A Study of the Temporary Bridge Crossing for Appalachia After Hurricane Helene

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ABSTRACT

Hurricane Helene triggered more than 2,000 landslides and resulted in severe flooding across western North Carolina, which widened stream channels and caused damage to 7,000 stream crossings. Some of the stream channels have widened more than three times the original stream width. In the recovery effort, many temporary bridges (20 ft to 70 ft) were built with steel girders and wood decks. Due to the lack of design guidelines, the qualities of the constructed temporary bridges may vary. In this study, a low-cost, vibration-based bridge monitoring strategy is suggested for these temporary bridges.

INTRODUCTION

On 25–28 September 2024, Hurricane Helene traveled through the western mountain regions of North Carolina and triggered thousands of landslides. Originating in the Caribbean Sea, Helene started on 22 September as a tropical low-pressure disturbance and within a short period intensified to a Category 4 hurricane (26 September). By the time Helene arrived in Georgia, it was downgraded to a post-tropical cyclone and eventually reached the western mountain region of North Carolina following the path shown in Figure 1 [1]. Hurricane Helene produced large amounts of precipitation, caused excessive flooding and landslides, and destroyed infrastructures, including numerous bridges and roadways throughout the western part of the state [2].

In addition to highway bridges, the flooding caused by Hurricane Helene also led to the failure of numerous local stream crossings. More than 7,000 low-volume stream crossings, private bridges, and culverts were washed out due to the severe flooding [1], leaving many residents stranded in their homes and cutoff from their community. Detailed studies of 13 local bridges revealed that creek channels widened significantly due to flooding, with most bridges and culverts being completely washed away.

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Table I summarizes local crossing failures studied in Ashe County, NC, where bridge structures were swept away and channel widths at the crossing sites increased by as much as 300% of their original size as in Figure 2, highlights the failed local stream crossing in Creston, NC, where a washed-out culvert was in a stream that experienced a 377% increase in channel width. Before-and-after images of the site are shown in Figure 3. Most of these failed crossings were over 20 years old, and their destruction underscores multiple vulnerabilities: Limited capacity to accommodate floodwater, insufficient resistance to scour, and a lack of structural support to withstand the hydrodynamic forces of extreme flooding.

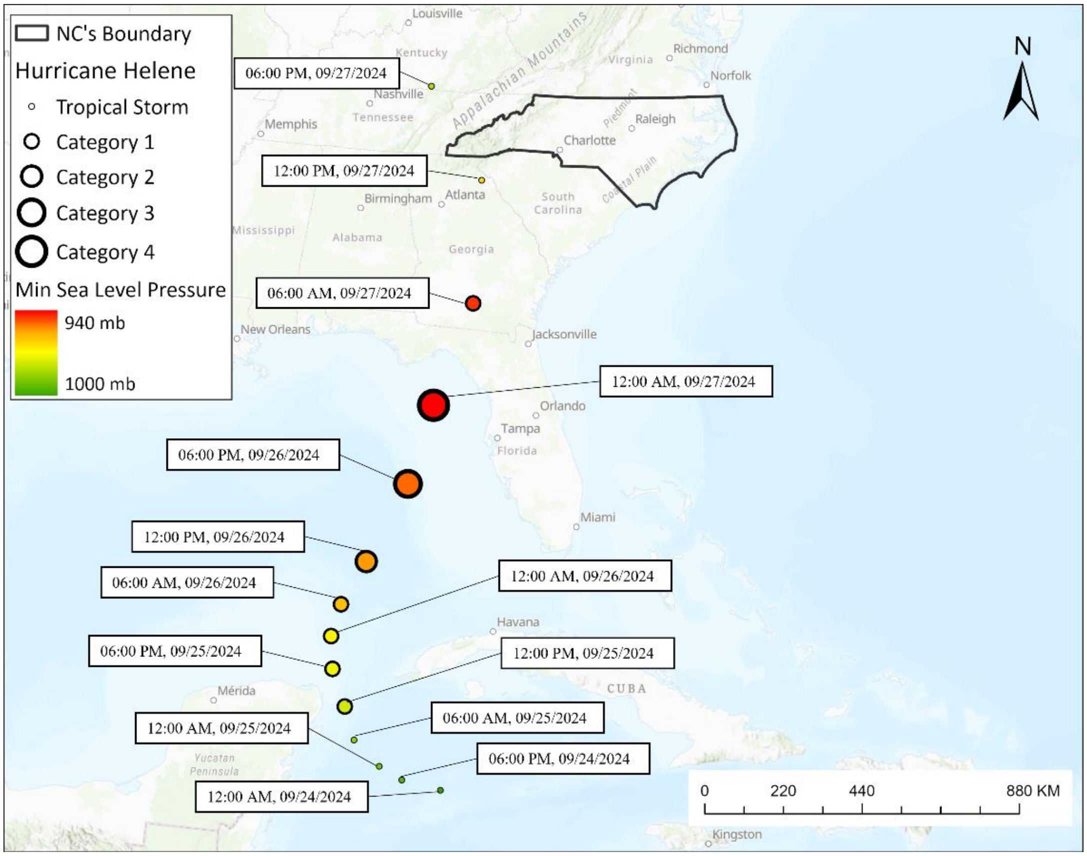

Figure 1. Path of Hurricane Hellene moving through the Gulf of Mexico

Recovery efforts—including temporary bridge installation, stream realignment, and sediment removal—are rapidly progressing but can vary widely in quality and approach. Intended for either single car crossing, most of the temporary bridges built are steel girder bridges with wood decks as seen in Figure 3. Even though these bridges are designed for temporary crossings, it is still critical to ensure their structural integrity is consistent with design requirements.

To ensure the long-term performance of these bridges, a monitoring strategy is devised using vibration-based sensing techniques [5]. The goals of the monitoring strategy are to establish performance predictability and to enhance value proposition [3].

TABLE I. SUMMARY OF 13 LOCAL ACCESS BRIDGE FAILURES IN ASCHE COUNTY, NORTH CAROLINA

Bridge No.	Bridge Site	Original Width	Current Width	Channel Expansion	Embankment Condition
PO 48	Lansing NC	32 ft	48 ft	50 %	Damaged
PO 49	Lansing NC	34 ft	73 ft	113 %	Damaged
PO 62	Lansing NC	35 ft	53 ft	50%	Washed out
PO 46	Lansing NC	15 ft	36 ft	138 %	Damaged
PO 44	Todd	10 ft	15 ft	50 %	Washed out
PO 235	W. Jefferson	23 ft	68 ft	193 %	Damaged
PO 18	Lansing, NC	17 ft	70 ft	310 %	Washed out
PO 136	Lansing, NC	30 ft	27 ft	9 %	Washed out
PO 225	W. Jefferson	12 ft	40 ft	237 %	Washed out
PO 141	Creston	15 ft	72 ft	377 %	Washed out
PO 243	W. Jefferson	12 ft	53 ft	341 %	Washed out
PO 40	Warrensville	15 ft	12 ft	22 %	Washed out

Figure 2. Local Crossing (PO141) in Creston, NC, 377% Channel Width Widened

Figure 3. Typical temporary bridge built after Hurricane Helene in Wester

TEMPORARY BRIDGE MONITORING

The proposed monitoring strategy is based on a theoretical approach [6] where the bridge crossing is simplified as a short-span beam structure with a moving load. To formulate the bridge model, effective mass, stiffness, damping and loading terms are established to account for vehicle motion, boundary condition and thermal expansion. For most short single-span bridges, since the maximum deflection happens almost always at the mid-point of the bridge, only the displacement at the middle of the bridge will be studied. The dynamic equation of motion the bridge model is defined as:

$$M * X(t)'' + C * X(t)' + K * X = F(t) \tag{1}$$

$$M = \int_0^L m(x)\varphi^2(x)dx \tag{2}$$

$$K = \int_0^L EI(x)\{\varphi''(x)\}^2 dx \tag{3}$$

$$C = \int_0^L c(x)\varphi^2(x)dx \tag{4}$$

$$F(t) = \int_0^L p(x,t)\varphi(x)dx \tag{5}$$

where M is the generalized mass of the vehicle and bridge, C is the generalized damping of the bridge, K is the generalized stiffness of the bridge, $F(t)$ is generalized impact force and $\varphi(x)$ is the mode shape function. Figure 4 shows the first mode shape functions with different boundary conditions.

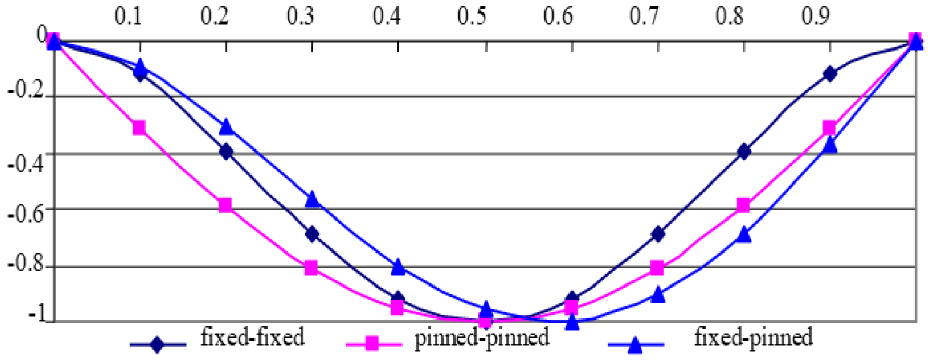

Figure 4 Mode Shapes for Different Boundary Conditions

Assuming the vehicular load acts as an impulsive load that is applied at six different locations on the bridge (Figure 5) and considering thermal expansion and pre-stress loads, the dynamic model is revised as:

$$(M_b + m_{vt}) * X(t)'' + C_b * X(t)' + (K_b + K_t) * X = F_{vt}(t) \tag{6}$$

where *i* represents six load locations, M_b is bridge mass, m_{vi} is vehicle mass, C_b is damping, K_b is bridge stiffness, K_t is stiffness change due to temperature loading effect, and $F_{vt}(t)$ is impact force from vehicle motion. Figure 6 shows the modified mode shapes computed from vehicle loads applied at different locations.

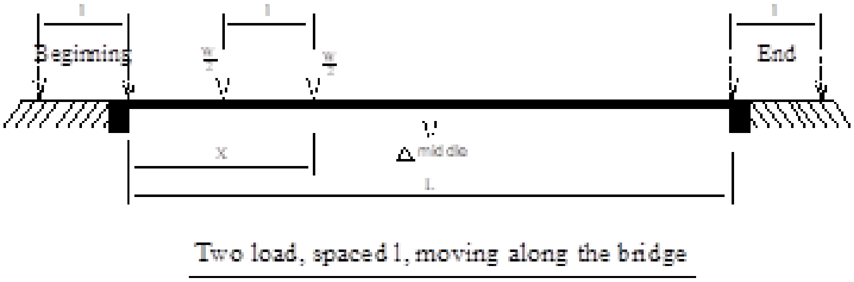

Figure 5 Vehicle Simplified as Two Wheel Loads Applied on the Bridge

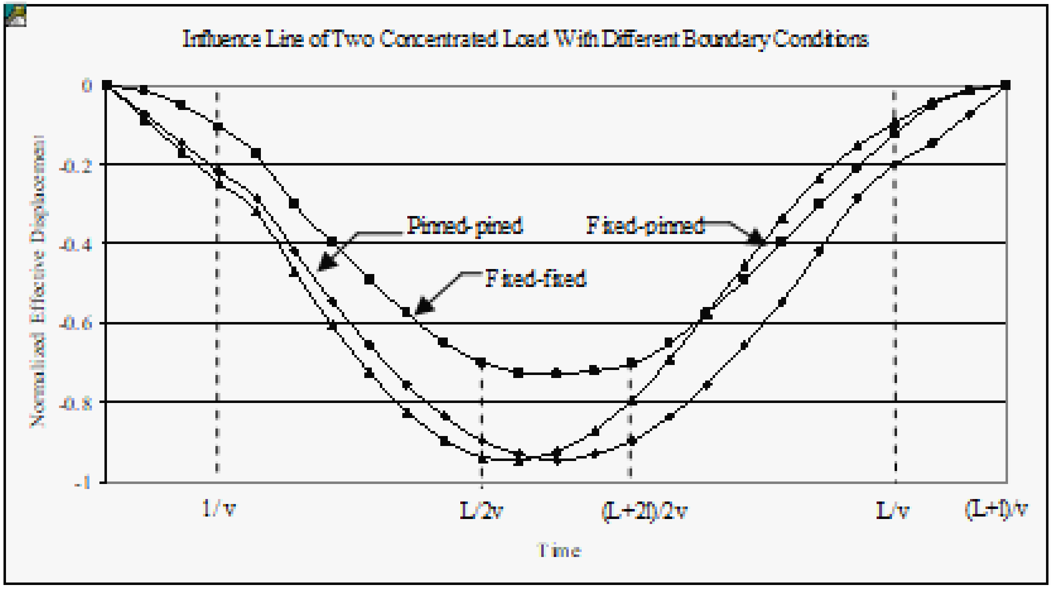

Figure 6 Modified Dynamic Bridge Model with Different Boundary Conditions

Using the simple dynamic model, the proposed monitoring strategy suggests installing vibration sensors on the bridge and determining the vibration responses (vibration frequencies and amplitudes) of the bridge during single vehicle crossings. Since vehicle crossings will be at a very slow speed (< 10 mph), the effect of speed is ignored.

The testing strategy targets rapid data collection with minimal testing setups, thus minimizing the disturbance to the residents. Since many of these bridges are replacement bridges of the original crossings, they may not have the required clearance against future floodings, hence, it is suggested that the monitoring be performed after each flooding. The last point is particularly important, because many streams in the region have already changed their hydraulic conditions and the flooding potential is hard to predict. Future flooding may result in erosion at the bridge abutments or supports and result in boundary conditions change.

Using field vibration measurements and response analyses, the model can be used to predict dynamic behaviors and compare with the vibration responses. The validated bridge conditions can then be used in structural static analysis to determine bridge capacity [6]. The comparison may reveal if the bridge befits the original design or if the bridge conditions have changed over time. Such diagnostics can help the bridge owner to decide if repair works may be needed.

DISCUSSION

Stream crossing safety predictability

One of the challenges about flood disaster in the western mountain region is the lack of insurance for bridge crossings. Hence, an effective monitoring strategy can help enhance resident safety and bridge performance predictability. This engineering analysis - based predictability can help the bridge owner to demonstrate his/her due diligence in safeguarding stream crossing during negotiating with insurance companies regarding home protection coverage.

It is likely that vibration measurement can be performed by a professional engineer who has a fundamental understanding of structural dynamics and the basis of vibration measurements and dynamic signal processing. The vibration measurement instruments are reasonably cost effective for a professional engineer to acquire for field studies. The benefits of the proposed monitoring strategy lie in the fact that only limited sensing is required. The current approach suggests that only a single accelerometer may be installed underneath the bridge for vibration measurements.

Monitoring technology selection is extremely important because most of the bridges are built by volunteers and paid for by donations. Hence, the technology costs must be affordable by engineers or bridge builders.

Currently, there are no inspection requirements for stream crossings, however, with bridges exceeding 20 ft length, it is important to ensure safety for bridge crossings. It should be noted that the proposed technique does not replace the current bridge inspection approach.

Reliability in vibration-based structural monitoring techniques

Several assumptions are made in the simple bridge model including: 1) Only the first bending mode is assumed; 2) the bridge support conditions do not change; 3) all girders deform by the same amount; and 4) only a single vehicle passes over the bridge at any time. While assumptions 3 and 4 can be controlled by constraints determined in experimental design, assumptions 1 and 2 are harder to control. For example, if the bridge is skewed or lacks lateral bracings, the bridge dynamic responses can be more complicated to interpret. In such cases, the resident or bridge owner needs to be warned about bridge safety, and a more detailed analysis is warranted.

It should be recognized that the vibration measurement technique suggested in current study is a low sensitivity approach which may not warrant a strong potential for advanced damage detection for the bridge. The argument for monitoring technology selection and design is again a factor of economy: The appropriate technology should have a rationale-based diagnostic algorithm with reasonable computing time and able to provide reliable and usable outcomes. Current proposed method can be correlated with the change of boundaries and the reduction of stiffness of the bridge – Two critical parameters that are comprehensible to most competent bridge engineers.

CONCLUSION

After hurricane Helene of 2024, several temporary bridges have been constructed for residents that depend on stream crossings to connect to the outside world. To evaluate and monitor the performance of these temporary bridges, a vibration measurement-based structural monitoring strategy is suggested. The technique employs a simple bridge model that assumes a first beam bending mode and quantifies the bridge response with a moving concentrated load application. The strategy is selected for its sound theory in mechanics, reliability of vibration measurements and also the interpretation of the results.

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