VIBRATION SERVICEABILITY ASSESSMENT OF A STRESS-RIBBON FOOTBRIDGE

Marija Nefovska-Danilović[1], Vitomir Racić[2]

Summary:

With advancements in structural modelling and construction techniques, contemporary footbridges have become increasingly susceptible to vibrations induced by human activities, such as walking, jogging and jumping. This study aims to evaluate pedestrian-induced vibrations of a stress-ribbon footbridge. A three-dimensional finite element model of the footbridge was developed, considering nonlinear behavior of the structure and staged construction. Vibration serviceability assessment was carried out using HIVOSS design guidelines. Numerical modal analysis showed that the lateral modes of vibration cannot be excited in resonance by pedestrians walking. However, the footbridge is prone to vertical pedestrian-induced vibrations. The first torsional mode shape is the most critical. It can be excited in resonance by the first harmonic of the vertical pedestrian loading, yielding vibration response beyond the suggested acceleration limit in some extreme scenarios of pedestrian loading.

Key words: pedestrian-induced loading, nonlinear behavior, modal analysis, numerical model, dynamic response

NASLOV RADA, MAKSIMALNO TRI REDA, STIL: NASLOV RADA

Rezime:

Napredne tehnike modeliranja konstrukcija i savremene tehnologije gradnje dovele su do izgradnje modernih pešačkih mostova koji su posebno osetljivi na dejstvo vibracija izazvanih ljudskim aktivnostima kao što su hodanje, trčanje i skakanje. U ovom radu prikazana je analiza vibracija pešačkog mosta sistema prednapregnute trake, usled dinamičkog dejstva pešaka. Formiran je 3D numerički model primenom metode konačnih elemenata, uzimajući u obzir faznu gradnju i nelinearno ponašanje mosta. Procena uticaja vibracija izvršena je prema preporukama HIVOSS pravilnika. Rezultati numeričke analize su pokazali da ne postoji mogućnost pojave rezonantnih poprečnih vibracija mosta usled hodanja. Međutim, most je osetljiv na vertikalne vibracije. Najkritičniji je prvi torzioni ton mosta, za koji postoji mogućnost pojave rezonantnog odgovora usled prvog harmonika dinamičke sile pešaka, a samim tim i prekoračenja dozvoljenog nivoa vertikalnih vibracija pri kritičnim slučajevima pešačkog opterećenja.

Ključne reči: pešačko opterećenje, nelinearno ponašanje, modalna analiza, numerički model, dinamički odgovor

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1. INTRODUCTION

With advancements in structural modelling, building materials and construction techniques, footbridges are often designed as flexible structures [1]. Consequently, contemporary footbridges have become increasingly susceptible to vibrations induced by human activities, such as walking, jogging and jumping [2]. Human-induced vibrations are a serviceability issue, i.e. they do not cause structural damage but can cause discomfort and annoyance to pedestrians. Therefore, vibration serviceability assessment has become the governing criterion for the design of long-span footbridges.

Extensive studies have been carried out to address key challenges related to the vibration serviceability assessment of footbridges [1]. Damping generally features as one of the most uncertain structural parameters at the design stage. However, knowledge about dynamic loading induced by pedestrians is far more sparse and limited. So, it is commonly associated with the greatest level of uncertainty.

Stress-ribbon bridges are gaining popularity in the design and construction of medium and long-span footbridges due to their lightness, aesthetic appeal, high level of prefabrication, easy construction and low maintenance requirements [3]. Main load-bearing elements of the stress-ribbon footbridge are bearing tendons, catenary–type cables usually anchored at the concrete abutments. The bridge deck is usually made of precast concrete segments installed over the bearing tendons and linked together through a cast in-situ concrete layer. After the deck construction, the additional prestressing tendons are posttensioned, forming a composite section of the stress-ribbon footbridge with an increased stiffness. Such a design concept results in a very slender structure having large displacements, which requires application of the geometrically nonlinear analysis. In addition, stress-ribbon footbridges are particularly prone to human-induced vibrations, which has been confirmed through several experimental studies [4-5].

Caetano and Cunha [6] carried out both experimental and numerical investigation of a stress-ribbon footbridge to assess the modal properties and vibration levels due to pedestrian traffic. The measured vibration levels due to a single pedestrian were relatively high but within the acceptable limits. However, large vibration levels were recorded due to a high-density flow of pedestrians whose walking frequency closely matches the natural frequencies of the two experimentally identified vertical vibration modes around 2Hz. The measured damping factors were between 1.7% and 2.6%, indicating slightly higher damping factors than those specified in the guidelines (usually 1%).

This paper presents a numerical study of the modal properties and pedestrian-induced vibrations of a stress-ribbon footbridge. A three-dimensional finite element model of the footbridge was developed, considering geometrically nonlinear behavior of the structure and staged construction. Vibration serviceability assessment was carried out using HIVOSS design guidelines [7].

2. DESCRIPTION AND BEHAVIOUR OF THE BRIDGE

The footbridge was designed as a 30 cm thick stress-ribbon concrete slab with the span of 102 m, width of 3.8m and 2.3 m sag at the end of the construction, Fig. 1. A typical cross section of the footbridge is depicted in Fig. 2. The bearing cables are embedded in the concrete slab, providing a catenary shape to the bridge. The bridge goes through the following construction stages:

- Installation of the bearing cables between the abutments – the bridge behaves as a bare cable,
- Installation of a 3m-long precast concrete segments along the bearing cables – the bridge still behaves as a bare cable with additional dead load,

- Concrete is cast over the segments to achieve monolith and composite section with the bearing cables – the bridge still behaves as an additionally loaded bare cable, as long the concrete is wet,
- Posttensioning using the set of posttensioning tendons – the concrete section had hardened, and the bridge from this stage starts to behave as a stress ribbon (i.e. cables and prestressed concrete form a composite section),
- Application of superimposed dead load (fences, waterproofing etc.) – the bridge behaves as a stress-ribbon with the additional load – this is the end of the construction,
- Service life of the bridge (pedestrian loading, temperature, shrinkage, creep, relaxation) – the bridge behaves as a stress-ribbon.

Due to large displacements, geometrically nonlinear analysis was applied in each construction stage.

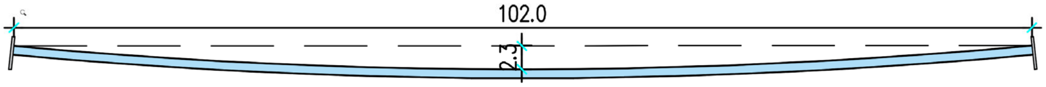


Fig. 1 Longitudinal section of the bridge

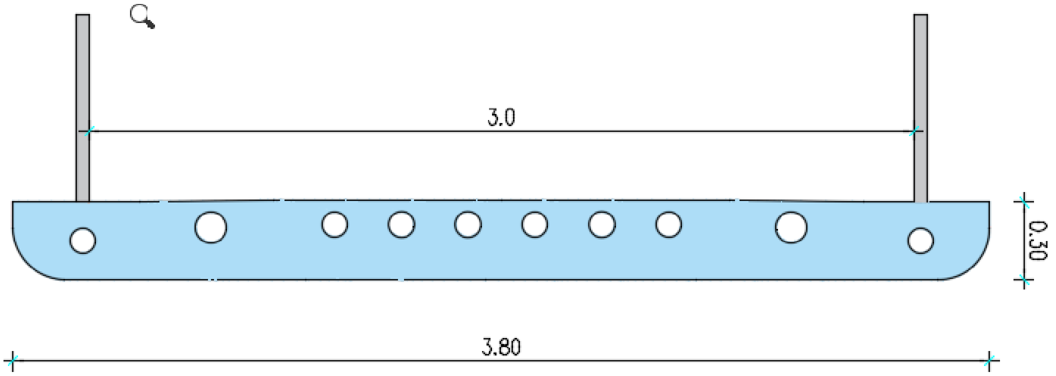


Fig. 2 Typical cross-section of the bridge

3. NUMERICAL MODEL AND ANALYSIS

To account for prescribed loads, geometry of the structure and forces in the cables that change at each construction stage of the stress-ribbon footbridge, a numerical model (Fig. 3.) was developed using the finite element-based software SAP2000 and applying geometrically nonlinear analysis. The finite element model consists of 1836 SHELL elements. The bearing cables were modelled using curved frame elements (CURVED FRAME), while the prestressing tendons were modelled using TENDON type finite elements, with their actual positions in the horizontal plane of the bridge cross-section. In this way, the real stiffness of the bridge in the horizontal plane was taken into account.

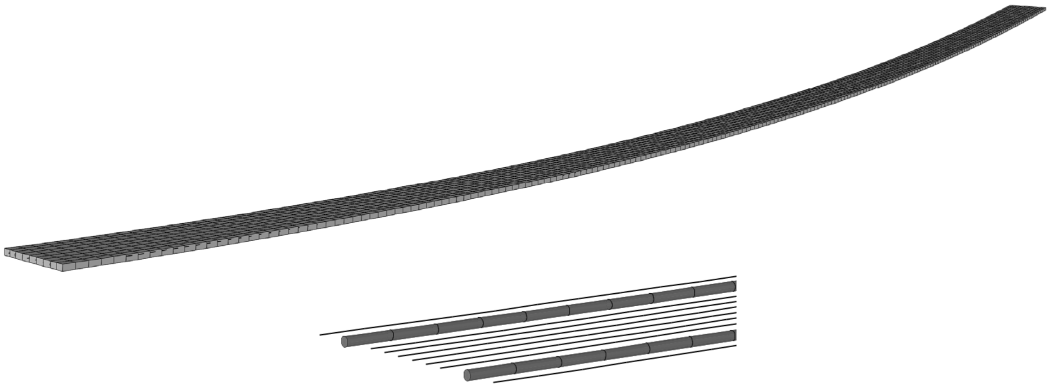


Fig. 3 Finite element model of the bridge: shell elements and position of bearing and prestressing cables

First, static analysis was carried out under the action of permanent loads (the self-weight of the bridge plus additional permanent loads) and prestressing, using geometrically nonlinear staged construction analysis. The change in axial stiffness of the cross-section due to concrete curing was taken into account, as well.

After the static analysis, a modal analysis was run to obtain the natural frequencies and mode shapes of the bridge. This was followed by a dynamic response analysis designed to calculate the maximum vertical acceleration induced by pedestrians crossing the bridge. The pedestrian harmonic loading was determined according to the HIVOSS guidelines [7], as well as the subsequent vibration serviceability evaluation. Considering the dimensions of the bridge deck along which pedestrians (P) can move freely, the bridge location, as well as its purpose, the expected level of pedestrian traffic on the bridge in most cases will not exceed density d = 0.2 P/m^2. This corresponds to a group of 60 pedestrians present on the bridge. Consequently, vibration serviceability assessment was carried out for two pedestrian-induced loading scenarios, i.e., traffic classes:

- TC1 – group of 15 pedestrians crossing the bridge,
- TC2 – traffic density d = 0.2 P/m^2.

The critical range of natural frequencies of the bridge according to HIVOSS is between 1.25 Hz and 2.3 Hz for the vertical and longitudinal direction. This frequency range corresponds to the typical range of walking frequencies (also called footfall rates) for the healthy human population. Moreover, vertical and longitudinal vibration modes with natural frequencies in the range between 2.5 Hz and 4.6 Hz can also be excited to the resonant vibrations by the second harmonic of the pedestrian force model. However, amplitudes of the second force harmonic are significantly lower than the amplitudes of the first harmonic across the whole range of footfall rates. This means that the resonant footbridge vibrations due to the second harmonic of pedestrian excitation are unlikely to reach critical values that might cause human discomforts [8].

HIVOSS suggests the minimum and the average damping factors 0.7% and 1%, respectively. In this study, the maximum acceleration response of the bridge was calculated assuming damping factors in the range between 1% and 2%.

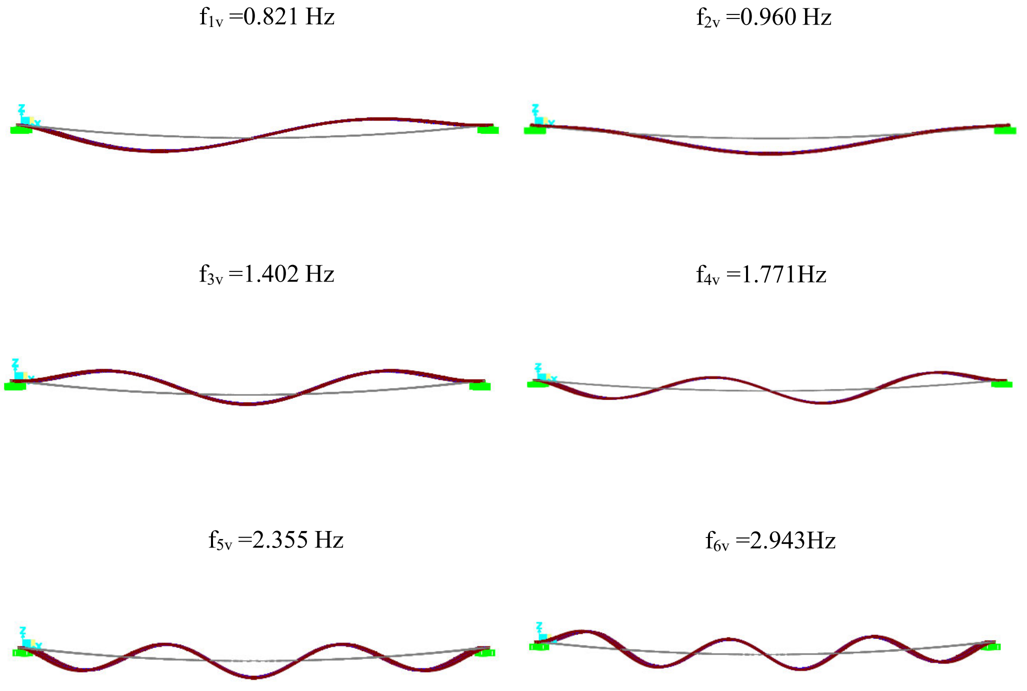
4. RESULTS AND DISCUSSION

4.1. MODAL PROPERTIES

The first twelve natural frequencies (i.e. all bellow 5Hz) and directions of the corresponding modes (V – vertical, L – lateral, T – torsional) are presented in Tab.1, while the mode shapes are illustrated in Figs. 4-6. Note that the first vertical mode shape is asymmetric, which is influenced by the high axial stiffness of the cables in comparison to the bending stiffness of the footbridge deck. As the natural frequency of the lateral-torsional mode is out of the critical range between 0.5 Hz and 1.2 Hz for the lateral vibrations according to HIVOSS, the footbridge is unlikely to be excited by the pedestrians in the lateral direction. Therefore, only the vertical dynamic response of the bridge will be analyzed in the remaining part of the paper.

Tab. 1 First twelve natural frequencies of the bridge

Mode no.	f [Hz]	Mode direction
1	0.821	V1
2	0.960	V2
3	1.402	V3
4	1.430	LT1
5	1.771	V4
6	2.075	T1
7	2.355	V5
8	2.943	V6
9	3.409	LT2
10	3.646	V7
11	4.201	T2
12	4.394	V8



f_{1v} =0.821 Hz

f_{2v} =0.960 Hz

f_{3v} =1.402 Hz

f_{4v} =1.771Hz

f_{5v} =2.355 Hz

f_{6v} =2.943Hz

Figure 4. First six vertical mode shapes of the bridge

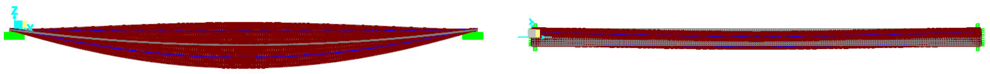


Figure 5. First torsional mode shape of the bridge: top view (left), side view (right)

Figure 6. First lateral-torsional mode shape of the bridge: top view (left), side view (right)

4.2. VIBRATION RESPONSE ANALYSIS

Results of the modal analysis elaborated in the previous section have shown that the vertical mode shapes V3 and V4, as well as the first torsional mode T1, are the most critical. This is because they can be excited in resonance by the first harmonic of the pedestrian-induced dynamic load. Therefore, a vibration response analysis was carried out to determine the maximum vertical acceleration response of the bridge considering only these three vibration modes. The results of numerical simulations considering relevant traffic classes and damping factors were summarized in Tabs. 2-4.

Tab. 2 Maximum vertical acceleration of the bridge considering mode V3

Traffic class	TC1 (15 P)			TC2 (0.2 P/m^2)		
Damping factor (%)	1.0	1.5	2.0	1.0	1.5	2.0
Acceleration (m/s^2)	0.10	0.08	0.07	0.19	0.16	0.14

Tab. 3 Maximum vertical acceleration of the bridge considering mode V4

Traffic class	TC1 (15 P)			TC2 (0.2 P/m^2)		
Damping factor (%)	1.0	1.5	2.0	1.0	1.5	2.0
Acceleration (m/s^2)	0.26	0.21	0.18	0.52	0.43	0.47

Tab. 4 Maximum vertical acceleration of the bridge considering mode T1

Traffic class	TC1 (15 P)			TC2 (0.2 P/m^2)		
Damping factor (%)	1.0	1.5	2.0	1.0	1.5	2.0
Acceleration (m/s^2)	0.43	0.35	0.30	0.87	0.71	0.61

The maximum acceleration responses of the bridge occurred when the walking frequency of the pedestrians matched the natural frequency of the first torsional mode shape. The damping factor, as the most uncertain parameter in the dynamic response analysis, can significantly affect the vibration levels of the bridge. According to HIVOSS, maximum pedestrian comfort due to the vertical bridge vibrations is assured by limiting the maximum acceleration to 0.5 m/s^2 (comfort class CL1). In this study, for vibration mode

T1 the maximum acceleration is exceeded for all considered damping factors. On the other hand, for vibration mode V4 excessive accelerations are obtained only for 1% damping.

5. CONCLUSIONS

The finite element modelling of a stress-ribbon footbridge presented in the paper has shown that the structure exhibits complex dynamic behavior that requires a stage construction modelling approach and geometrically nonlinear analysis. This is in line with findings reported in experimental studies of already constructed stress-ribbon footbridges worldwide [4, 6].

Vibration serviceability assessment of the investigated footbridge was carried out using HIVOSS guidelines, considering two pedestrian-induced loading scenarios (i.e. two traffic classes).

The footbridge is not sensitive to lateral-induced vibrations as the natural frequency of the first lateral-torsional mode is out of the critical range for the lateral vibrations. However, there are two vertical modes and one torsional mode that can be excited in resonance by the first harmonic of the pedestrian-induced dynamic load. The torsional mode T1 was found to be the most critical, as maximum vertical acceleration response reached 0.87 m/s^2 for damping of 1%, which was beyond the acceleration limit of 0.5 m/s^2 corresponding to maximum pedestrian comfort according to HIVOSS.

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