Indirect Bridge Monitoring from Instrumented Vehicles

MUATH ALHUMAIDI and BRETT A. STORY

ABSTRACT

This paper investigates the sensitivity of a rotation-based damage estimation method applied to simply supported beams under a quasi-static moving load. The method estimates three damage parameters, damage start location (L_1), end location (L_2), and severity (β), using rotation observed at the load location. In this study, results from finite element model (FEM) simulations of three damage scenarios characterize how these damage parameters affect the rotation response. For each case, two parameters are fixed to their best estimated values while the third is varied across its top 100 values. The resulting sensitivity, i.e. change in rotation with respect to each parameter, illustrates rotation changes with respect to the moving load location and parameter variation. This establishes the sensitivity of the method and motivates the use of rotation-based damage detection methodologies.

INTRODUCTION

Aging and deteriorating infrastructure, especially road and railway bridges, presents a growing global concern [1, 2]. Structural damage, such as cracks or stiffness loss, can critically affect safety and performance if not identified early [3, 4]. Thus, extensive research has been conducted, and various structural health monitoring (SHM) techniques have been developed [5, 6]. SHM aims to detect such issues using non-destructive sensing to monitor damage presence, location, severity, and in some cases, predict remaining life [3, 7, 8]. Several studies have used methods based on a structure's response to moving loads, which include quasi-static moving load tests, where the load moves slowly to reduce dynamic effects [9, 10].

Displacement influence lines (DILs) have been explored to localize damage, showing potential when comparing healthy and damaged states [11, 12]. Yet,

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Muath Y. Alhumaidi, Ph.D. Student, Department of Civil and Environmental Engineering, Southern Methodist University, Dallas, TX 75205
Brett A. Story, Ph.D., Associate Professor, Department of Civil and Environmental Engineering, Southern Methodist University, Dallas, TX 75205

measuring multiple vertical deflections at many locations can be difficult over extended monitoring windows; new non-contact methods are now being developed to address this challenge [13, 14]. However, DIL methods are sensitive to noise and often require multiple sensors [15, 16]. As an alternative, rotation measurements have shown promise for damage detection due to their higher sensitivity to local stiffness changes and can be used to construct rotation influence lines (RILs) that reflect both damage location and severity [17, 18].

Rotation response is a highly effective indicator for structural damage due to its strong sensitivity to local stiffness changes [17]. It shows a clearer response to damage than deflection, even for small damages, and typically requires fewer sensors than modal-based approaches [17, 19]. Rotation measurements are also less affected by environmental factors such as temperature, making them more reliable in field conditions [20]. Additionally, rotation influence lines (RILs) shift noticeably when damage occurs, supporting accurate localization [12, 21].

Rotation measurements observed directly at the moving load location have shown strong potential. Unlike methods that rely on deformations of the beam full span, this approach focuses on a single, highly sensitive location, making it possible to estimate damage with fewer sensors [22].

This study aims to analyze how rotation, measured at the moving load location, changes in response to variations in key damage parameters: damage start location (L_1), end location (L_2), and severity (β). By applying a sensitivity analysis using the first derivative of the damaged rotation equation, the goal is to understand how each parameter independently influences the rotation response. This investigation is supported by finite element model (FEM) simulations of three different damage scenarios and is based on earlier analytical studies [22].

METHODOLOGY

Damage Parameters and Rotation-Based Estimation

The methodology estimates damage by observing the rotation response at the moving load location, which is derived theoretically based on the principle of virtual work. The damaged rotation equation depends on four main parameters, three are related to the damage and one is related to the moving load. The four parameters are defined as:

- L_1: start of damage.
- L_2: end of damage.
- β: stiffness reduction ratio (damage severity).
- x_F: the moving load location.

In previous work, the damage related parameters were estimated by minimizing the error between the theoretical expression and the observed rotation profiles [22]. The theoretical expressions are created by performing a grid search through multiple possible combinations of L_1, L_2 and β. In this paper, the approach is evaluated by analyzing how changes in each damage parameter affect the rotation response.

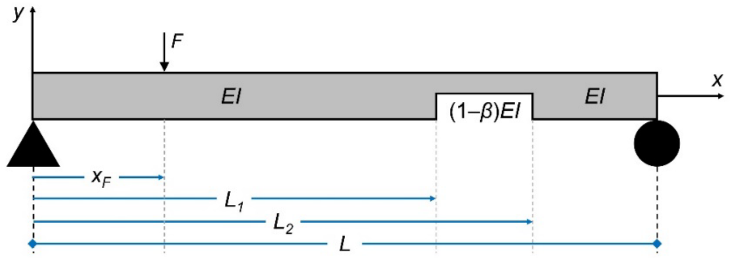

Figure 1. Damaged Simply Supported Beam Under Quasi-Static Moving Load

Sensitivity Analysis Using First Derivatives

To study the sensitivity of the rotation response related to each parameter, the first partial derivative of the damaged rotation equation is computed with respect to each of the three damage related parameters:

$$S_1 = \frac{\partial \theta_d(x_F)}{\partial L_1}, \qquad S_2 = \frac{\partial \theta_d(x_F)}{\partial L_2}, \qquad S_3 = \frac{\partial \theta_d(x_F)}{\partial \beta} \tag{1}$$

These derivatives show how variations in each parameter affect the rotation response when the load is traversing the beam at location x_F. Although the exact form of $\theta_d(x_F)$ is not provided in this paper for simplicity, its theoretical equation is derived using piecewise integration of internal real and virtual moment functions following the virtual work technique [22].

In each sensitivity analysis, two parameters are fixed at their top estimated values, while the third parameter varies across the top 100 estimated values, where all estimations are extracted from the damage estimation of a FEM damage scenario rotation response with 9% added noise. For each variation, the rotation sensitivity is plotted as a function of the moving load location x_F; each variation produces 100 curves per parameter for each damage scenario.

FINITE ELEMENT MODEL AND DAMAGE SCENARIOS

To apply the sensitivity analysis, a FEM of a simply supported beam, shown in Figure 1, is developed using SAP2000. The beam is modeled as a 2D Euler-Bernoulli beam and discretized into 1000 elements (1001 nodes), which allow for accurate observation of the rotation response at each location. A unit quasi-static moving point load is applied across the span of the beam (L) at low velocity with step size of $0.001L$. The rotation is measured at the moving load location as it traverses the beam. This rotation response is used as a benchmark for the estimation methodology. Three damage scenarios are selected and introduced to the estimation method:

- DS1: $L_1 = 0.60L$, $L_2 = 0.70L$, and $\beta = 0.20$
- DS2: $L_1 = 0.30L$, $L_2 = 0.37L$, and $\beta = 0.10$
- DS3: $L_1 = 0.50L$, $L_2 = 0.51L$, and $\beta = 0.40$

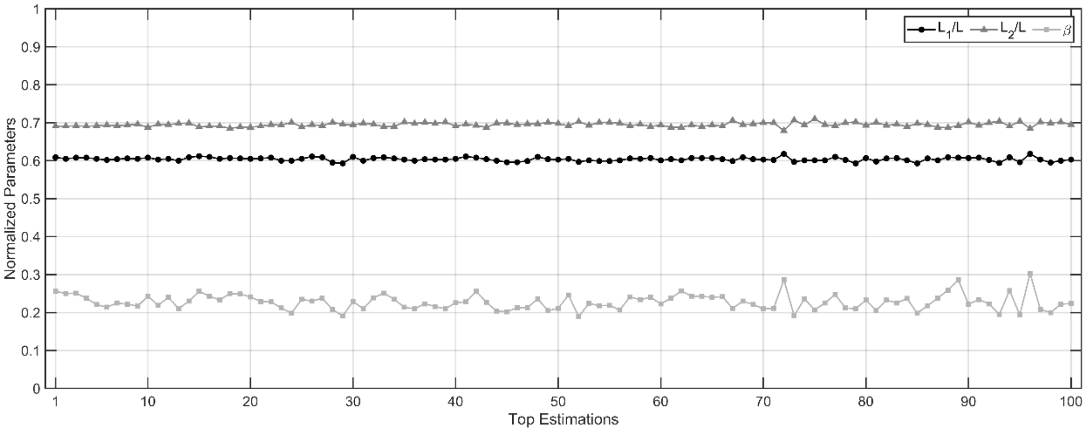

Figure 2. DS1 Damage Parameters Top 100 Estimations

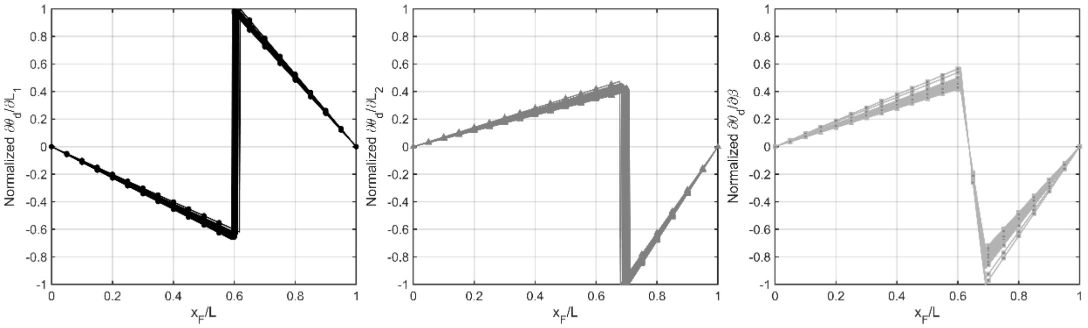

Figure 3. DS1 Sensitivity Curves

These damage scenarios represent common damage types, where DS1 and DS2 might reflect distributed damage such as corrosion or loss of composite, while DS3 illustrates a localized or crack-like damages. For each scenario, the top 100 estimations of L_1, L_2, and β are extracted to be used in the sensitivity study.

RESULTS AND DISCUSSION

Rotation Sensitivity of DS1

In this scenario, the damage is located on the right side of midspan. The top 100 estimations for each parameter are plotted to check their stability. Both L_1 and L_2 values are tightly estimated, showing that the method estimates the damage location reliably. However, the top 100 values for β varies much more, which means that severity estimation is less stable in this scenario. These behaviors are demonstrated in Figure 2.

The first derivative of the rotation with respect to each parameter is computed and plotted in Figure 3 as a function of the moving load location using Equation (1). The sensitivity curves related to L_1 and L_2 are almost overlapping across the 100 estimations, which indicate that small changes in L_1 or L_2 have a low effect on rotation. On the other hand, the sensitivity curves related to β demonstrate more variation, especially around the location of L_2 as shown in Figure 3. This shows that the rotation response is more sensitive to severity than to damage locations in this scenario, which means that severity is the main parameter to identify a damage.

The reason for having more variation around the location of L_2 is most likely that L_2 is closer than L_1 to the right boundary of the beam, where regions close to boundaries are stiffer and experience less deformation. Therefore, the change in rotation is affected by the change of severity at the damage edge located closer to a beam boundary, located at a stiffer region.

Rotation Sensitivity of DS2

For this scenario, the damage is located on the left side of midspan. Similar to DS1, the top 100 estimations for L_1 and L_2 are closely estimated, which indicates a stable estimation for the damage location. The values of β again showing more variation, which similarly means that the severity plays a strong role in affecting the rotation. Figure 4 shows these results on the top plot.

The sensitivity curves in Figure 5 related to L_1 and L_2, similar to DS1, showing small variation across the top 100 estimations. However, the curves related to β show larger spread, this time near the location of L_1 as shown in Figure 5.

The reason for this is that L_1 is now closer to the left support than L_2, making the region around L_1 stiffer and less deformable. Like DS1, the change in rotation is affected by the change of severity for this DS at the damage start location (L_1).

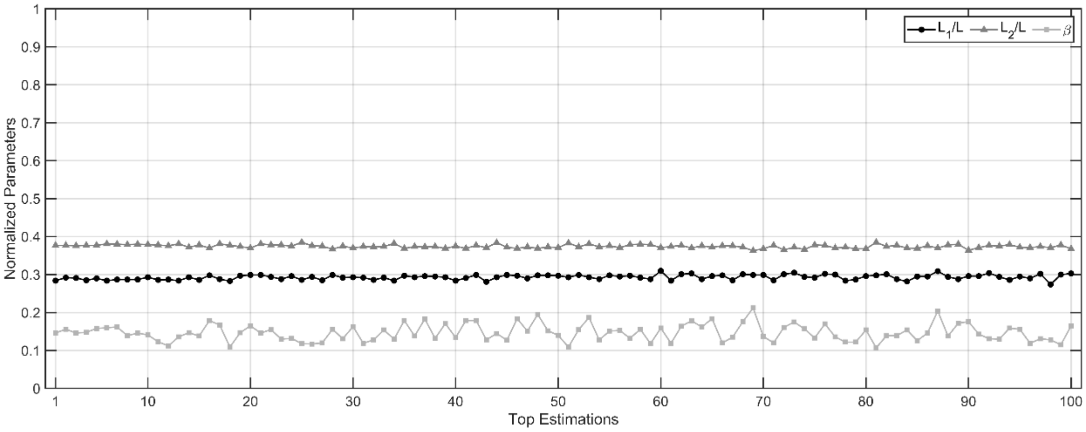

Figure 4. DS2 Damage Parameters Top 100 Estimations

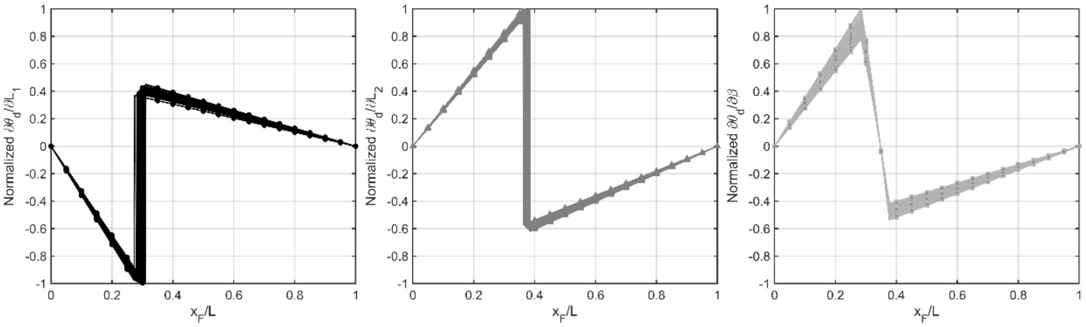

Figure 5. DS2 Sensitivity Curves

Rotation Sensitivity of DS3

In this scenario, the damage is extremely short but sever, and it is located at the midspan. The top 100 estimations for L_1 and L_2 are again stable, while the β estimations again have more variation, just like in previous scenarios as demonstrated in Figure 6.

The sensitivity plots in Figure 7 for this scenario showed that the curves related to β are clearly varying from one another, even when compared to DS1 and DS2, due to the extreme short damage length. The maximum sensitivity occurred at both L_1 and L_2 locations, Figure 7, which make sense because both locations are approximately at the midspan of the beam and are almost equally spaced from both beam's boundaries. Around both locations, the stiffness of the beam is balanced, thus the change in rotation is equally affected.

These findings confirm the theory that the rotation is more sensitive to severity (β) than to damage edges changes. Also, it shows how beam symmetry influences where that sensitivity develops.

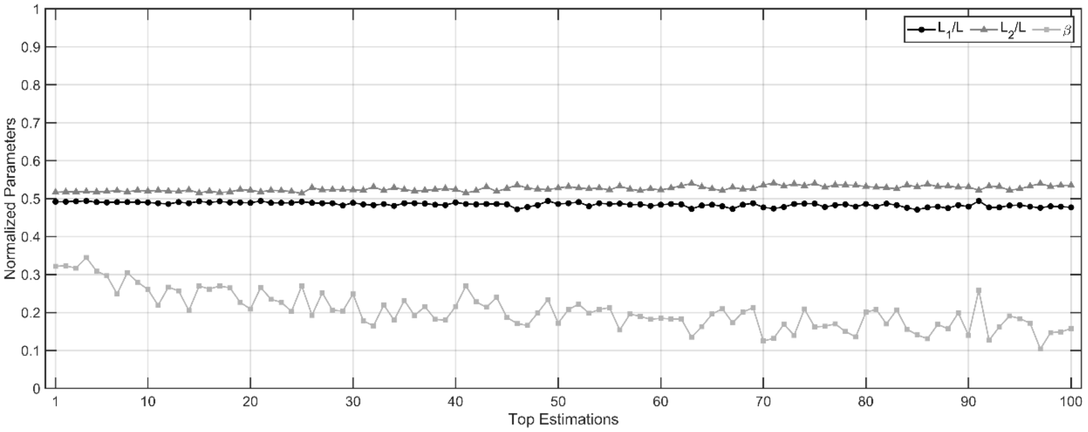

Figure 6. DS3 Damage Parameters Top 100 Estimations

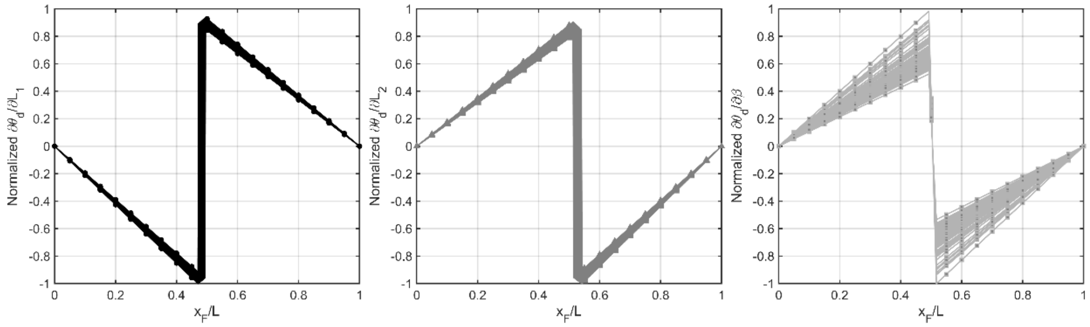

Figure 7. DS3 Sensitivity Curves

CONCLUSION

This paper examined the sensitivity of the rotation response in simply supported beams to main damage parameters when subjected to a quasi-static moving load. This study analyzed the impact of changes in damage start location (L_1), end location (L_2), and severity (β) on the rotation response observed at the moving load location. Three different FEM damage scenarios were investigated. For each DS, the top 100 parameters estimations were analyzed to evaluate both the stability of the estimations and their influence on rotation.

The observed results showed that the top 100 estimations of L_1 and L_2 were closely grouped in all DSs, which indicate that the method always estimate the damage location. On the other hand, the parameter that represents the severity β showed greater variability, implying that the rotation response is more sensitive to changes in damage severity than to damage edge's locations.

This conclusion was supported by computing the first derivatives of the damaged rotation equation with respect to each parameter. The sensitivity curves indicated that L_1 and L_2 produced a limited, localized changes, while β led to large and notable changes in rotation. Furthermore, the location of maximum sensitivity differs according to the location of the damage along the beam, which depends on the damage closeness to beam boundaries.

These outcomes offer deeper understanding into how each damage parameter influence the rotation response, and severity has the greatest impact on estimation variability. Understanding these sensitivity trends can improve the reliability of rotation-based damage detection methods, especially dealing with noisy cases.

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