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THE EFFECT OF BOLTED CONNECTION TIGHTNESS ON NATURAL FREQUENCY AND STIFFNESS OF TRUSS BRIDGES

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ABSTRACT: Monitoring and inspection of bridge health are compulsory in maintaining the reliability of the bridge structure. One parameter commonly measured is the natural frequency, which can be determined using a vibration test. The natural frequencies can be post-processed to obtain bridge stiffness and the corresponding deflection. For truss bridges, these parameters depend on joint tightness and load conditions at the time of measurement, which is the aim of this paper. An experimental test on a steel truss model was conducted to investigate the interaction between bolt clamping forces and load conditions on the truss bridge's natural frequency and stiffness. The results showed that the natural frequencies of truss bridges typically decreased as clamping forces were reduced, even in the absence of an external load. However, the added external weight to the truss bridge increased the natural frequency, as in a chain mechanism. The measurement of natural frequencies for truss bridges should account for the bridge's existing load condition. Moreover, natural frequency predictions for bridges with loose bolt connections are recommended to be applied conservatively by reducing theoretical natural frequencies by 30% (based on the typical assumption of a tight bolt connection).

Keywords: Truss bridge; Health monitoring; Bolt tightness; Natural frequency

1. INTRODUCTION

Structural health monitoring (SHM) is paramount for ensuring functional reliability throughout their lifespans. Therefore, the evaluation technique must be appropriately selected to determine the extent of structural damage and the required rehabilitation [1]. Among the infrastructure components, the structural health of bridges is particularly challenging to predict accurately due to differences in bridge type, materials, and connections.

Steel truss bridges have been primarily used for their fast, straightforward construction, economical cost-to-weight ratio, and flexibility of component replacement [2,3]. They also exhibit excellent durability against vertical loads (static and dynamic), lateral loads (e.g., wind), fatigue, and temperature fluctuations [4,5]. However, due to improper maintenance or excessive loading, steel truss bridges can experience material deterioration and large deformations, leading to structural failures [6,7].

The failure of a truss bridge generally refers to the structure's inability to meet specific functional requirements, including loss of load-carrying capacity, instability, fatigue, corrosion, excessive vibration, and plastic deformation. One crucial parameter for assessing structural reliability is the bridge's structural stiffness, which can generally be determined directly by conducting a full loading test and measuring deformation with LVDTs or Total Stations [8-10]. However, this procedure is relatively complex and can be destructive to bridge integrity. As a more conservative approach, the stiffness of truss bridges can be predicted using the natural frequency method, in which natural frequencies are measured through vibration tests [11-15].

Studies have shown that several factors affect the accuracy of vibration testing for assessing bridge condition, i.e., the members' modulus of elasticity [16], deck mass, joint assemblies, and connection conditions [17], and traffic loading [18]. Analytically, inaccuracies in the models' simulations of the actual bridge condition made it difficult to predict the bridge's natural frequency [19]. Several methods have been developed to improve accuracy, including an AI-assisted system [20], the SSI-COV method [21], and the FEM model [22]. However, the sensitivity of natural frequency to multiple influencing factors requires careful interpretation. Distinguishing between frequency changes caused by structural damage and those induced by environmental variability remains a major challenge in SHM applications.

Particularly for the effect of bolt connections on the modal parameters of bridges, under adverse connection conditions, bolt clamping forces can loosen due to corrosion, overload, or fatigue from dynamic loading from moving vehicles [23]. This mechanism results in a transition from a slip-critical to a bearing-type connection condition, thereby affecting the connection's stiffness and the associated natural frequency. This corresponding clamping force cannot be accurately determined due to the nature of the bolt-tightening process. To measure bolt loosening, the vibration method is preferred, although other methods can be used. Du et al. stated that the Time Reversal method provides higher accuracy in estimating bolt loosening than the wave energy dissipation technique [24]. Nikravesh and Gourdazi suggested that impact and vibroacoustic modulation methods are among the most sensitive for detecting looseness in bolted structures [25]. In comparison, Li et al. utilize piezoelectric transducers and three-dimensional numerical modeling to predict bolt loosening [26].

On simple bolt connection systems, several studies found that increasing tensile stress and strain (resulting from bolt tightening) increases the bending and transverse mode frequencies but decreases the torsional and longitudinal mode frequencies [27,28]. Xu found that the modal frequency increases with increasing bolt tightness due to reduced structural damping [29]. Rashid et al. demonstrated that the protruding end length of the bolt also affects the system's natural frequency; the longer the protrusion, the lower the natural frequency [30]. Overall, the bolt tightness affects the natural frequency for simple connections.

However, only a few have studied more complex cases, such as steel truss systems. Pan et al. investigated the effect of bolt preload loss on a truss system with bolted-ball joints [31]. The study suggested that insufficient preload reduced joint stiffness, thereby altering the joint's structural behavior. Bang et al. observed frequency shifts in the tower crane truss system due to variations in preload [32]. Despite numerous studies on the truss system, vibration testing on the system with the gusset-bolt connection joint remains unexplored, which is the primary aim of this paper.

Hence, to obtain more comprehensive findings about the correlation between three parameters — connection condition, stiffness, and natural frequency of the steel truss system — experimental tests, comprising vibration and flexural loading tests, were conducted on a truss bridge specimen in the laboratory.

2. RESEARCH AND SIGNIFICANCE

This research contributes to improving non-destructive evaluation techniques for steel truss bridges by investigating the relationship between natural frequency and structural stiffness. Since traditional loading tests to determine stiffness can be complex and potentially damaging to the structure, this study supports the use of vibration-based testing as a safer and more efficient alternative for assessing bridge condition.

The study addresses a critical knowledge gap regarding gusset-bolt connections in steel truss bridges. While previous research has examined the effects of bolt tightness in simple connection models, there is limited understanding of how connection conditions influence the stiffness and natural frequency of full truss systems. This research, therefore, expands understanding of the mechanics of connections and their influence on global structural dynamics.

3. MATERIALS AND SPECIMENS

The test specimen was a K-type steel truss bridge spanning 600 cm, as shown in Fig. 1. The height and width of the bridge specimen were about 50 cm and 90 cm, respectively. The total self-weight of the specimen was about 173 kg. Simple supports, such as pins and rollers, were used to simulate statically determinate structures. All prominent truss members were made of steel angle 40×40×4, with yield and ultimate strengths of 353 MPa and 515 MPa, respectively, as determined from the tensile test. The truss elements were connected using gusset plates and bolt systems. The steel gusset plate had a yield strength of 658 MPa, while the 8 mm diameter high-tensile bolts had yield and tensile strengths of 640 MPa and 800 MPa, respectively.

4. VIBRATION TEST

4.1 Methods and Test Setup

The effect of bolt tightness on the natural frequency was investigated by conducting two cases of various load increments and bolt tightness as follows (refer to Tables 1 and 2):

a. Case A was intended to study the effect of the loading and unloading process on different bolt tightness. This is useful to simulate the joint condition of the bridge connection with time, i.e., 1) the joint connection is still tight for the new bridge, 2) the loosening of bolt torque during the service lifespan, and 3) the increasing bolt tightness after maintenance.
b. Case B aimed to investigate the effect of bolt tightness on the bridge under various load conditions, specifically, no-load and loaded conditions.

The impact load was applied on the truss bridge using a rubber mallet, as shown in Fig. 2. The tightness of the bolt was set using a torque wrench at approximately 20.0 Nm, 12.0 Nm, and 2.0 Nm to simulate the transition from a slip-critical to a bearing-type condition of the bolted connection and its effect on natural frequency. The formula suggested by Hemmati Vand et al. is used in this study [33] using Eq. (1), as shown in Table 3.

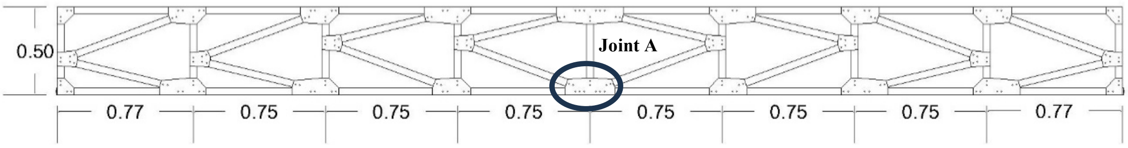
$$\boldsymbol{F_{cl} = 973.95\,T} \quad (1)$$

Where:

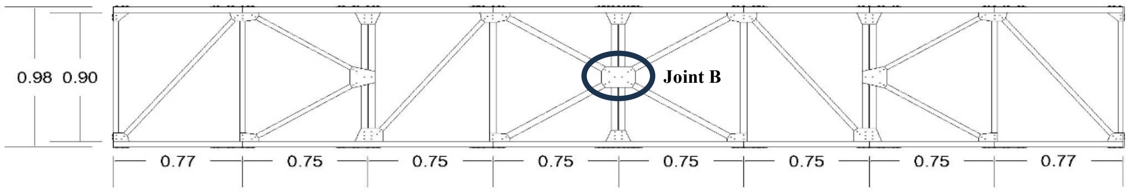
F_{cl} = the clamping force of the bolt (in kN)

T = the bolt torque (in Nm)

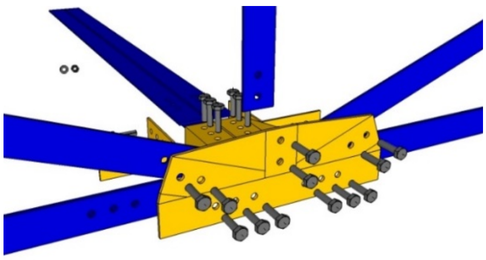
The additional 150 kg external weight was placed on the floor beams, at the third- and two-thirds-span positions of the bridge, using a steel basket filled with concrete blocks, as shown in Fig. 3. The magnitude of the external loads was determined to keep the truss members elastic during testing. Therefore, the natural frequencies measured were influenced only by the condition of the bolt connection, not by the structural members.



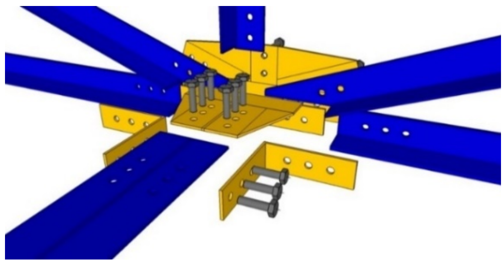
a. Layout of the truss system



b. Layout of floor beam and lateral bracing



c. Joint connection at main truss (joint A)



d. Joint connection at floor beam (joint B)

Fig. 1 Setup of truss bridge specimen

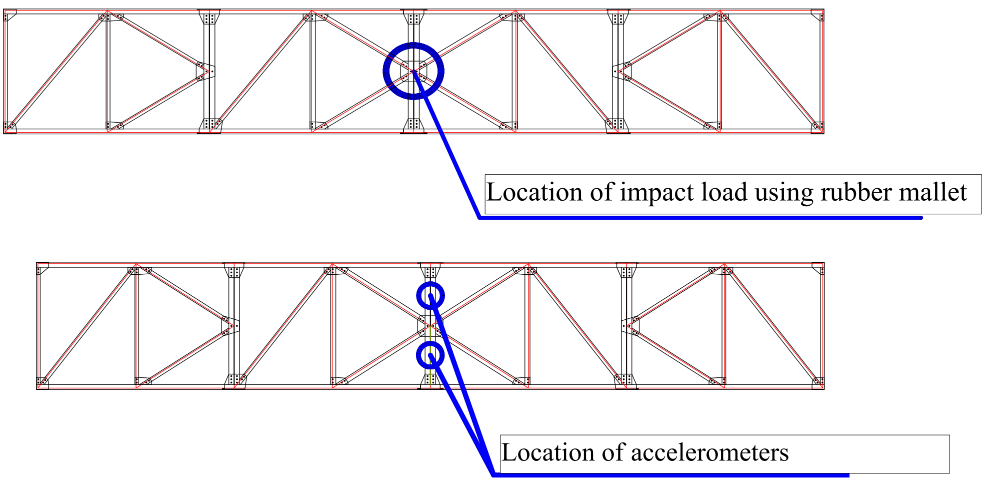


Fig. 2 Test setup for vibration test

4.2 Test Results

The effect of bolt tightness on the natural frequency was investigated by conducting two cases with varying load increments and bolt-tightness levels (see Tables 1-3). Representative acceleration curves as a function of time were recorded using two piezoelectric accelerometers connected to the DAQ program. The transducers were tightly mounted to the bridge's floor beam, as shown in Fig. 2, and three acceleration data points were recorded for each step to ensure the validity of the measurements. For all tests, the sampling frequency was 104 samples/s, with a 5 s time interval. The recorded acceleration data was then post-processed using FFT analysis, converting the time-domain data to the frequency domain. Figs. 4-5 show a sample of the recorded acceleration-time curve and FFT results. The resulting natural frequencies for all cases are presented in Fig. 6 and then are further analyzed separately in Figs 7-9.

Table 1. Test setup for case A: The effect of the loading and unloading stage on various bolt tightness

Step for Case A		Bolt Torque (Nm)	Loading
1	Bolt Tightness High to Low	20	U
2		20	L
3		12	U
4		12	L
5		2	U
6	Bolt Tightness Low to High	2	L
7		12	U
8		12	L
9		20	U
10		20	L

Table 2. Test setup for cases B1 (self-weight) and B2 (with external load)

Case B1	Step				
	1	2	3	4	5
Bolt Torque (Nm)	20.0	12.0	2.0	12.0	20.0
Loading type	U	U	U	U	U
Case B2	Step				
	1	2	3	4	5
Bolt Torque (Nm)	20.0	12.0	2.0	12.0	20.0
Loading type	L	L	L	L	L

Note: U = no-load, L = fully loaded

Table 3. Set up for bolt tightness and corresponding clamping force.

	Bolt Tightness		
Bolt Torque (Nm)	20.0	12.0	2.0
Clamping force (kN)	19.48	11.69	1.95

Fig. 3 External weight placement, each at a third and two-thirds span of the bridge specimen

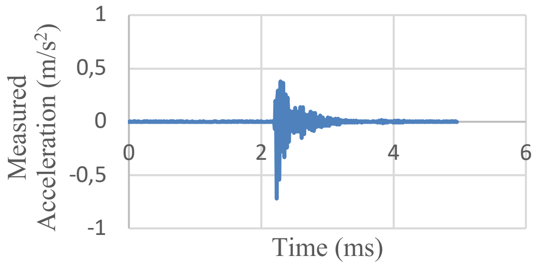


Fig. 4 Historical dynamic response of truss bridge during the test (sample no. 0.2-1)

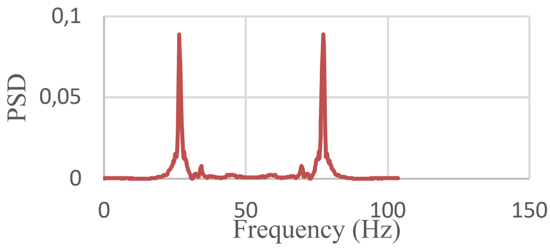


Fig. 5 Power spectral density (acceleration) of the recorded data (sample no. 0.2-1)

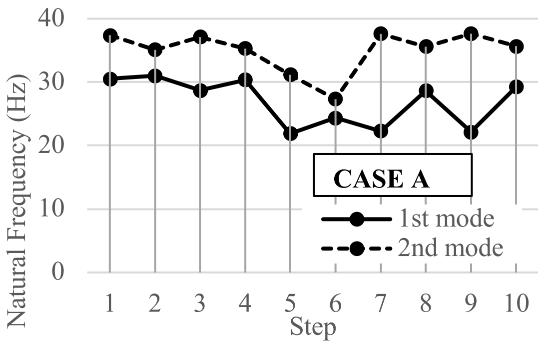


Fig. 6 Measured natural frequency for test case A

From the test results, as shown in Figs. 7-9, it can be observed that the effect of bolt tightness on the natural frequency depended on the mechanism of the bolted connection and the loading state as follows:

a. As shown in Fig. 7a, for specimens in the no-external load state (case B1), the alteration of bolt torque did not necessarily change the natural frequency of the truss bridge. It appeared that the magnitude of the self-weight was not significant enough to break the bolt's clamping force, even with the loosened level of bolt tightness.

b. For cases when the external load takes effect (cases A and B2), the bolt torque level affected the measured natural frequencies (refer to Figs. 8a-8d) as follows:

i. When the bolt torque level was reduced (from 20 Nm to 12 Nm), the slip-critical type bolt connection still provided sufficient clamping force, so the natural frequencies only slightly decreased

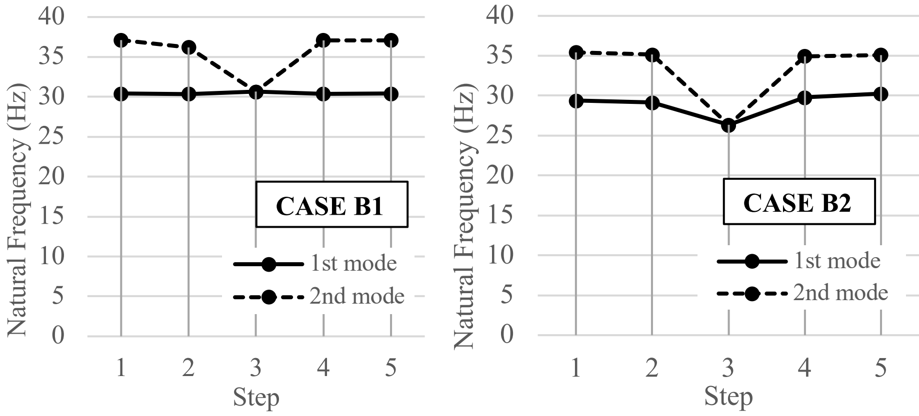
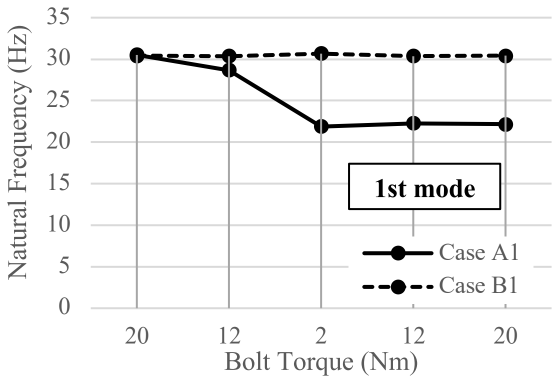
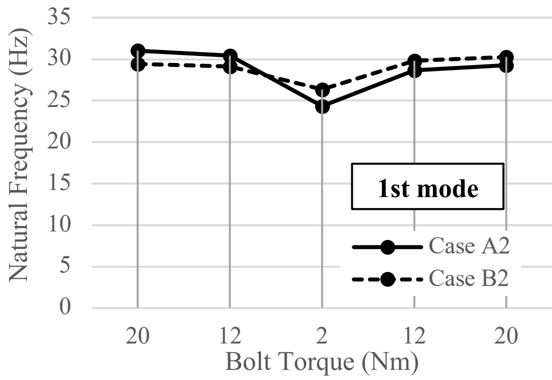


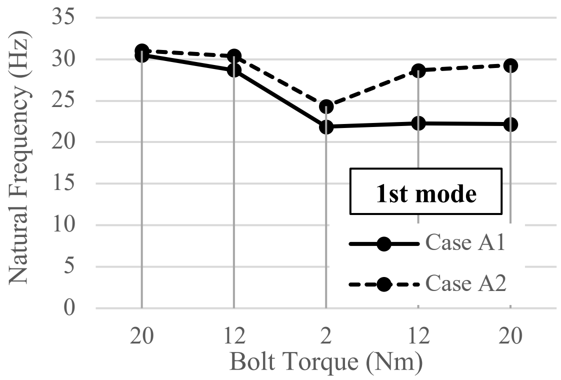
Fig. 7 Measured natural frequency for test case B.



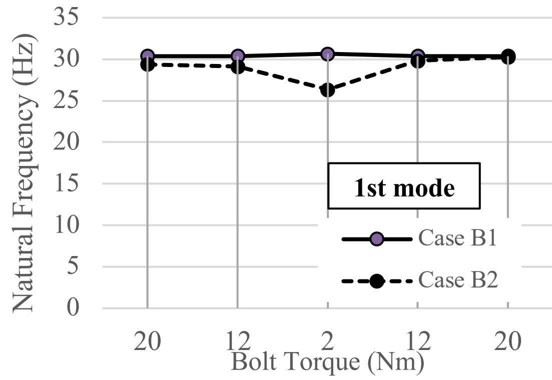
a. Natural frequency comparison between Case A1 and case B1



b. Natural frequency comparison between Case A2 and case B2

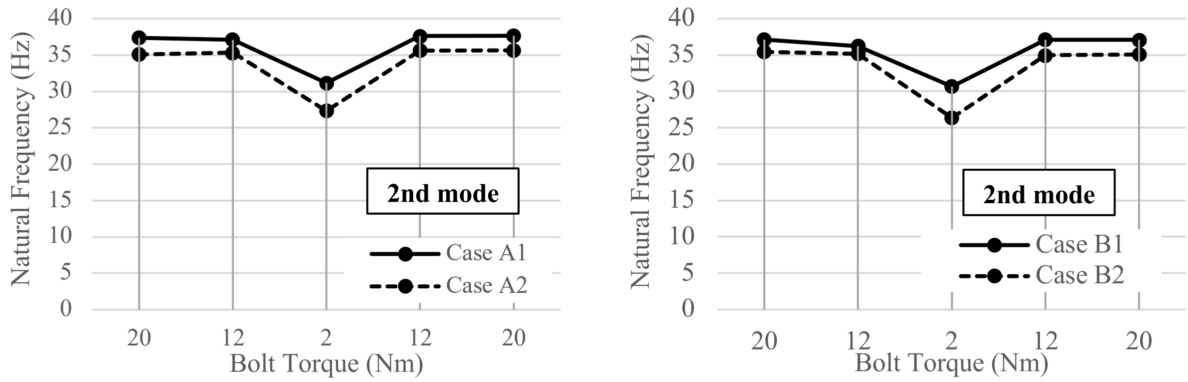


c. Effect of loading history on natural frequency at first mode for case A1 and A2.



d. Effect of external weight on the natural frequency at first mode for case B1 and B2

Fig. 8 Natural frequency comparison between cases A1, A2, B1, and B2 for 1st mode.



a. Effect of loading history on natural frequency at the second mode for case A1 and A2.

b. Effect of external weight on the natural frequency at the second mode for case B1 and B2.

Fig. 9 Natural frequency comparison between cases A1, A2, B1, and B2 for 2nd mode.

ii. However, further reducing the bolt torque from 12 Nm to 2 Nm caused the bolt mechanism to transition from slip-critical to bearing-type, resulting in a significant decrease in natural frequency.
This transition is evident in Fig. 8a, where the truss bridge deflection dropped significantly after the bolt torques were reduced from 12 Nm to 2 Nm. This sudden jump in deflection was attributed to bolt slip within the holes as the external loads were applied, while the steel members and gusset plates remained elastic.

iii. Retightening the bolt torque to its original tightness produced opposite results in cases A1 and A2-B2.
   - Without an external load (case A1), re-strengthening the bolted connection does not significantly change the recorded natural frequency; it remains approximately the same.
   - Conversely, tightening the bolt increased the natural frequencies under full-load conditions (cases A2 and B2). This is caused by a “chain-like mechanism” in which the truss structure with loose-bolt connections behaves like a chain, becoming stiffer when fully stretched under load and more flexible otherwise. This contrasts with the understanding that adding mass might reduce the natural frequency, according to the classic formula $\omega=\sqrt{k/m}$. The classic formula is more suitable for systems with rigid connections than one with a “chain mechanism,” such as truss bridges.

The phenomena described above must be considered when conducting a vibration test on an actual truss bridge, as the test results will differ depending on whether the bridge is in a no-load (self-weight) condition or is fully loaded.

c. Figs. 9a and 9b show that the classic natural frequency for the 2nd mode applies to stable loading conditions. The added loads reduce the bridge's natural frequencies due to the increased total mass.

5. DISCUSSIONS

5.1 Numerical Simulation

The experimental findings from the vibration and bending tests were then compared with numerical simulations. Cases of truss bridges with self-weight loading were analyzed. The modal parameter calculation was performed using dynamic analysis in STAAD Pro, employing the Finite Element Method (FEM), to obtain natural frequencies, damping ratios, and mode shapes. The theoretical analyses can reasonably predict the natural frequencies measured in the experimental results, as shown in Table 4. Therefore, numerical simulation can estimate the natural frequency of truss bridges in unloaded conditions. However, loosening the bolt joints from 20 Nm to 2 Nm reduced the measured natural frequencies by approximately 28% and 22% for unloaded and loaded bridge conditions, respectively. A natural frequency prediction for bridges with loose-bolt connections is recommended to be conservatively reduced by 30% relative to the analytical natural frequencies (with the typical assumption of a tight bolt connection).

Table 4. Natural frequency of analytical and experimental data

Mode	Natural Frequency (Hz)		
	Theoretical	Case A1	Case B1
1st Mode	31.2	30.5	30.4

5.2 Stiffness Analysis

The truss system's stiffnesses were then calculated using a typical relationship $k = \omega^2 m$ for each natural frequency, as presented in Fig. 10. In the no-load condition (U), the mass m_U uses the bridge model's mass of 1763 N. Whereas, in the fully loaded condition (L), the mass m_L uses the mass summation of bridge models, baskets, and concrete cylinders for a total of about 4800 N. It shows the trend in truss stiffness, showing that when the bolt mechanism shifted from slip-critical to bearing-type, the stiffness of the truss bridge dropped by approximately 50% and 30% when measured at the unloaded and fully loaded bridge, respectively.

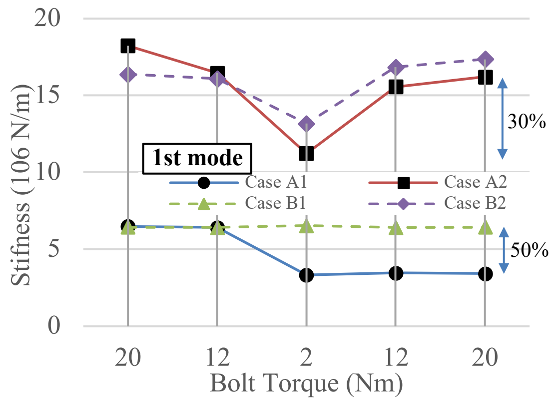


Fig. 10 Curves of calculated stiffness of a truss bridge

6. CONCLUSION

A vibration test has been conducted on a truss structure to investigate factors affecting the readings and results of the bridge health monitoring project. The following conditions should be considered when carrying out a vibration test on a bridge truss system:

a. The truss bridge's natural frequency and deflection depend on the tightness and loading condition of the bolted connection.
b. The loading condition affects the natural frequency measurement during the more common loading-unloading of a bridge load.
   i. If the joint connection remains tight, as is typical for relatively young bridges, the load alteration does not significantly alter the measured natural frequency.
   ii. When bolt torque decreases during the service life due to inadequate maintenance, the natural frequencies will decrease significantly regardless of loading/unloading conditions.
   iii. After corrective action is taken by restoring the bolt to its initial torque level, the measured natural frequencies vary under external loading. If the vibration test is conducted under no external load, the natural frequencies remain low despite the higher bolt torque. Conversely, the natural frequencies increase under loaded conditions. In this situation, the added weight increases the natural frequency, contrary to the common belief. This is caused by a "chain-like mechanism" in which the truss behaves like a chain, becoming stiffer when fully stretched and more flexible otherwise. The additional load on the loose truss structure causes the bolted connections to act in a bearing mode rather than a friction mode. This suggests that the truss system's natural frequency formula should account for bolt tightness.
c. When the bolt mechanism shifted from slip-critical to bearing-type, the measured stiffness of the truss bridge dropped by approximately 50% and 30% at the no external load condition and at the fully loaded condition, respectively.

Analytically, classical theoretical predictions can be used to determine the bridge's natural frequency under the combined condition of tight bolted connections and no external load. A 25%-30% reduction in natural frequency is recommended for loose-bolted connections. Overall, stiffness-based bridge health metrics tend to be overestimated when analytical approaches do not account for bolt looseness in the model.

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