Energy Harvesting from Train-Induced Response in Bridges

Paul Cahill1; Nora Aine Ni Nuallain2; Nathan Jackson3; Alan Mathewson4; Raid Karoumi5; and Vikram Pakrashi6

Abstract: The integration of large infrastructure with energy-harvesting systems is a growing field with potentially new and important applications. The possibility of energy harvesting from ambient vibration of bridges is a new field in this regard. This paper investigates the feasibility of energy harvesting for a number of trains considering their passage over a bridge. The power that can be derived from an energy-harvesting device due to a train crossing a bridge at different speeds is compared against typical demands of small wireless devices and is found to be adequate for powering such devices. These estimates of harvested energy also relate to the individual signatures of trains. In this work, the modeled dynamic responses of a bridge traversed by trains are compared against full-scale experimental analysis of train–bridge interactions. A potential application in structural health monitoring (SHM) using energy harvesting has also been demonstrated and compared with laboratory experimental data. Consistent and monotonic damage calibration curves have been constructed using estimated harvested energy.

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Introduction

With the current advances in microsystems and the potential this creates for autonomous sensing systems, substantial consideration has been given to the efficient use and supply of power to such systems, particularly for wireless sensor networks. This requirement has resulted in significant investigations into the use of different energy-harvesting techniques for the powering of wireless networks (Harb 2011), with much of the attention being focused on the use of vibration-based electromagnetic, electrostatic, and piezoelectric solutions (Beebey et al. 2006).

Of these energy-harvesting techniques, devices based on the use of piezoelectric materials have proven to be especially effective (Cook-Chennault et al. 2008; Sodano et al. 2004; Anton and Sodano 2007). Significant research has been carried out on the optimization of the design of the piezoelectric energy harvesters, including cantilever-based applications (Jackson et al. 2013a, b; Erturk and Inman 2008), a bimorph cantilever (Ajitsaria et al. 2007), and a dual-mass vibration harvester (Tang and Zuo 2011). With large differences in the physical properties of piezoelectric materials, which range from ceramics to polymers, identifying the most suitable for specific applications is essential (Vatansever et al. 2011).

The potential use of energy-harvesting systems for civil infrastructure (Sazonov et al. 2009) has recently begun to receive attention and the true potential for applications in the field of civil engineering has yet to be realized. A recent study (Ali et al. 2011) investigated the feasibility of using tuned piezoelectric energy harvesters as a method of powering microsystems through the parasitic harvesting of ambient structural vibrations from bridge infrastructure. Different methods of piezoelectric energy harvesting for bridges have also received attention (Erturk 2011).

Structural health monitoring (SHM) for civil infrastructure elements, on the other hand, is a field in a continuous state of development and evolution (Chang et al. 2003; Cattus et al. 2008; Moaveni et al. 2009; Pakrashi et al. 2013). Modern advances in the development of smart sensors has suggested the potential for the creation of wireless sensor networks for use in the monitoring of infrastructure elements (Lynch and Loh 2006; Gangone and Whelan 2011). Lead zirconate titanate [Pb(ZrTi)O3] or PZT sensors have been embedded within RC elements and compared against traditional methods of detection, namely strain gauges and linear variable differential transformers (LVDT), under different loading conditions (Song et al. 2007). Polyvinylidene fluoride [(C2H2F2)n or PVDF] sensors have also been utilized for the wireless monitoring of tension conditions in cable stayed bridges (Liao et al. 2001). SHM of bridge infrastructure has also received some attention, with a number of methods proposed to determine the condition of bridges (Brincker et al. 2003; Zhang et al. 2005; Sepe et al. 2005). One such method is using the dynamic response of train–bridge interaction and sensitivity analysis using stiffness variation for the detection of damage (Zhan et al. 2011; Shu et al. 2013). A bridge weigh-in-motion (B-WIM) with accelerometers has also been implemented for the monitoring of actual traffic load (Karoumi et al. 2005; Liljencrantz et al. 2007; Liljencrantz and Karoumi 2009), but this is totally reliant on external power supplies. Consequently, evidence suggests that the monitoring of train–bridge interaction under operational conditions may be beneficial for SHM of structures as the structure is not required to be closed for use.

This paper demonstrates that energy harvesting from vibration due to the response of train passages across bridges can provide sufficient power for small devices with low power demand. The additional advantage of this is that the harvested energy can be used for SHM.
The levels of power that can be harvested from train–bridge dynamics under operational conditions have been investigated for
- A range of passenger trains from international stock,
- A freight fleet from experimental data, and
- A SHM system using the harvested energy as a metric.

**Energy Harvesting from Train-Induced Responses**

**Piezoelectric Energy-Harvesting System**

Significant research into the design and optimization of piezoelectric energy-harvesting systems has taken place, with emphasis being placed into the design of systems powered through the vibrations of the host structure (Erturk 2011). A limitation to the cantilever-based energy-harvester approach is the requirement to tune the harvester to the natural resonant frequency of the host structure to optimize energy-harvesting potential (Ali et al. 2010). Potentially more effective is an energy-harvesting system based on an adhesive patch that could be bonded to the host structure to generate power. This is achieved directly from the variation in the strain conditions from the surface to which it has been attached. It is envisaged that such an energy-harvesting system could be used for multiple applications without the need for determining and tuning to the natural frequency of the host structure. In such circumstances, it is important to assess the order of energy harvested from a certain system and assess the potential applications. For this paper, an adhesive patch energy-harvesting system is evaluated for energy harvesting from bridge dynamics due the passage of trains and the potential applications of such a system identified and investigated.

**Piezoelectric Materials**

Because of the large variations in the nature of piezoelectric materials, as described previously, it is imperative to investigate different materials for their use as an energy harvester in these applications. Two commercially available piezoelectric materials of rectangular geometry, PZT and PVDF, were chosen for use as the basis of the energy-harvesting system. PZT is the most commonly used piezoelectric material for energy harvesting because of its excellent piezoelectric properties. A drawback of PZT, however, is its brittle nature because it is a ceramic material. This can lead to difficulty in terms of the design, handling, and durability of the energy-harvesting systems and, as a consequence, may render it unsuitable for certain applications (Woo and Goo 2007). PVDF is a polymer that exhibits a high mechanical strength while retaining excellent flexibility (Vinogradov and Holloway 1999) and thus can be simply formed into different shapes. While it is not subject to the same physical limitations as PZT, its lower piezoelectric properties require higher strain conditions to produce a similar power output (Lin and Giurgiutiu 2006). The representative piezoelectric and physical properties of both energy harvesters considered in this paper are outlined in Table 1, including Young’s modulus, $E$, the piezoelectric constants $d_{31}$ and $e_{33}$, and the length, width, and thickness of the materials, $l$, $w$, and $t$, respectively.

**Modeling of Energy Harvester**

In this work, energy-harvesting systems are designed to be attached externally to the underside surface of the finite-element model. The 31 mode, relating to the piezoelectric nature of the material whereby the material is poled in the vertical direction, 3, during its manufacture, and strain acts along the longitudinal direction, 1, is the mode of operation of the energy-harvesting system (Anton and Sodano 2007). It is assumed that there is a perfect connection between the energy harvesters and the surface of the bridge, and thus, almost identical strain conditions will act on both surfaces with no losses arising from an adhesive substrate. The model used for the calculation of the power output of the system is based on the piezoelectric principle for coupled electromechanical behavior and the modeling of the voltage is obtained from Sirohi and Chopra (2000). The strain profile that acts upon the location at which the energy harvesters are to be positioned are evaluated and the potential voltage was subsequently calculated, (Eq. 1), where $\varepsilon$ is the evaluated strain averaged over the harvester length and $C_p$ is the capacitance of the material, Eq. (2). The power for each train passage was calculated from the root mean squared (RMS) of the generated voltage for the entire train passage, Eq. (3), where $R$ is the resistance, assigned a value of 100 k$\Omega$. The system would also incorporate an energy storage and power-handling circuit that would be able to consistently provide power to the low-power sensors and enable them to become autonomous wireless sensors. The design and modeling of the circuit is beyond the scope of this paper and, thus, no reduction in power due to losses through the circuit is assumed in this paper. In operational circumstances, losses will not affect the order of the energy harvested because the extent of losses will be small, dependent on the circuit. Circuit losses range from 60 to 84% efficiency (Tabesh and Fréchette 2010), with some circuits reporting a 96% efficiency rate (Magno et al. 2013). Furthermore, the losses experienced because of the circuit would be a constant value for each of the harvesters, because of identical circuits being used for the harvesters, and over a time period. As such it can be expected that the consistent losses would not influence the relative power output potentials between different trains and thus not influence the feasibility of using the energy output to power devices that have small power demands (Cook-Chennault et al. 2008) or the potential for using such energy harvesters and devices for the purposes of SHM (Farrar et al. 2006)

$$V_p = \frac{d_{31} Eb}{C_p} \int \varepsilon dx$$

(1)

$$C_p = \frac{e_{33} lw}{t}$$

(2)

$$P = \frac{(V_{RMS})^2}{R} = \frac{\left( \frac{1}{T} \int_0^T V^2(t) \, dt \right)^2}{R}$$

(3)

**Train-Bridge Modeling**

**Train Models**

Five international trains were chosen for the purposes of comparing the potential for energy harvesting from train passages over a bridge (Fig. 1). These are the Irish 071Loco and 201Loco, the French Train à Grande Vitesse (TGV), the German Intercity-Express (ICE) and

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**Table 1. Piezoelectric and Physical Properties of PZT and PVDF Energy Harvesters**

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>PZT</th>
<th>PVDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus, $E$</td>
<td>10$^9$ Pa</td>
<td>71</td>
<td>6</td>
</tr>
<tr>
<td>$d_{31}$ constant</td>
<td>10$^{-12}$ C/N</td>
<td>-274</td>
<td>24</td>
</tr>
<tr>
<td>$e_{33}$ constant</td>
<td>10$^{-9}$ F/m</td>
<td>30.1</td>
<td>0.106</td>
</tr>
<tr>
<td>Thickness, $t$</td>
<td>10$^{-3}$ m</td>
<td>320</td>
<td>110</td>
</tr>
<tr>
<td>Length, $l$</td>
<td>m</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Width, $w$</td>
<td>m</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>
the Japanese Shinkansen (Wang et al. 2003; Hagiwara et al. 2001). Each train was modeled with the same configuration as it would have under operational conditions, including the number of motorcars and carriages and the length and load of axles (Table 2). The 071Loco and 201Loco trains are powered by a single diesel motorcar, while the remaining are electric trains with locomotives located at both ends of the train. The TGV has a total of 10 carriages, with the carriages connected to the motorcar being 21.9 m in length and the remaining eight being 18.7 m.

**Modeling of Train Passage over Bridge**

For the purposes of modeling the change in strain conditions of a bridge that arise because of a train passage, a three-dimensional finite-element sectional model of the bridge was created using Strand7 finite-element analysis system. The double-track model was created using 20 node hexahedral bricks (Fig. 2) and has dimensions 10.6 m in length and 10 m in breadth. The train axle loads were modeled as point loads at distances determined by the individual axle spacing for each train as outlined previously, acting along a load path along the length of the track. A total of seven speeds, ranging from 40 to 160 km/h, were chosen for the purposes of this investigation. The models were analyzed along the base surface at the midspan of the support beams, the position at which the energy-harvesting system are located. Single-train passage and double-train passage with trains traveling in opposite directions were considered.

For the purposes of comparison with the finite-element model, a differential equation model for train passages over a bridge was created for a simply supported bridge. A beam model proposed by Fryba (2001) was used in this regard. The input values were obtained so as to be identical to the finite-element model and the trains as described in previous sections. The model was then solved for all single-passage cases and the harvested energy output for each model

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**Table 2. Summary of Train Fleet**

<table>
<thead>
<tr>
<th>Element description</th>
<th>071Loco</th>
<th>201Loco</th>
<th>TGV</th>
<th>ICE</th>
<th>Shinkansen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locomotive length (m)</td>
<td>17.4</td>
<td>21.0</td>
<td>22.2</td>
<td>20.2</td>
<td>26.1</td>
</tr>
<tr>
<td>Number of locomotives</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Locomotive axle load (kN)</td>
<td>161.9</td>
<td>182.5</td>
<td>158.3</td>
<td>190.0</td>
<td>107.3</td>
</tr>
<tr>
<td>Carriage axle load (kN)</td>
<td>117.7</td>
<td>117.7</td>
<td>158.3</td>
<td>140.0</td>
<td>107.3</td>
</tr>
<tr>
<td>Total train length (m)</td>
<td>178.4</td>
<td>182.1</td>
<td>237.6</td>
<td>357.1</td>
<td>402.1</td>
</tr>
<tr>
<td>Total train load (kN)</td>
<td>4,266.8</td>
<td>4,390.6</td>
<td>4,748.0</td>
<td>8,240.0</td>
<td>6,867.0</td>
</tr>
</tbody>
</table>

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was calculated from the evaluated strain. Finite-element and differential equation models were compared for dynamic strain responses for each train passage (Fig. 3) and a good correlation in the appearance of the dynamic strain response was found. However, the magnitudes of the responses obtained from the finite-element model were higher than those of the comparable differential equation models. This response from the finite-element models produced a 34.1, 33.0, 28.2, 29.7, and 31.6% increase in the magnitude of the average strain for the 071Loco, 201Loco, TGV, Shinkansen, and ICE, respectively, when compared with the differential equation counterparts. This is mostly because the finite-element model takes into account the noncentralized nature of the track and thus the transverse loading due to the train passages.

Results

Single-Train Passage

All train models were analyzed for passages of different speeds and the harvested energy levels were evaluated from the dynamic strain responses from the finite-element and differential equation model (Fig. 4). The power outputs from the PZT energy-harvesting systems are higher than that of its PVDF counterpart, again because of higher piezoelectric coefficients of PZT. It was found that the PVDF power outputs were approximately 52% of the PZT power outputs. This corresponds to PZT having a power figure of merit, a nondimensional figure of the piezoelectric constant squared over the dielectric constant, double that of PVDF. The finite-element models produced a higher
power output than the differential equation, which was expected during comparisons of the strain profiles. The finite-element models show a small increase in the power outputs with increasing train speed, while there is a relatively higher increase from the differential equations. The 201Loco was observed to have the highest potential of power output per train passage. From the finite-element PZT model, the power harvested ranged from 382 μW at 40 km/h to 397 μW at 160 km/h, while ranging from 223 to 363 μW from the differential equations. The Shinkansen was observed to have the lowest estimated power outputs, ranging from 197 μW at 40 km/h to 203 μW at 160 km/h from the finite-element PZT model. The differential equation model ranged from 112 μW at 40 km/h to 163 μW at 140 km/h. Each train is observed to have a signature power output that can be used to determine the identity of the train that has traveled over the bridge. This signature power output, and the subsequent potential of different trains toward energy harvesting, is consistent with existing investigations into the characterization of different vehicles’ loading effect on bridges (Brady et al. 2006; O’Brien et al. 2009).

As shown even with a simplified differential equation model, the harvested energy for a single energy-harvesting system for a single-train passage is observed to be of the order of 100 μW. The power requirement of an autonomous wireless sensor network in sleep mode requires on the order of hundreds of nanowatts (Magno et al. 2013) and typically requires approximately 100 μW (Torah et al. 2008; Wang et al. 2011) to operate in active mode. In SHM, the signal does not need to be transmitted after each passing train, but over an extended period of time. Hence, charge generated from each train can be stored and information transmitted periodically and through the highly routine nature of train networks, the time between cycles is highly predictable. Bridges that experience high levels of traffic and exhibit more dynamic behavior would lend themselves to higher levels of harvesting. These are often the same bridges that require more attention in terms of monitoring. Consequently, a natural potential exists for the energy harvesters to be used as a monitor.

Double-Train Passage
After studying the effects of single trains on the models, the energy-harvesting potential from double-train passages was investigated (Fig. 5). For this, the finite-element model was used exclusively and modeled with trains traveling in opposite directions. As previously found in the single passages, the PZT system produced a higher power output than the PVDF system produced. The highest figure of power produced was 588 μW from the PZT system and 307.1 μW from the PVDF system for the ICE trains, traversing the model in opposite directions at a speed of 120 km/h. The Shinkansen again produced the lowest amount of power, ranging from 269 to 285 μW at speeds of 40 and 160 km/h, respectively, from the PZT harvesting system and 140 to 149 μW at speeds of 40 and 160 km/h, respectively, from the PVDF harvesting system.

There was found to be a considerable increase in the power generated from passing trains when compared with their single-train counterparts (Figs. 4 and 5); however, a double-train passage does not result in a doubling of the power output. Instead it is dependent on the characteristics of the trains and their speed, with an increase in power output ranging 34–52%. This again is consistent with both theoretical and experimental investigations into the effects of vehicle loadings on bridges (O’Brien and Enright 2013; Brady and O’Brien 2006).

Energy Harvesting: Experimental Data
Full-scale strain and acceleration measurements from train–bridge interaction were conducted at Skidträsk Bridge, located in Northern Sweden (Fig. 6). The bridge is a single-span steel–concrete composite bridge that carries a single ballasted track, spans 36 m and is 6.7 m in width. The rails are supported by concrete sleepers, 0.65 m apart,
which lie on a 0.5-m layer of ballast and a 0.5-m layer of subballast. The ballast layers lie on a RC slab, ranging in depth between 0.3 and 0.4 m, supported through two steel beams.

**Train Loading**

Two different cases have been investigated for the purposes of determining the potential of energy harvesting from real-time train–bridge interaction. The first case is a single-locomotive passing over the bridge at speeds ranging from 60 to 180 km/h. The locomotive is 10.4 m long with two bogies, located 7.7 m apart, with the two axles on each bogie a distance of 2.7 m apart. The total load from the locomotive is 191.2 kN. The second case considered for the purposes of this investigation is a loaded freight train, namely the Steel Arrow, a common iron ore freight train in Sweden. The Steel Arrow is composed of two locomotives and 26 wagons, with the locomotives the same as in the first case. The wagons are a total of 10.4 m in length, with two bogies 8.6 m apart, and with the bogie containing two axles 1.8 m apart. The total load from each axle is 245.2 kN. The train has a total length of 388 m.

**Monitoring System**

The bridge was monitored by the Division of Structural Engineering and Bridges, KTH Royal Institute of Technology, Stockholm, Sweden. Two monitoring systems, one permanent and one temporary, were installed on the bridge (Lorieux 2008). The permanent system consisted of four strain gauges measuring longitudinal strain on the main steel beams, two strain transducers measuring transverse strain on the concrete slab, and three accelerometers measuring vertical bridge deck acceleration, all at varying points on the slab and steel beams. The temporary system consisted of four accelerometers installed on the sleepers and within the ballast. The speed of the passing trains was obtained from two optical laser sensors, placed a distance of 26.05 m apart. The sensors’ output was used to determine the number of wagons of the train and the distance between two axles. This enabled the speed and length of the train to be determined through the distance between axles, bogies, and wagons.

**Comparisons with Modeling**

Two computational models were created for comparison against the experimental data. The first is the differential equation model, which was referred to in the previous section. The second was a finite-element model created using the LUSAS finite-element analysis software. A two-dimensional simply supported beam model was created with five different cross sections representing the variation in the Skidträsk Bridge. The elements used are BEAM elements, which are two-dimensional linear beam elements, at a mesh size of 0.1 m. For both models, calibration was performed using actual properties and measurements of the Skidträsk Bridge. The experimental data, finite-element model, and differential equation model all correlated well (Fig. 7). The power output from the train and locomotive passages was then evaluated for the experimental data and corresponding differential equation model.

**Results**

### Locomotive Passages

The potential power output obtained from a single-locomotive passage was evaluated for speeds ranging from 61 to 180 km/h (Fig. 8). Again, it was found that the PZT energy harvester generated more...
power when compared with its PVDF counterpart. For a single passage of the locomotive, a maximum of 1.55 μW was produced at a speed of 118 km/h from the experimental-based PZT harvester, with a corresponding model value of 1.31 μW. From the same speed, the PVDF harvester produced 0.83 and 0.7 μW from the experimental and modeled data, respectively. However, as the PVDF is less brittle than the PZT, its long-term reliability is believed to be significantly higher than that of PZT. Comparing the experimental power output with the finite-element double-track model bridge from the previous section, it can be determined that for energy harvesting, train passages are more efficient over short-span bridges. While the energy harvested from a single-train passage is relatively low for the locomotive passage, the energy harvested from multiple-train passage can be stored to a predefined level, which, when reached, is capable of powering a wireless communication device. With the highly timetabled nature of train networks, the system can be calibrated so as to act as a SHM tool.

Steel Arrow Passages
The estimated power outputs from single passages of the 388-m-long Steel Arrow train at varying speeds was found for speeds ranging from 6 to 118 km/h (Fig. 9). The PZT harvester produced power outputs ranging from 24.1 to 16.9 μW at speeds of 65 to 118 km/h, respectively, from experimental data and power output of 23.4 and 16.1 μW from the models. The PVDF harvester produced 12.8 and 12.4 μW from the same experimental conditions and 9 and 8.6 μW from the models. The values are lower than the finite-element modeling considered in the previous section but significantly higher than that produced by a single locomotive. Apart from the difference in stiffness characteristics of the bridge considered in this paper, the Steel Arrow being a freight train may also be a contributing factor as the spacing between the axles are far smaller than the passenger trains previously investigated. Again, with multiple train passages and through storage and calibration, the potential use of the energy harvesters to power small, low-powered devices for the purposes of SHM is confirmed.

Structural Health-Monitoring Potential
The use of the energy-harvesting adhesive patch system as a method for the detection of damage and the SHM of bridges was subsequently investigated. With the change in stress conditions created as a result of damage to the structure (Pakrashi et al. 2010; Perry and Koh 2008), there will be a subsequent change in the levels of energy harvested from the structure. As the harvested power is related to the RMS voltage and to the accumulation of dynamic responses filtered by electromechanical coupling over the period of the train passage, the use of an energy-harvesting system for SHM is not dependent on individual measurements over time. This is an advantage because the ratio of undamaged to damaged energy-harvesting potential is less affected by localized noise and is expected to be more robust because of the natural averaging that is carried out while energy is harvested.

The calibration of the energy-harvesting system for use in SHM is dependent on a number of factors. These include the power generated from a single passage over the undamaged bridge, the storage capacity of the system, the power requirements for the wireless transmitter, and the number of train passages over the bridge for a given period of time. Upon these parameters being determined, any damage to the bridge, be it instantaneous or gradual, would result in a change in the amount of energy harvested. The damage mechanism alters the strain conditions of the structure and thus would be detected by utilizing this method, be it due to spalling (Schuler et al. 2006), bond slip (Monti and Spacone 2000), the yielding of the steel reinforcement (Mansour et al. 2001) and the buckling and yielding of steel columns (Nakashima and Liu 2005), or bolt damage (McCarthy et al. 2005). The strain variation results in changes in the energy-harvesting levels and thus can indicate the presence and position of the damage, but not the type of damage. Through the factoring of this change against the undamaged levels, the magnitude of the damage can be determined, as outlined in the subsequent sections.

Modeling of Damage
The finite-element model utilized in the previous sections for the determining of energy-harvesting potential from train–bridge dynamics was employed for assessing the feasibility of SHM using the energy-harvesting system. The 201Loco train, traveling at 100 km/h, was chosen as an example to demonstrate how damage evolution and position can influence the energy harvested at a given device. Damage was modeled at two different locations, with varying crack depth ratio (CDR) ranging from 0.05 to 0.20, in increments of 0.05. Each 0.05 CDR increment represents an increase of 40 mm in the crack depth. Two crack widths were chosen, of width 400 and 800 mm, to investigate the relationship between increased width of damage and the effect on the energy-harvesting system. A relatively localized damage, as opposed to diffused damage with larger influences on the global dynamics of the structure, is considered in this paper (Fig. 10). Consequently, successful application of SHM on this localized damage will ensure the potential of using energy harvesting for health monitoring in a wide range of damage situations.

Damage Detection
SHM is a four-step process with the detection of the presence of damage, the location of damage, and the extent of damage being the first three steps. The final step is the assessment of remaining service life and this is usually treated independently (Rytter 1993). The ability of the energy-harvesting system to determine the presence, location, and magnitude of the damage are investigated to determine whether it satisfies the first three criterion of SHM. The power-harvesting profile from the model with localized damage was evaluated and compared against the power-harvesting profile for an undamaged model, with the undamaged situation providing a benchmark. Using a monotonic descriptor of damage detection is typically

![Fig. 9. Energy-harvesting system power outputs from Steel Arrow passages](image-url)
considered to be a good method for estimating the damage extent (Pakrashi et al. 2007). The influence of the damage was determined through the modeling of the energy-harvesting system as an array located along the bottom beam supports of the finite-element model. The locations of the harvesting system and the grid spacing can be made commensurate with resolution at which damage effects need to be identified and the consequences of damage at a certain location. Such locations or spacing may be assessed from standard static analysis. At each chosen position, the influence of damage was determined through the normalized calibration of the harvested energy against the energy harvested from the undamaged model case (Fig. 11).

The damage was introduced centered about the midspan of the central support beam, with the solid line signifying the normalized power with damage of 0.8 m width and the broken line representing the normalized power with damage of 0.4 m width. The region closest to the damage experiences the largest variation in the normalized power harvested and the normalized power for the damage of width 0.8 m is more significant when compared with its 0.4-m-width damage counterpart. The change in the normalized power harvested with increasing CDR is related to the proximity of the energy harvesters to the damage location [Fig. 11(a)]. Energy harvesters positioned closest to the damage location experience a more significant change than their counterparts positioned at greater distances. For the 0.8-m-wide damage of CDR = 0.20, at the location 3.4 m from the edge of the damage, the normalized power harvested was 0.97, compared with 0.70 at the location of 0.4 m. For the 0.4-m-wide damage, again at CDR = 0.20, the normalized power was 0.98 at a location of 3.6 m and 0.81 at a location 0.6 m. The use of a number of the energy harvesters can therefore be used to identify the position of the damage, with increased change in the normalized power generated indicating a position closer to the damage.
damage. It was found that at the location of damage, the normalized power increases significantly [Fig. 11(b)]. For 0.8-m damage width, at a CDR = 0.20, the normalized power increases to 3.56 at the damage edge 4.9 m along the length of the span, labeled Edge 1A, and 3.31 at the damage edge 5.7 m along the length of the span, labeled Edge 2A. For 0.4-m damage width, again at CDR = 0.20, the normalized power increases to 2.50 at the damage edge 5.1 m along the length of the span, labeled Edge 1B, and 2.31 at the damage edge 5.5 m along the length of the span, labeled Edge 2B. This marked increase in the normalized power can be used to identify the magnitude to which the damage has developed in the structure, because of the monotonic nature of the curves upon the introduction of damage to the structure.

The ability of the energy-harvesting system to detect damage at a nonsymmetrical location was also investigated. Damages, again of widths 0.4 and 0.8 m with CDR ranging from 0.05 to 0.20, were introduced centralized about the quarter-span located 2.65 m from the support along the central support beam. The results of quarter-span damage (Fig. 12) are in keeping with that of midspan damage. The influence of the damage can again be detected through the reduction in the normalized power at energy-harvester positions situated along the length of the beam [Fig. 12(a)], with the proximity to the damage location again being a critical factor. For damage of width 0.8 m for CDR = 0.20, the normalized power is 0.44 at a location 0.45 m from the damage and for damage of width 0.4 m for similar CDR, the normalized power is 0.68 at a distance of 0.65 m. Because of the nonsymmetrical location of the damage, between the closest support and the position of damage for both damage widths, shown as negative distances in the figure, there is an increase in the normalized power between CDR of 0.15 and 0.20. At the position of damage, there is again a marked increase in the magnitude of the normalized power with increasing CDR [Fig. 12(b)]. For 0.8-m damage width, at CDR = 0.20, the normalized power increases to 48.51 at the damage edge 2.25 m along the length of the span, labeled Edge 1A, and 6.92 at the damage edge 3.05 m along the length of the span, labeled Edge 2A. For 0.4-m damage width, again at CDR = 0.20, the normalized power increases to 37.74 at the damage edge 2.45 m along the length of the span, labeled Edge 1B, and 9.03 at the damage edge 2.85 m along the length of the span, labeled Edge 2B. Again through the calibrated system, the magnitude of the damage can be determined, because of the quite monotonic nature of the normalized power-harvesting curves once damage is detected.

Structural Health Monitoring: Experimental Data
Experimental data from a laboratory-scale experiment on damaged beam and model vehicle interaction was considered next (Pakrashi et al. 2010). This entailed a model two-axle vehicle, with an axle distance of 0.11 m, traversing a phenolic beam of length 0.91 m. Damage was introduced in the form of an open crack located along the lower section of the beam, with CDR of 0.167, 0.33, and 0.5. The vehicle was accelerated from a resting position by means of a string that was coiled around a motor located at the opposite side as the initial position. The response due to the bridge–vehicle interaction was recorded by means of two strain gauges, located at distances 4 and 6 mm from the position of damage. The strain data were subsequently analyzed and the normalized power harvesting for the varying CDR was evaluated (Fig. 13). With increasing CDR, the presence, location, and magnitude of the damage can be ascertained through the use of the energy-harvesting system, thus satisfying the first three criteria of SHM.
normalized power increases, with proximity to the location of the damage being directly related to the magnitude, as was previously established in the finite-element damage analysis.

Conclusions

This paper presents the feasibility of using train–bridge interaction for energy harvesting and proposes a possible application in SHM. Two different piezoelectric materials, PZT and PVDF, were compared for energy-harvesting purposes. Although PZT showed a significant increase in power generated, the brittle nature of the material is a potential reliability risk. Therefore the PVDF material is believed to be the better option at this time. Five international trains were chosen to determine their potential for energy harvesting from train–bridge dynamics. A three-dimensional finite-element model was created and compared against differential equation based models. Full-scale testing data, along with calibrated finite-element and differential equation models for train–bridge interaction, were used and potential power output of the energy-harvesting system was determined. Piezoelectric harvesting systems were observed to be appropriate for harvesting energy support to wireless sensors with low power demand. Important trains were observed to have individual signatures of energy harvesting and potential of harvesting for bridge structures. Multiple crossings of trains do not produce double the amount of energy as compared with a single-train passage. Train passages were found to produce power outputs up to 588 $\mu$W for passenger trains, namely the ICE, and 24.1 $\mu$W for freight trains, the Steel Arrow, both from PZT-based energy-harvesting systems. Bridges with high dynamic responses, which are often identified as more in need of SHM than bridges with low dynamic responses, are more suited to energy harvesting from train passages over bridges. The use of energy-harvesting systems for use in the SHM of train bridges was investigated. It was found that an array of energy-harvesting systems have the potential for determining the location and the magnitude of damage throughout a bridge and compared against laboratory experiments. The extent of damage can be monotonically represented by the harvested energy.

References

LUSAS 14.7 [Computer software]. Kingston upon Thames, Surrey, U.K., LUSAS.


Strand7 2.4.4 [Computer software], Sydney, New South Wales, Australia, Strand7 Pty.


