



# Comparison of Vibration Serviceability During Typhoon and Abnormal Vibration for Steel Cable Bridges

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## Abstract

Steel cable bridges are relatively light and known to be prone to large deformation and vibration. However, excessive vibration may cause serviceability problems such as discomfort or motion sickness to pedestrians and passengers. Recently, several excessive or abnormal vibration events on cable bridges have been reported from various places around the world. In this study, vibration serviceability is evaluated and compared for several steel cable bridges during the recent typhoons passing the Korean peninsula and abnormal vibration cases. Assessment criteria used in this study are Reiher-Meister curve using displacement amplitude and ISO 2631–1 using weighted RMS (root-mean-square) acceleration. Most cable bridges are equipped with a monitoring system that measures displacement, acceleration, wind speed, temperature, and etc. Displacement amplitudes were calculated using displacement data at mid-point of the main span using the GNSS system. RMS acceleration were also calculated from acceleration data at mid-point of the main span and weighting factors described in ISO 2631–1. Evaluation of vibration serviceability was performed on four cable bridges during nine typhoons passing in 2019 and 2020. Evaluations were also done in two cases of abnormal vibrations on two cable bridges in 2014 and 2019. Based on these results, equations for limit and warning values for displacement amplitude and RMS acceleration, are proposed respectively. Results of this study may be the basis for evaluation criteria for vibration serviceability in steel cable bridges.

**Keywords** Vibration · Serviceability · Steel cable bridges · Long-span · Monitoring · Typhoon

## 1 Introduction

Cable bridges such as suspension bridge and cable-stayed bridge show relatively large deformation and vibration due to their structural characteristics. Excessive vibration and deformation may cause serviceability problems to passengers and pedestrians. Several incidents have been reported over the world regarding on bridge closures by complaining

of user discomfort and excessive vibration (<http://www.mdilbo.com/detail/ilgftp/442143>, <https://news.kbs.co.kr/news/view.do?ncd=4250001>, <https://www.thecivilengineer.org/news-center/latest-news/item/2253-violent-oscillation-in-chinese-bridge-caused-by-high-winds>). Therefore, appropriate vibration serviceability standards and assessment criteria are required in terms of design and operation. Main causes of vibration are passing vehicles and high wind but abnormal vibration may occur under special circumstances (Hwang et al. 2019a, b).

The purpose of this study is to evaluate the vibration serviceability of cable bridges (suspension and cable-stayed bridges) during recent typhoons passages and abnormal vibration incidents.

Two criteria are used in this study for the evaluation of vibration serviceability: Reiher-Meister criteria (1931) and ISO2631-1 standard (1997). In Reiher-Meister curve, the vibration serviceability is evaluated by the maximum displacement amplitude based on the first vertical natural frequency of the structure, as shown in Fig. 1. The serviceability level is divided into six categories, from A (very

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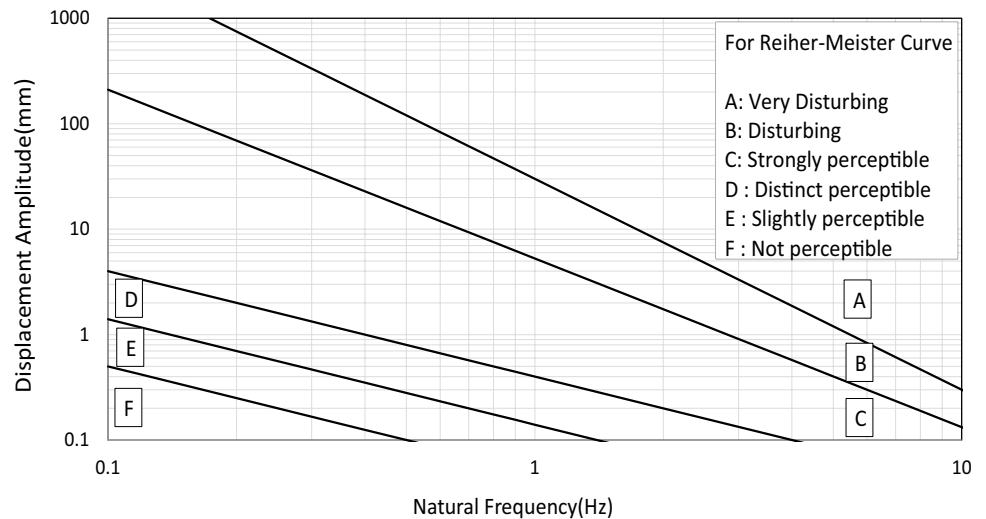
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**Fig. 1** Reiher-Meister curve (1931)



**Table 1** Comfort level recommended in ISO 2631–1

Comfort level	Value of weighted RMS acceleration (m/s <sup>2</sup> )
Not uncomfortable	~0.315
A little uncomfortable	0.315–0.63
Fairy uncomfortable	0.5–1
Uncomfortable	0.8–1.6
Very uncomfortable	1.25–2.5
Extremely uncomfortable	2.0~

disturbing) to *F* (not perceptible). The frequency range (horizontal axis) is extended to 0.1 Hz to be applied to structures having low natural frequencies or long periods, such as long-span steel cable bridges. It should be noted that these criteria are based on the displacement amplitude, not the bridge deflection. ISO2631-1(1997) standard specifies the general requirements for the evaluation of human exposure to the whole-body vibration. Its criteria are based on the weighted RMS (root-mean-square) acceleration, as shown in Eq. 1. The weighting factor,  $W_k$  is based on the first natural frequency of the vertical mode.

$$a_w = \left[ \frac{1}{T} \int_0^T (W_k a(t))^2 dt \right]^{1/2} \tag{1}$$

Even though this standard does not specify any serviceability limit or criteria, the appendix recommends six levels of comfort, as shown in Table 1. In this study, limiting values in terms of displacement amplitude based on

**Table 2** Bridges considered in this study

Bridge	Type	Girder	Width (m)	Span length(m)	
				Main	Total
A	Suspension	Steel box, 3-spans	27	1,545	2260
B	Suspension	Steel box, 3-spans	12.5	890	990
C	Cable stayed	Steel box, 3-spans	25.7	344	484
D	Cable stayed	Steel box, 3-spans	11.5	510	1004

Reiher-Meister curve and RMS acceleration based on ISO 2631–1 are proposed based on the comparison of abnormal vibration events and typhoon events.

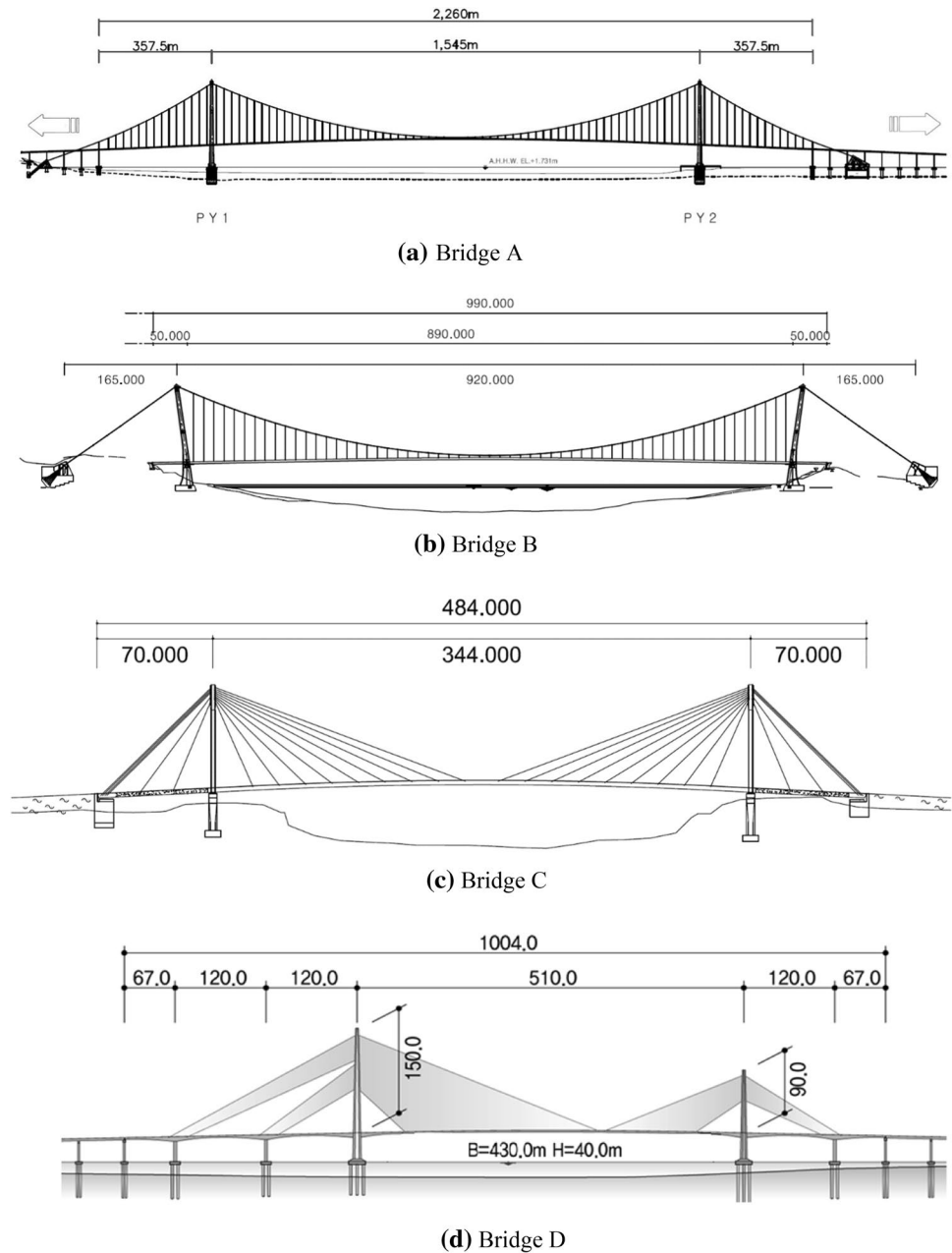
## 2 Example Bridges, Monitoring System and Typhoons

In this study, several cable bridges that are located in the southern and western coasts of the Korean peninsula are considered for analysis. Table 2 shows the structural information of two suspension and two cable-stayed bridges, and their shapes are shown in Fig. 2.

Cable bridges usually have a monitoring system that measure displacement of girder and pylons, acceleration of girder and cables, temperature, wind speed, and etc. A typical monitoring system is shown in Fig. 3. To evaluate vibration serviceability in this study, vertical displacement (using GNSS system), acceleration (vertical and horizontal) and wind speed that measured at 1/2 point of main span are used.

During the years of 2019 and 2020, nine typhoons had affected the bridges. Table 3 shows the names of the nine typhoons, effective periods, and maximum instant wind

**Fig. 2** Typical shapes of suspension and cable-stayed bridges



speed reported by meteorological stations. The paths of these typhoons are shown in Fig. 4 along with the locations of the bridges considered in this study.

### 3 Processing Measured Data for Evaluation of Vibration Serviceability

To apply the Reiher-Meister curve, the displacement amplitude of the bridge must be calculated from the GNSS measuring system. Inherently, the GNSS raw data measured on the bridge contains signal noise which can be removed using Low-Pass-Filter (LPF) (Park 2019; Park and Hwang 2016).

Figure 5 shows the GNSS data before and after LPF. After filtering, the displacement amplitude is calculated from the inflection points also shown in Fig. 5. The fast Fourier transform of the GNSS data shows that the first natural frequency of the vertical mode of bridge is 0.434 Hz, as shown in Fig. 6. Therefore, the cutoff frequency of the LPF was set to 2.0 Hz.

To apply the ISO 2631–1 standard, the weighted RMS accelerations are calculated from the vertical acceleration measured at the midspan of the center span. RMS value was calculated based on 10-min periods. According to ISO 2631–1,  $W_k$  or  $W_f$  factor can be applied.  $W_k$  factor is used for comfort evaluation and  $W_f$  factor can be used for the evaluation

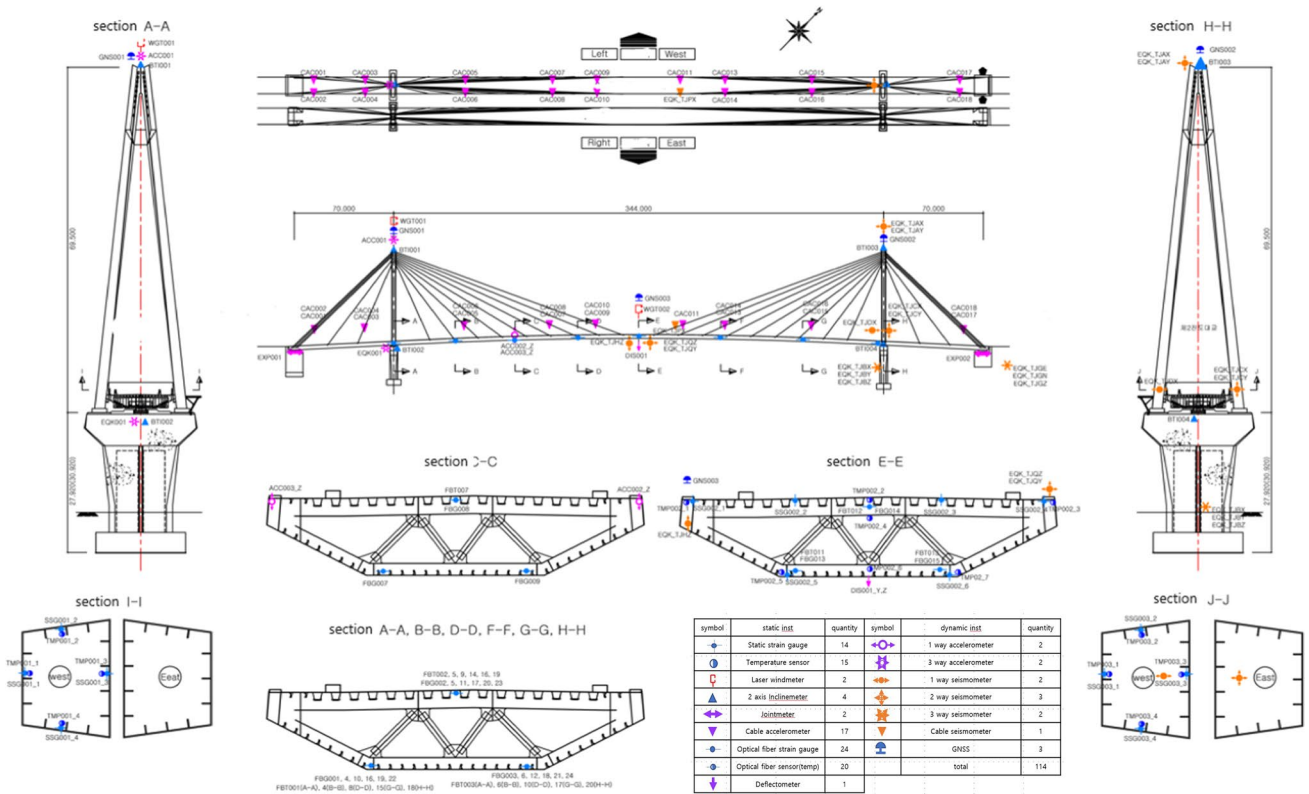


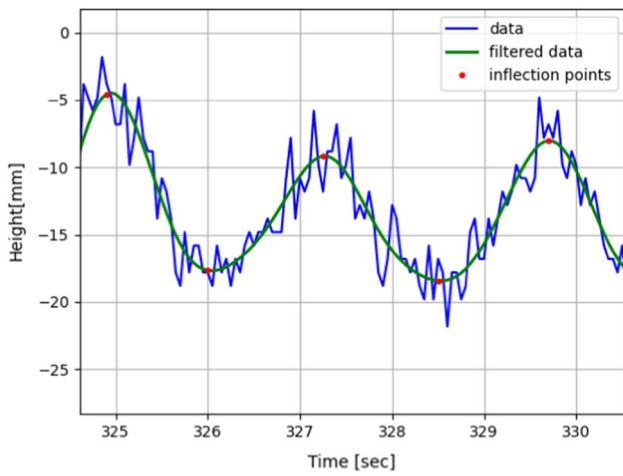
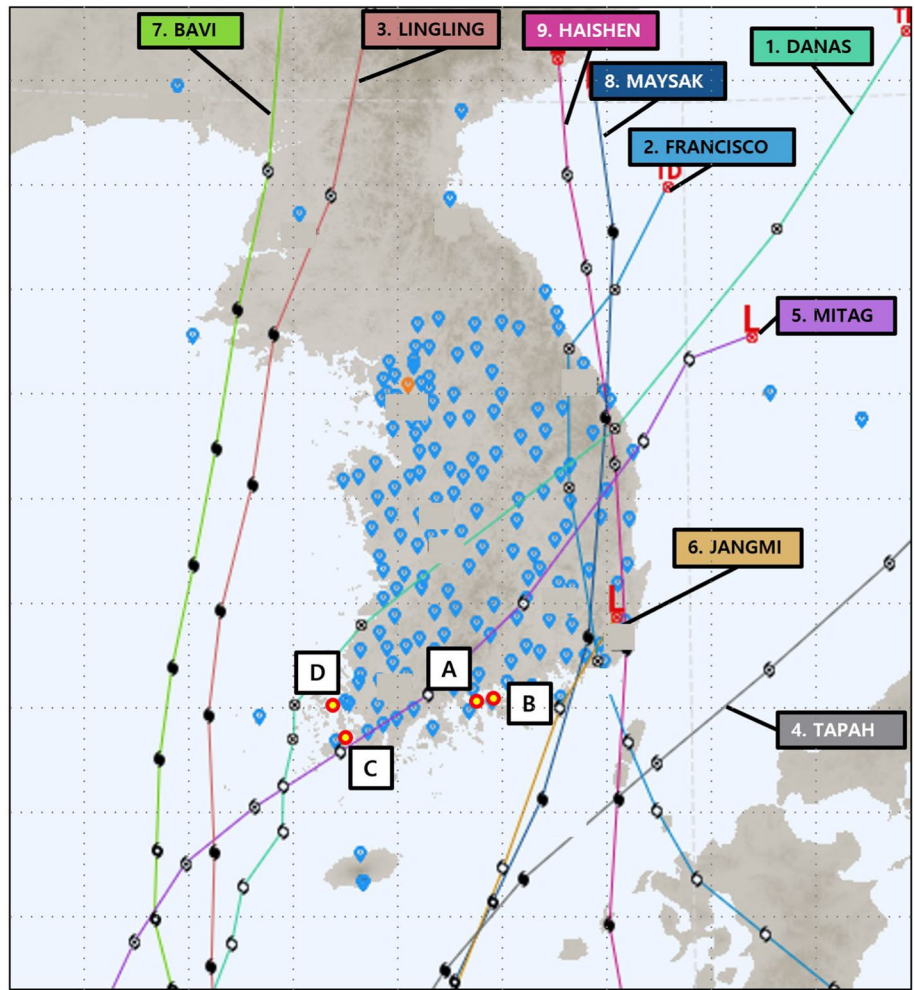
Fig. 3 Typical monitoring system of cable bridges

Table 3 Typhoons in 2019 ~ 2020 affecting the bridge

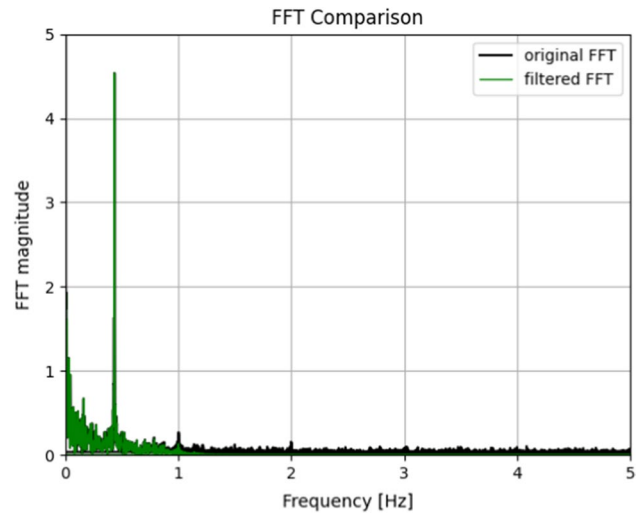
Name	Period	$V_{max}$ (m/s)			Weather station(instant)
		A	B	C	
DANAS	2019.07.19 ~ 07.22	17.18	11.88	16.43	24
FRANCISCO	2019.08.05 ~ 08.08	8.67	7.56	7.39	32
LINGLING	2019.09.05 ~ 09.08	21.89	10.71	27.48	47
TAPAH	2019.09.21 ~ 09.24	17.48	17.61	11.62	55
MITAG	2019.10.01 ~ 10.04	16.32	13.98	14.24	37
JANGMI	2020.08.09 ~ 08.11	11.55	10.84	8.63	19
BAVI	2020.08.25 ~ 08.28	17.85	7.45	20.7	45
MAYSAK	2020.09.01 ~ 09.04	22.66	18.18	21.14	49
HAISHEN	2020.09.05 ~ 09.08	16.45	16.69	18.35	55

of motion sickness (Table 4). These factors vary based on the first natural frequency of the bridge, as shown in Fig. 7. Since the first natural frequencies of long span steel cable bridges

**Fig. 4** Typhoons passing through Korean peninsula during 2019–2020 with the bridge locations



**Fig. 5** GNSS displacement data before and after LPF



**Fig. 6** FFT of GNSS data before and after LPF

**Table 4** Maximum RMS acceleration during typhoons

Name	RMS Acceleration (cm/s <sup>2</sup> )		
	A	B	C
ISO2631-1 limit	37.9	31.4	95.6
DANAS	15.9(42.0%)	9.4(29.9%)	14.1(14.7%)
FRANCISCO	15.6(41.2%)	5.3(16.9%)	5.3(5.5%)
LINGLING	20.1(53.0%)	7.4(23.6%)	25.5(26.7%)
TAPAH	15.5(40.9%)	23.3(74.2%)	8(8.4%)
MITAG	15.2(40.1%)	4.9(15.6%)	70.1(73.3%)
JANGMI	14.7(38.8%)	4.5(14.3%)	4.3(4.5%)
BAVI	17.1(45.1%)	4.9(15.6%)	15.5(16.2%)
MAYSAK	16.0(42.2%)	11.9(37.9%)	13.6(14.2%)
HAISHEN	15.2(40.1%)	13.8(43.9)	17.9(18.7%)

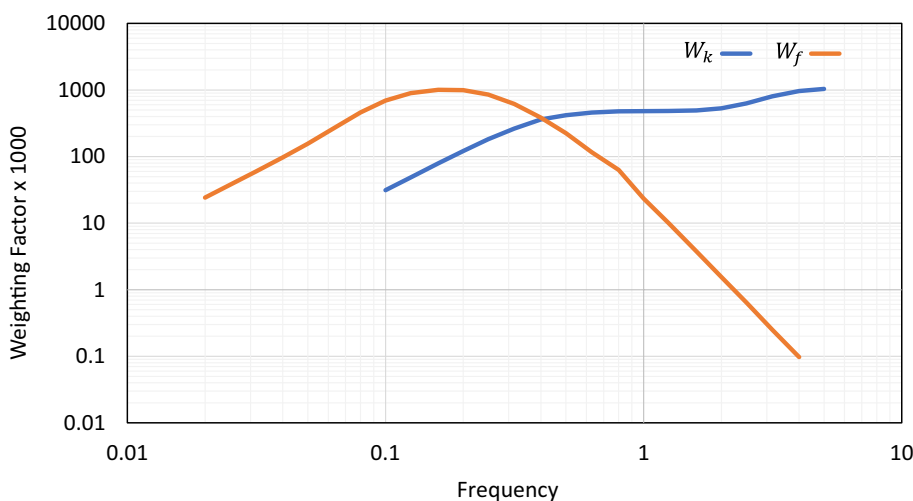
range mostly between 0 and 0.5 Hz,  $W_f$  factor are used for the evaluation by ISO 2631–1.

### 4 Evaluation of Vibration Serviceability

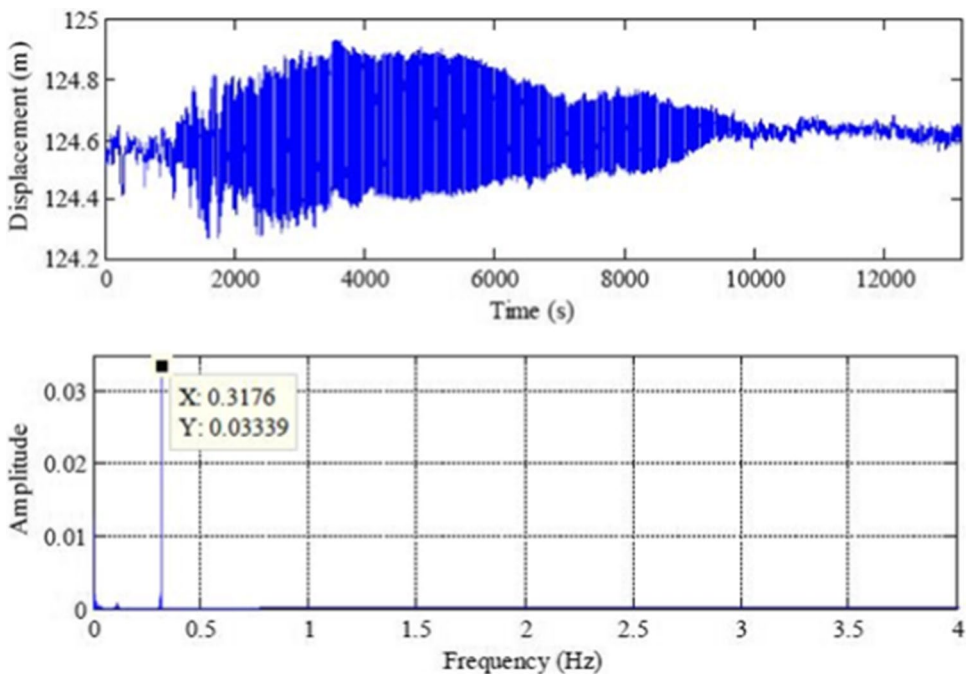
#### 4.1 During Abnormal Vibration Events

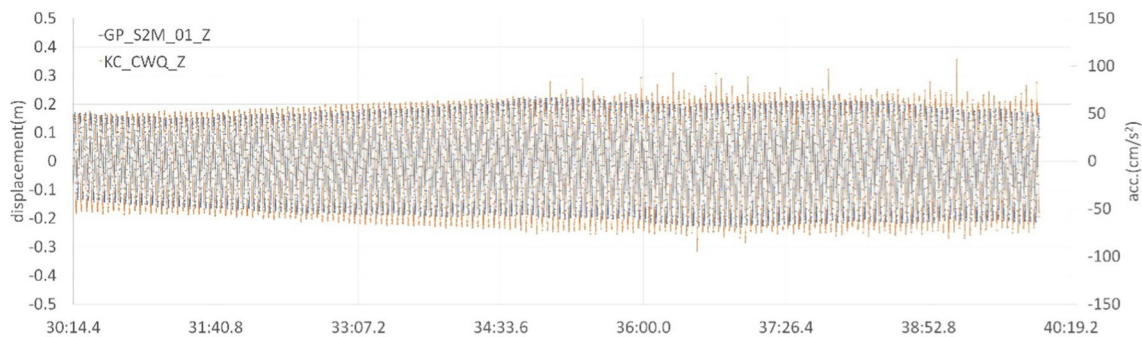
In 2014, Bridge A experienced excessive vibration which led to bridge closure for a few days. Investigations on this phenomenon revealed that the main cause of the vibration was the temporary curtain wall installed over the barrier for repaving work (Hwang et al, 2020). Figure 8 shows the GNSS displacement record during the incident and its FFT

**Fig. 7**  $W_k$  and  $W_f$  factor in ISO 2631–1

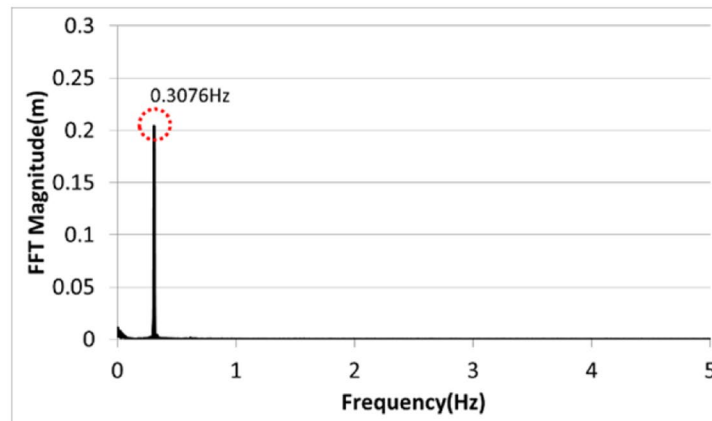


**Fig. 8** Displacement and FFT analysis result of abnormal vibration event of Bridge A in 2014





(a) Displacement amplitude and acceleration



(b) FFT analysis result

**Fig. 9** Displacement amplitude, acceleration and FFT analysis results of abnormal vibration event of Bridge D

results. The major frequency of the vibration was 0.3176 Hz, the fourth vertical symmetrical mode of the bridge, which is different from the first vertical natural frequency of Bridge A, 0.113 Hz. The maximum displacement amplitude was 0.262 m. According to Reiher-Meister curve, the limit value of Level A and B for frequency of 0.3176 Hz is 297 and 33 mm, respectively. Even though actual accelerations were not measured during this event due to sensor maintenance work, RMS acceleration can be calculated using displacement. The calculated maximum 10-min RMS acceleration was  $0.661 \text{ m/s}^2$ .

After the opening of Bridge D, there were several complaints on excessive vibration and user discomfort. Figure 9 shows the vertical displacement (GP\_S2M\_01\_Z) and acceleration at midspan (KC\_CWQ\_Z) and its FFT results. The major frequency was 0.3076 Hz, which is the same as the first natural frequency of the bridge. The maximum displacement amplitude was 0.220 m. According to Reiher-Meister curve, the limit value of Level A and B for frequency of 0.3076 Hz is 317 and 34.8 mm, respectively. The maximum instant acceleration was about  $1.0 \text{ m/s}^2$  and maximum 10-min RMS acceleration was  $0.450 \text{ m/s}^2$ .

## 4.2 During Typhoons

For a period of approximately 4 days during typhoon passage, maximum displacement amplitudes were calculated based on 10-min records by the method explained in Sect. 3. RMS acceleration was also calculated based on 10-min records. Figure 10, 11 and 12 shows typical examples of vibration serviceability during typhoon passages.

Figure 10 shows a graph of the maximum displacement amplitude of Bridge A over time during a typhoon LINGLING (2019.09.05 ~ 2019.09.08). This figure also shows the 10-min average wind speed (V10) (m/s) measured at the midspan of the main span. The figure shows that displacement amplitude and wind speed are well correlated. The report by Hwang (2021) shows a similar trend for Bridge B and C. Before the passage of typhoon LINGLING, the maximum displacement amplitude was about 33 mm which may be primarily due to normal traffic conditions. During typhoon passage, it increases to about 77 mm. Under the expectation that there is minimal traffic during peak influence of the typhoon, this displacement amplitude value may be solely due to wind loading. In the Reiher-Meister curve, the limiting values for the B and A levels corresponding to the natural frequency of this bridge are 20.1 and 159.3 mm,

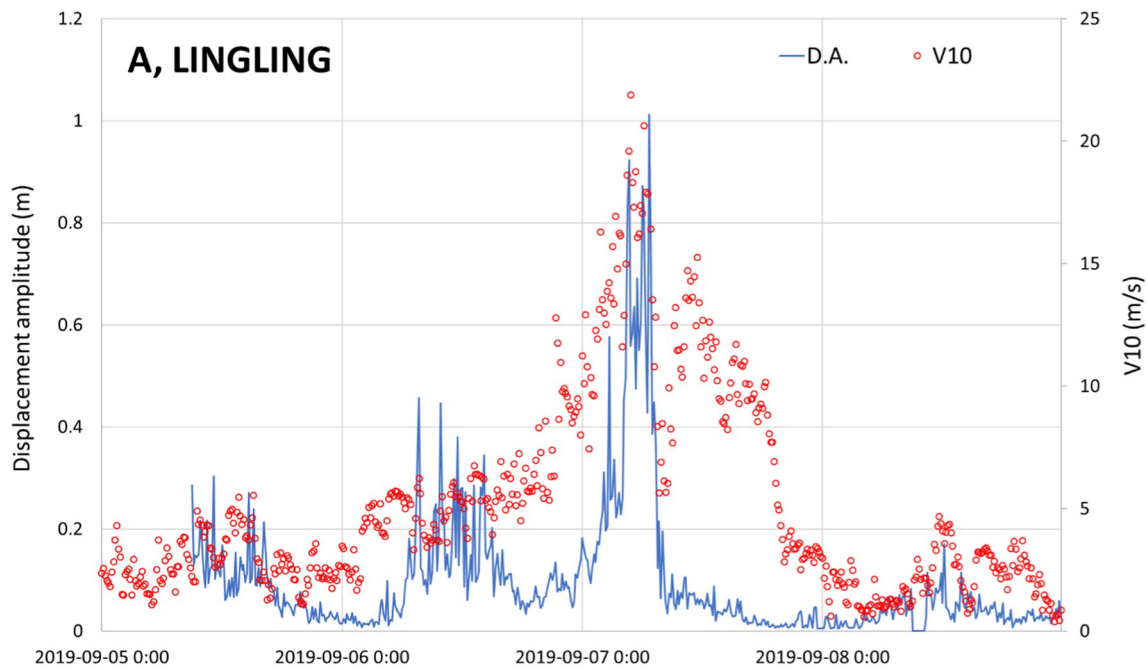


Fig. 10 Maximum displacement amplitude vs wind speed during typhoon LINGLING in Bridge A

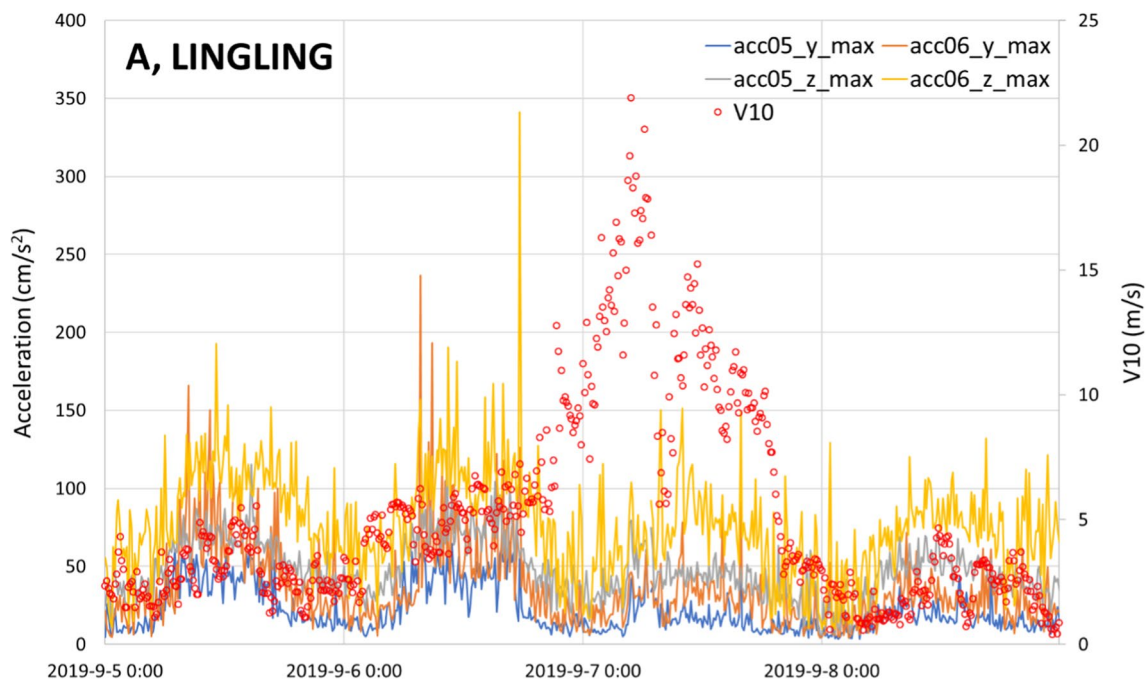


Fig. 11 Maximum instant acceleration vs wind speed during typhoon LINGLING in Bridge A

respectively. It indicates that during typhoon LINGLING and sometimes under normal traffic conditions, the bridge serviceability is at Level B.

Figure 11 shows the maximum instantaneous acceleration for 10 min with the 10-min average wind speed (V10)

during typhoon LINGLING at Bridge A. The accelerations from two vertical (acc05\_z\_max, acc06\_z\_max) and two horizontal sensors (acc05\_y\_max, acc06\_y\_max) are included. It shows that maximum instantaneous acceleration of the bridge and wind speed are not always correlated. The



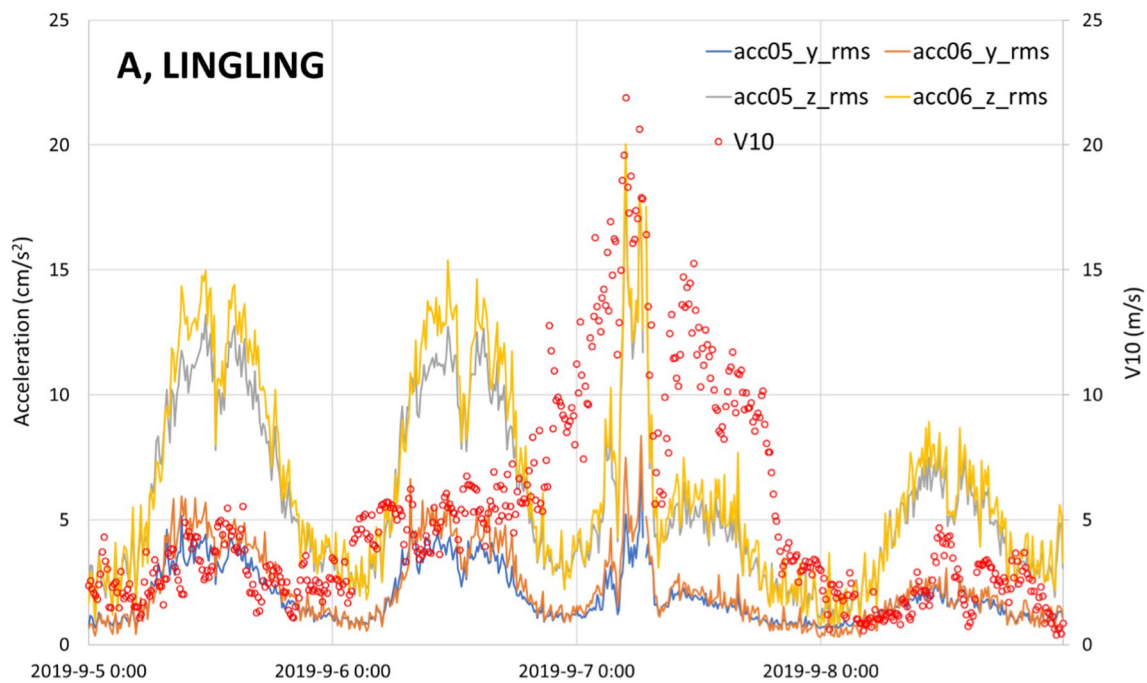


Fig. 12 RMS acceleration vs wind speed during typhoon LINGLING in Bridge A

maximum instantaneous acceleration in the vertical direction was about  $3.41 \text{ m/s}^2$ . In the design guideline for steel cable bridge (KSCE, 2014) and Korean Highway Bridge Design Code (Limit State Design Method) – Cable Supported Bridge (KBRC, 2018), the maximum horizontal and vertical acceleration at the stiffening girder is limited to  $0.5 \text{ m/s}^2$  at the wind velocity below traffic control velocity, which is normally  $25 \text{ m/s}$  unless specified. Maximum acceleration and the acceleration at wind speeds of  $25 \text{ m/s}$  during typhoon LINGLING is well above this limit. According to Hwang (2021), the maximum horizontal and vertical acceleration at the stiffening girder of Bridge B and C are also larger than  $0.5 \text{ m/s}^2$  at wind velocities of less than  $25 \text{ m/s}$ . The specification in the code may be not suitable for vibration serviceability evaluation and need to be modified. Maximum instant acceleration during the normal traffic was about  $0.33 \text{ m/s}^2$ .

Figure 12 shows the 10-min RMS acceleration (without the weighting factor) with the 10-min average wind speed (V10). The accelerations from two vertical (acc05\_z\_rms, acc06\_z\_rms) and two horizontal sensors (acc05\_y\_rms, acc06\_y\_rms) are included. It shows that RMS acceleration of the bridge and wind speed are well correlated. The maximum RMS acceleration was about  $0.255 \text{ m/s}^2$ . Maximum RMS acceleration during normal traffic conditions was about  $0.09 \text{ m/s}^2$ .

### 4.3 Effect of Wind Speed on Vibration Serviceability

For Bridge A, B and C, maximum displacement amplitudes and maximum RMS accelerations were calculated for each typhoon passage, with results shown in Fig. 13. In general, with increasing wind speed, maximum values of displacement amplitude and RMS acceleration increase as well. However, for Bridge C, maximum values occur during typhoon MITAG at wind speeds of about  $14 \text{ m/s}$ . Figure 14 shows displacement and acceleration records of Bridge C during peak influence of typhoon MITAG. It shows similar results with the abnormal vibration event described in Sect. 4.1. Maximum displacement amplitude was  $166.1 \text{ mm}$ , which is above Level A ( $157.1 \text{ mm}$ ) in Reiher-Meister curve. Maximum RMS acceleration was  $0.701 \text{ m/s}^2$ .

### 4.4 Comparison of Vibration Serviceability

Evaluation results of vibration serviceability for all bridges during all typhoons are compared with Reiher-Meister curve and ISO 2631–1 standards.

Figure 15 shows Level A and B lines of Reiher-Meister curve and maximum displacement amplitude during typhoons (Sect. 4.2) and abnormal vibration event (Sect. 4.1). Maximum displacement amplitudes during most typhoons are in Level B. However, the values from abnormal vibration events in Bridge A and D and typhoon MITAG in

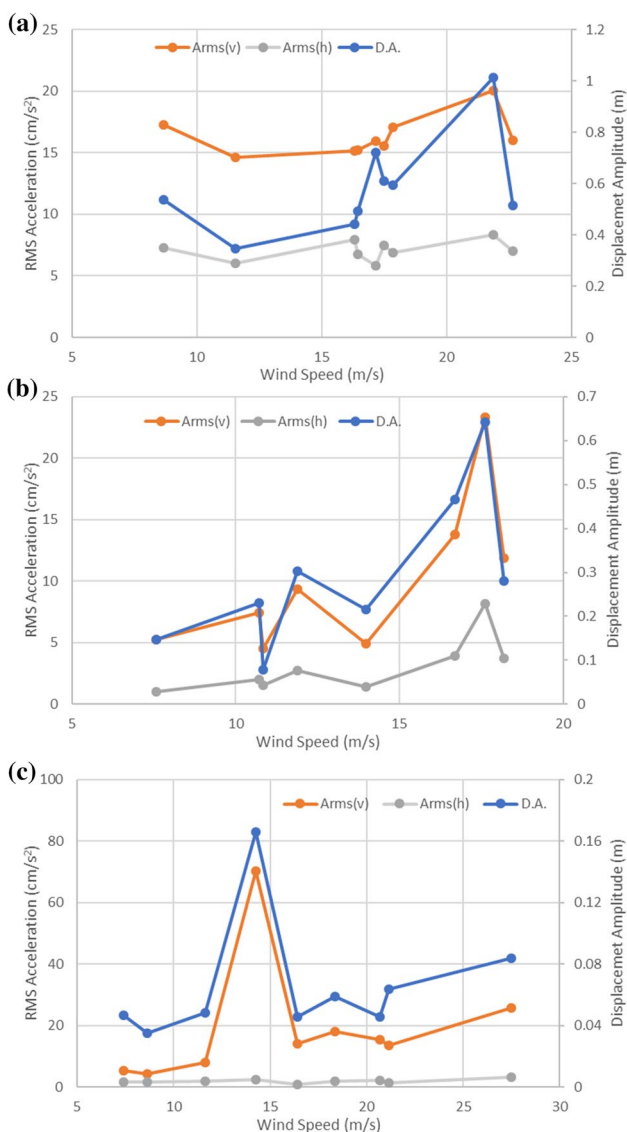


Fig. 13 Maximum RMS acceleration vs wind speed in Bridge A, B and C

Bridge B are very close to or slightly above Level A. Considering these events, the red line may be used for limit value for vibration serviceability. The yellow line is also proposed as a warning level for vibration serviceability, which considers the values under normal traffic conditions. Equations for limit and warning value for displacement amplitude are as follows:

$$\text{limit value} = 23.7/f^{1.7} \text{ (mm)} \tag{2}$$

$$\text{warning value} = 14/f^{1.65} \text{ (mm)} \tag{3}$$

Since ISO2631-1 uses weighted RMS acceleration, the weighing factor must be applied to RMS acceleration. However, in this study, instead of applying the weighting factor to the acceleration value as shown in Eq. 1, the weighting factor is applied to the limit value. From appendix of the standard, 0.315 m/s<sup>2</sup> is recommended as the comfort level, as shown in the first row in Table 1. It is not clearly shown in the standard which weighting factor must be used for serviceability evaluation of the bridge. For the natural frequency of the bridge, with the first natural frequency value of 0.434 Hz,  $W_k$  factor is calculated as 0.379 and  $W_f$  factor as 0.330. Thus, limit value may be 0.831 m/s<sup>2</sup> or 0.955 m/s<sup>2</sup> based on the limit value of 0.315 m/s<sup>2</sup>. Figure 16 shows maximum RMS accelerations during typhoons (Sect. 4.2) and abnormal vibration events (Sect. 4.1) with three lines of limiting values. The blue line represents 0.315 m/s<sup>2</sup> (ISO 2631–1 recommended value) multiplied by the weighting factor  $W_f$ . Maximum RMS acceleration during abnormal vibration event in Bridge A is larger than this limit and maximum RMS acceleration during abnormal vibration event in Bridge D is slightly less than this limit. Considering these events and case of Bridge B during typhoon MITAG, the red line may be used for limit value for vibration serviceability. Yellow line is also proposed as a warning level for vibration serviceability. Equations for limit and warning value for RMS acceleration are as follows:

$$\text{limit value} = 0.22/W_f \text{ (m/s}^2\text{)} \tag{4}$$

$$\text{warning value} = 0.14/W_f \text{ (m/s}^2\text{)} \tag{5}$$

### 5 Conclusions

In this study, vibration serviceability of long span steel cable bridges was evaluated and compared during recent abnormal vibration events and typhoons, based on the measured displacement from GNSS system and acceleration. Reiher-Meister curve and ISO 2631–1 standard are used for the evaluation. The following conclusions can be made:

- (1) Reiher-Meister curve based on displacement amplitude and ISO 2631–1 standard based on weighted RMS acceleration can be effectively used for the evaluation of the vibration serviceability of long span cable bridges.
- (2) The displacement amplitude and RMS acceleration are well correlated to 10-min average wind speeds during typhoons.

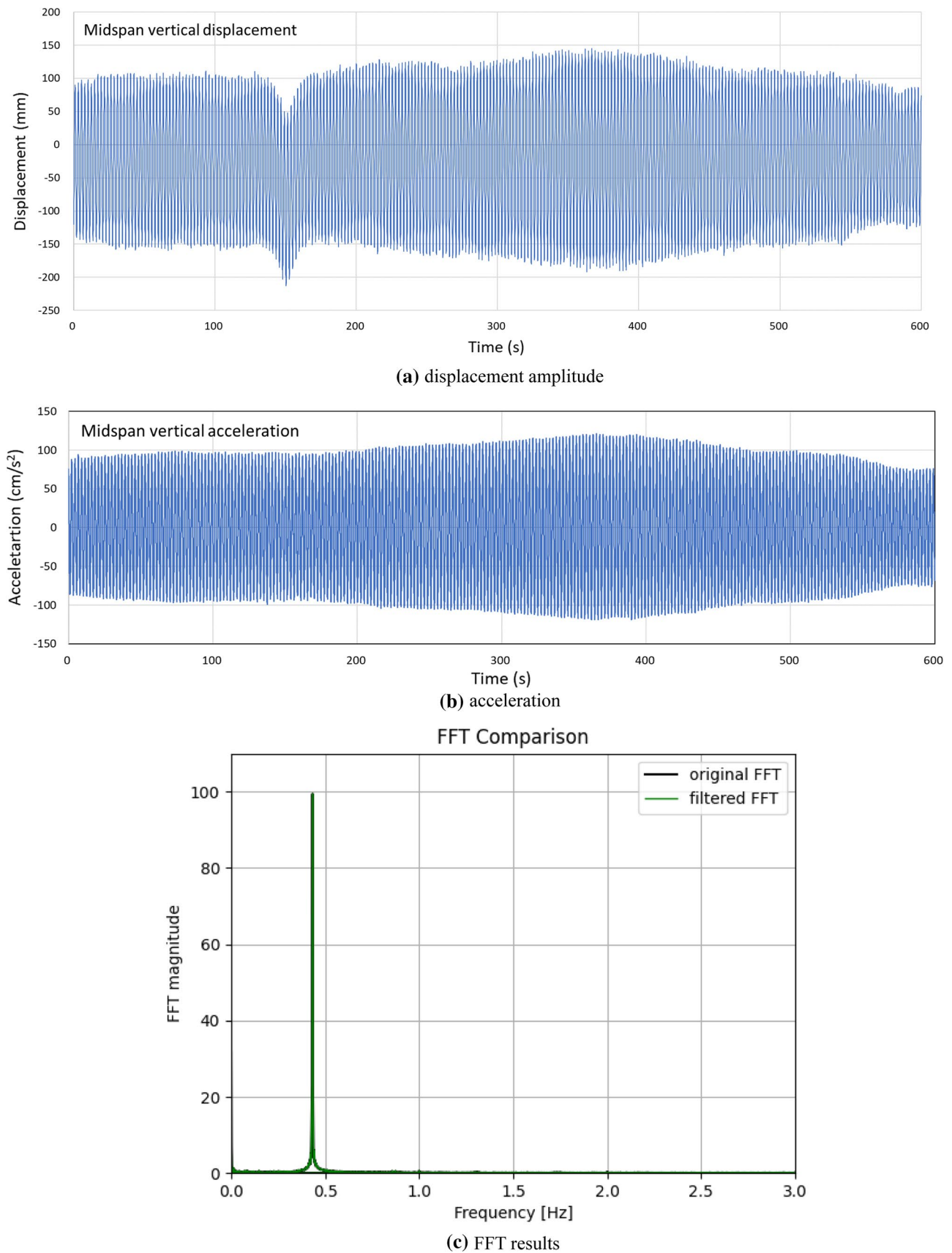
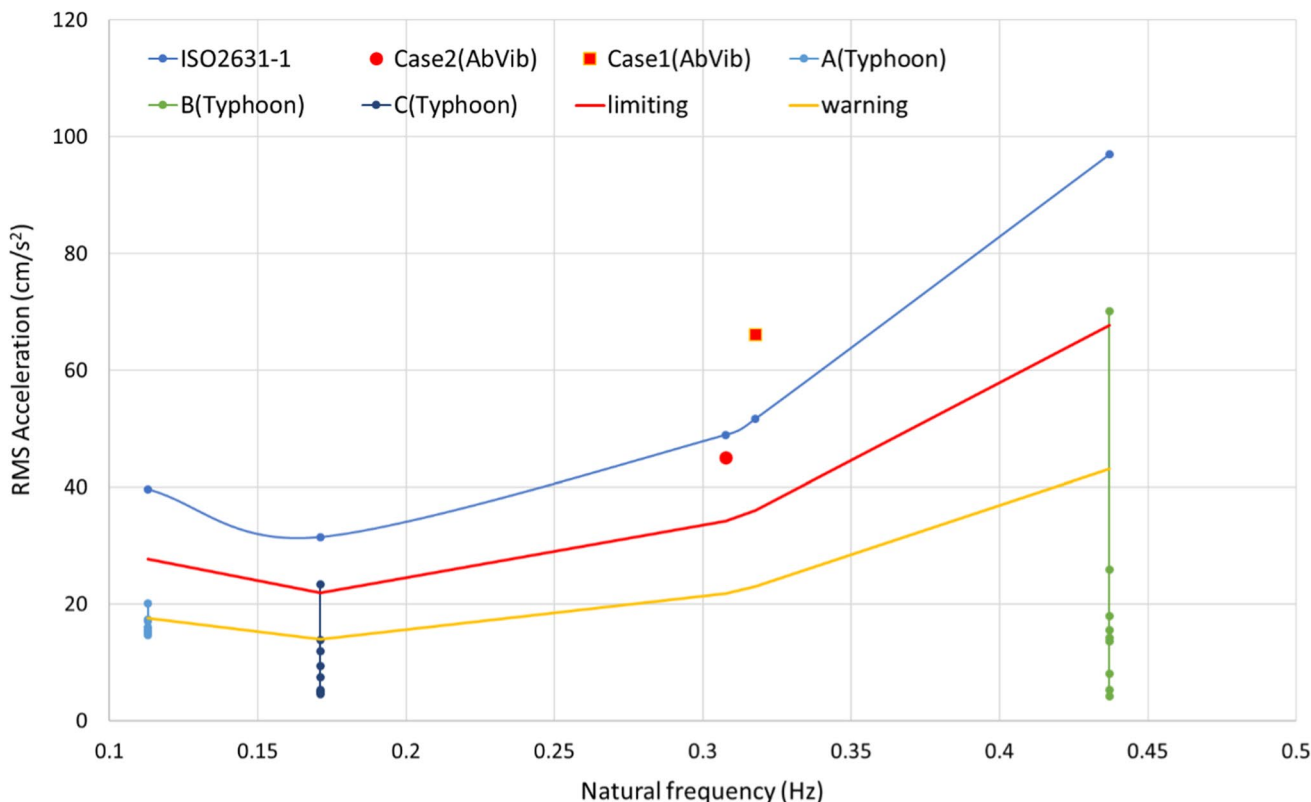
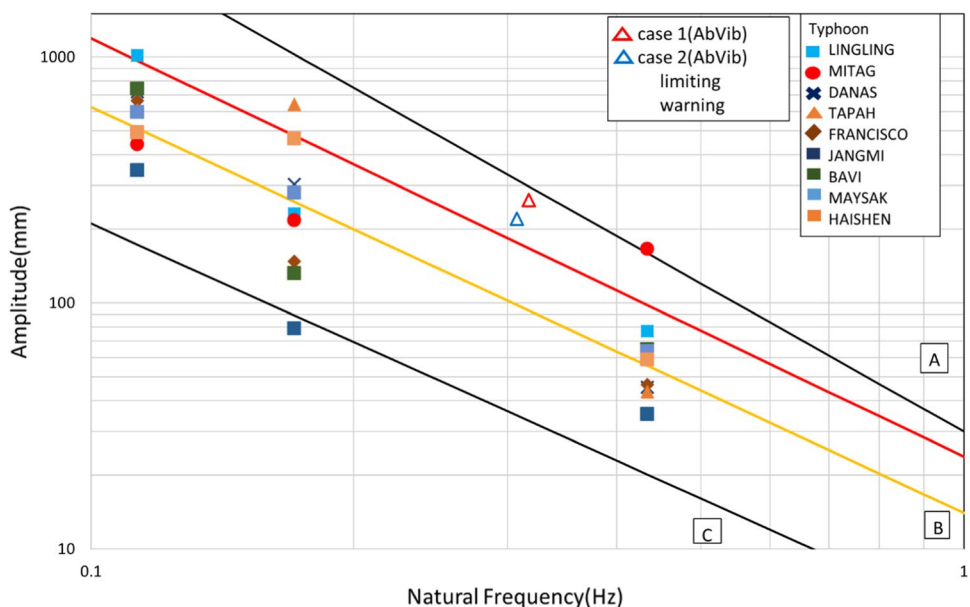


Fig. 14 Displacement amplitude, acceleration and FFT results of Bridge C during 10 min peak time of typhoon MITAG

**Fig. 15** Displacement amplitude during typhoons and abnormal vibration on Reiher-Meister curve



**Fig. 16** Evaluation criteria using ISO 2631–1 (weighted RMS acceleration)

- (3) Based on the comparison between abnormal vibration and typhoon events, evaluation criteria are proposed using displacement amplitude and RMS acceleration. They may be used for bridge management purposes.

Proposed criteria for vibration serviceability are as follows:

Based on displacement amplitude, limit =  $23.7/f^{1.7}$  and warning =  $14/f^{1.65}$  (mm).

Based on RMS acceleration, limit =  $0.22/W_f$  and warning =  $0.14/W_f$  ( $m/s^2$ ).

Further studies should be performed for the comprehensive evaluation of vibration serviceability for cable bridges, such as more data from a variety of bridges, precise signal conditioning, clear human comfort standard and so on.

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