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A STATE OF ART REVIEW ON STRUCTUTAL HEALTH MONITORING OF BRIDGE

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Abstract: Bridges are ubiquitous in all societies and impact the aspects of personal, sociological, environmental, economic, ethnic, and artistic nature of these communities. The requirement for SHM arises because the properties of both concrete and steel are highly dependent on a large number of variables that are frequently difficult to anticipate in practice. The representative parameters chosen for monitoring the health of a structure can be mechanical, physical, or chemical. Regularly monitoring the condition and serviceability of bridges is essential for proper management and serviceability. SHM system have developed continuously evaluating and analysing working conditions of bridges, thereby repairs, supervision, and planning are also enhanced. This study reviews SHM systems technology, communication and analytical approaches of remotely sensed data, and prognosis and earlier than usual frameworks to evaluate the existing procedure and emerging developments of bridge monitoring. This study seeks to consolidate case studies concerning structural health monitoring of numerous bridges utilizing a variety of techniques, efficiency assessment, and immediate alert systems from across the world.

Keywords: Bridges, Fiber Optic Sensor, IoT, FEM, Structural Health Monitoring.

I. INTRODUCTION

From the beginning of 1980s, there has already been a growing recognition of the degradation and poor efficiency of civil infrastructure systems. As the Romanian infrastructure expands and gets old, assessing the status by observing the structural behavioural patterns of old and newer bridges become increasingly important[1].Bridges made tremendous advances to social and economic growth. Nonetheless, they have invariably led to bridge engineering safety hazards, like those of material oxidation, structural failure and fracturing, low reliability, and operational breakdown and injuries caused by load, environmental deterioration and natural catastrophes[2].If these variations are not diagnosed and treated in a timely manner, they result in structural downturn and breakdown, accompanied by substantial monetary and socioeconomic costs. In this scenario, conventional monitoring and repair methods must only be used for a preliminary valuation of structural parameters. Those very techniques become unproductive when used in isolation, and they typically require a disproportionate amount of time, tools, and personnel investment. Sophisticated monitoring approaches, such as Structural Health Monitoring (SHM), have been formulated to suit the security and economic demands of society and to extend the life cycle of structures via "timely" preventive and corrective actions[3].SHM is a structural assessment method that employs an array of sensors tethered to or integrated into a structural system. These sensors record and process numerous types of data, which are then stored for future comparison and evaluation. The data can be used to evaluate a structure's safety, reliability, strength, or performance, as well as to diagnose any damage. Assessment throughout each phase of a bridge's useful life is crucially important and can provide rich data that enables a greater comprehension of structural response and, as a result, more efficient and cost-effective management[4].Because of rapid progress in constructing large-scale bridges, Bridge SHM has gotten a lot of attention. Real-time SHM systems are now being installed on an increasing number of bridges[5]. Venoge steel-concrete composite bridge, Austria has no expansion joints or bearings on it. The inability of temperature-induced strain to dissipate results in stresses inside the bridge deck. Consequently, an assessment program was created to quantify intrinsic deformations during the curing of cementitious materials using SOFO fibre optical sensors. The SOFO system is based on a tandem configuration low coherence double Michelson interferometer[6],[7].A system must be engineered to uninterruptedly supervise the ailment of bridges in order to ensure general safety and reduce the casualties. The Varadhi bridge project employs a legitimate circuit for structure health monitoring. This sensor framework has the ability to analyse the displacement or dislodgement of the bridge using data collected from accelerometer sensors mounted on the bridge deck[8].SHM examinations of the Port Bridge and the Slovak National Uprising Bridge, Slovakia involves monitoring accelerometer polygons synchronised via Wi-Fi connection, synchronising video evidence with measured data, etc. As a result of modal analysis, a few normal vibrations and mode shapes have been documented. Comparing the calculated and observed vibrations reveals a high degree of congruence. Large structure vibration measurements managed to prove beneficial for the utilised calibration process. Such evaluations can serve as a foundation for forthcoming repeated measurements to evaluate the integrity of the bridge structures[9].The monitoring system on the I-35W Bridge consists of an SHM system that uses various sensors to monitor the bridge's behaviour and conditions. Concrete corrosion and moisture content sensors, vibrating wire strain gauges, rtds, linear potentiometers, accelerometers. Furthermore, SOFO long-gauge fibre optic deflection sensors are accessible, and the SDB Operating system can reveal genuine data and color-coded measurement results based on pre-warning levels[10].The Naini Bridge's Structural Health Monitoring System (SHMS) was structured utilising the most cutting-edge technologies, such as sophisticated GPS, which demonstrates that the bridge is reacting to fluctuations in heat, and Weigh-in-Motion monitoring, which has been demonstrated to be possible to perceive the frequency of heavily loaded vehicles crossing the bridge, with regulations for design validation, user safety assistance, and enhancement of maintenance management. In addition, the system was designed to function via a distributed data acquisition channel comprised of standardized data acquisition modules and standard data acquisition software[11].In Europe, Japan, and China, the progression of Structural Health Monitoring has increased over the years. SHM method brings valuable data to assess safety following occurrences and catastrophes. Consequently, the SHM process provides additional information for planning the inspection, rehabilitative services, maintenance, and feasible rehabilitation of bridges, and it is utilised to monitor the structural stability of bridges all through construction, repair, and reconstruction. Therefore, the development and implementation of a SHM system presents obstacles that necessitate inter-disciplinary research to apply innovative technologies from other fields[12]. Internet of Things (IoT) technology is utilised in the tracking of structural safety alongside the growth of smart recognition terminal technology. The smart terminal recognition technology enables practical tracking, computation, and analyzation of smart terminal data, as well as the evolvement of safety alerts, at construction sites[13].Bridge SHM also employs Big Data and Artificial Intelligence quantitative tactics to construct a comprehensive data-oriented SHMS platform[14],[15].A secure internet interface will allow remote access to monitoring data and results and the required control room devices for BSHMS of Delhi's new Signature Bridge[16].This paper presents a logical framework that incorporates structural health monitoring (SHM) techniques[17],[18],[19].

II. METHODOLOGIES

A. Sensory system for SHM in bridges

The sensors used in SHM on bridges have come a long way in the last few decades, so this article focuses primarily on the most recent developments in that field. Especially Detecting and monitoring contribute to the improvement and expansion of structural behaviour patterns insights, as well as the appropriate evaluation of computational methods characterising and identifying future behavioural patterns. Thereby further, design and construction can indeed be structurally and economically streamlined. Perpetual surveillance and inspecting can also provide early warning signs of structural failure. In such a way, safety measures can be presumed in a timely manner, and structural interventions can be carried out instantaneously with marginal monetary harm. The utilisation of sensor system depends on the level of the structural system to be scrutinised. There are numerous methods to assess a structure, and we can divide them into three fundamental subgroups: stationary monitoring, vibrational monitoring, and system identification and modal analysis and also these three can be combined[4].This segment discusses the findings of the latest advancements and implementations of intelligent sensing systems, such as fibre optic sensors (FOS), dial and strain gauges, and accelerometers. The system should interconnect and integrate the current practise, which is focused primarily on visual inspections, and merge the outcome of a multitude of separate reliable sensors integrated just on structural system to monitor the heinousness of deformation with improved realistic deterioration models[1]. The sensory system of Sorraia River Bridge is constituted by FBG (fibre Bragg grating sensors) and electric sensors implemented in the same sensor holder[3]. As the principal aim throughout construction was to secure a proper engagement among old and new concrete, the perks of structural health monitoring throughout the structure's entire existence are proffered and depicted by the findings acquired using the SOFO system. Just as long-gage sensors permit inspection at the structural level and short-gage sensors permit inspection at the material level, long-gage sensors are utilized. Examples of discrete long-gage, distinct short-gage, and dispersed sensors include SOFO, Bragg-grating, and Brillouin scattering-based sensors. SHM employs low-coherence interferometer usage[4].For something like the assessment of strain-induced deflections in the concrete block, using fibre optical deformation sensors (FOS) is suggested. The SOFO method incorporates a tandem configuration of low coherence double Michelson interferometers. Fig .1. A Michelson interferometer measures displacement by splitting the intensity of a light wave into two phases that travel along distinct pathways. Because

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SOFO sensors have two fibres, temperature variations affect fibres length and refractive index. The amalgamation of optical fibre sensors and temperature sensors permits the separation of heat exchange effects from mechanical strain. Resistance temperature detectors (RTD) were incorporated to separate temperature effects from the evaluated strain[6],[7].Structural health of the varadhi road bridge is conducted by measuring its vibration and displacement and assessing its condition using accelerometers. This project made use of a real-time sensor network to characterize the bridge vibrations which includes ADXL335 accelerometer and Arduino UNO microcontroller[8].It is described how SHM tests were conducted on the Port Bridge and the Slovak National Uprising Bridge in Bratislava, Slovakia. The traffic density on the port bridge was anticipated from a video stream and implemented to the model as movable loads[9].The inspection devices on the I-35W Bridge will analyse dynamic and static variables to aid close monitoring of the bridge's behaviour throughout its expected life span. SHM system uses various sensors to monitor the bridge's behaviour and conditions: such as accelerometers, thermistors, strain gauges, potentiometers[10]. Naini bridge's SHMS was created that would offer basic design validation, user safety assistance, and maintenance planning augmentation. Using an advanced GPS monitoring programme, it was possible to conduct extremely accurate RTK GPS measurements by post-processing data based on special algorithms and by using WIM system number of overloaded vehicles and the bridge's reaction to such loads was decided[11]. Papaloapan Bridge SHM was based on fibre optics sensors. El Carrizo Bridge was integrated with FOS, tilt meters, gauges. The SHM of the Juarez Bridge was performed utilising GPS receivers. GPS technology provides positioning information in three dimensions[12]. To resolve the actual scenario, in which bridge crack identification is typically focused on arbitrary visual inspection and the possible risk is exceptionally high, a virtual and sophisticated detection algorithm was investigated in an effort to maximise the efficacy of bridge safety diagnosis and reduce the risk. Internet of Things makes reference to multiple information devices, including radio frequency identification (RFID) devices, infrared sensors, GPS systems, and laser scanners, among others[13]. Bridge SHM uses BD computing to build an extensive data-oriented SHMS framework and fix the computing choke point[14]. For Delhi's new signature bridge BSHMS is provided where Dial gauges are used to measure deflections at the locations. A "Crack detection microscope" was used to monitor the occurrence of flexural cracks and their width. The deck structure will have four hygrometers measuring relative humidity and temperature, and the pylon base structure will have chloride ion and corrosion sensors. In each leg plinth, a 3D high-definition accelerometer will monitor seismic events. Accelerometers can move along the length of the structure to measure natural vibrations[15]. Laser traffic analysers will classify vehicles and track lane usage. Photographers capture traffic jams, accidents, and other hiccups in colour at 30fps. Strain gauges were welded to the tower and bolted to the deck girders. In each set of cables sensors will measure the forces on the wires of varying lengths and can be moved during and after construction to calculate damping and estimate harmonic changes[16]. Twenty-four strain gauges for each cantilever span, strain gauges were installed on the top, bottom, and two side slabs. All tendons were measured throughout the day to compare strains before and after prestressing. Record initial and final cable prestress deflections. Water tubes are at both ends are used; the first and last readings are taken on all three pipes. Side reading before and after prestressing is the deflection. Temperature is monitored by PT sensors inside and outside the bridge. The bridge span has a thermometer[17]. The monitoring system measures the pillars' rotations using LSOC-1-C electrical inclinometers. The LVDT DCRH2000C/371 measured joint displacement. The sensors were PT100[19].

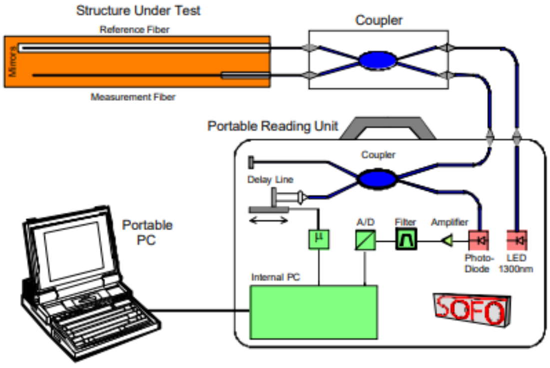

Fig. 1. Low-coherence double interferometer setup[7].

B. Data Acquisition system:

The activity of acquiring and preserving various forms of monitoring findings from multiple sensors mounted on the monitored equipment is referred to as data acquisition. The data collection system's selection of the best effective data capture algorithm is crucial. This decision is based on the amount of data recorded and the sort of diagnostic data available. For electric sensors, the technique is implemented in a data logger, and for FBG sensors, it is implemented in demodulation hardware. CPU is integrated with data acquisition software and DeTransfer software is used for demodulation equipment[3].The Arduino (microcontroller) collects the vibration readings using simple coding. The Hansford vibration monitoring application simplified the vibration readings obtained, and the last graph is depicted on the PC[8].SDB software gives legitimate data in comparison to preset warning levels[9].The monitoring framework used data acquisition units dispersed over bridge to gather and evaluate the data from sensors. LabVIEW was used to program data acquisition units. The SHMS was structured by COWI in 2000 and installed by DIPL from 2002 to 2005[11].Dual-core systems run industrial cPCI software. The unit controls all sensor functions to ensure timing. Modules of 24-bit A/D converters surround the sensors. It has GPS time sources in case of network failure. This is vital in traffic accidents or earthquakes. In the control room of the wireless LAN bridge operator future permanent monitoring systems can also use the server[16]. The Data acquisition system is consisting of a DT80 and a CEM20, two equipment from Data Taker[19].

C. Data Transmission system:

The significant proportion of bridge SHM systems were developed with wired data transfer systems to start generating data sets. In recent times, WSN has been the focal point for bridge SHM investigation. WSN in bridges grant numerous benefits. First, they can completely eradicate the linking cables and minimize the total overall costs by a significant amount. Sec, because wireless nodes are tiny in stature, they can be implanted in locations where cable incorporation is burdensome. Thirdly, WSN can employ a variety of wireless transmission strategies to fulfil varying transmission distance specifications. Bluetooth, Internet of Things (IoT), Wi-Fi, and GSM are typical remote monitoring methods utilized in bridge SHM systems.

Through Global System for Mobile Communications, information is transmitted wirelessly in SHM of Sorraia River Bridge. For transmitting data between the location and the destination host, one modem is interconnected to the structure's CPU, while the other is connected to a CPU device (server) located at the central station[3]. Metallic boxes with a connection board contain the sensors and allow their connection to the reading component. Thereby, connectors are guarded all through construction and for the duration of the bridge's life[7]. The primary constituents were linked using a network switch, wireless antennas, and a 100-meter-long FTP network cable[9]. The monitoring system is currently interacting via satellite with the Mexican Institute of Transportation's monitoring station for bridges and intelligent structures[12]. Four layers make up the Internet of Things' structural framework: the perception layer, network layer, processing layer, and application layer Fig.2. [13]. The data correlation between the main server on the bridge and the bridge operator's control tower is assisted by a wireless LAN bridge with a private IP it can operate from four to five kilometres away[16]. The data communication is made through a Ethernet protocol and stored in a website to be easily looked up[19].

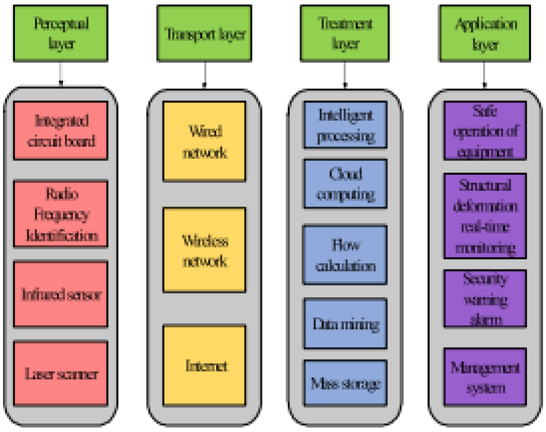

Fig.2. Four layers of internet of things for bridge damage detection[13].

D. Storage and diagnostics of processed data:

Bridge data processing implies the application of suitable statistical analysis modalities to scrutinize a large quantity of sensing information recorded over period. This procedure can be further subdivided into data fusion, pattern recognition, data processing, and data visualization steps. For ease of accessibility, both the data processing and archiving system, which is accountable for the storage and diagnosis of all data collected, and the impact detection and modelling system, which is liable for the structural behaviour analysis, were indeed installed in a control centre. It is composed of a Database System Consultation, which is accountable for the storing and management of all acquired values and vital information, and a Structural Behaviour System Visualization, which gives significant structural behaviour accompaniment. The DSC module was created using SQL and ODBC access type that recognizes SQL requests. The PHP programming language was used to generate the filters that process the gathered information, a feature that makes the entire system adaptable to changes happening. The SBSV is based on an algorithm that accomplishes the structurally deformed shape by incorporating data from seven continuously monitored sections. This configuration was also developed in PHP and C++[3]. The Hansford vibration monitoring application simplified the vibration readings obtained to displacements, the graph is depicted on the PC[8]. An authentic LabVIEW system was launched. The framework included the following components: CompactRIO (NI CRIO) 9067 outfitted with input output d/01 modules NT 9234, NLRIC 9074 outfitted with 3 10 modules NI 9234, and 2 NI EtherCAT 9149 devices. The core parts were linked using a network switch, Wi-Fi, and a 100-metre-long FTP network cable. All data collected were salvaged as a TDMS file on the motherboard CRIO 9067[9]. LabVIEW was utilized to write code the data acquisition units and SCADA software in the control tower. Using the findings of the structural health monitoring system and the primary evaluation (SHMS), the rating system has been generated. The data acquisition system relies on NI hardware and LabVIEW and DIAdem software; as a result, a highly developed and configurable health monitoring system that can be remotely managed and operated at a cost-effective rate is developed. The system processes and provides information on catastrophic events and alarms in real-time, and it can also serve as a serve as an excellent repair tool[11]. Using the Test of Quality Check software, the GPS evaluation data were converted to RINEX format and statistically analysed for quality. In addition, the data was analysed GAMIT/GLOBK software in kinematic differential mode. The conversion of time - series data to apparent displacement relative to the mean value[12]. Dual-core systems run industrial cPCI software. The unit controls all sensor functions to ensure timing. Modules of 24-bit A/D converters surround the sensors. The raw sensor data was stored on hard drives to avoid loss of data. It has GPS time sources in case of network failure. This is vital in traffic accidents or earthquakes. A cooled cabin guards the unit. Digital Signage Technology Suite comprising of LCD monitors linked to computer workstations displays the user interface in the control booth. control room user interface also offers real-time data viewing, table-based data viewing, historical data file browsing, and an interface for configuring alarm levels and email notifications[16]. A Data Taker DT80 and a CEM20 are used to collect data. The data communication is made through a Ethernet protocol and stored in a website to be easily looked up[19].

E. Structural behaviour analysis by FEM modelling and Experimental study:

Post-processing the evaluated outcome to anticipate the spot and extent of the problem necessitates the use of suitable mathematical models. The finite element methods are prevalent. FEM is an effective numerical method for resolving issues governed by partial differential equations over complex systems. It is typically used to rectify forward issues in structures, i.e., for a given loading (input), it is easy to ascertain the deformations that the structure experiences (output). During the different stages of construction and static load testing, the Sorraia Bridge was modelled using a Finite Element Program. The model was updated regularly with the collected data, and specific conclusions regarding the structure's behaviour were drawn. Awhile back, strategies that account for unpredictability in both procured data and model parameters are being devised and executed within the framework of finite elements. This will ensure that procured and estimated data can be compared consistently[3]. During a load test, the vertical displacements of the Versoix bridge were calculated using double integration of curvature and values obtained from SOFO sensors[4]. A polynomial of the second order was used to describe the effect of shrinkage. Actual measurement deviations from the fitted curve were taken into account as random deviations and then used to determine standard deviations. As the next step in the investigative process, a correlation of the evaluated deformations with simulations by FE models is planned[6]. Both the port bridge and the Slovak National Bridge were modelled with beam and shell elements in ANSYS depicted in Figures 3 and 4. After calculating the natural frequencies and mode shapes, a time history analysis was conducted. The vibration measuring system demonstrated its suitability for measuring the vibrations of large structures. Subsequent measurements will act as a base for repeated measurements to determine the structural health of these massive Danube bridges[9]. The I-35W Bridge has a greater number of load allocation and design evaluation instruments. It permits significant association and comparison of measurements. Lastly, the data may assist designers in refining future specs for concrete box girder bridges. SDB Software is able to showcase legitimate data and color-coded measurements based on pre-set warning thresholds [10]. The monitoring of El Carrizo Bridge focuses on modes and vibration frequencies, stress-strain responses, and dead load changes. The design limits and rehabilitation step determine the threshold limits for all aspects. An FE model with calibrated parameters is used to understand bridge behaviour. Data from all installed extensometers were processed to monitor system data and maintenance stage progress for the first two natural frequencies. In SHM of Culiacan's Juarez Bridge, conversion of time series to apparent displacement relative to the mean value was made. The moving average filter was used to extract semi-static and dynamic displacements from the time series, respectively. To examine the stochastic behaviour of semi-static displacements, histograms were constructed for every evaluation session and compared to AASHTO-recommended deflection limits[12]. A classification model for the convolutional neural network used to detect bridge cracks was developed. MATLAB 2016a was used to model the processed image. This strategy has the ability to efficaciously tackle the problems of inefficient rupture diagnosis and elevated domestic fracture factors. Bridge safety inspections that are computer controlled and sophisticated are becoming increasingly common[13].Data visualisation is an essential branch of BD evaluation as a supplement to other pattern recognition methods in SHM analysis. Visuals and data over the period are the two types of data that deep learning makes use of to process bridge SHM applications. Various CNN architectures were used to classify, detect, and semantically segment defects on structure surfaces[14].A three dimensional model on the basis finite element method of arch bridge has been analysed using the STAAD software package to obtain the theoretical deflections that were compared to actual deflections[15]. A more rigorous evaluation allows to collect displacement and rotation real values used for the numerical model calibration with purpose to recreate the structure behaviour. The Sao Joao das Areias Bridge 3D model used several elements based on the bridge configuration. Individual beams were modelled using a T-section frame element and their longitudinal development. A shell represented the span slab. A-frame elements represented the pillars due to their similarity. The abutments were free and fixed longitudinally, with the well calibrated model it was possible, not only to simulate damages in the pillars bases related to the deterioration conditions and evaluate the effects on the structure, but also to get information about the impact of the damage in the structure integrity[19].

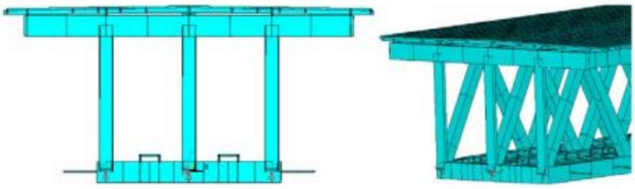

Fig.3. Port bridge ANSYS model[9].

Fig.4. Slovak National Uprising Bridge ANSYS model[9].

III. CONCLUSION

SHM's necessity provides solid justifications for its incorporation into a structure. India is embracing particular SHM strategies, although they are fundamental and produce ineffective outcomes. Technological advances such as sensors-based SHM, Wireless SHM, SHM software, SHM based on IoT and Big Data and Artificial Intelligence, which are already utilised in the aforementioned research papers, can improve them. Fiscally, SHM is not that cost prohibitive, costing between 2 and 5 percent over a decade for monitoring structures. Since concrete is a heterogeneous compound made up of inclusions (aggregate) and discontinuities (cracks), long-gage sensors are prescribed for condition monitoring. As concrete undergoes significant geometric and structural changes during the cement hydration, it is advised that encapsulated sensors begin monitoring at an extremely young age. For example, SHM of bridges aids in identifying particular design loads which may result in extensive damage. In addition, the SHM methodology could provide legitimate data to ascertain safeness after occurrences and catastrophes. Consequently, the SHM framework allows the planning of bridge inspection, rehabilitation, maintenance, and possible rehabilitation. The SHM can also be utilised to monitor the structural stability of bridges during building, repair, and restoration. Therefore, the development and implementation of a SHM system presents obstacles that necessitate inter-disciplinary study to integrate technological innovations from other fields.

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