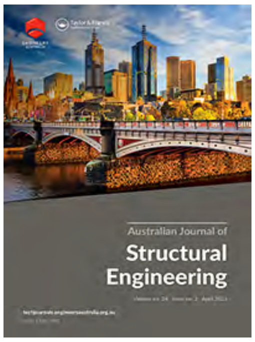

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ORIGINAL ARTICLE

Damage identification in bridge structures: review of available methods and case studies

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ABSTRACT

Bridges are integral parts of the infrastructure and play a major role in civil engineering. Bridge health monitoring is necessary to extend the life of a bridge and retain safety. Periodic monitoring contributes significantly in keeping these structures operational and extends structural integrity. Different researchers have proposed different methods for identifying bridge damages based on different theories and laboratory tests. Several review papers have been published in the literature on the identification of damage and crack in bridge structures in the last few decades. In this paper, a review of literature on damage identification in bridge structures based on different methods and theories is carried out. The aim of this paper is to critically evaluate different methods that have been proposed to detect damages in different bridges. Different papers have been carefully reviewed, and the gaps, limitations, and superiority of the methods used are identified. Furthermore, in most of the reviews, future applications and several sustainable methods which are necessary for bridge monitoring are covered. This study significantly contributes to the literature by critically examining different methods, giving guidelines on the methods that identify the damages in bridge structures more accurately, and serving as a good reference for other researchers and future works.

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Bridge; damage detection; crack detection; condition assessment; bridge health monitoring

1. Introduction

Nowadays, there are several types of bridges that each serves a purpose and applies to different conditions of the environment. Some of them are in poor condition and need repairs; according to the US. Federal Highway Administration, more than 47,000 of America’s bridges are structurally deficient. The slab-stone single-arch bridge across the river Meles in Izmir, Turkey, is the oldest bridge still in use which dates from 850 BC. There are several factors that will affect the bridge failures, some of which are infrastructure issues, design and manufacturing flaws, floods and collisions, earthquake, overload, construction incidents, etc. Civil engineers build bridges to facilitate the smooth, even flow of traffic. Bridges, like other structures, lose their efficiency over time and are damaged by stress and other forces; therefore, it is very important to detect the damage location and examine the damage severity in these structures. There are several techniques for damage identification in bridges that are based on different theories and parameters. One of the methods that has attracted considerable attention in recent years is structural health monitoring which can be categorised in four main steps: ascertainment of damage existence, defining its location, identification of the damage severity, and the prediction of the remaining lifetime of the damaged structure (Rytter 1993). Nowadays, larger modern bridges are inspected with a variety of sensors. Some of the most widely used sensors for structural health monitoring are as follows: Fibre optic sensors have been widely used in recent years for measuring various parameters such as natural frequencies, acceleration, strains, etc. Accelerometer is used to estimate acceleration forces in single and multi-axis directions. The two types of vibrating wire sensors are vibrating wire strain gauge and vibrating wire displacement transducer which are used for measuring strain and long-term movement, respectively. To measure the linear displacement of structural members subjected to live loads and temperature fluctuations, linear variable differential transformer (LVDT) is commonly used. Another most common sensor for strain measurement is strain gauge which converts physical quantities such as force, pressure, etc., into an electrical signal. Since smaller bridges could be remotely monitored by skilled inspectors, they have attracted considerable attention in the last few years. An inspection vehicle with a number of sensors drives across the bridge, and the measurements of the installed sensors are indicative of damage in smaller bridges (Yang, Lin, and Yau 2004; Yang and Yang 2018). Some of the other techniques for bridge health monitoring are based on vibration data, Rayleigh–Ritz method, etc. Choosing the best

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method for monitoring the bridges depends on a different factor such as the type and age of the bridge, the type and extent of the damage, cost and availability of the materials, etc. Several review papers have been published in the literature on bridge health monitoring in the last few decades (Chen et al. 2017; Nair and Cai 2010; Kim, Lee, and Lee 2018; Sun et al. 2020). Each of these used different evaluation methods and compared the results of their work with other researchers' articles. This paper reviews the papers undertaken by various researchers on damage identification in bridge structures based on different methods and theories. The gaps and superiority of each paper are investigated, and future applications and several sustainable methods which are necessary for bridge monitoring are covered. This paper gives guidelines on the methods that identify the damages in bridge structures more accurately for the researchers' references.

The paper is organised as follows: in the next section, bridges and different types of failures are investigated. In section 3, a cumulative review of articles on the existing methods of monitoring the bridges based on different techniques and theories is provided. At the end, some conclusions are presented which can be used for further studies.

2. Bridges and different types of failures

Bridge failures have adverse consequences and can lead to injuries, loss of life, and property damages. The best way to prevent these consequences is to investigate different and cost-effective approaches to monitor the bridges in order to identify the damages and the factors that cause the bridges to collapse. The most common causes of bridge failures can be summarised as follows:

- Erosion of soil around the foundation of a bridge: An example is Ovilla road bridge in Texas.
- Concrete deck cracking and steel girders corrosion: An example is I-95 girder bridge.
- Earthquake and extreme events: Bridge failures in California are good examples.
- Fatigue: Various steel, railway, and composite bridges.
- Overload: Various old bridges.
- Structural and design shortcomings: An example is New York City's Brooklyn Bridge.
- Lack of monitoring and repair.

In the past few years, rapid failure of different types of bridges has become a serious problem in different countries. To overcome the consequences caused by the deterioration, repairing and strengthening need to be conducted from time to time.

3. Existing methods of monitoring the bridges

In the past few years, various bridge damage identification techniques have been proposed by different researchers. These approaches are based on different theories and parameters. Some of these approaches are modal curvature (MC) technique, Bayesian probability-based method, vibration-based damage detection, neural network system, ambient vibration investigation, etc. This section introduces a comprehensive insight into the existing literature on different bridge health monitoring techniques.

3.1. Existing fatigue damage evaluation methods

Fatigue is a critical aspect of bridge safety and maintenance. Different methods and techniques have been used for fatigue damage assessment, such as physical testing and finite element fatigue analysis. This subsection introduces an insight into the existing fatigue damage evaluation methods.

Li et al. (2001) developed an approach for fatigue damage evaluation and service life prediction of bridge-deck sections based on structural health monitoring (SHM) data which is shown in Figure 1. A fatigue damage model based on continuum damage mechanics (CDM) was proposed to assess the incremental fatigue damage. To validate the proposed CDM-based approach, a modified Palmgren–Miner rule was carried out to compare the findings. The superiority of the proposed approach was that the stress spectrum's upgrading of the representative block of cycles was included in this approach. The results have shown that the proposed approach was capable of detecting the location of fatigue damage by comparing the fatigue values of the welds near the crucial members which led to the service life prediction of the bridge (Li, Chan, and Ko 2001).

Li et al. (2002) investigated the typhoon's impact on fatigue damage in steel decks of Tsing Ma Bridge based on the strain response and wind data obtained from the structural health monitoring system. The fatigue damage models based on continuum damage mechanics (CDM) and Miner's law were presented to evaluate the incremental fatigue damage. It was revealed that the measured data from the CDM model was smaller than that of Miner's law, the the impact of typhoon on fatigue damage was greater than the impact of traffic loading, and the hourly stress spectrum disclosed a pattern similar to Rayleigh distribution. The results also suggested that assessing fatigue damage caused by typhoon is necessary for the long-span bridges at the high-risk areas (Li, Chan, and Ko 2002).

The CDM-based models developed in the above-mentioned papers are a significant contribution to the literature by providing the evaluation of the

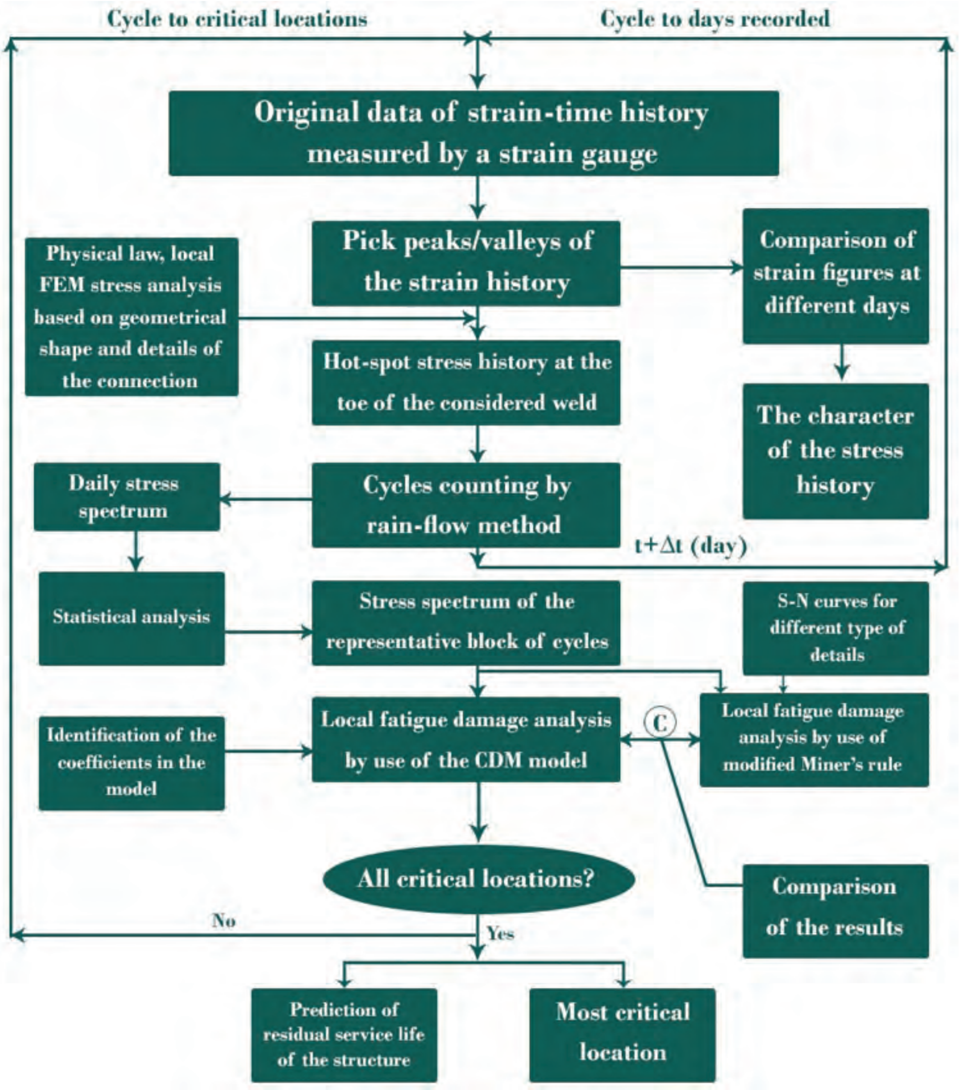

Figure 1. Flowchart of the proposed method for the fatigue analysis of a bridge-deck section (Redrawn from Li, Chan, and Ko (2001)).

incremental fatigue damage as well as its physical process such as fatigue damage growth. These two papers proved that the influence of the typhoon on fatigue damage is much more considerable than the normal traffic, especially for a bridge under both railway and highway traffic.

Li et al. (2003) studied the fatigue life of a long-span steel bridge's deck section based on the statistical analysis of the strain response obtained from the structural health monitoring system which is shown in Figure 2. A representative block of daily cycles of strain response was achieved using statistical analysis and then, the block's stress spectrum was evaluated through the rain-flow counting approach. The primary assessment of fatigue life was carried out through the categorisation of bridge components' details, and a modified probability model based on the British Standard BS5400 (BSI 1982) was proposed for the fatigue assessment. The findings revealed that the proposed modified model was only valid for bridge's service life assessment under traffic loading. This paper provides a reliability evaluation of the fatigue life of a bridge deck which is of great importance in the field of fatigue damage detection. For a more precise analysis, a practical strategy for efficient utilisation of strain history data should be proposed (Li, Chan, and Zheng 2003).

Li et al. (2005) studied the fatigue life and fatigue crack growth in welded bridge members under traffic loading. Creation of a fatigue damage aggregation model and an approach for evaluating the stress intensity factor were considered to show the cracking count rate and the efficient stress intensity factor relationship based on the theory of continuum damage accumulation. Geometric shape corrections were carried out with the aim of reflecting the impact of welding type and geometry. The measured fatigue results for the primary cracking conditions were in good agreement with the two types of welded members extensively used in steel bridges. It was also revealed that the proposed relation was similar to the strain energy density (SED) model; however, it did not represent

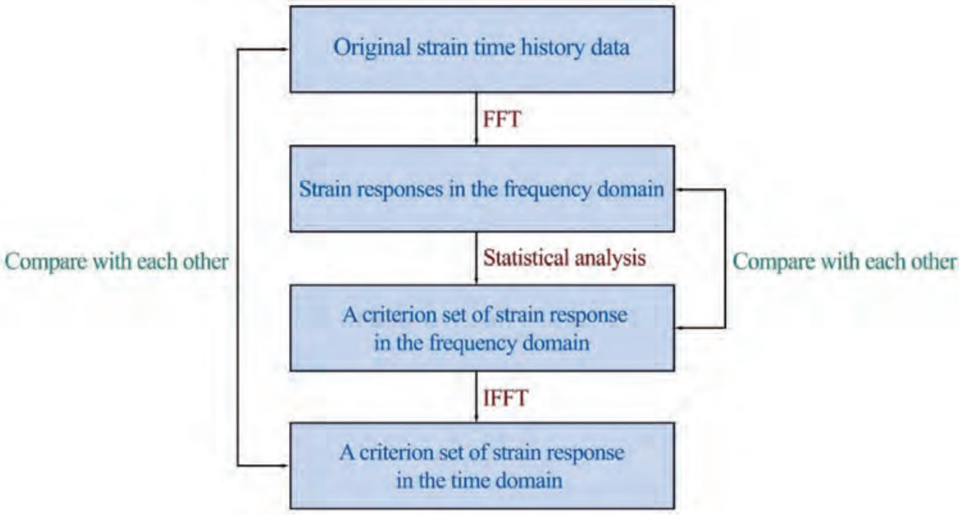

Figure 2. Flowchart of the proposed method for statistical analysis in frequency domain (Redrawn from Li, Chan, and Zheng (2003)).

a straight line on a log–log plot. This study was only part of the existing structural health monitoring and did not present any rehabilitation method. It should be noted that the findings of this paper should only be used for fatigue life and fatigue crack growth assessment with small initial crack size (Li, Chan, and Zhou 2005).

MacDougall et al. (2006) investigated the fatigue damage growth of steel bridge girders subjected to traffic loads. A model was developed to measure the bridge compatibility of air-sprung and steel-sprung vehicles. The proposed model was based on the modal shapes, the number of vehicles' crossings, and the natural frequencies of the bridge. The findings have shown that the fatigue failure occurred sooner under the steel-sprung vehicle due to the dynamic properties of the suspension systems, an equality between the natural frequencies of the suspension and bridge-surface profile caused the largest fatigue damage, critical surface profile and first natural frequency of the steel-sprung vehicle caused fatigue faster than an air-sprung vehicle, and the reduced stiffness impact can be disregarded in measuring the bridge's response and fatigue life due to the fact that the fatigue failure occurs before the cracks' growth. The authors investigated the fatigue life in a short-span and a medium-span bridge and did not provide any results for a long-span bridge (MacDougall, Green, and Shillinglaw 2006).

For a better perception, a critical comparison is made for the two above-mentioned papers ((Li, Chan, and Zhou 2005; MacDougall, Green, and Shillinglaw 2006)) in Table 1.

Guo et al. (2008) investigated the impact of environmental temperature on the fatigue damage of welded bridge decks. In this paper, it has been proven that the representative block of cycles fails to cover the temperature change and the increasing traffic flow. An equivalent vehicle load approach was proposed to determine the relationship between temperature, fatigue damage, and increasing traffic flow. Moreover, the Runyang Suspension Bridge was taken as a model for finite element analysis. The findings showed that the environmental temperature had a linear impact on the welds' fatigue damage in the orthotropic decks of steel bridges due to the change in pavement stiffness, traffic flow had a direct impact on the fatigue damage, and the traffic growth should take into account for the fatigue life prediction (Guo, Li, and Wang 2008).

Xu et al. (2009) presented a framework to examine the long-term fatigue damage of a suspension bridge subjected to wind by incorporation of SHM-based finite element model, the numerical technique for wind-induced stress analysis, and the continuum damage mechanics (CDM)-based fatigue damage evaluation approach. A density function of wind direction and speed using recorded wind data was first developed and then, the numerical technique based on a finite element model was utilised to determine the stress properties at hot spots. Finally, fatigue damage to the critical members during 120 years of design life was determined using a CDM-based fatigue assessment model. The findings showed that the proposed framework had good wind-induced fatigue damage evaluation in a suspension bridge, and the impact of monsoon buffeting-induced fatigue on the bridge was not noteworthy. Additional research is required to apply the proposed framework to the long-term fatigue damage caused by typhoon (Xu, Liu, and Zhang 2009).

The two above-mentioned papers (Guo, Li, and Wang 2008; Xu, Liu, and Zhang 2009) are a valuable contribution to the literature since the rigidity of the pavement is affected by temperature fluctuations, resulting in changes in stress and fatigue damage.

Table 1. Critical comparison of refs (Li, Chan, and Zhou 2005; MacDougall, Green, and Shillinglaw 2006).

Ref.	Methodology	Type of bridge member	Type of load	Type of modelling	Presented data	Advantages/Disadvantages
(Li, Chan, and Zhou 2005)	Fatigue life and fatigue crack growth evaluation	Welded bridge members	Traffic loading	Physical testing	Fatigue evaluation for welded members – Fatigue failure results for semi-elliptical crack with different depth to the half surface length – Fatigue life of butt-welded members	Appropriate for fatigue estimation of welded bridge members with small initiated crack/No specific method for rehabilitation
(MacDougall, Green, and Shillinglaw 2006)	Fatigue crack growth evaluation	Steel bridge girders	Traffic loading	Physical testing	Fatigue failure comparison between air-sprung and steel-sprung vehicles – Effect of surface profile and first natural frequency on fatigue failure	Analysis of various surface profiles, vehicle types, and speeds for fatigue estimation/No long-span bridge results

Table 2. Critical comparison of Refs (Guo, Li, and Wang 2008; Xu, Liu, and Zhang 2009).

Ref.	Methodology	Type of bridge/ member	Type of load	Type of modelling	Tested bridge	Critical evaluation
(Guo, Li, and Wang 2008)	Fatigue damage assessment	Welded bridge decks	Temperature & traffic	Physical testing	Runyang suspension Bridge	It is proved that temperature has a linear effect on fatigue damage – For Ref Xu, Liu, and Zhang (2009), fatigue damage caused by typhoon's wind needs to be analysed for a better analysis.
(Xu, Liu, and Zhang 2009)	Fatigue damage assessment	Long suspension bridge	Wind	Physical testing	Tsing Ma Bridge	

A critical evaluation of these papers is presented in Table 2.

Li et al. (2012) monitored fatigue damage of carbon fibre reinforced polymer (CFRP) bridge cables and analysed its progression process based on acoustic emission (AE) approach. The failure modes of the bridge, including matrix cracking and fibre breakage, were evaluated through kurtosis index and the *b* values, and various damage types were achieved according to the abrupt change points' analysis of these values. The wavelet transformation was utilised to obtain the AE signals' frequencies. The results have shown that the matrix and fibre-matrix interface failures were observed at the early stage of the fatigue testing, the location and magnitude of the fatigue damage were successfully evaluated through the indicators' changes, and fibre failure mode and matrix cracking mode were estimated by high-amplitude and low-amplitude signals, respectively. This paper is an important contribution to the literature by studying the causes of fatigue damage in CFRP bridge cables for the first time. The AE approach used in this paper provides a visual overview of the entire fatigue deterioration process of the cable, which is of great importance (Li, Hu, and Ou 2012).

Aggarwal and Parameswaran (2015) studied the impact of overweight vehicles on fatigue damage of a highway bridge. The aim of this study was to determine the relationship between fatigue damage aggregation and truck overloading. The fatigue damage was estimated for a longitudinal girder of a steel-concrete bridge under cyclic loading, and the truck was loaded with Gross Vehicle Weight (GVW) limits. The fatigue damage analysis showed that an increase of 50% in the truck weight caused an increase of 80% in fatigue damage aggregation which can be seen in Table 3. The findings also revealed that the fatigue damage

Table 3. Impact of overloading above permissible GVW of trucks on fatigue damage (Aggarwal and Parameswaran 2015).

Overload factor	Fatigue damage accumulation due to overloaded truck	Increase in fatigue damage accumulation (%)
1.05	7.0×10^{-7}	41
1.1	8.1×10^{-7}	49
1.15	9.2×10^{-7}	55
1.2	1.0×10^{-6}	60
1.25	1.2×10^{-6}	65
1.3	1.3×10^{-6}	69
1.35	1.48×10^{-6}	72
1.4	1.7×10^{-6}	75
1.45	1.83×10^{-6}	78
1.5	2.03×10^{-6}	80

aggregation and the truck overloading relationship was nonlinear. The results of this study were practical for the bridge's fatigue design in heavy industrial regions or near mines. This study investigated the effect of vehicles on the fatigue damage and did not state any rehabilitation method (Aggarwal and Parameswaran 2015).

Orthotropic steel decks (OSDs) have been widely employed in steel bridges due to their advanced mechanical properties, such as lightweight, ease of assembly, high load-bearing capacity, etc. However, fatigue cracks caused by various negative influences, such as traffic loads, weld defects, etc., have been observed for OSDs in the early stages of operation, and these have considerably decreased the service life of such structures. In the following reviews, fatigue damage in orthotropic steel decks is investigated using different methodologies.

Yan et al. (2016) proposed a scheme for fatigue performance and fatigue life prediction of welded joints in orthotropic steel deck cable-stayed bridges based on stress history, Miner's damage role, and traffic data. Surface effect and stress level were measured using a mixed-dimensional finite element modelling method, and Monte Carlo simulation was used to simulate the stress history of the traffic loads at critical joints with regard to the weight of the axles and transverse positions (Figure 3). The mixed-dimensional modelling represented great accuracy and efficiency for bridge modelling and fatigue assessment, and it was capable of extracting the bridge global responses and cables' transverse effects. Accordingly, bridge global behaviour and stress concentration were collected for fatigue evaluation. The results have shown that Monte Carlo simulation reduced the efficiency to some degree due to its dependence on the field traffic data, the proposed scheme accurately estimated the fatigue life of welded joints, and AASHTO code (Aashto 2010) was more conservative in comparison to the Eurocode (Eurocode 1993). One of the advantages of this paper was that it demonstrated the whole fatigue evaluation process through a case study (Yan, Chen, and Lin 2016).

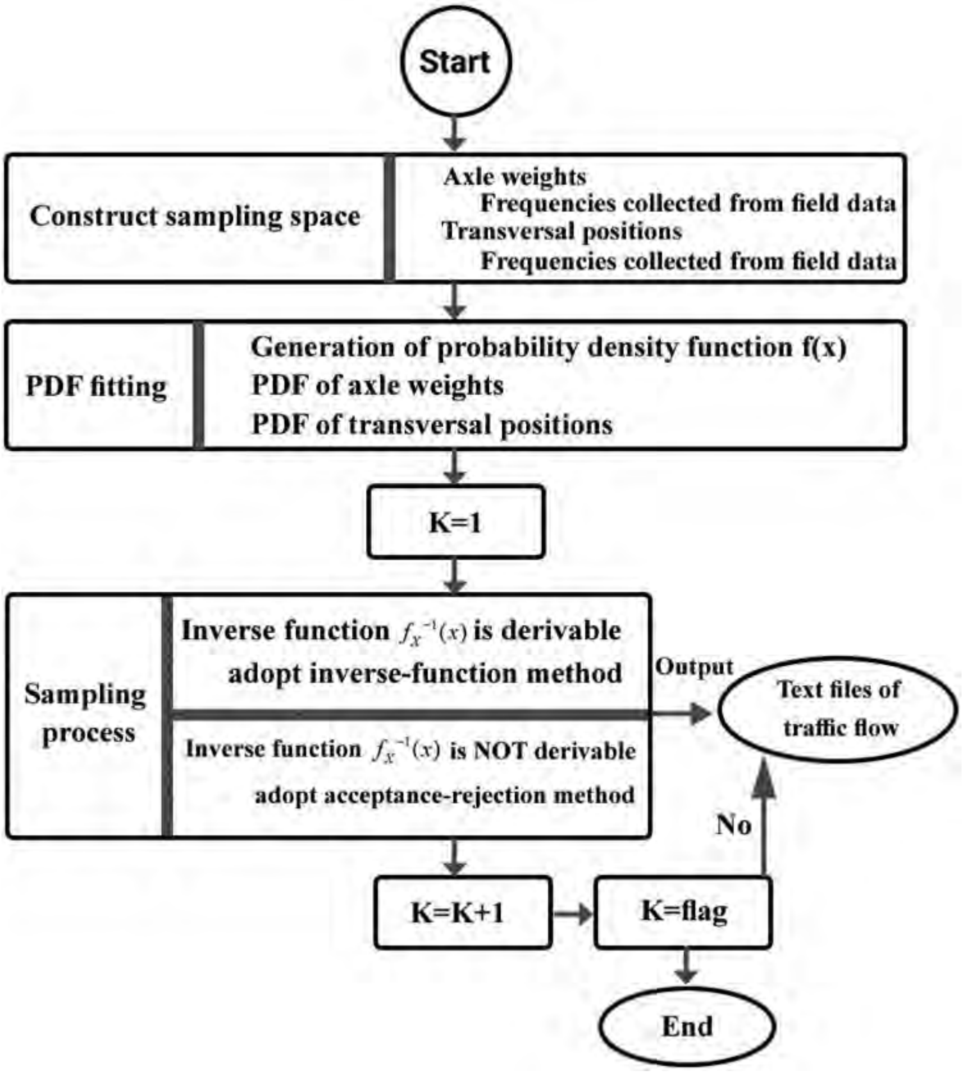

Figure 3. Flowchart of the Monte Carlo simulation (Redrawn from Yan, Chen, and Lin (2016)).

Fu et al. (2017) studied the fatigue life and strength of the roof and U-rib welds of orthotropic steel bridge decks with various thicknesses and penetration rates. Hot-spot and nominal stresses were estimated, and stress intensity factors and crack distribution were analysed through the finite element method (FEM). It was observed that an increase in the thickness and penetration rate led to a decline in the crack distribution rate. The findings showed that thicker decks had more impact on fatigue life and slowing the crack distribution rate, and a lower penetration rate and an increased penetration rate led to a decline in bearing strength and stress intensity factors, respectively (Fu et al. 2017).

Cui et al. (2018) estimated fatigue damage of orthotropic steel decks (OSDs) subjected to a combination of weld residual stresses (WRSs) relaxation and cyclic loadings. An elastic-plastic fatigue damage model was proposed based on continuum damage mechanics and then it was validated through fatigue tests on U-rib weld connection samples. The findings showed the applicability of the proposed fatigue damage model in estimation of WRSs and fatigue damage in OSDs. It was revealed that the WRS relaxation rate was larger in the longitudinal direction due to higher tensile stress. With all this, it can be inferred that it is necessary to consider the impacts of WRSs to avoid the miscalculation of fatigue life and nonconservative structural design (Cui et al. 2018).

Table 4 critically evaluates the three above-mentioned papers.

With the public transportation growth in recent years, truck overloading poses a significant threat to bridge safety, and may even lead to its failure. Traditional methods investigated the fatigue damage of bridges caused by overloading mostly by finite element analysis (FEA) which is model dependent and with high computational cost. To overcome these issues, Yan et al. (2019) investigated fatigue failure probability of a steel girder bridge subjected to vehicle overloading based on machine learning and Monte Carlo techniques which is shown in Figure 4. First of all, the bridge responses were collected based on a finite element model and then, a feedforward neural network was developed. Finally, the developed machine learning algorithm was merged with Monte Carlo technique for the fatigue failure reliability prediction. Based on the performed analysis, the accumulative fatigue damage was successfully estimated using the proposed method which was capable of providing an instant evaluation of the fatigue life with great accuracy. It was revealed that the fatigue damage probability increased nonlinearly with time, and the service time had a great impact on fatigue damage. Moreover, by means of the feedforward neural network as an assistance in fatigue damage analysis, it was determined that the machine learning method was able to predict the fatigue damage and extrapolate the unknowns in the hyperdimension space. Based on this paper, it can be concluded that machine learning as an artificial intelligence (AI) tool is capable of making predictions and extrapolating unknown data; therefore, the probabilistic machine learning method may have the potential to predict the fatigue damage with the realistic measurement data and with a great accuracy (Yan et al. 2019).

Cui et al. (2020) developed a framework for the fatigue damage prediction of the deck-to-rib (DTR) weld joints of orthotropic steel deck (OSD) in long-span cable-stayed bridges. The flowchart of the proposed framework is shown in Figure 5. Some of the main components of this framework were pavement and OSD interaction, coupled bridge-vehicle system, the impact of asphalt pavement temperature, fatigue damage prediction, hourly vehicle loading prediction and simulation, multi-scale finite element bridge model, and DTR joint's stress response. The findings showed the necessity of the annual average hourly traffic (AAHT) for hourly traffic loading and pavement temperature. The response surface model which was developed from the bridge-vehicle model showed the stress response amplitude at the DTR joint dependent on vehicle's type and weight, pavement temperature, and road unevenness. It was also concluded that the hourly fatigue aggregation at the DTR joint could be estimated using test-based S-N curve

Table 4. Critical comparison of Refs (Yan, Chen, and Lin 2016; Fu et al. 2017; Cui et al. 2018).

Ref.	OSD/OSD member(s)	Type of modelling	Type of load	Critical evaluation
(Yan, Chen, and Lin 2016)	Welded joints	Finite element modelling	Traffic loading	Comparison of AASHTO & Eurocode results – Using various procedures and developing a model for obtaining more precise results
(Fu et al. 2017)	Roof and U-rib welds	Finite element modelling	Traffic loading	Considering various thicknesses and penetration rates – Calculating hot-spot and nominal stresses, crack-propagation rate, bearing capacity, and fatigue strength – Recommending a thicker roof for heavily trafficked bridge lanes
(Cui et al. 2018)	OSD	Finite element modelling	Traffic loading	Presenting the first evaluation of WRS – Comparing the WRS's relaxation in perpendicular and parallel directions – Achieving fewer errors in comparison with other methods

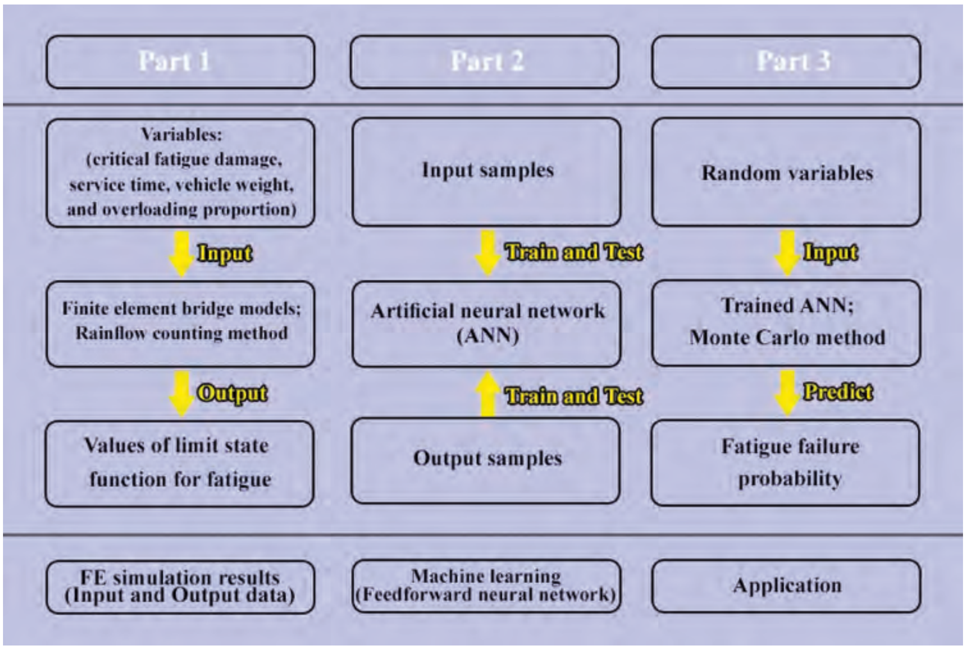

Figure 4. Framework of probabilistic machine-learning-based technique (Redrawn from Yan et al. (2019)).

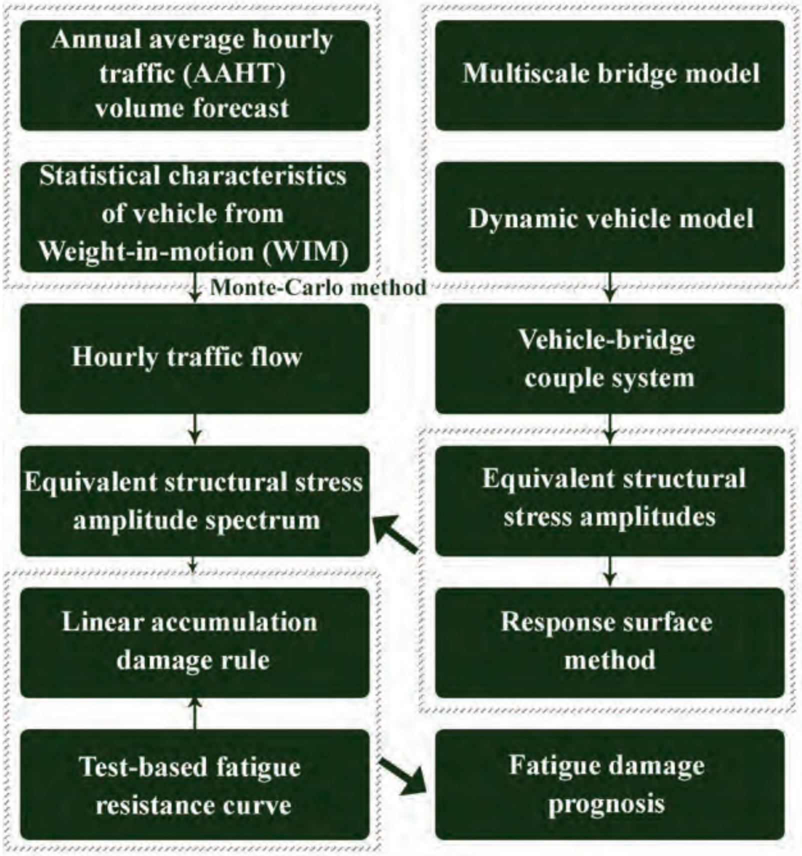

Figure 5. Flowchart for fatigue damage prediction of DTR joint of OSD in bridge (Redrawn from Cui et al. (2020)).

and linear aggregated damage theory. It can be inferred from this paper that, without applying the pavement temperature and road conditions, the fatigue damage of DTR joint will be underestimated (Cui et al. 2020).

Liu et al. (2020) proposed an orthotropic composite deck utilising large U-ribs and engineered cementitious composite (ECC) to improve the fatigue resistance. The ECC was used as a high-performance overlay. Full-scale composite decks were experimentally tested in order to evaluate the fatigue failure and resistance, and to verify a finite element (FE) model which was designed to investigate the impact of ECC on the fatigue performance.

The findings showed that the ECC overlay enhanced the fatigue resistance and significantly decreased the stress ranges at the welded joints which is shown in Table 5, and the proposed composite deck presented a high fatigue resistance even when damages occurred in the deck. This study was intended to extend the knowledge of the impact of ECC on the fatigue performance; however, further research on the proposed composite deck is required to verify all of these findings (Liu et al. 2020b).

Table 6 critically compares the above-mentioned papers regarding fatigue damage prediction of joint in orthotropic steel deck (OSD).

Table 7 summarises other papers regarding fatigue damage detection in bridge structures.

3.2. *Different bridge structural health monitoring methods*

Wahab (1999) investigated damage detection in a prestressed concrete Z24 bridge based on modal curvature (MC) technique. The author used data from a continuous and simple beam in order to establish this method. This paper is divided into two parts: 1) introducing a new parameter called curvature damage factor (CDF), and 2) Applying this technique to Z24 bridge. The results have shown that using MC method for damage detection in structures was encouraging, however, for higher modes, special caution should be taken (Abdel Wahab and De Roeck 1999).

Table 5. Stress ranges of welded joints (Liu et al. 2020b).

	Stress range (MPa)			
Details	Stage I	Stage II	Stage III	Stage IV
Rib-to-deck and diaphragm joints	298	448	596	747
Rib-to-diaphragm joints	116	162	208	254

In a similar study, in 1999, Maeck and Roeck investigated damage detection of asymmetrically loaded reinforced concrete (RC) beams and prestressed concrete Z24 bridge based on modal bending moments and curvatures. The bridge was progressively damaged by cutting the Koppigen pier and installing the steel plates. The results have shown that this technique was capable of detecting various damage locations without any assumptions and also, for finding the stiffness reduction, no analytical model was necessary (Maeck and De Roeck 1999).

The above-mentioned papers conducted damage identification based on dynamic parameters. It is concluded that damage has a significant impact on dynamic properties of the bridge such as natural frequencies and stiffness which were examined in these two papers. This method which gained considerable attention in the last decade has several advantages, especially no numerical method and assumption is required to detect damage. In contrast, special caution should be taken for higher modes, and improved techniques should be developed to increase the quality of the measured mode shapes.

Sohn and Law (2000) conducted an experimental investigation of a Bayesian probability-based method to locate the plastic hinge deformation in a reinforced concrete (RC) bridge column based on vibration tests' data and simplified analytical models. In this study, the column was pushed statically with progressive lateral displacement until the plastic hinge formation in the column, and the modal parameters were utilised to constantly update the damage probabilities. The results showed the superiority of the Bayesian approach in continuous monitoring of structures compared with other deterministic approaches, and the Bayesian approach could easily update the damage probabilities in case new test data are achieved. The proposed method overcame some crucial challenges that many structures were facing such as the impact of

Table 6. Critical comparison of Refs (Yan, Chen, and Lin 2016; Fu et al. 2017; Cui et al. 2020; Liu et al. 2020b).

Ref.	(Yan, Chen, and Lin 2016)	(Fu et al. 2017)	(Cui et al. 2020)	(Liu et al. 2020b)
Tested member(s)	Welded joints	Roof & U-rib welds	Deck-to-rib (DTR) weld joints	U ribs
Type of load	Traffic loading	Traffic loading	Traffic loading	Concentrated loads
Developed model	Mixed-dimensional finite element model	Finite element model	Multi-scale finite element model	Finite element model
Computational cost	Low	Low	High	Low
Ease of installation	×	✓	×	×
Remote sensing	✓	✓	×	✓
Presented data	1) Fatigue life prediction 2) Stress concentration results 3) Comparison of AASHTO & Eurocode results 4) Global structural behaviour	1) Fatigue life assessment 2) Effect of deck thickness & penetration rate 3) Bearing capacity 4) Local stress-intensity factor 5) Fatigue strength results	1) Fatigue damage assessment 2) Effect of various factors such as pavement temperature and hourly traffic on fatigue damage 3) Stress response of DTR joints 4) Evaluating hourly fatigue accumulation	1) Fatigue behaviour assessment 2) Stress range & fatigue resistance results 3) Mechanical behaviour assessment

Table 7. Review of other papers regarding fatigue damage detection in bridge structures.

Ref.	(Mohammadi and Polepeddi 2000)	(Sim and Oh 2004)	(Imam, Righiniotis, and Chryssanthopoulos 2007)	(Pipinato et al. 2011)	(Shifferaw and Fanous 2013)	(Megid et al. 2019)
Methodology	1) Development of a method for bridge rating based on fatigue damage due to overload 2) Development of a fatigue index in order to provide a limit on the damage	Conducting fatigue tests on fibre-reinforced polymer (FRP) strengthened bridge decks	Fatigue evaluation of riveted railway bridges	Conducting laboratory and static fatigue tests on a riveted railway bridge	1) Conducting finite element analysis and physical testing to evaluate the distortion behaviour of web-gap in a skewed multi-girder bridge 2) Recommendation of retrofitting possibilities for web-gap distortion reduction	Conducting a monitoring procedure to evaluate the initiation and/or growth of fatigue cracks in steel bridges' eyebars based on Acoustic Emission (AE)
Tested structure(s)	Five simulated bridges	A prototype deck panel	A double-lap joint and a riveted bridge connection	Meschio railway bridge, Italy	A four-span bridge in Black Hawk County, Iowa	Alexandra bridge, Canada
Type of load	Overloads	Traffic loads	A freight train	Concentrated loads	Traffic loads	Normal traffic and a loading truck
Type of modelling	Computer modelling	3D non-linear finite element model	3D Finite element model	Physical testing	Physical testing and finite element models (ANSYS SHELL63 element)	Physical testing
Computational cost	Low	High	Low	High	High	Low
Ease of installation	_	✓	_	✓	✓	✓
Remote sensing	✓	✓	✓	×	✓	×
Presented results	1) Fatigue life assessment 2) Bridge rating 3) Assessment of fatigue damage amount by the developed index	1) Assessment of the fatigue life limits 2) Prediction of the decks' fatigue life with the S-N relationship 3) Presentation of the decks' failure patterns 4) Comparison of fatigue life and damage accumulation of carbon fibre sheet (CFS) decks, carbon fibre reinforced plastic (CFRP) decks, and glass fibre sheet (GFS) decks	1) Identification of fatigue-prone locations of the connection 2) Evaluation of stress histories at various regions of the connection 3) Evaluation of the effect of rivet's stress on fatigue damage 4) Prediction of the fatigue damage initiation patterns	1) Description of base material tests including tensile and impact tests, and rivets' hardness tests 2) Description of static tests including bending and shear tests 3) Description of fatigue tests including bending and shear tests	1) Comparison of field and finite element analyses' results 2) Results of adopting different retrofit alternatives in order to reduce the web-gap's distortion, strains, and stresses. 3) Results of the web-gap height study and its influence on strains 4) Finding the reason of web-gap's distortion which is the girders' differential deflection caused by fatigue crack	1) Identification of possible fatigue crack locations using AE monitoring 2) Confirmation of AE sources and monitoring the fatigue crack growth 3) Evaluation of fatigue crack condition and verification with Magnetic Particles Inspection (MPI)
Advantages/ Disadvantages	Beneficial to older bridges/ Requiring very thorough and strict analysis – Requiring the availability of the bridge's load and stress data	Evaluation of the decks' fatigue behaviour under traffic loads since few investigations have been done before/Inability to extend to the entire bridge	Conducting a more detailed investigation on stress-induced fatigue damage/ Lack of physical experiments	Cumulative description of the tests – Better rivets' fatigue behaviour assessment/ Unavailability of the tested bridge's materials' properties – Utilisation of the widest load range to decrease the test duration	Conducting both field tests and finite element analysis – Retrofitting methods recommendation/ Lack of web-gap's fatigue life evaluation	Cost-effective – Reliable technology for fatigue crack assessment – Capability of inspecting the entire bridge – Safety enhancement – Providing early warning of failures/Inability to assess the shape and size of cracks

(*Continued*)

Table 7. (Continued).

Ref.	(Mohammadi and Polepeddi 2000)	(Sim and Oh 2004)	(Imam, Righiniotis, and Chryssanthopoulos 2007)	(Pipinato et al. 2011)	(Shifferaw and Fanous 2013)	(Megid et al. 2019)
Recommendation	Evaluation of the proposed method under more diverse load population	Conducting fatigue tests on other types of fibre-based reinforcement – Taking care when choosing the reinforcement method	Using this paper as a guideline for connections' fatigue damage evaluation in large structures	Conducting further research to verify the results of this paper	Fatigue life assessment of the web-gap under different retrofits – Conducting further research to evaluate the effect of the web-gap's distortion	Conducting further research and a remote AE monitoring

uncertainties, the difficulty of modelling the structures with complex geometry and various materials, and the lack of a large number of measurement points. However, this method needs to be upgraded in order to provide more accurate results even with one test data (Sohn and Law 2000).

During the life span of bridges, especially fibre reinforced plastic bridges, various structural degradation such as cracks, and changes in the properties of materials may happen which cannot be identified by visual monitoring. Thus, developing a method to overcome these issues is necessary. Aref and Alampalli (2004) investigated damage identification of a fibre reinforced plastic bridge based on dynamic response which was achieved from finite element analysis, validated with field tests, and used for various damage scenarios. The results have shown that the lowest modes of frequency were very sensitive to damage, and this damage detection method was capable of identifying the location and the rate of damage in the bridge. Further research should be carried out to cover more potential deteriorations (Aref and Alampalli 2004).

Peeters and Roeck (2001) introduced an approach to differentiate normal and abnormal eigenfrequencies changes caused by damage and presented the results of one-year Z24 bridge monitoring. The authors proposed an automatic modal analysis (AMA) procedure to recognise modal parameter's changes from abnormal changes. Since the Young's modulus of the concrete bridge increased during the first months, identification models for the bridge were done after a few months. It was revealed that in order to find an accurate model, temperature measurement at one location was enough. It was also concluded that the temperature was the only factor that was related to the eigenfrequencies, the mass of the bridge did not change due to the moisture absorption. One of the main contributions of this paper is to examine the effect of temperature, humidity, rainfall, and wind. However, only a relation between temperature and eigenfrequencies was found and analysed. On the contrary, further research needs to be done in order to add the traffic loads and low-temperature data. The proposed approach also requires validation on other bridges (Peeters and De Roeck 2001).

Liu and Sun (2001) developed a neural network system using simulation data for the damage detection of simply supported, three-span bridge. A moving truck with a constant mass and speed was driven across the bridge (Figure 6), and longitudinal elongations of the bridge were used as an indicator of the damage. The results have shown that the proposed monitoring system was insensitive to noise and was capable of identifying the locations of multiple damages, partial damages, and different damage zone grouping. This paper is a significant contribution to the literature by identifying multiple-damage zones. Since the proposed monitoring system included various neural networks, and each one was dedicated to a portion of the bridge, the training time and training samples were significantly decreased. However, the

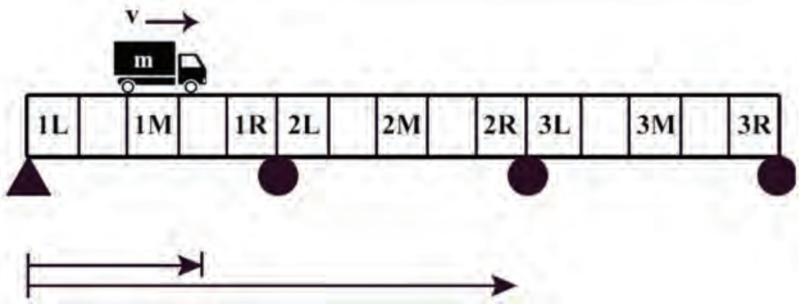

Figure 6. Simulation of the bridge under a moving truck with a constant speed and mass (Redrawn from Liu and Sun (2001)).

proposed system should be verified by experiments to justify the obtained results (Liu and Sun 2001).

Ko et al. (2002) developed a multi-stage damage identification scheme based on modal data obtained from an online system. The authors applied the proposed scheme to the cable-stayed Kap Shui Mun Bridge in Hong Kong. The aim of this strategy was to identify the incidence, location, and severity of damage. The first stage was damage alarming based on auto-associative neural networks which only required a series of natural frequencies. In the second stage which was damage detection in the deck, the bridge deck was partitioned into 149 segments, and the index vectors were determined by the modal curvature and modal flexibility. The goal in the third stage was to detect the locations and severity of certain damaged members based on a multilayer perceptron neural network. The findings have shown that the proposed scheme was capable of identifying damage when the frequency change level was lower than the noise level and a few modal components were available. Moreover, the modal flexibility index performed better for damages occurred at the supporting system, while the modal curvature index presented better results for damages near the bridge towers. Consequently, the combination of these two indices could provide a reliable damage detection in bridge decks. The developed scheme is highly promising in operation containing noise (Ko, Sun, and Ni 2002).

There were some main issues with the novelty neural network-based detection method developed in (Ko, Sun, and Ni 2002). This method utilised only vertical modes as inputs and could not distinguish the input vectors from the output vectors caused by an anomaly. In addition, an enhanced novelty index should be formulated for a better damage detectability in using various distance measures, various noise patterns and levels, and various input vectors. The novelty index (Ko, Sun, and Ni 2002) could not discern actual damage from the anomaly due to variable noise level. Therefore, Ni et al. (2002) studied the problems of the novelty detection method for damage detection of long-span bridges by taking Tsing Ma Bridge as a model. The main focus of this paper was to develop an enhanced novelty index, which always represented structural damage information. In case of difference between the noise level of undamaged and damaged structures, the improved novelty index provided more reliable damage information. The enhanced novelty index is highly promising in practical applications; however, it is still incapable of identifying the damage severity. Therefore, further research to make this method more feasible is necessary (Y-Q et al. 2002).

Kullaa (2003) investigated the damage identification of the Z24 bridge using various univariate and multivariate control charts and based on modal parameters. The author found out that dimensionality reduction significantly increased the sensitivity of the control chart, and Shewhart charts and Hotelling T for individual variables were the best options for large shifts in comparison with CUSUM and EWMA. This method could be performed both online and offline. In offline damage identification, various control charts were utilised which made damage detection much easier. However, further research needs to be done to remove false alarms (Kullaa 2003).

Kim and Stubbs (2003) presented a non-destructive crack detection (NCD) approach for full-scale bridges in order to detect a crack's location and assess its size based on the modal parameters. First, the theoretical background of the NCD was provided then, and a field experiment on a steel plate-girder bridge was performed to demonstrate the applicability of the proposed approach. The findings showed that the proposed approach was capable of locating the crack and estimating the crack geometry with a small localisation error, without any knowledge of the material properties, and with the knowledge of a few frequency responses and mode shapes. Further research needs to be carried out to extend the NCD methodology to more complex structures and to justify the variations in modal properties of real structures (Kim and Stubbs 2003).

In another attempt, Kim et al. (2004) examined the variation of modal parameters under temperature impacts for the frequency-based damage identification of plate-girder bridges. Various tests on model bridges under different temperature conditions were performed then, and a series of frequency-correction formula were developed based on temperature–frequencies relationship. Lastly, a frequency-based approach was utilised to evaluate the location and severity of damage based on experimental modal data. The obtained results using undamaged and damaged frequencies from the same temperature condition were valid which is shown in Table 8 and 9. One of the key issues was that the increase in the temperature gap between the pre-

Table 8. Prediction of damage location in model bridge (Kim, Yun, and Park 2004).

Damage Case	Real damage location at 23°C (Element No.)	Predicted damage locationElement No. (location error %)			
		0-Deg	10-Deg	20-Deg	30-Deg
1	100	109 (4.5)	112 (6.0)	109 (4.5)	113 (6.5)
2	100	112 (6.0)	112 (6.0)	110 (5.0)	116 (8.0)

Table 9. Prediction of damage severity in model bridge (Kim, Yun, and Park 2004).

		Predicted damage severity			
Damage Case	Real damage severity at 23°C	0-Deg	10-Deg	20-Deg	30-Deg
1	0.454	0.944	0.874	0.702	N/A
2	0.770	0.963	0.918	0.819	N/A

damage and post-damage conditions decreased the precision of this method (Kim, Yun, and Park 2004).

Calvert and Mooney (2004) discussed the steps of preparation and testing of fibre grating strain sensors as a system for damage detection and real-time data extraction of a bridge's response to a dynamic data. The performance of the sensors was shown in the laboratory tests, and the sensors were deployed on the Broadway Bridge for assessment. The sensors were sufficiently robust in harsh weather conditions and were resistant to damage during or after installation (Calvert and Mooney 2004).

Huth et al. (2005) studied the performance of various damage detection approaches based on experimental modal data which was achieved from tests on a prestressed concrete highway bridge subjected to progressive artificial damage. In this study, a mode shape area index based on modal shapes was developed. The results have shown that severe damage had a low effect on natural frequencies especially when the cracks were closed after the loading cycle, the environmental parameters, especially temperature variations, had a considerable impact on natural frequencies, and the proposed index was more sensitive to mode shapes' changes than the modal assurance criterion (MAC). It was also concluded that detecting or locating damage through changes in the flexibility matrix was far better than natural frequencies, and an early-stage damage detection on the bridge was extremely difficult by any applied approaches due to the stiffness recovery and the impacts of environmental parameters. This paper is a significant contribution to the literature by evaluating different damage detection methods such as changes in the flexibility matrix, direct stiffness calculation, and sensitivity-based model updating method. None of the approaches performed in this study were reliable in detecting, locating, and quantifying damage at an early stage due to the fact that modal data was not significantly affected by cracks. In view of these findings, a modal shape-based damage indicator is more costly than one based on natural frequencies since it needs a large number of sensors and more complicated algorithms (Huth et al. 2005).

Siddique et al. (2005) presented the initial outcomes of the application of vibration-based damage identification approaches to a two-span, slab-on-girder, integral abutment bridge using finite element modelling (FEM) which was calibrated to pair with frequencies and mode shapes. The results disclosed a decrease in natural frequencies with an increase in temperature and did not report the influence of temperature effects on mode shapes. Moreover, it was concluded that damage might be identified by means of any of the approaches which were influenced by a number of sensors, and locating damages close to a support was more difficult. In addition, the number of measurement points was found to have a considerable impact on the performance of the approaches with regard to their capability in locating damage. Since the presented results in this paper are preliminary, further research needs to be carried out. However, comparing the results of this study with other studies shows that vibration-based damage identification approaches have a good potential for use on actual structures (Siddique, Wegner, and Sparling 2005).

Lee and Yun (2006) proposed a damage identification approach for steel girder bridges based on ambient vibration data which is shown in Figure 7. Conventional back-propagation neural networks (BPNNs) with a noise injection learning algorithm were utilised for model-based detection of the damage locations and severities (Figure 8). A two-stage strategy was performed to improve the proposed method's efficiency. First, a modal strain energy-based damage indicator was used to inspect the damaged members and then, the conventional back-propagation neural networks were utilised for a better damage identification. This approach was validated through numerical examples on a multiple-girders bridge and a field experiment on the Hannam Grand Bridge. It was revealed that averaging an adequate amount of data enhanced the estimation accuracy, and the considered neural networks presented good results in all damage cases despite many errors in the first step. The proposed approach offers several advantages, including low computational cost and high accuracy. Since the damage identification was performed on a small number of members, the results were more accurate (Lee and Yun 2006).

Xu and Humar (2006) presented a two-phase approach for damage identification that utilised a modal damage index to identify the location of damage and also an artificial back-propagation neural network to calculate the extent of damage in a girder bridge. This approach was validated through a finite element model and an actual bridge named Crowchild Bridge. The results have shown that the modal damage index was highly effective in locating damage, and the neural networks were effective in determining the extent of damage even in the existence of substantial errors. This paper is a significant contribution to the literature by demonstrating that the curvature modes provide far better results in determining the location of damage even in the existence of considerable errors (Xu and Humar 2006).

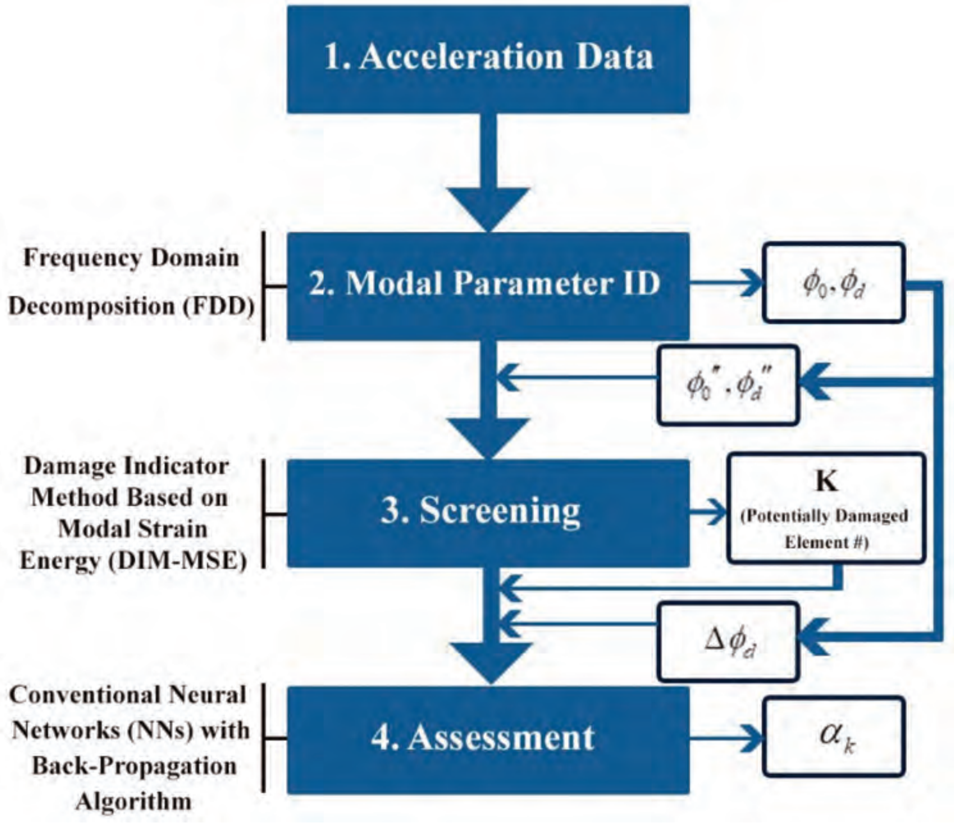

Figure 7. Flowchart of the proposed damage identification approach (Redrawn from Lee and Yun (2006)).

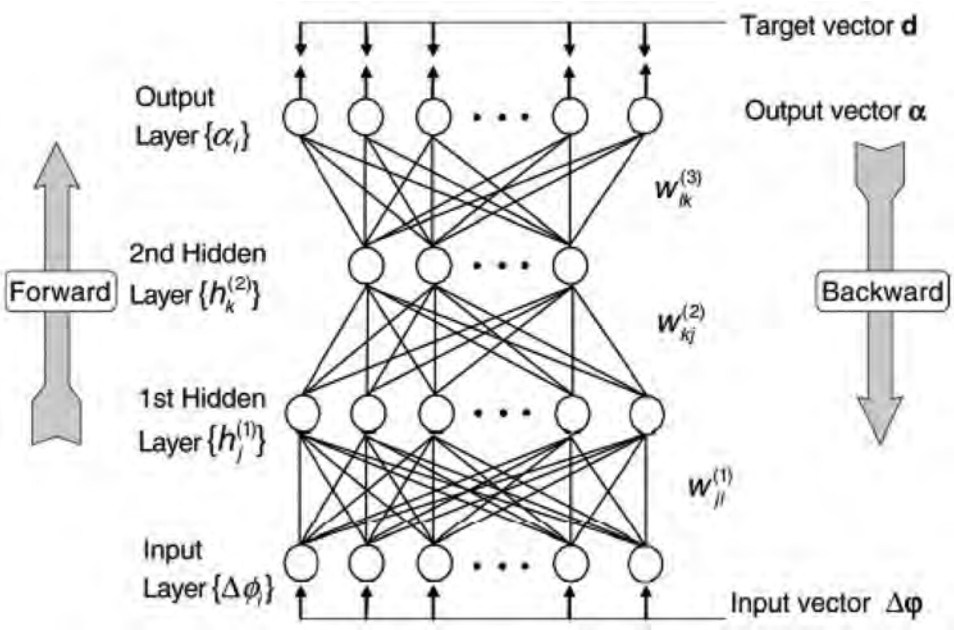

Figure 8. Back-propagation neural networks (Reproduced from Lee and Yun (2006)).

Kim et al. (2006) investigated seismic responses of a multi-span girder simply supported bridge to evaluate the impact of possible bearing damage based on developed analytical models. Parts with proper friction between the superstructure and pier were considered as damaged bearings. The developed analysis tool evaluated the seismic responses of the bridge successfully in terms of bearing damage. It was concluded that the response results in the system with damaged bearings were in quite different shapes compared to the system without damaged bearings, and existing multi-span girder simply supported bridges with common structural shapes may not need to be rehabilitated in moderate seismic regions. Further research is required to take into account the impact of the unseating superstructures' failure during earthquake excitations for a better bridge response assessment (Kim, Mha, and Lee 2006).

Zhang (2007) presented a 4-step statistical damage detection approach for bridge health monitoring based on ambient vibration data which is shown in Figure 9. Both undamaged and unknown structures were monitored, and their data was obtained. A statistical damage index was introduced for identifying the damage and its location. The proposed scheme was validated with numerical studies utilising a three-span continuous girder bridge. It was found that damage at early stage was successfully identified with the proposed approach even in noise-contaminated condition, and the proposed approach was not input-dependent. One of the main obstacles of the vibration-based damage detection approaches, the inherent uncertainties in experimental data, was the main focus of this study. The main limitation of this paper was that the assumptions on the damping property, the structural behaviour, and the measurement noise were adopted. Finally, an experimental study is necessary to validate the applicability of the proposed approach (Zhang 2007).

For a better evaluation, a critical comparison is made for the references (Lee and Yun 2006; Xu and Humar 2006; Zhang 2007) in Table 10.

Dynamic modal parameters are simple to assess and use, making them appealing for structural damage detection. However, under uncertain temperature condition, especially in large structures, their usage becomes limited. To fill this gap, Kim et al. (2007) introduced a damage identification scheme for predicting the damage incident, location, and extent under uncertain temperature conditions based on dynamic modal parameters. First of all, experiments for obtaining modal data under uncertain temperature conditions on a plate-girder bridge were carried out and then, damage incident was identified through a damage warning model. Finally, the location and extent of damage were predicted by a damage index method which was based on modal strain energy. The first four modes of the pre-damage state of the bridge were measured under different temperature conditions, and two damage scenarios were proposed with a fixed temperature condition. The obtained results using undamaged and damaged frequencies from the same temperature condition were accurate, but as the temperature gap increased, the accuracy of the results decreased (Kim, Park, and Lee 2007).

In recent years, the genetic algorithm (GA) has gained a significant attention in structural damage detection area. One of the key features of the GA is its efficiency and robustness in managing noise and uncertainty. Moreover, GA, unlike the mathematical approaches, utilises multiple points to find the solution. Zhu and Xiao (2007) developed a damage identification approach for long-span cable-stayed bridges based on genetic algorithm which is shown in Figure 10. The algorithm was achieved through the monitored data of the cable force and strain in the main girder. A planar finite element method was performed for initial damage identification and reduction of the running time. Damages in the concrete cable-stayed bridges were accurately identified by the proposed approach, and the results were well aligned with periodic investigations. The proposed approach is suitable for continuous damage detection in beam-type structures as it makes it possible to detect elements with very little damage (Zhu and Xiao 2007).

In another attempt in bridge damage detection based on neural network technique, Mehrjoo et al. (2008) presented a multi-layer perceptron neural network-based approach for the joints' damage intensity assessment in truss bridges. A numerical analysis was

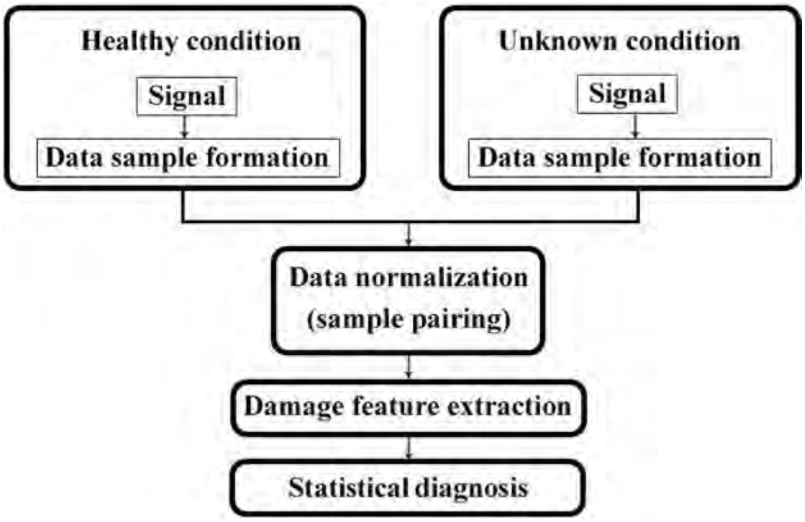

Figure 9. Proposed damage detection approach (Redrawn from Zhang (2007)).

Table 10. Critical comparison of Refs (Lee and Yun 2006; Xu and Humar 2006; Zhang 2007).

Ref.	(Lee and Yun 2006)	(Xu and Humar 2006)	(Zhang 2007)
Methodology	Damage detection using ambient vibration data and conventional back-propagation neural networks	Damage detection using a modal damage index and an artificial back-propagation neural network	Damage detection using ambient vibration data
Tested bridge	Hannam Grand Bridge	Crowchild Bridge	A numerical model of 3-span continuous bridge
Type of load	Traffic loading	Static and dynamic loads	Traffic loading
Developed model	A simply-supported bridge model using SAP2000	Finite element model	Finite element model
Computational cost	Low	Low	Low
Ease of installation	✓	✓	_
Remote sensing	✓	✓	✓
Critical evaluation	The neural network technique which has gained considerable attention in recent years are an effective tool for bridge damage identification since it does not require much computing time, it is efficient for cases with more than one type of input data, and it is especially efficient in providing solutions even in the presence of errors and uncertainties. Moreover, early-stage damages can be easily identified using methods based on ambient vibration data even in noise-contaminated condition.		

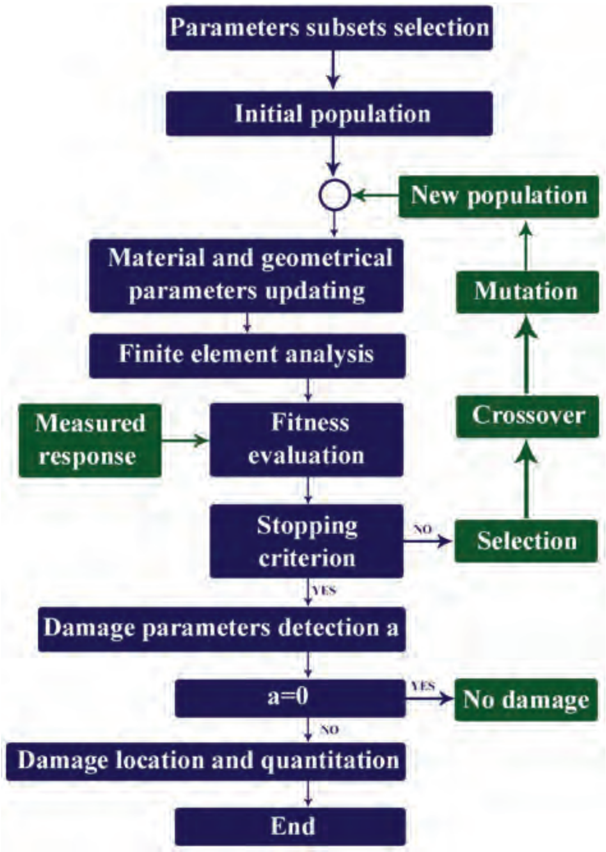

Figure 10. Flowchart of GA-based damage detection (Redrawn from Zhu and Xiao (2007)).

performed both on a simple truss and an actual bridge to illustrate the efficiency of the proposed approach. The proposed method identified the location and extent of the damage with only five modes designations and about 1% error, and it was found suitable for online and real-time damage detection. The proposed substructural approach was developed to address the issue related to many unknown parameters. Despite its many advantages, the neural network technique functions exactly like an interpolation function and loses its generalisation feature when the network errors are reduced to zero (Mehrjoo et al. 2008).

Most of the bridge health monitoring methods use vibration parameters to identify damage, but in real situations, bridges are also subjected to environmental impacts. Therefore, developing a reliable method that can differentiate the changes caused by structural damage from those by the environmental impacts is highly recommended. To address this issue, Koo et al. (2008) introduced a novel approach using modal flexibility for detecting the deflection of bridge structures under temperature variations. The main idea of this paper was that the change in temperature resulted in an overall increase or decline in deflections over the entire bridge. In contrast, structural damage may induce local changes in deflections close to the damaged locations. First, the modal flexibility matrix and positive-bending-inspection-load were estimated, and then correlated nature in deflection at different locations was introduced. Finally, the outlier analysis was utilised for the damage detection. To validate the feasibility of the proposed approach, various experimental tests were performed on a steel box-girder bridge. The results indicated that the damage extent and location were successfully detected under thermal variations using this method, and the deflections were correlated with daily temperature changes. The successful application of the proposed approach on test bridges demonstrates its robustness in detecting small and severe damages under daily temperature changes (Koo, Lee, and Yun 2008).

The use of wireless system as part of structural health monitoring was originally introduced as a way to reduce installation costs in large structures. Over the years, several researches have been carried out, and many structures have been equipped and inspected with wireless systems. These comprehensive field studies demonstrate the precision and reliability of wireless system. Weng et al. (2008) carried out an ambient vibration investigation of a long-span cable-stayed bridge using frequency domain decomposition (FDD) and stochastic subspace identification (SSI) approaches and proposed a rapid-to-deploy technique to obtain the bridge dynamic properties based on a new wireless structural monitoring scheme. Ten modal frequencies along with their modal shapes were obtained from the interaction between the bridge's deck and cables' vibrations. The results revealed that the proposed approach had no data loss and was suitable for short-term field studies, the evaluation of the structural response to wind and traffic ambient levels led to the bridge dynamic properties, the SSI method could be applied in the time domain and was able to obtain the mode shapes, while the FDD method could be applied in the frequency domain, vertical vibration of the deck was in close relation with the cable vibrations, and the SSI method was very effective in identifying the mode shapes and eliminating unrelated noise. As it can be concluded, the ambient vibration data could be achieved easily and conveniently through wireless sensing units. Moreover, the installation of the wireless system requires less effort and labour, making it suitable for short-term field studies. However, more research is required to assess the accurate damping ratios (Weng et al. 2008).

One of the attractive approaches for evaluating the structural integrity is the finite element updating procedure which is based on vibration parameters. This non-destructive approach estimates the extent of damage and unlike acoustic or ultrasonic approaches, and it does not need any data about the damage location. Degrauwe et al. (2009) utilised the fuzzy number theory to study the errors and uncertainties in the damage detection of a cable-stayed bridge based on a finite element updating procedure. In particular, monitoring the cables' natural frequencies was utilised to identify damage in a cable-stayed bridge. The two uncertain variables investigated in this paper were frequency and temperature. The analysis revealed that the change in frequency was related to the temperature variation between the two calculation dates. Further research is needed to determine the level of damage (Degrauwe, De Roeck, and Lombaert 2009).

In recent years, damage detection of prestressed concrete (PSC) girder bridges has gained considerable attention. To ensure the safety and serviceability of these bridges, engineers are required to inspect the girders and tendons on a regular basis. Kim et al. (2010) developed a novel hybrid health monitoring system for the tendon and girder damage detection in prestressed concrete (PSC) girder bridges based on sequential vibration-impedance approaches. The proposed system which is shown in Figure 11 included three phases: warning of the damage incident by means of acceleration characteristics, prestress-loss and added-mass classification of damage by means of impedance and vibration characteristics, and damage extent and location evaluation by means of modal strain damage index approaches. A laboratory-scaled model was used to evaluate the applicability of the proposed system. The proposed system evaluated the extent and location of the damage with high precision but was unable to evaluate the severity of the damage. The sequential impedance-based damage detection is a type of local structural health monitoring (SHM), so it does not cover the whole structure. Additionally, this local SHM has the potential to detect small damages as it requires locally sensor arrays (Kim et al. 2010).

Leander et al. (2010) performed a large-scale monitoring scheme on the Soderstrom railway bridge to evaluate the difference between theoretical calculations and field inspections with regard to the fatigue cracks. An improved evaluation of the lifespan of the bridge was employed in this paper. According to the theoretical studies, poor connections of the beams and webs' out-of-plane bending caused cracks. The findings showed that the monitoring scheme was capable of providing reliable and sufficient results for the bridge monitoring, and the estimation of the fatigue life in earlier theoretical studies was verified. Since the tested bridge was in service and had reached its design life, more thorough analyses and short inspections were required to evaluate the cumulative fatigue damages. In addition, further investigations into the source of the cracks in the main beams and a more detailed fatigue evaluation using non-linear damage approaches are highly recommended (Leander, Andersson, and Karoumi 2010).

Bridge health monitoring utilising traffic-induced vibration data has been introduced recently, which mainly requires inverse analysis for the damage identification. Increasing structural members in the inverse analysis causes considerable numerical errors, leading to serious issues in practical applications. Therefore, employing only direct analysis is necessary. He et al. (2011) developed a bridge identification method based on train-induced vibration data and genetic algorithm (GA) optimisation (Figure 12). In this method, the possible damage patterns were supposed first and then, a train-bridge analysis was performed to model the bridge vibration. When the measured and recorded responses were identical, this damage pattern was the solution. Due to the high number of damage patterns, the GA optimisation was employed to identify the location and degree of damage in the damage pattern. In this study, the difference between the pseudo-measurement data and the analytical acceleration response is defined as the object function (OBJ). The results were in good agreement with the analytical achievements; therefore,

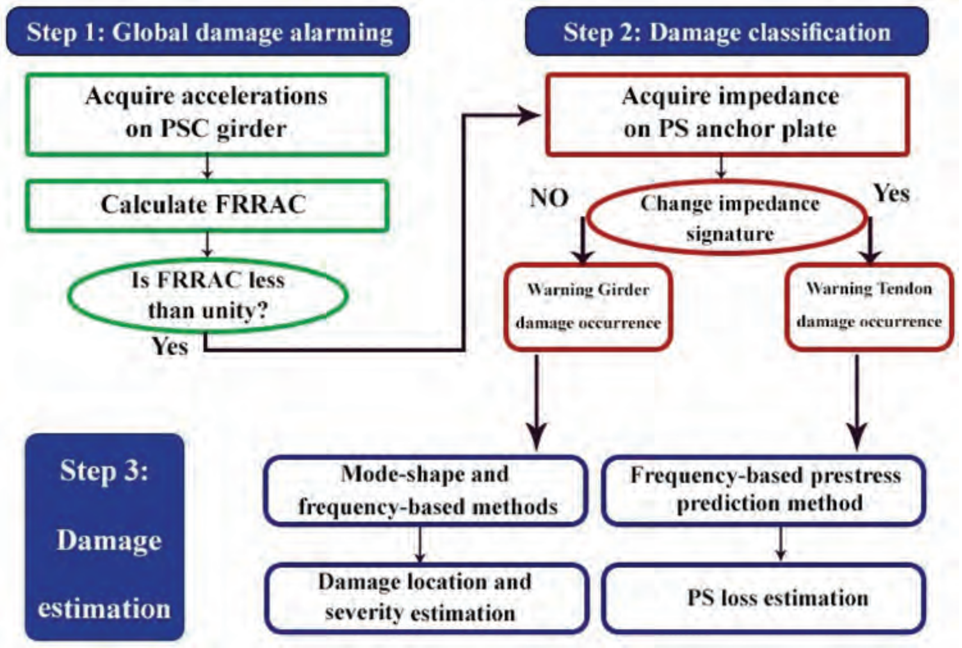

Figure 11. Novel hybrid health monitoring scheme for prestressed concrete girder bridges (Redrawn from Kim et al. (2010)).

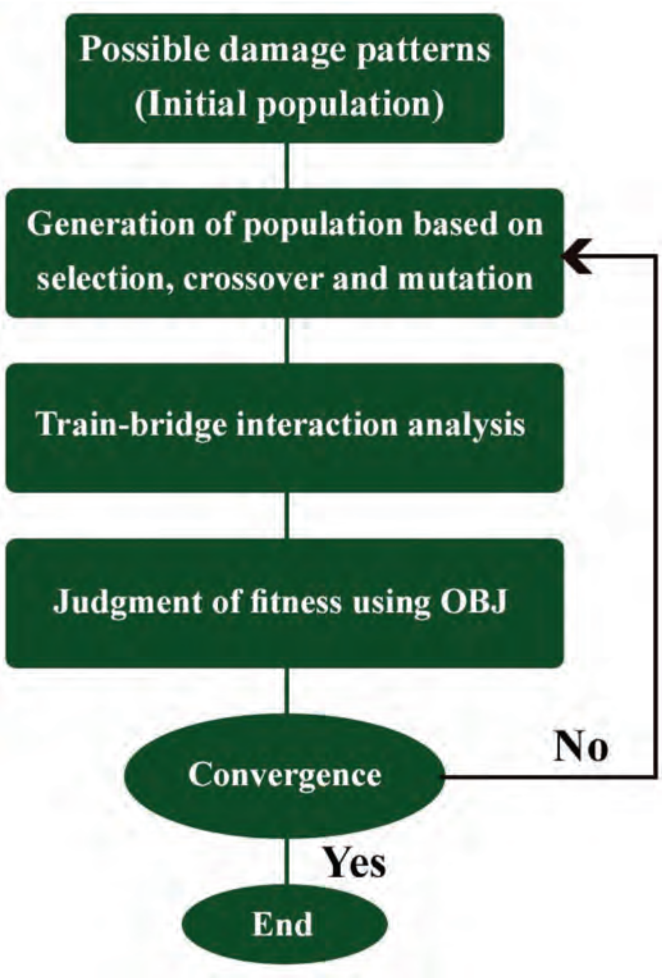

Figure 12. Flowchart of GA algorithm (Redrawn from He et al. (2011)).

the applicability of the proposed method was verified. The superiority of this method was its direct analyses through soft computing approaches. However, one of the main issues of this method that leads to its infeasibility in a real process is for a large-scale structure which needs significant computational capacities. Therefore, a neural network technique is required to address this issue. Further studies such as an updated GA algorithm under complicated analytical conditions are required for the actual feasibility of the proposed methodology. In addition, the analytical procedure should be validated through experiments and field tests (He et al. 2011).

Table 11 critically evaluates two reviewed papers in this section regarding the GA algorithm.

Zhan et al. (2011) proposed a non-destructive evaluation approach for railway bridges using train-bridge dynamic responses and sensitivity analysis. A damage index based on the element's stiffness variation was used for the damage detection. Based upon a comparison between the theoretically measured response and the computed one, the damage was identified and measured using a finite element model. The proposed approach was validated through a numerical three-span continuous bridge model. The results have shown that the location and extent of the damage were successfully identified by the proposed approach, the proposed approach was insensitive to the deviations in the track geometry and noise level up to 10%, and relative or absolute damage could be detected only by one measurement point. This paper is a significant contribution to the literature by investigating the damage identification of railway bridges by the train-bridge dynamic responses. However, there are some limitations and assumptions to the analysis. The train speed was constant, and only the bridge's vertical response was utilised. Furthermore, the wheel-set's degree of freedom was considered only in the Z direction. In addition to the limitations, disruptive environmental impacts should be minimised when implementing this approach in practice (Zhan et al. 2011).

Talebinejad et al. (2011) compared four different damage identification algorithms: Enhanced Coordinate Modal Assurance Criterion (ECOMAC), Damage Index (DI) method, Mode Shape Curvature (MSC) method, and Modal Flexibility Index (MFI) method on a long-span cable-stayed bridge based on a linear elastic finite element model. Modal shapes and natural frequencies were achieved through a numerical model of the bridge in ANSYS. The Effective Independence Method was utilised to find the best sensors' distribution on the bridge. The results showed that the DI method and MSC were capable of detecting both single and multiple damages in the cables and single damage on the deck with a few numbers of sensors, the DI method performed well in higher intensity level of damage, and the MSC method proved to be more sensitive to the noise than any other methods. Neither method could identify multiple damages on the deck. It was also concluded that ECOMAC was unable to identify damage even in the high damage intensity and no noise. This paper is a significant contribution to the literature by providing the benefits and deficiencies of different damage identification methods in cable-stayed bridges. Since these methods only identified damages with high intensity, their feasibility in bridge health monitoring requires further investigations (Talebinejad, Fischer, and Ansari 2011).

Cable-stayed bridges have become popular due to several benefits such as cost-effectiveness and anti-seismic features. Cables, the main stress elements of these bridges, are continuously exposed to cracks, corrosion, wind, etc. One of the most reliable and low-cost damage identification techniques for these bridges is the magnetic flux leakage (MFL) technique. Xu et al. (2012) proposed a magnetic flux leakage-

Table 11. Critical evaluation of Refs (Zhu and Xiao 2007; He et al. 2011).

Ref.	(Zhu and Xiao 2007)	(He et al. 2011)
Methodology	Developing a damage detection approach for long-span cable-stayed bridges based on genetic algorithm	Developing a damage detection approach based on train-induced vibration data and genetic algorithm optimisation
Tested bridge	Zhaobaoshan large-span cable-stayed bridge	–
Developed model	Finite element model	A simple girder bridge and two train models
Computational cost	Low	Low
Ease of installation	✓	–
Remote sensing	✓	✓
Main gap	Use of limited monitored data	Lack of critical discussions and complex models
Advantages	Suitability for continuous damage detection in beam-type structures with very little damage	Direct analyses through soft computing approaches
Recommendation	Use of an updated GA algorithm for achieving better results	1) Use of an updated GA algorithm under complicated analytical conditions 2) Verification of analytical procedure through experiments and field tests
Critical evaluation of GA-based methods	The GA algorithm is efficient and robust in managing noise and uncertainty and unlike the mathematical approaches, it utilises multiple points to come up with the solution. Moreover, GA does not need function derivatives and works with a mix of discrete, continuous, and integer variables. However, more researches need to be done to ensure that the GA algorithm is a reliable method for bridge health monitoring.	

based testing technique with an online non-destructive testing (NDT) modular sensor to examine the stay cables of a cable-stayed bridge. Each sensor consisted of multiple sensor units, and two magnets and one Hall sensor were set up on each of the sensor units to evaluate the magnetic flux density. To validate the proposed technique, an artificial cable with various cracks was built and analysed. The findings showed that the broken wire in the cable was successfully identified by the proposed technique, the sensor was easily installed on the cables with different diameters and the condition of the inner wires was properly inspected, and the modular sensor was capable of evaluating the damage through signal processing approach. One of the main gaps of the proposed technique was its inability to analyse the damage three dimensionally due to the low number of signals. A further study to optimise the modular magnetic sensor is required to improve the proposed technique (Xu, Wang, and Wu 2012).

In another attempt in cable's damage identification in cable-stayed bridges, Ho et al. (2013) introduced an image-based automatic cable surface damage identification method for cable-stayed bridges based on image processing and pattern identification methods. A visual overview of the proposed identification method is illustrated in Figure 13. Median filter, histogram equalisation, and principal component analysis (PCA) (Figure 14) were utilised to enhance the quality of the images which are captured by three cameras and transferred to a server computer. Laboratory tests were utilised to validate the proposed method. The distance between the input and sample patterns was identified by the mahala Nobis square distance. The results showed that the proposed method provided post-processing and online inspection with an easy-to-use software interface and identified the size and location of the damage zone accurately. This method was introduced to resolve the issue that most cable damage identification methods lack post-processing software and automatic online identification capability. According to the results and laboratory tests, the proposed method has the potential to identify damage in real bridge cables (Ho et al. 2013).

Possible change in bridge elements' properties signifies damage. Time-dependent materials' behaviours such as ageing, shrinkage, and creep also lead to changes in structural characteristics. It is therefore desirable to examine the impact of this behaviour on the dynamic properties and health monitoring. Si et al. (2013) studied the impacts of time-dependent materials' behaviour on incessantly dynamic characteristic variations of undamaged concrete cable-stayed bridges regardless of geographical locations. Five design codes including CEB-FIP Model Code 1993 (Comité Euro-International du Béton 1993), BS 5400 (British Standards Institution 2000), ACI 209 (ACI Committee 209, 1997), BS EN 2008 (British Standard Institution 2008), and JTG 2004 (Ministry of Communications of the People's Republic of China 2004) were used to prove the independency of the dynamic properties from the codes. To validate the proposed model, dynamic characteristics of post-tensioned concrete beams were monitored. The findings revealed that concrete ageing was the most effective factor in frequency increment with time, and it was necessary to employ the time-dependent behaviour in damage detection of concrete bridges since the damage had a propensity to reduce the frequencies in contrast with the time-dependent behaviour. In this study, a model was developed to simulate the long-term dynamic properties, and it was proved to be useful for engineers in the area of bridge health monitoring regardless of the geographical locations. Investigating the impact of time-dependent materials' behaviour on concrete structures and demonstrating

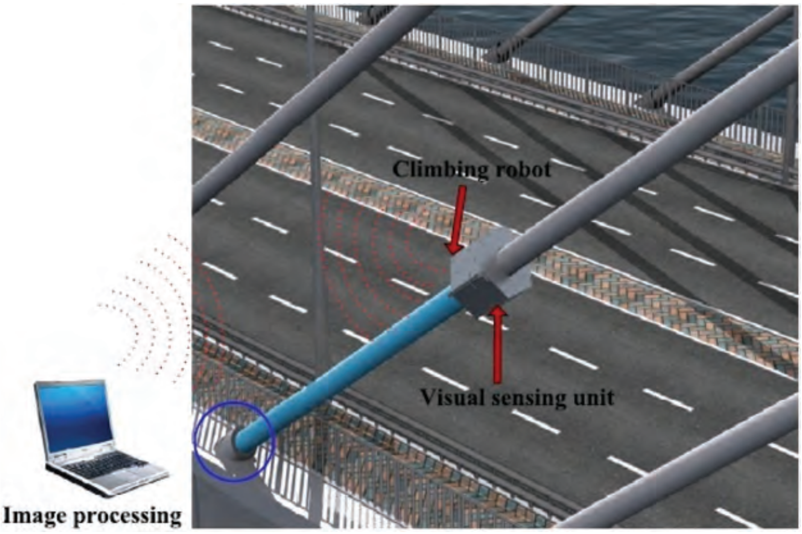

Figure 13. Image-based automatic cable surface damage detection system (Reproduced from Ho et al. (2013)).

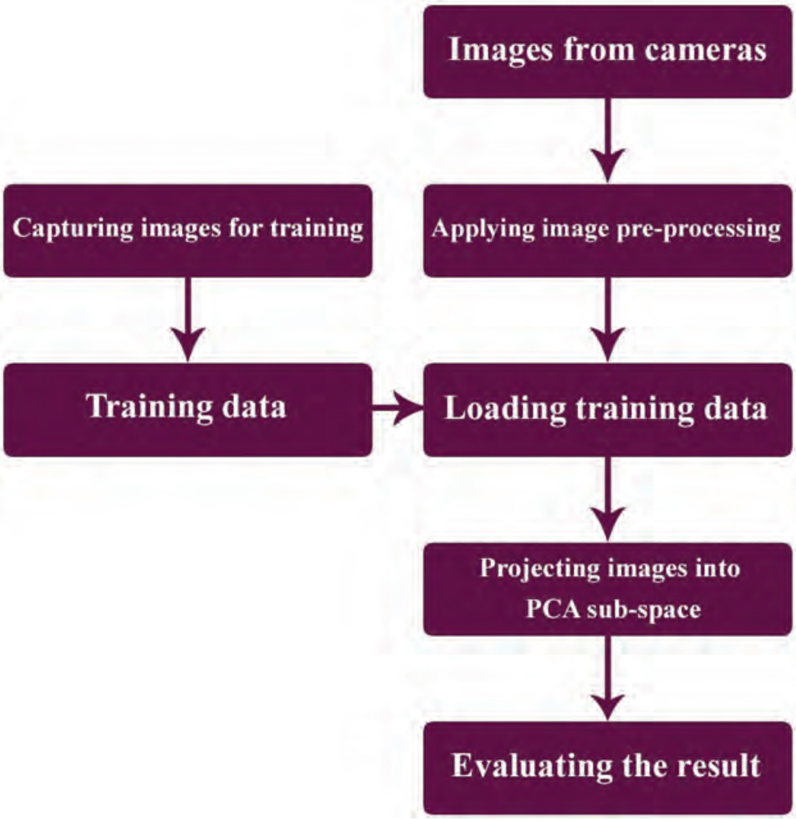

Figure 14. PCA-based damage detection algorithm (Redrawn from Ho et al. (2013)).

that the absence of this effect would underestimate the damage severity were the main advantages of this paper (Si, Au, and Li 2013).

Cast steel which is very common in bridge construction requires a proper process to avoid any fabrication defects such as pores and cavities. These defects endanger the structural integrity and, in time, the whole bridge integrity. Terán-Guillén et al. (2014) determined the structural integrity of the cast steel anchorage of a cable-stayed bridge based on Failure Assessment Diagram (FAD). This assessment required material classification and analysis of the effect of the notch which was turned out to be ineffective on fracture resistance. The analysed defects were surface defects and two specific defects which were found in certain anchorages. Two residual stress scenarios and two load theories including 30-year traffic estimation and the load of four heavy trucks were considered. The results showed that in the first theory and without residual stress, the anchorage worked under safe circumstances, but in the second theory and with or without residual stress, it worked unsafe. Consideration of residual stresses was also found to have a significant impact on the structural integrity of the anchorages, with a significant decrease in the size of critical defects. With all this, it can be inferred that taking into account remedial actions is necessary. Moreover, in order to avoid the replacement of the anchorages, it is best to limit the traffic loads until existing defects and residual stresses do not jeopardise the structural integrity of the anchorages (Terán-Guillén et al. 2014).

Lonetti and Pascuzzo (2014) proposed a numerical approach to evaluate the cable's vulnerability behaviour in hybrid cable-stayed suspension (HCS) bridges subjected to failure mechanisms and moving loads. A nonlinear finite element formulation was developed to include the impact of local vibrations and large displacements, and four damage scenarios in the main cables, stays, and hangers were conducted. To determine the vulnerability index and to emphasise the improved characteristics of the HCS bridges, comparisons between suspension, cable-stayed, and HCS bridges were made. The results revealed that HCS bridges showed lower ductility and stress failure indexes and were able to better transfer extra stresses in the bridge elements. It was also concluded that a large displacement of girder occurred in the pure cable-stayed bridge in the scenario of failure of the anchor stay, suspension bridge behaviour was affected by high values of main cable's damage, and cable-stayed and suspension bridges could not be analysed with post-tensioning institute (PTI) code (Post-Tensioning Institute (PTI) 2007). Based on the findings, it can be inferred that HCS bridges provide an improved behaviour to reduce stresses caused by failure mechanisms in comparison with the suspension and cable-stayed bridges. They also produce lower ductility and stress variables in different elements such as girder, cable, and pylon. However, further research is necessary to validate this behaviour also in the short- and medium-span bridges (Lonetti and Pascuzzo 2014).

Bridge health monitoring and maintenance strategies generally rely on visual inspections which are difficult to undertake quickly in case of emergencies. Visual inspections, especially for cable-stayed bridges, limit the safety management since these bridges have complicated behaviours, and they are subjected to environmental effects. Therefore, remote bridge health monitoring is necessary for the safety and behaviour assessment of cable-stayed bridges. Ju et al. (2015) studied remote bridge damage identification and maintenance strategies for long span cable-stayed bridges subjected to typhoons based on Unified Remote Monitoring System (URMS). The main functions of URMS are listed in Table 12. It was revealed that the structural behaviours during this type of natural disaster could be determined using this method, and the stiffening girder vertical acceleration was in a more stable position than other sensors. It was also concluded that the bridge stiffening girder tilt behaviour was the most effective factor in response to the strong wind; however, more sensors were needed for a better analysis. The advantage of this study is that it provides a reasonable and quantitative response to the maintenance of stress-sensitive cables. However, additional analysis for crucial members, considering other types of natural disasters, and further study on sensor attachments and data acquirement are needed (Ju, Park, and Kim 2015).

Modal-based damage identification approaches have been extensively studied in the literature. In these approaches, modal parameters such as natural frequencies and mode shapes are obtained and compared with the undamaged state. Any discrepancy signifies damage. Damage is generally associated with a reduction in stiffness, which imposes the abnormal reduction in the natural frequencies. A reliable damage identification approach requires an appropriate formulation for the optimisation issue and avoidance of local optima. Casciati and Elia (2017) investigated the damage location in a cable-stayed bridge using artificial bee colony (ABC) and the firefly algorithms (FA) which were utilised for the optimisation issue. The flowcharts of the mentioned algorithms are shown in Figure 15. To reduce the variation between experimental and analytical modal characteristics, a highly nonlinear objective function was taken into account. The results revealed that both of the algorithms could converge and identify damage, but the FA was more effective with respect to the computational cost and iteration for convergence. The main advantage of this approach is that, unlike the existing methods, it does not require any knowledge of the eigen properties of the undamaged structure (Casciati and Elia 2017).

Table 12. Main function of URMS (Ju, Park, and Kim 2015).

Function	Role
Monitoring	• Real-time alarming against the emergency situation • Real-time reporting of the acquired data to the technical engineer
Analysis	• Data analysis, building and updating the database • Managing and analysing the acquired data with short- and long-term monitoring data
Management	• Monitoring the data and safety of the system • Reporting the malfunction and temporary error of the system to the technical engineer
Control	• Control of the entire system using remote access module

Since cables are the main supporting elements of cable-stayed bridges, inspecting and evaluating the serviceability and the condition of stay cables and suspenders are necessary. Cable tension is one of the most important bridge health indicators, and inspecting the cable tension in the long term is necessary for a reliable bridge health monitoring. However, utilising the cable tension as the only condition indicator is not suitable since it is affected by various factors such as external load, noise, and environmental effects. Therefore, a condition indicator that only considers the cable condition and is independent of these factors is required. Li et al. (2018) proposed a pattern recognition model for the condition assessment of stay cables based on a vehicle-induced cable tension ratio which was modelled by Gaussian Mixture Model (GMM). Cable tension ratio was extracted based on the relationship between cable pairs' tension response. It was revealed that the cable tension ratio was only related to the properties of the cable and the location of a vehicle which made it possible to utilise for the condition evaluation of the cables. The number of ration patterns and GMM parameters were calculated by Bayesian Information Criteria (BIC) and Expectation-Maximisation (EM) algorithm which were also used to indicate the cables' condition. The proposed model was validated through finite element (FE) analysis. The results showed that GMM parameters were capable of being used as a stay cables' condition indicator, the tension ratio was able to assess the condition of the cables, and the pattern number was dependent on the cable position. It was also concluded that the proposed model was sensitive to the damage of wire breakage and insensitive to the damage of corrosion. The main advantage of the proposed model was that it addressed the issue related to its dependency on various factors. However, further research is required to consider more vehicle-induce d tension ratio to avoid any data pre-processing (Li et al. 2018).

Alamdari et al. (2019) proposed a novel bridge damage identification approach based on Rotation Influence Line (RIL) which relies on the bearing

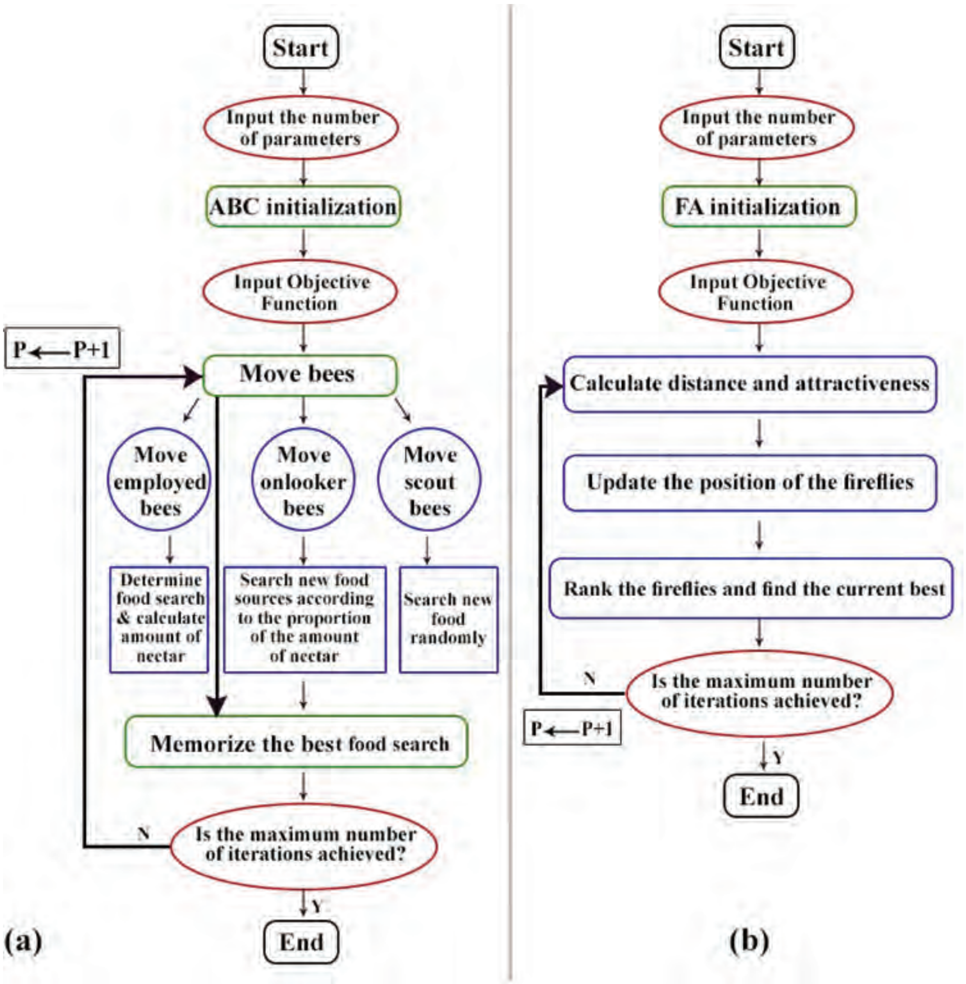

Figure 15. Flowchart of a) artificial bee colony algorithm and b) firefly algorithm (Redrawn from Casciati and Elia (2017)).

assessment at each end of the bridge. A model of a one-dimensional simply supported beam and a cable-stayed bridge is considered to validate the proposed approach. Sixteen damage scenarios of cable's loss were designed in a finite element model (FEM) which was developed through static and dynamic properties to obtain the strain influence lines (SILs) and RILs. Moreover, a novel damage index using the RIL's difference between the benchmark and unknown states was developed, and it was revealed that either of RILs was capable of identifying the damage in each of the damage scenarios. Through numerical and field test examinations, it was concluded that only two control points were sufficient for evaluating the integrity of the bridge through RIL which was independent of the damage location, and SILs may not provide any indication of cable damage in a bridge. In this paper, a robust RIL-based damage detection approach is presented for the first time, which depends on two measurement points at each end of the bridge. Conventional strain-based measurement requires a high number of sensors to accurately identify damage which is not cost-effective and has some difficulty in locating and quantifying cable damage. In contrast, the proposed approach is capable of damage detection, even far from the location of the sensor. To address the issue related to the prediction error in RIL, which is affected by uncertainties and variabilities, a stochastic characterisation is required. For this purpose, utilisation of machine learning algorithm would be of great benefit. To reduce the variability of data, a vehicle that frequently crosses the bridge may be chosen to obtain enough data for assessment and training. In addition, further research is required to study the feasibility of the proposed approach in damage localisation of both statically determinate and indeterminate bridges. Finally, it is strongly recommended applying this approach on different types of bridges (Alamdari et al. 2019).

Bridges, especially heavily trafficked bridges, need regular monitoring to maintain their serviceability and safety. The conventional approaches of bridge health monitoring require visual inspections and installation of various sensors which lead to higher labour costs. Moreover, since the sensors are permanently placed on a bridge, they are highly susceptible to breakage. As a result, it is in high demand to develop robust and cost-effective indirect bridge health monitoring approaches. Kildashti et al. (2020) presented an indirect damage identification approach to evaluate the location and intensity of cable damages using a moving vehicle's responses for the first time. Illustration of FE model of the bridge, vehicle model, and bridge–vehicle interaction model is shown in Figure 16. The Intrinsic Mode functions (IMFs) were utilised to develop a damage index to identify, localise, and estimate the damage severity. The proposed approach was validated through 15 damage scenarios and a numerical example of a cable-stayed bridge. A finite element model was developed and verified using field experiments and modal decoupling (MD) technique to model the vehicle–bridge interaction (VBI). It was revealed that under specific parameters of the vehicle, the damage along with its location and severity were accurately identified through the bridge vibration response. The results were in good agreement with previous studies and clearly showed that a better damage detection requires a vehicle with higher mass. This paper is the first attempt to extend the VBI scheme to a 3D numerical model and to evaluate the damages through vehicle's realistic parameters instead of bridge responses. Extensive numerical studies on a statically indeterminate bridge were utilised to verify this approach. Moreover, the importance of various parameters on the feasibility of the approach was studied. However, this approach has several limitations, including the speed of the vehicle should be kept as slow as possible, the proximity of the resonance condition restricts the performance of this approach, and it worked well only for road profiles with class of A and B. To address the issue related to the vehicle's response, which is affected by uncertainties and variabilities, a stochastic characterisation is required and also, designing a specialised test vehicle may alleviate the impact of road profiles. Finally, further studies are required to validate the feasibility of the proposed approach in practice and to consider more bridges with various structural designs (Kildashti et al. 2020).

Table 13 critically evaluates the above-mentioned papers regarding the cable damage identification.

Bridge health monitoring is a tool for maintaining the serviceability, safety, and integrity of bridges through long-term monitoring. This tool should ideally be deployed to identify damage at an early stage, enabling preventive measures to reduce costs. A critical step in the novelty damage detection approaches is related to the operational and environmental effects which lead to false damage signals. Removing these effects from the structural response known as data normalisation is mandatory for assessing the performance of damage identification approaches. Tomé et al. (2020) proposed a data-based method for early damage identification under operational and environmental effects using multivariate cointegration analysis and statistical process control. The proposed method was applied to a cable-stayed bridge in which the stay cables were utilised as damage-sensitive elements. Various damage scenarios were conducted including the stay cables' progressive section loss. An analysis was carried out to examine the impacts of training period size, which was the cointegrating vectors developed using data from the undamaged bridge, on the efficiency of data

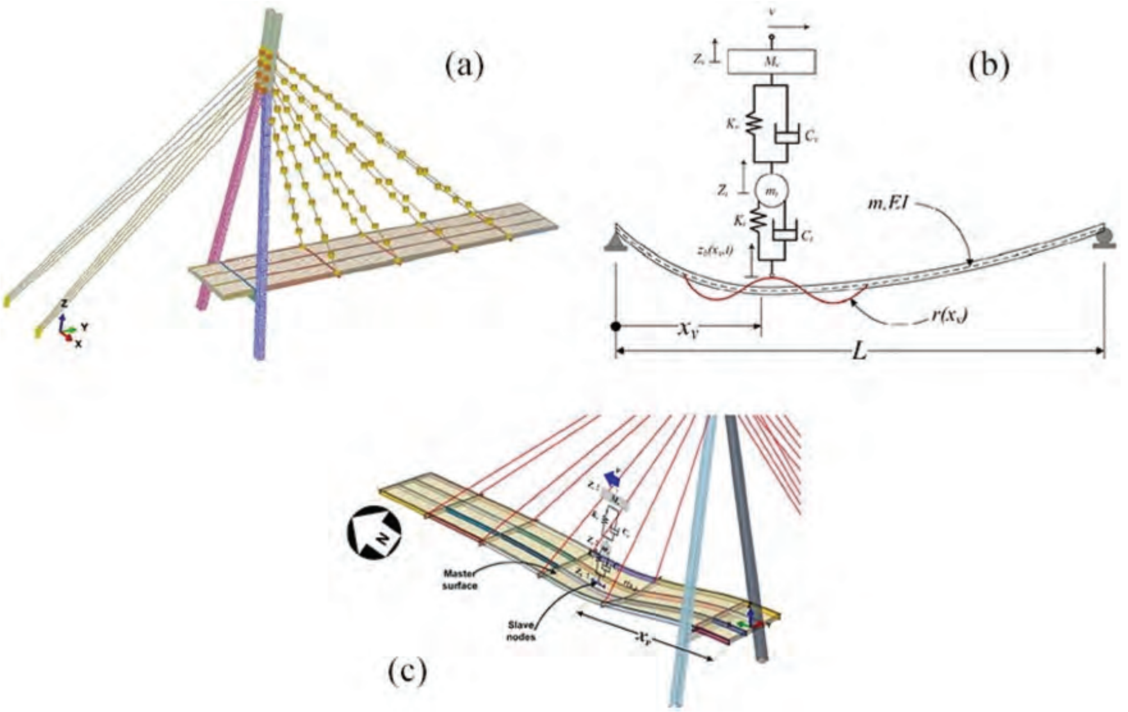

Figure 16. Illustration of a) FE model of the cable-stayed bridge, b) Six parameters vehicle model, c) Bridge–vehicle interaction model (Reproduced from Kildashti et al. (2020)).

Table 13. Critical evaluation of Refs (Ho et al. 2013; Lonetti and Pascuzzo 2014; Li et al. 2018; Kildashti et al. 2020).

Ref.	(Ho et al. 2013)	(Lonetti and Pascuzzo 2014)	(Li et al. 2018)	(Kildashti et al. 2020)
Methodology	Developing an image-based cable surface damage identification method for cable-stayed bridge	Proposing a numerical approach to evaluate the cable's vulnerability behaviour in hybrid cable-stayed suspension bridges	Proposing a pattern recognition model for the condition assessment of stay cables based on a vehicle-induced cable tension ratio	Presenting an indirect damage identification approach to evaluate the location and intensity of cable damages using a moving vehicle's responses
Tested bridge	Laboratory tests on three types of cables	_	A long-span cable-stayed bridge in China	A cable-stayed bridge in Australia
Developed model	A visual sensing unit and data processing software	Finite element model	Finite element model	Finite element model
Computational cost	Low	Low	High	Low
Ease of installation	✓	_	_	✓
Remote sensing	✓	✓	✓	✓
Main gap	A time-consuming process of preparing and training database	Limited number of damage scenarios and considering only the maximum displacements of midspan girder	1) The requirement of data pre-processing 2) Insensitivity to corrosion	1) Keeping the speed of the vehicle as slow as possible 2) Low performance in the proximity of the resonance conditions 3) Low performance for road profiles with class of C or above
Advantages	1) Allowing automatic online damage identification 2) Easy-to-use software interface 3) Allowing post-processing damage identification	1) Providing systematic studies to distinguish design and structural performance 2) Considering the impacts of static and dynamic damage 3) Evaluation of initial cable forces using an optimisation approach	1) Independency to various factors such as external load, noise, and environmental effects 2) Sensitive to the damage of wire breakage	1) Extending the vehicle-bridge-interaction scheme to a 3D numerical model 2) Cost-effectiveness 3) Requirement of limited number of sensors 4) Performing extensive numerical studies for the validation of the proposed approach
Recommendation	Application of the proposed method on real bridge cables	Verification of the proposed approach with short and medium span bridges	Considering more vehicle-induced tension ratio to avoid any data pre-processing	1) Designing a specialised test vehicle 2) Verification of the proposed approach in practice 3) Considering more bridges with various structural designs
Critical evaluation	Since cables are the main supporting elements of cable-stayed bridges, inspecting and evaluating their serviceability and condition are necessary. Indirect cable damage identification methods which have gained considerable attention in the past few years need to be upgraded in order to ensure that these methods are reliable enough for cable damage identification.			

normalisation and sensitivity to damage. It was revealed that expanding the training period size reduced the number of false positives and enhanced the discrepancy between the undamaged and damaged conditions. One of the main shortcomings of the proposed methodology was its inability to identify small damages. By examining different scenarios, it was found that instrumenting more stay cables or adopting a post-processing scheme led to the identification of small damages by the proposed method. This paper is a significant contribution to the literature by providing a method for early damage identification in a cable-stayed bridge subjected to operational and environmental effects. In addition, this paper shifts the structural health monitoring from academia to industry and utilises a bridge with 3.5 years of experimental data. However, the proposed methodology should be further validated by means of bridges

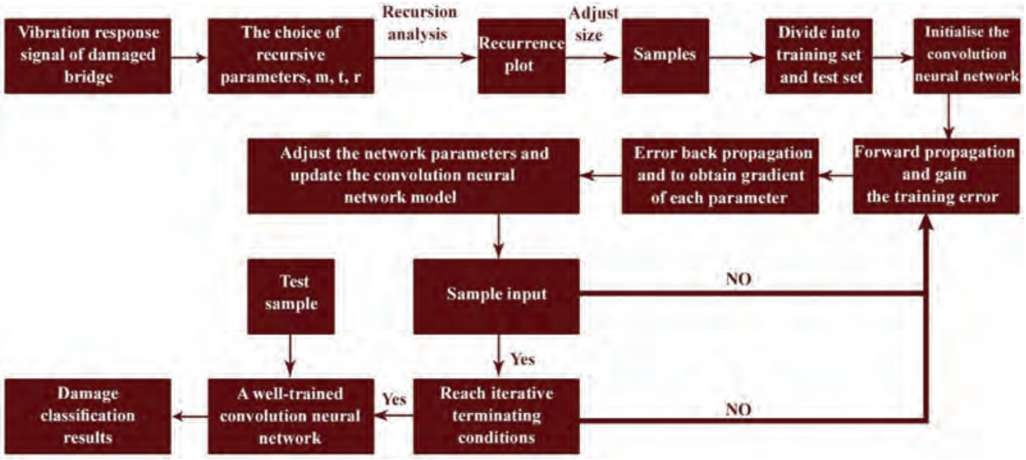

Figure 17. Flowchart of bridge damage recognition approach based on CNN and BP (Redrawn from He et al. (2021)).

Table 14. Review of other papers regarding bridge health monitoring.

Ref.	(Ko and Ni 2005)	(Li, Zhou, and Ou 2011)	(Döhler et al. 2014)	(Mei, Gül, and Boay 2019)	(Liu et al. 2020a)	(Sarmadi et al. 2021)
Methodology	Investigation of some main issues regarding large-scale bridges' damage detection: 1) Ongoing status and methods 2) Application of novel sensing, data collection, and computational methods 3) Structural and bridge health monitoring linkage	Utilisation of glass fibre reinforced polymer (GFRP) – optic fibre Bragg grating sensors (OFBGS) for stay cables' health monitoring	Presenting two stochastic subspace-based approaches to consider intrinsic uncertainties in bridge health monitoring	1) Development of a novel approach based on Mel-frequency cepstral coefficients (MFCCs) utilising drive-by data 2) Proposing a mobile sensor network based on MFCC and principal component analysis (PCA) to address the shortcomings of a single drive-by data	Development of a physical data-driven approach based on vehicle's acceleration signals and dimensionality reduction	Development of a novel machine-learning approach based on k-medoids clustering and threshold evaluation for early identification of damage under environmental changes
Tested structure(s)	Different large-scale bridges	ErBian DaDu River Bridge	S101 Bridge in Austria	Experimental setup of a simply supported bridge	A lab-scale bridge model	Z24 bridge
Type of load	_	Point load (loading and unloading process)	_	Traffic loads	Traffic loads	_
Type of modelling	_	Manufacturing of GFRP-OFBG sensor	Physical testing	Finite element model of a single span beam-type bridge	Finite element model	Mathematical formulations
Computational cost	Low	Low	Low	Low	Low	Low
Ease of installation	_	✓	✓	✓	✓	_
Remote sensing	_	✓	×	✓	✓	✓
Presented results	1) Demonstrating the importance of signal processing and sensing systems for bridge monitoring 2) Demonstrating the importance of data achieved from bridge health monitoring regarding bridge integrity, reliability, and maintenance. 3) Demonstrating the importance of linkage, which makes it possible to obtain direct data for bridge monitoring and maintenance	1) Higher strain sensitivity and temperature sensing coefficients of the developed sensor in comparison with the bare OFBGS 2) Higher limit strain of the developed sensor in comparison with the bare OFBGS	1) Evaluation results of the structural damage, system response, and behaviour of the damage 2) Evaluation results of the change in the modal parameters 3) Uncertainty assessment results in each modal parameter 4) Results of damage detection in column and tendon	1) Identification of damage based on boundary conditions and stiffness changes 2) Damage severity assessment 3) Investigation of mobile sensor network's potential for bridge health monitoring	1) Identification of damage severity through the low frequency and high frequency responses instead of fundamental frequencies 2) Discussing the importance of utilising the vehicle's full bandwidth frequency response 3) Providing evidence for the feasibility of indirect bridge monitoring	1) Demonstrating the robustness of the proposed approach in damage identification under significant environmental changes 2) Demonstrating the ability of the k-medoids clustering in enhancing the damage detectability and dealing with the negative impacts of environmental changes 3) Demonstrating the superiority of the proposed approach over conventional approaches

(*Continued*)

Table 14. (Continued).

Ref.	(Ko and Ni 2005)	(Li, Zhou, and Ou 2011)	(Döhler et al. 2014)	(Mei, Gül, and Boay 2019)	(Liu et al. 2020a)	(Sarmadi et al. 2021)
Advantages/ Disadvantages	Providing an approach for failure probability – Reviewing and evaluating different methods/Not covering all the issues and methods	Long lifespan – Easy installation – High resistance – Suggesting the layout process of the GFRP–OFBG smart bars in the cable/Inability to monitor the whole steel strand damage procedure	Robustness – Being an automated bridge monitoring method – Suitability for vibration analysis/ Disregarding of environmental and temperature changes	Done for the first time – Being an indirect bridge health monitoring method – Utilising data from multitude vehicles – Noise robustness – Scanning a range of frequencies/No attempts of damage localisation	Investigation of theoretical formulation of the vehicle-bridge interaction (VBI) system – Description of vehicle's full range of frequency responses/ Disregarding of environmental factors and different vehicle's speeds	Development of a novel damage indicator for decision making – Development of a novel approach for dealing with environmental changes – Improvement of damage detectability/ Sensitivity to the number of samples
Recommendation	Using this paper as a guideline when inspecting large-scale bridges – Conducting further research to cover a broader range of methods	Conducting further research to upgrade the developed sensor for the whole steel strand damage assessment	Conducting further research to evaluate the feasibility of the proposed approaches under temperature and environmental changes	Conducting further research to utilise deep learning methods and to investigate the location of damage	Conducting further research to study the impact of different environmental factors and vehicle speed on the proposed approach	Conducting further research to calculate the number of training samples

where damage has already been identified (Sousa Tomé, Pimentel, and Figueiras 2020).

Traditional modal-based bridge health monitoring approaches typically identify damage, according to the variation of modal parameters such as natural frequencies and mode shapes. However, in real-world conditions, modal parameters are highly influenced by environmental effects; as a result, these approaches have limited ability to detect local and minor damages. Statistical pattern recognition methods such as artificial intelligence (AI) can better represent uncertainties and effectively transform them into mathematical expressions. However, traditional AI-based methods have several limitations, such as requirement for too much training data. Therefore, it is necessary to improve the accuracy and performance of available methods. He et al. (2021) proposed a novel damage detection approach for bridges based on recurrence graph and convolutional neural network (CNN) in order to improve the accuracy and performance of available approaches. The similarity, internal structure, and damage data were easily categorised by the recurrence graph which was sensitive to the structural response's signal changes, so it can be utilised to characterise the features of small damages. CNN was able to extract several types of features from images and had a great recognition for the damage degree and location. The proposed approach was validated through a finite element model of a continuous girder bridge which was subjected to a moving mass. First, the damaged bridge's signals were filtered by wavelet packet and then, the recurrence analysis was performed. Through the use of CNN, the damage detection was established. The process of damage recognition based on CNN and back propagation (BP) is shown in Figure 17. The results demonstrated the efficiency and accuracy of CNN in locating and quantifying minor damages. In addition, the vibration response signal was obtained to model the environmental vibration of the bridge during hammering test. The results showed that the proposed approach was able to identify the location and degree of damage with 100% and 94.1% accuracy, respectively. The findings verified the feasibility of the proposed approach in actual damage detection, which can serve as a reference for damage identification of other actual bridges. Finally, more studies are required to build a better structure of neural network, present more discriminative damage feature vectors, and perform practical experiments (He et al. 2021).

Table 14 summarises other papers regarding bridge health monitoring.

4. Conclusion

This study has presented a review of literature of the existing damage identification approaches in bridge structures. The advantages and gaps of the papers along with future applications and sustainable methods are provided in this paper. Based on the literature review, the following conclusions are drawn:

- Researchers have used different approaches, especially vibration-based methods to investigate damage in different types of bridges.
- In many cases, single damage types have been carried out.
- There are a few methods for the multiple damage detection in bridges; they have a lot of limitations and need to be upgraded.
- Indirect bridge health monitoring has attracted a lot of attention recently; however, it has the disadvantage that it is influenced by the dynamic characteristics of the bridge and the vehicle's motion.
- Temperature has a negative impact on the static and dynamic analyses of bridges, and some of the existing methods did not yield valid results under temperature impacts.
- An early-stage damage detection in bridge is extremely difficult with most of the applied approaches due to the stiffness recovery and the impacts of environmental parameters.
- Despite the fact that wireless sensing is increasingly utilised in bridge health monitoring, there are still challenges which hinder it from being used exclusively rather than conventionally.
- Since bridges have little in common and each bridge is distinctive, it is very challenging to design a uniform and robust SHM method valid for any bridge.
  - The developed VBI method in Ref Kildashti et al. (2020)needs to be improved for a better damage detection in different road profiles and various vehicle speeds.
  - More recently, machine-learning-based damage detection has achieved a lot of attention which requires further investigation.

Finally, it can be concluded that there is still a long way to go in the field of bridge damage detection, and this requires the construction of a comprehensive information model for bridges.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Saman Karimi is a Ph.D. student at Western Sydney University. During his master's degree, he was ranked first among all the graduate master's students and worked on damage identification in functionally graded beams and circular plates. He wrote several papers in the area of Structural Engineering including analytical identification of damaged areas in porous circular plates resting on elastic foundation based on modal shapes derivatives, and effects of elastically restrained edge on natural frequencies of functionally graded beams. Most recently, he introduced a new model of springs to model the damaged elements of the functionally graded beams for the first time. He is currently working on fatigue damage detection in bridge steel deck under moving vehicles and providing a strengthening approach to increase the bridge life cycle.

Olivia Mirza is an Associate Professor at Western Sydney University. She has several awards, recognitions, and professional memberships; some of which are Top 15 Women Engineers that make changes to engineering community, Nominations for Prime Ministers for Science Award in Australia, etc. She has great experiences in bridge structures, bridge failures, and bridge rehabilitation. Her research is mostly concentrated on the behaviour and design of shear connectors on composite steel and concrete structures and rehabilitation on existing bridge structures. The issues emphasised in her research are mostly looking at the structural health monitoring, rehabilitation and retrofitting, and structural behaviour. As a forensic bridge engineer, she works closely with Transport for New South Wales (locally), Mobility and Transport European Commission, Malaysian Road and Transport Department, and US Department of Transport (Internationally). Her duties can be divided into two parts. They consist of investigation and engineering. She is responsible to collect data by observing the wreckage and collecting evidence of the damaged materials to determine the reasons for structural failure. In order to advance her research and contribute to engineering community, Olivia also works closely with industry partners (AJAX Fastener, One Steel, Bluescope and VSL prestressed) and government department.

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