



NEW ACTIVE SEISMIC DAMPER CONCEPT INTEGRATING SHMS, BIM, IoT, AI, DIGITAL TWIN, AND EARTHQUAKE SENSOR

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Abstract. Most bridges in Indonesia are not in good condition, and the number of collapsed national bridges is relatively high. In addition to poor maintenance, construction-related accidents during bridge projects are also frequently reported. Therefore, a system such as the Structural Health Monitoring System (SHMS) is needed to monitor and control bridge conditions. Nowadays, SHMS has been integrated with Building Information Modeling (BIM), supported by technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and Digital Twin (DT). However, these technologies have not yet been effectively utilized for mitigating the impacts of earthquake. Current technologies for mitigating seismic forces remain passive and have not yet incorporated sensor-based technologies. This study proposes an active structural response framework to seismic excitation, utilizing real-time sensing and advanced digital integration. Sensors are used to continuously monitor structural movement and transmit data directly to the cloud using IoT technology. This real-time data is then integrated with Building Information Modeling (BIM) to create a virtual representation of the structural response through digital twin technology. The movement data is further analyzed using AI to determine the magnitude and timing of the corrective force needed to restore the structure to its original state. However, the proposed concept has a key limitation: the corrective force is applied with a one-period delay, as it is based on the structural response from the previous vibration cycle.

Keywords: SHMS, BIM, Earthquake Sensor, Artificial Intelligence, Digital Twin

1 INTRODUCTION

According to data from the Directorate General of Highways (Ditjen Bina Marga), the number of bridges on Indonesia's national roads has increased steadily over the years. However, the number of damaged or even collapsed bridges has also risen annually [1]. These bridge failures can be attributed to operational or environmental factors. Notable incidents include the collapse of the Kartanegara Bridge (2011), which had been in service for only 10 years despite its designed lifespan of 25 years [2]. Other case, the Pasar Minggu Pedestrian Bridge collapsed in 2016 due to missing bolts and unaccounted-for additional billboard loads during the bridge's design phase [3], [4]. In

2024, a bridge in Deli Serdang collapsed, with local residents reporting 22 missing support beams, 18 steel plates, and numerous absent bolts [5].

Table 1. National bridge condition data

Source: [1]

Year	Condition						
	Excellent	Moderate	Minor Damage	Moderate Damage	Severe Damage	Critical	Collapsed
2013	6997	3201	2975	-	1404	309	46
2014	6609	3137	3253	-	1360	314	37
2016	6685	4418	4371	-	1942	484	114
2019	5677	10197	2442	-	-	235	97
2020	5658	10839	2086	-	246	-	87
2021	155	11328	4545	-	2808	-	89
2022	228	-	3608	12484	2287	261	122
2023	170	13844	2546	-	2366	320	131

The substantial number of damaged bridges across Indonesia necessitates comprehensive monitoring of the nation's bridge infrastructure. The technical process for identifying structural deterioration in existing bridges is termed *Structural Health Monitoring* (SHM). In SHM terminology, *damage* refers specifically to any measurable changes in material properties, geometric configurations, boundary conditions, or connection systems that may compromise structural integrity [6]. The primary objective of a Structural Health Monitoring System (SHMS) is to identify and quantify structural damage at both local and global scales [7]. This involves the continuous or periodic observation and analysis of a structure's condition using integrated sensor systems, enabling early detection of anomalies that may compromise structural integrity.[8]

Indonesia has initiated the implementation of Structural Health Monitoring Systems (SHMS), with the Suramadu Bridge—connecting the islands of Java and Madura—serving as a notable example. Nevertheless, the performance of the installed sensors has been not optimal due to inadequate management and incidents of sensor theft [9]. The primary impediment to the effective functioning of SHMS in Indonesia is the absence of a well-defined management framework [10]. One proposed solution to address this deficiency is the integration of Building Information Modeling (BIM). BIM has the potential to enhance communication among project stakeholders and to serve as a comprehensive digital repository for project-related data, thereby reducing the likelihood of conflicts [11], [12]

In addition to inadequate bridge maintenance, Indonesia is highly prone to natural disasters, particularly earthquakes. The country is situated at the convergence of several major tectonic plates, including the Indo-Australian Plate, the Philippine Plate, and the Pacific Plate [13]. Bridge collapses due to seismic activity are relatively frequent in Indonesia. One notable case occurred in 2005, when six bridges in Gunung Sitoli, Nias, were destroyed following a major earthquake. The damage severely hindered the delivery of emergency aid, as one of the collapsed bridges served as a critical access route to the airport [14]. Another significant event occurred during the 2018 earthquake in Palu, which led to the collapse of the Jembatan IV Bridge [15]. Similarly, the 2023

earthquake in Bima caused the failure of a bridge connecting the Waworada area to Doro O'o [16].

Currently, the integration of Building Information Modeling (BIM) with Structural Health Monitoring Systems (SHMS) has been implemented in several countries and has shown promising results for bridge maintenance. However, the use of SHMS technology with BIM to mitigate the impacts of earthquakes has not yet been implemented. Previous Active Mass Dampers studies [17]–[22] still relied on a single type of sensor, as they were unable to integrate data from Structural Health Monitoring Systems (SHMS). Consequently, prior research has primarily focused on developing equations that enable accelerometer data to substitute for measurements typically obtained from velocimeter and Linear Variable Differential Transducer (LVDT). Recent developments have enabled the integration of BIM and SHMS with Internet of Things (IoT), Artificial Intelligence (AI), and digital twin technologies, allowing real-time monitoring of bridge conditions. This real-time structural movement information can be utilized to actively mitigate the impact of earthquakes. Traditionally, seismic protection has been passive, relying on materials and design features to absorb seismic forces. In contrast, with real-time knowledge of structural motion—such as predicting directional shifts—seismic forces can potentially be counteracted actively, offering a more responsive and adaptive approach to earthquake resilience.

2 STRUCTURE HEALTH MONITORING SYSTEM

Structural Health Monitoring (SHM) is a system designed to monitor the behavior of structures in real time, with the aim of evaluating their performance in response to applied loads, detecting structural damage, or identifying any degradation in performance. This system can be implemented in both new and existing constructions to assess the condition of the structure and serve as an early warning mechanism for damage that may not yet be visible. [23]

Long-term monitoring systems for bridges have been widely implemented in various countries, including those in Europe, the United States, Canada, Japan, Korea, China, and others [24]. According to Ko and Ni, a Structural Health Monitoring System (SHMS) generally provides the following key functions:

- Validation of design assumptions and parameters, which supports the development of similar structures in the future.
- Detection of anomalies in structural responses, enabling early identification of damage or structural degradation.
- Provision of real-time information regarding structural conditions, even following extreme events or disasters.
- Guidance for inspections and both major and minor repairs, based on the system's continuous monitoring data.
- Performance evaluation of the structure after repairs.
- Supply of essential data for future research, including seismic or wind-resistant design, evaluation of new structural types, and assessment of innovative construction materials.

Sensors used in Structural Health Monitoring Systems (SHMS) can be broadly classified into three categories: kinematical, mechanical, and physical/ambient sensors [25], [26]. Kinematical sensors are employed to measure structural responses such as displacement, velocity, and acceleration, which are essential for analyzing dynamic behavior. Mechanical sensors focus on monitoring internal forces, deformation, and stress within structural elements, providing valuable insights into the structural load-bearing capacity and integrity. Meanwhile, physical or ambient sensors capture environmental parameters such as wind speed, humidity, and temperature, all of which can significantly affect structural performance and long-term durability. [25], [26].

2.1 Kinetic Sensor

Kinematic sensors, essential in Structural Health Monitoring Systems (SHMS), are categorized into accelerometers, velocity sensors, and displacement sensors. Among these, accelerometers are most commonly used to measure vibrations and assess structural dynamics. There are four main types: capacitive (detects changes in capacitance due to movement), piezoelectric (uses stress-induced electric charge in crystals for high-frequency detection), force balance (uses a servo-controlled mechanism to balance acceleration-induced force), and MEMS (miniaturized, cost-effective capacitive sensors) [25], [26]. Velocity sensors include Doppler-effect velocimeters, which use laser frequency shifts, and electromechanical types that generate current via coil-magnet interactions [25], [26]. Displacement sensors, like the LVDT, offer accurate real-time data within limited ranges, making them ideal for continuous monitoring despite their restricted span [26], [27].

2.2 Mechanic Sensor

Mechanical sensors play a vital role in monitoring structural integrity by measuring force, deformation, and stress—primarily through load cells and strain gauges [26]. Load cells convert force into electrical signals, while strain gauges detect strain that can be translated into deformation and stress when combined with force data [26]. Recent advancements include fatigue sensors, which detect progressive damage in structures (especially bridges) by sequential failure of ligaments with varying strain sensitivities [26], [28]. Additionally, corrosion sensors have been developed, such as electrochemical types that measure impedance differences to detect corrosion levels, and RFID-based sensors that estimate corrosion using high-frequency magnetic waves and signal-induced currents [26], [29]–[31]. These technologies enhance the ability to monitor and predict structural degradation over time.

2.3 Environmental Sensor

Environmental sensors are among the most commonly used sensors, not only in Structural Health Monitoring (SHM) but also in various other applications. First, there is the anemometer, which measures wind speed. This data can be compared with the design wind speed to assess the impact of wind loads on the structure. Next, the thermometer measures air temperature, and modern thermometers can now also measure humidity. Finally, water elevation measurement tools are crucial, especially for bridges with piers

located in water. Monitoring water elevation allows for estimating the level of protection against corrosion and can serve as a basis for calculating the additional loads exerted by water flow. [26], [29]

3 BUILDING INFORMATION MODELING

Building Information Modeling (BIM) is a software-assisted technology designed to manage comprehensive project information, including materials, costs, scheduling, and other relevant aspects, all of which are structured within various BIM dimensions. These dimensions extend the utility of BIM beyond traditional 3D modeling and are classified as follows: 3D modeling, 4D time schedule, 5D cost estimation, 6D sustainability development, 7D lifecycle and maintenance management, 8D construction safety monitoring, 9D construction efficiency, 10D industrialization of construction [32].

BIM can be integrated throughout the entire life cycle of a building—from the planning and design phases to pre-construction, construction, and post-construction (maintenance). It enhances efficiency at every stage [12], [33]. BIM facilitates collaboration among various disciplines by consolidating data into a single model, thus minimizing conflicts between disciplines and streamlining processes. For instance, if the dimensions of a window are altered, the corresponding wall dimensions and material volumes can be automatically updated by the BIM system [11]. The integration capabilities of BIM have evolved further with the advent of cloud-based data storage, allowing seamless connectivity with other applications [11], [12], [34]. One such compatible application is Autodesk Revit, which supports structural modeling, load input, and material definition, and can be integrated with finite element-based software like Autodesk Robot for structural analysis [34], [35].

4 INTEGRATED SHMS WITH BIM

Research integrating Structural Health Monitoring Systems (SHMS) with Building Information Modeling (BIM) was initially conducted by Theiler in 2017. At that time, SHM lacked a well-defined mathematical framework for managing monitoring data. BIM was proposed as a solution to store and model SHM information, including sensor algorithms and monitoring strategies, thereby improving the organization and accessibility of structural performance data. [36].

Another study was conducted by Li in 2022, in which SHMS was integrated with BIM, allowing sensor data to be incorporated into damage analysis and subsequently visualized to reflect the structural condition of the bridge. In this research, damage identification was performed using the Wigner-Ville Distribution (WVD), a bilinear time-frequency analysis technique. This method analyzes structural data collected before and after damage occurs, providing key information such as phase, amplitude, and other signal characteristics, which are essential for accurate damage assessment and visualization. [37]

The experiment was conducted on a laboratory-scale cable-stayed bridge model under various damage scenarios, using both strain gauge and accelerometer sensors. The results demonstrated that the Wigner-Ville Distribution (WVD)-based method could accurately identify both the location and severity of structural damage. The study concluded that integrating Building Information Modeling (BIM) with Structural Health Monitoring Systems (SHMS) is beneficial for enhancing data visualization and processing of sensor outputs. Furthermore, the WVD method significantly improves the accuracy of damage detection in bridge structures. [37]

A similar study was conducted in China focusing on heritage buildings made of timber. The case study involved the Feiyun Wooden Pavilion, where a BIM model was developed based on field survey data. Sensors were installed to monitor the deformation and stress of the wooden structure. The collected data were used to define early warning thresholds, which were categorized into three levels:

- Yellow : Minor changes but require attention
- Orange : significant changes that require further inspection
- Red : severe changes that require immediate action

BIM was utilized to integrate the monitoring data and compare it against threshold values derived from finite element-based modeling in Revit software. Information related to structural reinforcement and ongoing monitoring was also incorporated into the BIM model. [38]

The integration of Building Information Modeling (BIM) with Structural Health Monitoring (SHM) has been utilized to detect structural damage caused by earthquakes. In this approach, data from SHM sensors are integrated into the BIM model to predict damage levels following seismic events. Through BIM, information can be accessed in real-time via cloud computing. The sensor data are directly processed using fragility curves and subsequently input into BIM software based on finite element analysis (FEA). According to this study, BIM-based SHM significantly reduces the time and cost associated with post-earthquake inspections.[39]

The integration of SHM with BIM typically still relies on offline data processing, which can delay problem detection. The innovative use of Digital Twin (DT) technology enables a real-time virtual representation of BIM, allowing for immediate identification of structural issues. In the framework proposed by this study, IoT-based wireless SHM data are collected in real-time, then processed and denoised by the DT system. The cleaned data are subsequently used for structural simulations within the BIM model, which is analyzed using finite element analysis (FEA)-based software. [40]

The utilization of SHMS and BIM has primarily been limited to the maintenance phase. During the construction phase, existing research has largely focused on the use of environmental sensors to improve project management in response to changing field conditions [41]. This study proposes the integration of SHMS sensors with BIM during the construction phase, allowing for the systematic documentation of the bridge's structural history from the onset. Additionally, the implementation of SHMS during construction is expected to help mitigate potential risks throughout the building process.

5 INTEGRATED SHMS WITH BIM

Earthquakes are among the most frequent natural disasters occurring in Indonesia and often result in significant damage, particularly to structural systems. An earthquake is defined as ground shaking caused by the sudden release of energy from within the Earth's crust, primarily due to tectonic plate movements [42]. While earthquakes remain inherently unpredictable, recent advancements in seismic sensor technology have enabled the development of early warning systems. One such system is UrEDAS, designed by Yukata Nakamura, which aims to provide rapid alerts to mitigate the impact of seismic events..

UrEDAS detects P-waves, which are the primary waves generated by an earthquake, prior to the arrival of the more destructive secondary S-waves [43]–[45]. P-waves are the fastest seismic waves and can be recorded by sensors earlier than other wave types, making them a key indicator for the onset of an earthquake [46], [47]. The UrEDAS system utilizes the disparity between the speed of telecommunications signals—approximately 300,000 km/s—and the much slower speed of seismic waves, which is about 8 km/s [44]. One notable case study was conducted in Kawaguchi, where the P-wave was detected 2.9 seconds after the earthquake originated at the epicenter. One second later, or 3.9 seconds after the initial quake, the earthquake alarm was triggered. The S-wave arrived 2.5 seconds after the alarm was activated, or 6.4 seconds after the quake's origin, and the tremor was felt at the surface approximately one second after that. Thanks to the early warning provided by UrEDAS, a train in operation at the time received the alert 3.5 seconds before the ground shaking occurred, allowing it to stop in time and reduce the potential impact of the earthquake [44].

Another study on earthquake early warning systems was conducted by Sherki et al. (2015), employing both P-wave and S-wave approaches. The system utilized a 3D accelerometer sensor, specifically the Bosch BMA-180, which is sensitive to seismic frequencies ranging from 0.1 to 30 Hz. A digital bandpass filter was applied to eliminate noise and retain only vibrations within the desired frequency range. A key innovation of this study was the use of triangulation, which requires a minimum of three sensors and involves azimuth angle calculations. Based on the collected data, Power Analysis was conducted to evaluate energy distribution. If the vertical power component exceeded a defined threshold, the corresponding wave was identified as a P-wave. In addition to Power Analysis, Energy Analysis was also implemented by comparing short-term and long-term energy levels. A sudden spike in short-term energy, while long-term energy remained relatively stable, was interpreted as an indication of the arrival of either a P-wave or an S-wave. [48].

An earthquake sensor system based on the Internet of Things (IoT) and Wireless Sensor Networks (WSNs) was developed by Alphonsa and Ravi (2016). This system utilizes both P-wave and S-wave detection and is designed to deliver early warning messages to the public via smartphones. Real-time data collected by the sensors are transmitted to a cloud platform, while signal processing is handled through LABVIEW software. The system employs Zigbee as the wireless communication protocol to transmit data from the accelerometer to the gateway. The operational process begins with the accelerometer detecting seismic waves, which are then transmitted via a Zigbee transmitter and received by a Zigbee receiver. These data are subsequently processed by a com-

puter system running LABVIEW, which converts the raw signals into interpretable numerical data. When a P-wave is detected, a PIC microcontroller verifies the magnitude of the signal based on the processed data. If the magnitude exceeds a predetermined threshold, an early warning notification is issued to the public via smartphone, enabled by cloud connectivity. [49].

6 RESULTS AND DISCUSSION

The integration of Structural Health Monitoring System (SHMS) technology with Building Information Modeling (BIM), Internet of Things (IoT), Artificial Intelligence (AI), and Digital Twin (DT) has been implemented primarily during the maintenance phase of structural systems. However, comprehensive integration encompassing all these elements has not yet been widely implemented. During bridge maintenance, installed sensors monitor the condition of specific structural elements and generate data outputs. These data are transmitted to the cloud through IoT technologies. Once stored in the cloud, BIM assisted by DT creates a real-time model representing the current state of the structure. The analysis results from this model are then interpreted by AI, which evaluates whether the monitored parameters exceed predefined threshold values. Real-time structural condition monitoring and rapid analysis can be leveraged for active seismic response control. Traditionally, seismic protection systems have primarily relied on passive mechanisms such as base isolation, which uses laminated rubber or elastomeric materials to absorb seismic forces and prevent them from being transferred to the main structure [50], viscous dampers, which dissipate seismic energy through specially formulated fluids [51], and Tuned Mass Dampers (TMDs), which utilize a secondary mass with a natural frequency different from that of the main structure to reduce structural drift [52]. Research into active seismic control systems has also been conducted. These systems typically involve the use of masses connected to springs, designed to move in opposition to the motion of the building during seismic events. This counteractive movement helps balance the structure and reduce vibrations [18], [53].

Data obtained from Structural Health Monitoring Systems (SHMS), such as acceleration and displacement measurements, can serve as a reference for developing active seismic control systems. Displacement values can be used as inputs for analysis to calculate the necessary force required to return the structure to its original position. Acceleration data, on the other hand, provide critical information about the direction of movement—indicating when the structure shifts to the left or right. These sensor data can be transmitted to the cloud via Internet of Things (IoT) technologies, where they are processed and visualized using Building Information Modeling (BIM) and Digital Twin (DT) systems. These models can compute the magnitude of force needed in real time. Artificial Intelligence (AI) can then be utilized to determine the optimal timing for applying these counteracting forces.

Although such analysis can be performed continuously, constantly computing and applying corrective forces would be highly energy-intensive. Therefore, it is suggested to integrate an earthquake early warning system. This system would activate the active seismic control mechanism only upon detection of primary (P) waves.

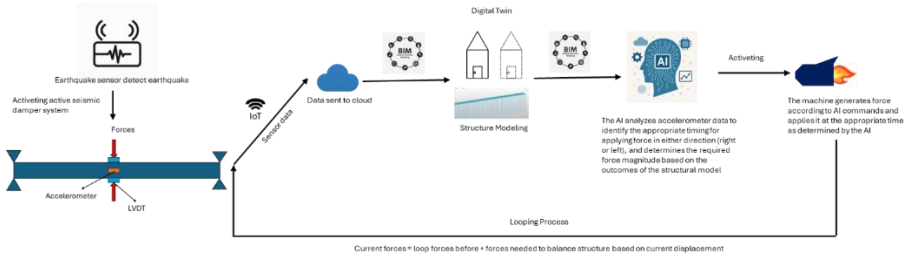


Figure 1. active seismic damper proposed schematic

The operational scheme of the active seismic damper begins with an earthquake sensor that detects P-waves, subsequently activating the active seismic damper system. Accelerometers and LVDT sensors are pre-installed on the bridge to measure the natural frequency, detect the timing of structural movement to the left or right, and quantify the magnitude of displacement. These sensor data are transmitted to the cloud using IoT technology. Once stored in the cloud, the data are integrated with a Building Information Modeling (BIM) system. This BIM system is supported by digital twin technology, which enables real-time representation of the actual structural condition. The collected data are then input into a pre-established model.

The displacement values obtained are processed within the model to calculate the required force needed to return the observed point back to its neutral or zero position. In the next stage of integration, BIM data—specifically accelerometer readings—are processed using artificial intelligence (AI) to accurately determine the timing of the structure’s leftward or rightward movement. Simultaneously, the modeling data from BIM are utilized by the AI to select the maximum force to be applied. The AI determines both the magnitude of force to be exerted by the actuator and the precise timing at which this force should be applied. This system operates in a continuous loop, where after the first cycle, the applied force is calculated using the following equation:

$$F_i = F_{i-1} + F_{ci} \tag{1}$$

F_i = Current forces (kN)

F_{i-1} = Forces 1 loop before (kN)

F_{ci} = Forces needed to balance structure based of current displacement (kN)

In this system, the output force is generated to match the required force from the previous period in order to neutralize the earthquake. The proposed technology concept does not entirely eliminate the displacement caused by the earthquake. However, it can effectively reduce the seismic effects by providing an active response to the ground motion.

7 CONCLUSION

The rapid advancement of digital technology has significantly influenced various sectors, including bridge monitoring systems. One notable application is the use of sensor systems that enable real-time monitoring of bridge conditions, thereby enhancing safety and improving maintenance efficiency. Currently, Structural Health Monitoring Systems (SHMS) have been integrated with Building Information Modeling (BIM), supported by technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and Digital Twin (DT). As a result, integrating SHMS with these advanced technologies enables the feasible development of an active seismic protection system, since it is now possible to accurately determine both the necessary counteracting forces and the exact timing of structural movements.

One of the main challenges to date is the unpredictability of when an earthquake will occur and the lack of real-time data on the actual structural response during such events. However, these challenges can be addressed through the integration of Structural Health Monitoring Systems (SHMS), Building Information Modeling (BIM), the Internet of Things (IoT), Artificial Intelligence (AI), Digital Twin (DT) technologies, and seismic sensors.

At present, the active seismic damper system remains at the conceptual stage, with future work envisioned to begin through scaled experimental testing. The most significant current challenge lies in the development of machines capable of generating forces at extremely high speeds. Given that earthquake periods are very short—especially in smaller structures—there is a critical need for actuators or machines that can deliver responsive forces within millisecond timeframes. This concept has the potential to shift the direction of active seismic damper research from relying solely on accelerometer data as a substitute for velocimeter and Linear Variable Differential Transducer (LVDT) inputs, toward integrating data from multiple sensor sources. Furthermore, the concept provides a framework for determining the optimal timing of force application—specifically, at the instant when acceleration is about to change direction—while the magnitude of the force is determined from the displacement response. Although the applied force inherently lags by one cycle, as it is based on the force from the previous period, it can nevertheless significantly reduce the seismic effects acting on the structure.

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