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Numerical simulation on the effectiveness of using viscoelastic materials to mitigate seismic induced vibrations of above-ground pipelines

Kaiming Bi *, Hong Hao

Centre for Infrastructure Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Kent Street, Bentley, WA 6102, Australia

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ABSTRACT

Pipeline systems are commonly used to transport oil, natural gas, water, sewage and other materials. They are normally regarded as important lifeline structures. Ensuring the safety of these pipeline systems is crucial to the economy and environment. There are many reasons that may result in the damages to pipelines and these damages are often associated with pipeline vibrations. Therefore it is important to control pipeline vibrations to reduce the possibility of catastrophic damages. This paper carries out numerical investigations on the effectiveness of using viscoelastic materials to mitigate the seismic induced vibrations of above-ground pipelines. The numerical analyses are carried out by using the commercial software package ANSYS. The numerical model of the viscoelastic material is firstly calibrated based on the experimental data obtained from vibration tests of a 1.6 m long tubular sandwich structure. The calibrated material model is then applied to the above-ground pipeline system. The effectiveness of using viscoelastic materials as the seismic vibration control solution is investigated. The influences of various parameters, including the constraining arrangement scenarios, the constraining length and angle, the thicknesses of the viscoelastic material and constraining layer are discussed in detail. The influence of earthquake frequency content is discussed as well. Numerical results show that with properly selected viscoelastic materials and constraining layers, the proposed method can be used to effectively mitigate seismic induced vibrations of above-ground pipelines.

1. Introduction

Pipeline systems are commonly used to transport oil, natural gas, water, sewage and other materials. They are normally regarded as important lifeline structures. Ensuring the safety of these pipeline systems is crucial to the economy and environment. There are many reasons that may result in the damages of pipelines. These include possible corrosion and fatigue damages after the pipeline is in service for a number of years [1], damage owing to large bending deformation and excessive stresses in the pipe wall induced by large external loadings [2–4] and damage related to lateral buckling, upheaval buckling or propagation buckling [5]. Often damages may also be associated with pipeline vibrations. For example, vortex-induced vibrations (VIV) of subsea pipelines [6], vibrations caused by earthquake excitations in seismic active zones [7] or vibrations induced by strong winds [8]. These dynamic loadings may induce excessive stresses in the pipe structure and lead to damage. Even if the vibration level is not large enough to cause overstress in the pipeline structure, relatively large continuous vibration such as VIV certainly reduces the fatigue life of the pipe. Therefore, it is important to control pipeline vibrations to reduce the possibility of catastrophic damage.

When the soil deformations produced by the buried pipelines are unacceptably large, the above-ground pipeline can be an option to carry fluid or gas [9]. These pipelines are generally supported along their length by discrete concrete blocks. The suspended spans may undergo excessive vibrations during a severe earthquake, which in turn can result in damages to the pipelines. Previous studies on the seismic responses of above-ground pipelines are surprisingly rare. Anderson and Johnston [10] investigated the dynamic behaviour of above-ground oil pipelines. These pipelines are allowed to slide back and forth on intermediate supports during strong earthquakes. The sliding is restrained by friction between the pipe and the top of the support. The effect of this non-linear friction on both the static and dynamic stresses in the pipe was discussed. Powell [9] developed a procedure to compute the seismic response of above-ground, cross-country pipelines. The procedure can account for the effects of initial static loads, slipping of the pipe on its supports and out-of-phase ground motions at

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* Corresponding author. Tel.: +61 8 9266 5139; fax: +61 8 9266 2681.
E-mail address: kaiming.bi@curtin.edu.au (K. Bi).

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different supports along the pipe. Soliman and Datta [11] carried out parametric studies on the seismic responses of overground pipelines to multi-component random ground motions. The mean square responses of the pipelines were obtained by frequency domain spectral analysis. Lanzano et al. [12] presented a large database of earthquake-induced damage for steel and non-steel pipelines.

To mitigate the excessive structural vibrations induced by various sources, three types of control strategies, i.e., active, semi-active and passive controls, can be used in the structural vibration resistance design [13]. Considerable attention has been paid to research and development of structural control devices, with particular emphasis on the mitigation of wind and seismic induced responses of buildings and bridges. Studies on pipeline vibration control are relatively less and they are mainly focused on the passive control of VIV [6]. More recently, tuned mass dampers (TMD) were introduced to control wind [8] or vortex-induced [14] vibrations of pipelines. However, it has been observed that most of these methods are difficult to achieve a good balance between performance, cost and simplicity [6].

Constrained viscoelastic layers have been widely used to reduce excessive vibrations of engineering structures due to its effectiveness and simplicity (e.g. [15–18]). Normally a layer or multiple layers of viscoelastic materials (VEM) and a constraining layer (CL) are added to the original structure. The shear deformation of the VEM can obviously increase the damping of the original structure which in turn reduces its vibration. Extensive research efforts have been made to study the vibration characteristics of beam and plate structures with constrained damping layer after the pioneering work done by Kerwin [19] and Ross et al. [20]. For the vibration and damping characteristics of cylindrical shells with constrained damping layer(s), the investigations are relatively less and the natural frequencies and damping of the constrained shell were generally derived based on the finite element method. For example, Chen and Huang [21] presented a mathematical model for a cylindrical shell with partially constrained layer damping treatment. A thin shell theory in conjunction with the Donnell–Mushtari–Vlasov assumptions is employed to yield the model. Wang and Chen [22] derived the equations of motion for the composite system based on a discrete layer theory. Many lengthy formulas were included in these studies, which impedes the application of these theories by researchers and especially engineers. A more readily applicable method, e.g. the numerical simulation method presented in this study, is deemed necessary.

This paper investigates the effectiveness of using constrained VEM layers to mitigate seismic induced vibrations of above-ground pipelines. This idea originates from the recent work done by Borges et al. [16], in which they proposed and investigated a concept aimed at suppressing vibrations in steel catenary risers by the use of viscoelastic sandwich layers. A series of experimental studies were carried out to find out the frequencies and damping of different vibration modes of the riser equipped with different (eleven) scenarios of VEM. Instead of performing experimental studies, numerical simulations are carried out in the present study to investigate the effectiveness of using viscoelastic materials as the seismic vibration control solution to above-ground pipelines by using the commercial software package ANSYS [23]. The numerical model of the viscoelastic material is calibrated based on the experimental data obtained from testing a 1.6 m long tubular sandwich structure [16] in Section 2. The calibrated material model is then applied to the above-ground pipeline system. The effectiveness of using constrained VEM as the seismic vibration control solution is investigated. The influences of various parameters, including the constraining arrangements, the constraining length and angle, the thicknesses of the VEM and CL are discussed in detail. The influence of earthquake frequency content is discussed as well.

2. Numerical model calibration

2.1. Tested original and sandwich tubes

Borges et al. [16] carried out a series of experimental studies to identify the modal parameters (vibration frequencies and damping) of the original structure and structures assembled with different VEMs and CLs. The original structure consists of a brass beam with tubular cross section that is cantilevered at one end and free at the other. The length of the original structure is 1.6 m. To increase the damping of the original structure, viscoelastic layers and its associated brass constraining layers are assembled. The VEM used is the self-adhesive double face tape under code VHB4955, manufactured by 3M®. The viscoelastic and constraining layers are designed to be free at the both ends. Fig. 1 shows the cross section of the sandwich beam and Table 1 presents the geometric properties of the tube layers.

For the brass original tube and CLs, the Young's modulus is $E_b = 121.8$ GPa and the density is $\rho_b = 8770$ kg/m^3. For a linear, homogeneous and isotropic VEM, the complex shear modulus can be expressed in the frequency domain as

$$G^*(\omega) = G(\omega)[1 + i\beta(\omega)] \tag{1}$$

where $G(\omega)$ is the storage modulus, $\beta(\omega)$ is the dissipation loss factor, ω is the circular frequency in rad/s and $i = \sqrt{-1}$ is the imaginary number. $G(\omega)$ and $\beta(\omega)$ can be obtained by using one of the following two types of tests, i.e., the direct measurements using a Dynamic Mechanical Analyser (DMA) [15,24] or back calculation from experimental results performed on the sandwich structure [15]. For the VEM used in the present study, the following parameters are identified: Young's modulus $E_v = 6.88$ MPa, density $\rho_v = 795$ kg/m^3 Poisson's ratio $v = 0.49$ and dissipation loss factor $\beta = 0.75$. The shear modulus is thus $G = E/[2(1+v)] = 2.31$ MPa. These parameters are adopted from Stutz et al. [25], in which the same VEM was used.

It can be seen from Fig. 1 that the original tube was not fully covered by the VEMs and CLs, a gap was designed between different faces of cover layers. The angle of the gap was not mentioned in [16]. Based on the provided figure (Fig. 8 in [16]), the angle is estimated to be 18° and used in the present study, the angle of each constraining layer is thus 72° as shown in Fig. 1.

2.2. Finite element modelling

The finite element software package ANSYS is used in the present study to carry out the analyses. The original tube, VEMs and

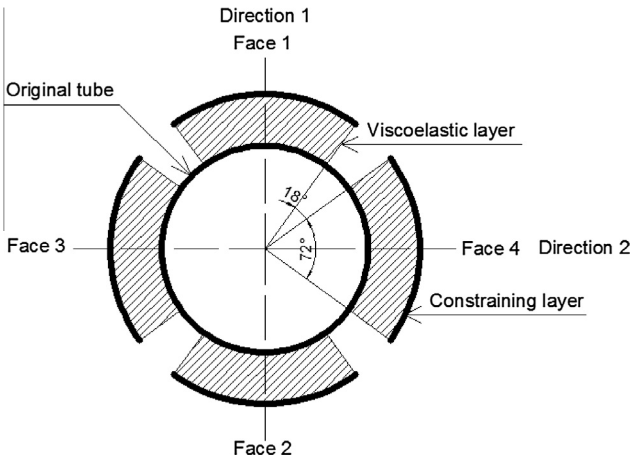

Fig. 1. Tubular cross section of the sandwich beam structure (not to scale, after [16]).