Cable Stayed Bridges Vibrations Mitigation Using Composite Bearings

Issad Naim[1],
Zellat Kaoutar[2],
Djemai Mohammed.C[3]

[1]Djillali Liabes Faculty of Technology, Materials and Hydrology Laboratory, Algeria, naimissad@yahoo.fr
[2]Material and Construction Process Laboratory, Abdelhamid Ibn Badis Faculty of Technology, Algeria, kouky88@hotmail.fr
[3]Saad Dahleb University, Civil Engineering Department, Algeria, djmai.medcherif@gmail.com

Résumé:

La vibration est un phénomène dominant dans les ponts à haubans vue qu'ils sont soumis à une variété des charges dynamiques. L'atténuation des vibrations transmises par l'introduction des appuis spéciaux entre la superstructure et l'infrastructure était l'objectif de nombreux travaux de recherche. Le présent travail consiste à une étude comparative du comportement dynamique de trois ponts à haubans équipés de différents types d'appuis y compris les appuis ordinaires, les appuis en caoutchouc et plomb et les appuis composites. L'étude se focalise sur le dernier type construit en fibres de carbone et plastique où son module de résistance et sa densité sont de 5 à 10 fois plus celui d'acier. Les résultats obtenus montrent l'efficacité de ces appuis dans l'augmentation de la période des vibrations de telles structures ainsi que la dissipation d'énergie.

Abstract:

Vibration is a governing behaviour in cable stayed bridges as they are subjected to a variety of dynamic loads. Mitigation of the transmitted vibrations was the aim of many research works by the introduction of special bearings between the superstructure and the substructure. The present work involves a comparative study on dynamic behaviour of a cable stayed bridge equipped with three types of bearings that are the ordinary, lead rubber and composite bearings. Where the last are in the form of carbon fibres and plastics and whose strength and density ratio is 5 to 10 times the ones of steel ratio. The obtained results show the height efficiency of these bearings in the structure period elongation and energy dissipation.

Keywords: Bearings, bridge, carbon fibres, composites, lead rubber, plastic, simulation

1. Introduction

Cable stayed bridges structural design consists of a rigid deck and a series of cables, their low stiffness, light weight and long spans increase their lateral and torsional stiffness as compared to regular non-cable bridges [1]. They are generally employed in vast areas such as rivers, coasts and valleys, what makes them exposed to a variety of random natural charges. Therefore, many vibrations occur in real long-span bridges and cause a high failure and damages to their structural components.

In order to protect cable stayed bridges against undesirable vibrations, many research works have been conducted all over the world in the field of bridges isolation using special bearings. Isolation bearings also called asseismic bearings represent a kind of control devices that try to decouple the structure from the damaging effects of ground motion when an earthquake occurs and provides it with damping. The added damping allows the earthquake energy to be absorbed by the isolation systems and therefore reduces the energy transferred to the structure. Seismic isolation is physically achieved by placing the structure on isolators. The isolators are laterally flexible elements, yet they are able to carry the vertical loads of the structure. Since the isolators are more flexible than the structure, most of the lateral movements occur in the isolators. As a result the isolated structure experiences less motion and reduced forces [2].

Bridges isolation bearings may be simply classified as hysteretic or viscoelastic. Hysteretic isolators include the yielding of metals due to flexure, shear, torsion, or extrusion (metallic dampers) and sliding (friction dampers). They are all essentially displacement-dependent devices. Viscoelastic systems include viscoelastic solids, fluid orificing (fluid dampers), and viscoelastic fluids. They are essentially velocity-dependent devices (viscous in nature) and many are also frequency dependent. Some other energy dissipators are modifications of the above set and may include elastic springs or pressurized cylinders to develop pre-load and re-centering capabilities.

Various kinds of devices have been used for this scope, this study sheds light on two types to be the friction and sliding bearings and proposes a new kind of bearings made of composite materials.

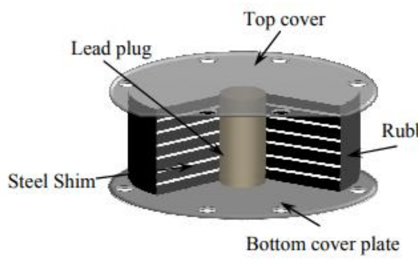
In this research work a comparative study was elaborated on bridges vibrations control using various types of bearings including the LRB, FPS and composites bearing made of carbon fibers and plastics where the composite materials present excellent properties [3]. The sandwich composite materials replace the metals having the same excellent strength and slighter weight.

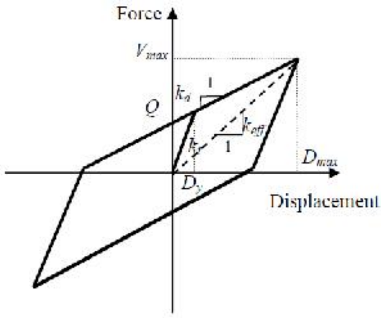
For this purpose, three cable stayed bridges were considered with the same geometrical properties and different bearing conditions. The comparative study was in term of vibration period, displacements and base shear restriction. The dynamic analysis was applied on the structures using SAP2000 V16 software where the bridges were modeled as finite elements. The structures were subjected to a combination of dynamic loads including earthquake which represents the most several case of loading. Dynamic excitations were modeled as time history spectrums. And finally dynamic analyses were performed for each bearing case.

2. Bearings description and characteristics

1. Lead Rubber Bearing

The lead rubber bearings (LRB) represent the most commonly used devices for bridges control; they belong to the category of elastomeric isolators. The basic components of LRB are steel and rubber plates [4], built through vulcanization process in alternate layers; they consist of two steel fixing plates located at the top and bottom of the bearing, several alternating layers of rubber and steel shims and a central lead core as shown in Figure 1(a). The elastomeric material provides the isolation component with lateral flexibility; the lead core provides energy dissipation (or damping), while the internal steel shims enhance the vertical load capacity whilst minimizing bulging.





(a) Components *(b) Idealized Hysteresis Loop*

Figure 1. LRB Isolation bearing (Viewed on: https://structurae.net/)

All elements contribute to the lateral stiffness. The steel shims, together with the top and bottom steel fixing plates, also confine plastic deformation of the central lead core. The rubber layers deform laterally during seismic excitation of the structure, allowing the structure to translate horizontally, and the bearing to absorb energy when the lead core yields.
The nonlinear behavior of a LRB isolator can be effectively idealized in terms of a bilinear force-deflection curve, with constant values throughout multiple cycles of loading as shown on Figure 1(b). The parameters of the bilinear approximation expressing the law of hysteretic behavior are the following:

D_y: the yield displacement with [5]:

$$D_y = Q/(K_1 - K_2) \tag{1}$$

D: The design displacement of lead rubber bearing LRB

E_H: Energy dissipated by cycle corresponding to the design displacement, equal to the total area of hysteresis loop, it is given by the following formula:

$$E_H = 4Q(D - K_y) \tag{2}$$

F_y: The yield force in a monotonous loading

Q: The force, corresponding to null displacement during a cyclic loading, represents also the characteristic strength and the yield force of lead bar for the LRB.

$$Q = F_y - K_2 D_y \tag{3}$$

F_{max}: The maximum shear force corresponding to the design displacement D

K_1: Elastic stiffness for a monotonous loading also equals to the stiffness of unloading in cyclic loading, with:

$$K_1 = F_y / - D_y \tag{4}$$

K_2: The post elastic stiffness, with:

$$K_2 = (F_{\max} - F_y)/(D - D_y) \tag{5}$$

K_{eff}: The effective stiffness of the LRB, it is given by the following formula:

$$K_{eff} = K_2 + \frac{Q}{D} \qquad D \geq D_y \tag{6}$$

B_{eff}: The effective damping factor of the seismic base isolation system, it is expressed as follows:

$$\beta_{eff} = \frac{4Q\ (D - D_y)}{2\pi K_{eff} D^2} \tag{7}$$

2. Friction Pendulum System

One of the most popular and effective techniques for seismic isolation is through the use of sliding isolation devices. The sliding systems exhibit excellent performance under a variety of severe earthquake loading and are very effective in reducing the large levels of the superstructure acceleration.

A FPS is comprised of a stainless steel concave surface, an articulated sliding element and cover plate. The slider is finished with a self-lubricating composite liner (e.g. Teflon) [6]. During an earthquake, the articulated slider, within the bearing, travels along the concave surface causing the supported structure to move with gentle pendulum motions as illustrated in Figure 2.

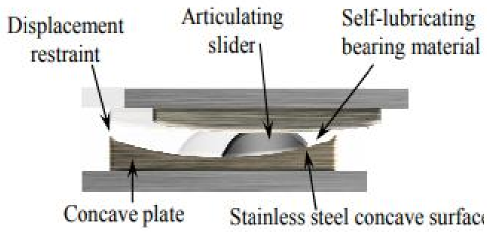


Figure 2. FPS Isolation bearing (Viewed on: http://www.earthquakeprotection.com/)

Movement of the slider generates a dynamic frictional force that provides the required damping to absorb the earthquake energy. Friction at the interface is dependent on the contact between the Teflon-coated slider and the stainless steel surface, which increases with pressure. Values of the friction coefficient ranging between 3% and 10% are considered reasonable for a FPS to be effective.
The isolator period is a function of the radius of curvature (R) of the concave surface. The natural period is independent of the mass of the supported structure, and is determined from the pendulum equation [7]:

$$T = 2\pi\sqrt{\frac{R}{g}} \tag{8}$$

Where g is the acceleration due to gravity
The horizontal stiffness (K_H) of the system, which provides the restoring capability, is provided by:

$$K_H = \frac{W}{R} \tag{9}$$

W: is the weight of the structure
The movement of the slider generates a dynamic friction force that provides the required damping for absorbing earthquake energy. The base shear V, transmitted to the structure as the bearing slides to a distance (D), away from the neutral position, includes the restoring forces and the friction forces as can be seen on the following equation, where μ is the friction coefficient:

$$V = \mu W + \frac{W}{R}D \tag{10}$$

The characterized constant (Q) of the isolation system is the maximum frictional force, which is defined as:

$$Q = \mu W \tag{11}$$

The effective stiffness (k_{eff}) of the isolation system is a function of the estimated largest bearing displacement (D), for a given value of μ and R, and is determined by the following formula:

$$K_{eff} = \frac{V}{D} = \frac{\mu W}{D} + \frac{W}{R} \tag{12}$$

A typical hysteresis loop of a FPS can be idealized as shown in Figure 3. The dissipated energy (area inside the hysteretic loop) for one cycle of sliding, with amplitude (A), can be estimated as:

$$E_D = 4\mu\, WA \tag{13}$$

Thus the damping of the system can be estimated as:

$$\beta = \frac{E_D}{4\pi K_{eff} A^2} = \frac{2}{\pi}\frac{\mu}{A/R + \mu} \tag{14}$$

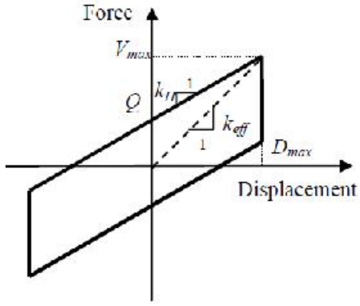


Figure 3. Hysteresis loop of a FPS

3. Composite bearings

Composite bearings represent new isolation devices used to maintain separation and control friction between two moving parts. The distinguishing characteristic of a composite bearing is that the bearing is made of a combination of materials such as resin reinforced with fiber or Carbone fibers reinforced with plastics and this may also include friction reducing lubricants and ingredients. They are lighter than a rolling element bearing; it can be one-tenth the weight of the traditional rolling element bearing [8] where no heavy metals are used in its manufacture [9].

The bearings used herein belong to new elastomeric isolators' family called fiber-reinforced elastomeric bearings (FREB) used in bridges. They are made of high damping rubber and carbon fiber reinforced polymer (FRP) composite plates as mentioned in Figure 4.

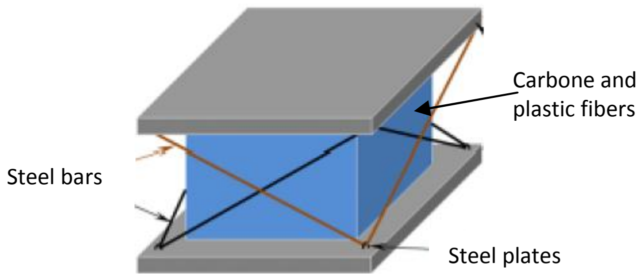


Figure 4. Composite FREB (seen on https://people.ok.ubc.ca/shahria/index_files/Page1369.htm)

Carbon fibers offer a high strength to weight ratio and stiffness to weight ratio, they provide a driving force for the use of composite materials because of their good corrosion resistance, wear resistance, electromagnetic transparency, enhanced fatigue life, thermal acoustical insulation, low thermal expansion and low thermal conductivity [10].

The performance of FREB is characterized by assigning different weights to its operational specifications which are the effective horizontal and vertical stiffnesses and the equivalent viscous damping[11]. These parameters are highly dependent on the shear modulus of the Carbone layers, the number of layers and thickness of the whole layers. They can be effectively calculated as the elastomeric bearings mentioned in previous sections.

3. Dynamic analysis

A dynamic analysis was applied on a cable stayed bridge with a long span and continuous deck made of reinforced concrete in order to demonstrate the effectiveness of vibrations control devices in the case of strong earthquakes. Each component was modeled separately then all data were gathered and included in computational structural software where the dynamic analysis was elaborated on the basis of FE method.

1. Cable stayed bridge

A cable stayed bridge was considered in this study view its high popularity and sensitivity to dynamic loads. The properties of the bridge deck, pylon and cables are given with detail in Table 1.

Table 1. Bridge model characteristics

Length (m)	Width (m)	Modulus of Elasticity (Gpa)	Pylon Height (m)	Cable Diameter (m)
200	6	19	50	0,6

The bridge is modeled as finite elements model as shown in Figure.5. The fundamental time period of the pylons is about 0.1 sec and the corresponding time period of the non-isolated bridge works out to be 0.55 sec in both longitudinal and transverse directions. The damping in the deck and piers is taken as 5% of the critical in all modes of vibration. In addition, the number of elements considered in the bridge deck, pylon and cables are 21, 2 and 36, respectively.

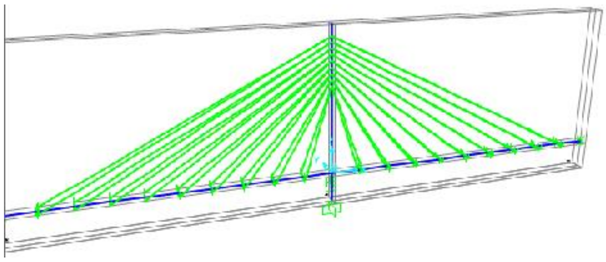


Figure 5. 3D modelling of isolated bridge

2. Earthquake excitation model

The earthquake excitation was inset as a time history spectrum (Acceleration according to time) as shows Figure.6. The seismic excitation corresponds to Solomon earthquake in 2004 with a magnitude of 6.8 obtained from vibration data website (PEER Ground Motion Database).

Response quantities of interest for the bridge system under consideration (in both longitudinal and transverse directions) are the base shear in the pylon and the relative displacement of the aseismic bearings at the top of pylon. The pylon base shear is directly proportional to the forces exerted in the bridge system due to earthquake ground motion. On the other hand, the relative displacements of the isolation bearing are crucial from the design point of view of isolation system and separation joints at the abutment level.

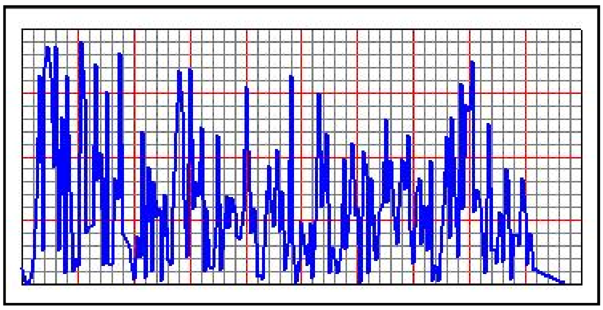


Figure 6. Solomon earthquake time history function

3. Bearings models

SAP2000 facilitates the dynamic modeling of base isolators as link elements, which can be assigned various stiffness properties. By the help of this software the bridge model with different types of bearings was created in a numerical simulation to validate the mathematical model, two categories of isolation systems were used characterized by three types of bearings that are: the elastomeric bearings LRB and FREB the sliding bearing FPS isolator which were modeled using N-link command; each device has its own properties as detailed in Table 2.

Table 2. Physical and mechanical characteristics of isolation bearings

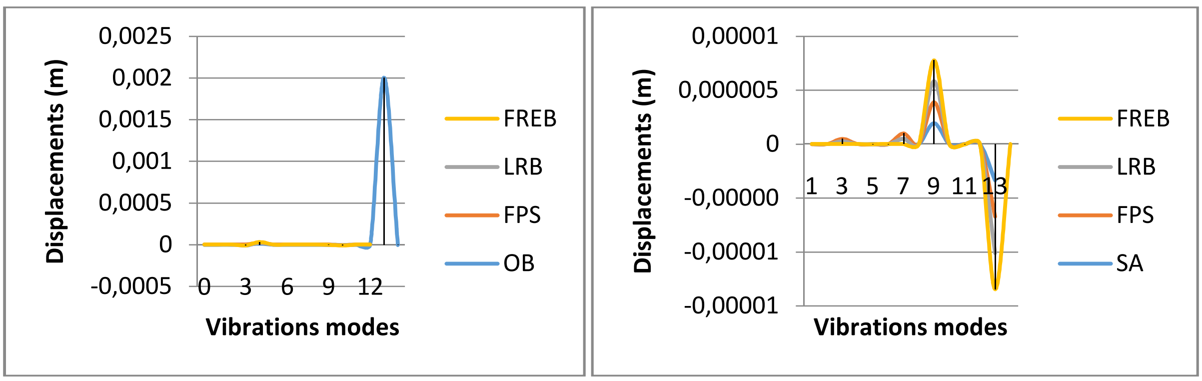
Bearing Model	Rotational Inertia (Kgm^2)	Mass (Kg)	Weight (KN)	Diameter (m)	Effective Stiffness K_{eff} (KN/m)	Effective Damping ζ (%)
LRB	1,82x10E10	84	845	0,8	2477	30
FPS	1,1x10E10	68	687	0,7	2000	10
FREB	8x10E9	20	200	0,5	545	44,2

4. Results and discussion

SAP2000 structural analysis software is capable of Time History Analysis, including Multiple Base Excitation. In this work twelve vibration modes were taken into account in the bridge response analysis, the comparison results is between the isolated and non isolated structures. As illustrated in Table 3 the presence of aseismic bearings has a considerable effect on the fundamental period of vibration of the structure for all kinds of bearings with a little difference between the period increasing values (66%) LRB bearing, (23%) for the FPS bearing and (77%) for FREB composite type which confirms the high effectiveness of composites materials in period of vibrations lengthening in such civil structures.

Table 3. Natural vibration period of the isolated and non isolated bridge model

	Period of Vibration			
Vibration Mode	OB	LRB	FPS	FREB
1	0,553148	0,919365	0,681502	0,980125
2	0,553138	0,553138	0,553138	0,609594
3	0,220941	0,553127	0,553109	0,553109
4	0,219809	0,220941	0,220941	0,220941
5	0,193147	0,219809	0,219809	0,219809
6	0,193143	0,193143	0,193143	0,193143
7	0,098952	0,193142	0,193142	0,193142
8	0,098951	0,098951	0,098951	0,098951
9	0,06629	0,09895	0,09895	0,09895
10	0,066257	0,06629	0,06629	0,06629
11	0,061753	0,066257	0,066257	0,066257
12	0,061752	0,061752	0,061752	0,061752



Longitudinal direction *Transverse direction*

Figure 7. Bearing displacements (get from SAP2000 modeling)

Moreover, and as shown in Figure.7, the displacement of the isolation bearing is significantly reduced in longitudinal direction for all vibration modes. In the case of the transverse direction it's obvious that the FREB bearing represents the highest value of displacement which justifies the capability of the bearing to move and protect the structure from damaging effects.

5. Conclusion

This research work sheds light on recent and economical techniques for bridge protection against several damages and collapse due to vibrations transmitted from ground motion in the case of several earthquakes. The study discusses the effectiveness of the employment of isolation bearings in bridges construction in particular cable stayed bridges and proposes a new type of asseismic bearings based on composites materials. Further, a comparative study on isolated bridges against dynamic natural and human induced vibration was conducted where the most emphasis was put on the time variation of base shear and bearing displacements. The results show that the base shear in the pylons is significantly reduced for the isolated system as compared to the non isolated system in both directions of the bridge for all attitudes except the bearing location in order to protect the structure from damaging. Finally, bridge fundamental period is significantly increased using isolation devices with a higher rate in the case of FREB bearing as compared to the LRB and the FPS bearings; which indicates that the use of aseismic systems is effective in reducing the dynamic response of the bridge.

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