Predictive Maintenance and Damage Mitigation in Bridge Structures usingIntegrated Acoustic Emission and Digital Image Correlation Techniques

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ABSTRACT

Aim: To examine the predictive maintenance and damage mitigation in bridge structures using integrated acoustic emission and digital image correlation techniques.

Problem Statement: Bridges are essential infrastructural facilities in any society. However, cases of loss of lives coupled with massive financial losses have been reported resulting from bridgefailures. The acts of using bridge structures beyond their life expectancy and original design loads have been prevailing.

Significance of Study: Dependable techniques are needed to monitor bridges and ensuretheir efficiency and safety because they are essential part of society's infrastructure. Numerous non-destructive methods are present forlocal structural health monitoring whose mechanisms of operation are based on the principle of electromagnetic waves, mechanical waves and fiber optics. However, the advantages of acoustic emission and digital image correlation techniques have been found promising over other methods.

Methodology: Recent relevant published articles in the area of predictive maintenance and damage mitigation in bridge structures using integrated acoustic emission and digital image correlation techniqueswere consulted.

Discussion: In this critical review, predictive maintenance and damage mitigation in bridge structures using integrated acoustic emission and digital image correlationwere discussed. Digital image correlation is a sensing techniquehaving a full field, non-contact, optical measuring technique that utilizes digitalcameras to evaluate the displacement, surface geometryand strain. Concrete and steel, beingthe most commonly utilized materials for building, were referenced and considered under integrated acoustic emission technique. The basic principle of DIC image tracking involvesits coding with a matrix of natural numbers (such as using 0 to represent white areas and 100 to stand for black). The use of a suitable algorithm via specialized software is subsequently encouraged in order to identify the region with amatching distribution of pixel shades. In short, this review has presented the research gaps that should be bridged in the future studies.

Conclusion: In conclusion, integrated acoustic emission and digital image correlation are effective techniques for predictive maintenance and damage mitigation in bridge structures.

Keywords: Predictive Maintenance, Integrated Acoustic Emission, Digital Image Correlation, Damage Mitigation, Bridge Structures

1. INTRODUCTION

Globally, it has become a usual habit of using bridge structures beyond their life expectancy and original design loads. Nonetheless, there is a rise in the financial pressure on bridge authorities in ensuring increase in their life expectancy whilst the public safety is equally assured [1]. A huge part of improving life expectancyis accomplished via consistent visual inspection with reference to appropriate repairs ormaintenance. However, it is generally believed that visual inspection is cumbersome and time consuming which makes the process to be extremely difficult. Special lighting equipment and breathing apparatus are required in related cases to steel box girder bridges. It is well-established that the internal corrosion in steel-reinforced concrete structures cannot be visualized. Thus, relevant techniques are needed to monitor bridges and ensuretheir efficiency and safety because they are essential part of society's infrastructure [2].Bridges weaken over time anddamage detection at early stage assists in preventing catastrophic failures and prolonging their lives. Many of the bridges that were built decades ago are still relevant today. They are currently subjected to changes in load patterns which can result in localized distress causing bridge failure if not addressed on time. Structures monitoring are usually executed in the past via structures tapping using a small hammer and visual inspection. However, recent technological advancements of information technologies and sensors have led to new methods of structures performance monitoring [3].

Also, one of the greatest challenges to bridge safety is scour from sediments around bridge foundations which is an erosional process that takes place in rivers as a result of interaction between the river flow and any type of structure located underwater. It has been established to be the leading cause of bridge failure globally causing disruption to road networks and significant direct losses in terms of transportation operation, high traffic,petrol, additional laborers as a result of detours to the network road, temporary closure and reconstruction works. Any scour process can be classified in four different phases which include: initial; progressing; developing; and equilibrium. In the initial phase, the scour process starts showing erosional patters on the lateral side of the cylindrical pier while in the progressing phase, the erosional patterns progress from the lateral side to the front of the pier. From the moment the two scour patterns coincide at the front of the pier, the deepest scour depth is achieved.The scour process develops, and the scour rate slows down in thedeveloping phase. Lastly, erosion inside the scour-hole becomes negligible in the equilibrium phase [4].

Bridges are essential section of society's infrastructure. Cases of loss of lives coupled with massive financial losses as a result of bridgefailures have been reported such as the occurrence of the collapse of Mississippi River Bridge in August 2007 in the United State of America. Deterioration of bridges occur as time progresses and damage early detection assists in extending the lives. About 3000 bridges are in existence in Queensland alone requesting more than 20 million dollars for the annual maintenance cost and two billiondollars for the replacement worth. Previous statistics have shown that about 41 percent ofthe 577,710 bridges in USA are either functionally obsolete or structurally deficient. An efficient monitoring system is therefore essential in ensuring the bridge safety. A lot of recent research studies around the world are aimed at exploring newtechnologies and improving existing ones [4].

It is very crucial to execute inspection and structuralhealth monitoring of bridges over large areasas the global highway bridges ages. This is quite inexpensive, robust and easy to interpreton a wide scale. Bridges are often constructed to last for approximately 50 years. In America, the average bridge was 43 years old as stated by the American Society of Civil Engineers(ASCE) in 2008 [5]. This is a strong indication that thousands of bridges are approaching or have gone beyond their design life. This also indicates that about half of

America's bridges will go beyond the 50-year design life in the next fifteen years. With reference to these facts, 161,892 bridges were classified as being obsolete or structurally deficient in 2008. Thus, thorough bridges inspection is vital to ensure bridge failures are prevented and public safety is ensured. Presently, visual inspection is utilized in the assessment of bridgehealth. Despite the fact that visual inspection is executed by trained personnel, variability in the assigned ratings by each inspector is usually significant and prevailing. Also, it is difficult to detect or quantify some kinds of damages via visual inspection. For instance, girders sagging or bulging can be difficult to measure orrecognize;concrete spalling is easily recognized but hard to quantify; it is difficult to identify small cracks; and internal components damage such as prestressed and rebar tendons is very hard to diagnose [6].

As a result of these, more advanced and reliable non-destructive test techniques have been adopted for use to aid the assessment and evaluation of bridge health.Instruments such as strain gages, fiber optic sensors, accelerometers, and displacement transducers are becoming moreprevailing in structural health monitoring. Several limitations and challenges are usually attributed generally with these types of sensors which require external power such as cabling/antenna for data transmission; high data acquisition channel counts; and they onlymeasure along a line or at discrete points [7]. These sensors can be effectively utilized to constantly monitor forabnormalities that show damage, but the nature of the damage can be difficult to detect from discretepoint measurements. Also, the damage may not be easily detected if it is outside the sensor’s proximity. Structural health monitoring (SHM) simply means the adopted steps for the assessment of the structures condition in order to monitor their performance and early damage detection. This thus increases the structures safety, reliability and efficiency.The process of SHM typically entailsstructure monitoring over some time frame via appropriate sensors,damage sensitive features extraction from thegiven measurements by the sensors and the features analysis in order to evaluate the present state of the structure [8].

Nowadays, different new techniques which are independent onhuman’s interpretation skills are present. Damage to a structure is examined via the measurement of the changes in the the structure global properties (such as stiffness, mass and damping) in the globalmonitoring techniques. These techniquesrequire the recognition of resonant frequencies changes or shift in the structural mode shape. Seldom, somedamage exhibits negligible adjustment in dynamic properties andmay go unobserved. While the vibration based global techniquescan show the availability of damage in a structure, localtechniques are essential in finding the damaged real location. Numerous non-destructive methods are present forlocal structural health monitoring [5]. Most usually adopted non-destructive methods are based on the utilization of electromagnetic waves(eddy current testing, magnetic testing and radiographictesting), mechanicalwaves (acoustic and ultrasonic) and fiber optics. The fiber optics technique can recognize different parameters change in bridges. They are usually utilized to sensetemperature and displacement. Sensing is based on the light waves’ wavelength, intensity and interference [2].

Thebenefits of fiber optics include capability for sensing different perturbations and geometric conformity with little or no electricinterference. However, they are expensive and highlyskilled professionals are required for the construction and placement of thesystem. In recent time, much attention is needed onacoustic emission (AE) application technology in the health monitoring of bridgestructures. AE waves are stress waves thatemanate from strain energy rapid release which follows microstructural alterations in a material. Common AE sources include cracks initiation/growth, bonds failure, yielding, composites de-lamination and fiber failure. AE waves arerecorded via sensors located on the surface [9]. Thesensors are designed with piezoelectric elements whichhelp in the conversion ofmechanical waves into electrical signals. The signals analysis provides information about the emission source. They have the ability tolocate the source initiation and are highly sensitive. It is categorized as passive methodand can be utilized for real time monitoring.

Studies have shown that acoustic emissiontechnology possesses numerous benefits over other techniques andbased on these, it has become an attractive route forstructures monitoring [8]. The study of acoustic emission began in 1950s and from 1960s onwards it has been utilized for aerospace structures and monitoring of pressure vessels. Gradually, its applications in monitoringof bridge structures rose and researchers and engineers startedfocusing their efforts in making AE technology a morereliable technique and in overcoming existing shortcomings. Rapid risein advancement of sensor technology and computing resources have greatly enhanced this development. Another promising technique to curb the attached shortcomings of the recently adopted traditional sensors for monitoring of bridges (such as displacement sensors and strain gages) is the three-dimensional (3D) digital image correlation (DIC) [10].

DIC is a sensing technique for improved monitoring of bridge structural health. 3D DIC is a full field, non-contact, optical measuring technique that utilizes digitalcameras to evaluate the displacement, surface geometryand strain. It is expected that DIC can be adopted for bridges monitoring via periodicimaging of a bridge and computing displacement and strain from the recorded images at various operating conditions or dates.The digital image correlation (DIC) is a progressing measurement method that has been recentlyproposed alone in enhancing bridge inspection. DIC is a non-contact optical and full field measuring technique that utilizestwo digital cameras in the measurement of displacement, surface geometry and strain [4-8]. To execute these measurements, a stochastic pattern is usually applied to theinterested surface and a series of photographs are taken in stagesas the surface deforms. Strain iscalculated via the comparison between the deformed surfacestochastic pattern and the pattern initial reference measurement.Three-dimensional information is gotten from the stereophotogrammetry principles. DIC can be utilized forstructural health monitoring via comparison of current displacement, strain measurements and surface geometry to baselinemeasurements conducted days, months, or even years prior. The monitoring of these parameters as time progresses will enable the inspectors toquantify the structural members' displacement, strain, crack growth and spalling [9].

However, each technique works on a different principle and has its own shortcomings. Acoustic emission technology was used to detect crack initiation and growth by analyzing the characteristics of the stress wave signal. However, the signals are affected by environmental noise, and multiple sensors are needed to locate the cracks. The DIC system also has some limitations such as (1) the system dependence on natural lighting conditions requiring the use of artificial light when registering images with high frequency and (2) the need to apply calibration tables which are appropriate to the size of the tested sample area and capacious storage media required to archive recorded images and to obtain research results.This paper provides a technical review of predictive maintenance and damage mitigation in bridge structures using integrated acoustic emission and digital image correlation techniques.

2.0 PREDICTIVE MAINTENANCE AND DAMAGE MITIGATION IN BRIDGE STRUCTURES USING INTEGRATED ACOUSTIC EMISSION

Application of AE technology for monitoring of bridges hasbeen anvigorousarea of study. A general overview of the history together with the development of acoustic emission applications in concreteengineeringfor monitoringof bridges has been previously discussed. Concrete and steelare two commonly utilizedmaterials for building of bridges and numerous studies have generally focusedon specimen made fromthese two materials [11].

2.1 Acoustic Emission (AE) Technology in Steel Bridge Structures

Previous study had performed AE tests on plates and steel beams and was also examined for real bridge [12]. The location of AE was based on Lamb wave modes arrival at the transducer. During the process, extensional mode appeared as higher-velocity but the amplitude waves that precede the flexural mode were lower. In order to recognize the peak frequencies, Fast Fouriertransform (FFT) was performed and required low pass filtering and high pass to collect the intended signal waves.AE signals were observed to be produced when the bridge components were subjected to rubbing and passing traffic. Thefrequency of the signals can be as high as 500 kHz. It was concluded that local monitoring withdistances of less than 1 m, the modal method was not worthwhile. In another study, Also, AE has been studied in steel bridge hanger having known fatigue cracks via analyzing and recording full waveform in order to get an in-depth knowledge of crack and noise related acoustic emission [10]. The signal amplitudes were observed to be extremely low generally when compared with the background noise. Background noise was recognized as the main shortcoming behind the successful execution. The crack growth was characterized via long durations and short rise times. Nonetheless, low pass and high passfilters have been applied to the source waveform in testing steel bridges using Lamb wave theory to locate the source location. It was revealed that waveform acquisition settings must be adopted and captured in order to ensurethe first arrival of both acquisitionsample rate and modes. These are necessary to satisfy the Nyquist criterion required for the upperfrequency limit of the high pass filter. This was after recording the arrivaltimes of different frequency components [13].

In another previous study, a box-girder bridge having was monitored in SouthWales using the acoustic emission. The box-girder bridge is as composite construction and has a sum span of about 300 m with a concreteroad deck reinforced with four steel box-girder beams [7].Each box-girder is around 1.2m square having a maximum span of 31 m. At various positions, two types of 10-mm thick steel diaphragms were welded inside the girder. One type maintains torsional rigidityand provides cross sectional stiffness, while the second type was engaged in transferring the shear forces carried by the girders to the support bearings. At the initial stage, a global technique to AE bridge monitoring was completedand numerous diaphragmsemitting high activity were recognized. Subsequently, a local technique of the most emissive diaphragms wasthen executed.Figure 1 is the box girder beam indicating internal diaphragm and sensor attachment using AE [14]. Around the outside perimeter of the diaphragm, four PAC WDI sensors were mounted such that the sensor face was affiliated with the diaphragm internal edge. In order to remove any peaks, the painted surfacewas lightly sanded. Magneticclamps were used to mount the sensors into position.Grease was applied as an acoustic couplant. The verification of the installed sensitivity of the system was executed via the H-N source. For a period of 90 minutes, AE feature data was recorded underservice loading using an acquisition threshold of 30 dB.

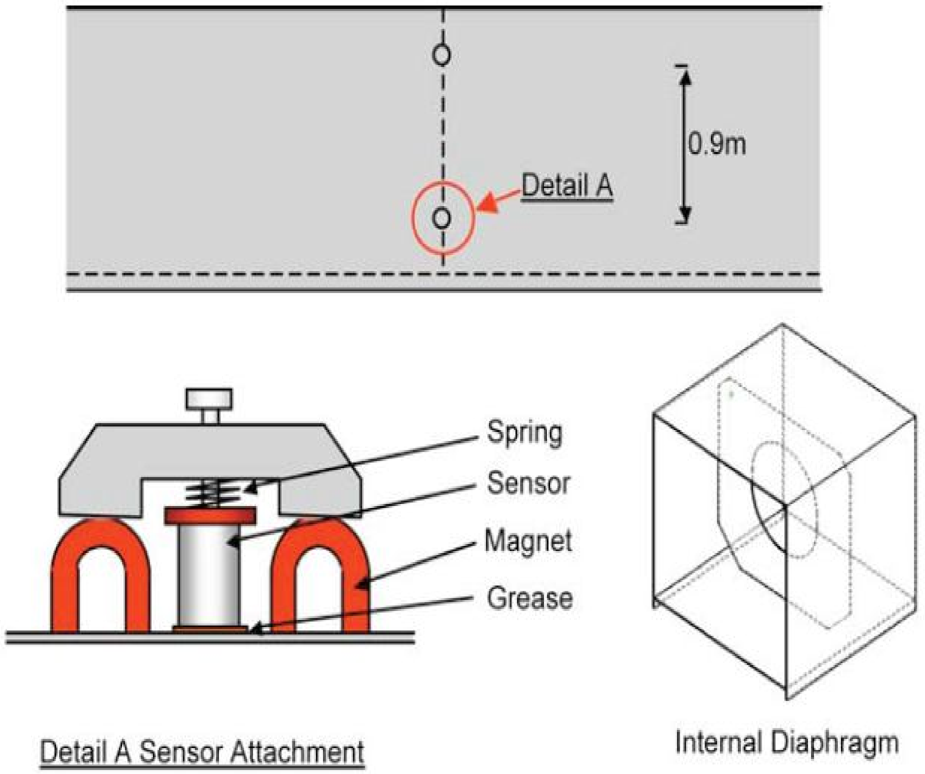


Figure 1: Box girder beam indicating internal diaphragm and sensor attachment using AE

2.2. Acoustic Emission (AE) Technology in Concrete Structures

AcousticEmission (AE) Technology was adopted in concrete structures andAE energy was explored using an effective parameter toevaluate the damagequantitatively. The relaxation ratio was stated as an average energy duringunloading phase to average energy during loading phase with reference to the Kaiser effect. Therelaxation ratio of more than 1 means a serious damage.Nonetheless, AE emission was analyzed in reinforced concrete bridges via studying of the hits and energy(which is the measured area under rectified signal envelope) [15]. Also, high-strength tendon of pre-stressed concretebridges was analyzed and it was noticed that analysis of detected AE signalparameters like the amplitude enabled distinguishingmeaningful AE events from the failures from remaining sources astraffic noises. Figure 2 shows the demonstration of the application of AE technique on a steel-reinforced concrete hinge joint. The joint comprises a beam construction.The bridge is an over-bridge on the M4. The realinternal reinforcement bars positioning across the joint was not known. However, they were ascertained to be at308-mm centres while grease was applied as an acoustic couplant [10].Figure 3 shows the flow chart of AE signal. The first step involves recalling of acoustic emission signal data after which one of the lead data is selected. Then, wavelength decomposition of acoustic emission signals is executed. The other stages include extraction of wavelength coefficients at each scale, denoising and reconstruction based on thresholding and output denoised acoustic emission signal.

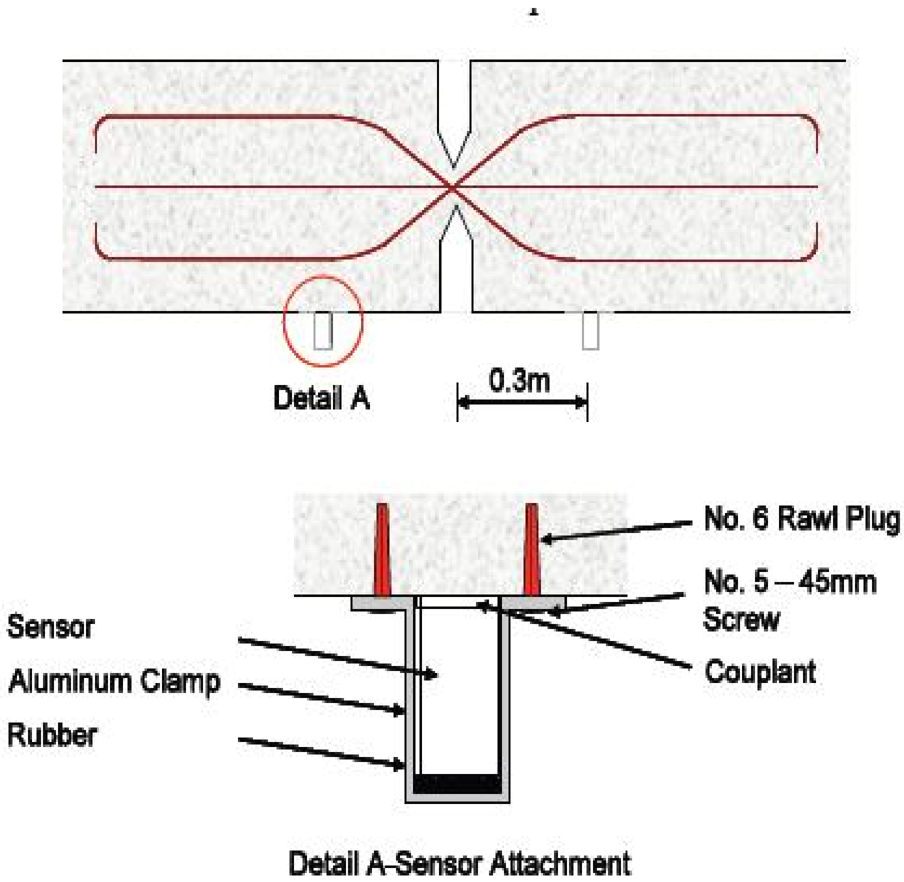


Figure 2: Application of AE technique on a steel-reinforced concrete hinge joint

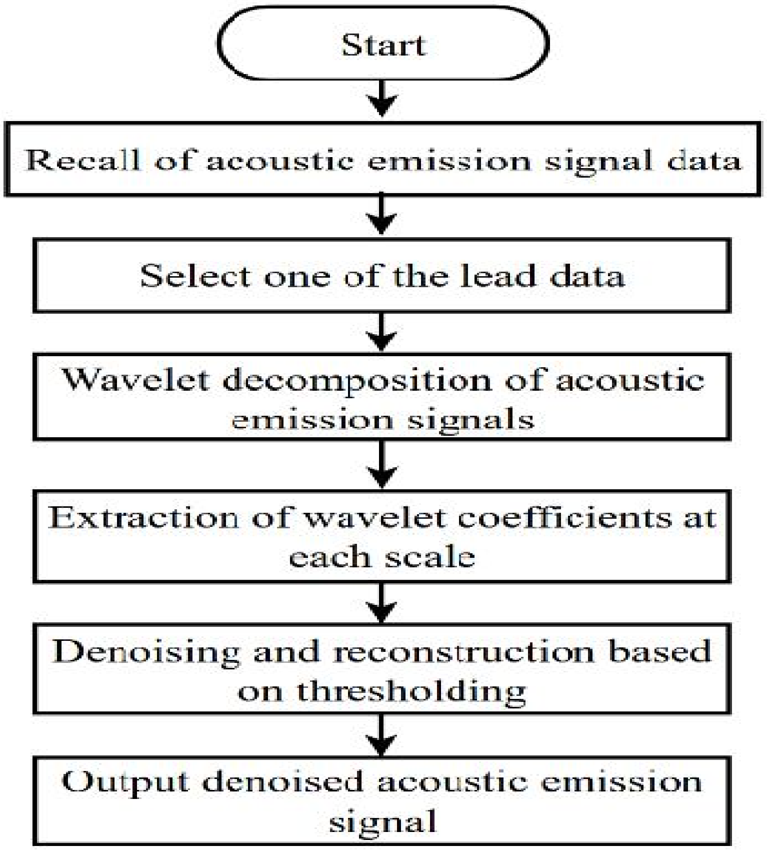


Figure 3: Flow chart of AE signal

3.0 PREDICTIVE MAINTENANCE AND DAMAGE MITIGATION IN BRIDGE STRUCTURES USING DIGITAL IMAGE CORRELATION TECHNIQUES

Digital Image Correlation (DIC) is a multi-stage approach which allows remote contactlessmeasurement of strains and full-field displacements on objects' surfaces. DIC has been broadly adopted in different fields including biomechanics,structural analysis, materials testingandexperimental mechanics. This provides valuable insights into materials' structure and their mechanical behavior. Although this method has been adopted many years back with resounding history of modifications and development, its specific features is a function of the particular application field [16]. It generallyincludes numerous key steps as shown in Figure 4 indicating the general stages of DIC technique for strain and displacement measurement. The major steps include image acquisition, image pre-processing, image correlation, displacement calculation, visualization and analysis, and lastly results iterations.

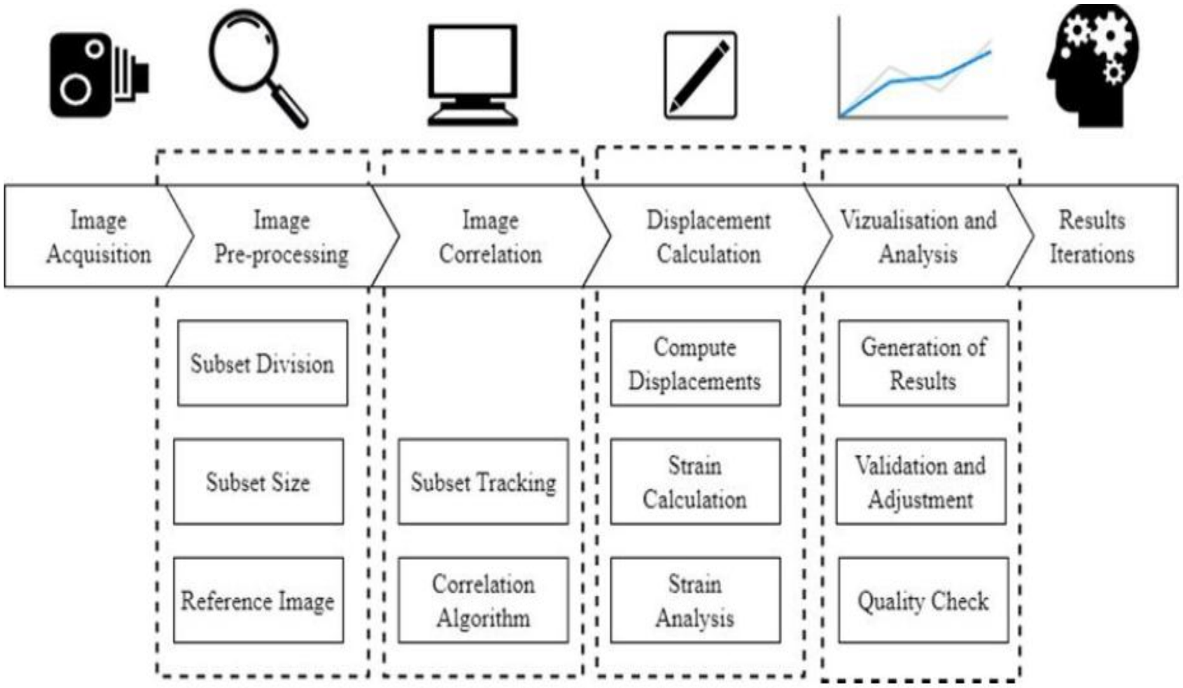
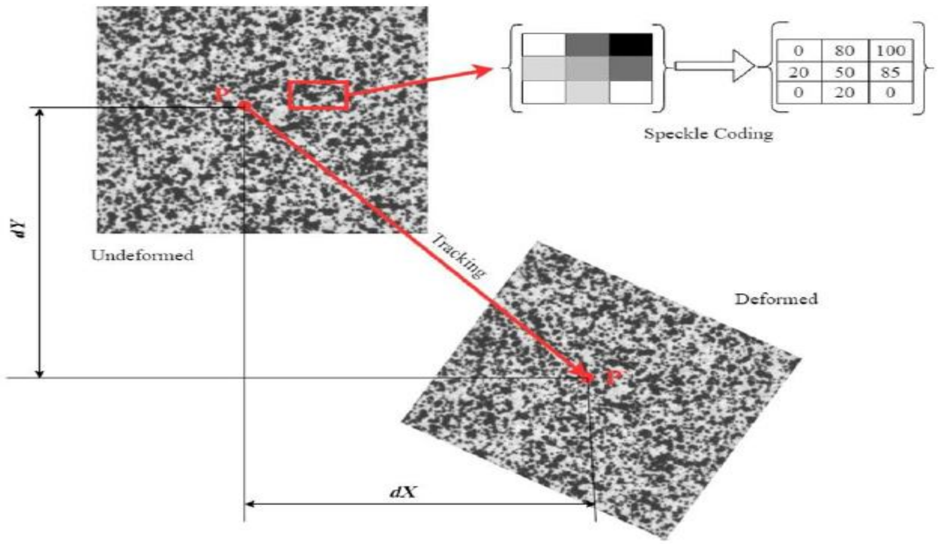


Figure 4: General stages of DIC technique for strain and displacement measurement

The first step involves capturing of the object's surface high-resolution digital images using a camera that covers the complete area of interest.Images are broken down into smaller regions at the pre-processing stage in order to track the entire deformation process further. The level of detail required and the expected deformation were used to determine the size of the subsets. The initial image which correspondsto an un-deformed condition was selected as the reference image for comparison purpose with the subsequent images. The basic principle of DIC image tracking involvesits coding with a matrix of natural numbers (such as using 0 to represent white areas and 100 to stand for black). Thus, theimage subset which is normally a square with a 10–50 pixels side will comprise the group of points having variousunique numerical coding and grey level variations. Figure 5 indicates the principle of subset tracking and grey level coding in the DIC method [17].



0	80	100
20	50	85
0	20	0

Figure 5: Principle of subset tracking and grey level codingin the DIC method

A particular subsetcentre used as the reference point serves for its further tracking viathe coordinates identification and subsequent “deformed” images. The core principle adopted inthe DIC method entails aligning a specific pixel's location on the reference image with itscorresponding position on the deformed surface images. The region around the stated reference pointis represented by an arbitrarily shaped area, within which a distinctiveshades distribution is available [13].The use of a suitable algorithm via specialized software is subsequently encouraged in order to identify the region with amatching distribution of pixel shades. Sets ofnumbers are analytically shifted until the pattern on the deformed image optimally aligns with thereference image in the entire correlation procedure. This alignment is evaluated via the assessment of the total difference in grey levels foreach corresponding point.It is evident, that for precise and effective correlation, the tracked area could have specificfeatures which are easily identified at the processing stage [8].

For this reason, either the surface should be artificially prepared before starting the measurement, or the natural speckle pattern on a surface can be utilized. The latter technique involves the speckle separate printing on the paper andglueing to the examined surface (that is artificial target) or creation of the specklepattern directly to the surface.The target-tracking technique, which is specifically broadly adopted for on-site DIC correlationtesting of full-scale structures involve using an artificial target as an independent sensor on thestructure [18]. In order to prevent any possible rotation or movements, targets with known parameters and significant features should be rigidly attached to the surface of the structure. The targets` size is evaluated via the field of view (FOV) and, thus, the distance between the camera and structure is determined. A larger FOVvalue indicates a bigger target size. Therefore, the unique dots configuration present on the coded targets represents ananalogous of the stochastic pattern marking. This facilitates the mutual recognition and orientationof the 3Dcoordinates from subsequent images using software. The direct formation of the speckle pattern on theexamined surface is more efficient for obtaining a full field of strains. However, it is laborconsuming and waste more time and it’s also usually associated with on-site setbacks for long-term access [19].

The spatial measurements having synchronized stereo camera system (3D-DIC)technique, on the other hand, allow the capturing of out-of-plane displacements. Thus, the technique tends to generate more precise results,especially when the experiment is not properly arranged [20].A comprehensive calibration step required in defining the scale for all-direction displacement and the spatial coordinate system is one of the requirements for reliable 3D-DIC measurement. InDigital Image Correlation (DIC), camera calibration is a procedure that entails the determination ofa camera system extrinsic and intrinsic parameters to ensure a perfect change from images (in pixels) toreal-world coordinates presented in engineering units (e.g. mm). The intrinsic parameters include lens distortion, focal length and optical centre, while the extrinsic parameters include the camera's orientation and positionin the 3D space [21]. Figure 6 represents typical illustration of the 3D-DIC measurement process main parameters while Figure 7 is the flow chart of DIC method ranging from test record, file format convert, software preparation, run Ncorr program, strain method, DIC parameters, DIC processing and calibration and scale.

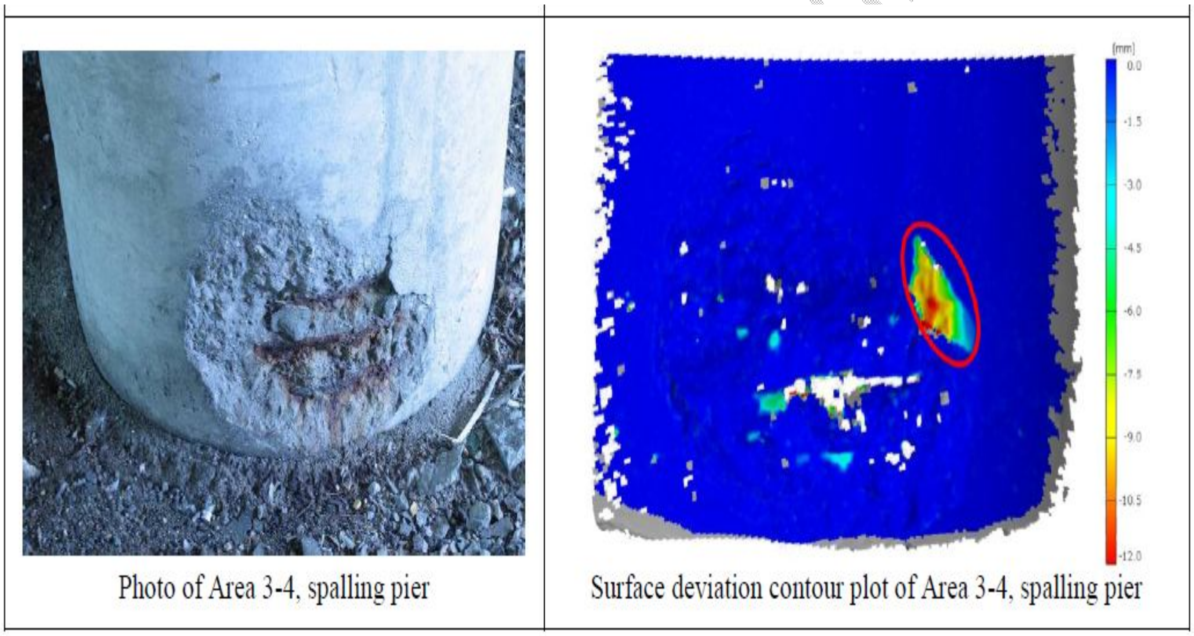


Photo of Area 3-4, spalling pier

Surface deviation contour plot of Area 3-4, spalling pier

Figure 6: Illustration of the main parameters 3D-DIC measurement process

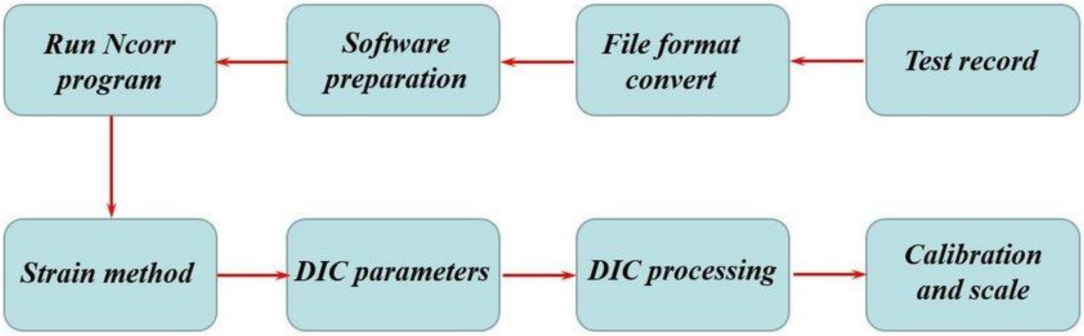


Figure 7: Flow chart of DIC method

3.1 PRACTICAL APPLICATION OF AE AND DIC

The study conducted by Górszczyk et al. [23l applied DIC method for some selected laboratory tests of building materials. The results of the tests on the samples of the materials normally applied in road construction, i.e., asphalt mixtures (HMA), stone, soil stabilized with a hydraulic binder, and geosynthetics were investigated. The conducted research pointed out the possibilities of using the DIC method to measure the deformation of road materials in laboratory tests giving considerations to their specificity. The variety of samples tested (materials)were allowed to signify the areas in which the DIC method was effective. The algorithms applied in evaluating the results give a significant advantage compared to tensometric measurement methods. Figure 8 shows the flow diagram of the general AE-monitoring concept used TÜV AUSTRIA Group. The concept developed by TÜV Austria Group was successfully adopted for several monitoringprojects: short- or continuous long-term. The methodology offered a variety of options foradapting and using it on different objects and in different environments due to its flexibility. A wide temperature rangecan be covered up to +450°C with the application of an in house developed waveguide.By establishing the well-known concept for monitoring application, a real-time examination of the condition of the object could also besuccessfully applied. An online presentation of the measurement data via the dashboard graphical interface provided the customer and the responsible technician with the possibility to viewthe data in real time.

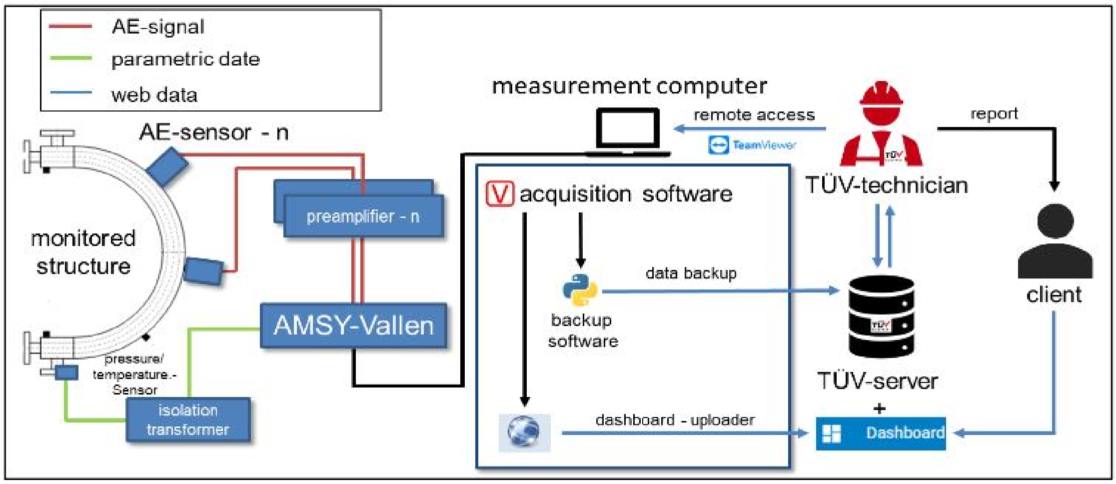


Figure 8: Flow diagram of the general AE-monitoring concept used TÜV AUSTRIA Group

4. CONCLUSION

Bridges are essential infrastructural facilities in any society. However, cases of loss of lives coupled with massive financial losses have been reported resulting from bridgefailures. The acts of using bridge structures beyond their life expectancy and original design loads have been prevailing. It should be noted that bridges weaken with age and their damage detection at early stage helps in preventing catastrophic failures and prolonging their lives.Thus, dependable techniques are needed to monitor bridges and ensuretheir efficiency and safety because they are essential part of society's infrastructure. Numerous non-destructive methods are present forlocal structural health monitoring whose mechanisms of operation are based on the principle of electromagnetic waves, mechanical waves and fiber optics. However, the advantages of acoustic emission and digital image correlation techniques have been found promising over other methods. In this critical review, predictive maintenance and damage mitigation in bridge structures using integrated acoustic emission and digital image correlationwere discussed. Digital image correlation is a sensing techniquehaving a full field, non-contact, optical measuring technique that utilizes digitalcameras to evaluate the displacement, surface geometryand strain.Concrete and steel, beingthe most commonly utilized materials for building, were referenced and considered under integrated acoustic emission technique. The basic principle of DIC image tracking involvesits coding with a matrix of natural numbers (such as using 0 to represent white areas and 100 to stand for black). The use of a suitable algorithm via specialized software is subsequently encouraged in order to identify the region with amatching distribution of pixel shades.In conclusion, integrated acoustic emission and digital image correlation are effective techniques for predictive maintenance and damage mitigation in bridge structures.It is also recommended that the challenges and shortcomings attached to using AE and DIC should be critically investigated in future studies.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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