was easy to discriminate frequency by modes but in some higher modes it was difficult to discriminate the correct frequency and in these cases, they were judged as no reliability and not included as experiment result. Fig. 4 illustrates change of natural frequencies by modes to examine the tendency of change in natural frequency, and while the ‘2’, ‘3’ specimens with higher bending stiffness index shows linear tendency of change in natural frequency by increasing modes, ‘1’ specimen with lower bending stiffness index shows non linear tendency as it moves to higher modes, which appears the effect of bending stiffness to work greatly in higher modes. One of objectives of this experiment is to make it possible to measure the natural frequency of cable correctly by measurement of just one accelerator on the position easily accessed by cable. This is for the reason of possiblility to improve the easiness in measurement of vibration in the field. In this study, 5 accelerators were attached from the upper to the bottom of cable to examine this issue. Fig. 5 shows FRF of 5 accelerators about PC-B1 which is affected greater by bending stiffness and deflection as well as PC-B3

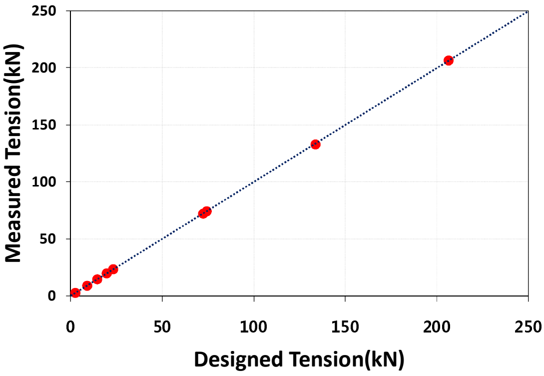


Figure 3 : Comparison of designed & measured tension

Table 2 : Experimental results

Mode order	PC-A1	PC-A2	PC-B1	PC-B2	PC-B3
1	13.6	39.1	4.7	9.4	17.2
2	41.4	78.9	7.0	18.8	35.1
3	54.2	120	46.1	28.6	52.6
4	66.7	161	60.2	38.6	70.1
5	80.5	203	147	50.2	87.5
6	105.3	248	N.A.	62.5	105
7	130.0	295	225	69.6	123
8	155.5	345	-	81.1	141
9	183.0	396	-	92.5	160
10	224.7	451	-	108.9	N.A.
11	271.0	508	-	N.A.	198
12	316.0	N.A.	-	131	218
13	361.0	627	-	145	238
14	N.A.	-	-	159	260
15	470.0	-	-	176	282

* N.A : Not allowable

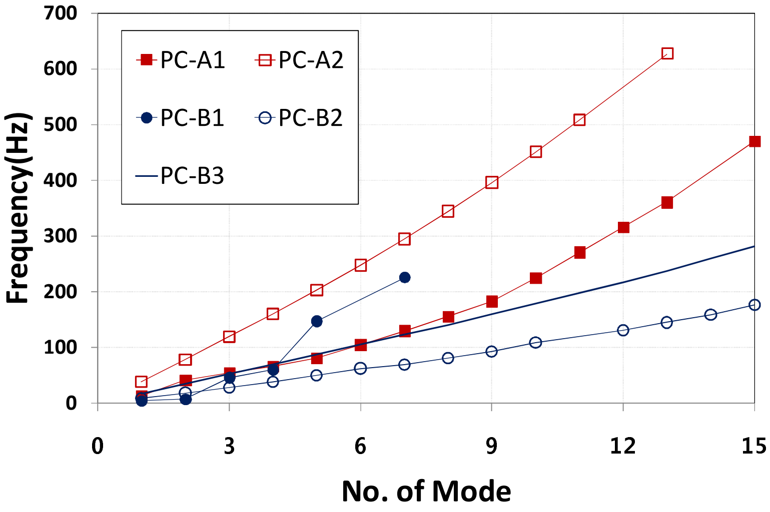
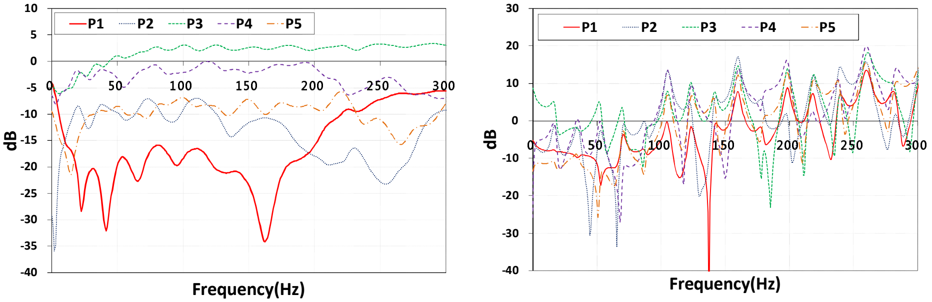


Figure 4 : Natural frequency by modes

which is affected relatively less by those two parameters. It shows mode of vibration on the horizontal axis and natural frequency on vertical axis. In case of PC-B1, frequencies measured on 5 points do not show clearly discriminated peak on the same position and this tendency is confirmed to show more greatly as it moves higher modes.



(a) PC-B1 (b) PC-B3

Figure 5 : FRF of PC-B1 & B3

In this case, if it can be measured with one accelerator only on the end of the cable where can be easilly accessed by man, it considers that seriously wrong results would be able to estimate as the case may be. On the other hand, in case of PC-B3 which is affected less by bending stiffness, it shows the peak at the same frequency on all 5 points up to higher modes so that it can be judged possible to measure the natural frequencies on just one representative point only and according to the result from experiment, it judges that there should be almost no error by measuring positions if the bending stiffness index shows higher than 100.

3. Verification of Practical Formulas from Some Researchers

The most important purpose of this study is to examine the applicability of formulas for estimated tension proposed from previous studies. Therefore, in this clause, the utility was examined focusing on the methods using single mode of vibration such as the taut string, the method by Robert [3], Zui et al [4], and Wei-Xin Ren et al [5] as well as the method by Shimada, T. [6] using multiple modes of vibration.

3.1 In case of using single mode of vibration

Fig. 6 shows estimated tension error by modes with both specimens of PC-A, B to examine estimated error in case of estimated tension by application of the taut string theory and it presents the result from direct use of measured natural frequency together with result from estimated tension using equivalent frequency proposed by Robert [3] to reflect the effect of bending stiffness. Fig.6 shows that the estimated tension by application of the taut string theory becomes very different by modes in use and especially, this error appears much more as the index of bending stiffness is bigger and the order of modes is higher. This result tells that ‘1’ series of specimens are much more affected by bending stiffness than ‘2’ series of specimens and also effect of bending stiffness is much greater as order of modes is higher.

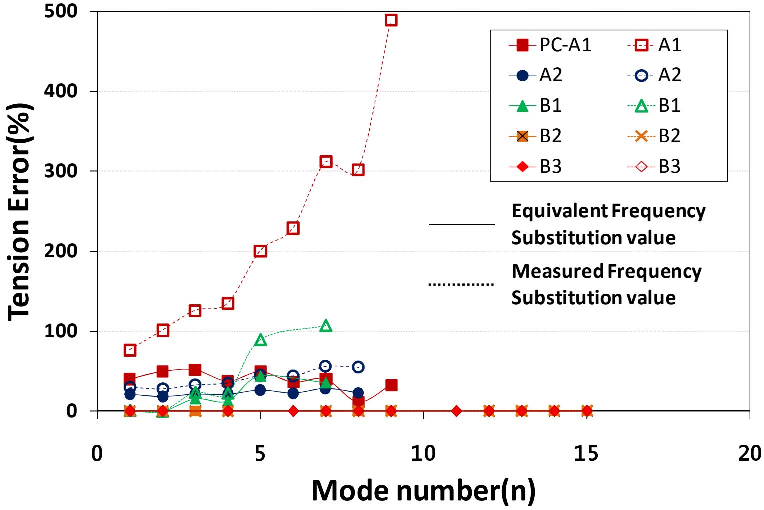


Figure 6 : Estimated tension error of the taut string theory

Therefore, it judges that estimated tension by the taut string theory should be the most reasonable to use the lowest order of mode but even in this occasion, error shows around 30% and estimated tension by this method shall be included by significantly big error. The method by Robert [3] proposes the equivalent frequency modifying the measured frequency to reflect the effect by bending stiffness. From the comparison result in Fig.6, it shows good improvement of such error in higher order of modes but the average error is still big as around 15% and in case of '1' series of specimens affected greatly by bending stiffness, still it shows increasing error in higher order of modes so it judges that the effect of bending stiffness cannot be fully reflected.

Fig. 7 illustrates estimated tension error by the proposed formula by Zui *et al*[4] and Ren *et al*[5] according to changes in bending stiffness index. The proposed formula by Zui *et al* and Ren *et al* is given for directly estimated tension considering the effect of bending stiffness and especially in case of Zui *et al*, the proposed formula is given to consider the effect of bending stiffness differently by the effect range of deflection. The first noticeable point from the figure is that whole estimated error is decreasing as bending stiffness index is increasing. But This variation of error means that both of those two proposed formulas are not considering the variation of the effect of bending stiffness sufficiently.

Furthermore, such error shows the result of overestimation about tension of cable in the '1' series so that it needs special attention at estimating tension. The average error of specimens is 7.94% of Zui *et al* and 8.74% of Ren *et al* and in comparison of those two methodologies, error shows difference within 1%, which is almost same estimated result.

Also for estimated error by those two methodologies, it shows to be affected by applied tension force too.

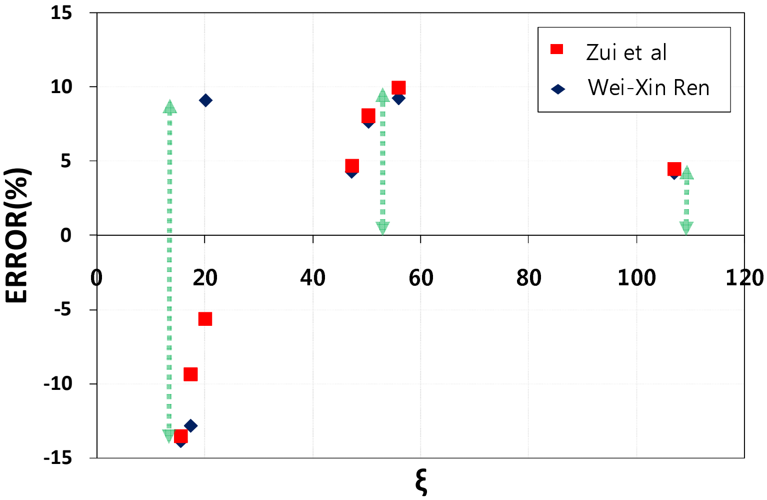


Figure 7 : Estimated tension error by Zui et al & Wei-Xin

3.2 In case of using multiple modes of vibration

This method is using the property of regression for the square term of natural frequency, $(f_n/n)^2$, and the order of mode, (n^2), to the first linear relation on the assumption that the bending stiffness of cable is uniform over the whole length and the tension of cable can be estimated when the y intercept b can be gained of the first linear regression equation. In this method, the lower order of modes largely affected by deflection are excluded and higher order of modes are only used. Fig.8 illustrates the result from estimated tension of PC-B(1~3). Since this method needs to gain multiple modes of vibration, it has difficulty in the experiment and also since it is required to solve difficult nonlinear equation, no way but to use computer so that even it has the difficult problem of demerit unable to utilize easily in the field, the estimated error cannot be improved so much in comparison of the single mode of vibration. As already mentioned in the case of using single mode of vibration, natural frequency appears nonlinear property by increasing the order of modes in case of cables with the effect of bending stiffness so it judges as error caused by the basic assumption of which the square term of natural frequency and order of modes is regressing to the first linear relation.

4. Conclusion

In this study, we examined various estimation of tension of cable considering the effect of bending stiffness in reflection of characteristics of cables applied to 2002 World-Cup stadiums in Korea and as the result from experiments for applicability of previous proposed methods using vibration method,

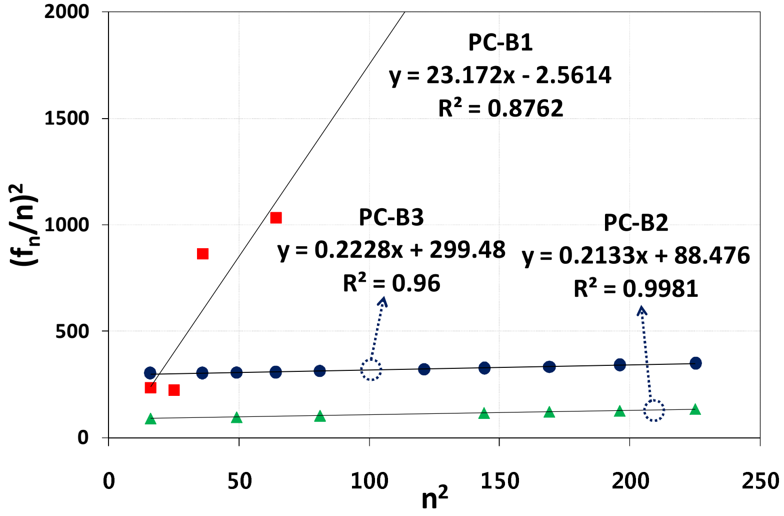


Figure 8 : Linear regression for measured frequencies

we could get the following conclusions:

(1) For correctly estimated tension, the taut string method should be surely modified in reflection of the effect of bending stiffness and it appears that error can be down to within around 15% if equivalent frequency proposed by Robert is used.

(2) Regarding methodologies by Zui and Ren using single mode of vibration, it appears excellent result of estimated tension within the error within 8% almost for same both of them but for the range of cable affected greatly by bending stiffness($\xi \leq 17$), it appears the tendency to increase estimated error and considers to need additional study of this range.

(3) In case greatly affected by bending stiffness, it appears that estimated tension error cannot be improved so much in comparison to the case using single mode of vibration even through multiple mode of vibration is used.

(4) If single mode of vibration is used, the tension force of the real cables could be exaggerated, and the reliance of the tension force experimentally determined could be changed by tension in the cable.

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