Identifying damage in a bridge by analysing rotation response to a moving load

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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. In the study a number of damage scenarios and sensor locations are investigated, and their influence on the ability of the algorithm to detect damage are reported.

KEY WORDS: Structural Health Monitoring (SHM); Bridges; Rotation; Accelerometers; Damage Detection; Influence Line.

1 INTRODUCTION

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

1.1 *Background*

Bridges are a critical component of a nation's infrastructure, connecting communities and aiding economic activity. Bridges are costly, and over time are exposed 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 [1] and so are nearing the end of their design lives. Thus, bridge owners are particularly vested in methods for verifying safety, condition, and remaining service life of such ageing structures.

In most developed countries, visual inspections are the predominate assessment method used for the maintenance and preservation of bridges. While such techniques currently remain the most reliable practice in industry, they are time consuming and subjective. They may also be expensive and can require road or lane closures which can be disruptive to traffic. As a result, the interest in electronic Structural Health Monitoring systems has arisen.

Structural Health Monitoring refers to the process of implementing a damage detection strategy for engineering structures by monitoring the system over a period of time using measurements from a sparse array of sensors. In the past decade the Structural Health Monitoring field has seen significant achievements with improvements in sensors, data acquisition electronics and computing technology.

1.2 *Objectives and outline*

Section 2 gives a brief background on existing Structural Health Monitoring systems.

Section 3 details the rotation sensors used throughout the study. Within this section the sensors are placed on a real bridge to determine realistic rotational properties for the study.

Section 4 covers a numerical analysis on a 1-D numerical beam model loaded with single point force.

Section 5 details an experimental study on a 3m 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.

This paper hopes 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 is the optimum sensor location for recording rotations on a simply supported structure?

2 BACKGROUND

Broadly speaking, existing Structural Health Monitoring systems in the literature use strain, deflection and acceleration responses of a bridge to evaluate its condition. Although these approaches have been shown to provide useful information about the bridge structural behaviour, each of the aforementioned parameters have certain shortcomings. A review of vibration based monitoring techniques [2] concludes that, despite their popularity, they are insensitive to damage except for the most severe damage scenarios. The methodologies utilising strains as a main parameter for damage identification measure a local response of a structure. Hence, they can only 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. Deflection is a global property, and hence a parameter that is sensitive to damage at any location along the length of a bridge. However, by the nature of this parameter 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 [3].

This paper proposes a damage detection method using rotation measurement for a single span beam and slab bridge and explores it numerically and experimentally.

3 MAGNITUDE OF ROTATION THAT CAN BE FEASBILY MEASURED ONSITE

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 caused by gravity.

The performance and accuracy of inclinometers have been significantly improved in the last decade, and it is now possible to measure inclinations to microradian (10^{-6} rad) accuracy using the state-of-the-art sensors [4],[5],[6],[7].

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 1a.

Rotations were calculated using the 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 1a). These accelerometers can sense frequencies as low as 0 Hz, so they are able to sense gravity and are suitable to be used as inclinometers. Figure 1b shows peak rotation at approximately 0.1 deg.

This test indicates typical rotation values and demonstrates the performance of the sensors. The same sensors will be ultilised again in laboratory experiments (as described in Section 5) to establish the ability of commercially available sensors to detect damage.

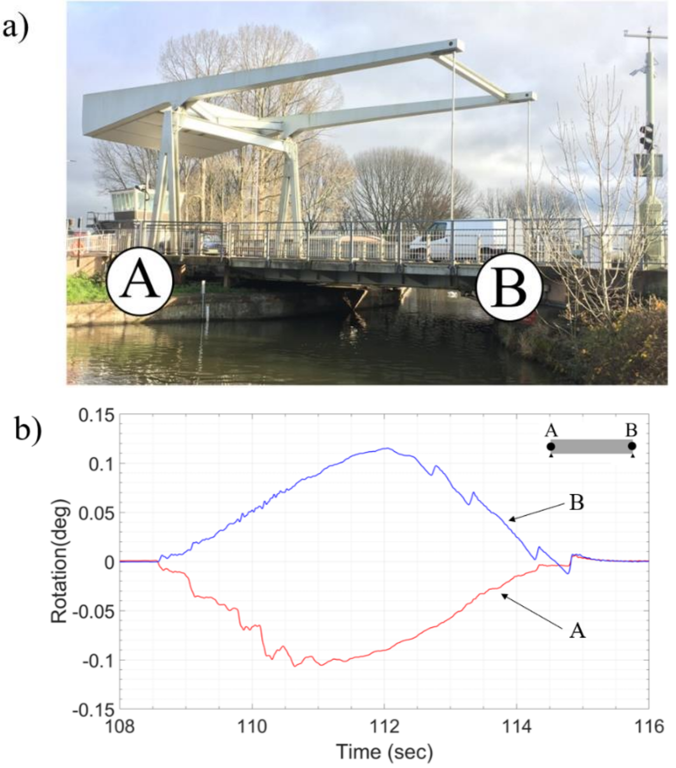


Figure 1. Recording rotations on a real bridge, (a) Elevation of the test structure (b) Rotation time history calculated at support locations.

4 NUMERICAL ANALYSIS

This section illustrates the concept of using rotation measurements for damage detection. Specifically, Section 4.1 shows the rotation response along the length of the beam due to a static load. The rotational response was obtained for a healthy beam and a damaged beam. As it is not practical to measure rotation at many points along 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 beam 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.

4.1 Rotation profile along length of beam due to single point load

The structure modelled is a 3m long 1-D simply supported beam structure, as illustrated in Figure 2a. The flexural properties adopted for the beam are similar to those of a 127×76×13 universal beam loaded in the weak direction [8]. The Young’s modulus is defined as 210 GPa and loaded with a 31kg load at 3L/8.

Figure 2b illustrates the rotation of the beam to the stationery point load. 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, when damage is modelled the rotation of the beam increases.

The difference in rotation of the healthy beam and the damaged beam is presented in Figure 2c. 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 at 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. The is explored later in Section 4.2 to identify favourable locations on the beam as to extract data.

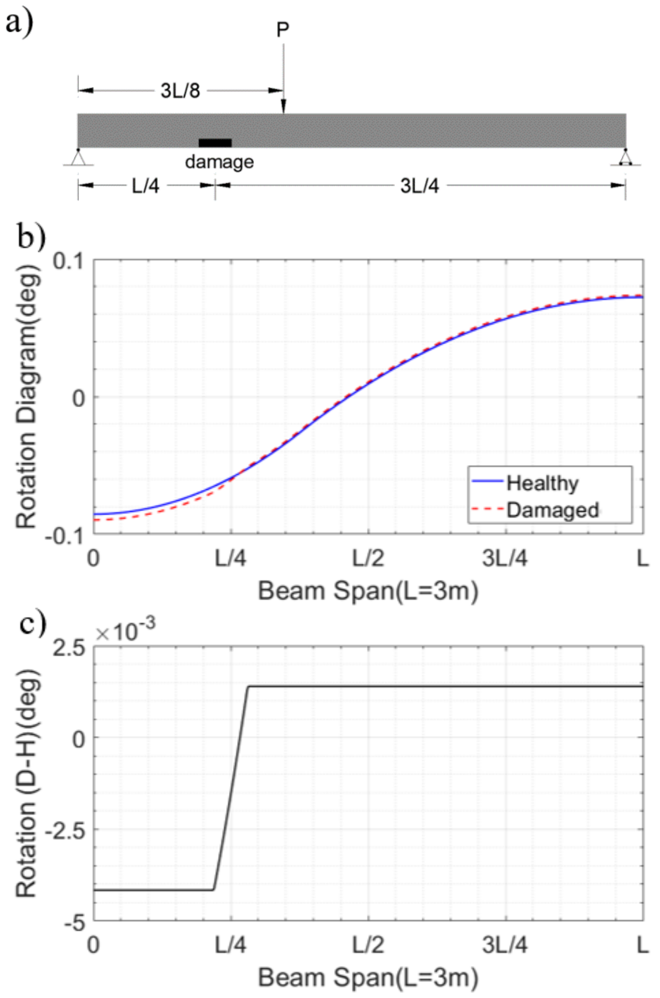


Figure 2. Displacement responses of healthy and damaged beam models loaded with a single point load at 3L/8, (a) Sketch of the 1D model (b) Rotation (c) Difference in rotation between healthy and damaged cases.

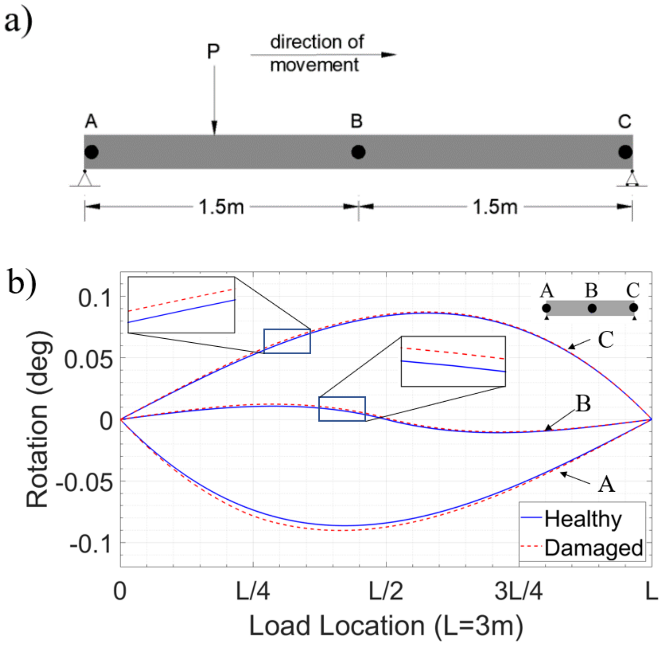
4.2 Rotation signal at a single point due to moving load

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

Figure 3b 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 that, as expected, rotation increases when stiffness is reduced.

The differences between the rotation responses for the healthy and damaged beam cases, are plotted in Figure 3c. 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 4.8 mdeg for Sensor A, located at the left-hand support and 1.5 mdeg for Sensors B and C, located at mid-span and the right-hand support.

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 2c.



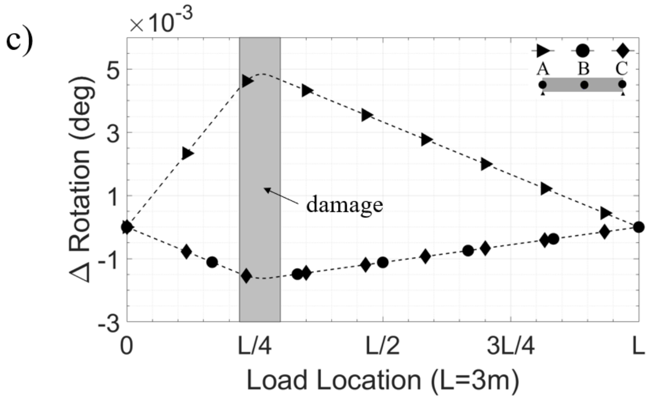


Figure 3. Effect of quarter-point damage on beam rotation measurements, (a) Sketch of the 1-D beam model (b) Rotation time history recorded for healthy and damaged beam cases (c) Differences between the healthy and damaged rotation signals shown in part (b).

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 4.25 mdeg 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 2c.

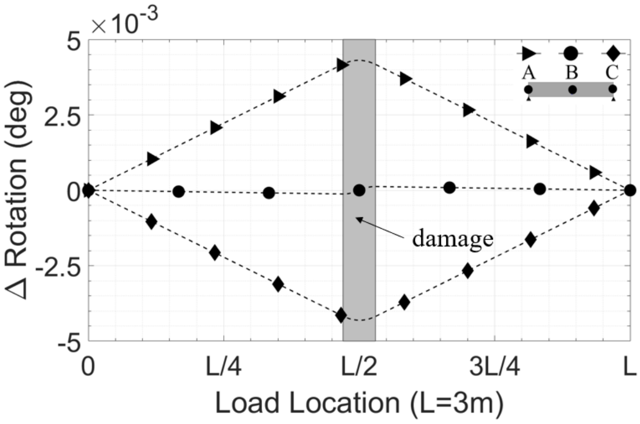


Figure 4. Difference in rotation measurements for healthy and damaged beams where damage is at midspan.

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 for both locations is a 30% reduction in stiffness over 180 mm. It is clearly visible in Figure 5 that there are two slope discontinuities can be seen in each plot, corresponding to the passing of the load over the damage locations. The rotation difference amplitudes are approximately 5.5 mdeg and 3.25 mdeg at the damage locations for Sensors A and C. The corresponding results for Sensor B, located at midspan, are approximately 1 mdeg and vary in sign.

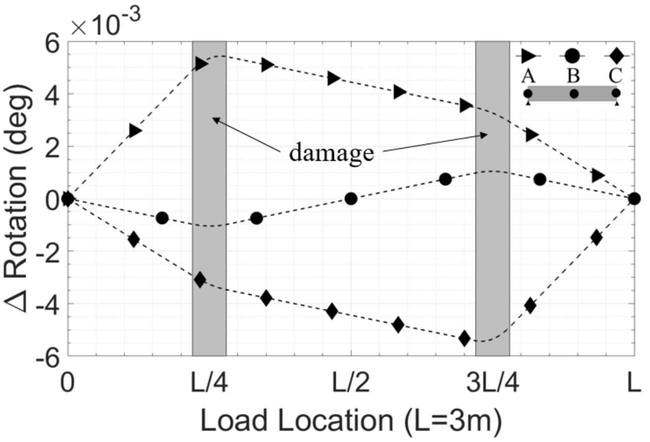


Figure 5. Difference in rotation measurements between healthy and damaged beam cases where damage is modelled at L/4 and 3L/4.

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.

5 EXPERIMENTAL VALIDATION

An experimental study was carried out on a 3m 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.

5.1 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 in 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.

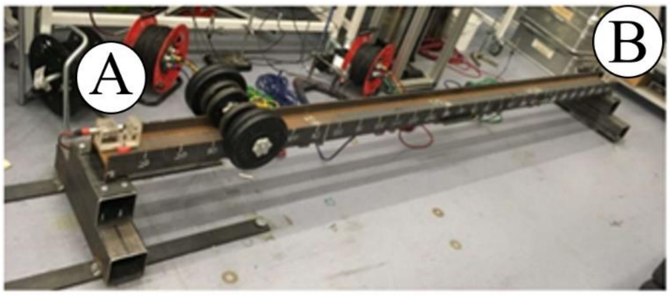


Figure 6. 3m long simply supported beam structure set up in the laboratory with load at 0.4m and rotation sensors at supports.

5.2 Damage detection using rotation measurements of a test beam

The simply supported beam structure in the laboratory 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 midspan location using steel angle sections to simulate ‘negative damage’. 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. The steel angle sections were 180 mm long and increased the second moment of area of the cross section by 33%.

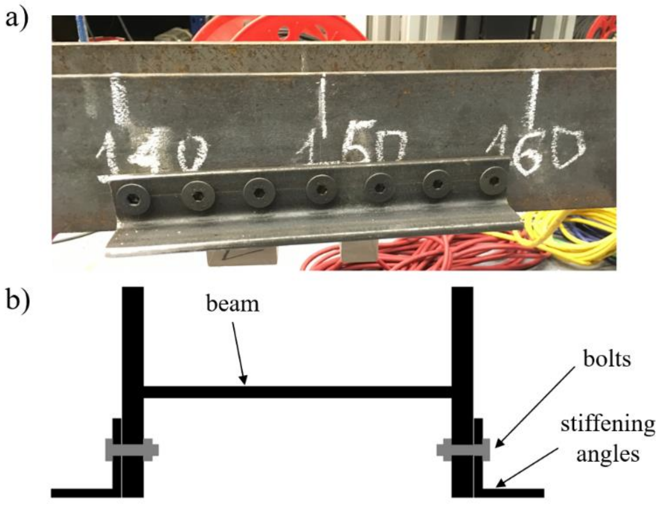


Figure 7. Beam stiffening detail, (a) Elevation view of the stiffening angles (b) Cross section of beam and stiffeners

Figure 8a 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.

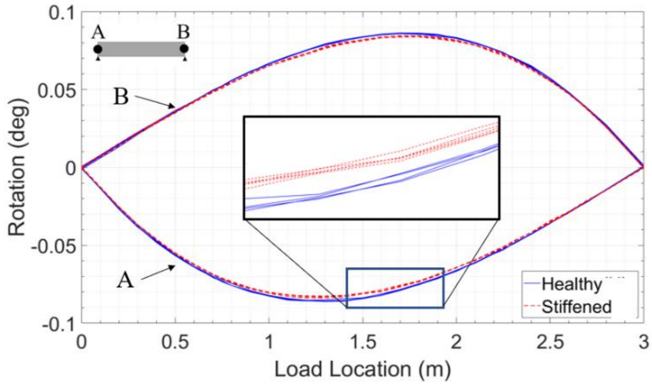


Figure 8. Effect of damage on beam rotation measurements, rotation versus load location

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 9a and b respectively. Each point in the plots represents the rotation difference for a given loading position. The solid line plots in Figures 9a and b show the numerically predicted difference in rotation calculated using the numerical model discussed in 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. It can be concluded that stiffening at this level can be successfully detected by sensors in a laboratory setting.

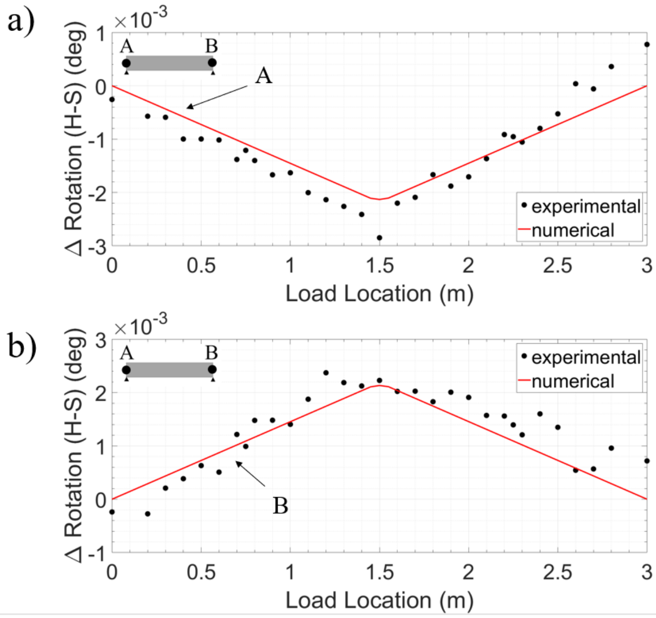


Figure 9. Effect of damage on beam rotation measurements, (a) Difference in rotation measurements for healthy and stiffened beam cases for sensor at the left-hand support (Point A) (b) Difference in rotation measurements for healthy and stiffened beam for sensor at the right-hand support (Point B).

6 CONCLUSION

This paper discusses a bridge condition assessment methodology using rotation measurements. Initially numerical and experimental analysis are carried out on a 1-D beam model to investigate the sensitivity of rotation as a parameter to identify damage on bridge type structures.

The conclusions are as follows:

- 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.
- 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.

Further work on this concept aims to explore this concept using more complex models, scaled laboratory testing and field experiments.

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REFERENCES

[1] Žnidarič, A., Pakrashi, V., Obrien, E. & O'Connor, A. 2011. A review of road structure data in six European countries. Proceedings of the Institution of Civil Engineers - Urban Design and Planning. Thomas Telford Ltd, 164(4), pp. 225–232.

[2] Brownjohn, J., De Stefano, A., Xu, Y-L., Wenzel, H. & Aktan, A. 2011. Vibration-based monitoring of civil infrastructure: Challenges and successes. Journal of Civil Structural Health Monitoring 1(3–4):79–95

[3] Alamdari, M., Kildashti, K., Samali, B. & Goudarzi, H. 2019. Damage diagnosis in bridge structures using rotation influence line: Validation on a cable-stayed bridge. Engineering Structures 185:1-14

[4] Inaudi, D. and Glisic, B. 2002. Interferometric inclinometer for structural monitoring. 15th Optical Fiber Sensors Conference Technical Digest. IEEE 391–394

[5] Wu, C.-M. & Chuang, Y.-T. 2004. Roll angular displacement measurement system with microradian accuracy. Sensors and Actuators A: Physical. Elsevier, 116(1):145–149.

[6] Wyler, A. G. 2016. Levelmatic 31 - High precision analog inclination sensor technical specification. Available at: www.wylerag.com.

[7] Bruns, D. G. 2017. An optically referenced inclinometer with sub-microradian repeatability. Review of Scientific Instruments 88(11):115111.

[8] SCI. Steel Building Design: Design Data. The Steel Construction Institute and The British Constructional Steelwork Association Ltd, 2015.

[9] Concast Precast Group Concrete Prestressed Girders Technical Guide 2009

[10] Moses, F. 1979. Weigh-in-Motion System Using Instrumented Bridges. Transportation Engineering Journal of ASCE 105(3):233-249

[11] McNulty, P. & O'Brien, E. 2003. Testing of Bridge Weigh-In-Motion System in a Sub-Arctic Climate. J Test Eval 2003; 31: 11686.

[12] OBrien, EJ., Quilligan, MJ. & Karoumi R. 2006. Calculating an influence line from direct measurements. Proceedings of the Institution of Civil Engineers - Bridge Engineering, 159(1):31–34.

[13] Yamaguchi, E., Kawamura, S., Matuso K, et al. 2009. Bridge-Weigh-In-Motion by Two-Span Continuous Bridge with Skew and Heavy-Truck Flow in Fukuoka Area, Japan. Adv Struct Eng 2009; 12: 115–125.