A REVIEW ON FATIGUE MONITORING OF STRUCTURES

ABSTRACT

Significant research has been conducted in the field of structural health monitoring (SHM). The literature on fatigue calculation, fatigue testing, fatigue modelling and remaining fatigue life is also extensive. However, the number of publications related to the fatigue monitoring process is scarce. Thus, a review was undertaken on this topic. Firstly, this paper reviews existing SHM techniques, addresses their principal classifications and presents the main characteristics of each technique, with a particular emphasis on modal-based methodologies. Secondly, a methodology to perform real-time structural fatigue monitoring is proposed, which can be simultaneously combined with other vibration-based SHM techniques to produce a significant increase in the reliability of monitoring techniques. Furthermore, given that fatigue monitoring requires the calculation of stresses at critical points of the structure, a review of stress measurement and estimation techniques is also presented. Finally, the most common techniques used in fatigue assessment for both the time and frequency domains are described.

Keywords: *SHM, fatigue monitoring, damage, structural analysis, failure analysis*

1 INTRODUCTION

Engineering structures are subject to dynamic loadings which can be random (e.g. wind, waves, etc.) or artificial in nature (Jeary, 1998; Kappos, 2001; Simiu and Yeo, 2019). These dynamic loadings generate internal forces, stresses and strains with variable amplitudes, which can lead to fatigue failure (Bolotin, 1999; Schijve, 2008; Suresh, 1998). Fatigue is a progressive process in which each stress cycle causes an incremental increase in damage.

Fatigue design refers to the calculation of fatigue damage accumulated during the lifetime of structures. Well-established practices in fatigue assessment include the determination of stress time histories, the calculation of the fatigue stress spectrum (cycle counting) and the evaluation of total fatigue damage (Bolotin, 1999; Schijve, 2008; Suresh, 1998). In addition to stress-based methods, approaches based on strain, energy and fracture mechanics (Bjørheim et al., 2022) can be used for fatigue assessment. In stationary random processes (Newland, 2005; Wirsching et al., 1995), fatigue analysis can also be addressed in the frequency domain, in which the fatigue stress spectrum is obtained from the spectral moments of stress power spectral densities (PSDs; Benasciutti, 2012; Bishop, 1999; Bishop and Sherratt, 1990; Dalpiaz et al., 2004; Guennec et al., 2014; Slavič et al., 2020; Zigo et al., 2019).

The stresses needed to perform fatigue assessment can be predicted using finite element dynamic analysis in the time or frequency domains. Dynamic behaviour is defined by mass, damping and stiffness matrices (Beards, 1996; Chopra, 2019; Clough and Penzien, 1993) and simplified fatigue loading models from codes and standards (API, 2000; British Standards Institution, 2005; ISO 13819-2:1995, 1995; NORSOK Standar, 2004) are usually considered in fatigue analysis.

However, actual fatigue performance may differ from design calculations. On the one hand, fatigue loading models do not describe actual loads but are selected to represent similar effects as those created by real loadings. On the other hand, discrepancies in mass and stiffness between the numerical model and the real structure are unavoidable due to the difficulty of modelling supports, joints, interaction with fluids, etc. Moreover, all mechanisms related to the damping of structures are difficult to accurately model.

More accurate fatigue life predictions can be achieved if several parameters in the finite element model are updated with experimental data obtained through modal testing (Friswell and Mottershead, 1995; Marwala et al., 2016) to attain good agreement in terms of eigenvalues and eigenvectors. Fatigue life calculations can also be improved if strain time histories are measured with strain sensors or estimated from structural responses obtained using other sensors, such as accelerometers. If experimental responses are used to estimate fatigue in real time, fatigue damage can be monitored.

Two fatigue analysis approaches are usually considered in codes and standards to predict fatigue performance: safe life design and damage tolerance analysis. Safe life is based on preventing damage initiation, and a regular in-service inspection is not needed (British Standards Institution, 2005; Śledziewski, 2017). Meanwhile, damage tolerance analysis is based on good structural fatigue performance in the presence of a defect or damage, and detailed inspection and maintenance planning is required to detect and correct fatigue damage throughout the structure's design service life (British Standards Institution, 2005; Śledziewski, 2017).

Structural health monitoring (SHM) methods are a set of techniques that can be used to detect, locate and assess the extent of damage in engineering structures. They provide an alternative approach to local non-destructive inspection techniques. In SHM, damage is defined as changes to the material and/or geometric properties of a structural system, including changes to boundary conditions and system connectivity (Boller et al., 2009; Chen and Ni, 2018; Crane, 2017; Farrar and Worden, 2012).

According to Rytter and Kirkegaard (Rytter and Kirkegaard, 1994), four levels of monitoring can be defined: detection, location, assessment and prediction. This paper focuses on detection and localisation SHM techniques.

Experimental responses can be used to simultaneously estimate fatigue and detect and localise damage in a structure. Thus, fatigue monitoring can be combined with other SHM techniques to significantly increase the reliability of monitoring techniques used in structures.

Nevertheless, previous reviews of SHM or fatigue failure calculation techniques have typically presented these topics separately, which indicates the necessity of a study that provides a complete overview of the main contributions of both approaches. Thus, the current paper provides a comprehensive overview of existing SHM techniques (Section 2), with a particular emphasis on modal-based methodologies (Section 3), and the most common techniques used in fatigue assessment (Section 4).

Furthermore, conclusions from the review process and the main challenges identified in relation to SHM and fatigue assessment techniques are presented, with the expectation that the combination of both approaches in the future would improve the safety and effectiveness of real-time fatigue monitoring for entire structures.

2 STRUCTURAL HEALTH MONITORING

Structural health monitoring generally refers to any type of damage detection procedure for civil, aerospace or mechanical engineering structures (Dervilis, 2013). Damage can be defined as changes introduced to a system, either intentionally or unintentionally, that affect its current or future performance (Farrar and Worden, 2012). For this reason, SHM is considered an alternative to current local inspection methods, which are more expensive for large structures.

Several review papers on SHM have been published (Amafabia *et al.*, 2017; Bagavathiappan *et al.*, 2013; Barke and Chiu, 2005; Carden and Fanning, 2004; Chang *et al.*, 2003; Ciang *et al.*, 2008; Doebling *et al.*, 1996; Fan and Qiao, 2011; Goyal and Pabla, 2016; Gunes and Gunes, 2013; Li *et al.*, 2014; Lynch, 2006; Mitra and Gopalakrishnan, 2016; Montalvão *et al.*, 2006; Sohn *et al.*, 2003; Ye *et al.*, 2016), which indicates that a rich body of literature exists on this topic. The first general review of SHM was published in 2004 (Sohn *et al.*, 2003). Later, Gunes and Gunes (Gunes and Gunes, 2013) addressed the main damage assessment methodologies and challenges and gaps in SHM. These challenges include the optimisation of sensor number and location, the identification of features that are sensitive to low levels of damage, the ability to identify changes in these features and the development of statistical methods. Li et al. (Li et al., 2014) reviewed SHM innovations and applications for infrastructures and proposed some theories and methods for SHM, such as sensing technology, sensor placement, signal processing and data fusion, system identification and damage detection. Review papers on specific applications of SHM have also been published. For example, Barke and Chiu (2005), Montalvão et al. (2006), Ciang et al. (2008) and Chang et al. (2003) addressed SHM applications in relation to the railway industry, composite materials, wind turbines and civil infrastructure, respectively. In addition, Bagavathiappan et al. (Bagavathiappan et al., 2013) discussed advances in infrared thermography, Mitra and Gopalakrishnan (Mitra and Gopalakrishnan, 2016) reviewed wave-based SHM and Lynch (Lynch, 2006) focused on sensors for SHM. Reviews on vibration-based SHM have been also undertaken (Carden and Fanning, 2004; Fan and Qiao, 2011).

With regard to SHM techniques, this paper mainly focuses on previous developments in modal-based methods (Section 3) due to their popularity, applicability and robustness in SHM. Nevertheless, before examining modal-based methods, it is useful to review the possible classifications of SHM techniques and explain how information is organised in the paper.

Firstly, SHM techniques can be divided into continuous or intermittent techniques based on the frequency of their application (Cawley, 2018). Intermittent techniques measure responses for specific periods of time; no information is gathered on structural responses the rest of the time. The advantage of this methodology is that the instrumentation can be utilised to monitor other structures. Moreover, experimental responses can be later processed at the office and compared with the undamaged state. By contrast, continuous monitoring requires a more complicated infrastructure since experimental responses must be transmitted in real time to the site where the measurements are processed (also in real time) (Cawley, 2018).

Secondly, SHM methods can also be classified into local and global methods based on the scope of the variables. Local methods use high-frequency ultrasonic waves whose wavelengths should be smaller than the size (Fritzen, 2005). By contrast, global methods typically use the lower modes of the structure.

Finally, SHM methods can be divided into static methods, which are used to measure changes in static responses, and dynamic-based methods, which make use of a structure's vibration properties. This was the classification selected to organise the literature review conducted for this paper (see Fig. 1). In the following subsections, each category of SHM methods is briefly introduced.

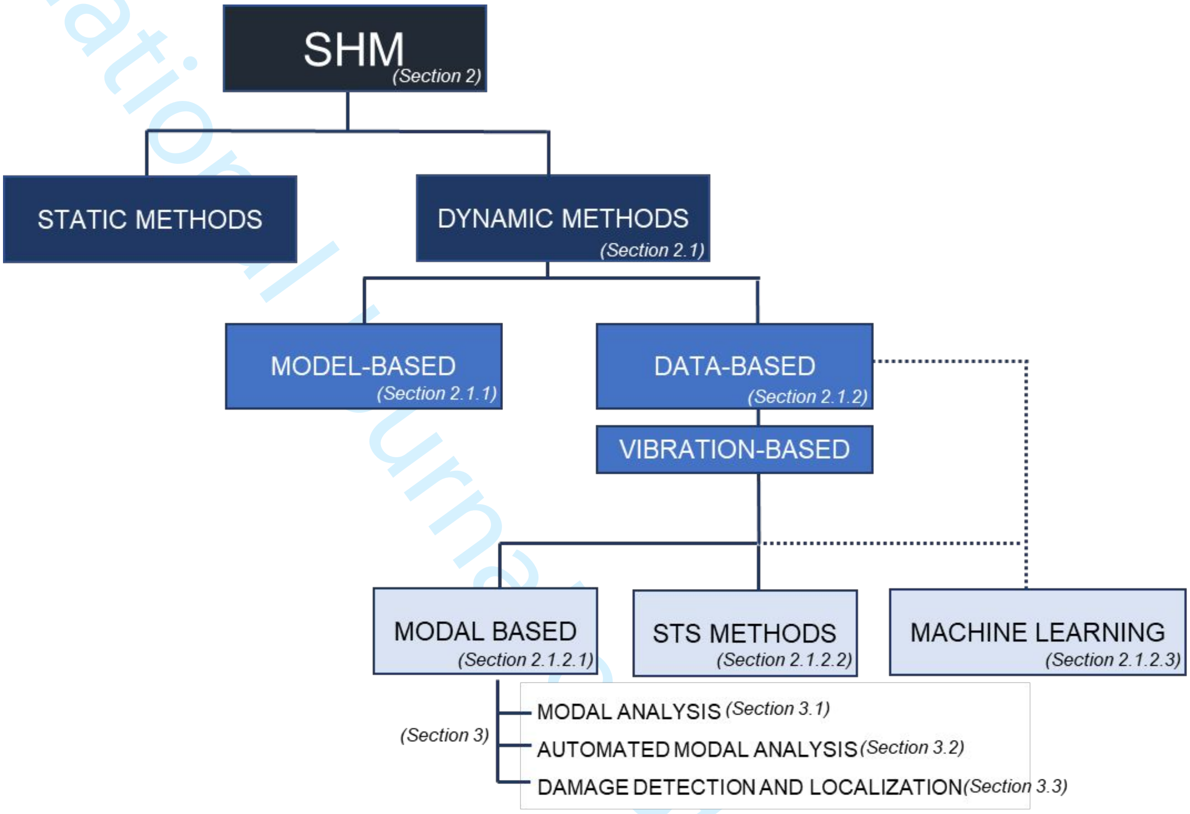

Figure 1. Classification of structural health monitoring (SHM) methods.

2.1 STATIC SHM METHODS

As previously established, static SHM methods are based on the evaluation of changes in static response (i.e. slowly varying parameters over a long period). Although static methods can be used for a wide range of applications, it has been proven that they are a powerful tool in masonry heritage structures. Examples of the most common tests reviewed by Pallarés et al. (Pallarés et al., 2021) include infrared thermography, X-ray imaging, tomography, ultrasound/sonic test, sonic tomography, georadar, acoustic emission, thermography, flat jack tests, endoscopy/videoboroscopy inspection, impact echo testing, coring, hardness tests, penetration tests and ground-penetrating radar. Applications in real structures have also been published, for example, Saisi et al. (Saisi et al., 2016) used static SHM to assess the structural condition of a historic belltower.

Static and dynamic methods have been reviewed by Kralovec and Schagerl (Kralovec and Schagerl, 2020), and the theoretical capabilities of combining such dynamic methods with static methods were also discussed in that paper. Additionally, data processing and analysis is an important subject in static methods, for this reason, Baraccani et al.

(Baraccani et al., 2017) worked on the interpretation of data from static and dynamic SHM.

As previously indicated, static methods lie beyond the scope of this review and are therefore not discussed in detail.

2.2 DYNAMIC SHM METHODS

Dynamic methods use vibration responses to gather information about changes in a structure's dynamic properties, which enables its health to be monitored. Dynamic SHM methods can be classified as model-based SHM or data-based SHM

Model-based techniques enable the construction of a well-correlated model of the structure, which is used to predict the dynamic response of the structure and allows damage to be detected and located. Meanwhile, data-based techniques are used to assess the health of a structure based on the evolution of real data obtained through experimental measurements over time.

In the following subsection, more detailed descriptions of both subdivisions (model-based and data based) and previous research contributions are presented.

2.2.1 *Model-based SHM*

Model-based SHM consists of constructing a finite element model, which is later used to identify and localize damage in either mass or stiffness (Avendaño-Valencia and Fassois, 2017; Gardner, 2018; Lee and Cho, 2016; Moore et al., 2012; Park and Reich, Gregory W., 1999). However, the accuracy provided by the finite element model depends on the level of correlation with the real structure. Thus, the numerical model must be firstly correlated with test data obtained from the real structure. Then, different techniques, known as model updating, must be applied in order improve the accuracy of the numerical model, which consists of adjusting some parameters of the numerical model in order to minimize the discrepancies (in terms of eigenvalues and eigenvectors) between the numerical model and the real structure, by using test data (see Fig. 2).

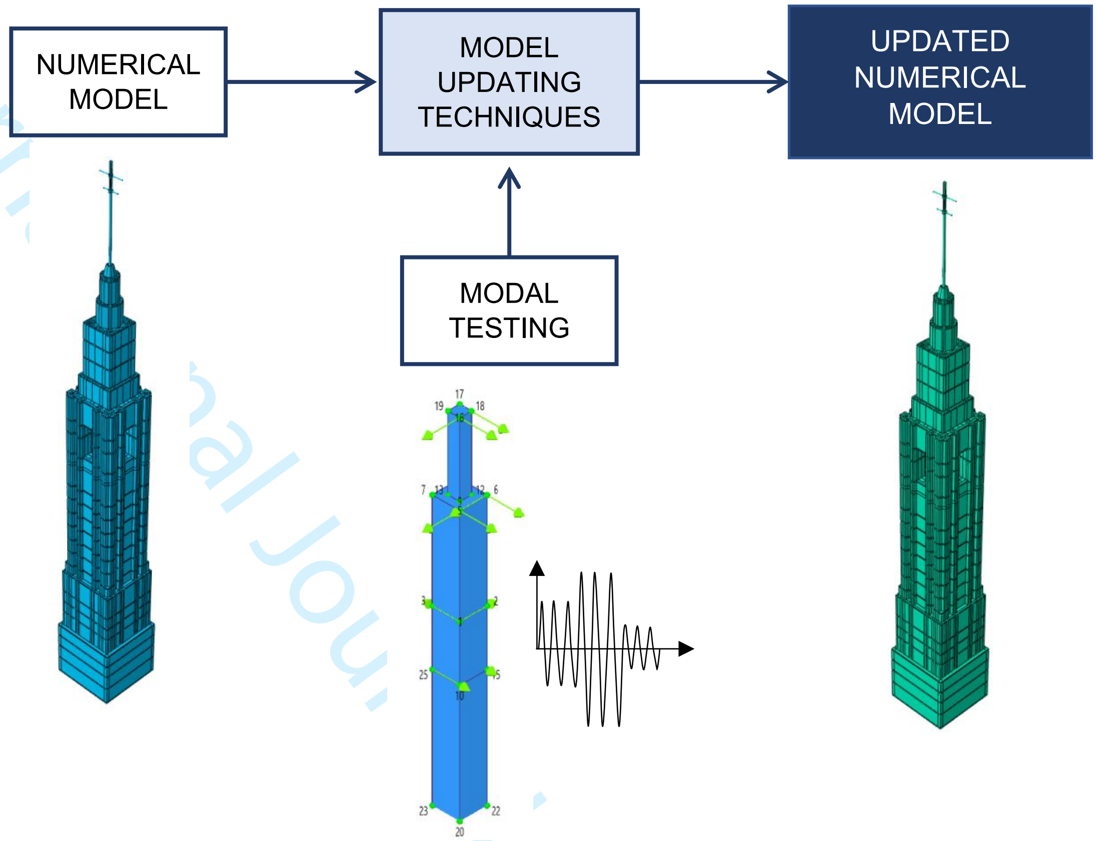

Figure 2. Modal updating process.

Many practical applications of model-based techniques have been published. For example, Stull et at. (Stull et al., 2011) described their use in naval applications, particularly on ship hulls. In addition, Tewolde et al. (Tewolde et al., 2017) applied model-based SHM in relation to wind turbines.

Moreover, there is a vast body of literature on model-based SHM applications in damage detection and localisation (Abdel Wahab and De Roeck, 1999; Ahmadian et al., 1996; Hajela and Soeiro, 1990; Natke and Cempel, 1991; Wahab et al., 1999; Zimmerman and Kaouk, 1994), based on updating certain parameters of the numerical model using experimental modal parameters. Wahab et al. and Zimmerman and Kaouk (Wahab et al., 1999; Zimmerman and Kaouk, 1994) proposed an algorithm based on a minimum rank update theory to provide insights on the location and extent of structural damage. Moreover, Hajela and Soeiro (Hajela and Soeiro, 1990) updated numerical models using static and modal analysis techniques. Finally, Ahmadian et al. (Ahmadian et al., 1996) presented two damage location indicators based on the observation that a change in a particular substructure results in a change in its modes.

2.2.2 *Data-based SHM*

Data-based SHM techniques use real data about a structure obtained through experimental measurements. Data-based SHM involves the observation of a system over time using experimental responses measured through an array of sensors and the extraction and analysis of damage-sensitive parameters (e.g. experimental modal parameters). The structure's undamaged state, which corresponds to a healthy structure, is used as a pattern. Then, data obtained from posterior measurements are compared with the healthy state.

Data-based techniques which rely on the measurement of vibration signals are known as vibration-based methods, and a vast body of literature exists on the topic (Brownjohn et al., 2011; Carden and Fanning, 2004; Deraemaeker et al., 2008; Fan and Qiao, 2011; Fritzen, 2005; Goyal and Pabla, 2016; Khodabandehlou et al., 2019; Magalhães et al., 2012; Ubertini et al., 2016). Goyal and Pabla (2016) reviewed several vibration monitoring and signal processing methods used in SHM. Moreover, Fritzen (2014, 2005) discussed the use of modal information and the direct use of forced and ambient vibrations; they proposed different SHM strategies, depending on the type of measurement data. Brownjohn et al. (2011) reviewed the vibration-based monitoring of civil infrastructure (covering a range of applications, mainly bridges) and highlighted both challenges and successes. Convolution neural networks (Khodabandehlou et al., 2019) and the effect of changing environmental conditions (Deraemaeker et al., 2008) had also been studied. Vibration-based SHM applications have also been reported in the scientific literature in relation to bridges (Brownjohn et al., 2011; Dederichs et al., 2023), arch bridges (Magalhães et al., 2012), historic belltowers (Ubertini et al., 2016) and other structures. The use of actuators, sensing devices and smart sensors in the structure (with on-board computational and communication capabilities) leads to modern concepts of smart structural health monitoring (Fritzen, 2005, 2014). Moreover, in vibration-based SHM, the structural vibration response can be used to detect changes that may indicate damage or degradation (Fritzen, 2014).

In vibration-based methods, temperature, wind velocity, wind direction, wave height, wave direction, humidity and operational conditions (loading conditions, mass loading and speed loading) are known to influence the modal parameters of structures that are subject to these environmental conditions (Chang et al., 2003; Christensen, 2020). The undesired effects of environmental or operational variations must be removed through data normalisation procedures to separate signal changes caused by operational and environmental variations in the system from structural changes of interest, such as structural deterioration or degradation (Kullaa, 2010; Sohn, 2007).

Vibration-based SHM methods can be classified into two main types: modal-based methods and statistical time series (STS) methods (see Fig. 1).

2.2.2.1 Modal-based methods

Modal-based methods use one or a set of the following modal parameters: natural frequencies, mode shapes, strain mode shapes and other variables that are dependent on modal parameters (frequency response functions, change in flexibility, etc.).

Modal analysis is a technique used to obtain the modal parameters through experiments (Avitable, 2017; Brincker and Ventura, 2015; Ewins, 2000a; Fu and He, 2001; Heylen *et al.*, 2007; Mendes Maia and Montalvão Silva, 1997). Experimental modal analysis (EMA) (Ewins, 2000a; Heylen et al., 2007; Mendes Maia and Montalvão Silva, 1997) is based on input-output system identification and has been used for decades. Modal parameters are estimated from frequency response functions or impulse response functions. Operational modal analysis (OMA) (Au, 2017; Brincker and Ventura, 2015b; Rainieri and Fabbrocino, 2014) is an output-only technique (i.e. only structural responses are used in the estimation process). OMA is attractive in many situations because it does not require excitation to be measured, which is very practical for large structures.

In modal-based SHM, automated modal analysis and automated damage detection techniques must be used because the estimation of modal parameters and the detection of damage must be performed in real time (Andersen et al., 2007; Bajrić et al., 2018; Brincker et al., 2007; Cabboi et al., 2017; Chhipwadia et al., 2000; Rainieri et al., 2007; Rainieri and Fabbrocino, 2010, 2015; Reynders et al., 2012; Sun et al., 2017; Ubertini et al., 2013; Wu et al., 2020). Once the damage is detected, techniques to localise and quantify it can be applied.

2.2.2.2 ***Statistical time series methods***

STS methods for vibration-based SHM combine random excitation and/or response signals (time series) and statistical and decision-making tools to infer the state of a structure (Fassois and Kopsaftopoulos, 2013). Non-parametric STS methods are based on non-parametric time series representations, such as PSDs, frequency response functions and residual variances. Parametric STS methods are based on time series representations, such as autoregressive moving average models (Fassois and Kopsaftopoulos, 2013).

2.2.2.3 ***Machine learning for SHM***

Machine learning (ML) for SHM consists of data-driven approaches (usually vibration-based) which have become popular in recent years due to technological advancements in sensors, high-speed internet and cloud computing. ML is a subcategory of artificial intelligence and refers to a set of algorithms that are capable of learning from available response data by automatically extracting hidden patterns in a large group of data to make predictions (Tibaduiza et al., 2018). ML techniques mainly consist of two steps: feature extraction and training (Azimi et al., 2020; Ye et al., 2019). In several methods, the feature extraction process is based on identifying certain modal parameters from the structural system. Then, the trained ML system is utilised to identify the presence and location of structural damage by performing classification (Avci et al., 2021). Deep learning is a machine learning method commonly used in image recognition (Dong and Catbas, 2021).

3 MODAL-BASED SHM

Among the SHM techniques presented in the previous section, modal-based SHM is perhaps one of the most popular for the monitoring of civil structures due to recent developments in the field of OMA and the availability of several robust and automated OMA algorithms (Rainieri et al., 2019).

Modal-based SHM methods use modal parameters (natural frequencies, mode shapes and damping ratios) estimated from the experimental responses. In other words, a modal analysis technique must be used to extract modal parameters from the experimental responses. Changes observed in modal parameters with respect to a predefined reference condition are used as indicators of the formation, location and severity of structural damage.

3.1 MODAL ANALYSIS

Modal analysis is used to characterise a structure's dynamic behaviour. Modal analysis separates a structure's response into vibration modes which are defined by the following modal parameters: natural frequencies, mode shapes, damping ratios and modal masses. On the one hand, modal analysis is termed theoretical modal analysis when modal parameters are determined using an analytical model or a numerical model. On the other hand, when modal parameters are determined using an experimental approach, modal analysis is known as experimental modal analysis (EMA) or OMA, depending on the type of excitation used in the experiments. Modal testing encompasses the experimental techniques (vibration testing) used to measure experimental responses (utilised in EMA and OMA) and excitation forces (utilised in EMA). The basic assumptions of modal analysis are linearity, time invariance and observability (see Fig. 3).

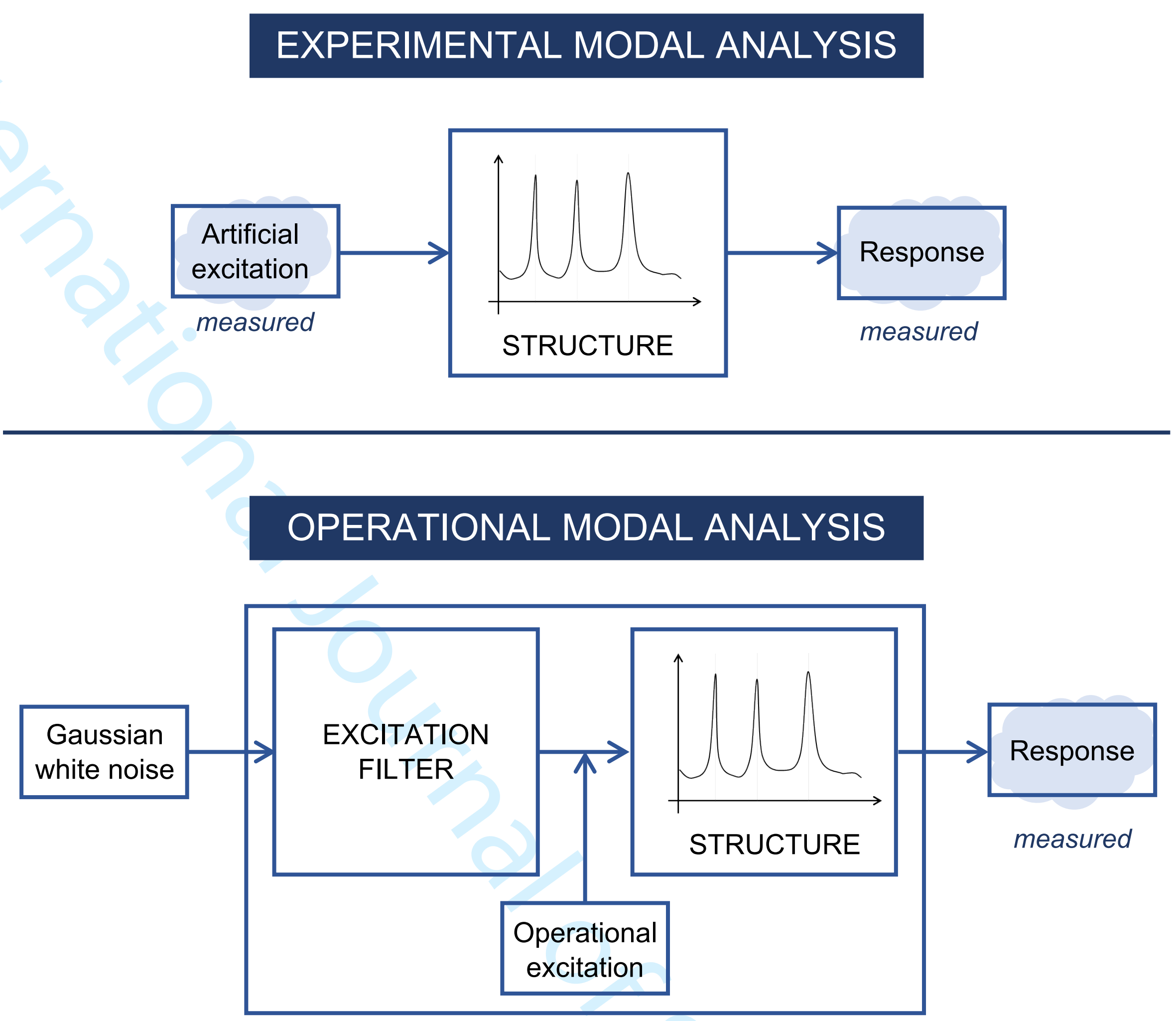

Figure 3. Modal testing techniques: EMA and OMA.

In EMA, both excitation forces and responses must be known to determine modal parameters (Ewins, 2000a; Fu and He, 2001; Heylen et al., 2007; Mendes Maia and Montalvão Silva, 1997). The loading used to excite the structure is commonly artificial, and no other excitation loading is allowed when using this technique.

OMA is used to determine modal parameters without knowledge of input excitation. In short, the forces which are naturally present during the operation of the structure are used as excitation and not measured (Au, 2017; Brincker and Ventura, 2015; Rainieri and Fabbrocino, 2014). A stochastic framework is used in OMA, assuming that the excitation is Gaussian white noise.

When both artificial and operational forces are acting on a structure, OMA and EMA can be combined in the identification process (i.e. both measured and unmeasured forces are considered.) This technique is called operational modal analysis with exogenous input (OMAX; Guillaume et al., 2006) or operational modal analysis with harmonic (OMAH) excitation (Brandt et al., 2019).

Although EMA can be used for SHM, OMA is the most commonly used technique for periodic or continuous monitoring in structures.

3.2 AUTOMATED MODAL ANALYSIS

When using SHM techniques based on modal parameters, periodic or continuous estimation of the latter is needed, which involves a significant amount of user interaction (Neu et al., 2017; Reynders et al., 2012). In SHM, the modal parameter estimation of a single dataset is of little importance because the evolution of modal parameters with time (modal tracking) is the variable of interest. Thus, considerable data must be processed in a short amount of time; thus, methodologies to automatically estimate modal parameters have gained attention in recent years (Andersen et al., 2007; Christensen et al., 2021; Rainieri and Fabbrocino, 2010, 2015; Reynders et al., 2012; Sun et al., 2017). Automated techniques for OMA have also been reported in the literature. For instance, Rainieri and Fabbrocino (2010) developed a new automated algorithm, which was validated in civil engineering structures. Subsequently, Rainieri and Fabbrocino (2015) developed an algorithm for automated estimation of tensile loads in cables and tie rods. Moreover, Reynders et al. (2012) proposed a fully automated, three-stage clustering approach for interpreting stabilisation diagrams. Christensen et al. (2021) compared the poly-reference least squares complex frequency (PLSCF) and the multi-reference Ibrahim time domain (MITD) algorithms and developed a new automated modal analysis algorithm. Finally, Andersen et al. (2007) studied automated modal estimation in large structures, while Sun et al. (2017) examined the topic in the context of a cable-stayed bridge.

Furthermore, several methods have been proposed for automated modal estimation in both the time and frequency domains. They can, in turn, be classified as parametric and non-parametric methods (Avitable, 2017; Brincker and Ventura, 2015; Ewins, 2000a; Heylen *et al.*, 2007; Mendes Maia and Montalvão Silva, 1997). Non-parametric frequency domain methods are based on selecting the peaks of variables (complex mode indicator, function, normalised power spectral density, singular values, etc.) derived from frequency response functions or PSDs (Andersen et al., 2007; Rainieri et al., 2007; Rainieri and Fabbrocino, 2010). Automated parametric methods are based on the automated interpretation of stabilisation diagrams (Christensen and Brandt, 2020; Reynders et al., 2011; Su et al., 2021; Zonno et al., 2017), which involves tracking estimates of modal parameters as a function of model order (Christensen, 2020; Reynders et al., 2012; Ubertini et al., 2013). As the model order is increased, the estimates of physical modal parameters stabilise. Poorly excited modes may not stabilise until a very high model order, whereas very active modes stabilise at a very low model order (Christensen, 2020; Neu et al., 2017; Reynders et al., 2012). Reynders et al. (2012) presented a classification of methods for the automated interpretation of stabilisation diagrams, while Christensen (2020) studied the effect of model order, number of time lag values and starting time lag value in the estimation of modal parameters. Moreover, Zini et al. (2022) proposed a statistical method to automatically define the cut-off thresholds in the hierarchical clustering phase. He et al. (2022) proposed a fully automated unified modal identification, with a focus on structures with many or very few sensors deployed. Dederichs et al. (2023) compared numerous automation algorithms to identify structural modes from the stabilisation diagram using experimental data from the monitored Hardanger Bridge.

Finally, Li et al. (2022) proposed an automated OMA algorithm based on a combination of parametric and non-parametric algorithms: second-order blind identification (SOBI) and covariance-driven stochastic subspace identification (SSI-COV).

3.3 DAMAGE DETECTION AND LOCALISATION

In this section, damage detection and localisation techniques are reviewed in depth.

3.3.1 DAMAGE DETECTION

The most common modal-based techniques used to detect damage are the eigenfrequency method, which is used to monitor changes in natural frequencies, and eigenvector-based criteria, which are used to monitor changes in mode shapes (Frigui *et al.*, 2018) (see Fig.4).

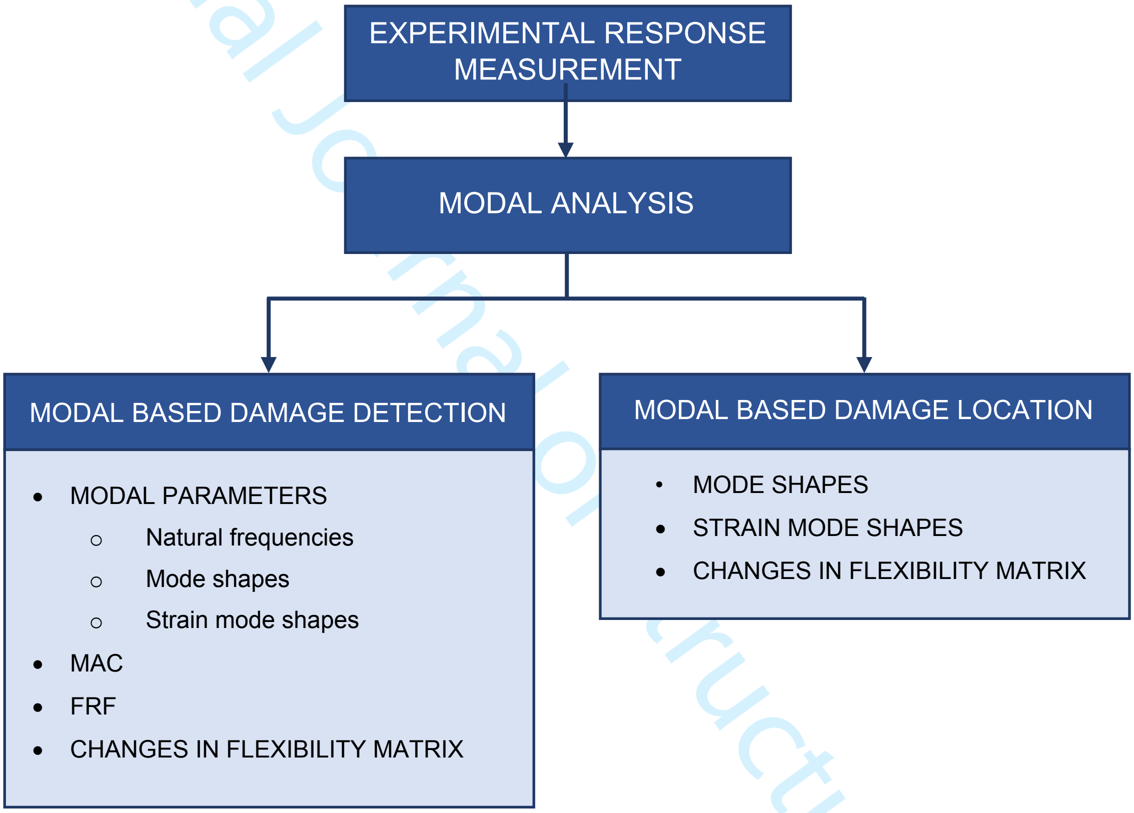

Figure 4. Modal-based damage detection and location methods.

The monitoring of natural frequencies (see Fig. 4) is a simple method and consists of comparing a set of natural frequencies for two states:

$$\Delta f_j = f_{dj} - f_{uj} \tag{1}$$

where j denotes the j-th mode, d the damaged state and u the undamaged state. When using this technique, mode pairing is mandatory.

One of the advantages of natural frequencies is that they are very sensitive to damage. However, they are also sensitive to other mechanical and environmental effects (Frigui et al., 2018). It is well-known that changes in temperature, wind velocity, wave height, wind direction and wave directionality modify natural frequencies (Christensen, 2020; Li et al., 2009; Peeters and De Roeck, 2001; Ubertini et al., 2017). Moreover, boundary conditions, which depend on the soil type, can affect modal parameters.

The criteria based on eigenvectors compares a set of mode shapes (see Fig. 4) (Ewins, 2000b; Lein and Beitelschmidt, 2014). A mode pairing is also mandatory. The best-known method is the modal assurance criterion (MAC) (Allemang, 2003; Allemang and Brown, 1982; Fotsch and Ewins, 2000; Rigner et al., 1998; Vacher et al., 2010), which compares the shapes of two eigenvectors based on the inner product of both vectors. If two vectors ϕ_{di} (damage state) and ϕ_{uj} (undamaged state) are compared, MAC (ϕ_{di}, ϕ_{uj}) is given by the following equation:

$$MAC(\phi_{ui}, \phi_{dj}) = \frac{\left|\phi_{ui}^{T}, \phi_{dj}\right|^{2}}{\left(\phi_{ui}^{T}, \phi_{uj}\right)\left(\phi_{di}^{T}, \phi_{dj}\right)} \qquad (2)$$

The first paper about MAC was published in 1982 by Allemang and Brown (1982). Allemang (Allemang, 2003) reviewed the historical development of the original MAC, along with other related assurance criteria proposed between 1982 and 2002. Moreover, typical abuses of MAC were also identified. MAC can also be applied in the frequency domain (Fotsch and Ewins, 2000) and extended to complex modes (Vacher et al., 2010). Lein and Beitelschmidt (2014) conducted a comparative study of different model correlation methods.

Mode shapes are affected by damages, however, for low severity damages the method indicates damage only in higher-order modes, which are more sensitive to damage but also more difficult to identify in real-life situations. Moreover, the estimation of mode shapes is not as precise as the estimation of natural frequencies (Frigui et al., 2018). West (1984) used MAC to detect structural changes. Fox (1992) compared the use of natural frequencies and mode shape data to detect damage.

Techniques based on monitor strain mode shapes have also been proposed in the literature (see Fig. 4). They are based on the relationship between mode shape curvatures and flexural stiffness (i.e. when a structure is damaged, its stiffness decreases and induces a variation in mode shape curvature) (Frigui et al., 2018). The modal curvatures of the lower modes are generally more accurate than those of higher modes (Frigui et al., 2018). Pandey et al. (1991) used changes in strain mode shapes to detect damage. In addition, Abdel Wahab and De Roeck (1999) detected damage using modal curvatures and applied this technique to a real bridge.

Changes in frequency response functions or flexibility can be also used to detect damage. The change flexibility matrix can be computed using experimental modal parameters as follows:

$$[\Delta \mathrm{f}] = \sum_{r=1}^{N} \frac{\phi_{ru}\phi_{ru}^{T}}{\omega_{ru}^{2}} - \sum_{r=1}^{N} \frac{\phi_{rd}\phi_{rd}^{T}}{\omega_{rd}^{2}} \qquad (3)$$

where ϕ_r denotes the *r*-th mode shape, ω_r the *r*-th natural frequency, *d* the damaged state, *u* the undamaged state and *N* the number of modes.

The computation of flexibility matrices from vibration data requires mass-normalised mode shapes. If OMA is used to estimate modal parameters, an additional technique to scale the mode shapes is needed (Aenlle and Brincker, 2019, 2014; Aenlle et al., 2007a, 2007b; López-Aenlle et al., 2005, 2010). López-Aenlle et al. (2005) proposed some methods to determine scaled mode shapes. Modal scaling was performed using a finite element model in a study by Aenlle and Brincker (2014) and using a mass change strategy in studies by Aenlle et al. (2007a, 2007b) and López-Aenlle et al. (2010). Furthermore, Aenlle et al. (2007a) proposed a methodology to optimise the number, location and magnitude of attached masses, which was validated for a cantilever beam by Aenlle et al. (2007b). Damage detection through changes in modal flexibility has been studied by Pandey and Biswas (1994, 1995) and Toksoy and Aktan (1994). Finally, Salawu (1995) applied the integrity index method to a concrete highway bridge.

3.3.2 DAMAGE LOCALISATION

Modal-based damage localisation methods (see Fig. 4) are traditionally based on changes in mode shapes, mode shape derivatives or the flexibility matrices assembled from available modes (Doebling et al., 1996; Fox, 1992; Pandey et al., 1991; Pandey and Biswas, 1994, 1995; Salawu, 1995; Stubbs and Kim, 1996; Toksoy and Aktan, 1994; West, 1984).

Mode shapes can be easily estimated using modal analysis, but the localisation of damage based on the curvature of mode shapes has been shown to be more sensitive to damage than mode shapes (Abdel Wahab and De Roeck, 1999; Pandey et al., 1991).

Shokrani et al. (2018) used mode shape curvatures for damage localisation under varying environmental conditions. Frigui et al. (2018) proposed a new parameter called curvature damage factor (CDF), in which the difference in modal curvature between the damaged and undamaged states is averaged over all modes. If the structure contains several damaged locations, CDF provides a clear identification of these locations. When the method is applied to real structures, irregularities in measured mode shapes can arise, and a curve fitting must be applied before calculating modal curvature.

Bernal (Bernal, 2006; Bernal and Gunes, 2002, 2004) proposed a damage localisation method based on changes in the experimental flexibility matrix. The technique identifies the damaged elements of a structure as belonging to the set of elements whose internal forces under the action of a certain set of load vectors (designated as damage location vectors or DLVs) are zero. These vectors define a basis for the null space of the change in flexibility.

4 FATIGUE MONITORING

In this section we deal with the steps needed to perform continuous fatigue monitoring in structures. The organization of this part of the paper is summarized in Figure 5. Firstly, we introduce the most common techniques used to predict fatigue failure. Then the available techniques to estimate stresses are discussed. Finally, the methods for fatigue assessment in both time and frequency domains are reviewed and analysed.

Well-established practices in fatigue assessment include the determination of stress time histories, the calculation of the fatigue stress spectrum (cycle counting) and the evaluation of total fatigue damage (Bolotin, 1999; Schijve, 2008; Suresh, 1998). In the time domain, the fatigue stress spectrum is obtained from time stress histories using counting algorithms such as the rainflow (Johannesson, 2002; Lindgren and Rydén, 2002; Rychlik, 1996a, 1996b) or reservoir methods (BS5400: Part 10, 1980). Fatigue damage is estimated using a damage accumulation model, the best-known being the Palmgren-Miner model (Miner rule; Miner, 1945). However, different damage accumulation models have been proposed in the literature (Benkabouche et al., 2015; Fatemi and Yang, 1998).

Stress-based models are mainly used to predict fatigue life for high-cycle fatigue, whereas strain-based models are suitable for low-cycle fatigue in which plastic deformation is significant. Energy-based models can consider out-of-phase hardening behaviour because both the stress and strain terms are inherent in the energy expression (Wei and Liu, 2020). Moreover, for welded details, a fatigue approach based on nominal or geometrical stress is preferred to local approaches based on continuum mechanics (Leonetti et al., 2021).

A combination of cycle counting and the Miner rule is generally accepted as one of the best time domain methods for fatigue life estimation. However, this methodology presents some drawbacks in random loadings because the stress time history is only known in a statistical manner, which can be overcome by simulating time histories from the random process. In addition, another negative aspect to consider is the inability to handle load sequence effects. Different studies (Branco et al., 2022; Fiedler and Vormwald, 2016) have examined sequence effects and the consequences of neglecting them.

Stress-based fatigue assessment may be applied using nominal stresses, hot spot stresses or local stresses (Bolotin, 1999; Schijve, 2008; Suresh, 1998). Nominal S-N curves are considered with fatigue life based on nominal and local stresses, whereas hot-spot S-N curves should be used with hot-spot stresses. Several investigations of the hot-spot stress approach have been conducted in recent years. For example, Viana et al. (2019) performed a fatigue assessment based on hot-spot stresses obtained from global dynamic analysis and local static sub-modelling using finite element models. Moreover, Bao et al. (2022) proposed an indirect method for evaluating hot-spot stresses induced by complex load conditions.

In stationary random processes (Newland, 2005; Wirsching et al., 1995), fatigue analysis can also be addressed in the frequency domain; the fatigue stress spectrum is obtained from the moments of stress PSDs (Benasciutti, 2012; Bishop, 1999; Bishop and Sherratt, 1990; Dalpiaz et al., 2004; Guennec et al., 2014; Slavič et al., 2020; Zigo et al., 2019). This technique is much more rapid than a transient dynamic analysis in the time domain. Frequency fatigue can be used in combination with FEM software to evaluate fatigue after the loading is known and the dynamic analysis has been performed. As many authors consider the rainflow method to be the most accurate, frequency domain cycle counting techniques attempt to obtain a cycle distribution according to the rainflow counting method in the time domain (Benasciutti, 2012; Slavič et al., 2020).

Continuous fatigue monitoring means calculating accumulated fatigue damage in real time during the period that the structure is in operation (Česnik et al., 2012; Jiang et al., 2015; Mršnik et al., 2013). Fatigue monitoring consists of three steps:

- Localisation of the structure's hot spots to identify the most probable locations of fatigue damage, defined during the fatigue design analysis.
- Measurement or estimation of stresses at the hot spots. Stresses can be measured using appropriate sensors, which are continuously monitored, or estimated from structural responses measured (in real time) using displacement, velocity or acceleration sensors. Stress estimation is explained in detail in the following sections.
- Calculation of accumulated fatigue damage and remaining fatigue life.

Fatigue monitoring can be combined with other SHM techniques. For instance, experimental responses can be used to simultaneously estimate stresses and to detect and localise damage in the structure using a vibration-based SHM technique, which significantly increases the reliability of monitoring techniques used in the structure (i.e. by providing redundancy).

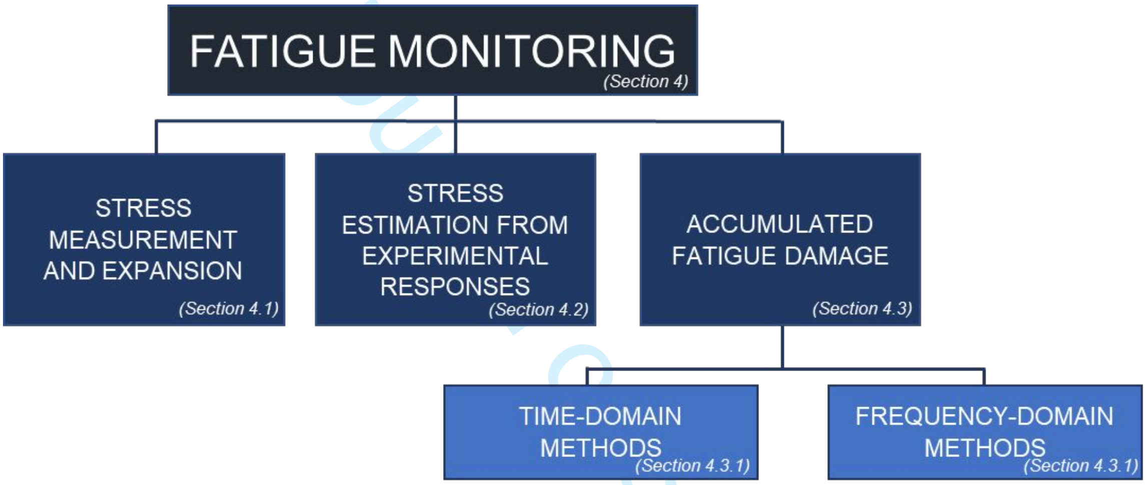

Figure 5. Organization of the fatigue monitoring section.

4.1 STRESS MEASUREMENT AND EXPANSION

Most fatigue analysis techniques consider stresses (stress range, stress amplitude and maximum stress) as the principal variable responsible for fatigue damage. However, no sensors that measure stresses can be found in the market. Therefore, stresses are indirectly obtained from strain measurements. The most common devices for measuring strain are strain gages, such as Wheatstone Bridge Circuit (four-element strain gauge bridge circuit), fibre Bragg grating sensors (Kong et al., 2022; Rao, 1997) and integrated circuit piezoelectric (ICP) strain sensors (Fujimoto et al., 2003). Fibre Bragg grating sensors have several advantages; they are small, lightweight, do not require electrical connections and are compatible with non-invasive remote sensing (Sahota et al., 2020). However, temperature compensation for strain error through thermal fluctuation is essential. On the other hand, ICP sensors have superior signal-to-noise ratio and high frequency noise rejection compared to conventional strain gages (Sirohi and Chopra, 2000).

Using strain sensors, accumulated fatigue damage can be calculated at the stress measurement points by using appropriate stress concentration factors. In addition, strain mode shapes can be obtained through strain modal analysis if an appropriate distribution of sensors is considered, which can be expanded to unmeasured degrees of freedom (DOFs) to estimate stresses at any point of the structure. Moreover, strain measurements can be effective for crack detection because of the sensitivity of strain change to the opening and closing of a crack. However, sensors may not provide adequate information for fatigue crack monitoring since their small size hinders their ability to cover an adequate surface for areas that are prone to fatigue cracks (Taher et al., 2022).

The steps needed to perform real-time stress estimation using experimental strain measurements are shown in Figure 6. It is assumed that the strain mode shapes are known from experiments or a numerical model (1). Firstly, the hot spots (2) to be monitored and the sensor location (3) strategy must be defined. The measured strains $\varepsilon_{xa}(t)$ (4) are then used to estimate the strain modal coordinates $q_\varepsilon(t)$ (5) using the experimental strain mode shapes ϕ_{ε_a} (1). The strains $\varepsilon(t)$ (6) at the selected points of the structure are estimated with the expanded strains mode shapes and the modal coordinates $q_\varepsilon(t)$. Finally, stress time histories $\sigma(t)$ (7) are calculated using $\varepsilon(t)$ and the stress-strain relationship.

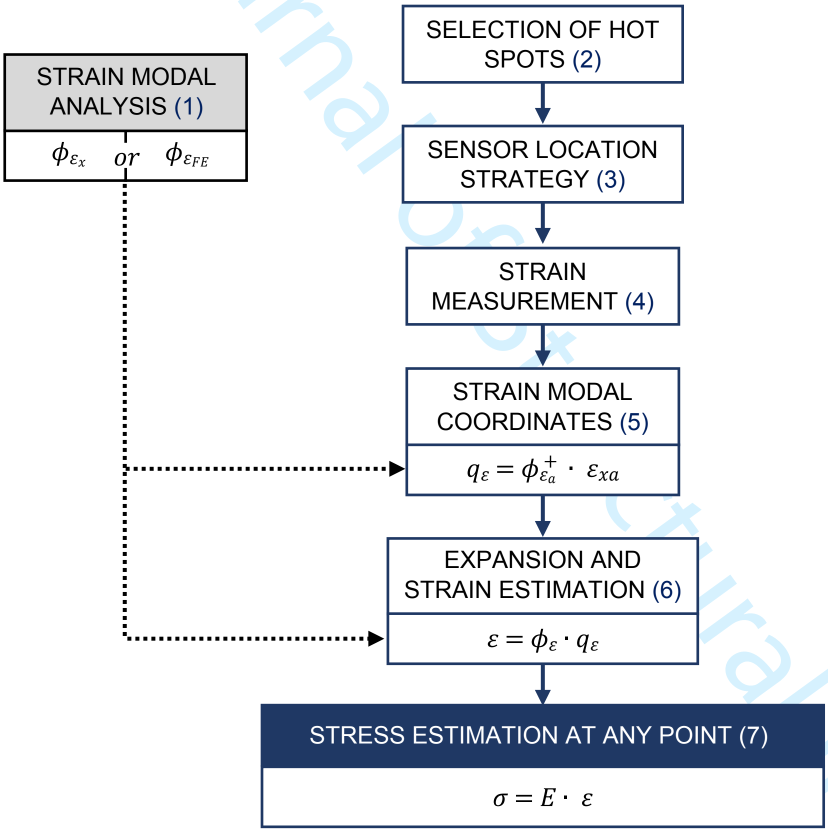

Figure 6. Real-time stress estimation using strain measurements.

4.2 STRESS ESTIMATION FROM EXPERIMENTAL (NON-STRESS) RESPONSES

Stress estimation from experimental (non-stress) responses are techniques commonly based on modal superposition, which allows the modal coordinates to contain information about natural frequencies and damping. Numerical or experimental mode shapes can be used. As experimental mode shapes are only known at a reduced number of points, they are expanded to the unmeasured DOFs using a finite element model. Thus, a numerical model is needed to estimate stresses, but only a good numerical-experimental correlation in terms of mode shapes is required. Different types of finite element models can be used; only a good dynamic correlation is needed, mainly in terms of mode shapes (Fernández et al., 2009; Pelayo et al., 2015).

Brincker et al. (Brincker et al., 2003) published a paper on several potential applications of OMA, such as SHM, load estimation and vibration-level estimation. Moreover, to reduce uncertainty from loading modelling in fatigue calculations, a methodology to estimate stresses at any point of the structure using its experimental response was presented (Hjelm et al., 2005; Pelayo et al., 2015).

The methodology allows stresses to be estimated at any point of the structure using experimental displacement, the structure's velocity or acceleration responses, which are measured at several discrete points (Aenlle et al., 2013; López-Aenlle et al., 2013).

The structure's experimental response can be measured in displacement, velocity of acceleration formats. Accelerometers can be classified into three main groups: piezoelectric, capacitive or piezoresistive accelerometers. Piezoelectric accelerometers have very low noise and offer superior performance to the capacitive and piezoresistive. Capacitive MEMS (micro-electro-mechanical systems) accelerometers are cheap; small; and exhibit high vibration, shock and temperature resistance. However, they have poor temperature characteristics. Finally, piezoresistive accelerometers require amplifiers and temperature compensation, but they have a very wide bandwidth and low noise characteristics (Hanly, 2016).

When measuring displacements, laser Doppler vibrometers are widely recognised as valid measurement tools for structural dynamic measurements (Warren, Niezrecki, et al., 2011). Displacement measurements using the FFT-DDI (Direct Digital Integration) method with different types of accelerometers have been studied (Ribeiro et al., 2003). The performance of laser Doppler vibrometers, digital image correlation and accelerometers have been investigated by Rossi et al. (2002; Warren, Niezrecki et al. (2011; and Warren, Pingle et al. (2011).

The theory needed to estimate stresses has been published in several papers (Aenlle et al., 2013; Fernández et al., 2009; Hjelm et al., 2005; López-Aenlle et al., 2013; Pelayo et al., 2015). If the structure's response is measured with accelerometers, the acceleration modal coordinates $\ddot{q}_x(t)$ can be obtained as follows:

$$\ddot{\boldsymbol{u}}_x(\boldsymbol{t}) = \boldsymbol{\Phi}_x \cdot \ddot{\boldsymbol{q}}_x(\boldsymbol{t}) = \sum_{\boldsymbol{r}=\boldsymbol{1}}^{\boldsymbol{N\ modes}} \boldsymbol{\phi}_{xr} \cdot \ddot{q}_{xr}(t) \quad (4)$$

where subindex x indicates experimental parameters, $\ddot{\boldsymbol{u}}_{\boldsymbol{x}}(\boldsymbol{t})$ is the measured acceleration vector and $\boldsymbol{\Phi}_{\boldsymbol{x}}$ is the experimental mode shape matrix, which can be estimated using EMA or OMA.

Normal stresses in a beam at coordinate x can be estimated with the following equation (Aenlle et al., 2013; Fernández et al., 2009; Hjelm et al., 2005; López-Aenlle et al., 2013; Pelayo et al., 2015):

$$\boldsymbol{\sigma}(\boldsymbol{x},\boldsymbol{t}) = \boldsymbol{y} \cdot \sum_{\boldsymbol{r}=\boldsymbol{1}}^{\boldsymbol{N\ modes}} \boldsymbol{\phi}_{\boldsymbol{\epsilon x r}}(\boldsymbol{x}) \cdot q_{xr}(t) \tag{5}$$

where q_{xr} is the r-th displacement modal coordinate obtained through integration, y is the distance to neutral beam axis and $\boldsymbol{\phi}_{\boldsymbol{\epsilon x r}}(x)$ is the strain mode shape of the r-th mode, which is related (in beams), with mode shapes $\boldsymbol{\phi}_{\boldsymbol{x}}$ as follows:

$$\boldsymbol{\phi}_{\boldsymbol{\epsilon x}} = \frac{d^2\boldsymbol{\phi}_{\boldsymbol{x}}}{dx^2} \tag{6}$$

The experimental mode shapes must be expanded to unmeasured DOFs to estimate the strain mode shapes at the desired points. A finite element model can be used to this end; experimental mode shapes are expressed as a linear combination of FE mode shapes (Brincker et al., 2014).

The steps to perform real-time stress estimation using the structure's displacement, velocity or acceleration response is shown in Figure 7. It is assumed that the strain mode shapes are known from experiments or a numerical model (1). Firstly, the hot spots (2) to be monitored and the sensor location (3) strategy must be defined. The measured responses (displacements, velocities or accelerations) (4) are then used to estimate the strain modal coordinates $q(t)$(5). The strains $\varepsilon(t)$ (6) at the selected points are estimated with the expanded strain mode shapes and the modal coordinates $q(t)$. Finally, stress time histories $\sigma(t)$ (7) are calculated using $\varepsilon(t)$ and the stress-strain relationship.

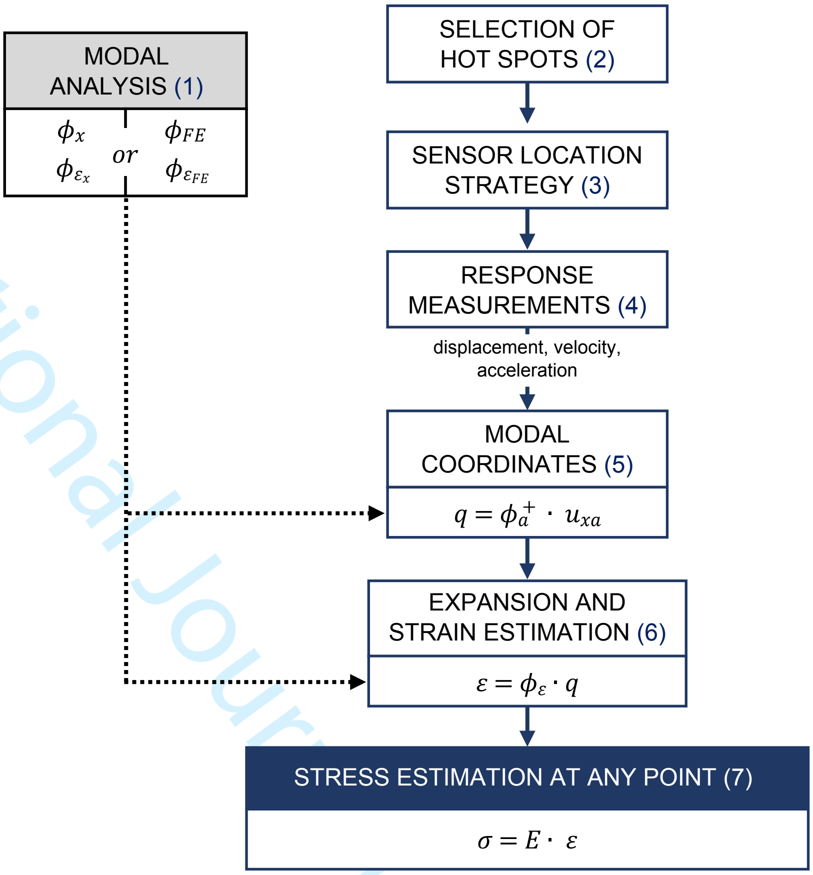

Figure 7. Real-time stress estimation using experimental (non-strain) responses.

This technique has been validated through experimental tests on lab-scaled structures (Fernández *et al.*, 2009; Hjelm *et al.*, 2005; López-Aenlle *et al.*, 2013; Tarpø *et al.*, 2020) and real structures (Christensen, 2020; Dascotte *et al.*, 2013; Henkel *et al.*, 2019, 2020; Hjelm *et al.*, 2005; Iliopoulos *et al.*, 2017; Nabuco *et al.*, 2020; Noppe *et al.*, 2018).

Papadimitriou (Papadimitriou et al., 2011) proposed a methodology for estimating damage resulting from fatigue using spectral methods and operational vibration measurements at a limited number of locations. Using the experimental response time history and a model of the structure, a Kalman filter approach was used to predict the PSDs of stresses in the entire body of the structure. This technique was validated using analytical and numerical models and by considering simulated measurements.

In addition, Gulgec et al. (Gulgec et al., 2020) proposed a technique to estimate strain responses using experimental acceleration responses as inputs for a multistage deep neural network based on long short-term memory and fully connected layers. This technique was validated in a lab-scaled structure.

4.3 ACCUMULATED FATIGUE DAMAGE

Once stresses are estimated for identified hot spots where failure is most probable, the corresponding accumulated fatigue damage must be estimated. Using data from constant amplitude tests to estimate fatigue damage under variable amplitude loading requires a cycle-counting method, a damage accumulation law and consideration of the load sequence effect (Kondo, 2003). To this end, material fatigue characterisation based on the S-N field – or, equivalently, the ε-N field – allows fatigue lifetime to be analytically defined as a previous step in damage assessment. Alternatively, fracture mechanics can also be used to estimate crack growth until its critical value is reached.

Methodologies applied in fatigue damage assessment were traditionally formulated in both the time and frequency domains, which is explained in detail in the following subsections and summarised in Figure 8.

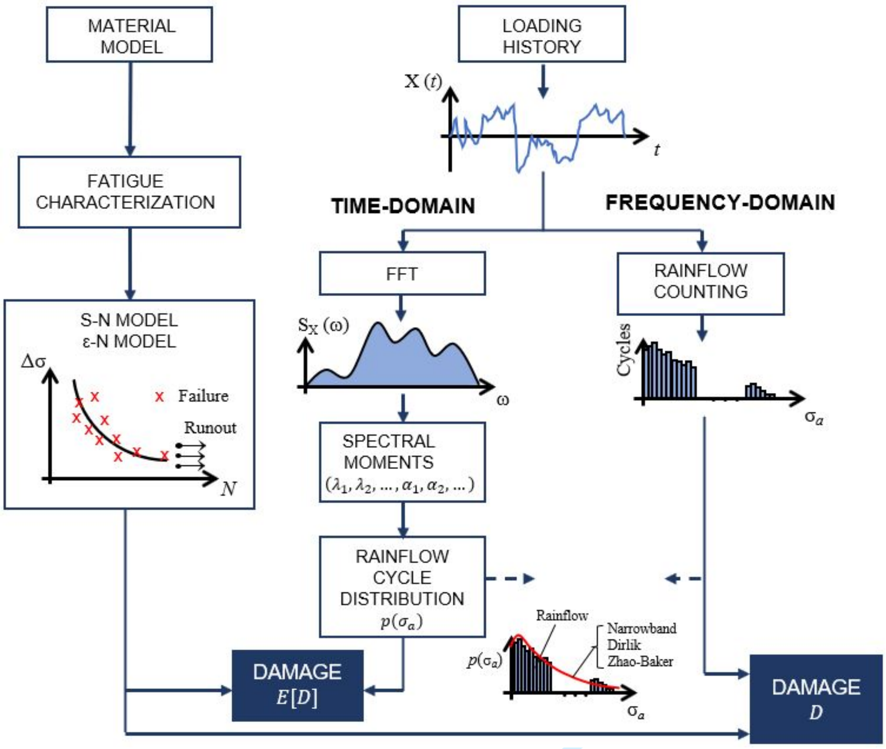

Figure 8. General flowchart of fatigue damage assessment using both time and frequency domain approaches.

4.3.1 TIME DOMAIN METHODS

Time domain methods were formulated first and applied more frequently than frequency domain methods. The analysis of loading history is accomplished using different counting algorithms, such as the rainflow method developed by Matsuishi and Endo (Matsuishi and Endo, 1968), to obtain an equivalent set of counted cycles with constant amplitudes. This allows fatigue damage to be estimated. Despite being widely used as a reference procedure, the rainflow method entails some important disadvantages, such as its dependence on a particular time window selected in the loading history and time-consuming nature.

An extensive literature review on the proposed damage variables and methodologies can be found in the literature (Castillo et al., 2007; Fatemi and Yang, 1998; Santecchia et al., 2016). Five different categories can be distinguished in these proposals:

- *Linear damage models*. Palmgren (Palmgren, 1924) first proposed the linear damage rule and Miner (Miner, 1945) subsequently popularised it as one of the most widely applied approaches to calculating damage due to its easy formulation, which is only based on the ratio between the applied cycles n_i and the total cycles to failure N_i for the i-th load level:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{7}$$

where D is a damage index ($0 \leq D \leq 1$) and k is the number of different stress levels.

Linear accumulation models use the S-N curve from constant amplitude tests; they assume no load sequence effects and no damage for stress repetitions below the fatigue limit (Kondo, 2003).

Manson and Halford (Manson and Halford, 1986) proposed the double linear damage rule. Double linear models were also proposed by Langer (Langer, 1937) and Grover (Grover, 1960), separating the initiation and propagation stages. Despite being widely applied, its main drawbacks are independence with respect to both load level and load sequence.

In variable amplitude loading, stress repetitions below the fatigue limit also cause damage. Haibach's rule (Haibach, 1970) and the Corten–Dolan rule (Corten and Dolan, 1956) have been proposed to account for this effect.

- *Non-linear damage models*. In an attempt to improve the incongruences of linear damage rules, Richart and Newmark (Richart and Newmark, 1948) and Marko and Starkey (Marco and Starkey, 1954) proposed the first non-linear damage rule based on a powering cycle ratio to x_i variable for the i-th loading:

$$D = \sum_{i=1}^{k} \left(\frac{n_i}{N_i}\right)^{x_i} \tag{8}$$

A non-linear modification to Miner's rule for damage accumulation was proposed to reduce the scatter between experimental fatigue life and fatigue life predicted using the Miner rule (Blacha, 2021).

Si-Jian et al. (2018) proposed a non-linear fatigue damage accumulation model which considered the effects of loading history and loading sequence under multi-level stress loading using the S-N field and the Miner rule.

- *Energy-based damage models*. As an alternative to previous phenomenological approaches, different authors have proposed energy-based definitions of fatigue damage, the Smith-Watson-Topper parameter (Watson et al., 1970) being one of the most widely recognised:

$$D = \frac{4\sigma'_f}{E}(2N_N)^{2b_1} + 4\sigma'_f\varepsilon'_f(2N_N)^{b_1+c_1} \tag{9}$$

where σ'_f and ε'_f are fatigue strength and ductility coefficients, respectively; N_N is the number of reversals to failure; and b_1 and c_1 are constants that depend on an instantaneous strain-hardening law.

- *Continuum-based damage models*. This novel approach addresses the continuum mechanical behaviour of a medium in degenerating conditions, which was originally stated by Kachanov (Kachanov, 1984) and Rabotnov (Rabotnov, 1969). Thanks to Chaboche and Lesne (Chaboche and Lesne, 1988), this proposal has been popularised as a highly non-linear damage rule that takes into account the mean stress effect:

$$D = 1 - \left[1 - \left(\frac{n}{N_N}\right)^{1/1-\alpha}\right]^{1/\beta - 1} \quad (10)$$

where α is a function of the stress state and β is a material function.

- *Probabilistic damage models*. Finally, probabilistic approaches have recently appeared due to the work of Fernández-Canteli (Castillo et al., 2007; Fernández-Canteli et al., 2014). In it, the classical Miner's rule was converted to a random variable from which the statistical distribution of the number of cycles to failure and the stress range can be numerically computed (Castillo and Fernández-Canteli, 2009):

$$p = 1 - exp\left[-\left(\frac{(logN - B)(log\Delta\sigma - C) - \lambda}{\delta}\right)^{\beta}\right] \quad (11)$$

where B and C are the horizontal and vertical asymptotes (that is, the cycle value below which failure does not occur and the fatigue endurance limit, respectively), while λ,β and δ are the location, shape and scale Weibull parameters, respectively.

4.3.2 FREQUENCY DOMAIN METHODS

Frequency domain or spectral methods (Bishop, 1999; Gao and Moan, 2008; Quigley *et al.*, 2016; Sherratt *et al.*, 2005; Zalaznik and Nagode, 2011) allow complex loading histories to be directly and rapidly computed as part of a more consistent statistical and analytical approach than time domain methods.

Loading history is classified as a random narrow-band (NB) process or a broad-band (BB) process (Wirsching et al., 1995). The former leads to simpler and easier formulations about statistical properties, while the latter offers more complex identification of stress cycles. In this sense, the statistical information contained in the spectral density $S_X(\omega)$ of a random process X can be summarised by means of the m-th spectral moments λ_m as follows:

$$\lambda_m = \int_{-\infty}^{\infty} \omega^m S_X(\omega) d\omega \quad m = 0,1,2,... \quad (12)$$

where the even moments are directly related to the variance σ_X^2 of the random process and its derivatives, as in $\lambda_0 = \sigma_X^2$. From a statistical perspective, the rainflow cycle distribution could be considered a bivariate distribution with maximum and minimum stresses, $p_{RFC}(\sigma_{max},\sigma_{min})$, or, equivalently, with mean and amplitude stresses, $p_{RFC}(\sigma_a,\sigma_m)$ (Benasciutti and Tovo, 2005, 2006). Indeed, one of the most relevant differences between frequency and time domain approaches is that the former use analytical definitions for the rainflow cycle distribution in fatigue damage assessment.

However, due to the inherent complexity of pairing procedures for peak-to-valley in the rainflow algorithm, there is no explicit analytical solution for the bivariate rainflow cycle distribution (Benasciutti and Tovo, 2006; Lalanne, 2013). Thus, the bivariate distribution is usually simplified by neglecting the mean stress effect and considering only the stress amplitude; as a result, different approximate proposals in the literature are defined in terms of $p_{RFC}(\sigma_a)$ instead.

Amongst these proposals, three are most widely applied:

- *Narrow-band approximation* is based on the assumption that the random process is of NB type; that is, each peak and valley is coincident with each cycle. Thus, the stress amplitude can be considered to follow a Rayleigh distribution:

$$p_{RFC}^{NB}(\sigma_a) = \frac{\sigma_a}{\sigma_X^2} exp\left[-\frac{1}{2}\left(\frac{\sigma_a}{\sigma_X}\right)^2 \right] \tag{13}$$

- *The Dirlik model* (Dirlik, 1985; Dirlik and Benasciutti, 2021) suggests a mixture distribution between an exponential component and two Rayleigh components:

$$p_{RFC}^{DK}(\sigma_a) = \frac{1}{\sigma_X}\left[\frac{D_1}{Q} exp\left(-\frac{Z}{Q} \right) + \frac{D_2 Z}{R^2} exp\left(-\frac{Z^2}{2R^2} \right) \right] \tag{14}$$

where $Z = {}^{\sigma_a}/_{\sigma_X}$ is the normalised amplitude and D_1,D_2,Q and R are constants that depend on the spectral moments.

- *The Zhao and Baker model* (Zhao and Baker, 1992) proposes a mixture distribution with Rayleigh and Weibull components:

$$p_{RFC}^{ZB}(\sigma_a) = w\alpha\beta Z^{\beta-1} exp(-\alpha Z^{\beta}) + (1-w) Z exp\left(-\frac{Z^2}{2} \right) \tag{15}$$

where w is a weighting factor ($0 \le w \le 1$) as a function of the spectral parameters and α and β are the scale and shape Weibull parameters, respectively.

- *Tovo–Benasciutti* (Dirlik and Benasciutti, 2021; Tovo, 2002) proposed that the amplitude–mean joint probability distribution of rainflow cycles lies between two limit distributions and can be estimated as their linear combination:

$$p_{RFC}^{TB}(\sigma_a) = \sigma_a p_{LCC}(\sigma_a, m) + (1 - w) p_{RC}(\sigma_a, m) \tag{16}$$

where w is a weight factor that must be determined. The two functions $p_{LCC}(\sigma_a, m)$ and $p_{RC}(\sigma_a, m)$ represent the amplitude–mean distributions of the level-crossing counting (LCC) and of the simple-range counting (RC).

Once the rainflow cycle distribution for the stress amplitude has been analytically defined, the fatigue damage assessment can be performed. By considering the Basquin law ($s^k N = C$) from the material characterisation step, the expected rainflow damage rate $\overline{D}_{RFC}$ (i.e. damage/sec) can be calculated as follows (Rychlik, 1993):

$$\overline{D}_{RFC} = \nu_a C^{-1} \int_0^\infty \sigma_a^k p_{RFC}(\sigma_a) d\sigma_a \tag{16}$$

where ν_a is the rate of occurrence of counted cycles (that is, counted cycles per second) and $p_{RFC}(\sigma_a)$ can be defined according to the previously mentioned proposals. Finally, from Equation (16), total expected damage D until failure can be directly obtained as follows:

$$D = \overline{D}_{RFC} T_f \tag{17}$$

where T_f is the time to failure (that is, the fatigue lifetime). Moreover, it should be noted that, depending on the particular analytical definition of the rainflow cycle distribution in Equation (16), the total expected damage in Equation (17) could be different.

5 DISCUSSION AND CONCLUSIONS

This paper was mainly motivated by the lack of comprehensive literature on the combination of SHM and fatigue assessment techniques. Thus, a general overview of existing SHM techniques was presented, with a particular emphasis on modal-based methodologies and the most common techniques used in fatigue assessment.

Given that the literature on both topics is usually presented separately, the main discussions and conclusions in this paper are divided into three subsections: (a) SHM, (b) fatigue monitoring and (c) a general overview that includes both approaches.

Each subsection summarises the main contributions and tendencies that have emerged in recent decades in relation to each topic and the main challenges for future research identified by the authors.

5.1 Structural Health Monitoring

The most frequently used SHM techniques are modal-based methods, which assume that structural damage can be detected from changes in one or a set of modal parameters. The development of automated modal identification techniques in recent years has contributed to an increase in the use of these techniques.

Despite the numerous benefits of SHM, there are some challenges that this technique must overcome. Damage is in most times a local phenomenon, whereas many SHM techniques try to detect global damage and, consequently, damage might not be detected. The key challenge in the SHM is to avoid false alerts (false positives or false negatives) which reduce the confidence of the SHM techniques.

On the one hand, an improvement of the existing technologies and methods involved in the monitoring process (type of sensors, location of sensors, sensor resilience, effects of nonlinearities, nonstationary methods for SHM, removal of the environmental effects, data processing, identification techniques, big data, statistical analysis, etc.) will result in a better and more accurate damage prediction with SHM.

Cost is another challenge in SHM. Nowadays SHM is expensive in large structures and the owners need to be convinced that the cost will not exceed the benefits given by the SHM.

Environmental and operational conditions are known to influence the modal parameters of structures. These undesired effects must be removed through data normalisation procedures to eliminate the effect of changes caused by operational or environmental variations. Although some techniques have been developed to remove the effect of temperature, better techniques are needed to remove the effect of other variables such as wind speed, wind direction, wave height, wave direction, etc.

SHM must provide an automated and real-time assessment of a structure; modal-based SHM uses automated modal analysis identification techniques, but other techniques such as model based SHM are more difficult to automate. Thus, another challenge is the application of machine learning techniques for damage identification and localization under unsupervised learning mode.

5.2 Fatigue Monitoring

Firstly, the literature review on stress measurement techniques for fatigue assessment leads to the conclusion that real-time stress time histories can be estimated from experimental strains measured with strain sensors, which must be expanded to unmeasured DOFs using an expansion method. Sensors based on Bragg gratings are expensive due to the need of a sophisticated interrogation system. The presence of electric and/or magnetic fields can superimpose electrical noise on the strain measurements when using strain gage. On the other hand, different papers in the literature have demonstrated that the use of strain gages or fibre Bragg grating sensors to measure experimental stresses could lead to significant errors if the influence of temperature change is disregarded. For this reason, different methods have been introduced to compensate for the influence of temperature change and reduce the thermal effect on measurements, which can also be mitigated by using self-temperature-compensation strain gages.

Secondly, a literature review on stress estimation techniques which are based on modal superposition methods was presented. These modal superposition methods rely on experimental or numerical mode shapes and the modal coordinates estimated from the structure's experimental response (displacement, velocity, or acceleration). The measured response must also be expanded to unmeasured DOFs. One advantage of this technique is that information about natural frequencies and damping ratios is contained in the modal coordinates; in other words, this technique is less sensitive to changes in environmental or operational conditions than SHM based on modal parameters.

Finally, regarding the performance of fatigue analysis in the time domain, it can be concluded that the most common practice is to assume a Basquin linear S-N field, combined with the rainflow algorithm to perform the cyclic counting and the Miner Rule to accumulate the damage. Nevertheless, there are more advanced models that include non-linear behaviours, energetic approaches, and probabilistic aspects; based on their promising results, they are likely to become more relevant in the future. Regarding the performance of fatigue analysis in the frequency domain, the Miner rule is also commonly used, but the fatigue stress spectrum is obtained from the moments of the stress PSDs, which provide deeper insights on the problem than the information provided by a rainflow algorithm, which is performed in the time domain. However, most frequency domain techniques proposed in the literature can only be applied to linear systems that are subject to stationary Gaussian processes.

5.3 General Overview (Both Approaches)

Despite the great advancements in knowledge about fatigue failure that could potentially result from combined works on SHM and continuous fatigue monitoring of real structures, very few studies to date have simultaneously examined both techniques.

On the one hand, works on SHM that were identified in the literature typically focus on introducing new models to detect or localise failure but do not calculate the accumulation of fatigue damage. When they do, the fatigue models used tend to be the simplest ones, which are based on uniaxial stress amplitude and the Miner rule.

On the other hand, works on the improvement of fatigue assessment are usually centred on presenting new critical parameters (based on stress, strain, energy, etc.), cyclic counting techniques or accumulated damage models (linear, exponential, energetic, etc.). Nevertheless, their application is usually demonstrated through simplified examples with constant amplitude loading (or constant loading steps), and SHM techniques are not used in parallel.

This has led to excellent models in both fields – SHM and fatigue assessment – but separately. For this reason, future research should focus on demonstrating the potential of combined methodologies, which could improve the real-time fatigue monitoring of entire structures and understanding of the causes of fatigue failure.

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REFERENCES

Abdel Wahab, M.M. and De Roeck, G. (1999), "Damage detection in bridges using modal curvatures: application to a real damage scenario", *Journal of Sound and Vibration*, Vol. 226 No. 2, pp. 217–235.

Aenlle, M. and Brincker, R. (2019), "Basic Concepts of Modal Scaling", *8th International Operational Modal Analysis Conference*.

Aenlle, M.L. and Brincker, R. (2014), "Modal scaling in OMA using the mass matrix of a finite element model", *Conference Proceedings of the Society for Experimental Mechanics Series*, Vol. 4 No. February 2014, pp. 263–270.

Aenlle, M.L., Fernández, P.F., Brincker, R. and Canteli, A.F. (2007a), "Scaling factor estimation using an optimized mass change strategy. Part 1: Theory", *Proceedings of the 2nd International Operational Modal Analysis Conference, IOMAC 2007*.

Aenlle, M.L., Fernández, P.F., Brincker, R. and Canteli, A.F. (2007b), "Scaling factor estimation using an optimized mass change strategy. Part 2: Experimental Results", *Proceedings of the 2nd International Operational Modal Analysis Conference, IOMAC 2007*.

Aenlle, M.L., Skafte, A., Fernández, P. and Brincker, R. (2013), "Strain Estimation in a Glass Beam Using Operational Modal Analysis", *Conference Proceedings of the Society for Experimental Mechanics Series*, pp. 375–382.

Ahmadian, H., Mottershead, J.E. and Friswell, M.I. (1996), "Damage detection from substructure modes", *ISMA21 - Noise and Vibration Engineering*.

Allemang, R.J. (2003), "The modal assurance criterion - Twenty years of use and abuse.", *Sound Vib.*

Allemang, R.J. and Brown, D. (1982), "Correlation Coefficient for Modal Vector Analysis", *Proceedings of the International Modal Analysis Conference & Exhibit.*

Amafabia, D.A.M., Montalvão, D., David-West, O. and Haritos, G. (2017), "A review of structural health monitoring techniques as applied to composite structures", *SDHM Structural Durability and Health Monitoring*, Vol. 11 No. 2, pp. 91–147.

Andersen, P., Brincker, R., Goursat, M. and Mevel, L. (2007), "Automated modal parameter estimation for operational modal analysis of large systems", *Proceedings of the 2nd International Operational Modal Analysis Conference, IOMAC 2007*.

API. (2000), "Recommended Practice for Planning, Designing and Constructing. Fixed Offshore Platforms."

Au, S.-K. (2017), *Operational Modal Analysis - Modeling, Bayesian Inference, Uncertainty Laws*, *Operational Modal Analysis*, Springer Singapore.

Avci, O., Abdeljaber, O., Kiranyaz, S., Hussein, M., Gabbouj, M. and Inman, D.J. (2021), "A review of vibration-based damage detection in civil structures: From traditional methods to Machine Learning and Deep Learning applications", *Mechanical Systems and Signal Processing*, Vol. 147, p. 107077.

Avendaño-Valencia, L.D. and Fassois, S.D. (2017), "Gaussian Mixture Random Coefficient model based framework for SHM in structures with time–dependent dynamics under uncertainty", *Mechanical Systems and Signal Processing*, Vol. 97, pp. 59–83.

Avitable, P. (2017), *Modal Testing: A Practitioner's Guide*, Wiley.

Azimi, M., Eslamlou, A. and Pekcan, G. (2020), "Data-Driven Structural Health Monitoring and Damage Detection through Deep Learning: State-of-the-Art Review", *Sensors*, Vol. 20 No. 10, p. 2778.

Bagavathiappan, S., Lahiri, B.B., Saravanan, T., Philip, J. and Jayakumar, T. (2013), "Infrared thermography for condition monitoring - A review", *Infrared Physics and Technology*, Vol. 60, pp. 35–55.

Bajrić, A., Høgsberg, J. and Rüdinger, F. (2018), "Evaluation of damping estimates by automated Operational Modal Analysis for offshore wind turbine tower vibrations", *Renewable Energy*, Vol. 116 Part B, pp. 153–163.

Bao, S., Wang, W., Li, X., Qi, S. and Zhou, J. (2022), "Experimental study of hot spot stress for three-planar tubular Y-joint: II. Combined loads", *Thin-Walled Structures*, Vol. 177, p. 109416.

Baraccani, S., Palermo, M., Azzara, R.M., Gasparini, G., Silvestri, S. and Trombetti, T. (2017), "Structural Interpretation of Data from Static and Dynamic Structural Health Monitoring of Monumental Buildings", *Key Engineering Materials*, Vol. 747, pp. 431–439.

Barke, D. and Chiu, K.W. (2005), "Structural health monitoring in the railway industry: A review", *Structural Health Monitoring*, Vol. 4 No. 1, pp. 81–93.

Beards, C.F. (1996), *Structural Vibration: Analysis and Damping*, Butterworth-Heinemann.

Benasciutti, D. (2012), *Fatigue Analysis of Random Loadings*, LAP Lambert Academic Publishing.

Benasciutti, D. and Tovo, R. (2005), "Spectral methods for lifetime prediction under wide-band stationary random processes", *International Journal of Fatigue*, Vol. 27 No. 8, pp. 867–877.

Benasciutti, D. and Tovo, R. (2006), "Comparison of spectral methods for fatigue analysis of broad-band Gaussian random processes", *Probabilistic Engineering Mechanics*, Vol. 21 No. 4, pp. 287–299.

Benkabouche, S., Guechichi, H., Amrouche, A. and Benkhettab, M. (2015), "A modified nonlinear fatigue damage accumulation model under multiaxial variable amplitude loading", *International Journal of Mechanical Sciences*, Vol. 100, pp. 180–194.

Bernal, D. (2006), "Flexibility-based damage localization from stochastic realization results", *Journal of Engineering Mechanics*, Vol. 132 No. 6, pp. 651–658.

Bernal, D. and Gunes, B. (2002), "Damage Localization in Output-Only Systems: A Flexibility Based Approach", *Proc. Of the International Modal Analysis Conference (IMAC)*, pp. 1185–1191.

Bernal, D. and Gunes, B. (2004), "Flexibility based approach for damage characterization: benchmark application", *Journal of Engineering Mechanics*, Vol. 130 No. 1, pp. 61–70.

Bishop, N. (1999), “Vibration Fatigue Analysis in the Finite Element Enviroment”, *Anales de Mecanica de La Fractura*.

Bishop, N. and Sherratt, F. (1990), “A theoretical solution for the estimation of ‘rainflow’ ranges from power spectral density data”, *Fatigue & Fracture of Engineering Materials and Structures*, Vol. 13 No. 4, pp. 311–326.

Bjørheim, F., Siriwardane, S.C. and Pavlou, D. (2022), “A review of fatigue damage detection and measurement techniques”, *International Journal of Fatigue*, Vol. 154, p. 106556.

Blacha, Ł. (2021), “Non-Linear Probabilistic Modification of Miner’s Rule for Damage Accumulation”, *Materials*, Vol. 14 No. 23, p. 7335.

Boller, C., Chang, F.-K. and Fujino, Y. (Eds.). (2009), *Encyclopedia of Structural Health Monitoring*, *Encyclopedia of Structural Health Monitoring*, John Wiley & Sons, Ltd, Chichester, UK, available at:https://doi.org/10.1002/9780470061626.

Bolotin, V. V. (1999), *Mechanics of Fatigue*, CRC Press, Boca Raton.

Branco, R., Costa, J.D., Prates, P.A., Berto, F., Pereira, C. and Mateus, A. (2022), “Load sequence effects and cyclic deformation behaviour of 7075-T651 aluminium alloy”, *International Journal of Fatigue*, Vol. 155, p. 106593.

Brandt, A., Berardengo, M., Manzoni, S., Vanali, M. and Cigada, A. (2019), “Global scaling of operational modal analysis modes with the OMAH method”, *Mechanical Systems and Signal Processing*, Vol. 117, pp. 52–64.

Brincker, R., Andersen, P. and Jacobsen, N.J. (2007), “Automated frequency domain decomposition for operational modal analysis”, *Conference Proceedings of the Society for Experimental Mechanics Series*.

Brincker, R., Skafte, A., López-Aenlle, M., Sestieri, A., D’Ambrogio, W. and Canteli, A. (2014), “A local correspondence principle for mode shapes in structural dynamics”, *Mechanical Systems and Signal Processing*, Vol. 45 No. 1, pp. 91–104.

Brincker, R. and Ventura, C.E. (2015), *Introduction to Operational Modal Analysis*, John Wiley & Sons, Ltd, Chichester, UK, available at:https://doi.org/10.1002/9781118535141.

Brincker, R., Ventura, C.E. and Andersen, P. (2003), “Why Output-Only Modal Testing is a Desirable Tool for a Wide Range of Practical Applications”, *Proceedings of IMAC-21*.

British Standards Institution. (2005), “Eurocode 3: Design of steel structures.”, BSI, London.

Brownjohn, J.M.W., de Stefano, A., Xu, Y.L., Wenzel, H. and Aktan, A.E. (2011), “Vibration-based monitoring of civil infrastructure: Challenges and successes”, *Journal of Civil Structural Health Monitoring*, Vol. 1, pp. 79–95.

BS5400: Part 10. (1980), “Cycle Counting by the reservoir method”.

Cabboi, A., Magalhães, F., Gentile, C. and Cunha, Á. (2017), “Automated modal identification and tracking: Application to an iron arch bridge”, *Structural Control and Health Monitoring*, Vol. 24 No. 1, p. e1854.

Carden, E.P. and Fanning, P. (2004), “Vibration based condition monitoring: A review”, *Structural Health Monitoring*, Vol. 3 No. 4, pp. 355–377.

Castillo, E. and Fernández-Canteli, A. (2009), *A Unified Statistical Methodology for Modeling Fatigue Damage*, Springer Netherlands.

Castillo, E., Fernández-Canteli, A., López-Aenlle, M. and Ruiz Ripoll, M.L. (2007), “Some fatigue damage measures for longitudinal elements based on the Wohler field”, *Fatigue & Fracture of Engineering Materials and Structures*, Vol. 30 No. 11, pp. 1063–1075.

Cawley, P. (2018), “Structural health monitoring: Closing the gap between research and industrial deployment”, *Structural Health Monitoring*, Vol. 17 No. 5, pp. 1225–1244.

Česnik, M., Slavić, J. and Boltežar, M. (2012), “Uninterrupted and accelerated vibrational fatigue testing with simultaneous monitoring of the natural frequency and damping”, *Journal of Sound and Vibration*, Vol. 331 No. 24, pp. 5370–5382.

Chaboche, J.L. and Lesne, P.M. (1988), “A non-linear continuous fatigue damage model”, *Fatigue & Fracture of Engineering Materials and Structures*, Vol. 11 No. 1, pp. 1–17.

Chang, P.C., Flatau, A. and Liu, S.C. (2003), “Review paper: Health monitoring of civil infrastructure”, *Structural Health Monitoring*, Vol. 2 No. 3, pp. 257–267.

Chen, H.-P. and Ni, Y.-Q. (2018), *Structural Health Monitoring of Large Civil Engineering Structures*, Wiley-Blac., John Wiley & Sons, Ltd, Chichester, UK, available at:https://doi.org/10.1002/9781119166641.

Chhipwadia, K.S., Zimmerman, D.C. and James, G.H. (2000), “Evolving autonomous modal parameter estimation”, *Shock and Vibration Digest*.

Chopra, A.K. (2019), *Dynamics of Structures: Theory and Applications to Earthquake Engineering*, Pearson.

Christensen, S.S. (2020), *Vibration and Strain Monitoring of an Offshore Structure*, University of Southern Denmark, Faculty of Engineering.

Christensen, S.S. and Brandt, A. (2020), “Parameter study of statistics of modal parameter estimates using automated operational modal analysis”, *Dynamics of Civil Structures - Conference Proceedings of the Society for Experimental Mechanics Series*, Vol. 2, Springer, Cham, pp. 243–254.

Christensen, S.S., Manzoni, S., Vanali, M., Cigada, A. and Brandt, A. (2021), “Quantitative Study on the Modal Parameters Estimated Using the PLSCF and the MITD Methods and an Automated Modal Analysis Algorithm”, *Proceedings of the 38th IMAC, A Conference and Exposition on Structural Dynamics 2020.*, pp. 159–168.

Ciang, C.C., Lee, J.R. and Bang, H.J. (2008), “Structural health monitoring for a wind turbine system: A review of damage detection methods”, *Measurement Science and Technology*, Vol. 19 No. 12, p. 122001.

Clough, R.W. and Penzien, J. (1993), *Dynamics of Structures*, McGraw-Hill, New York.

Corten, H.. T. and Dolan, T.J. (1956), “Cumulative Fatigue Damage”, in Engineers, I. of M.E. and A.S. of M. (Ed.), *Proceedings of the International Conference on Fatigue of Metals*, pp. 235–42.

Crane, R.L. (2017), “7.17 Introduction to structural health monitoring”, *Comprehensive Composite Materials II*, pp. 355–357.

Dalpiaz, G., Del Rincón, A.F. and Mucchi, E. (2004), “Efficient computation of spectral moments for determination of random response statistics”, *Proceedings of the 2004 International Conference on Noise and Vibration Engineering, ISMA*, ISMA Publications, pp. 2677–2692.

Dascotte, E., Strobbe, J. and Tygesen, U.T. (2013), “Continuous Stress Monitoring of Large

Structures", *Proceedings of the 5th International Operational Modal Analysis Conference*.

Dederichs, A.C., Øiseth, O., Petersen, Ø.W. and Kvåle, K.A. (2023), "Comparison of Automated Operational Modal Analysis Algorithms for Long-Span Bridge Applications", *Conference Proceedings of the Society for Experimental Mechanics Series*, Springer, Cham, pp. 27–35.

Deraemaeker, A., Reynders, E., De Roeck, G. and Kullaa, J. (2008), "Vibration-based structural health monitoring using output-only measurements under changing environment", *Mechanical Systems and Signal Processing*, Vol. 22 No. 1, pp. 34–56.

Dervilis, N. (2013), *A Machine Learning Approach to Structural HealthMonitoring with a View towards Wind Turbines*, University of Sheffield.

Dirlik, T. (1985), *Application of Computers in Fatigue Analysis*, University of Warwick.

Dirlik, T. and Benasciutti, D. (2021), "Dirlik and Tovo-Benasciutti Spectral Methods in Vibration Fatigue: A Review with a Historical Perspective", *Metals*, Vol. 11 No. 9, p. 1333.

Doebling, S.W.S., Farrar, C.R.C., Prime, M.B.M. and Shevitz, D.W.D. (1996), "Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review", *Los Alamos National Laboratory*, available at:https://doi.org/10.2172/249299.

Dong, C.-Z. and Catbas, F.N. (2021), "A review of computer vision–based structural health monitoring at local and global levels", *Structural Health Monitoring*, Vol. 20 No. 2, pp. 692–743.

Ewins, D.J. (2000a), *Modal Testing: Theory, Practice and Application*, Wiley.

Ewins, D.J. (2000b), "Model validation: Correlation for updating", *Sadhana*, Vol. 25 No. 3, pp. 221–234.

Fan, W. and Qiao, P. (2011), "Vibration-based damage identification methods: A review and comparative study", *Structural Health Monitoring*, Vol. 10 No. 1, pp. 83–111.

Farrar, C.R. and Worden, K. (2012), *Structural Health Monitoring: A Machine Learning Perspective*, *Structural Health Monitoring: A Machine Learning Perspective*, available at:https://doi.org/10.1002/9781118443118.

Fassois, S.D. and Kopsaftopoulos, F.P. (2013), "Statistical Time Series Methods for Vibration Based Structural Health Monitoring", *New Trends in Structural Health Monitoring*, pp. 209–264.

Fatemi, A. and Yang, L. (1998), "Cumulative fatigue damage and life prediction theories: a survey of the state of the art for homogeneous materials", *International Journal of Fatigue*, Vol. 20 No. 1, pp. 9–34.

Fernández-Canteli, A., Blasón, S., Correia, J.A.F.O. and de Jesus, A.M.P. (2014), "A probabilistic interpretation of the Miner number for fatigue life prediction", *Frattura Ed Integrità Strutturale*, Vol. 8 No. 30, pp. 327–339.

Fernández, P., Aenlle, M.L., Brincker, R. and Canteli, A.F. (2009), "Stress estimation in structures using operational modal analysis", *IOMAC 2009 - 3rd International Operational Modal Analysis Conference*.

Fiedler, M. and Vormwald, M. (2016), "Considering fatigue load sequence effects by applying the Local Strain Approach and a fracture mechanics based damage parameter", *Theoretical and Applied Fracture Mechanics*, Vol. 83, pp. 31–41.

Fotsch, D. and Ewins, D.J. (2000), “Application of MAC in the frequency domain.”, *Proc Int Modal Anal Conf - IMAC*.

Fox, C.H.J. (1992), “The location of defects in structures: A comparison of the use of natural frequency and mode shape data.”, *Proc., 10th Int. Modal Analysis Conf., San Diego*, pp. 522–528.

Frigui, F., Faye, J.P., Martin, C., Dalverny, O., Peres, F. and Judenherc, S. (2018), “Global methodology for damage detection and localization in civil engineering structures”, *Engineering Structures*, Elsevier, Vol. 171, pp. 686–695.

Friswell, M.I. and Mottershead, J.E. (1995), *Finite Element Model Updating in Structural Dynamics*, Vol. 38, Springer Netherlands, Dordrecht, available at:https://doi.org/10.1007/978-94-015-8508-8.

Fritzen, C.P. (2005), “Vibration-Based Structural Health Monitoring – Concepts and Applications”, *Key Engineering Materials*, Vol. 293–294, pp. 3–20.

Fritzen, C.P. (2014), “Vibration-Based Methods for SHM”, *NATO STO, STO-EN-AVT-220*, Vol. 5, pp. 1–24.

Fu, Z.-F. and He, J.H. (2001), *Modal Analysis*, Elsevier Ltd.

Fujimoto, Y., Shintaku, E., Pirker, G. and Liu, G. (2003), “Piezoelectric sensor for stress intensity factor measurement of two dimensional cracks”, *Engineering Fracture Mechanics*, Vol. 70 No. 9, pp. 1203–1218.

Gao, Z. and Moan, T. (2008), “Frequency-domain fatigue analysis of wide-band stationary Gaussian processes using a trimodal spectral formulation”, *International Journal of Fatigue*, Elsevier, Vol. 30 No. 10–11, pp. 1944–1955.

Gardner, P. (2018), *On Novel Approaches to Model-Based Structural Health Monitoring*, University of Sheffield.

Goyal, D. and Pabla, B.S. (2016), “The Vibration Monitoring Methods and Signal Processing Techniques for Structural Health Monitoring: A Review”, *Archives of Computational Methods in Engineering*, Vol. 23, pp. 585–594.

Grover, H.J. (1960), “An observation concerning the cycle ratio in cumulative damage”, *Symposyum on Fatigue of Aircraft Structures*, American Society for Testing and Materials, Philadelphia, PA.

Guennec, B., Ueno, A., Sakai, T., Takanashi, M. and Itabashi, Y. (2014), “Effect of the loading frequency on fatigue properties of JIS S15C low carbon steel and some discussions based on micro-plasticity behavior”, *International Journal of Fatigue*, Vol. 66, pp. 29–38.

Guillaume, P., De Troyer, T., Devriendt, C. and De Sitter, G. (2006), “OMAX - A combined experimental-operational modal analysis approach”, *Proceedings of ISMA2006: International Conference on Noise and Vibration Engineering*.

Gulgec, N.S., Takáč, M. and Pakzad, S.N. (2020), “Structural sensing with deep learning: Strain estimation from acceleration data for fatigue assessment”, *Computer-Aided Civil and Infrastructure Engineering*, Vol. 35 No. 12, pp. 1349–1364.

Gunes, B. and Gunes, O. (2013), “Structural health monitoring and damage assessment Part I: A critical review of approaches and methods”, *International Journal of Physical Sciences*, Vol. 8 No. 34, pp. 1694–1702.

Haibach, E. (1970), "The allowable stresses under variable amplitude loading.", *Proceeding Conf. Fatigue Welded Struct*, Gurney TR, TWI – The Welding Institute: Cambridge, pp. 328–339.

Hajela, P. and Soeiro, F.J. (1990), "Structural damage detection based on static and modal analysis", *AIAA Journal*, Vol. 28 No. 6, pp. 1110–1115.

Hanly, S. (2016), *Shock Vibration Testing Overview EBook*, Mide Technology.

He, M., Liang, P., Zhang, Y., Yang, F. and Liu, J. (2022), "Unified method for fully automated modal identification and tracking with consideration of sensor deployment", *Engineering Structures*, Vol. 260, p. 114223.

Henkel, M., Häfele, J., Weijtjens, W., Devriendt, C., Gebhardt, C.G. and Rolfes, R. (2020), "Strain estimation for offshore wind turbines with jacket substructures using dual-band modal expansion", *Marine Structures*, Vol. 71, p. 102731.

Henkel, M., Weijtjens, W. and Devriendt, C. (2019), "Validation of virtual sensing on subsoil strain data of an offshore wind turbine", *8th IOMAC - International Operational Modal Analysis Conference, Proceedings*, pp. 765–774.

Heylen, W., Lammens, S. and Sas, P. (2007), *Modal Analysis Theory and Testing*, Katholieke Universiteit Leuven, Belgium.

Hjelm, H.P., Brincker, R., Graugaard-Jensen, J. and Munch, K. (2005), "Determination of Stress Histories in Structures by Natural Input Modal Analysis", *Proceedings of IMAC-XXIII*.

Iliopoulos, A., Weijtjens, W., Van Hemelrijck, D. and Devriendt, C. (2017), "Fatigue assessment of offshore wind turbines on monopile foundations using multi-band modal expansion", *Wind Energy*, Vol. 20 No. 8, pp. 1463–1479.

ISO 13819-2:1995. (1995), "Petroleum and Natural Gas Industries - Offshore Structures - Part 2: Fixed Steel Structures."

Jeary, A.P. (1998), *Designer's Guide to the Dynamic Response of Structures*, CRC Press.

Jiang, Y., Yun, G.J., Zhao, L. and Tao, J. (2015), "Experimental Design and Validation of an Accelerated Random Vibration Fatigue Testing Methodology", *Shock and Vibration*, pp. 1–13.

Johannesson, P. (2002), "On rainflow cycles and the distribution of the number of interval crossings by a Markov chain", *Probabilistic Engineering Mechanics*, Vol. 17 No. 2, pp. 123–130.

Kachanov, L.M. (1984), "Time to the rupture process under creep conditions", *Izvestiia AN SSSR*, Vol. OTN No. 8, pp. 26–31.

Kappos, A. (2001), *Dynamic Loading and Design of Structures*, CRC Press.

Khodabandehlou, H., Pekcan, G. and Fadali, M.S. (2019), "Vibration-based structural condition assessment using convolution neural networks", *Structural Control and Health Monitoring*, Vol. 26 No. 2, pp. 1545–2255.

Kondo, Y. (2003), "Fatigue under Variable Amplitude Loading", *Comprehensive Structural Integrity*, Vol. 4 — Cyclic, pp. 253–280.

Kong, C., Zhao, D., Zhang, J. and Liang, B. (2022), "Real-Time Virtual Sensing for Dynamic Vibration of Flexible Structure via Fiber Bragg Grating Sensors", *IEEE Sensors Journal*, pp. 1–1.

Kralovec, C. and Schagerl, M. (2020), “Review of Structural Health Monitoring Methods Regarding a Multi-Sensor Approach for Damage Assessment of Metal and Composite Structures”, *Sensors*, Vol. 20 No. 3, p. 826.

Kullaa, J. (2010), “Vibration-Based Structural Health Monitoring Under Variable Environmental or Operational Conditions”, *New Trends in Vibration Based Structural Health Monitoring*, pp. 107–181.

Lalanne, C. (2013), *Mechanical Vibration and Shock Analysis*, 3rd ed., John Wiley & Sons.

Langer, B.F. (1937), “Fatigue Failure From Stress Cycles of Varying Amplitude”, *Journal of Applied Mechanics*, Vol. 4 No. 4, pp. A160–A162.

Lee, Y.J. and Cho, S. (2016), “Shm-based probabilistic fatigue life prediction for bridges based on fe model updating”, *Sensors (Switzerland)*, Vol. 16 No. 3, p. 317.

Lein, C. and Beitelschmidt, M. (2014), “Comparative study of model correlation methods with application to model order reduction”, *Proceedings 26th ISMA (International Conference on Noise and Vibration Engineering)*.

Leonetti, D., Maljaars, J. and Snijder, H.H. (Bert). (2021), “Fracture mechanics based fatigue life prediction for a weld toe crack under constant and variable amplitude random block loading—Modeling and uncertainty estimation”, *Engineering Fracture Mechanics*, Vol. 242, p. 107487.

Li, H., Li, S., Ou, J. and Li, H. (2009), “Modal identification of bridges under varying environmental conditions: Temperature and wind effects”, *Structural Control and Health Monitoring*, p. n/a-n/a.

Li, H.N., Yi, T.H., Ren, L., Li, D.S. and Huo, L.S. (2014), “Reviews on innovations and applications in structural health monitoring for infrastructures”, *Structural Monitoring and Maintenance*, Vol. 1 No. 1, pp. 1–45.

Li, J., Bao, T. and Ventura, C.E. (2022), “An automated operational modal analysis algorithm and its application to concrete dams”, *Mechanical Systems and Signal Processing*, Vol. 168, p. 108707.

Lindgren, G. and Rydén, J. (2002), “Transfer-function approximations of the rainflow filter”, *Mechanical Systems and Signal Processing*, Vol. 16 No. 6, pp. 979–989.

López-Aenlle, M., Brincker, R. and Fernández-Canteli, A. (2005), “Some Methods to Determine Scaled Mode Shapes in Natural Input Modal Analysis”, *IMAC-XXIII : A Conference & Exposition on Structural Dynamics*, Society for Experimental Mechanics, p. 11.

López-Aenlle, M., Fernández, P., Brincker, R. and Fernández-Canteli, A. (2010), “Erratum to ‘Scaling-factor estimation using an optimized mass-change strategy’ [Mech. Syst. Signal Process. 24(5) (2010) 1260–1273]”, *Mechanical Systems and Signal Processing*, Vol. 24 No. 8, pp. 3061–3074.

López-Aenlle, M., Hermanns, L., Pelayo, F. and Fraile, A. (2013), “Stress Estimation in a Scale Model of a Symetric Two Story Building”, *Proceedings of the 5th International Operational Modal Analysis Conference*.

Lynch, J.P. (2006), “A Summary Review of Wireless Sensors and Sensor Networks for Structural Health Monitoring”, *The Shock and Vibration Digest*, Vol. 38 No. 2, pp. 91–128.

Magalhães, F., Cunha, A. and Caetano, E. (2012), “Vibration based structural health monitoring of an arch bridge: From automated OMA to damage detection”, *Mechanical Systems and*

Signal Processing, Vol. 28, pp. 212–228.

Manson, S.S. and Halford, G.R. (1986), "Re-examination of cumulative fatigue damage analysis—an engineering perspective", *Engineering Fracture Mechanics*, Vol. 25 No. 5–6, pp. 539–571.

Marco, S.M. and Starkey, W.L. (1954), "A concept of fatigue damage", *Transactions ASME*, Vol. 76, pp. 627–632.

Marwala, T., Boulkaibet, I. and Adhikari, S. (2016), *Probabilistic Finite Element Model Updating Using Bayesian Statistics: Applications to Aeronautical and Mechanical Engineering*, John Wiley & Sons, Ltd, Chichester, UK, available at:https://doi.org/10.1002/9781119153023.

Matsuishi, M. and Endo, T. (1968), "Fatigue of metals subject to varying stress", *Proc. Kyushu District Meeting*, Fukuoka, Japan, pp. 37–40.

Mendes Maia, N. and Montalvão Silva, J. (1997), *Theoretical and Experimental Modal Analysis.*, Research Studies Press.

Miner, M.A. (1945), "Cumulative Damage in Fatigue", *Journal of Applied Mechanics*, Vol. 12 No. 3, pp. A159–A164.

Mitra, M. and Gopalakrishnan, S. (2016), "Guided wave based structural health monitoring: A review", *Smart Materials and Structures*, Vol. 25 No. 5, p. 053001.

Montalvão, D., Maia, N.M.M. and Ribeiro, A.M.R. (2006), "A review of vibration-based structural health monitoring with special emphasis on composite materials", *Shock and Vibration Digest*, Vol. 38 No. 4, p. 295.

Moore, E.Z., Nichols, J.M. and Murphy, K.D. (2012), "Model-based SHM: Demonstration of identification of a crack in a thin plate using free vibration data", *Mechanical Systems and Signal Processing*, Vol. 29, pp. 284–295.

Mršnik, M., Slavič, J. and Boltežar, M. (2013), "Frequency-domain methods for a vibration-fatigue-life estimation - Application to real data", *International Journal of Fatigue*, Vol. 47, pp. 8–17.

Nabuco, B., Tarpø, M., Tygesen, U.T. and Brincker, R. (2020), "Fatigue Stress Estimation of an Offshore Jacket Structure Based on Operational Modal Analysis", *Shock and Vibration*, Vol. 2020, pp. 1–12.

Natke, H.G. and Cempel, C. (1991), "Fault detection and localisation in structures: a discussion", *Mechanical Systems and Signal Processing*, Vol. 5 No. 5, pp. 345–356.

Neu, E., Janser, F., Khatibi, A.A. and Orifici, A.C. (2017), "Fully Automated Operational Modal Analysis using multi-stage clustering", *Mechanical Systems and Signal Processing*, Vol. 84, Part A, pp. 308–323.

Newland, D.E. (2005), *An Introduction to Random Vibrations, Spectral & Wavelet Analysis*, Dover Publications Inc.

Noppe, N., Tatsis, K., Chatzi, E., Devriendt, C. and Weijtjens, W. (2018), "Fatigue stress estimation of offshore wind turbine using a Kalman filter in combination with accelerometers", *Proceedings of International Conference on Noise and Vibration Engineering (ISMA 2018), International Conference on Uncertainty in Structural Dynamics (USD 2018)*, pp. 4847–4855.

NORSOK Standar. (2004), "Design of Steel Structures".

Pallarés, F.J., Betti, M., Bartoli, G. and Pallarés, L. (2021), “Structural health monitoring (SHM) and Nondestructive testing (NDT) of slender masonry structures: A practical review”, *Construction and Building Materials*, Vol. 297, p. 123768.

Palmgren, A. (1924), “Die lebensdauer von kugellagern”, *VDI-Zetischrift*, Vol. 68, pp. 339–341.

Pandey, A.K. and Biswas, M. (1994), “Damage Detection in Structures Using Changes in Flexibility”, *Journal of Sound and Vibration*, Vol. 169 No. 1, pp. 3–17.

Pandey, A.K. and Biswas, M. (1995), “Damage diagnosis of truss structures by estimation of flexibility change”, *Int. J. Anal. Exper. Modal Anal.*, Vol. 10 No. 2, pp. 104–117.

Pandey, A.K., Biswas, M. and Samman, M.M. (1991), “Damage detection from changes in curvature mode shapes”, *Journal of Sound and Vibration*, Vol. 145 No. 2, pp. 321–332.

Papadimitriou, C., Fritzen, C.-P., Kraemer, P. and Ntotsios, E. (2011), “Fatigue predictions in entire body of metallic structures from a limited number of vibration sensors using Kalman filtering”, *Structural Control and Health Monitoring*, Vol. 18 No. 5, pp. 554–573.

Park, K.C. and Reich, Gregory W. (1999), “Model-Based Health Monitoring Of Structural Systems: Progress, Potential And Challengetle”, *Proceedings of the 2nd International Workshop on Structural Health Monitoring*.

Peeters, B. and De Roeck, G. (2001), “One-year monitoring of the Z24-Bridge: environmental effects versus damage events”, *Earthquake Engineering & Structural Dynamics*, Vol. 30 No. 2, pp. 149–171.

Pelayo, F., Skafte, A., Aenlle, M.L. and Brincker, R. (2015), “Modal Analysis Based Stress Estimation for Structural Elements Subjected to Operational Dynamic Loadings”, *Experimental Mechanics*, Vol. 55 No. 9, pp. 1791–1802.

Quigley, J.P., Lee, Y.-L. and Wang, L. (2016), “Review and Assessment of Frequency-Based Fatigue Damage Models”, *SAE International Journal of Materials and Manufacturing*, Vol. 9 No. 3, pp. 2016-01–0369.

Rabotnov, Y.N. (1969), *Creep Problems in Structural Members*, North Holland, Amsterdam.

Rainieri, C. and Fabbrocino, G. (2010), “Automated output-only dynamic identification of civil engineering structures”, *Mechanical Systems and Signal Processing*, Vol. 24 No. 3, pp. 678–695.

Rainieri, C. and Fabbrocino, G. (2014), *Operational Modal Analysis of Civil Engineering Structures*, Springer New York, New York, NY, available at:https://doi.org/10.1007/978-1-4939-0767-0.

Rainieri, C. and Fabbrocino, G. (2015), “Development and validation of an automated operational modal analysis algorithm for vibration-based monitoring and tensile load estimation”, *Mechanical Systems and Signal Processing*, Vol. 60–61, pp. 512–534.

Rainieri, C., Fabbrocino, G. and Cosenza, E. (2007), “Automated Operational Modal Analysis as structural health monitoring tool: Theoretical and applicative aspects”, *Key Engineering Materials*, Vol. 347, pp. 479–484.

Rainieri, C., Magalhaes, F. and Ubertini, F. (2019), “Automated Operational Modal Analysis and Its Applications in Structural Health Monitoring”, *Shock and Vibration*, Vol. 2019, pp. 1–3.

Rao, Y.-J. (1997), “In-fibre Bragg grating sensors”, *Measurement Science and Technology*, Vol. 8 No. 4, pp. 355–375.

Reynders, E., Houbrechts, J. and De Roeck, G. (2011), "Automated interpretation of stabilization diagrams", *Conference Proceedings of the Society for Experimental Mechanics Series*, Vol. 3, Springer New York LLC, pp. 189–201.

Reynders, E., Houbrechts, J. and De Roeck, G. (2012), "Fully automated (operational) modal analysis", *Mechanical Systems and Signal Processing*, Vol. 29, pp. 228–250.

Ribeiro, J.G., De Castro, J.T. and Freire, J.L. (2003), "Using the FFT-DDI method to measure displacements with piezoelectric, resistive and ICP accelerometers", *Conference and Exposition on Structural Dynamics*.

Richart, F.E. and Newmark, N.M. (1948), "A hypothesis for the determination of cumulative damage in fatigue", *Proc., Am. Soc. Test. Mater*, Vol. 48, pp. 767–800.

Rigner, L., Golinval, J. and Razeto, M. (1998), "Modal assurance criteria value for two orthogonal modal vectors.", *Proceedings of the International Modal Analysis Conference - IMAC*.

Rossi, G., Marsili, R., Gusella, V. and Gioffrè, M. (2002), "Comparison between Accelerometer and Laser Vibrometer to Measure Traffic Excited Vibrations on Bridges", *Shock and Vibration*, Vol. 9 No. 1–2, pp. 11–18.

Rychlik, I. (1993), "Note on cycle counts in irregular loads", *Fatigue & Fracture of Engineering Materials and Structures*, Vol. 16 No. 4, pp. 377–390.

Rychlik, I. (1996a), "Extremes, rainflow cycles and damage functionals in continuous random processes", *Stochastic Processes and Their Applications*, Vol. 63 No. 1, pp. 97–116.

Rychlik, I. (1996b), "Simulation of load sequences from rainflow matrices: Markov method", *International Journal of Fatigue*, Vol. 18 No. 7, pp. 429–438.

Rytter, A. and Kirkegaard, P.H.P. (1994), *Vibration Based Inspection of Civil Engineering Structures*, Aalborg University.

Sahota, J.K., Gupta, N. and Dhawan, D. (2020), "Fiber Bragg grating sensors for monitoring of physical parameters: a comprehensive review", *Optical Engineering*, Vol. 59 No. 06, p. 1.

Saisi, A., Gentile, C. and Ruccolo, A. (2016), "Pre-diagnostic prompt investigation and static monitoring of a historic bell-tower", *Construction and Building Materials*, Vol. 122, pp. 833–844.

Salawu, O.S. (1995), "Non-destructive assessment of structures using the integrity index method applied to a concrete highway bridge", *Insight, 37(11)*, pp. 875–878.

Santecchia, E., Hamouda, A.M.S., Musharavati, F., Zalnezhad, E., Cabibbo, M., El Mehtedi, M. and Spigarelli, S. (2016), "A Review on Fatigue Life Prediction Methods for Metals", *Advances in Materials Science and Engineering*, Vol. 2016, pp. 1–26.

Schijve, J. (2008), *Fatigue of Structures and Materials*, Springer.

Sherratt, F., Bishop, N.W.M. and Dirlik, T. (2005), "Predicting fatigue life from frequency-domain data", *Eng. Integr.*, Vol. 18, pp. 12–16.

Shokrani, Y., Dertimanis, V.K., Chatzi, E.N. and N. Savoia, M. (2018), "On the use of mode shape curvatures for damage localization under varying environmental conditions", *Structural Control and Health Monitoring*, Vol. 25 No. 4, p. e2132.

Si-Jian, L., Wei, L., Da-Qing, T. and Jun-Bi, L. (2018), "A new fatigue damage accumulation model considering loading history and loading sequence based on damage equivalence", *International Journal of Damage Mechanics*, Vol. 27 No. 5, pp. 707–728.

Simiu, E. and Yeo, D. (2019), *Wind Effects on Structures*, Wiley-Blackwell.

Sirohi, J. and Chopra, I. (2000), "Fundamental Understanding of Piezoelectric Strain Sensors", *Journal of Intelligent Material Systems and Structures*, Vol. 11 No. 4, pp. 246–257.

Slavič, J., Mršnik, M., Cesnik, M., Javh, J. and Boltežar, M. (2020), *Vibration Fatigue by Spectral Methods: From Structural Dynamics to Fatigue Damage - Theory and Experiments*, Elsevier, available at:https://doi.org/10.1016/C2019-0-04580-3.

Śledziewski, K. (2017), "Fatigue assessment of bridge structures accoding to Eurocodes", *Journal of Civil Engineering, Environment and Architecture*, Vol. 64, pp. 185–204.

Sohn, H. (2007), "Effects of environmental and operational variability on structural health monitoring", *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 365 No. 1851, pp. 539–560.

Sohn, H., Farrar, C.R., Hemez, F.M. and Czarnecki, J.J. (2003), "A Review of Structural Health Monitoring Literature : 1996-2001", *Los Alamos National Laboratory, USA*, Vol. 1, p. 16.

Stubbs, N. and Kim, J.-T. (1996), "Damage localization in structures without baseline modal parameters", *AIAA Journal*, Vol. 34 No. 8, pp. 1644–1649.

Stull, C.J., Earls, C.J. and Koutsourelakis, P.S. (2011), "Model-based structural health monitoring of naval ship hulls", *Computer Methods in Applied Mechanics and Engineering*, Vol. 200 No. 9–12, pp. 1137–1149.

Su, L., Zhang, J.Q., Huang, X. and LaFave, J.M. (2021), "Automatic operational modal analysis of structures based on image recognition of stabilization diagrams with uncertainty quantification", *Multidimensional Systems and Signal Processing*, Springer, Vol. 32 No. 1, pp. 335–357.

Sun, M., Makki Alamdari, M. and Kalhori, H. (2017), "Automated Operational Modal Analysis of a Cable-Stayed Bridge", *Journal of Bridge Engineering*, Vol. 22 No. 12, p. 05017012.

Suresh, S. (1998), *Fatigue of Material*, Cambridge University Press.

Taher, S.A., Li, J., Jeong, J.-H., Laflamme, S., Jo, H., Bennett, C., Collins, W.N., *et al.* (2022), "Structural Health Monitoring of Fatigue Cracks for Steel Bridges with Wireless Large-Area Strain Sensors", *Sensors*, Vol. 22 No. 14, p. 5076.

Tarpø, M., Nabuco, B., Georgakis, C. and Brincker, R. (2020), "Expansion of experimental mode shape from operational modal analysis and virtual sensing for fatigue analysis using the modal expansion method", *International Journal of Fatigue*, Vol. 130, p. 105280.

Tewolde, S., Höffer, R. and Haardt, H. (2017), "Validated model based development of damage index for Structural Health Monitoring of offshore wind turbine support structures", *Procedia Engineering*, Vol. 199, pp. 3242–3247.

Tibaduiza, D., Torres-Arredondo, M.Á., Vitola, J., Anaya, M. and Pozo, F. (2018), "A Damage Classification Approach for Structural Health Monitoring Using Machine Learning", *Complexity*, Vol. 2018, pp. 1–14.

Toksoy, T. and Aktan, A.E. (1994), "Bridge-condition assessment by modal flexibility", *Experimental Mechanics*, Vol. 34 No. 3, pp. 271–278.

Tovo, R. (2002), "Cycle distribution and fatigue damage under broad-band random loading", *International Journal of Fatigue*, Vol. 24 No. 11, pp. 1137–1147.

Ubertini, F., Comanducci, G. and Cavalagli, N. (2016), "Vibration-based structural health monitoring of a historic bell-tower using output-only measurements and multivariate statistical analysis", *Structural Health Monitoring*, Vol. 15 No. 4, pp. 438–457.

Ubertini, F., Comanducci, G., Cavalagli, N., Laura Pisello, A., Luigi Materazzi, A. and Cotana, F. (2017), "Environmental effects on natural frequencies of the San Pietro bell tower in Perugia, Italy, and their removal for structural performance assessment", *Mechanical Systems and Signal Processing*, Vol. 82, pp. 307–322.

Ubertini, F., Gentile, C. and Materazzi, A.L. (2013), "Automated modal identification in operational conditions and its application to bridges", *Engineering Structures*, Vol. 46, pp. 264–278.

Vacher, P., Jacquier, B. and Bucharles, A. (2010), "Extensions of the MAC criterion to complex modes", *Proceedings of ISMA 2010 - International Conference on Noise and Vibration Engineering, Including USD 2010*, pp. 2713–2725.

Viana, C.O., Carvalho, H., Correia, J., Montenegro, P.A., Heleno, R.P., Alencar, G.S., Jesus, A.M.P. de, *et al.* (2019), "Fatigue assessment based on hot-spot stresses obtained from the global dynamic analysis and local static sub-model", *International Journal of Structural Integrity*, Vol. 12 No. 1, pp. 31–47.

Wahab, M., Roeck, G. and Peeters, B. (1999), "On the application of FE model updating to damaged concrete beams", *Proceedings of the International Conference on Identification in Engineering Systems*.

Warren, C., Niezrecki, C., Avitabile, P. and Pingle, P. (2011), "Comparison of FRF measurements and mode shapes determined using optically image based, laser, and accelerometer measurements", *Mechanical Systems and Signal Processing*, Vol. 25 No. 6, pp. 2191–2202.

Warren, C., Pingle, P., Niezrecki, C. and Avitabile, P. (2011), "Comparison of Image Based, Laser, and Accelerometer Measurements", *Structural Dynamics, Volume 3.*, pp. 15–21.

Watson, P., Smith, K.N. and Topper, T.H. (1970), "A stress-strain function for the fatigue of metals", *J Mater*, Vol. 5 No. 4, pp. 767–778.

Wei, H. and Liu, Y. (2020), "An energy-based model to assess multiaxial fatigue damage under tension-torsion and tension-tension loadings", *International Journal of Fatigue*, Vol. 141, p. 105858.

West, W.M. (1984), "Illustration of the use of modal assurance criterion to detect structural changes in an orbiter test specimen", *Proceedings in Air Force Conference on Aircraft Structural Integrity*, pp. 1–6.

Wirsching, P.H., Paez, T.L. and Ortiz, K. (1995), *Random Vibrations. Theory and Practice*, 1st ed., John Wiley & Sons, New York.

Wu, G., He, M., Liang, P., Ye, C. and Xu, Y. (2020), "Automated Modal Identification Based on Improved Clustering Method", *Mathematical Problems in Engineering*, Vol. 2020, p. 16.

Ye, X.W., Dong, C.Z. and Liu, T. (2016), "A Review of Machine Vision-Based Structural Health Monitoring: Methodologies and Applications", *Journal of Sensors*, Vol. 2016, p. 10.

Ye, X.W., Jin, T. and Yun, C.B. (2019), "A review on deep learning-based structural health monitoring of civil infrastructures", *Smart Structures and Systems*, Vol. 24 No. 5, pp. 567–585.

Zalaznik, A. and Nagode, M. (2011), “Frequency based fatigue analysis and temperature effect”, *Mater. Des.*, Vol. 32, pp. 4794–4802.

Zhao, W. and Baker, M.J. (1992), “On the probability density function of rainflow stress range for stationary Gaussian processes”, *International Journal of Fatigue*, Vol. 14 No. 2, pp. 121–135.

Zigo, M., Arslan, E., Mack, W. and Kepplinger, G. (2019), “Efficient frequency-domain based fatigue life estimation of spot welds in vehicle components”, *Forschung Im Ingenieurwesen*, Vol. 83 No. 4, pp. 921–931.

Zimmerman, D.C. and Kaouk, M. (1994), “Structural Damage Detection Using a Minimum Rank Update Theory”, *Journal of Vibration and Acoustics*, Vol. 116 No. 2, pp. 222–231.

Zini, G., Betti, M. and Bartoli, G. (2022), “A quality-based automated procedure for operational modal analysis”, *Mechanical Systems and Signal Processing*, Vol. 164, p. 108173.

Zonno, G., Aguilar, R., Castañeda, B., Boroschek, R. and Lourenço, P.B. (2017), “Laboratory evaluation of a fully automatic modal identification algorithm using automatic hierarchical clustering approach”, *Procedia Engineering*, Elsevier Ltd, Vol. 199, pp. 882–887.