46th International Scientific Conference EXPERIMENTAL STRESS ANALYSIS 2008
Department of Mechanics of Materials, VŠB - Technical University of Ostrava
June 2 - 5 2008, Horní Bečva, Czech Republic

Jan ZATLOUKAL*, Petr KONVALINKA**

FOOTBRIDGE ACROSS LITAVKA RIVER, BEROUN. DESIGN BASED ON VIBRATION EIGENFREQUENCIES AND EIGENMODES

NÁVRH KONSTRUKCE LÁVKY PŘES ŘEKU LITAVKU V BEROUNĚ, ODVOZENÝ OD CHARAKTERISTIK VLASTNÍHO KMITÁNÍ

Abstract

Description of unusual timber–steel footbridge, developed from original architectural design into employable structure. Original design suffered from insufficient stiffness of footbridge superstructure, resulting in excessive vibration. This design was modified in terms of stiffness and technology without altering the architect's visual concept.

Abstrakt

Popis neobvyklé lávky z kombinace materiálů dřeva a oceli, a její vývoj ze stádia architektonického návrhu do životaschopné konstrukce. Původní návrh vykazoval nadměrné vibrace, způsobené nedostatečnou tuhostí vrchní stavby lávky. Při úpravách konstrukce byl kladen důraz na zachování architektonického vzhledového konceptu.

1 INTRODUCTION

The proposed structure is supposed to bridge Litavka river near Beroun city center, allowing the city to expand its parks and leisure time areas to the river's so far inaccessible right bank. A 37 m single-span structure from architectural bureau HABE was chosen. It combines two usual building materials – glulam timber and steel into unique structure. This design respects existence of another nearby footbridge, massive glulam arch structure, being more subtle while crossing longer span. This subtlety brought lack of stiffness indeed, resulting in very low first eigenfrequencies and critical load. The structure required to be redesigned, in terms of structural engineering, but also keep its original visual appearance.

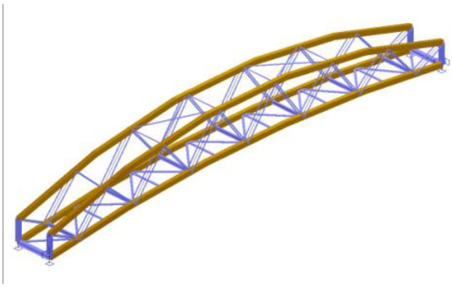

Fig. 1 View of the footbridge (3D computational model)

2 DESCRIPTION OF ORIGINAL STRUCTURE

The main load bearing elements of the original design are two 37 meters long arch-shaped trusses positioned on both sides of the footbridge. The truss girders are curved both in different radii and are made of glulam timber, rectangular cross section. The diagonals are round steel pipes. The

* MSc., Experimental Centre, Faculty of Civil Engineering, CTU Prague, Thákurova 7, Praha 6, tel. (+420) 2 2435 4499, e-mail jan.zatloukal@fsv.cvut.cz
** Doc. MSc. PhD., Experimental Centre, Faculty of Civil Engineering, CTU Prague, Thákurova 7 , Prague 6, tel. (+420) 2 2435 4306, e-mail petr.konvalinka@fsv.cvut.cz

wooden slab walkway is situated in the level of bottom girders' top surface, following their curvature. The superstructure was originally intended to be lodged directly on the concrete substructure.

All the features mentioned above turned out to be problematic: the subtle superstructure being too vulnerable to vibration yet the walkway too rigid and stiff and lodged without any bearings directly to the substructure. The first eigenfrequency was about 2.2 Hz, right in the step frequency interval (1.6 ÷ 2.4 Hz) with eigenmode representing lateral vibration with cross section deformation. The critical loading ratio for characteristic load combination was only about 4, which meant the structure is vulnerable to stability loss. These problems were fixed in the latter structure modification. Also, from the visual appearance point of view, the deck elements were placed atop the bottom main beam, being visible from side view of the footbridge. The redesign of deck was therefore also necessary.

3 MODIFICATION OF THE ORIGINAL DESIGN

First of all, the superstructure supports were changed to elastomere bridge bearings promising better static function and longer serviceability of the structure. Then original wooden walkway was replaced by steel one, yet plated with wooden sheets to maintain its visual appearance for users. It was possible to place the walkway in between the bottom girders not disturbing the side view of the footbridge anymore. More rigid horizontal stiffener has been added under the walkway to ensure greater lateral stiffness of the structure. This stiffener not only improved resistance of the superstructure to lateral loads but also improved its performance in dynamic response terms. Original design introduced wooden horizontal truss stiffener, which was replaced by steel structure. The "vertical" beams of the stiffener also act as crossbeam of the vertical stiffener.

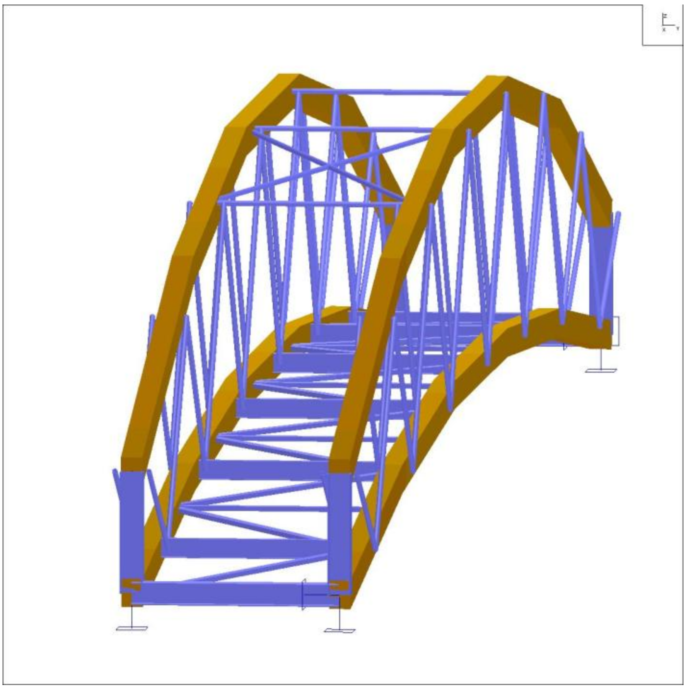

Fig. 2 Front view of the footbridge

The biggest changes were made to the superstructure itself. Original design allowed the main trusses to tilt freely around horizontal axis due to lack of any cross section stiffening. Many variants of cross section stiffening were judged and finally multiple U-shaped frames were chosen. Every in-plane truss diagonal works as out-of-plane stiffener strut, supporting the top girder in lateral direction. The bottom tie beam of the stiffener is also a part of horizontal stiffener and as non-visible member is made of an I-beam. The struts however need some visual appearance level and are required to be made of round pipes. Unfortunately single pipe of reasonable dimensions was found insufficient so twin pipe vertical mini-truss was introduced to the design.

Finally, the joint of the horizontal and vertical member of the cross section stiffeners had to be designed. It had to be stiff enough to act as frame cornet and also not violating the walkway profile. The complicated design resulted from its three dimensional function, joining six members in three different planes: wooden main truss bottom girder, steel diagonals of horizontal stiffener and tie beam and two struts of cross section stiffener, altogether with technological demand of being welding free since wooden elements were connected to this joint. Twelve variants of cornet were judged, with aspect of the overall stiffness of the superstructure. This required two-level modeling of the superstructure. On global level, whole superstructure was investigated using beam-element 3D model. The frame cornet was investigated separately, using much more detailed shell plane element 3D model of one symmetrical half of the crossbeam, frame cornet and pair of diagonals.

4 EIGENMODE BASED DESIGN

Critical point of the modification emerged soon after initial consideration. As well known fact, pedestrian loading has properties of harmonic loading in both vertical an lateral vibration. The load frequency in lateral direction is one half of the one in vertical direction, while in lateral direction whole loading cycle last for two paces and in vertical direction the whole cycle takes place in every single pace. These frequencies are in range from 1.7 to 2.3 Hz for vertical and 0.85 to 1.15 Hz for lateral action. Design codes (EN 1991-2: Action on bridges) present values from 1.0 to 3.0 Hz in vertical and from 0.5 to 1.5 Hz in lateral direction. The problem of lateral vibration of footbridge superstructure has been sometimes neglected in the past, resulting in several serviceability problems. The resulting excessive vibration displays some characteristics of self-induced vibration, because of the phenomena of pedestrian subliminal tuning their stepping frequency in the vibration frequency of moving structure they are moving on. This problem is dealt with in literature, namely [1]. Eigenfrequencies of the original proposed structure fell in this dangerous range and solution of this problem was required.

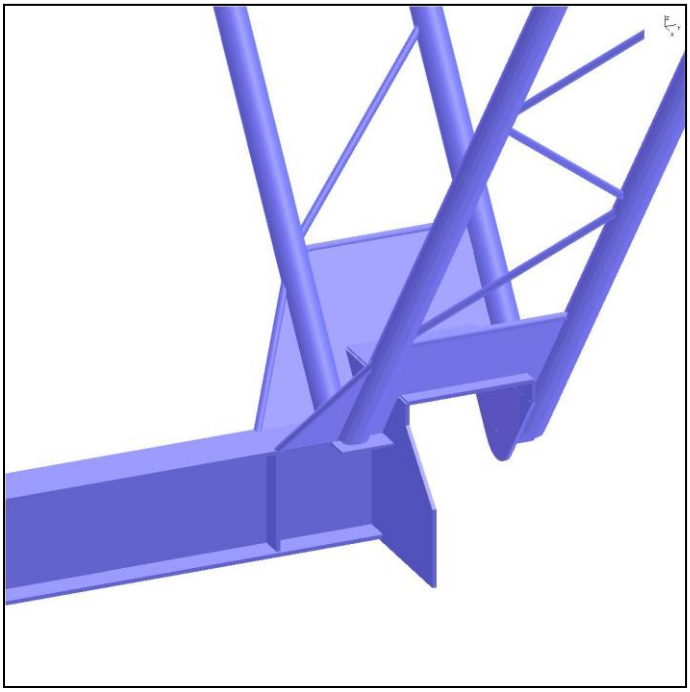

Fig. 3 Frame cornet 3D model – shell elements

For every variant a calculation of eigenmodes has been done on 3D FEM model in FEAT 3.0 software. The variant was found not compliant if any of eigenfrequencies was lower than 3.0 Hz, or the frequencies of three first eigenmodes (vertical, lateral and torsional vibration) differed in their order, or the critical load ratio was lower than 10. These conditions allowed us to balance the stiffness of the structure while keeping its other qualities.

The frame cornet stiffness was taken into account by calculating its torsional stiffness using shell model of symmetric half of one pair of stiffening frames with common tie beam. The deformation was compared with deformation of ideally stiff connected tie beam and diagonals under identical load. Having these values subtracted, the torsional stiffness of the cornet from known bending moment and deformation was calculated. This calculated stiffness was introduced to the global FEM model via springs connecting elements in certain nodes and eigenmodes were calculated. Every correction of the frame cornet layout resulted in different stiffness and different resulting eigenmodes and eigenfrequencies. For example, for very stiff frame first eigenmode represented torsion of the whole superstructure with quite high frequency (about 5 Hz) while for very compliant frame the first mode was tilting of the main girder around axle parallel to longitudinal axle of the bridge and very low frequency (about 1,5 Hz).

The finally chosen variant of frame cornet had to fulfil two different requirements, first, being enough stiff and second, not to interfere with the walkway. Also, ease of construction of such detail and economical aspects were taken into account so out of two solutions providing nearly same results the less complicated was selected.

5 CONCLUSIONS

The original design was revised in terms of structural engineering. The excessive vibration under pedestrian loading was probably avoided and general increase in structure serviceability and reliability was reached. Visual appearance of the structure was not affected by the undergone structural changes, furthermore, is valued as more appealing by the author of the original design. The structure is now ready to be built, waiting only for appropriate funding from the Beroun city.

REFERENCES

[1] NEWLAND, D. E. Pedestrian Excitation of Bridges – Recent Results, In *10th International Congress of Sound and Vibration (on CD published by the Int. Institute of Acoustics and Vibration),* Stockholm, 2003.

[2] ZATLOUKAL, J. *Footbridge across Litavka river, Beroun. Diploma thesis,* CTU Prague, 2007.

Reviewer: Dr. MSc. Tomáš NOVOTNÝ, VŠB - Technical University of Ostrava