DYNAMICS ANALYSES OF COMPOSITE MATERIAL FOOTBRIDGE UNDER ACTION OF PEDESTRIAN WALKING

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Abstract. This work aims the optimization of a design of footbridges made of pultruded glass fiber reinforced polymer (GFRP) profiles, under the dynamic effect of pedestrian walking. First, a footbridge with a structural arch associated to trusses was designed, respecting the ultimate and serviceability states for static analysis. The accelerations found in the dynamic analysis, was considerate intolerable for human comfort according with the design guides. Therefore, it was necessary to design a synchronized passive dynamic attenuator (SDA) to mitigate the excessive vibrations. Besides this first one, others structural conceptions using truss beams and inverted queen post truss were analyzed aiming the most efficient structural behavior. A computation program considering a two-dimensional model was developed to integrate the equation of the movement taking into account the pedestrian crowd load. The dynamics properties used in the two-dimensional model were obtained from one three-dimensional model using a finite element method. Since the pultruded profiles are lightweight, it was considerate the interaction between pedestrians and the structure by increasing the mass and the damping ratio. It was noticed that without considering the pedestrian versus structure interaction the accelerations were found to be excessive high showing that for very light structures, this consideration is extremely important. Also, it was seen that modifying the structural design increasing the stiffness and mass resulted in comfortable structures without the necessity of use SDA.

Keywords: Composite Material, Vibration Control, Dynamic Analysis

1 Introduction

The applications of new materials like the composite materials in civil structures leads many times to slender structures which can be more flexible, resulting in structures with low frequencies of the vibration modes that when submitted to dynamic loads could cause resonance with excessive vibration resulting in discomfort of user or even the collapse.

Glass fiber-reinforced polymers (GFRP) members has a high longitudinal tensile strength, typically exceeds 200 – 400 MPa and is comparable with structural steel although, the longitudinal elasticity modulus is low, about 1/10. The frequency of human walking load is low and since these structures have high slenderness and when associate with the low longitudinal modulus of elasticity their have low stiffness resulting in a low natural frequency, which can lead to resonance and consequently excessive vibration problems for footbridges.

There are many advantages of the use of GFRP in structural members such as, low specific weight, which enable faster assembly and high resistance for degradation, making possible the execution in corrosive environment reducing the necessity of maintenance. These characteristics shows that this material has potential to be use in footbridge. However, there is no footbridge made of GFRP in Brazil.

The objective of this paper is to develop several structural designs footbridge of composite material, using three-dimensional models, to verify the static analysis regarding of excessive displacements and safety about rupture. In relation to the comfort human, the dynamic properties of the structure were extracted from the free vibration analysis using the three-dimensional model and then introduced into a program developed considering a two-dimensional model that integrates the equation of motion of structure submitting to crowd loading. As a result, accelerations are obtained, which are used for checking dynamic comfort.

2 Analysis methodology

The footbridges were analyzed according to Serviceability Limit State (SLS) and Ultimate Limit State (ULS). The loads combinations used as well as the displacements limits were taken from the EUROCOMP [1] guide. In order to perform the statics and free vibrations analyses on each footbridge were developed three-dimensional (3D) models using the commercial software SAP2000 vr.14 based on Finite Element Method.

For the dynamic analysis of the structure in time domain was developed on computational program considering a two dimensional (2D) model to simulate the behavior of the structure under human load. For the definition of loading and verification of the level of human comfort for excessive vibrations, the Sétra Footbridges [2] design guide was used. The footbridges studied in this work were classified as Class 1, meaning that they have a high pedestrian density in the order of 1 person/m². The Sétra Footbridges [2] guide defines the crowd loading for the first human walking harmonic as is explicit in Eq. 1. The Eq. 2, represents the loading for the second human walking harmonic.

$$F(t) = 280d\cos(2\pi f_v t)\,1.85\sqrt{\frac{1}{n}}\,\psi \qquad \left(\frac{\mathrm{N}}{\mathrm{m}^2}\right) \tag{1}$$

$$F(t) = 70d\cos(2\pi f_v t)\,1.85\sqrt{\frac{1}{n}}\,\psi \qquad \left(\frac{\mathrm{N}}{\mathrm{m}^2}\right) \tag{2}$$

where:

d - is the density of pedestrians on the footbridge, which in this case is equal to 1 pedestrian / m²;

f_v – is the fundamental frequency of walking, ranging from 1.6 to 2.4 Hz for the first harmonic of walking and twice this value for the second harmonic;

t – is the time in seconds;

n – is the number of existing pedestrians at the footbridges;

ψ – is the minus factor taking into account the probability of occurs resonance, according to Figure 1;

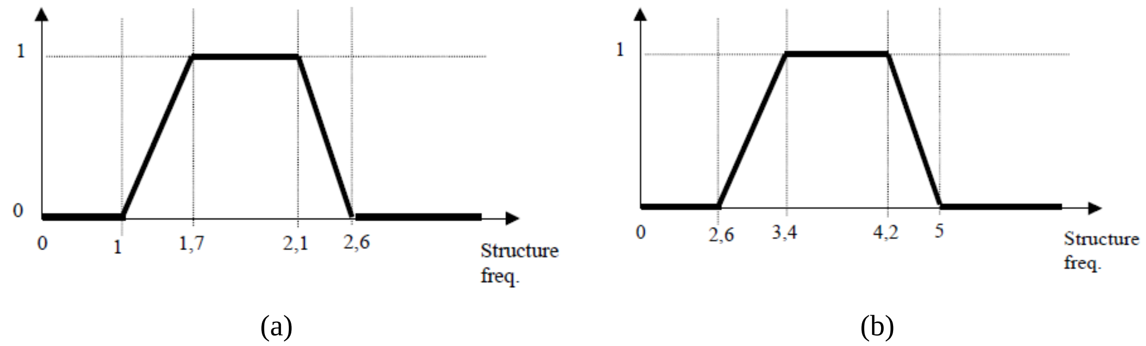

Figure 1. Parameter value of ψ for crowd loading for vertical modes: (a) first walking harmonic (b) second walking harmonic

Thus, the equilibrium equation of dynamics is defined in Eq. 3.

$$\ddot{y} = \frac{1}{m}[-ky - 2\xi\omega m\dot{y} + F(t)] \quad (3)$$

where, $\ddot{y}$ is the acceleration, m is the modal mass of the structure, k is the modal stiffness, y is the displacement, ξ is the damping ratio; $\dot{y}$ is the velocity; ω is the angular frequency and F(t) is the dynamic modal load.

Several studies have already shown that masses and damping generated by people significantly affect the dynamic properties of light structures. Pedersen [3] investigated the influence of the mass of people with the change in the vibration frequency and damping ratio of a slab. He conducted experimental tests comparing the influence of the mass of sandbag and the influence of the mass of people on those properties. He concluded that with both types of masses, the natural frequency of slab vibration decreased. Regarding the damping ratio, it was noted that sandbags did not affect this property, unlike the presence of people, which changed the damping rate from about 0.5% to 8%. Teixeira [4] and Costa [5] stated that highly populated structures may have damping rates in the range of 12%. Costa [6] reported that the codes from Canada, the United Kingdom, and Denmark, also uses this value for structures with high density of people.

Noting the importance of person-structure interaction, two dynamic analyzes were made to study the behavior of structures made of composite material. The first analysis was made using the uninhabited structure, with vibration frequencies obtained without consideration of pedestrian mass and using a damping rate of about 0.84%, a value found experimentally by other authors at Aberfeldy footbridge (Pimentel, apud Costa,[5]), an entire structure made of GFRP. The other analyses took into account the mass of pedestrians in obtaining vibration frequencies and it was considered 10% for damping ratio, according with Teixeira [4], Costa [5] and Pedersen [3].

To analyze the results, a computer program was implemented considering a two-dimensional structure model with the dynamic properties obtained in the free vibration analysis of the three-dimensional model. The integration of the equation of motion was done using the Runge-Kutta algorithm, thus obtaining the responses of the displacements, velocities and accelerations in time history.

3 The pilot design

3.1 The initial design

For the footbridge design, a span of 28 meters was chosen with height of 3 meters and a minimum width of 2.5 meters which was defined based on ISIT-219 DNIT manual [7]. The Figure 2 shows the geometry of the footbridge.

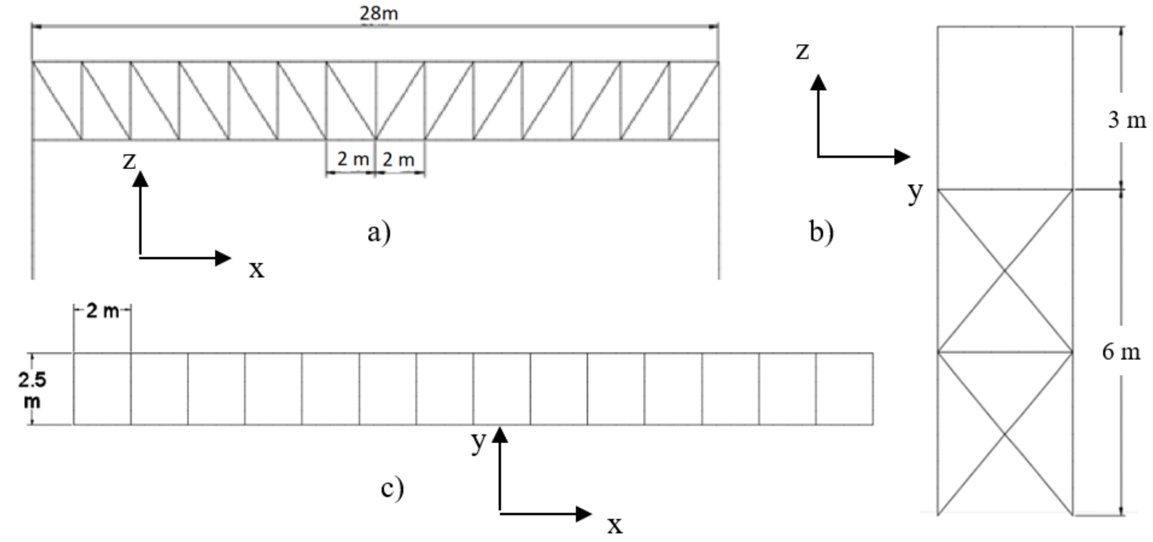

Figure 2. a) Side view of the footbridge; b) Front view of the footbridge; c) Top view of the footbridge

The slab used was the Plank MD from the Fiberline Composites company (Figure 3c). The railing (Figure 3b), also made of composite material, is from the Brazilian company ECO Engineering of Composites and for the footbridge cover a translucent tile from the Brazilian company Brasilit (Figure 3a) were chosen.

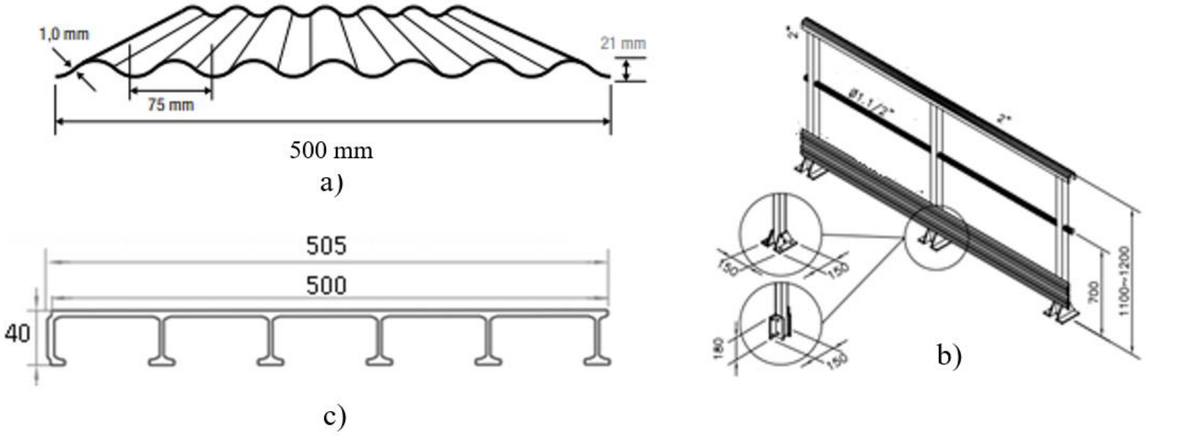

Figure 3. a) Tile from Brasilit; b) Railings made of composite material from ECO Engenharia; c) MD Plank from Fiberline Composite

According to DNIT ISF Manual [7] for footbridge, the minimum value for live load (LL) is 5 kN /m² so, this value was adopted in the design. The dead load (DL) was calculated based on the specific weight of the composite material of 18.5 kN/m³. The wind load (Wy) of 0.75 kN / m² was calculated based on NBR 6123 [8] and applied in the y direction (perpendicular to the side face). The Table 1 shows the load combinations for Service Limit State (SLS) and the Ultimate Limit State (ULS) in accordance with EUROCOMP [2]

Table 1. Loads combinations for SLS and ULS

	Service Limit State		Ultimate Limit State
1	1DL + 1LL	**1**	1.35DL + 1.5LL
2	1DL + 1Wy	**2**	1.35DL +1.5Wy
3	1DL + 0.9LL + 0.9Wy	**3**	1.35DL + 1.35LL + 1.35Wy

3.2 The 3D finite element model

The pultruded profiles used were modeled as frame elements. For the principal beams and columns, a square tubular section measuring 152x152x0.95 mm was chosen. For the secondary's elements a square tubular of 89x89x6.4 mm was used. On the other hand, the composite slab (Plank MD) was modeled as thin shell quadrilateral element with mesh size of 0.5 meters, once the convergence test performed showed that this discretization was enough to obtain a good result.

As the composite slab (Figure 3c) does not have a rectangular geometry, being composed of a plate associated with stiffeners, an equivalent shell model was created to represent the slab. A rectangular section was calculated in which its inertia was equal to the original plate, and a specific weight correction was made to maintain the original plate mass and weight.

Soil-structure interaction was not considered, with all nodes in foundations free to rotate and all the translations were restricted.

The mechanical properties used in the model were those found experimentally by Vieira et al. [9] and reported in Table 2.

Table 2. Mechanical properties of composite material found experimental by Vieira et al. [9].

Ex (GPa)	Ey (GPa)	Ez (GPa)	Gxy (GPa)	Gyz (GPa)	Gxz (GPa)	ν_{LT}	ν_{TL}
24.5	9.58	9.58	9.46	2.88	2.88	0.32	0.32

where: Ex is the longitudinal modulus of elasticity (parallel to the direction of the fibers); Ey and Ez are the transverse modulus of elasticity (transverse direction of the fibers); Gxy is the shear modulus xy; Gyz and Gzx are the shear modules in the yz and zx planes, respectively; ν_{LT} is the major Poisson's ratio and ν_{TL} is the minor Poisson's ratio.

GFRP pultruded material is highly anisotropic. Therefore, the influence of the material anisotropy was tested by comparing two models with only bar elements. In, one model an isotropic property was used while in the other model transversely isotropic properties (Ey = Ez) were used. This test showed no difference in the result, since the software uses the Timoshenko beam theory, in which only the longitudinal modulus of elasticity is considered in the constitutive matrix.

It was also analyzed the behavior of the structure assuming pin joints (trusses) and with rigid joints. The test showed that the trusses structure presented large displacements, which could be explained by the low stiffness of the structure while the structure with rigid joints, presented more satisfactory results. Thus, the generated model has rigidly rotational links between the bar elements and can be idealized with the use of angle profiles, for example.

The static analyze of the footbridge presented in Figure 2 showed that the structural elements satisfy the limits for ULS. Regarding the displacements, the third SLS load combination showed displacements greater than L/250, limit value required by EUROCOMP [1]. Thus, this initial footbridge did not respect the displacements limits. Since no higher dimension's square tubes profiles available in the company catalog, it was necessary to develop new design. In spite of this structural conception was not in accordance with all EUROCOMP [1] guide recommendations this one was considerate as the pilot design.

3.3 Footbridge associating arch and trusses

After verifying that the initially designed structure did not respect the static displacements imposed by design guide, a new design was proposed. Therefore, an arch was added to the structure of Figure 2, since the composite material has good tensile and compressive strength. The final proposed structure is shown in Figure 4, which was previously studied by Torres et al. [10].

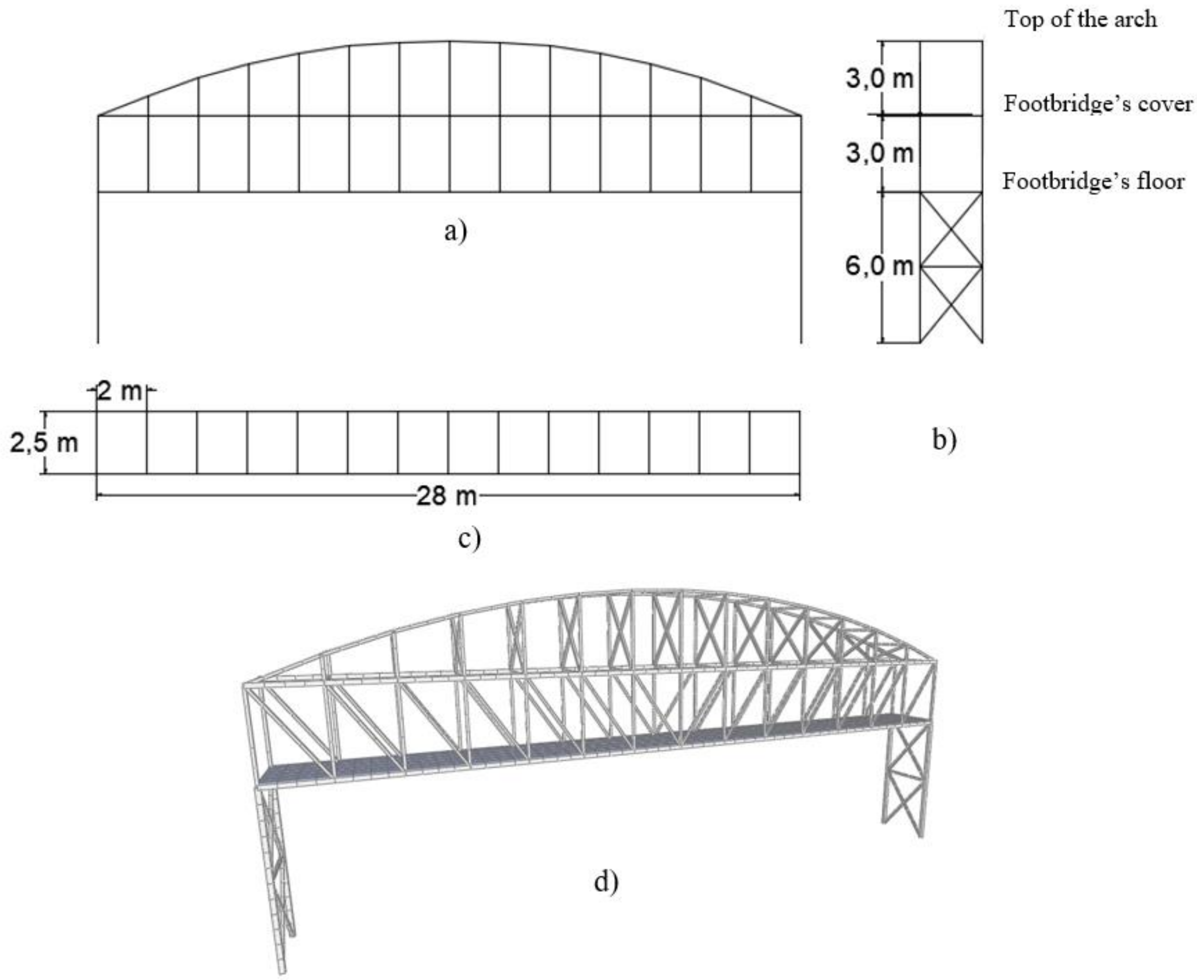

Figure 4. a) Side view of the footbridge; b) Front view of the footbridge; c) Superior View of the footbridge; d) 3D view of the footbridge

The profiles used to make the arch were the same square tubulars as used in the principal beams, with dimensions of 152x152x9.5 mm. After the static analyses were verified that both the ULS and SLS were satisfied.

4 Dynamic Analysis

4.1 Dynamic analysis of footbridge associating arch and trusses

The Table 3 shows the frequencies of vibration modes for the structure without person-structure interaction while in Table 4 are presents the frequencies of vibration modes considering it.

Table 3. Frequencies and shapes of the vibration modes without pedestrian mass attached (without considering Person-Structure Interaction - PSI)

	Frequency (Hz)	Mode
1º	1.63	1º Lateral
2º	2.69	2º Lateral
3º	3.20	1º Torsion
4º	3.83	3º Lateral
5º	4.15	1º Vertical

Table 4. Frequencies and shapes of the vibration modes with pedestrian mass attached (considering Person-Structure Interaction - PSI)

	Frequency (Hz)	Modo
1º	1.05	1º Lateral
2º	1.83	1º Vertical
3º	2.02	1º Torsion
4º	2.20	2º Lateral
5º	2.56	2º Vertical

It can be seen in Table 4 that the frequency of the first mode of vertical vibration is close of the frequency of the second harmonic of walking load while in Table 3 it is noted that the first mode of vertical vibration is in the range of first harmonic of the walking load. Therefore, it is necessary to do dynamic analyses for both these modes.

Using the damping ratio of 0.84% for model without PSI and 10% for the considering PSI, and using the Eq. 2 and 1, respectively, in the program for the integration of the equation of motion, the accelerations in time were obtained for the crowd load for both models (Figure 5(a) without PSI and Figure 5 (b) considering PSI).

When performing the dynamic analysis of the footbridge without PSI (Figure 5(a)), very high values for acceleration were found. The result, however, is unreliable as it is almost impossible for this light structure to receive this crowd loading without having interaction with pedestrians, considered here by addition of the masses of the persons and significant increase in damping.

Considering the mass of pedestrians added to the mass of the structure, and increasing its damping ratio, was obtained the results shown in Figure 5(b). Even though these results had a satisfactory order of magnitude, the maximum acceleration amplitudes of 2.6 m/s² shown to be intolerable values (> 2.5 m / s²) according to the Sétra Footbridges guide [2], requiring interventions to make the structure more comfortable for users.

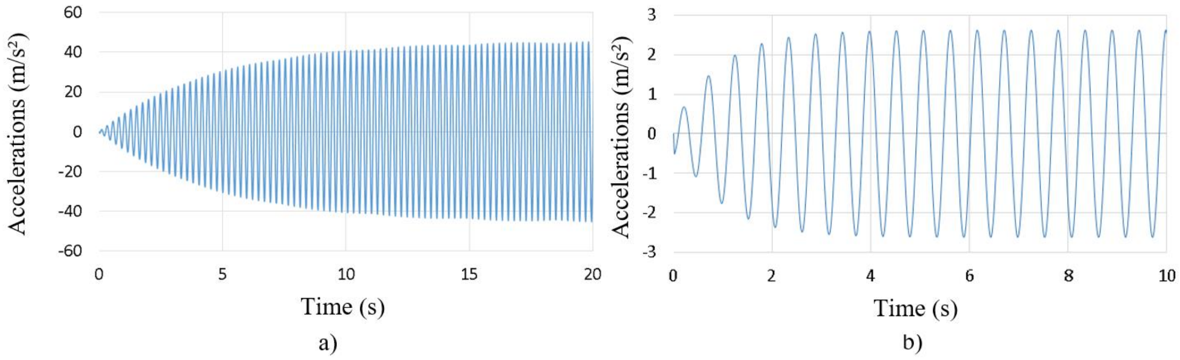

Figure 5. Response of accelerations in time history in the middle of footbridge; (a) without the interaction person-structure; (b) with the interaction person-structure

To mitigate the undesirable vibration, a synchronized dynamic passive attenuator (SDA) was designed. This vibration control device had a mass of 257 kg, natural frequency of 1.77 Hz and a damping ratio of 5%. Integrating the equations of motion with two degrees of freedom (one of the structure and the other of the attenuator) gives the acceleration signal in time history presented in Figure 6. The design of the SDA is reported in detail in Torres et al. [10]

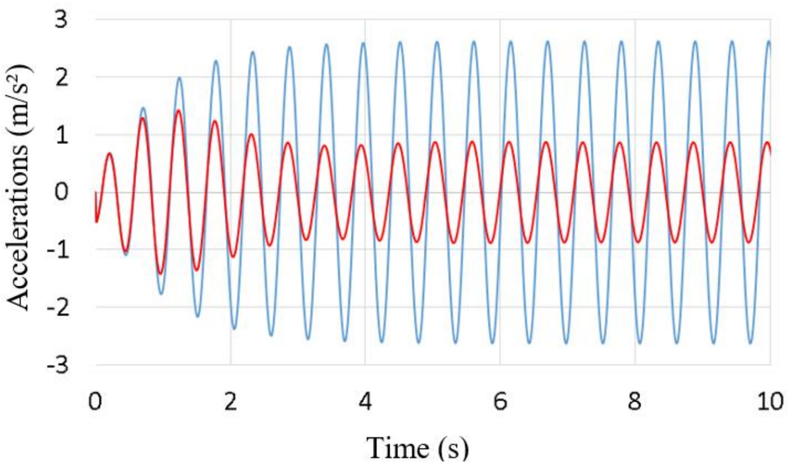

Figure 6. Comparison between responses of structure with SDA (red) and the original structure (blue)

It can be seen in Figure 6 that the attenuator was able to reduce the accelerations amplitudes from 2.6 m/s² to 0.76 m/s², which represents a reduction of 71%, showing the efficiency of this type of the device, removing the structure from intolerable comfort zone for medium comfort zone.

5 Others structures design without use of SDA

In order to avoid the use of a synchronized passive dynamic attenuator (SDA), it was decided to study other structural designs based on the structure of the Figure 2. The objective was to verify that if only by changing the design, the vibrations of footbridge would be considered comfortable to the users. For this purpose, three more structural conceptions were analyzed, checking the ULS and SLS. Regarding to the dynamic analysis, in all three conceptions were considerate the person-structure interaction.

5.1 Footbridge with trusses beams

For the first study, was added to the structure of Figure 2 two trussed beams with one meter high and placed at the bottom of the structure, as can be seen in Figure 7. The trusses were modeled with the same square tubes profiles from principal beams (152 x 152 x 9.5 mm) defined in section 3.1.

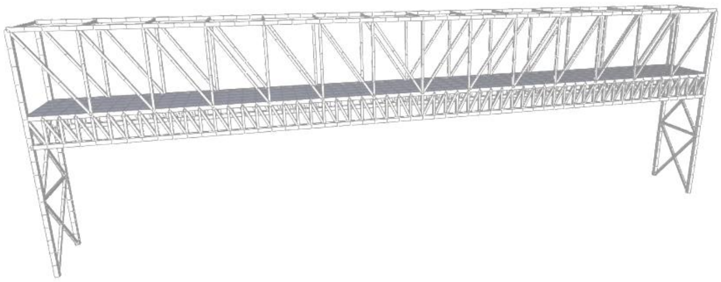

Figure 7. 3D View of the footbridge with beams made of trusses

From the static analysis, it was found that the footbridge satisfies the SLS and ULS states. The frequency and shape of vibrations modes obtained by the free vibration analysis are shown in Table 5.

Table 5. Frequencies and shapes of vibration modes for the footbridge with beams made of trusses

	Frequency (Hz)	Mode
1º	0.13	1º Longitudinal
2º	1.14	1º Lateral
3º	1.40	1º Vertical
4º	1.94	1º Torsion
5º	2.36	2º Lateral
6º	2.85	2º Vertical

It can be seen in Table 5 that it is necessary to study the acceleration responses in time history for the first vertical vibration mode. Using then a 10% damping ratio, it was obtained the response of time accelerations in the middle of the footbridge as shown in Figure 8.

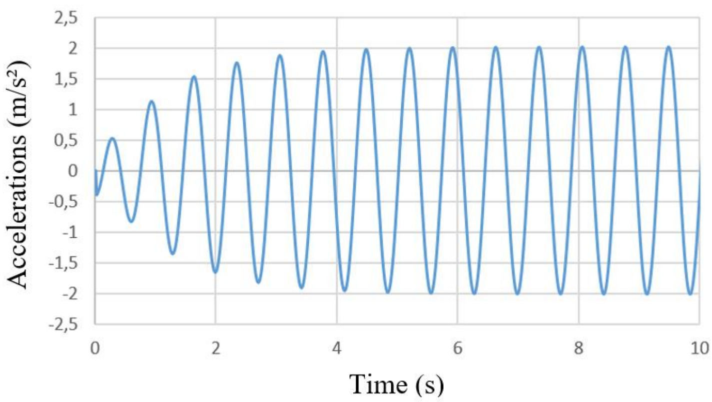

Figure 8. Response of accelerations in time history in the middle of the footbridge with beams made of trusses.

According to Sétra Footbridges [2] guide, vertical accelerations of 2 m/s² classify the structure with minimal comfort for vibrations, so other alternatives to reduce oscillations were sought. In order to decrease the frequency of the first vertical mode to from out the critical resonance range, (from 1.6 to 2.4 Hz), with the objective of to reduce the coefficient ψ of the crowd load simulation (Eq.1) the square tube profiles of the lower principal beams were filled with fluid cement grout weighing 20 kN/m3 meaning adding mass without changing the rigidity thus decreasing the natural frequency of vibration. A new free vibration analysis was made and the frequencies and shapes of vibration modes are shown in Table 6. Static analyzes were performed and the ULS and SLS limits were satisfied.

Table 6. Frequencies and vibration modes for the footbridge with beams made of trusses with mass added in the principal beams

	Frequency (Hz)	Mode
1º	0.11	1º Longitudinal
2º	1.00	1º Lateral
3º	1.25	1º Vertical
4º	1.63	1º Torsion
5º	2.08	2º Lateral
6º	2.74	2º Vertical

Another dynamic analysis was done for the first vertical flexural mode and the response of the acceleration in the middle of the footbridge, can be seen in Figure 9.

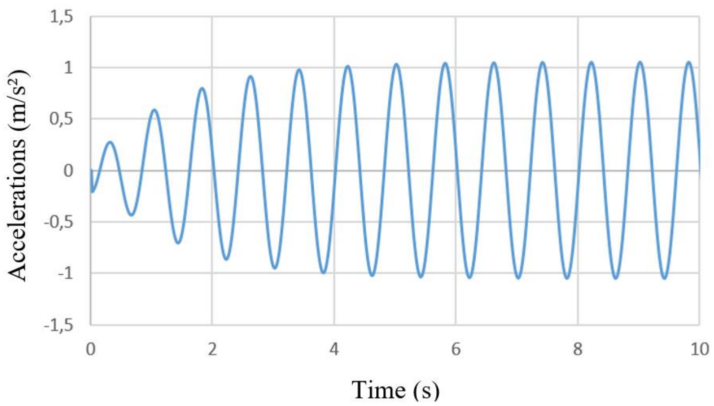

Figure 9. Response of accelerations in time history of the footbridge with beams made of trusses and principal beams filled with grout.

Since the accelerations still create discomfort for the users (Figure 9), more cement grout was added to the lower beams this time. However, after the e static analyzes it was found that it no longer respected the limit displacements defined in EUROCOMP [1]. Thus, another design is required.

5.2 Footbridge with two queen post trusses

The new conception for the structure was composed by two 1.75-meter-high queen post trusses placed at the bottom of the slab, using the square tubes with dimensions of 152x152x9.5 mm, as shown in Figure 10. The limits recommended by SLS and ULS were guaranteed after the static checks, the frequency and shapes of the vibration modes are presented in Table 7.

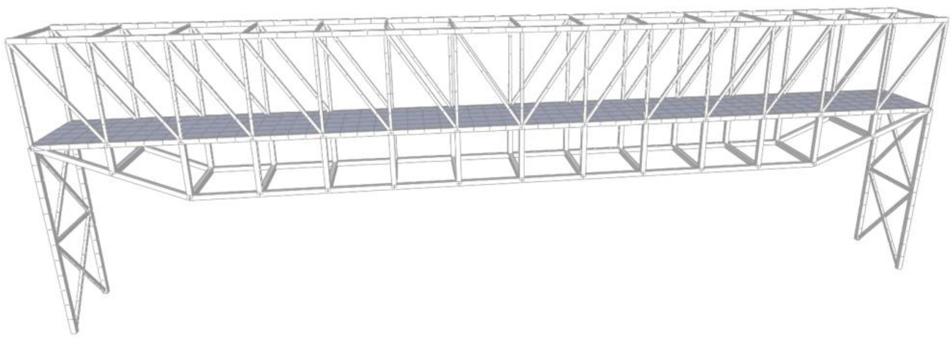

Figure 10. Model of the footbridge with two queen post trusses.

Table 7. Frequencies and shapes of vibration modes for the footbridge with two queen post trusses

	Frequency (Hz)	Mode
1º	0.10	1º Longitudinal
2º	1.15	1º Lateral
3º	1.52	1º Vertical
4º	2.09	1º Torsion
5º	2.35	2º Lateral
6º	2.96	2º Vertical

It can be seen in Table 7 that it is necessary to analyze the acceleration responses for the first vertical vibration mode. Figure 11 shows the response in time domain accelerations using a 10% damping ratio.

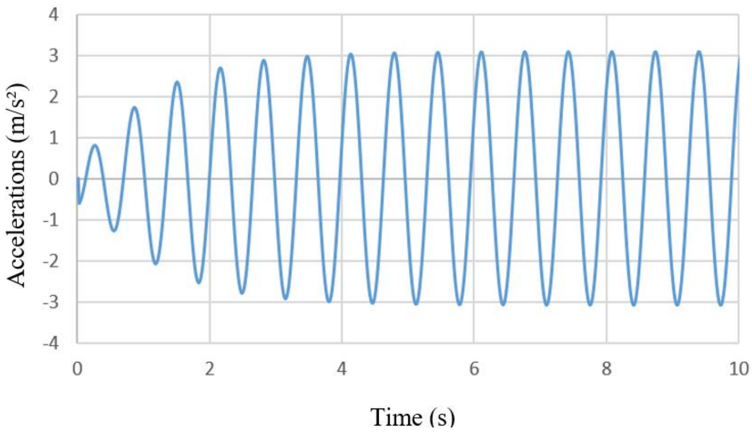

Figure 11. Response of accelerations in time history of the footbridge with two lower queen post trusses

As the accelerations are intolerable according to Sétra Footbridges [2] guide (greater than 2.5 m/s², see Figure 11), the previous solution using cement grout inside the square tubes of the inferior principal beams was also used. The structure continued to shows satisfactory according to SLS and ULS and the vibration frequency of the first vertical mode either decreased, as shown in table 8.

Table 8. Frequencies and shapes vibration modes for the footbridge with two queen post trusses with two principal beams filled with cement grout

	Frequency (Hz)	Mode
1º	0.09	1º Longitudinal
2º	1.00	1º Lateral
3º	1.31	1º Vertical
4º	1.67	1º Torsion
5º	2.07	2º Lateral
6º	2.48	2º Vertical

Then, checking the first vertical vibration mode for dynamic crowd loading, considering a 10% damping ratio, accelerations responses in time domain are presented in Figure 12.

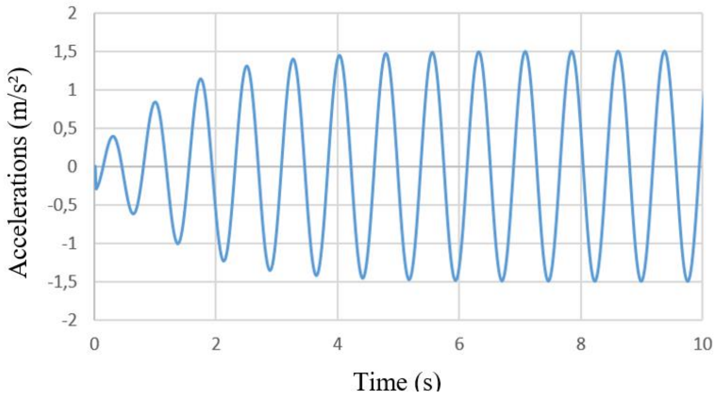

Figure 12. Response of accelerations in time history of the footbridge with two lower queen post trusses and two principal beams filled with cement grout

It can be seen in the Figure12 that the accelerations found are between 1 m/s² and 2.5 m/s². The Sétra Footbridges [2] guide sets this comfort level as minimum. In order to decrease the accelerations level, it was tried add cement grout to reduce natural frequencies but the maximum displacements prescribed by EUROCOMP [1] were not respected. Then, another design is required.

5.3 Footbridge with two lower and two upper queen post trusses

The last design studied has two bottom and two top queen post trusses, with one meter high and the profiles used was the square tubes of 152x152x9.5 mm. The model of the structure can be seen in Figure 13.

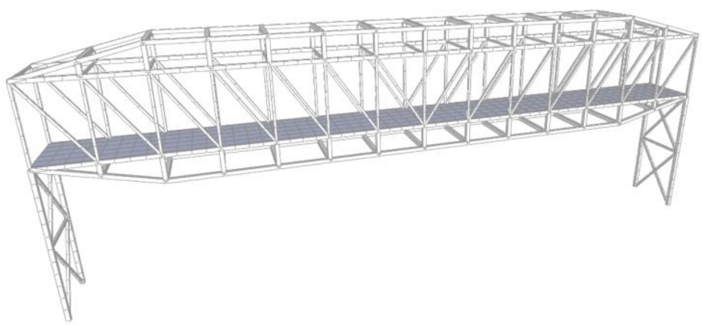

Figure 13. Tridimensional model of the footbridge with two bottom queen post trusses and two top queen post trusses.

As in the other cases, when checking SLS and ULS, all criteria were satisfied. Table 9 presents the shape and natural frequencies of vibrations modes

Table 9. Frequencies and vibration modes for the footbridge with four queen post trusses

	Frequency (Hz)	Mode
1º	0.10	1º Longitudinal
2º	1.13	1º Lateral
3º	1.69	1º Vertical
4º	2.07	1º Torsion
5º	2.34	2º Lateral
6º	3.19	2º Vertical

As can be seen in Table 9, the first vertical vibration mode should be analyzed because there is a high probability of resonance with the frequency of human walking. The responses of accelerations in time history was obtained and are presented in Figure 14.

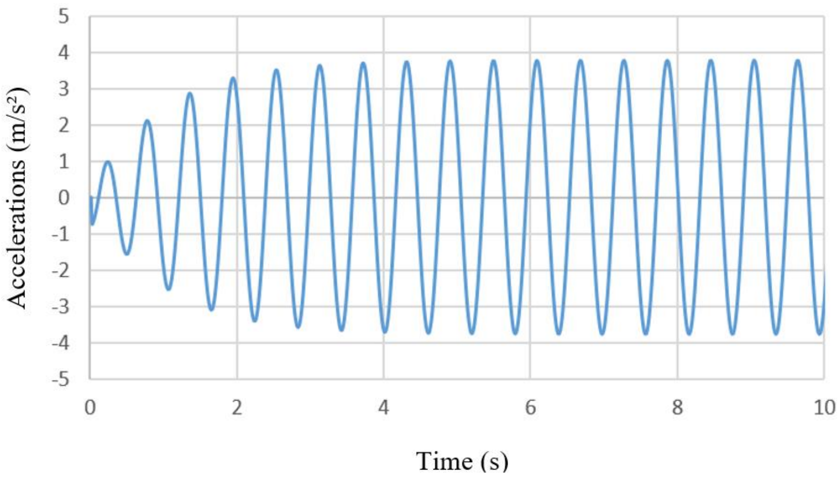

Figure 14. Response of accelerations in time history of the footbridge with four queen post trusses

Due to the intolerable accelerations (above 2.5 m/s², Figure 14), cement grout was introduced in the inferior beams to reduce vibration frequencies as well as the accelerations. The SLS and ULS were verified and satisfied. The shape of the vibration modes and their frequencies obtained from the free vibration analysis can be seen in Table 10.

Table 10. Frequencies and shapes of vibration modes for the footbridge with four queen post trusses and two principal beams filled with cement grout

	Frequency (Hz)	Mode
1º	0.09	1º Longitudinal
2º	1.00	1º Lateral
3º	1.51	1º Vertical
4º	1.85	1º Torsion
5º	2.09	2º Lateral
6º	2.99	2º Vertical

Figure 15 shows the time acceleration responses obtained from the dynamic analysis for the first vertical vibration mode considering damping ratio of 10%

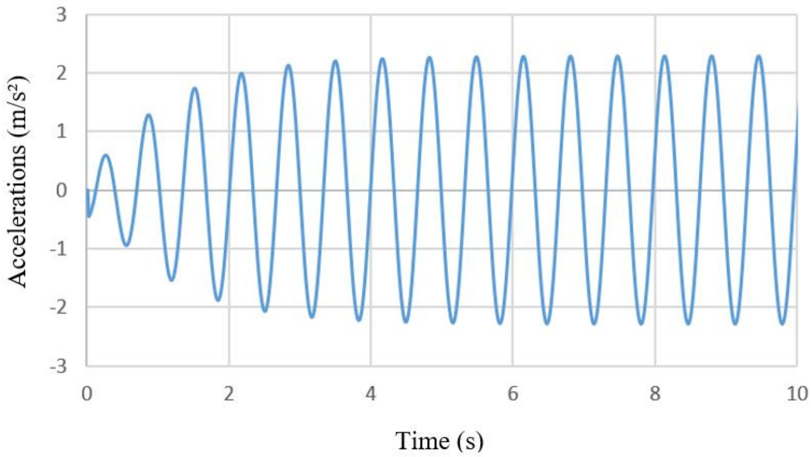

Figure 15. Response of accelerations in time history of the footbridge with four queen post trusses and two principal beams filled with cement grout

The accelerations shown in Figure 15 offer the minimal comfort according to the Sétra Footbridges [2] guide which limits values between 1 m/s² to 2.5 m/s². In other to scape of the resonance zone it was necessary to increase the mass of the structure to reduce the frequencies of vibration modes and, consequently, the accelerations. Since this structure is the most rigid of all the conceptions analyzed in this work, the displacements were satisfied even with all the principal beams and all the queen post trusses filled with cement grout, in totaling 8 filled profiles. Thus, was performed the free vibration analysis and the results are present in Table 11.

Table 11. Frequencies and vibration modes for the footbridge with four queen post trusses and all principal beams and all queen post trusses filled with grout

	Frequency (Hz)	Mode
1º	0.06	1º Longitudinal
2º	0.43	1º Lateral
3º	0.70	2º Lateral
4º	0.95	1º Torsion
5º	1.05	3º Flexão Lateral
6º	1.08	1º Flexão Vertical

The Figure 16 shows the responses of the accelerations for the first vertical vibration mode considering a 10% damping ratio. It can be seen in Figure 16 that introducing the cement grout mass into the composite material profiles it was possible to reduce the accelerations from an intolerable level to a maximum comfort level, respecting the limit state of vibration comfort, as well as the limits of SLS and ULS for the static analyze.

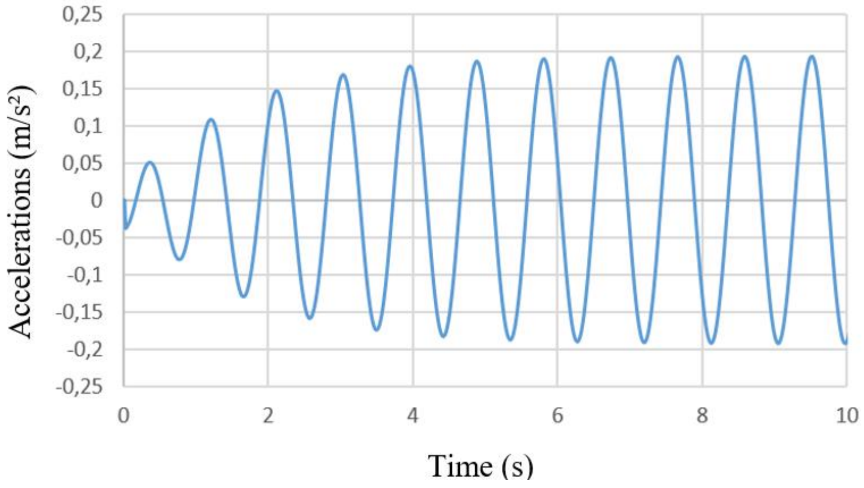

Figure 16. Response of accelerations in time history of the footbridge with four queen post trusses and all principal beams and all queen post trusses filled with cement grout.

5.4 Summary of the results and discussions

The principal results of the structures analyzed are presented in Table 12. It can be seen that all the structures respected the normative limits regarding to static displacements (SLS) and security (ULS). As for dynamic comfort, footbridge 1 achieved a medium comfort level when using a synchronized dynamic passive attenuator. The footbridges 2 and 3 presented a minimum level of comfort, while the footbridge 4 reached the maximum comfort level.

Table 12. Comparison between results of different structural conceptions

Footbridge	**Structure mass (tons)**	**Maximum vertical accelerations (m/s²)**	**Have the standards been satisfied?**
1-Arch and Trusses with attenuator	5.20	0.8	yes
2 -Beams made of trusses	5.18	1.0	yes
3 - Two queen post trusses	5.02	1.5	yes
4 - Four queen post trusses	5.98	0.2	yes

Comparing the structures with lower accelerations, footbridges 1 and 4, it can be observed that although the structure with bottom and top queen post trusses (footbridge 4) has about 15% more mass, its assembly is simpler than footbridge 1 (with arch), due the reducing connections and construction costs and further its guarantee the maximum of dynamic comfort.

5.5 Analysis of the influence of the dynamic fraction of people's mass on the model considering a person-structure interaction

Since pedestrians are in motion, their totally mass may not affect the dynamic properties of the structure, but a fraction of that value certainly may influence. To try to consider this fact, the pedestrian mass (70 kg) was reduced about 75% (52.5 kg), thus representing the modal mass of the persons. This value replaced the mass distributed per square meter in the three-dimensional model of the footbridge with two top and two bottom queen post trusses. The vibration modes and their respective frequencies can be seen in Table 13. Considering 10% of damping ratio, the accelerations of the first vertical vibration mode are presented in Figure 17.

Table 13. Frequencies and shapes of vibration modes for the footbridge with four queen post trusses, considering the modal mass of pedestrians

	Frequency (Hz)	Mode
1º	0.11	1º Longitudinal
2º	1.24	1º Lateral
3º	1.89	1º Vertical
4º	2.14	1º Torsion
5º	2.52	2º Lateral
6º	3.57	2º Vertical

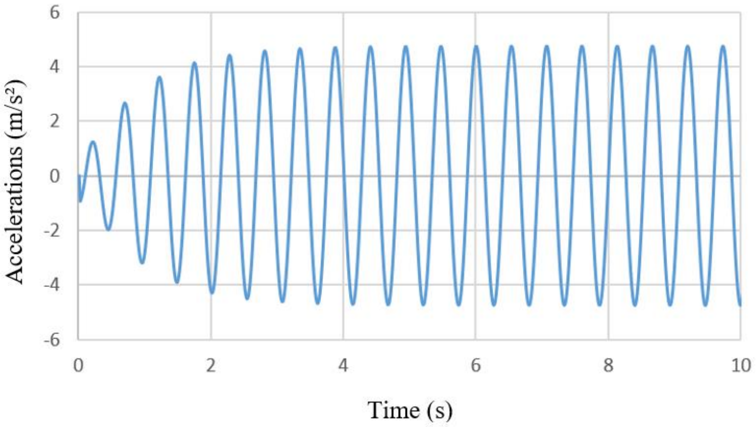

Figure 17. Response of accelerations in time history of the footbridge with four queen post trusses considering the modal mass of pedestrians.

In the free vibration analysis of the structure with all the queen post trusses and all principal beams filled with cement grout, the shape and frequencies modes are shown in Table 14 and the acceleration in time history for the first vertical vibration mode can be seen in Figure 18.

Table 14. Frequencies and shapes of vibration modes for the footbridge with four queen post trusses, considering the modal mass of pedestrians and all principal beams and queen post trusses filled with cement grout

	Frequency (Hz)	Mode
1º	0.06	1º Longitudinal
2º	0.43	1º Lateral
3º	0.70	2º Lateral
4º	0.99	1º Torsion
5º	1.05	3º Lateral
6º	1.12	1º Vertical

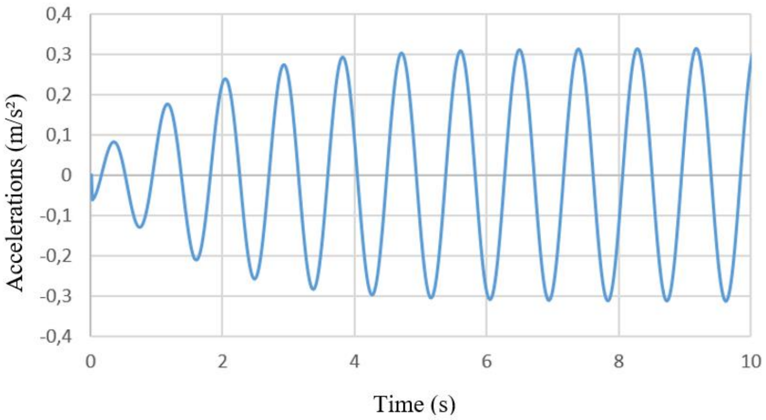

Figure 18. Response of accelerations in time history of the footbridge with four queen post trusses, considering the modal mass of pedestrians and all principal beams and queen post trusses filled with grout.

It can be concluded that considering the modal mass of the pedestrians, the vibration frequencies of the first vertical mode increased by 11% in the case of the footbridge without the profiles filled with cement grout. In the case of the footbridge with all the principal beams and queen post trusses filled with cement grout, the frequencies increased only 4%. As the structure without the use of cement grout is lighter, the variation off the pedestrian mass significantly affects the dynamic properties of the footbridge, a fact that has been evidenced in several studies, showing that it is important to consider the person-structure interaction.

Even with the increase of natural frequencies, satisfactory acceleration results were found (see Figure 18), reaching the maximum comfort zone, according to the Sétra Footbridges [2] guide.

6 Conclusion

The objective of this work was to optimize the conception structural of a footbridge consisting of pultruded composite material profiles, considering dynamic analysis. Initially, a trusses structural design was proposed. Since the analyze of three-dimensional model of the structure presented large displacements due to the low modulus of elasticity, a new conception structural was developed associating arches with trusses. Recommendations regarding static displacements in the Limit State of Service and the security in the Ultimate Limit State were analyzed, noting that it was respected, thus ensuring a structure according the normative criteria.

In relation to the dynamic analysis, the first goal was to understand how a light structure, such as those composed of composite material, behave considering the person-structure interaction. According to some authors, highly populated buildings suffer changes in their dynamic properties such as frequencies of the vibration modes and damping ratio. Thus, was simulated an uninhabited and inhabited structure prompted by a dynamic loading of a walking crowd. For the inhabited structure, the mass of pedestrians was added to the mass of the structure and the increase of its damping rate from 0.84% to 10%. As a result of these tests, it was realized that the not considering interaction with people, unfeasible acceleration results were found, showing that in the case of extremely light structures, this type of analysis should be taken into account.

By analyzing the inhabited structure of the footbridge 1 (Table 12) through a two-dimensional model developed to integrate the equation of motion by the Runge-Kutta algorithm, it was obtained responses of the accelerations in time, whose values were intolerable according to the design guide. Thus, to make the structure comfortable for use, a synchronized dynamic passive attenuator (SDA) has been designed, resulting a performance of about 70% reduction in acceleration, making the footbridge comfortable to use.

In order to avoid the design of the SDA, it was analyzed other structural conceptions. Thus, others three footbridges (footbridges 2, 3 e 4 - Table 12) were designed. All the footbridges satisfied the service limit states and the ultimate limit state considering static analysis. As for the dynamic analysis, considering the person-structure interaction, it was seen that all structures would generate some kind of discomfort. As the vibration modes frequencies of the structure were below the resonance zone, it was sought to add mass to further reduce its values and consequently decrease the probability that the load frequency would excite the first vertical vibration mode. Thus, the square tubular profiles were filled with cement grout to provide the desired mass increase. By adding cement grout within the bottom beam profiles, there were significant reductions in the accelerations suffered by the structure, from 2 m/s² to 1 m/s² to footbridge 2 , from 3 m/s² to 1.5 m/s² for footbridge 3 and from 3.8 m/s² to 2.2 m/s² for footbridge 4. Even with decreasing vibrations, the acceleration values for the footbridge 4 presented minimum comfort according to the Sètra guide, thus, it was necessary to inject more grout in other profiles. By significantly increasing its mass without changing its rigidity, the accelerations went from 3.8 m/s² to 0.2 m/s², reaching a maximum level of comfort

By conducting these analyses, it was realized that by seeking new structural conceptions, in addition to altering the mass of the structure, it is possible to design a structure with maximum comfort levels regarding the vibrations caused by the walking of a crowd. The conception of footbridge with four queen post trusses was the most efficiency, although its mass is 15% larger than that of the footbridge 1, the accelerations presented very low values, resulting in much greater comfort for vibrations induced by crowd. Besides that the footbridge 1 presents more connections which can not only make the design more expensive, but also significantly increase the weight of the structure if the connections are made with bolts and steel plates.

For the footbridge 4, the influence of the persons modal mass was verified, adopting this time a distributed mass of about 75% of the person's mass. The result showed that the influence of the presence of people is greater when there is no filling of the profiles with cement grout, since the mass of the structure is smaller and the mass of pedestrians becomes more significant. Thus, it is once again evidenced the importance of the consideration of person-structure interaction in case of light structures.

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