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Critical Phenomena for Footbridges, Covering Historic Sites

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Abstract

Historic and archaeological sites are often subjected to harmful environmental as well as human factors. Covering these sites with protective structures or shelters does not always render the desired result, since the authentic character of the site may be impaired. By building walkable covers above the area, social interest in historic remains can be promoted, as visitors can observe them from above without intruding activity or influence the ambient conditions. In addition, these walkways can be equipped with lateral cables to shift foils above the site, whenever visits are prevented by the weather. The aim of the study is to determine which are the detrimental loads and effects on such light structures. Firts three typologies of adapted footbridges are introduced. For each type, requirements of strength, stability, human induced vibration and effects of wind, including vortex are being verified. From these developments clearly results that vortex shedding is the most critical condition, albeit simple adequate systems can be installed for mitigating this detrimental effect. Hence, future improvements should emphasize on improving torsion stiffness or, as an alternative, including multiple connections, such as in cable structures.

1. Introduction

The recent corona pandemic and confinement of human interaction has clearly revealed that cultural activity is an important societal need. Care for historic remains and past civilisations determine cultural identity and should be remembered or allowed to be discovered. On one hand, historic sites should be accessible to the broad public, allowing to display the cultural heritage and thus improving social interest. On the other hand, important remains should be protected from human influence as well as from environmental impact [1]. For this, light covers of various types have been developed. A discussion was raised whether these covers may not be harmful in certain ways, for instance the existence of unwanted shadows, insufficient ventilation or increase of humidity. In addition, the cover may result in harming the authentic character of the site. Preservation and authenticity have gained importance as ICOMOS [2] has set up guidelines and is promoting a shift towards a sustainable long-term approach. However, the focus still is on protection and does not consider any possibility for the public to walk above historic sites. The latter would provide both : allow the public to see remains albeit from a bird's eye position and protect the site from environmental and human impact.

The idea of creating elevated walkways for visitors certainly is not original and has been applied in the Acropolis museum, at a Roman villa in Sicily and recently at the Kipdorp site above 16th century fortifications of the city walls [3].

Hence, this research concentrates on the development of walkable covers and tries to develop this type of structures for typical situations. Obviously, each situation may require an individual approach. Nevertheless, proposals for exemplary conditions may inspire particular projects and perhaps result in an alternative way of historic site tourism. The ultimate aim shall be to establish which loads or effects are more detrimental than others. This may result in improvement of the proposed designs.

2. Loads and requirements

Obviously, a walkable cover necessarily means people will be guided along a well-defined path. Thus, the cover does not encompass the whole area of the site and needs to be a footbridge. Should the whole area be covered, visitors will be unable to see anything of the remains. There should be no contradiction with the requirement to be able to shelter the whole area, since the footbridge may be equipped with cables running from its edges to the perimeter of the site enabling to draw foils between both limits. Hence, the cover becomes essentially a footbridge.

According to the relevant code [4], large footbridges should be designed for a vertical load of 2.5 kN/m² and possibly a service vehicle of 80 kN. As the number of visitors should be limited, a vertical load of 1.5 kN/m², which applies to rural walkways, has been considered and the service vehicle has been reduced to 3 kN. Wherever people can assemble, like at a central viewpoint, the design load has been increased to 2.5 kN/m², which corresponds to half of a normal crowd load. People in charge of exploiting the site should carefully oversee the limitation to these conditions, which are a very realistic assumption. In addition to this, wind load has to be considered as well as vibrations and comfort conditions for the public.

The horizontal clearance of the footbridge should be at least 2 m, allowing easy passage for visitors, the slope being limited to 1/12 for access by wheelchair users. In addition, larger spaces should be present at preferred locations. Another important requirement is to consider a horizontal load of 1 kN/m, caused by people leaning on railings, which often occurs on panoramic viewpoints. This load also produces a torque of 1.1 kNm, since the railing should be 1.1 m high. Obviously, the design will have to comply to comfort and stability requirements due to vibration and rain-wind effect [5]. This is being assessed in par 4.

3. Reference cases

A large survey among existing archaeological and historic sites was conducted This enabled to distinguish between smaller sites of about 50*50 m, as is the Birdoswald Roman fort and farmhouse with parts of the Hadrian wall (UK), shown in fig.1 and larger sites of 200*200 m, as the Palace of Galerius near Gamzigrad (Serbia).). Some of these are more circular, as the Bogazkale Hittite settlement (Turkey), whereas others are approximately square. Most sites are at ground level, others having a higher object, like a tower or elevated part of the remains. In most cases intermediate supports would certainly be disturbing.

Figure 1. Birdoswald *Roman fort with parts of Hadrian wall*

These data have been summarized in Table 1 of the reference cases under consideration.

Table 1. Reference *cases*

Nr	Form	Dimension	Level	Supports
1	Circular	Diam 200 m	Remains at ground level	No
2	square	200*200m	Ground level + 1 higher	No
3	square	50*50m	10 m above ground level	Allowed

Obviously, some sites may be underground or be larger than the dimensions of Table 1, or be located below the ground surface. However, the research had to be limited. Aesthetics will be an important requirement, albeit the structure should not be a monument or eye-catcher itself, since the people's attention should keep concentrated on the remains. Visitors should be able to interpret the site and understand what it stands for. The design has therefore been kept simple and straightforward. Most elements of the footbridges are circular tubes. This is inspired by the fact that tubes provide a dynamic aspect to longer structures and produce soft shade.

4.Design proposals

4.1 Straight passage

This concept would apply to a rather large circular site of 200 m diameter and the site not having any elevated parts. To cover the whole area, a straight arch footbridge is proposed, containing a central wider part for agreeable oversight and panoramic view. Both entrances are also wider and invite visitors to start their tour. The model can be seen in Fig. 2.

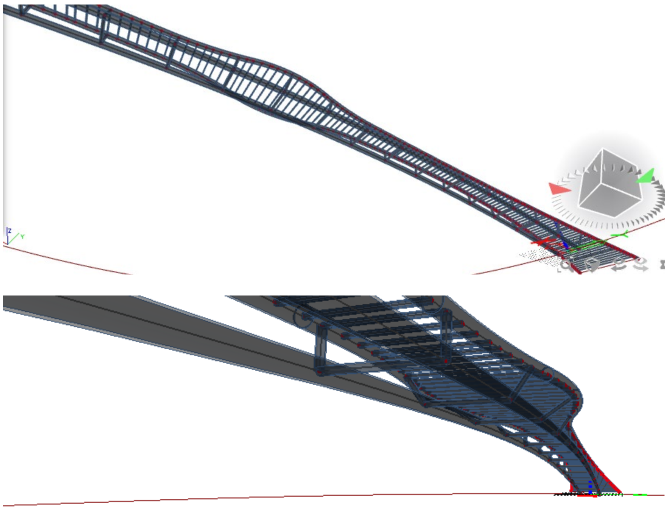


Figure 2. Straight *passage – various views*

The cross-section consists of 2 lateral tubes (1100*80mm) and 2 lower tubes (1300*80mm). The upper tubes show a tendency to buckling, the lowest modes corresponding to a single and 2-wave lateral pattern. The steel grade was increased to S 460 for tackling this problem. The final design shows a unity check of 0.97 and satisfies all requirements.

Concerning the effect of people walking on the footbridge, some natural frequencies are within the critical domain of 1.25 to 2.3 Hz for vertical vibration and 0.50 to 1.20 Hz for lateral movement. Hence, the accelerations have been determined according to [6]. These values should not exceed 0.5 m/s² for vertical – and 0.1 m/s² for horizontal vibration

Table 2. Vibration frequencies *straight passages*

Nr	Frequency	Mode type
	0.29 Hz	Lateral
2	0.63 Hz	Lateral
3	0.87 Hz	Vertical
4	1.08 Hz	Vertical
5	1.24 Hz	Longitudinal
6	1.30 Hz	Longitudinal

These requirements certainly are satisfied, since vertical accelerations are limited to 0.0035 m/s² and horizontal ones to 0.0069 m/s². Dynamic effects due to wind are equally excluded, since the critical wind velocity is out of the range of wind, as the Strouhal number equals 0.174. Rain-wind induced vibrations are sheltered, since the Scruton number equals 94, which exceeds the critical lower boundary of 20. The Scruton number is expressed as in eqn.(1).

$$S_c = 2\,\frac{2\,\delta_s\,m_m}{\rho\,b^2} \tag{1}$$

In eqn (1) δ_s equals the logarithmic damping decrement, m_e the effective mass, ρ the air density and b the characteristic width of the structure, in this case the span of the flat arch.

This design is light and allows a complete glass floor for maximum transparency. The arch springs are at ground level, just outside the site and allow limiting the slope of the entrance. It might be considered to include an elevator for wheel chair users in the abutments. The straight passage is a simple structure and does not conflict with more important objects as historic remains.

4.2 Tripod

This typology would be adequate to cover a rectangular area that may include a higher object, for instance a tower or series of remaining columns. Two legs of the tripod would surround the freestanding higher object. The structure is more complicated and covers a larger area. The general layout is similar to the straight passage, since wider entrance is provided at each leg and a central viewpoint is located at the highest area. The 3 legs together constitute an arch, although the transfer of the arch compression force is disturbed due to the angular rotation of the arch branches. Fig. 3 shows views from above and from below of the tripod alternative. The top view, also shows the subjacent site area and the location of the higher object.

Initially, the objective was to have a circular hole at the centre of the tripod. However, due to the deviation of the thrust force, the ring had to be reinforced heavily and the horizontally curved tubes would be exposed to heavy bending as well as buckling. As a consequence, the central area has to be closed completely with hollow core steel plate. The latter also enables to redistribute compression force from the inside tubular members towards the opposite direction. The lowest stability modes relate to buckling of this connection plate.

The dimensions of the tubes are similar to those of the straight passage and the unity check renders a maximum value of 0.97. As can be expected, the fundamental frequency is higher than for the previous typology and reaches 0.64 Hz for rotational vibration. The acceleration of the structure equals 0.00082 m/s² and is acceptable. All frequencies and the corresponding mode type are shown in table 3. Fig. 4 shows the fundamental modes.

Table 3. Frequencies *Tripod*

Nr	Frequency	Mode type
1	2.60 Hz	General torsion
2	3.11 Hz	Lateral legs
3	3.45 Hz	Vertical torsion

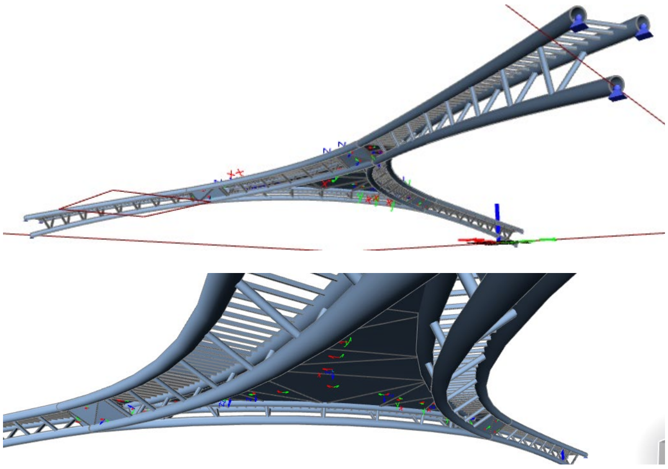


Figure 3. Tripod – various views

However, the wind loads can have a negative effect on this structure, since the critical wind speed equals 19 m/s² and the Scruton number equals 16.12 Hz. This means that vortex and rain-wind induced vibration is not excluded. Since this vibration is essentially torsional, it may effectively be eliminated by the simple solution of sealed TLCD (sealed tuned liquid column dampers) [7]. The latter is a simple device, which can be fabricated by any constructor and is less costly than tuned mass dampers. It is explained more in detail in par. 6.

This design is more imposing and eye-catching than the straight passage and prevents the incidence of light at the central area, the glass floor being limited to the three legs of the tripod. Again, the arch springs are at ground level, just outside the site and allow limiting the slope of the entrance. This is a more complex structure and may conflict with more important objects as historic remains, although it allows to approach the elevated object more efficiently.

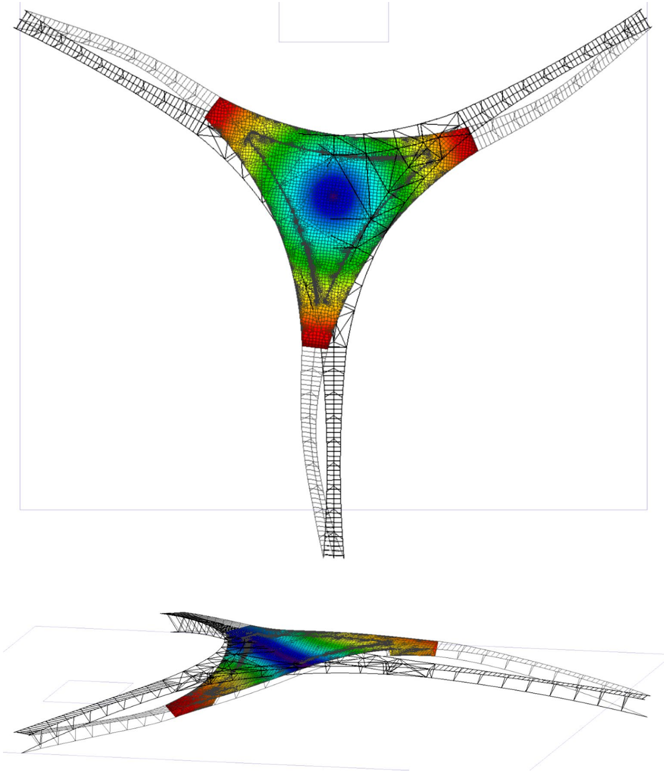


Figure 4. Tripod vibration *modes*

4.3 Circle

The idea of this typology is to allow elevated view from the perimeter of a smaller site, containing an elevated part and to walk completely around all remains. Visitors are able to physically approach each part to a maximum distance of half the ring diameter. A circular footbridge of approximately 250° is built around the perimeter, both ends being at ground level. This alternative approaches most the existing walkways that may be found in certain museums. Unfortunately, the ring needs to be supported by at least 2 intermediate columns, which have been designed as V-shaped tubular piers. The general layout is seen in Fig. 5.

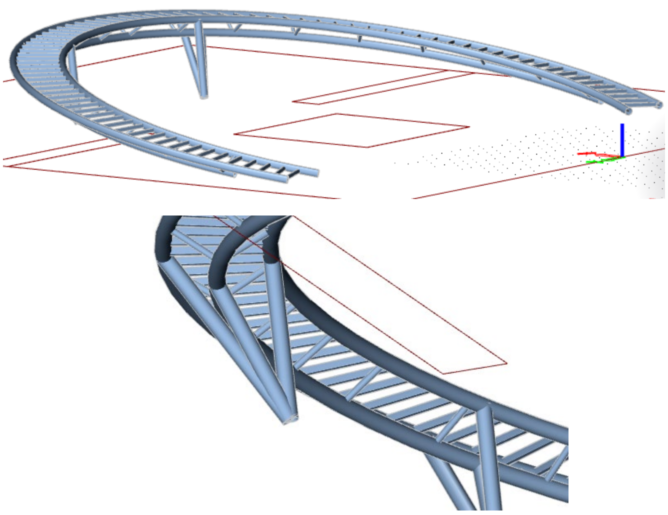


Figure 5. Circle *alternative – views*

The system of tubes is much lighter than those of the previous typologies. The lower tube is limited to CHS 500/12 whereas the upper edge members correspond to CHS 480/12. Obviously, this results from the smaller scale of the structure. In addition, the supports can be of the type CHS 480/10, the thickness being close to the limit for local crippling. Clearly, the largest span sections are subjected to large torsion and the critical buckling modes originate from the combined effect of torsion and bending, as can be seen in Fig. 6.

Since these elements are the lightest, the unity check for the columns is the most critical and reaches 0.99. The lateral edge tubes show a unity check of 0.86. Should a plated connection of the lateral tubes be added, in particular on the lower tube and the web tubes, the stability modes would certainly render higher critical load, thus seriously improving the buckling load. However, this would decrease the degree of transparency of the tubular structure and its overall quality. The natural frequencies vary from 1.48 Hz to 6.64 Hz and are at the edge of the critical range. Table 4 associates them with the mode type.

Table 4. Frequencies *Ring*

Nr	Frequency	Mode type
1	1.48 Hz	Torsional
2	1.81 Hz	Vertical torsion
3	2.43 Hz	Vertical torsion
4	2.45 Hz	Lateral

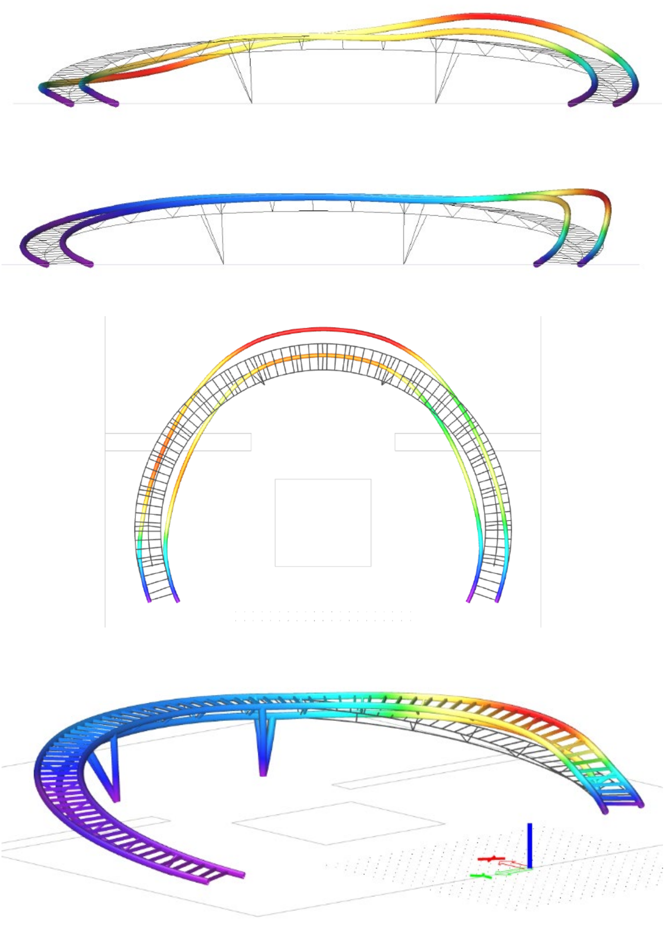


Figure 6. Circle *mode shapes*

The natural frequencies vary from 1.48 Hz to 6.64 Hz and are at the edge of the critical range. Table 4 associates them with the mode type.

The second vibration mode corresponds to the vertical-torsional deformation and results in 0.13 m/s² acceleration, which is considerably larger than for the other typologies, this being due to the lighter mass of the structure. The critical wind speed equals 16.21 m/s Hence, wind may certainly generate vortex and rain-wind induced vibration, since the Scruton number equals 18.9. As the vortex originates from torsional movement, sealed TLCD-dampers can easily prevent this type of vibration.

The alternative without intermediate supports has also been considered. Torsional effect and the cantilevering character of the structure introduce massive stability problems. The typology becomes unrealistic, since the size of the tubular elements should be tripled at least.

5. Critical phenomena for footbridges

The structural type of the 3 proposals is rather different. The straight passage essentially is an arch structure, relying on the action of thrust force. It shows large stiffness in the arch plane and lateral stiffness is increased by the larger width at the arch springs. However, this structure has the largest span of all 3 and thus would be expected to show the lowest resistance to lateral vibration. Indeed, the mode shape associated to the lowest frequency corresponds to lateral movement. Nevertheless, this structure is the most reliable and does not require any additional countermeasures.

The second proposal of the tripod also is an arched structure, albeit the thrust forces of the 3 legs are rotated. Hence, the thrust force induces some unwanted effects, mainly at the central converging area. As a result, torsion becomes an important factor and the mode shape associated with the lowest frequency is torsional. Possibly, this structure may be improved by providing closed section plated members. It is uncertain whether this would be sufficient to mitigate the critical condition of vortex shedding. The human induced vibrations are unimportant, precisely because of the 3-dimensional character of the structure.

The third proposal of a ring has the smallest overall dimensions and also has additional supporting columns. Hence, it would be expected to show the largest stiffness. However, the circle seems to perform poorer than both other alternatives. Obviously, the open structure has insufficient stiffness to resist torsional vibration and by this it is particularly sensitive to vortices. In addition, the human induced vibration becomes more important, also due to torsional effects. Hence, the open structure, desirable for its transparency, would be improved also by using closed section plated structures.

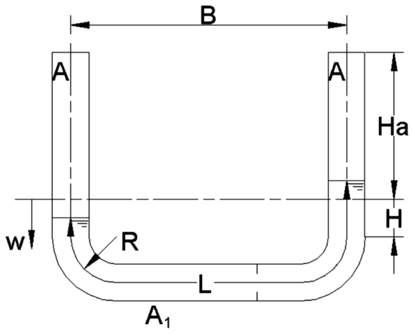
Albeit the first alternative is practically not critical in view of vortex shedding, both other structures certainly are. This has come as a surprise, since generally, it is believed that comfort values and human induced vibrations are the more detrimental phenomenon. The first alternative thus seems preferable from the structural point of view. It behaves perfectly for all phenomena.

However, the analysis has shown that all vortex vibrations are due to torsion or lateral movement. This type of wind-induced vibration can be easily counteracted. Mitigation of vertical vibrations would be counteracted effectively by tuned mass dampers only. The latter adds considerable mass to a type of structure that is meant to be as light as possible. The effective countermeasure for mitigation is the STLCD-device, presented in next paragraph.

6. TLCD dampers

As 2 of the proposals for walkable covers show vibration problems, which have to be overcome by dampers, an especially well adapted type is hereby being presented. Dampers of the TLCD-type are less complicated and certainly as reliable and efficient as tuned mass dampers, provided they are used for lateral and torsional vibration.

The tuned liquid column damper (TLCD) relies on the motion of a liquid mass in a rigid U-shaped tube. The external motion of the structural member on which the damper is fixed, induces a phase-delayed motion of the liquid mass. This motion creates internal forces in the tube, counteracting the external force. In addition, the kinetic energy accumulating in the structural element is dissipated by turbulent damping forces. arising from a built-in orifice plate with small opening. The effectiveness of a traditional TLCD with open vertical tubes decreases rapidly for frequencies exceeding 0.5 Hz. In addition, the open tubes are not really reliable since dust, rain and other liquids can penetrate. Therefore, it is useful to seal both the tube ends, as pressure can be built up. The undamped natural frequency is thus increased, away from the aforementioned critical range. The principle of the sealed tuned liquid column damper is shown above in Fig. 7. The weight of such devices is considerably lower as the liquid may also be ethanol, thus avoiding freezing or many other weather conditions. As the weight is low, the presence of these dampers does not influence the results obtained and the designs remain valid. In addition, different STLCD's may be installed thus covering all critical frequencies. The picture below in Fig. 7 clearly shows anybody may build such dampers and no particular skills are necessary to produce them.



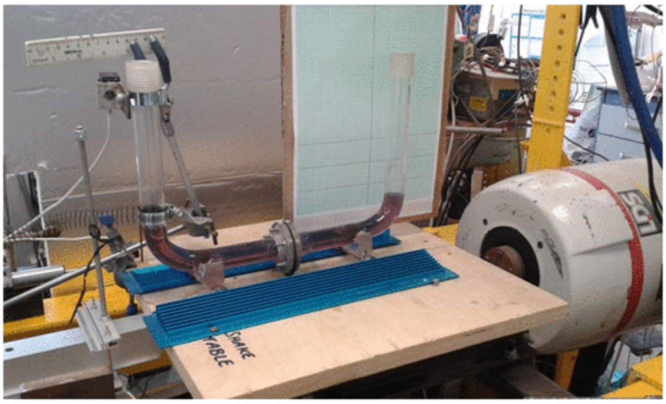


Figure 7. *STLCD fabricated and tested*

7. Outlook further developments

It has become clear that improvements of the proposed structures are possible, mainly by adapting some structural characteristics. However, these measures are in opposition to the view and purpose of the footbridges. Therefore, further developments will be concentrated on exploring the use of light cable structures, including lateral ties and struts, thus hoping to decrease possible lateral movements. Although cable structures are even more flexible, o more complex grid of connections may reduce the effect of the critical vortex phenomenon.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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