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An automatic system for the rapid post-earthquake safety assessment of bridges

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ABSTRACT:

This paper presents the development of an advanced system for the rapid post-earthquake safety assessment of bridges using advanced sensor technology. Upon completing the assessment, the system generates an automated report on bridge condition.
To evaluate the serviceability of bridges, engineers frequently employ sensors, such as accelerometers, strain gauges, and tiltmeters to measure accelerations, displacements, strain, tilt, and deflections. The obtained data are essential for theoretical and practical reasons. Engineers analyze the data to gain insights into real-world bridge dynamics and to develop and validate models that inform design codes. On the practical level, the data are used in structural health monitoring (SHM) systems to enhance public safety by providing reliable data about bridge conditions, both long-term and after unexpected events, such as disasters and earthquakes. Traditionally, bridge inspections are conducted every two years to detect potential deterioration. However, these inspections are expensive and may need to be done more frequently following extreme events like earthquakes, fires, or bridge strikes. To reduce costs, we propose an innovative automatic rapid assessment system that uses measured bridge response data to initiate and minimize re-evaluation efforts. The system works by converting the acceleration data to displacements; subsequently, a threshold that defines the serviceability of the bridge is established. When one of the thresholds is exceeded, a report on bridge condition is automatically generated. This system is particularly useful in post-earthquake events and after other emergencies. In such situations, fast and reliable decision-making is a strong necessity, but also a serious challenge due to common human conditions, such as panic and fear. Rapid, automated generation of reports ensures accurate assessments of damage, which are crucial for the reduction of serious economic losses and the maintenance of reliable infrastructure access.
In the paper we will discuss two case studies which illustrate the deployment of automatic, real-time assessment systems. As will be shown, these systems enhance the preparedness for disaster scenario and considerably improve bridge safety.

KEY WORDS: SHM; Disaster; Earthquake; Bridge Safety; Sensors; Automatic System; Safety Report.

1 INTRODUCTION

Bridges are vital components of transportation infrastructure, serving as critical links that facilitate the movement of goods and people. Their safety and serviceability are essential for public well-being, economic stability, and emergency response capabilities. The integrity of bridges must be maintained to prevent catastrophic failures that could lead to significant loss of life and disruption of transportation networks. This is particularly crucial in seismic-prone regions, where earthquakes pose a constant threat to bridge structures [1].

Following an earthquake, assessing bridge conditions rapidly and accurately is essential to prevent further damage, ensure public safety, and maintain transportation continuity. Earthquakes can induce severe structural damage, including cracks, joint displacements, bearing failures, and even complete collapses. Immediate post-earthquake assessments are necessary to determine whether a bridge can remain in service, requires immediate repair, or must be closed to avoid endangering the public. However, conducting these evaluations efficiently is challenging due to the scale of transportation networks and the inherent risks associated with manual inspections in post-disaster environments [2], [3].

Traditional inspection methods, which involve manual visual evaluations conducted every two years, are often inadequate in emergency scenarios. These assessments typically require trained personnel to physically inspect bridges, document damages, and make qualitative judgments about their structural integrity. Such methods are time-consuming, labor-intensive, and prone to human error, potentially delaying critical decisions about bridge usability. Additionally, access to bridges following an earthquake may be restricted due to debris, road blockages, or structural instability, further complicating manual inspection efforts [4].

To address these challenges, this paper presents an advanced system that leverages modern sensor technology and data analytics to facilitate rapid post-earthquake safety assessments of bridges. The proposed system integrates a network of sensors, including accelerometers, strain gauges, and tiltmeters, to continuously collect structural response data before, during, and after seismic events. By automating data acquisition, the system eliminates the need for labor-intensive manual inspections and provides real-time insights into the bridge's condition.

2 SENSOR TECHNOLOGY IN STRUCTURAL HEALTH MONITORING

Structural Health Monitoring (SHM) relies on various sensors to evaluate bridge conditions (see Figure 1).

Commonly used sensors include [5], [6]:

- Accelerometers: Measure vibrations and dynamic responses to external forces.
- Strain Gauges: Detect strain variations within bridge components.
- Tiltmeters: Monitor angular displacements and inclination changes.

The sensors such are strategically installed on key elements of the bridge, including the superstructure, bearings, and substructure. These sensors continuously or periodically record

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physical responses like vibrations, strains, and movements caused by traffic loads, environmental changes, or seismic events. Each sensor generates analog signals that reflect changes in the measured parameter, serving as the raw input for the monitoring system.

These analog signals are transmitted to a local data acquisition system (DAQ), which is typically housed in a weatherproof enclosure on or near the bridge. The DAQ performs several crucial functions: it converts analog signals to digital data through analog-to-digital converters, applies filtering and signal conditioning, and timestamps each measurement for synchronization across multiple channels. Depending on the configuration, the DAQ may operate in real time or in scheduled bursts, and it often includes onboard memory for local storage. Some systems also include edge processing capabilities to perform preliminary diagnostics or event detection directly at the site.

Once the data is digitized and preprocessed, it is transmitted from the DAQ to a local or remote data center using communication methods such as cellular networks (4G/5G), Wi-Fi, satellite uplinks, or fiber-optic lines. The data center acts as the central hub for data management, enabling long-term storage, advanced analysis, and integration with cloud platforms. Here, engineers and transportation agencies can access the data remotely via secure web portals or custom dashboards. Real-time data streams enable continuous monitoring, while automated algorithms can trigger alerts when structural anomalies are detected. This end-to-end system supports rapid decision-making, improves maintenance planning, and enhances the resilience of critical bridge infrastructure.

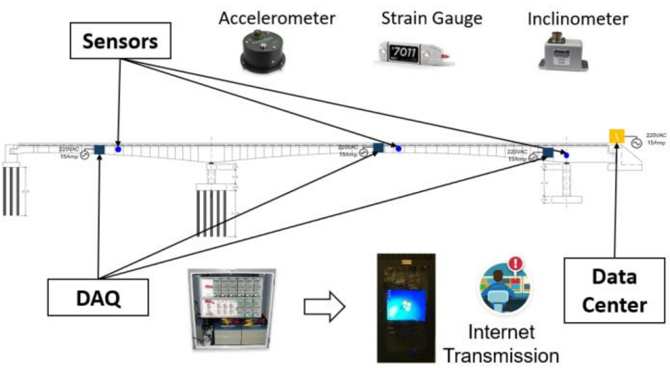

Figure 1. Typical instrumentation in bridge monitoring.

By continuously recording bridge responses, these sensors help engineers assess structural integrity, detect anomalies, and validate theoretical models that guide design and maintenance strategies.

3 CHALLENGES OF TRADITIONAL BRIDGE INSPECTION

Traditional bridge inspections are conducted biennially to identify potential deterioration. However, after extreme events such as earthquakes, additional inspections become necessary. Some key challenges include (see Figure 2) [7]:

- High Costs: Manual inspections require significant financial and human resources, including specialized personnel, equipment, and logistical support.
- Time Constraints: Evaluations can take days or weeks, delaying crucial transportation access and prolonging disruptions in emergency response efforts.
- Human Limitations: Panic, fatigue, and cognitive overload can impair decision-making during crises, leading to inconsistent or inaccurate assessments.
- Safety Risks: Inspectors working in post-disaster environments face significant hazards, including aftershocks, unstable structures, and difficult-to-access areas.
- Limited Coverage: Manual inspections may not comprehensively assess structural integrity, particularly in large-scale bridge networks where resources are constrained.

Figure 2. Challenges of Bridge Inspection.

The introduction of automated systems can significantly mitigate these challenges by providing rapid and accurate assessments without the need for extensive human intervention. Advanced technologies, such as sensor networks, computer vision, and artificial intelligence, enable continuous monitoring and real-time analysis, enhancing decision-making and improving overall safety and efficiency in bridge assessment processes [8].

By minimizing reliance on manual inspections, these automated systems not only reduce labor costs and human error but also allow for more frequent and consistent data collection. This continuous stream of high-quality data enables a shift from reactive maintenance to predictive maintenance strategies, where potential issues can be identified and addressed before they escalate. As a result, bridge management authorities can prioritize interventions more effectively, allocate resources efficiently, and extend the service life of critical infrastructure.

The collected sensor data is processed using advanced algorithms, to identify damage patterns, quantify structural deterioration, and predict the bridge's residual load-carrying

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capacity. This automated analysis enables the generation of detailed condition reports, which provide decision-makers with critical information needed to implement timely and effective mitigation measures. Furthermore, integrating this system with geographic information systems (GIS) and cloud-based platforms enhances accessibility and facilitates coordinated emergency response efforts.

4 PROPOSED AUTOMATIC RAPID ASSESSMENT SYSTEM METHODOLOGY

Structural Health Monitoring (SHM) is a critical tool for assessing the safety of bridges after an earthquake. The methodology involves 5 steps: pre-event preparation, real-time data acquisition during earthquake, post-event structural evaluation, decision-making process and reporting and action plan (see Figure 3).

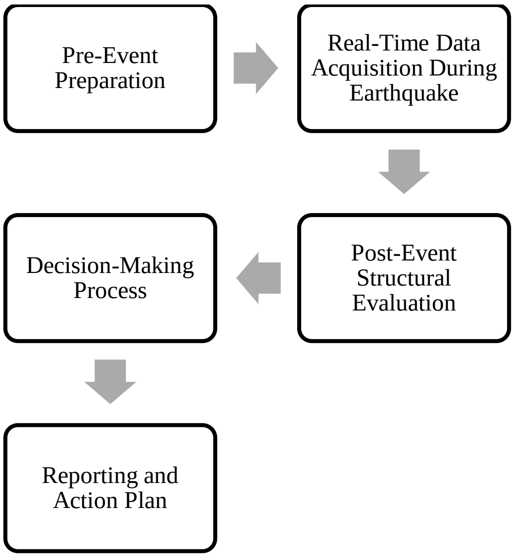

Figure 3. Proposed Automatic Rapid Assessment System Methodology.

4.1 Pre-Event Preparation

Effective rapid assessment begins with thorough pre-event preparation, which includes identifying critical bridges within a transportation network and prioritizing them based on factors such as structural vulnerability, traffic volume, and strategic importance. Engineers conduct baseline assessments to understand the bridge's current condition and develop models that simulate its response to different seismic scenarios. These models form the reference point for interpreting data during and after seismic events.

Sensor deployment is a key part of preparation. Various sensors including accelerometers, strain gauges, and tiltmeters are installed on structural components most susceptible to damage. The placement is informed by structural analysis and past performance data. In addition to physical installation, sensors are calibrated to ensure accuracy and synchronized with the local data acquisition system (DAQ), which includes real-time clocks and backup power sources to maintain continuity during power loss.

Finally, a communication framework is established for transmitting sensor data to remote servers or data centers. The infrastructure includes reliable network connectivity (e.g., cellular, satellite, or wired connections) and cybersecurity measures to protect data integrity. Pre-event simulations and drills are also conducted to validate the system's performance and ensure all stakeholders, engineers, emergency responders, and transportation officials are familiar with the protocols in the event of a real earthquake.

4.2 Real-Time Data Acquisition During Earthquake

When an earthquake occurs, the sensor network activates automatically or continues uninterrupted if running continuously. Force balance accelerometers capture ground and structural accelerations in three dimensions, while strain gauges and displacement sensors measure localized deformations. These signals are digitized by the DAQ and time-stamped to ensure synchronization across multiple channels and locations.

The DAQ processes the raw data using onboard algorithms to filter noise and detect events that exceed pre-set thresholds. Once significant shaking is detected, the system flags the event and immediately begins streaming prioritized data packets to the central server. Some systems also include edge computing capabilities, allowing for initial damage classification and triage to be performed locally and transmitted as summaries, reducing bandwidth requirements and accelerating response.

During this real-time acquisition phase, data flows continuously or in event-driven bursts to a central data center. There, automated software correlates input from multiple bridges, maps the earthquake's effects regionally, and compares the measured response with known damage thresholds from the pre-event models. This allows emergency management teams to quickly determine which bridges may be compromised and require immediate inspection or closure.

4.3 Post-Event Structural Evaluation

After the shaking subsides, the system transitions to post-event evaluation. This involves aggregating the seismic response data and analyzing it against the bridge's baseline condition and predicted performance models. Engineers can assess the magnitude of forces experienced by each structural component and detect anomalies such as excessive displacements, residual vibrations, or sensor signal losses, which may indicate potential damage.

The evaluation process uses advanced algorithms. These tools identify patterns in the data that correlate with specific types of damage (e.g., joint failure, deck uplift, or bearing dislocation). By automating this analysis, the system reduces reliance on manual inspections and accelerates decision-making, particularly when multiple bridges are affected over a large geographic area.

Visualizations such as shake maps, bridge health dashboards, and risk scores are generated for each bridge. These outputs are reviewed by structural engineers and decision-makers to confirm automated findings. In high-priority cases, the system may recommend sending an inspection team or deploying drones for visual assessment, thus focusing on limited resources where they are most needed.

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4.4 Decision-Making Process

The decision-making process combines sensor-derived analytics with predefined action thresholds to classify bridge conditions into categories such as “safe,” “needs inspection,” or “likely damaged.” This triage helps agencies prioritize their response efforts, enabling the reopening of safe routes and the timely closure or detour of potentially unsafe bridges.

A critical component of this process is the decision support system, which integrates real-time sensor data, historical performance, and geographic context to recommend next steps. The system presents stakeholders with actionable insights, supported by confidence levels and potential consequences, empowering transportation officials to make informed, defensible decisions under pressure.

Human oversight remains essential. While the system automates much of the analysis, expert engineers review key findings to validate system outputs, especially in cases of high uncertainty or critical infrastructure. Collaboration between departments of transportation, emergency response, and engineering is coordinated through centralized platforms to ensure consistent, fast communication and execution of response plans.

4.5 Reporting and Action Plan

Once the structural condition of each bridge is assessed, the system generates standardized reports that summarize sensor readings, algorithmic evaluations, and recommended actions. These reports include timestamps, structural response graphs, and comparison with design-level seismic criteria. They are shared through secure digital platforms with transportation authorities, emergency managers, and relevant stakeholders.

For bridges flagged as potentially compromised, the system issues automated alerts accompanied by suggested action plans. These may include full closures, restricted traffic use, or on-site inspection. In more advanced deployments, the system integrates with traffic management infrastructure to redirect traffic automatically, display warnings on digital signage, and update navigation systems.

The final component of the action plan involves post-event documentation and learning. All data and actions taken are archived for forensic analysis, regulatory compliance, and refinement of future response protocols. This feedback loop allows the system to improve over time, helping bridge operators become more resilient to future seismic events and more effective in their emergency response.

5 CASE STUDY 1: YUCAIPA EARTHQUAKE IMPACT ON BEAUMONT - I10/60 INTERCHANGE BRIDGE

In this case study, the automatic assessment system was deployed on Beaumont - I10/60 Interchange Bridge (see Figure 4). The bridge is located in Riverside County, California, near the city of Beaumont, where Interstate 10 (I-10) and State Route 60 (SR-60) converge (see Figure 5). This critical interchange lies in Southern California’s Inland Empire region and serves as a major transportation corridor linking Los Angeles to the Coachella Valley and beyond. Positioned in a seismically active area near the San Andreas Fault, the bridge plays a vital role in regional mobility and freight transport, making its structural integrity and seismic resilience essential for public safety and economic continuity.

Figure 4. Beaumont - I10/60 Interchange Bridge.

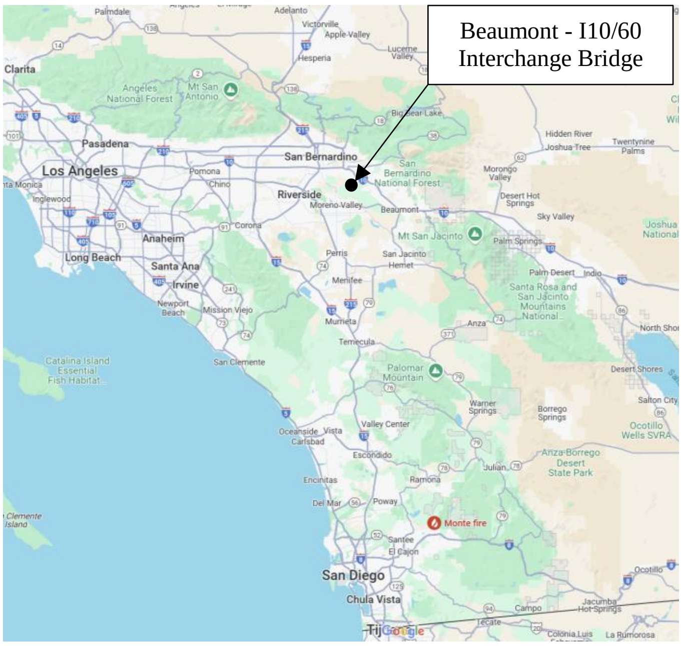

Figure 5. Bridge Location.

The bridge is composed of 2 abutments and 3 bents; the span of the bridge is 112.78 m (370 ft) and a height of 8.23 m (27 ft). In 1992, the bridge was instrumented with six force balance accelerometers as part of a seismic monitoring initiative (See Figure 6). This instrumentation was implemented through an interagency agreement between the California Department of Transportation (Caltrans) and the California Department of Conservation (DOC). The collaboration aimed to enhance the structural health monitoring capabilities of critical transportation infrastructure in seismically active regions, enabling the collection of high-quality acceleration data to support seismic performance assessment and emergency response efforts.

On June 16, 2005, the bridge was exposed to the Yucaipa Earthquake. The epicenter of the earthquake was located 3.39 km (2.1 mi) NE of Yucaipa, CA, USA; had a magnitude of 4.9 and a depth of 12.6 km (see Figure 7). The Yucaipa earthquake was a moderate seismic event and occurred at approximately 8:05 PM local time. Its epicenter was located within a seismically active zone influenced by the complex interactions between the San Andreas Fault and other nearby fault systems in the eastern Transverse Ranges. The event was widely felt throughout the Inland Empire and greater Los Angeles area, prompting temporary evacuations and raising concerns about infrastructure resilience in the region.

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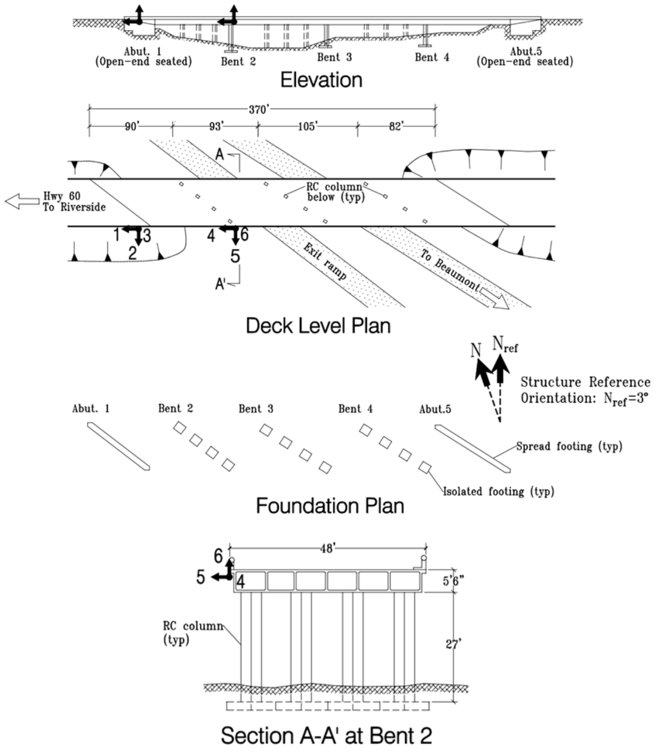
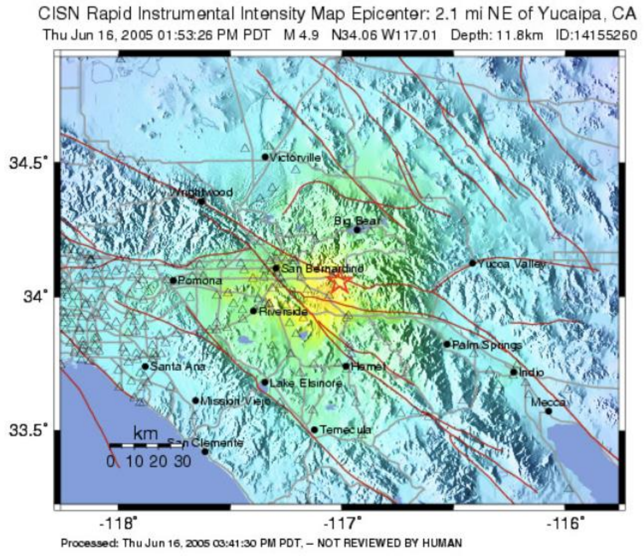


Figure 6. Instrumentation on the bridge (Source: Center for Engineering Strong-Motion Data -CESMD).

Although the 2005 Yucaipa earthquake did not result in any fatalities or major structural damage, it caused minor non-structural damage, such as cracked walls, fallen ceiling tiles, and items displaced from shelves in homes and businesses. The shaking intensity reached Modified Mercalli Intensity (MMI) level VI in the immediate vicinity, indicating strong shaking. The event highlighted the seismic hazard in this part of Southern California and reinforced the importance of earthquake preparedness and monitoring. For researchers and agencies, the earthquake served as a valuable data point for evaluating the performance of early seismic instrumentation, ground motion characteristics, and local soil amplification effects, especially in areas with vulnerable infrastructure such as bridges, schools, and hospitals.

In this context, the instrumentation installed on the bridge provided a critical opportunity to assess structural performance during the 2005 Yucaipa earthquake. The sensors captured real-time data on ground motion and structural response, offering insights that would have been difficult to obtain through visual inspections alone. This event demonstrated the practical value of instrumented bridges in seismic regions, as the recorded data allowed engineers to verify the integrity of the structure without interrupting service. The success of this monitoring effort laid the foundation for more advanced automated assessment systems, capable of rapidly analyzing sensor outputs, identifying potential damage, and supporting immediate post-earthquake decision-making—thus addressing many of the challenges associated with traditional inspection methods.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 7. Yucaipa Earthquake (Source: Center for Engineering Strong-Motion Data -CESMD).

Traditional inspections required extended closures and significant financial investment. Following an earthquake, the system could successfully:

- Detected abnormal vibrations exceeding the established serviceability threshold.
- Generated an automatic report, recommending immediate structural reinforcement.
- Enabled engineers to assess the damage remotely, reducing the need for manual inspections.

As a result, the system significantly decreased bridge downtime and ensured rapid decision-making for emergency response teams.

6 CASE STUDY 2: CALEXICO EARTHQUAKE IMPACT ON BEAUMONT - I10/60 INTERCHANGE BRIDGE

In this case the Beaumont - I10/60 Interchange Bridge was exposed to the Calexico Earthquake on April 4, 2010. The epicenter of the earthquake was located 49.57 km (30.8 mi) SSE of Calexico, CA, USA; had a magnitude of 7.2 and a depth of 10.0 km (see Figure 8). The Calexico earthquake and the Yucaipa earthquake differed significantly in both magnitude and regional impact. The Yucaipa earthquake registered a magnitude of 4.9 and occurred in the inland region of Southern California, near the San Andreas Fault system. It resulted in minor non-structural damage and served primarily as a data point for evaluating local ground motion and instrumentation performance. In contrast, the Calexico earthquake, also known as the El Mayor–Cucapah earthquake, was a much larger event with a magnitude of 7.2. It struck near the U.S.–Mexico border, affecting both countries and causing extensive structural damage in the city of Calexico and surrounding areas.

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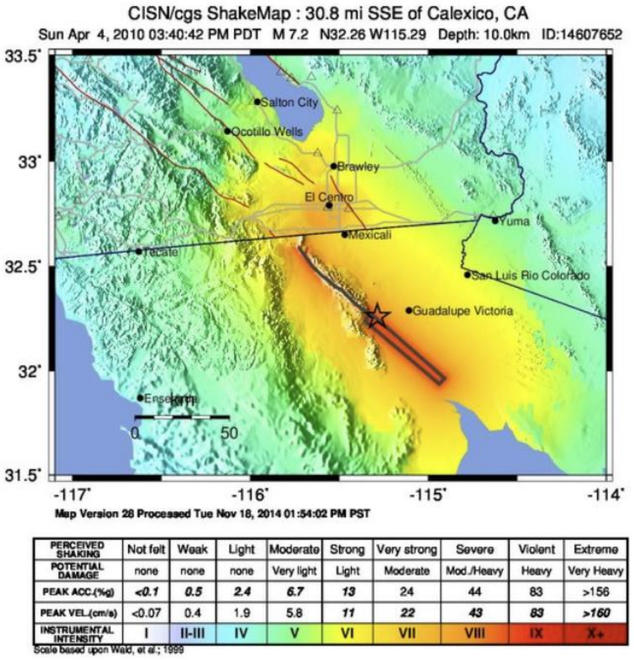

Figure 8. Calexico Earthquake (Source: Center for Engineering Strong-Motion Data -CESMD).

The automatic rapid assessment system showed higher displacements in the bridge for the Calexico Earthquake (see Figure 9 and Figure 10).

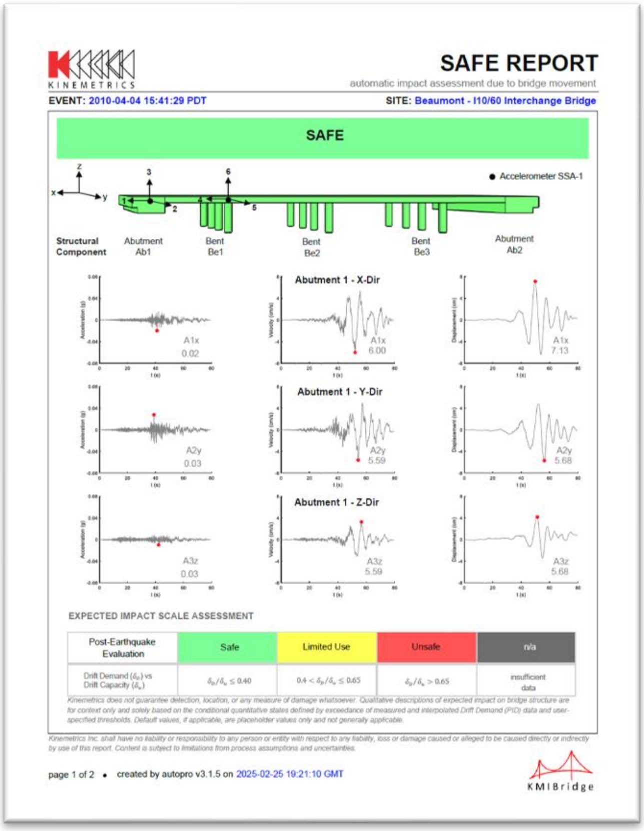

Figure 9. Automatic Rapid Assessment System 1/2.

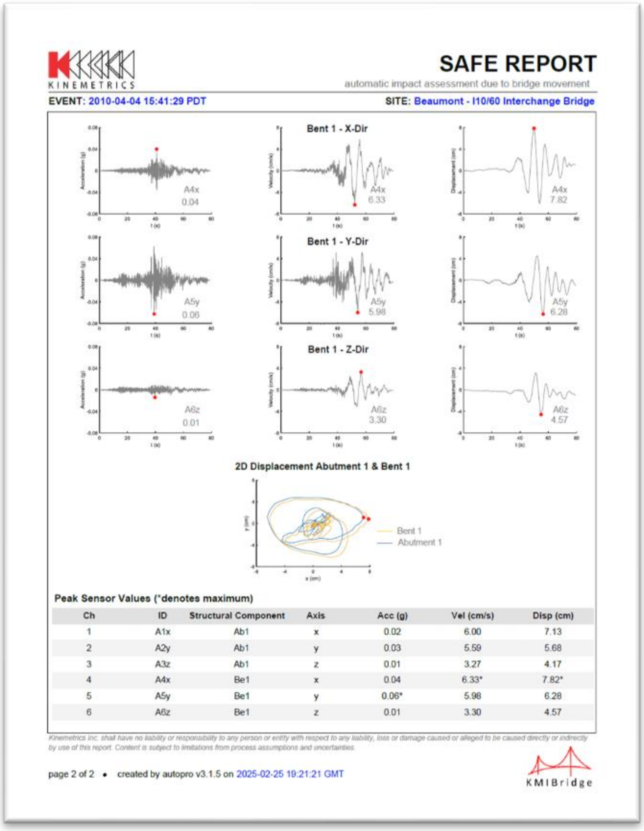

Figure 10. Automatic Rapid Assessment System 2/2.

What sets the proposed automatic rapid post-earthquake evaluation system apart from existing automated solutions is its ability to collect and process real-time acceleration, velocity, and displacement data immediately following a seismic event. Unlike conventional systems that primarily rely on periodic assessments or post-processed sensor data, this approach enables near-instantaneous evaluation of structural performance during and after an earthquake. By integrating high-frequency data acquisition with advanced algorithms, the system provides a more accurate and timely understanding of potential damage, allowing for faster decision-making and more effective emergency response.

Importantly, this system is designed to support, not replace, structural engineers. By delivering actionable data in real time, it empowers engineers to make informed decisions more quickly and confidently after events. The tool enhances professional judgment with rapid, data-driven insights, improving both the efficiency and reliability of post-earthquake assessments while maintaining the essential role of expert evaluation.

7 CONCLUSIONS

The proposed advanced system for rapid post-earthquake bridge safety assessments integrates sensor technology, automated data processing, and real-time reporting to enhance disaster response capabilities. By replacing traditional, labor-intensive inspections with automated evaluations, the system ensures timely, cost-effective, and reliable infrastructure

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assessments. The case study illustrates its effectiveness in different bridge settings, reinforcing its applicability in both urban and rural environments. Future advancements in SHM technology, including artificial intelligence integration, could further improve the accuracy and predictive capabilities of such systems, ultimately leading to safer and more resilient bridge infrastructure.

By adopting this technology-driven approach, transportation agencies and emergency management teams can significantly improve the efficiency and accuracy of post-earthquake bridge assessments. The implementation of modern sensor-based monitoring systems enhances safety by enabling early detection of structural vulnerabilities, reducing the reliance on subjective visual inspections, and expediting repair and maintenance actions. Ultimately, the integration of these advancements contributes to more resilient transportation infrastructure and ensures the continued functionality of bridges in the aftermath of seismic events.

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