ENHANCING RESILIENCE OF BRIDGES TO EXTREME EVENTS BY RAPID DAMAGE ASSESSMENT AND RESPONSE STRATEGIES

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ABSTRACT
The U.S. highway transportation network consists of more than 650,000 bridges that are essential to maintaining the performance of the network. The existing bridges are, however, vulnerable to a variety of natural and manmade hazards and may act as “bottle necks” in case of any failures. The most common extreme events include natural hazards such as ground excitation during earthquakes, high wind and storm surge in hurricanes, and scouring and debris impact during floods. Despite several advances in the available technologies for the design of new bridges and the retrofit of the existing ones, there are still incidents that the bridges fail partially or completely after an extreme event. In such cases, it is important for the federal, state, and local authorities to identify the damaged bridges, quantify the extent of damage, plan for rapid recovery, and also provide alternative routes for the emergency response and evacuation activities. For this purpose, NCHRP Synthesis Topic 46-11 gathered the relevant information on the technologies that are available for rapid post-extreme event damage assessment of the highway bridges, the availability of data from these techniques to transportation agencies and bridge owners, decision making tools or processes that would use the data, and the emergency planning protocols in place to address the failures in bridges. This paper provides a summary of the findings of this project.
INTRODUCTION
The performance assessment of aging transportation infrastructure under extreme events has been an issue of concern for engineers and decision-makers who are involved with the operation and management of civil infrastructure systems. A major aspect of transportation systems that makes it different from the other constructed facilities is the spatial distribution and connectivity of infrastructure components. This aspect has made the transportation systems more sensitive to the consequences of natural and manmade hazards as disruptions in only few components may result in detrimental effects on the performance of the entire system. Furthermore, at a larger scale, any damage to the infrastructure components may potentially cause extensive socio-economic losses, some of which cannot even be properly measured. To minimize the extent of disruption in the performance of the highway bridge infrastructure, it is of paramount importance to develop new technologies for the rapid assessment of their structural conditions and plan to address the possible consequences of failures. One of the major issues hindering such technologies is the variability of types of hazards that structures are exposed to throughout the U.S. Further to natural and manmade hazards, the transportation infrastructure is exposed to harsh environmental stressors, which may significantly affect the durability of structural components. This paper will provide an overview of the state bridge and hydraulic engineers’ opinions about the dominant causes of failure, and the outcome of the literature review on the post disaster activities including damage detection, emergency response, and performance restoration for the bridges as one of the most important components of the transportation network. The effort will focus on the current practices by the transportation agencies, local authorities, and the stakeholders throughout the nation to detect the bridge damage under different natural hazards with extreme nature using different remote, in-situ, or portable monitoring/damage detection techniques, the decision making process following the collection of the damage data in highly pressured emergency conditions, and the response and recovery actions following the event that would lead to restoration of the performance of the bridges.

ENHANCING RESILIENCE TO EXTREME EVENTS
Defining Resilience
The concept of resilience can be applied to systems such as buildings, bridges, facilities, infrastructure, network, economics, and communities. The general concept of resilience was first put forth by ecologists more than 40 years ago. According to Holling (1), resilience is the perturbation that can be absorbed before the system converges to another state of equilibrium. Resilience was redefined by Prim (2) as a speed measure for engineering systems to return to the equilibrium condition. In another study, the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions is considered resilience (3). Bruneau et al. (4) also conducted a comprehensive analysis of various aspects of resilience at the community level and suggested four dimensions for it, called the four “R’s”, which include robustness, redundancy, rapidity, and resourcefulness. Here, robustness is the ability of the system or system components to withstand external shocks without significant loss of performance. Redundancy is the extent to which the system satisfy and sustain functional requirements in the event of disturbance. Resourcefulness is the ability to diagnose and prioritize problems and to initiate solution by identifying and monitoring all resources, including economic, technical, and social information and rapidity is the speed at which recovery is accomplished. According to this definition, implementation of the resilience can enhance the performance of the system by reducing the probability of failure, consequences of failure, and time to recovery. A holistic definition of
resilient governance for communities was given by Godschalk et al. (5), in this definition resilient communities proactively protect themselves against hazards, build self-sufficiency, and become more sustainable, instead of sustaining repeated damage and continual demands for federal disaster reliefs. The National Academies (6) defines resilience as the ability to prepare and plan for, absorb, and recover from and more successfully adapt to adverse events. According to Haimes (7), the vulnerability assessment mainly contributes to a system’s degradation state under an extreme event, whereas the resilience assessment goes beyond this point and additionally includes system’s recovery following extreme events. As a case in point, hardening of a system against region-specific hazards (i.e., pre-event investment) may reduce the vulnerability of the system to the hazards, but if the recovery needs are not properly addressed, the resilience of the system in terms of recovery time and cost will not always be improved. To achieve an in-depth understanding of the resilience measures that help identify the most appropriate pre- and post-disaster activities, the resilience of the transportation network here in this paper is defined as its capacity to absorb, adapt to, and restore after a sudden shock. The shock absorptive capacity of the system is its ability to withstand a given level of stress without loss of function. As an example, at the structure level, strengthening the bridge piers with steel jackets in seismic areas increases their capacity to resist ground vibrations. This would lead to a higher absorptive capacity at the network level as well. The adaptive capacity of the system shows the extent to which alternative components exist to satisfy performance requirements in the event of losses in some components of the system. For instance in structures with high degree of indeterminacy, when failure in one of the elements occur the other components of the system provide the additional capacity to redistribute the loading this would lead into higher redundancy. At the network level, implementing redundancy for the critical roadways and bridges, increases the likelihood of having functional detours with acceptable lengths in case of failure of any of the links. The restorative capacity is the capability of the system to meet priorities and achieve goals in a timely manner so that recovery from a disruptive event can be accomplished as quickly as possible with the minimum cost. The restorative capacity could be improved by a number of strategies such as having rapid damage assessment techniques that would help identify the source and extent of the structural problems, implementing emergency response plans that would define the responsibilities of different involved parties in the most chaotic times after the extreme event, holding regular training sessions for the agency personnel to be prepared for the aftermath of extreme events and be familiar with their roles, plan for the available repair and replacement resources, and many other strategies that could be considered to increase the speed of the recovery with the optimized resources. To maintain all the listed capacities, sufficient resources must be allocated to the system for mitigation actions prior to and for restoration efforts following the occurrence of extreme events. To better illustrate the concept of resilience, here a system performance curve will be defined. The system performance could be measured in terms of different measures such as connectivity, accessibility, drivers’ delay, direct and indirect costs associated with the failures, etc. (8-9). For further illustration, Figure 1 depicts the changes in an arbitrary system performance measure, Q(t), over time.

A major drop is seen in the performance measure when an extreme event occurs (t0). Depending on the state of robustness, the absorptive capacity of the system is affected and the remained performance may become less than what was expected for a network with no degradation. The cross-hatched area under the performance curve can be considered as an indicator of the resilience of the system. After the occurrence of an extreme event, the role of adaptive capacity can be recognized based on the time in which the recovery of the system begins (ti). This is an indicator of the state of redundancy and rapidity of the system. Finally, the restorative capacity of
the system can be evaluated by the time in which the pre-disaster performance level is fully regained \( (t_f) \). This reflects the state of resourcefulness of the system (Figure 1). It should be noted that all the mitigation and recovery efforts planned for a large-scale system requires the expenditure of resources. Hence, in addition to the time-based measures, cost-based measures are investigated to obtain reliable estimates of the resilience of deteriorating highway transportation networks.

Figure 1 Estimation of the resilience measures through absorptive, adaptive, and restorative capacity of a system performance measure

One of the key concerns regarding the definitions currently available for resilience is the over emphasis on the pre-disaster activities aimed to reduce potential losses (i.e., strengthening of the infrastructure) and less attention to the post-disaster efforts required for emergency response and recovery. The scarcity of resources from economic, technical, and organizational aspects have however limited the amount of strengthening that could go into the bridges in a transportation network. This is amplified even more with the stochastic nature of the extreme events and the fact that the decision makers don’t have any definitive knowledge of what intensity event will hit next and which part of the transportation network it will affect. Additionally, even in case of availability of some limited of resources, the hardening of the system to one scenario doesn’t necessarily protect the system under other types of hazards or other scenarios. These facts underline the importance of having more effective post-event response strategies that would increase the recovery and restoration speed while ensuring the optimum use of resources.

**Defining Extreme Events**

The definition, classification, and diagnosis of extreme events are far from simple. There is no universal unique definition of what an extreme event is. From a mathematical point of view, to
define an extreme, a statistical distribution or a historical distribution is required. Extreme values based on observational data are very important in safety and life-cycle assessment of structures. The prediction of future conditions, especially extreme conditions, is necessary in bridge design and is performed based on an extrapolation from previously observed data combined with engineering judgement. Bier et al. (10) defined “extreme events” as being extreme in terms of both their low frequency and high severity. Ghosn et al. (11) defined extreme events as man-made or environmental hazards having a high potential for producing structural damage that are associated with a relatively low rate of occurrence. AASHTO-LRFD (12) introduces “Extreme Event Limit States” to deal with the performance of bridges during earthquakes, scour or other hydraulic events, ice loads or ship collisions but does not necessarily provide clear definitions of extreme events. The LRFD specification adopted a limit state philosophy or state beyond which a component ceases to satisfy the provisions for which it was designed. The idea of the limit state provides a systematic approach to ensure satisfactory short- and long-term performance of bridges (13). Alipour et al. (14) defined extreme events as those large intensity events with lower probability of occurrence that could push the structure beyond its expected response (that is the response that the engineer has designed the structure for). Following that definition, a holistic definition of an extreme event requires:

• Objective and unambiguous identification of the event

• Definition of the intensity of the event as a function of its features and the risk that it generates for the built environment

• Definition of an intensity-frequency probability density function that represents the statistics of the event occurrence for each class of intensity.

Here the author believes that for a more holistic definition of the extreme event three main factors should be considered:

• The definition of the extreme event is a function of space and time: i) events that are extreme in one area of the world may not be so for another one, and ii) events that are extremes at one time may not be so in the future or the past. For instance a specific earthquake intensity that is considered extreme in the state of Virginia may not be an extreme in the State of California, simply because such events have been considered in the design of bridges in the latter. Additionally, after the Loma Prieta and Northridge earthquakes major revisions were made to the seismic bridge design provisions, such that future events with similar intensities may result in lower failures in the region and hence not considered an extreme anymore.

• The characterization of extreme event should take into account for the spatial scale and temporal scale of the event in addition to its intensity. For instance, a river flooding may result in erosion of the foundations of many of the bridges downstream that would require full or partial closure until full inspections and repairs are conducted. This translates into a regional disruption with large spatial impact that could adversely affect the everyday life, and economy of the regions depending on those bridges. This is in contrast with the extent of disruption an over-height truck collision can create. In the latter case, only the traffic over the bridge and possibly the road underneath would be hindered making it an isolated event.

• The definition of an extreme event is a function of its consequences and the impacts that it has on the safety of the human and the built environment (here transportation assets). For instance, an event (even isolated) that could damage a critical bridge in a transportation network can have major
consequences on the performance of the system and as such categorized as extreme. A good example is the failure of the Skagit Bridge in Seattle that resulted in long detours and thousands of hours of traffic delays; in this case the event, although isolated, resulted in lasting effects in the regional transportation network.

SURVEYS OF STATE BRIDGE AND HYDRAULIC ENGINEERS
Two sets of surveys were sent to the “state bridge engineers” and “state hydraulic engineers” asking them to identify the hazards/threats that they consider most critical to the bridges in their jurisdiction. A high response rate of 85% was achieved through a combination of online surveys and phone interviews. The survey continued with asking the engineers regarding the rapid assessment technologies that were mostly used to identify and locate damage in the bridges after extreme events. Based on the responses from the engineers it was shown that despite availability of many modern damage detection technologies, the state engineers still heavily rely on visual inspection as the main means of assessing the structural integrity of the bridges and as the first means of detecting and locating the sources of damage. Furthermore, the engineers were asked to share any emergency response plans that specifically address the treatment of damage in bridges after extreme events. The state engineers were also given the option to share their experiences on a number of relevant recent extreme events. This resulted in collection of a large amount of data regarding actual events where emergency response plans were followed.

Multiple Threats Affecting Transportation Infrastructure
Different hazards of natural or man-made origins could affect the structural integrity of bridges and result in partial or full closures. The first set of questions in both the bridge and hydraulic engineers’ survey addressed the likelihood of different events occurring at each state. The hazards that were listed in the bridge engineer’s survey included a set of natural and man-made hazards such as earthquake, scour, wind, storm surge/waves, landslides, flood/debris flow, liquefaction, blast, fire, overload, and collision. The hydraulic engineers’ survey included questions about likelihood of scour, storm surge/waves, and flood/debris flow. It should be noted that the results just represent the likelihood of the events from the perspective of the responding parties- mostly affected by the historical events- rather than an in depth risk analysis.

According to the bridge engineers, collision was considered as an event with a high likelihood by 34% of the responding engineers and ranking first. The follow-up interviews showed that majority of the cases were over height collisions with a few ones that were collision with the piers or other structural components of the bridges. The collisions were followed by scour-related failures (with 20% considering high likelihood), wind-related failures (with 18% considering high likelihood), and flood/debris flow (with 16% considering high likelihood). Table 1 shows different likelihoods of different hazards as identified by bridge engineers. It should be noted that after the follow-up interviews with the engineers ranking the winds as high likelihood, it was found out that the wind events did not necessarily result in the structural failure of the bridges. They had ranked wind as events with high likelihood of causing failure because the secondary effects of the high winds had hindered the serviceability and performance of their bridges. This included conditions where high winds resulted in high surge levels that resulted in partial or full failure of the bridge or cases where winds resulted in falling of debris, power lines, signs, etc. on the bridges consequently hindering its service. The hydraulic engineers ranked flood/debris flow and scour as the event with highest likelihood of occurrence (identified by 28% of respondents). One state also mentioned that the overtopping of bridges is an issue. However, the issue normally resolves after
the water subsides and the failure is most of the time in service rather than structural integrity of the bridge.

TABLE 1  Expected likelihood of different hazards across the states in the US identified by state bridge and hydraulic engineers (in percent)

<table>
<thead>
<tr>
<th>Hazard Type</th>
<th>Bridge Engineer Responses</th>
<th>Hydraulic Engineer Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Highly Likely*</td>
<td>Likely*</td>
</tr>
<tr>
<td>Collision</td>
<td>34</td>
<td>39</td>
</tr>
<tr>
<td>Scour</td>
<td>20</td>
<td>54</td>
</tr>
<tr>
<td>Wind</td>
<td>18</td>
<td>27</td>
</tr>
<tr>
<td>Flood/Debris flow</td>
<td>16</td>
<td>53</td>
</tr>
<tr>
<td>Landslide</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Fire</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Storm surge/waves</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Earthquake</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Blast</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Liquefaction</td>
<td>0</td>
<td>5</td>
</tr>
</tbody>
</table>

*Unlikely: Less than 1% probability in the next year  Likely: Between 10% and 95% probability in the next year
Possible: Between 1% and 10% probability in the next year  Highly Likely: Almost 100% probability in the next year

In an effort to have a better understanding of the hazard rankings, the different likelihoods of occurrence have been weighted (High likely=4, Likely=3, Possible=2, unlikely=1), and the responses have been ranked again. Based on the weighted approach, a new ranking emerges with collisions ranking first, followed by scour and flood/debris flow as second and third. Reviewing the results of the surveys reveals that in contrast with the current statistics that underline hydraulic reasons (such as flood, scour, and debris accumulation) as the major reason for bridge failures (e.g. 15-16), the state Bridge Engineers have identified collision as the primary reason of failures or disruption in service for the bridges. This discrepancy can mainly be attributed to the fact that in most of the state DOTs, the issues related to hydraulic events are first referred to hydraulic engineers and as such don’t necessarily come up as a main cause of concern for all of the bridge engineers.

**Damage Detection Techniques Used By States**

All of the responders count on visual inspection, either cursory or more detailed at arm-reach inspection, as the first approach to examine the damage to bridges. In many cases the final decisions would be made based on the results of visual inspection, while in some other cases, they would resort to other methods for a more in-depth detection of damage. Figure 1-Top shows the breakdown of the responses from state bridge engineers that use different damage detection technique and percentage popularity of different techniques. As shown in Figure 1-Top, the hand held non-destructive testing techniques (NDT) hold the second rank after visual inspection. Figure 1-Bottom shows the responses from the hydraulic engineers. Similar to state bridge engineers, visual inspection was considered as the first and major approach for damage detection –with 100%
of responding states using it—followed by portable sonar surveys (with 36.4%), and manned/unmanned sonar surveys (with 21.2%), ranking as second and third, respectively. Figure 1-bottom lists different damage techniques used by the state hydraulic engineers with percentage of the use and a list of states using them.

The state bridge and hydraulic engineers were also asked to comment on whether the damage detection techniques currently in use by their agency are capable of giving sufficient data for bridge damage assessment after the natural hazards that their transportation systems are exposed to. Figure 2 shows the responses from the engineers.

**FIGURE 2** Type of damage detection techniques in percentage used by (Top) state bridge engineers, and (Bottom) state hydraulic engineers.
**Availability of Emergency Response Plans**

One of the questions in the survey addressed the availability of pre-defined emergency response plans in the agencies. 83% of responding states mentioned that such plans are available for their state but 17% mentioned that their agency has not developed such plans. From those states that have existing emergency response plans, many don’t share the plans publically due to different administrative, security, and operational reasons.

For the majority of the DOTs that had some form of emergency response plans in place, the procedure included a multi-level assessment and decision making. In these cases the damage assessments were broken down into three levels/stages (Example states: Alaska, Illinois, Indiana, and Oregon). The first level is basically to determine whether the traffic could be allowed on the bridge. It would include the more cursory damage detection that would require the local engineers to check all of the bridges within a couple of hours of the extreme event and report to the upper level management the status of the bridges. At this stage, in case of identification of major structural safety in the bridges, the team is advised to close the bridge and notify law enforcement. The bridges that require more in-depth inspection, are tagged accordingly and a higher level of damage assessment is conducted by more experienced bridge inspectors. A level three damage assessment may be requested by this engineer to decide on the decision that needs to be made.

One should note that, although emergency response plans are for the post-event activities, for them to be most effective, its best to prepare for the consequences of expected events. Some of the states had taken their emergency plans to another level by assessing the expected risk from different sources and prioritizing their emergency response based on the criticality of the bridges. For instance Missouri DOT had used a prioritization tool to categorize the bridges into four priority levels. In this case, after an extreme event like earthquake the higher priority bridges would be assessed first. This approach provides an opportunity to the DOT to focus its resources to ensure that the critical roads would stay open after the event (Figure 3-Left). A similar approach was taken by New York State DOT where the earthquake response was categorized into three levels based on the magnitude of the expected earthquake (Figure 3-Right).

**FINDINGS OF THE RESEARCH**

Reviewing the collected responses three major gaps and opportunities for development are identified:

- **Identification of vulnerable bridges and the most important links of the transportation network**

To identify the vulnerable bridges, a quantitative (or at least qualitative) risk analysis approach is required. This will show the likelihood/intensity of different events at the location of bridge and provide a measure of the bridge vulnerability to sustain such loads during its life cycle. The important bridges in the network could be identified using the techniques available through network analysis (17-18). Furthermore, the bridges could be weighted based on their importance to the system (e.g. access to critical facilities or major business regions) and then ranked using network performance indicators (19-20). This will perform as a preliminary prioritization tool that would help organize the recovery and restoration action in case of regionally distributed extreme events that result in disasters.
Application of emerging techniques for remote sensing

Visual inspection is identified as the number one damage detection technique by both bridge and hydraulic engineers. Disaster response requires an assessment of damaged infrastructure as quickly as possible; however, data collection can be dangerous in an area after a natural disaster. Also, it may not be possible to rally enough survey teams to cover a large disaster area. Traditional disaster assessment practices involve both detailed and rapid ground surveys, but these practices can be limited by timeliness. Information provided by remote sensing technologies have been proven to be beneficial to detecting and locating damage. Remote sensing is used to acquire data on the structures without making physical contact. It is a common method utilized in disaster assessment and recovery, especially for buildings and geotechnical features, due to its adeptness over traditional site observation. Technologies associated with remote sensing are able to obtain post-disaster data over a large area more quickly compared to in-field surveying. The rapidness of remote sensing allows for quicker decision making and quicker action on necessary repairs on infrastructure. Spatial data, including maps, aerial photography, satellite imagery, GPS data, rainfall data, etc., is an important component of disaster management. The different data types require a co-registering process that will bring them to a common map-basis. Image registration or co-registration is a process of converting different sets of data into one coordinate system which is necessary to integrate and compare the data. The volume of data can be overwhelming if handled through manual methods, but gathering and organizing technologies like remote sensing and geographic information system (GIS) have improved efficiency. In this section three major techniques of remote sensing will be discussed: Satellite imagery, Light Detection and Ranging (LiDAR), and Unmanned Aerial Vehicles (UAVs).

It’s also worthwhile to highlight the role of structural health monitoring techniques that could be used to detect the state of the bridge under different types of hazards. The respondents showed a level of distrust in the alarms, data collected from these systems, and the costs associated with their maintenance. However, considering the high promises of the techniques in the field of assessment of damages, specifically in cases with no access to the bridge location, more investments on development of these techniques at least for important bridges is beneficial.

Development of robust and organized emergency plans dealing with the failure of the bridges

Considering that the capability of the system to return to its pre-event performance level is highly dependent on the speed of recovery which by itself is a function of the technical, organizational, and financial preparedness of the agency, it’s important for the agencies to be proactive and come up with emergency plans that are tailored specifically for the bridges in their jurisdiction, the hazards that they are facing, and the resources that are available to them to conduct recovery actions.
PREPARING A RESPONSE PLAN
A review of the extreme events that have impede the performance of bridges and service of the transportation networks, it’s evident that the competing demands, limited budgetary, human, and technical resources, and the urgency of restoration in capacity of the system, underscore the importance of planning. This will reduce delays in response, and helps avoids conflicts at a chaotic time. The establishment of repair/replacement priorities before the event, will help guide decision making during the response and recovery process and will minimize the unintended consequences. With such an approach the decision making authorities, law makers, and response and recovery teams will all be working towards the established goals. Having a streamlined plan towards response and recovery will also help to organize teams in a more efficient way to responds to extreme events that were not necessarily foreseen in the original plan as it provides them with a hierarchy of actions that needs to be taken.

To have an effective planning tool, the process of response and recovery needs to be prioritized. This process should at least include the following steps:
i) Assessment of damage to the transportation network at the component- and network-level and identify the roadways and links that will most likely get damaged. For this purpose a detailed hazard characterization process and vulnerability assessment of the transportation systems both at the component- and network-level is required. The outcome of this analysis will highlight the nodes and links of the network that are most likely to fail due to the considered events.

ii) Prioritization of the response and recovery actions for damage assets: At this stage critical facilities, such as hospitals, police stations, etc., that need to be connected to transportation resources immediately after the event, need to be identified and prioritized. Then the results of previous step need to be weighed based on the importance to the performance of the system. Here different performance measures such as travel time, short-term and long-term economic impacts could be considered.

iii) Plan for a balanced portfolio of actions that could result in achieving the set goals for response and recovery. This will include a) implementation of strategies to identify the extent of damage as immediately and accurately as possible (training of on-site inspectors, use of health monitoring data, use of remote sensing technologies), establish a clear line of communication with the inspection team, and detection devices with the headquarters of transportation agencies, b) create regular training sessions for the response and recovery teams that would keep them up-to-date on the most recent organizational aspects of response, the recent technologies, and protocols; appointments to the response and recovery teams should be identified prior to the event so that members of the team can all understand their role in the recovery process and the actions they are expected to perform during the recovery period. This team may include transportation planners, transportation engineers, emergency management experts, environmental experts, and first responders. The team should include members that have experience responding to disasters. Identify the location of resources with respect to potential risk areas, and optimize the pathways to get materials, instruments, and work force to such areas.

iv) The different response and recovery approaches need to consider the component of time in addition to cost-benefit analysis to ensure the choice of best recovery actions that are conductive of a resilience response. Figure 4 provides a review of such approach.

![FIGURE 4 Holistic framework for enhancing resilience in face of extreme events.](image-url)
CONCLUSIONS
The importance of resilience in transportation networks has grown parallel to the increasing traffic volumes on highways and roads and the continued construction of urban and suburban areas, trends that will continue well into the future. Infrastructure resilience can be improved after assessing its current state, thereby reducing its vulnerability to disruptions and extreme events, allowing plans for possible failures, flexibility during probable disruptions, post-event responses, and eventual repairs. These components correspond to the preparedness, absorptiveness, adaptation, and recovery of a resilient infrastructure system. This can be done by analyzing the resilience of the infrastructure system, allowing a holistic approach that takes into account several different aspects to improve the network’s overall performance against disturbances.

With this fundamental concept in mind, this report reviewed the existing literature in rapid damage detection technologies that could be used for identification of damaged areas and structures in a timely manner after an extreme event. Furthermore, the current state of practice when dealing with unforeseen failures (normally resulting from extreme events) and the emergency response plans followed by state departments of transportation (DOTs) were studied. The study began with two surveys that were distributed to state bridge and hydraulic engineers as members of the AASHTO Subcommittee on Bridges and Structures and the AASHTO Technical Committee on Hydrology and Hydraulics. The surveys addressed three major thrusts: (1) type of hazards in terms of likelihood of occurrence, (2) type of damage detection in use for rapid assessment of damage in bridges, and (3) availability of emergency response plans.

The survey responses on the availability of emergency responses showed that 86% of states claimed to have an emergency response plan in place for extreme events. The follow-up interviews however revealed that not all of the response plans are necessarily tailored for bridge damages. Also, some of the plans primarily covered the mechanisms of receiving emergency funding rather than dealing with the technical and organizational aspects of the restoration and recovery of the bridges. Reviewing the collected responses revealed three major gaps and opportunities for development. More details regarding the needs for each of the identified gaps and relevant solutions were then provided.

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