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Comparative analysis of dynamic behaviour of two cable-stayed footbridges made entirely of steel and GFRP composite

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Abstract. This paper is focused on the comparative numerical analysis of the dynamic behaviour of two cable-stayed footbridges made entirely of steel and Glass Fiber Reinforced Polymer (GFRP) composite, with similar geometrical parameters and bearing capacity. The analysis was executed using the Autodesk Robot Structural Analysis Professional software. Firstly, the determination of modal parameters of both footbridges was done. For the further finite element analysis the damping ratio of the all-GFRP footbridge was measured in situ, whereas for the all-steel footbridge was taken from data published in the literature. Then, the dynamic responses of both structures were determined based on the Footfall harmonic analysis. In this case, the numerical models of analyzed footbridges were subjected to dynamic effects of human gait with various moving frequency. The maximal values of vertical acceleration of structural vibrations were obtained. The vibration comfort criteria for both footbridges were verified. The numerical results were compared and differences in dynamic responses of analyzed footbridges were examined. The obtained results delivered some important practical data regarding the dynamic response as well as vibration comfort criteria of cable-stayed footbridges which could be used at a design stage to make a decision on the construction material solution.

1. Introduction

Always at the beginning of a design process, bridge designers must decide on the choice of construction materials from which bridge structures will be made. The materials-selection decisions making by designers require consideration of important aspects in terms of material performance requirements which can be divided into five categories, i.e. functional requirements, resistance to service conditions, reliability, processability requirements, and costs, including the initial costs of materials and maintenance costs over the lifetime of a bridge structure. Practical guidelines concerning of these aspects are well discussed in the publication [1]. Considering materials selection problem of newly-designing footbridges a very important aspect is also their dynamic susceptibility to dynamic effects of the pedestrian traffic.

Over the past few decades, the number of newly-designed light-weight and slender footbridges significantly increased. The community also demands more architecturally attractive footbridges. Unfortunately, this leads to more likely serviceability problems. Contemporary slender footbridges are often susceptible to human induced vibrations. In some cases, these vibrations can attain high levels, especially when the walking pace of pedestrians approaches the natural frequency of a footbridge. Such a vibration state could result in a situation where the pedestrian feel uncomfortable or even
unsafe [2]. Although codes of practice were developed enabling a designer to evaluate the vibration serviceability of the structure based on simplified models of crowd load [3], the performance requirements for construction materials are higher than in the past. For this reason, besides the traditional materials, like steel, aluminum, concrete or wood, some innovative materials are introduced in contemporary footbridge structures. It should noticed that hybrid solutions combining elements made of different materials are also willingly used in bridges.

One of the most innovative materials being slowly introduced in contemporary bridge structures is Glass Fiber Reinforced Polymer (GFRP) composite material. There are several advantages of the GFRP material such as a high tensile strength, low self-weight, corrosion resistance, electromagnetic transparency, easy and quick assembly and creation of innovative shapes of pultruded profiles as well as whole structures. Besides these advantages GFRP has also some limitations like high initial costs, relatively low modulus of elasticity (Young’s modulus), low alkaline resistance, low fire resistance and low long-term strength due to stress rupture [4]. Among others, the relatively low Young’s modulus requires the use of relatively large cross-sections of structural elements in order to minimize serviceability problems of all-GFRP footbridges. Compared to GFRP composite, steel has the advantage of lower initial costs and several times higher Young’s modulus which leads to thin-walled cross-sections with smaller outer dimensions.

This paper is focused on the comparative numerical analysis of the comprehensive dynamic behaviour in the vertical direction of two medium span cable-stayed footbridges made entirely of steel and GFRP composite material, with similar geometrical features and bearing capacity. A three dimensional (3D) Finite Element (FE) model of the all-GFRP footbridge was created based on the geometrical and material data of the existing Kolding Footbridge, acquired from its available technical documentation. Then, the FE model of the all-steel footbridge was made taking into account new structural steel elements providing a similar bearing capacity of both footbridges. The first part of the paper presents the determination of modal parameters of analyzed footbridges, i.e. their natural frequencies and corresponding mode shapes. For the further finite element analysis the damping ratio of the all-GFRP footbridge was measured in situ, whereas for the all-steel footbridge was taken from data published in the literature. In the second part, the dynamic responses of both structures were identified based on the Footfall harmonic analysis. In this case, the numerical models of analyzed footbridges were subjected to dynamic effects of human gait with various moving frequency. The maximal values of vertical acceleration of structural vibrations were obtained. The vibration comfort criteria for both footbridges were verified according to Eurocode [5] and Sétra [6] guidelines. The numerical results were compared and differences in dynamic responses of analyzed footbridges were examined. The obtained results delivered some important practical data regarding the dynamic behaviour of cable-stayed footbridges which could be used at a design stage to make a decision on the construction material solution.

2. Description of analyzed footbridges
Two construction solutions of medium span cable-stayed footbridges were analyzed. The first one was the existing Kolding Footbridge made entirely of GFRP composite material. The geometrical and material data of the all-GFRP footbridge were acquired from its available technical documentation. The second one was the newly-designed all-steel footbridge with similar geometrical features and new structural steel elements providing a similar bearing capacity as in the case of the all-GFRP footbridge.

2.1. All-GFRP composite footbridge
The Kolding Footbridge is located in Kolding city, Denmark, providing pedestrian and cycle traffic, and crossing the main railway line leading to the Kolding city center. The whole bridge construction, including bridge deck, pylon and cables, is made of GFRP composite using 12 different pultruded profiles. The 40.30 m long and 3.21 m width footbridge comprises two continuous spans with lengths of 26.35 and 12.40 m, supported by a single A-shaped 17.61 m tall pylon. Four pairs of cables with a
length of 17.85, 17.66, 13.58 and 13.36 m were secured to the top of the pylon. The outer dimensions of the pylon are varying from 5.22x1.29 m at the bottom to 1.39x0.49 m in the upper part.

The structural system of the deck comprises two I-shaped pultruded profiles with a height of 1.5 m, thickness of 12 mm and length of 3.1 m used as main girders. Only bolts for assembly and abutments at the foundations were made of steel. The upper belt of the girders was designed from C-profiles with dimensions of 200x60x10 mm and 75x75x8 mm, being the handrail of the balustrade. Additional protection against buckling was made of transverse and longitudinal ribs constructed from angle beams with dimensions of 100x100x10 mm and 75x75x8 mm, respectively with a distance of 1.55 m and 0.73 m. The platform deck was made of composite platform gratings with a thickness of 50 mm. The usable width of the platform is 3.02 m. The supporting structure of the deck comprises cross-bars with C-shaped profiles and dimensions of 240x72x12 mm, and side-bars with I-shaped profiles and dimensions of 200x100x10 mm. All cables have square cross-sections with dimensions of 100x100x8 mm. The pylon structure was made of C-profiles with dimensions of 300x150x12 mm, while the side bracing beams were constructed from angle beams with dimensions of 75x75x8 mm. The longitudinal and cross-sections of the all-GFRP Kolding Footbridge are shown in Fig. 1(a-b).

2.2. All-steel footbridge
The structural system of the steel deck was designed from typical I-shaped profiles, i.e. comprises two HEB 300 profiles as the main girders, IPE 240 profiles as the cross-bars with a distance of 1.55 m, and IPE 200 as the side-bars. The platform deck was made of sheet metal with a thickness of 12 mm and with an epoxy resin surface of 5 mm. The usable width of the platform is 3.15 m. The balustrade was constructed from tie rods with a diameter of 3.0 cm, as security elements, and from tie rods with a diameter of 6.0 cm, as handrail elements connected by vertical banisters with I-shaped profiles with a distance of 1.55 m. The Macalloy 520 cable system was used to suspend the steel footbridge structure. The pylon structure was made of C-profiles with dimensions of 300x150x12 mm, while the side bracing beams were constructed from angle beams with dimensions of 75x75x8 mm. The cross-section of the all-steel footbridge is depicted in Fig. 1(c).

Figure 1. (a) Longitudinal and (b) cross-sections of the all-GFRP Kolding Footbridge, and (c) cross-section of the all-steel footbridge.

Both analyzed structural solutions, i.e. the all-GFRP and all-steel structures fulfill the condition of the geometric similarity as well as a similar load capacity of the main structural elements. To assess the differences in the bending stress $\sigma$ and degree of carrying load capacity of structural elements, the static analysis were carried out including the steady and service loads acting on both footbridges. The analysis was executed using the Autodesk Robot Structural Analysis Professional software. The limit stress value for GFRP composite was assumed in accordance with Fiberline guidelines [9] as $f_{b,0,0} = 185 \text{ MPa}$, while the assumed elastic limit of steel was $f_y = 235 \text{ MPa}$ [10]. Fig. 2 presents the bending stress $\sigma$ and degree of carrying load capacity of main structural elements of the all-GFRP and all-steel footbridges identified numerically taking into account the steady and service loads according to the Eurocode [7] and Polish Standard [8]. Based on the results presented in this figure, it can be concluded that the values of the capacity utilization factor of structural elements of both footbridges are very close. Thus, the structural similarity of the all-GFRP and all-steel footbridge was confirmed.
In addition, the maximum static deflections $q$ of both footbridges due to the steady and service loads according to the Eurocode [7] were numerically predicted in the mid-span of the main span and compared with the limit deflection values $q_{dop}$ [9,10]. The results of calculations are presented in Table 1. It should be noticed that the maximum static deflection of the all-GFRP footbridge is about twice higher than comparably value of the all-steel footbridge.

### Table 1. Predicted the maximum static deflections $q$ of the all-GFRP and all-steel footbridges compared with the limit deflection values $q_{dop}$ according to [9,10].

| Construction solution of footbridge | Deflection due to the steady load (cm) | Deflection due to the service load [7] (cm) |
|------------------------------------|----------------------------------------|------------------------------------------|
| all-GFRP                           | 2.5                                    | $5.0 < q_{dop} = 8.8$ [9]                |
| all-steel                          | 1.4                                    | $2.7 < q_{dop} = 10.5$ [10]              |

3. **FE models and modal analysis**

In order to identify the dynamic characteristics, i.e. the natural frequencies and corresponding mode shapes of both considered footbridges, a 3D FE models were modeled using Autodesk Robot Structural Analysis Professional 2018 software. The FE model of the all-GFRP footbridge was created using the geometrical and material data of the existing Kolding Footbridge, acquired from the available technical documentation (see subsection 2.1). The FE model of the all-steel footbridge was made, including newly-designed structural steel elements describing in subsection 2.2. The Young’s modulus of the GFRP material was adopted based on the test carried out in 2012 as $E=23.4$ GPa [11], while for the steel was assumed as $E=210$ GPa. The density of the GFRP profiles was 18.0 kN/m$^3$ while for the steel was assumed as 78.5 kN/m$^3$. The moment of inertia of all profiles was estimated from the geometry of its cross-sections. In order to predict a more realistic structural behaviour of footbridges all structural elements and accessory parts were taken into account in modeling process. The concrete foundations, considerably much stiffer than other structural elements, were not modeled.

Two kinds of finite elements were used in FE models of the all-GFRP and all-steel footbridges, i.e. 4429 and 5525 one-dimensional frame elements, and 11010 and 11843 two-dimensional shell elements, respectively, while the total number of active degrees of freedom was 59884 and 65626, respectively. The final FE models of both footbridges are shown in Fig. 3.

Sets of primary five natural frequencies and corresponding mode shapes of both footbridge models in the vertical direction are given in Fig. 4 and are summarized in Table 2. Based on the predicted fundamental natural frequencies, it can be stated that the all-steel footbridge is slightly stiffer than the all-GFRP footbridge, despite relatively smaller cross-sections of structural elements. Moreover, the same mode shapes sequences are observed for both footbridges.
Figure 3. 3D FE models of (a) the all-GFRP and (b) all-steel footbridges.

Figure 4. Primary five natural frequencies and mode shapes in the vertical direction of (a) the all-GFRP and (b) all-steel footbridges.

Table 2. Comparison of five natural frequencies predicted for the all-GFRP and all-steel footbridge models using FE analysis.

| Mode No. | Mode type | Natural frequency (Hz) | Difference (%) |
|----------|-----------|------------------------|----------------|
|          | all-GFRP  | all-steel              |                |
| 1        | Bending   | 4.35                   | 4.72           | 8.5            |
| 2        | Torsion   | 6.58                   | 7.61           | 15.6           |
| 3        | Bending   | 10.98                  | 8.33           | 24.1           |
| 4        | Torsion   | 11.50                  | 9.45           | 17.8           |
| 5        | Torsion   | 15.66                  | 11.23          | 28.3           |

4. Numerical Footfall harmonic analysis
Since human footfalls are the main source of footbridge vibration and it could cause discomfort to the structure users when the vibration level exceeds the recommended level, the serviceability
performance of both considered footbridge was numerically predicted. Footbridge structures are subjected mainly to the loads of pedestrians walking or running on them. Thus, in the analysis two loading cases were considered, i.e. one walking or running person acting on the footbridge.

To estimate the maximum acceleration of vertical vibrations due to human excitations the Footfall harmonic analysis option available in Autodesk Robot Structural Analysis Professional 2018 software was used. The Footfall analysis is an appropriate tool to predict the dynamic response of a structure to footfall-induced loading. The pedestrian activities are modeled by an application of harmonic load model applied to selected structural nodes with the assumed frequency range [12].

The calculations of both considered footbridges were carried out on the assumption that the harmonic load was applied to all nodes of the footbridge deck. This approach enables to locate deck regions of highest acceleration response. According to recommendations given by Bachmann [13], the pedestrian walking was modeled at frequencies between 1.4 and 2.4 Hz, while the pedestrian running at frequencies between 1.9 and 3.3 Hz. The pedestrian mass assumed in the analysis was 90 kg. As the appropriate case study the SCI P354 analysis was chosen [12]. The damping ratio of the all-GFRP Kolding Footbridge was measured in situ as 2.87%, and this value was included in the Footfall analysis. The detailed description of the methodology and results of dynamic characteristic investigations of the existing Kolding Footbridge are presented in the paper [14]. For the all-steel footbridge the damping ratio was selected as 0.5% from data published in the literature for similar light-weight steel footbridges [14]. In the analysis, the natural mode shapes and corresponding frequencies of both footbridges up to 20 Hz were considered.

Fig. 5 shows the Footfall analysis results as the contour plots of acceleration levels on the deck of both analyzed footbridges for two considered load cases, i.e. one walking and running person. In this figure, the nodes with highest acceleration response were also marked. Fig. 6 presents the representative results of acceleration of the deck of both footbridges in the node with highest acceleration response depending on the frequency of the harmonic forces.

![Footfall analysis results](image)

**Figure 5.** Footfall vertical acceleration response contours predicted for (a-b) the all-GFRP and (c-d) all-steel footbridges excited by one walking or running person, respectively.

5. Evaluation of comfort criteria
The critical acceleration values obtained from the Footfall analysis were compared with the limits provided by Eurocode [5] and Sétra guidelines [6]. According to the guidelines presented in the
Eurocode standard, the maximum vertical accelerations of spans of newly-designed footbridges should not exceed of 0.7 m/s², however, a dynamic analysis is required if the natural frequency of structure in the vertical direction is below 5 Hz. Much more advanced recommendations are provided by the Sétra technical guide. In these recommendations four classes of comfort criteria were formulated for footbridges regarding the measured critical accelerations. The risk of resonance could appear within the frequency range of 1÷5 Hz. Evaluation of vibration comfort criteria for the all-GFRP and all-steel footbridges for the vertical vibrations induced by one walking and running person is shown in Fig. 7.

**Figure 6.** Footfall analysis results of acceleration of the deck of considered footbridges in the node with highest acceleration response depending on the frequency of the harmonic forces for: (a) one walking person (1.4 and 2.4 Hz), (b) one running person (1.9 and 3.3 Hz).

**Figure 7.** Evaluation of vertical comfort criteria of the all-GFRP and all-steel footbridges by Eurocode [5] and Sétra guidelines [6].

### 6. Conclusions

This comparative study analyzed numerically the comprehensive dynamic behaviour in the vertical direction of two medium span cable-stayed footbridges made entirely of steel and GFRP composite material. The first considered structure was the existing all-GFRP Kolding Footbridge, whereas the second one was newly-designed all-steel footbridge with similar geometrical features and new structural steel elements providing a similar bearing capacity as in the case of the all-GFRP footbridge. Considering the steady and service loads according to the Eurocode [7] and Polish Standard [8], it was proved that the degree of carrying load capacity of main structural elements of the all-GFRP and all-steel footbridges was very close (see Fig. 2b), e.g. for the main girders of both footbridges it was between 35 and 47%, while for the main pylon structure between 32 and 40%. The predicted maximum static deflections of the main span of both footbridges were not exceeded the limit deflection values. However, the maximum static deflection of the all-GFRP footbridge was about twice higher than the calculated value for the all-steel footbridge.

Based on the results of the FE modal analysis sets of primary five the natural frequencies and corresponding mode shapes of both footbridges in the vertical direction were compared (see Fig. 4 and Table 2). As a result of nine times higher Young’s modulus and four times higher density of structural steel elements, the predicted fundamental natural frequency of the all-steel footbridge was 8.5% higher than for the all-GFRP footbridge. Thereby, it can be concluded that the structural stiffness of the all-
Steel footbridge is slightly higher than in the case of the all-GFRP footbridge, despite relatively larger cross-sections of GFRP structural elements. Both footbridge models have similar mode shapes and the same mode shapes sequences were observed for both structures. The damping ratio of the all-GFRP footbridge identified experimentally as 2.87% is much higher than the value of 0.5% (based on the literature data) for similar all-steel footbridge. This advantageous dynamic property of the all-GFRP footbridge has a crucial influence on the reduction of vibrations caused by pedestrian excitation.

The fundamental frequencies of both footbridges in the vertical direction were found within the critical ranges given by Eurocode [5] and Sétra guidelines [6]. In this case further analysis with respect to the maximum acceleration threshold was required. Based on the Footfall analysis results it was found that the predicted maximum accelerations of vertical vibrations due to human excitations of both considered footbridges are different. The maximum dynamic response in the middle of main span of the all-steel footbridge induced by one walking pedestrian, at frequencies between 1.4 and 2.4 Hz, was about 3.9 times higher compared to the all-GFRP footbridge, and about 3.6 times higher induced by one running pedestrian at frequencies between 1.9 and 3.3 Hz (see Figs 5 and 6).

Comparing the maximum acceleration values obtained from the Footfall analysis for both footbridges to the limit values provided by Eurocode [5] and Sétra guidelines [6] it can be concluded that the all-GFRP footbridge satisfied the vibration serviceability requirements given by Eurocode, and the comfort level was classified as maximum according to Sétra guidelines under both considered load cases. However, the all-steel footbridge was not fulfilled the limit value suggested by Eurocode, and according to Sétra guidelines the comfort level was classified as medium and minimal under one walking and running person, respectively.

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