Using measured rotation in a beam to detect changes in its structural condition

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Using measured rotation on a beam to detect changes in its structural condition

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ABSTRACT

A recent survey of Europe's highway infrastructure has concluded that almost half of Europe's bridges are nearing the end of their design live. Work in the wider Structural Health Monitoring sector is aiming to develop reliable and cost-effective methods for verifying condition, remaining service life and safety of ageing structures. Most bridge condition assessment methods are based on deflection, acceleration or strain measurements. This paper looks at the possibility of using rotation measurements as a main parameter to identify damage. This study looks at numerical analyses of a moving point load on a one-dimensional bridge model to provide the theoretical basis of the proposed damage detection method. It is shown that when local damage occurs, even when it is remote from a sensor location, it results in an increase in the magnitude of rotation measurements. This study looks at how best to exploit this fact for damage detection. A number of damage scenarios, sensor locations, and load arrangements are investigated in this study and their influence on the ability of the algorithm to detect damage are reported.

KEYWORDS

Structural Health Monitoring (SHM); bridges; rotation; accelerometers; damage detection; influence line

Introduction

This paper proposes the use of bridge rotation response to a moving load to identify damage in a bridge and its location. Similar to vertical deflection due to a moving force, rotation responds to local damage in a bridge. However, rotation is sometimes easier to measure than deflection.

Bridges can be our infrastructure lifelines, connecting communities and aiding economic activity. These are costly assets and are exposed over time to many degradation processes as a result of environmental factors and changing loading conditions. A recent survey of Europe's highway infrastructure revealed that almost half of Europe's bridges were built before the 1960s (Žnidarič et al., 2011) and are nearing the end of their design lives. Thus, bridge owners are often interested in methods for verifying safety, condition, and remaining service life of such ageing structures.

In most countries with a bridge management plan, visual inspections are predominantly employed for both maintenance and preservation of bridges. While such techniques currently remain the most popular, they can be time consuming, subjective and do not provide an estimate of capacity. They may also be expensive in terms of road or lane closures which can be disruptive to traffic and attract costs to the users. As a result, interest in Structural Health Monitoring (SHM) systems of bridges in their operational conditions has increased (Rytter, 1993).

A typical approach of SHM considers the presence, location and extent of damage, along with the estimation of remaining service life under certain conditions (Zelenika et al., 2020). To achieve this, the use of new technologies (Nichols et al., 2003), techniques (Jaksic et al., 2016) and markers (Worden et al., 2008) are used, along with the understanding of fundamental engineering (Papadimitriou, 2004). The use of sensors for the bridge sector is typically sparse and consequently bespoke ways of maximising data from a limited number of sensors are often sought after (Ko & Ni, 2005). In the same vein, this paper presents a new way of detecting bridge damage through rotation measurements, and demonstrates in with an Euler-Bernoulli beam example.

Section 2 gives a brief background of some of the SHM systems and approaches in the context of this problem. Section 3 details the rotation sensors used throughout the study and an implementation on a real bridge is carried out. Section 3 covers a numerical analysis of a 1-D numerical beam model loaded with single point force. Section 4 details an experimental study of a 3 m long simply supported beam to validate the results of the numerical simulations. It also covers the ability of the aforementioned sensors to pick up the change in rotation. Finally, section 5 looks at identifying damage when the bridge is loaded with a multi-axle vehicle.

This paper intends to address the following questions:

Is rotation a sensitive parameter to damage?

What is the effect of change in stiffness and its location on rotation measurements?

What may be the optimum sensor location for recording rotations on a simply supported structure?

Collectively, the work not only provides new evidence bases but also establishes pathways towards value of information around implementing SHM for such problems.

Background

Existing SHM approaches typically use strain, deflection and acceleration responses of a bridge to evaluate its condition

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(Brownjohn et al., 2011). Although they all provide useful information about the bridge structural behaviour, have their own shortcomings. Vibration-based monitoring technique performances tend to observe (Buckley et al., 2021) that, despite their popularity, many approaches are insensitive to damage except for the most severe damage scenarios. Methodologies utilising strain as a main parameter for damage identification measure a local response of a structure and is typically sampled at a significantly lower frequency than accelerometers (Li et al., 2015). However, this also means that they tend to sense the presence of damage in the immediate vicinity of sensor locations. Previous studies have shown the potential for detecting damage in a bridge by analysing its deflection response (Alamdari et al., 2019; Im et al., 2013). Deflection is a global property, and hence a parameter that is sensitive to damage at any location along the length of a bridge. However, it requires a reference point for measurement. This can often lead to difficulties recording deflections, especially over inaccessible areas such as roads, railways or deep water.

Using rotation as a damage indicator includes the advantage that it will prompt a global response in the bridge and negates the need for a reference point removed from the structure. Like displacement, rotation also captures static response information, but it is typically easier to measure.

A study into identifying simulated cable stiffness loss in a cable stayed bridge using rotation measurements concluded that only two measurement points were adequate to monitor the integrity of the bridge structure using rotation-based measurement (Al-Ghalib et al., 2011).

The theoretical basis of this approach comes from the fundamental ideas of moment-curvature relationship, in a dynamic sense (Chandrashekhar & Ganguli, 2009; Inaudi & Glisic, 2002; Majumder & Manohar, 2004, 2003).

Establishing sensor capability for rotation measurement

Inclinometers, or tiltmeters, are designed to measure angular rotation of a test specimen with respect to an "artificial horizon". The main operating principle of most inclinometers is that it performs measurements of different responses generated by pendulum behaviour in the presence of gravity.

The performance and accuracy of inclinometers have significantly improved, and it is now possible to measure inclinations to microradian (10^{-6} rad) accuracy using state-of-the-art sensors (Bruns, 2017; Tripura et al., 2019; Wu & Chuang, 2004; Wyler, 2016).

A performance test was conducted on a 17.8 m span bascule bridge, loaded with a 4-axle 32 tonne truck. When the bridge is down it behaves as a simply supported bridge. The test structure is shown in Figure 1(a).

Rotations were calculated using acceleration data obtained from two uniaxial Honeywell QA-750 accelerometers placed at the ends of the beam and orientated in the longitudinal direction (i.e., at points A and B in Figure 1(a)). These accelerometers can report very low frequencies, are able to sense gravity and suitable to be used as inclinometers. Figure 1(b) shows peak rotation at approximately 0.1°.

This test indicates the typical rotation values and demonstrates the performance of the sensors. The same sensors are utilised again in laboratory experiments, (presented in Section 5) to establish the ability of commercially available sensors to detect damage.

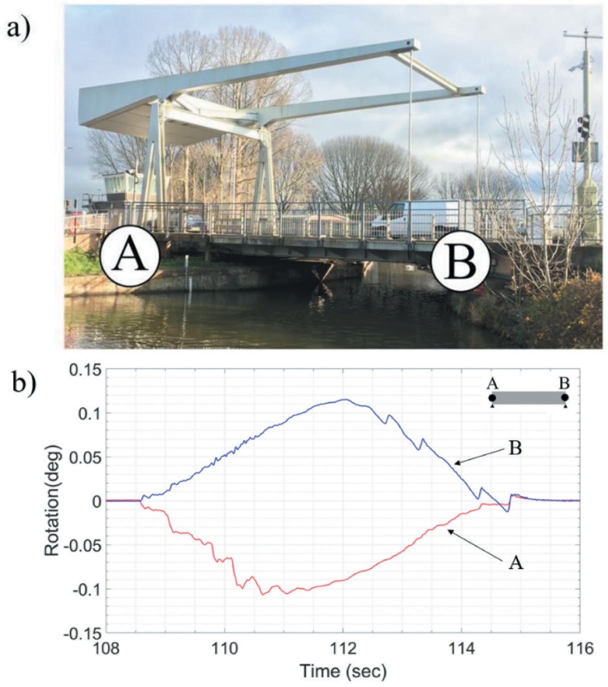

Figure 1. Recording rotations on a bascule bridge, (a) Elevation of the test structure and (b) Rotation time history calculated at support locations.

Numerical analysis

To present the feasibility of using rotation measurements for damage detection, numerical studies are carried out first. Section 4.1 illustrates the rotation response along the length of a beam due to a static load, where the rotational response was obtained for a healthy and a damaged beam, respectively. As it is not practical to measure rotation at too many points along the length of a bridge, Section 4.2 shows how the rotation of a single point changes due to the passage of a moving load. This also is illustrated for a healthy and a damaged beam. The rotation results obtained from the models are in-line with those obtained from the field measurements as seen in Figure 1. The numerical and experimental investigations are generally centred around a 30% reduction in stiffness over 5% of span and minor deviations from these values are indicated in the sub-sections. The level of damage considered in this paper is medium to relatively significant. Detection of smaller damages can be fraught with lower detection and false alarm probabilities, although there are a number of recent methods which have shown promising results for small damages (Kisa, 2004). Benchmarks around small damages should be developed in future in relation performances of such competing methods through different markers.

Damage occurring in multiple locations is not demonstrated in this paper but if they are close together, it often presents itself as combined and more extensive damage (Okosun et al., 2020). The method and sensor placement presented in this paper will reflect a combined effect of damages further apart as well. Closely spaced sensors can address this problem to some extent (O'Donnell et al., 2017), but their choice will be dependent on the need to detect individual damages over the combined effects. Demonstration of the work presented on full-scale bridges will further augment the prototype evidence base around the proposed idea in future. For such full-scale examples, establishing a healthy baseline will be important to obtain consistent results, which can be reasonably obtained from initial modelling and experimentation. The responses in full-scale tests are expected to be noisier than what has been presented in this paper. This can be improved through data processing (Jaksic et al., 2014) or averaging of experiments (SCI, 2015). While the presented approach is only for simply supported single span beams, a significant percentage of bridges around the world can approximated to this fundamental model (Žnidarič et al., 2011) and consequently the approach presented in this paper influence a wide range of bridge assets.

Rotation profile along length of beam due to single point load

A 3 m long simply supported Euler-Bernoulli beam is considered first, as illustrated in Figure 2(a). The flexural properties adopted for the beam are similar to those of a 127 × 76 × 13 universal beam loaded in the weak direction (SCI, 2015). The Young's modulus is 210GPa and the beam is loaded with a 31 kg load at 3 *L*/8, where *L* is the span.

Figure 2(b) illustrates the rotation of the beam to a stationery point load, a response obtained if the beam was installed incrementally with many rotation sensors. Although this approach is impractical for physical testing, it illustrates the behaviour along the whole length of the beam. The continuous curve represents the rotation of the healthy beam while the dashed curve shows the corresponding results for the beam with localised reduced stiffness, or "damage", at quarter-span. As expected, damage induces a higher rotation in the beam.

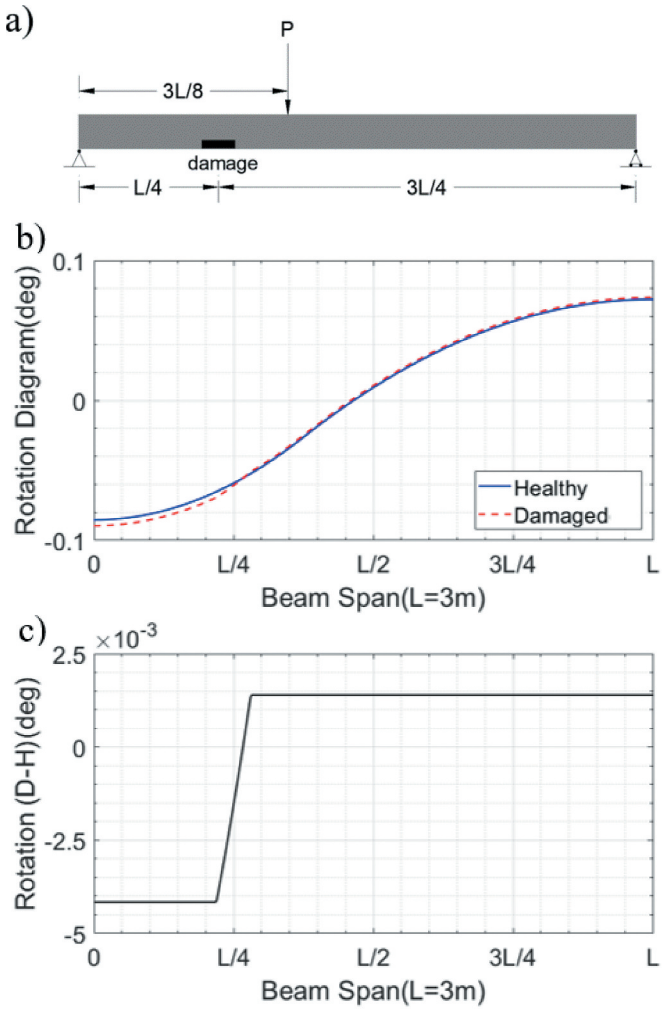

Figure 2. Displacement responses of healthy and damaged beam models loaded with a single point load at 3 *L*/8, (a) Sketch of the 1D model; (b) Rotation; and (c) Difference in rotation between healthy and damaged cases.

The difference in rotation of the healthy beam and the damaged beam is presented in Figure 2(c). The difference in rotation varies from constant negative to constant positive, with a sharp change at the damage location. For the loading and damage scenario illustrated, it can be noted that the amplitude of the rotation difference is greater on the left-hand side of the damage than on the right. At the mid-span and right-hand support, the same rotation difference is shown. This is explored later in Section 4.2 to identify favourable locations on the beam as to extract data.

Rotation signal at a single point due to moving load

The model considered in the previous section was augmented by a 31 kg moving point load, as depicted in Figure 3(a), with the rotational response obtained from simulated sensors at locations A-C.

Figure 3(b) presents the rotation response obtained from the simulated sensors for the healthy beam (solid plot) and a damaged beam (dashed plot) where damage is located at L/4. In this case, rotation is plotted against the location of the moving point force. Sensors A and C, placed at the support locations, experience negative and positive rotation, respectively, as the point load crosses the beam. Sensor B at mid-span initially experiences positive rotation but this becomes negative when the load passes this point. For sensor A, the increase in rotation due to damage is small but clearly evident. For sensors B and C the increase in rotation due to damage is smaller. Overall, the figure shows that when damage occurs, even if it is remote from the sensor location, it results in an increase in rotation at all three sensor locations and confirms the increase of rotation corresponding to reduction of stiffness.

Differences between the rotation responses for the healthy and damaged beam cases are plotted in Figure 3(c). The rotation difference for each sensor is triangular with maximum amplitude when the load is over the damage location (at *L*/4 in this case). The magnitude of the rotation difference, which reflects the sensitivity of a particular sensor to damage, is approximately 0.0048° Sensor A, located at the left-hand support and 0.0015° for Sensors B and C, located at mid-span and the right-hand support, respectively.

These results are similar to the findings presented in Figure 2. Since Sensor A is closer to the damage location, it is more sensitive to damage than Sensors B and C. It is also of note that Sensors B and C are both on the same side of the damage location (to the right in this case) and hence have the same sensitivity to damage. The reason that sensors B and C are showing the same sensitivity to damage can be understood by re-examining Figure 2(c).

Figure 4 shows the rotation difference when damage is simulated at midspan. For sensors A and C placed at the supports the differences are triangular with a peak value of 0.00425° and the peak corresponding to the damage location. However, for sensor B at midspan the amplitude of the difference in rotation is much smaller and it is not triangular in shape. This is because sensor B is located at the damage location, where the change in rotation due to damage is close to zero which is consistent with the behaviour previously observed in Figure 2(c).

Figure 5 shows the rotation difference plot for a multiple damage scenario, where damage is modelled similarly at the quarter and three-quarter span locations. The damage severity

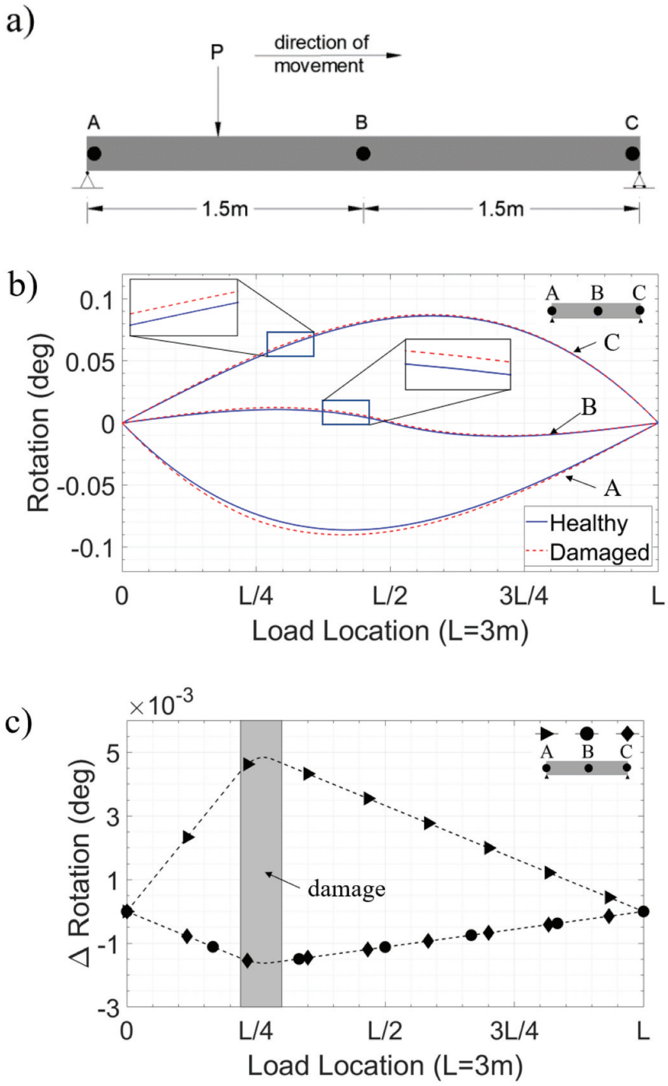

Figure 3. Effect of quarter-point damage on beam rotation measurements, (a) Sketch of the 1-D beam model; (b) Rotation time history recorded for healthy and damaged beam cases; and (c) Differences between the healthy and damaged rotation signals shown in part (b).

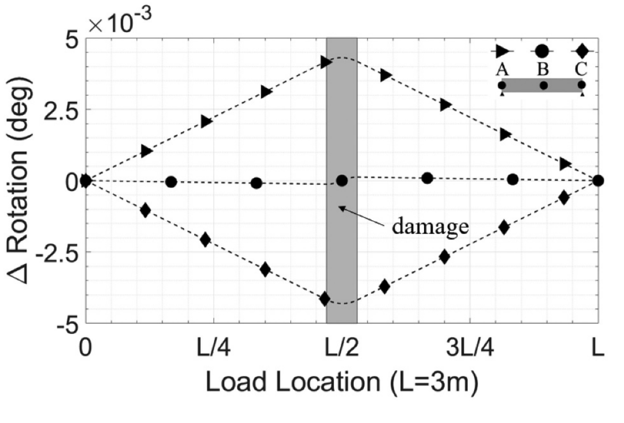

Figure 4. Difference in rotation measurements for healthy and damaged beams where damage is at midspan.

for both locations is a 30% reduction in stiffness over 180 mm. Two slope discontinuities are visible in Figure 5, corresponding to the passing of the load over the damage locations. The rotation difference amplitudes are approximately 0.0055° and 0.00325° at the damage locations for Sensors A and C. The corresponding results for Sensor B, located at midspan, are approximately 1×10^{-3} and vary in sign.

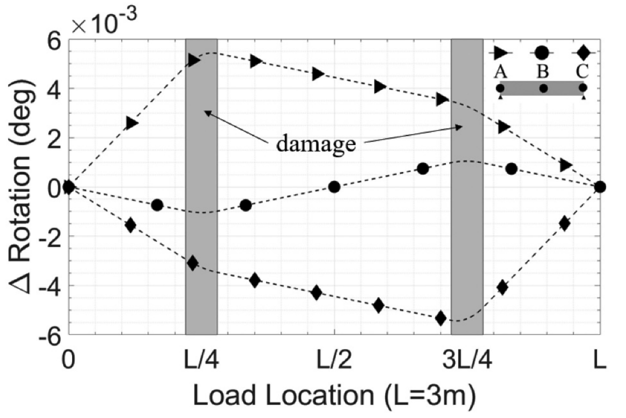

Figure 5. Difference in rotation measurements between healthy and damaged beam cases where damage is modelled at *L*/4 and 3 *L*/4.

In conclusion, when damage occurs in a bridge type structure, it is evident in rotation measurements. Furthermore, information on the damage locations can be found when the differences between rotations for healthy and damaged beam cases are examined. Sensitivity is improved for sensors placed between the damage location and the nearest support to the damage. However, there is a reduced magnitude of rotations for sensors close to the centre of the damage. Support locations are chosen here as a good compromise for short span bridges with the further advantage that access on site is likely to be easier. The validity of using support locations can be seen again in Section 5.

Experimental validation

An experimental study was carried out on a 3 m long simply supported beam to validate the results of the simulations presented in Figure 4, where damage was modelled at midspan. Section 5.1 describes the laboratory setup and instrumentation used, while Section 5.2 discussed the test and the results.

Test setup

The material and geometric properties of the beam structure were designed to be similar to the flexural properties defined for the 1-D beam model used in the numerical studies presented above. The beam was a 127x76x13 steel universal beam loaded in the weak direction. The supports of the beam were fabricated as pin and roller.

A 31 kg dumb-bell mass was used to load the structure at discrete points. The load was applied to a series of static load cases at 100 mm intervals along the length of the beam.

The sensors used on the beam to calculate rotations are the same ones as those used in the bridge test described previously in Section 3. The levels of rotation of the beam are similar to those experienced by the aforementioned bridge in Section 3. The test set-up can be seen in Figure 6.

Damage detection using rotation measurements of a test beam

The simply supported beam structure was initially loaded using the 31 kg point load in a series of static load cases at 100 mm intervals along the length of the beam. This is modelled as the healthy beam case. Subsequently, the beam was stiffened at the

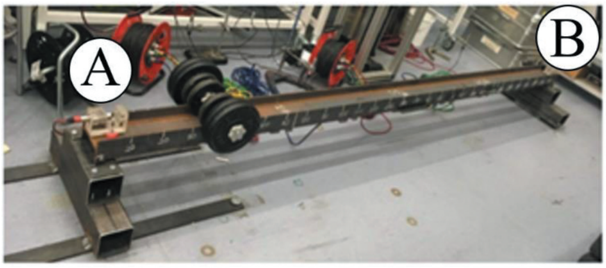

Figure 6. A 3 m long simply supported beam with load at 0.4 m and rotation sensors at supports.

midspan location using steel angle sections to simulate "negative damage". The steel angle sections were 180 mm long and increased the second moment of area of the cross section by 33%. The stiffening detail can be seen in Figure 7.

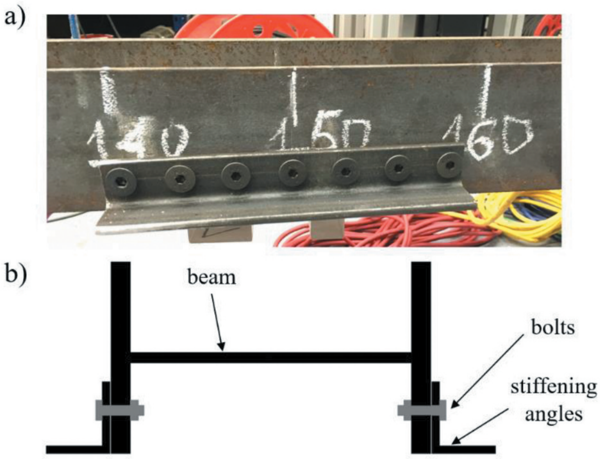

Figure 7. Beam stiffening detail, (a) Elevation view of the stiffening angles (b) Cross section of beam and stiffeners.

This negative damage concept allows for a non-destructive test and permits the beam to be used for other purposes after the test. To test repeatability, the healthy and stiffened beams were both loaded four times.

Figure 8 shows the rotations measured at the left end (sensor A) and right end (sensor B) for all load positions. In total there are four plots for the healthy beam and four for the stiffened, or "negatively damaged", beam for each sensor (illustrated in the insert in the figure). It can be seen in the figure that the measured rotations are consistent, showing the measurements to be accurate. It can also be seen in the figure that the rotations for the stiffened beam are less than for the healthy beam.

The average of the four rotation measurements calculated for the original healthy beam is subtracted from the corresponding average rotation for the stiffened beam and the results for sensor locations A and B are presented in Figures 9(a) and 9(b) respectively. Each point in the plots represents the rotation difference for a given loading position. The solid line plots in Figures 9(a) and 9(b) show the numerically predicted difference in rotation calculated using the numerical model discussed in

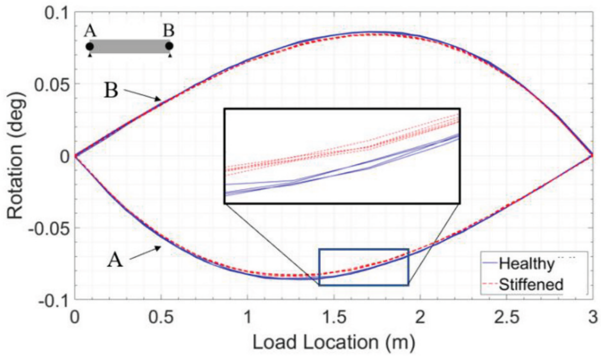

Figure 8. Effect of damage on beam rotation measurements, rotation versus load location.

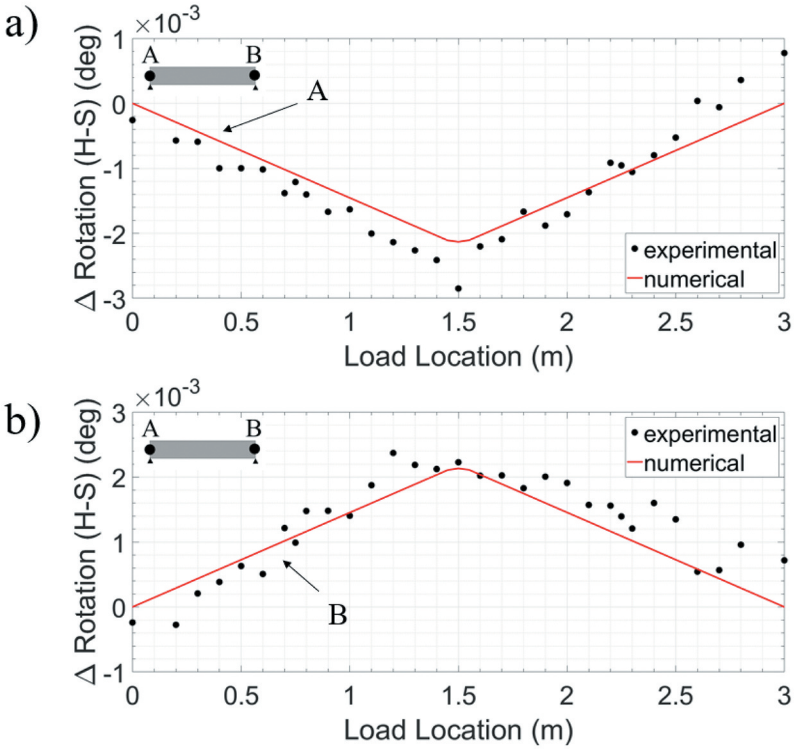

Figure 9. Effect of damage on beam rotation measurements, (a) Difference in rotation measurements for healthy and stiffened beam cases for sensor at the left-hand support (Point A) and (b) Difference in rotation measurements for healthy and stiffened beam for sensor at the right-hand support (Point B).

Section 4. It can be seen that the experimentally measured points agree well with the theoretical predictions and the plots approximate a triangular shape with the peak corresponding to the stiffening location. Stiffening at this level can thus be successfully detected by sensors in a laboratory setting.

Damage detection using rotation measurements from a multi-axle vehicle

Static analyses are carried out next on a beam model to investigate the application of the proposed damage detection method to a multi-axle vehicle situation.

The bridge is modelled as a 20 m long simply supported beam. The flexural properties adopted are typical for a 10 m wide bridge structure consisting of 9 Y3 precast beams spaced at 1.25 m centres with a 160 mm thick deck slab (Concast Precast Group Concrete Prestressed Girders Technical Guide, 2009). This results in a total depth of 1060 mm, a second moment of area of 0.76 m^4 about the neutral axis, and a total cross-sectional area of 5.2 m^2. The Young's modulus for concrete is assumed as 34 GPa. Hypothetical sensors A and B are placed at the left and right-hand support locations, respectively, to record rotations from a 40 t 5-axle moving vehicle load. The damage is simulated as a 30% reduction in stiffness over a 1 m length (5% of the bridge span) at the quarter span location, as shown in Figure 10.

Figure 11(a) presents the rotation responses for the healthy and damaged bridge cases as the 5-axle vehicle loading is moved incrementally across the bridge. The difference between the rotation time histories (ΔRotation) are given in Figure 11(b). In this case, it is difficult to identify the damage location accurately from Figure 11(b) as the plot is no longer triangular and the largest amplitude occurs away from the damage location. This is because each plot in Figure 11(b) is in effect the sum of 5 separate triangles, as illustrated in Figure 11(c).

It is proposed in this study to back-calculate the rotational influence line of the bridge from its response to the vehicle. As the influence line is the response to a unit load, the difference between healthy and damaged influence lines will be triangular. Obtaining the influence line is possible (Concast Precast Group Concrete Prestressed Girders Technical Guide, 2009; McNulty & O'Brien, 2003; Moses, 1979; OBrien et al., 2006) if the axle weights and spacings are known, as would be the case if a Weigh-In-Motion systems were present (Yamaguchi et al., 2009).

Here, the rotational influence lines are calculated (OBrien et al., 2006) for the two sensor locations (i.e. two supports) and depicted in Figure 12(a). The continuous curves depict the healthy bridge case and the dashed curves show the damaged bridge case. The increase in the amplitude of the unit rotation response is due to the presence of damage. Figure 12(b) shows the difference between calculated influence lines (Healthy-Damaged). As expected, difference is triangular with the maximum amplitude at $L/4$ span, where the damage is simulated.

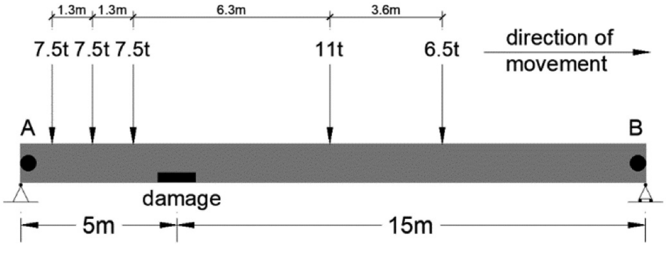

Figure 10. Sketch of 20 m long simply supported beam model representing a bridge and subject to 5-axle vehicle loading, with rotation sensors at A and B.

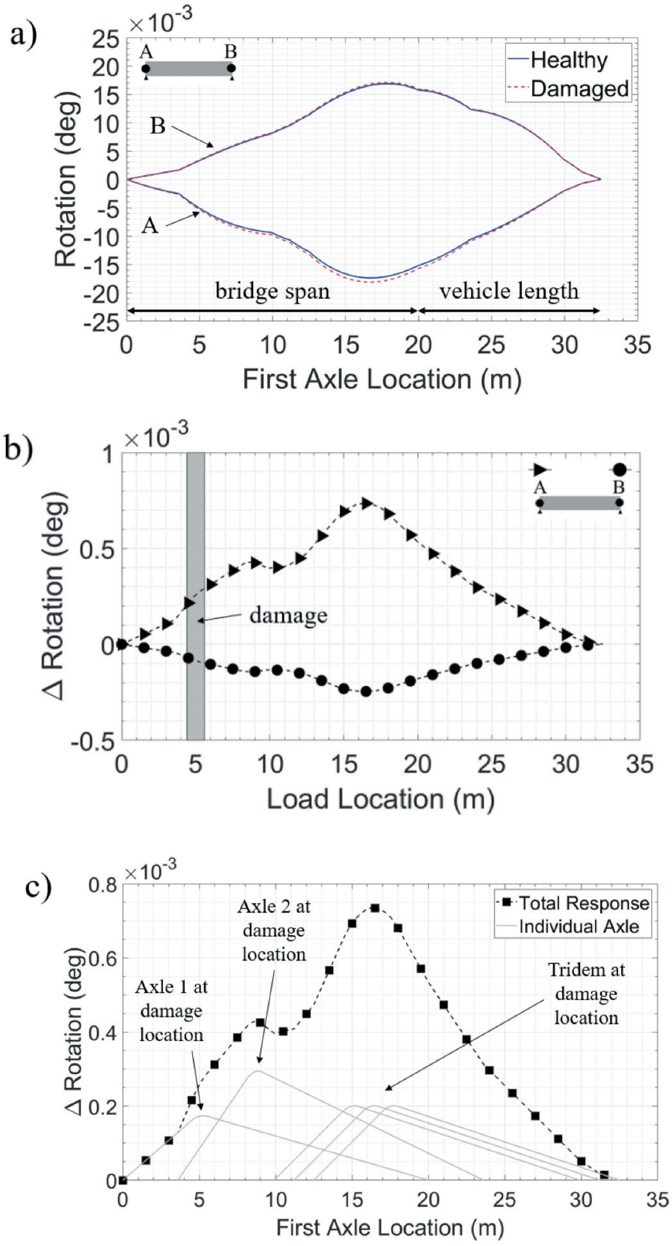

Figure 11. Simulation of rotation responses to 5-axle vehicle loading with (a) response for healthy and damaged bridge cases for sensor locations A and B, (b) difference in rotation measurements between healthy and damaged states and (c) difference in rotation measurements at A and contributions to the difference from each axle.

Conclusion

This paper discusses a bridge condition assessment methodology using rotation measurements. Initially numerical and experimental analysis are carried out on a beam model to investigate the sensitivity of rotation as a parameter to identify damage on bridge type structures.

Rotation is shown to be a sensitive parameter for identifying damage. In essence, if damage occurs, either locally or globally, it results in an increase in the magnitude of rotation measurements.

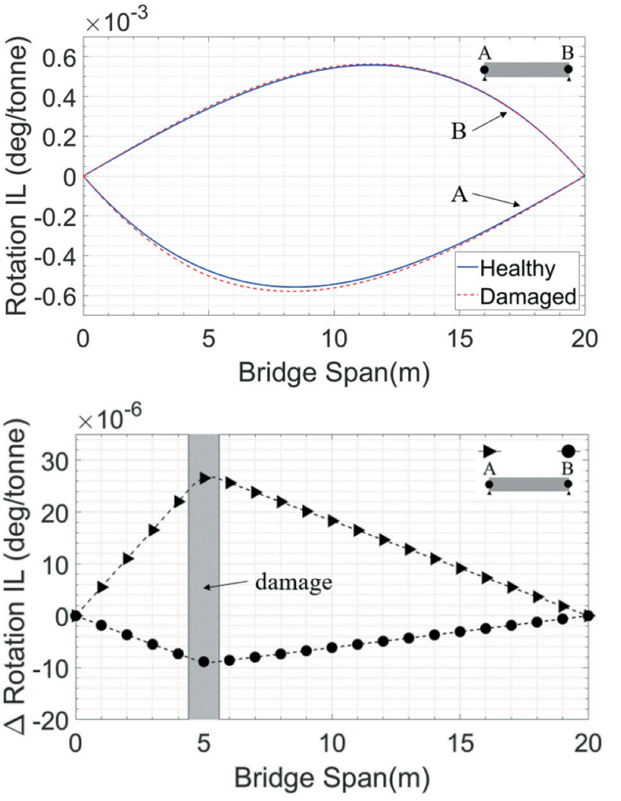

Figure 12. Effect of damage on calculated rotation influence lines, (a) Rotation influence line and (b) Difference in rotation influence lines for healthy and damaged states.

Numerical analyses carried out on a beam model, representing a bridge, with a multi-axle vehicle of known weight and axle spacing provides the theoretical basis of the proposed damage detection method. The difference in rotation influence lines obtained for healthy and damaged states using the response of a bridge to vehicles, can successfully identify damage and its location.

For simply supported bridge structures the most effective sensor locations to identify damage are supports, where the maximum amplitude of rotations occurs.

A sensor placed at a support location closer to a damage location is more sensitive to damage than a sensor placed at a remote location.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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