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REVIEW ARTICLE

DAMAGE IDENTIFICATION AND ASSESSMENT IN RC STRUCTURES USING VIBRATION DATA: A REVIEW

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Abstract. Inspection of structural components for damage is essential to decision-making for the maintenance of such structures. There have been many studies to assess the reinforced concrete (RC) structural elements. However, the experimental approach is still based on the conventional static test, which is time-consuming, costly, has intensive equipment and labour requirements and causes major disruptions to the existing use. Modal testing provides an integrated approach, i.e. both local and global characteristics can be ascertained for structural assessment. Depending on the accessibility to damage elements, little or no disruption to the existing use is incurred during testing works. The approach towards structural assessment work provides not only a viable but also a robust, less expensive and powerful alternative to conventional techniques. This paper presents the background of the behaviour of the RC material at different loading and unloading conditions, in order to understand its effect on the modal parameters. The use of modal testing for support stiffness deterioration is highlighted and studies on the use of modal testing for classification of damage source are presented. Studies on the use of modal testing for detection of damage severity and location algorithms and procedures are also presented.

Keywords: RC composite action; support conditions; damage classification; damage detection; modal testing.

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Introduction

Many reinforced concrete (RC) structures, when exposed to various external loads such as earthquakes, traffic, blasts and vibrations, suffer damage and deterioration over the years. RC structures can also be subjected to damage due to internal causes or material characteristics such as corrosion of reinforcement bars, segregation of concrete materials and alkali-aggregate reactions. RC structures need to be monitored in order to predict any defect which may become serious and may cause a failure within their lifetime. Modal testing is one of the vibration analysis tools providing measurements of dynamic characteristics (natural frequency, mode shapes and modal damping) that enable designing for optical dynamic behaviour or solving structural dynamic problems in existing designs. Modal testing was first applied around 1940, in researches efforts aimed at deepening the understanding of aircrafts. The modern modal testing started from 1970 based on the commercial availability of the Fast Fourier Transform (FFT) spectrum analyser, transfer function analysis (TFA) and discrete acquisition data analysis, together with the viability of increasing smaller, less expensive and more powerful digital computers to process the data. The basic idea behind this approach is that modal parameters, i.e. natural frequency, mode shape and modal damping, are functions of physical properties of a structure, namely mass, damping and stiffness. Therefore, any change in the physical properties will cause detectable changes in the modal parameters.

This paper presents the background of the behaviour of the RC material, i.e. concrete and steel, at different loading conditions, in order to understand the composite action of the RC structural elements at

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different loading scenarios. Past studies on the support stiffness deterioration, i.e. elastic bearings for bridge girders and tall buildings, are highlighted and studies on the classification of damage source either due to the support stiffness deterioration or due to the defect of the structural element stiffness are presented. Studies on the detection of damage severity and location algorithms and procedures are presented.

1. Composite actions of RC structures

In the last two decades, investigations on the dynamic properties of structural elements have been the subject of numerous research works. The primary reason for this is the increase in awareness and interest in using dynamic testing techniques for the purposes of health monitoring and damage detection for engineering structures. The dynamic properties of any structural element are governed by the relationship of the material properties and the boundary conditions. For steel, the dynamic properties relate to steel element properties, which are assumed to be the same under different load and boundary conditions. For concrete elements, such as plain concrete, the dynamic properties are related to the behaviour of the concrete element, which will have varying behaviour under different load and boundary conditions. RC structural elements have composite effects due to the presence of different materials that form the RC elements. Therefore, in order to simplify the mechanical behaviour of RC elements, the boundary conditions are assumed to be the same under different conditions in lieu with the objective of this study.

Although many studies have been carried out in the field of mechanical behaviour of RC elements, research in this area is still ongoing due to the complexities that arise from the composite nature of the materials used (Marfia *et al.* 2004). Thus, any investigation on the relationship between the dynamic and static properties of RC elements should take into consideration the behaviour of each material under different conditions, the interaction between steel bar and concrete and its influence on the overall element stiffness. When load is applied, the concrete stiffness in both tension and compression will change according to the loading levels and its behaviour under the compression or tension loading action. Cementitious materials are characterised by a softening response, which can vary depending on its strength in compression and tension. Experimental results show that these materials exhibit brittle behaviour in tension and inelastic deformation accompanied by damage effects in compression (Marfia *et al.* 2004). Steel stiffness will be governed by the stress–strain relationship obtained from tensile tests. The interacting forces in the interface element between the steel and concrete elements have zero value when no load is applied but increase correspondingly when load is gradually applied to resist the slipping of the steel bar.

Concrete is a material with a hugely heterogeneous internal structure. The presence of micro-cracks in the transition zone between the cement paste and the aggregate prior to any load application can be viewed as a source of weakness in the structure of the concrete (Neville, Brooks 1987). Some micro-cracks may develop during loading because of the difference in stiffness between the aggregate and the mortar. The gradual growth of these micro-cracks with further loading contributes to the nonlinear behaviour of concrete (Chen 1982). Concrete can behave as either a linear or a nonlinear material depending on the nature and the level of the induced stresses. Many experimental studies on the behaviour of concrete under uniaxial and multiaxial loading have been performed in the past.

The stress–strain relationship for concrete subjected to uniaxial compression is nearly linear elastic up to about 30% of its maximum compressive strength (f'_c). For stresses beyond this point, there is a gradual increase in curvature up to about $0.75f'_c$–$0.9f'_c$, after which it bends more sharply and approaches the peak point at f'_c. Beyond this peak, the stress–strain relationship has a descending trend until crushing failure occurs at some ultimate strain, ε_u, (Karsan, Jirsa 1969). The stress level of about 30% of f'_c has been termed the onset of localised cracking and has been proposed as a limit of elasticity (Kotsovos, Newman 1977). For concrete under uniaxial tensile stress, the stress–strain relationship has many similarities to that of uniaxial compression. Generally, at a stress level less than 60% of the tensile strength, the appearance of new micro-cracks is negligible. So, this stress level will correspond to a limit in elasticity. Beyond this level of stress, the growth of micro-cracks begins. The direction of crack propagation for uniaxial tension is transverse to the stress direction. The growth of each new crack will reduce the available load-carrying area and this reduction causes an increase in the stresses at critical crack tips. The failure in tension is caused by a few bridging cracks rather than by a higher number of cracks, as is the case for compressive states of stress (Hughes, Chapman 1966). Under different combinations of biaxial loading, concrete exhibits strength and stress–strain behaviour somewhat different from that under uniaxial conditions. For biaxial compression states, the maximum strength increases by approximately 25% at a stress ratio of 0.5, and 16% at a stress ratio of 1.0 (Kupfer *et al.* 1969). Under biaxial tension, concrete exhibits a constant strength (Kupfer *et al.* 1969) or a slight increase in tensile strength compared to values obtained under uniaxial loading (Tasuji *et al.* 1978). Under biaxial compression–tension, the compressive strength decreases almost linearly as the applied tensile stress is increased.

In plain and RC structures, cracking is not a perfectly brittle phenomenon and experimental evidence shows that the tensile stresses normal to a cracking plane are gradually released as the crack width increases. For RC structures where the behaviour is characterised by the formation of many closely spaced cracks, the nature of the stress release is further complicated by the restraining effect of the reinforcing steel. After cracking, the concrete stresses drop to zero and the steel supports the full load. The concrete between the cracks, however, still carries some tensile stresses. This ability of concrete to share the tensile load with the reinforcement is termed the tension-stiffening phenomenon (Chen 1982).

The tension-stiffening effect of concrete has been studied using two procedures. First, the tension portion of the concrete stress–strain curve was given a descending branch. This form of the tension-stiffening effect was first introduced by Scanlon (1971). Descending branches of many different shapes were employed, e.g. linear, bilinear and curved shapes. The second was to increase the steel stiffness. The additional stress in the steel represents the total tensile force carried by both the steel and the concrete between the cracks (Chen 1982). The tension-stiffening effect plays an important role in the post-cracking behaviour (Stramandinoli, La Lovere 2008).

Several mechanisms exist by which shear is transferred across RC sections. Among these mechanisms is the shear stiffness of the un-'cracked' portion of concrete, aggregate interlocking in the crack surface (or interface shear transfer), dowel action in the reinforcement bars and the combined effect of tension in reinforcement and arching action in concrete. For the shear transfer across the cracked concrete planes crossed by reinforcement, the two major mechanisms involved are the dowel action and the aggregate interlock. Shear transfer by these two mechanisms is accompanied by slippage or relative movement of crack surfaces. In the dowel action, shear forces are partially resisted by the stiffness of reinforcing bars because slippage imposes bearing forces on the bars in the opposite direction. The aggregate interlocking mechanism is of frictional nature. Slippage causes the irregular surfaces of the crack to separate slightly. Tensile stresses created in the steel bars by the separation of crack surfaces in turn develop into similar shear resistance (AlShaarbaf 1990).

Compared to concrete, steel is a much simpler material to represent. Its stress–strain behaviour is identical in tension and compression. The uniaxial stress–strain behaviour of reinforcement is represented by an elastic-linear work-hardening model. Steel will have linear behaviour till yield. Before the yield of steel, there is no change in steel stiffness during the unloading stage. Beyond the yield point, however, steel will exhibit nonlinear behaviour resulting in a decrease in steel stiffness at the unloading stage (AlShaarbaf 1990).

The fundamental role of the bond between steel and surrounding concrete through bond-slip is particularly remarkable in the cyclic behaviour of RC structures, where bond deterioration can occur due to damage caused by the load reversals. The definition of a suitable bond-slip mechanism is a widely discussed problem. The first study dates back to the 1960s. Rehm (1961) showed the existence of a slip between a steel bar and concrete and the related bond action. Subsequent to this study, many experimental and numerical relationships between bond stress and slip have been proposed (Marfia *et al.* 2004). The tension-stiffening action cannot be neglected (Marfia *et al.* 2004). The effect of longitudinal cracks on bond behaviour was significant, for when the crack width increased twofold, the bond strength also decreased twofold (Lindorf *et al.* 2009). A mathematical model for calculation of stress distribution along the steel–concrete interface for cracked RC beams was developed by Khalfallah (2008). It is realised that the mechanical phenomena occurring at the steel–concrete interface are complex. For low values of the stress at the interface, the bond efficiency is ensured mostly by chemical adhesion; this phase can be modelled by linear elastic behaviour. For higher values of the stresses, the chemical adhesion breaks down and micro-cracks appear. When micro-cracks develop into tensile cracks, tensile stress is transmitted from the steel to the concrete by means of bonding action. The stress–strain redistribution occurs along the structural elements, which in turn causes the stiffness of the element at tension zone to increase. When the applied load increases, the bonding action will increase, respectively, unless a slip occurs. Bonding actions are affected by many parameters, such as surrounding concrete properties and steel bar properties. Different shapes of steel bars, such as a deformed bar, will show different bonding actions compared to smooth bars, while steel bar diameters affect the interaction bonding area (Wang, Liu 2003; Ichinose *et al.* 2004; Fang *et al.* 2006; Berto *et al.* 2008; Haskett *et al.* 2008; Dahou *et al.* 2009; Wang 2009).

2. Damage source classification

A current alternative to conventional structural testing methods is dynamic testing, which acquires modal parameters and relates these to the health status of a structure. The fundamental idea underlying the dynamic approach is that modal parameters, namely natural frequency, mode shape and modal damping, are functions of physical properties of the structure, such as mass, damping, stiffness and the support conditions. Therefore, any change in the physical properties or support conditions will cause detectable changes in the modal parameters.

Several studies on the use of the modal parameters as an indicator for damage identification have been conducted. Some of these studies were concerned with issues related to use of these modal parameters in determining the magnitude and localisation of damage based on the relationship between dynamic and physical properties, and concluded that modal parameters are good indicators for damage detection (Doebling *et al.* 1998; Choubey *et al.* 2006; Zonta *et al.* 2008; Todorovska, Trifunac 2010; Zhong, Oyadiji 2011).

Elastic bearing pads are widely used for supporting bridge girders and as base isolation for tall buildings to reduce seismic demand. The bearings are exposed to various loading conditions and environmental changes which cause deterioration of its stiffness with time. Monitoring of changes in elastic bearing stiffness is very important for ensuring timely maintenance or replacement to prevent occurrence of any serious damage to the structure. Many previous studies have used elastic bearing isolation systems to reduce seismic demand on structures and many books have been written contributing to the design of these systems (Skinner *et al.* 1993; Naeim, Kelly 1999). Various types of elastic bearings have been introduced as isolation systems. A variety of isolation bearing devices have been developed and used practically for seismic design of buildings during the last 20 years in many countries. The detailed reviews on the isolation systems in bridges and buildings were reported by Kelly (1986), Buckle and Mayes (1990) and Jangid and Datta (1995). The isolation system worked by deflecting through the dynamics of the system and not by absorbing the earthquake energy (Kelly 1997). The difference in damping of the structure and the isolation system leads to the combination of motion equations and will need a complex model to analyse the system correctly (Tsai, Kelly 1993). The retrofit of an existing bridge by installation of bearing rubbers between the superstructure and the supporting columns was conducted by Kelly *et al.* (1984) and it improved the earthquake performance. The seismic response of a bridge structure with a seismic isolation system was examined by Xiaoming (1989), Tongaonkar and Jangid (1998), Abe *et al.* (2000), Jangid (1996) and Adachi *et al.* (2000). They found from the analysis that base isolation effect was present in all bridges. The isolation effectiveness was found to decrease corresponding to the increase in the flexibility of the supporting structure and vice versa.

The experimental results demonstrated a substantial reduction of the seismic substructure forces in comparison to the response of the non-isolated bridge (Tsopelas *et al.* 1996). Isolated bridges are found to be extremely sensitive to the characteristics of the ground motion due to low redundancy and domination of the deck mode of vibration (Reinhorn *et al.* 1998). Force and free-vibration tests were carried out on Ohito Viaduct Bridge 2, which was isolated by lead-rubber bearings (Ando *et al.* 1998). The frequencies were dependent on the exciting force since the amplitude reliance of the equivalent stiffness isolator and the isolator stiffness were found to be dependent on the displacement amplitude even in the linear range. A sliding-type base isolation system was found to be more effective than an LRB isolation system in case a stronger earthquake affected the bridge, based on the comparison of bridge dynamic characteristics (Sugiyama 2000). The flexibility of the bridge and reduction of the earthquake force using high-damping rubber bearing was done by Iwata *et al.* (2000), where bridge safety was confirmed through nonlinear dynamic analysis and a hybrid earthquake-loading test.

Some studies have also been carried out on the effect of support conditions on the dynamic properties of structures. The effect of support conditions on measured modal parameters was further investigated by Wolf (1984) and Carne and Dohrmam (1998), who validated the direct relationship between the support stiffness and the measured modal parameters obtained from previous studies. The effect of the change in the support conditions, due to loading process on the vibration characteristic of a rectangular plate was investigated by Souza (1994). A direct relationship was found between rubber stiffness and natural frequencies, whereby increase in rubber stiffness resulted in the increase in frequency (Dai *et al.* 2006). All the five longitudinal natural frequencies increased corresponding to the increase in the rubber pad stiffness and the first mode was the most affected by the rubber stiffness while the fifth mode was the least affected. Carne *et al.* (2007) investigated the effect of support stiffness and damping on measured modal frequencies and damping ratios using two different test models. The first model consisted of an extremely lightly damped beam that revealed changes in the measured modal frequency and damping. The second was a blade for a wind turbine, in which modal data were required to validate the analytical model of the blade. The changes in the measured modal parameters were significant and large enough that the support system was required to be taken into account when validating the analytical model of the blade. Investigation on the effect of stiffness of the supporting brace on the modal damping was done by Viola and Guidi (2009).

3. Damage detection (location and severity)

Numerous research works have been published in the field of damage detection and a variety of methods has been developed and proposed. Vibration test used for damage detection since 1970s and early 1980s by the offshore oil industry (Vandiver 1975; Begg *et al.* 1976; Coppolino, Rubin 1980). The basic idea behind this approach is that modal parameters, i.e. natural frequency, mode shape and modal damping, are functions of physical properties of structures, namely mass, damping and stiffness. Therefore, any change in the physical properties will cause detectable changes in the modal parameters. Cracks on main structural elements can be a major cause of concern since they can lead to structural failure. Thus, early crack detection is crucial in order to avoid sudden failure especially when there is a likelihood of overloading on the structure. Since the measuring of natural frequency is easier than that of change in structural damping, change can be detected from dynamic analysis using natural frequency and mode shapes. Classification for damage identification is defined at four levels with increasing difficulty of determination, namely detection of presence of damage, quantification of severity, locating damage position and prediction of the remaining service life of the structure (Rytter 1993). To date, vibration-based damage identification methods applied to civil engineering structural elements provide for the first two levels of damage identification with sufficient degree of reliability.

A considerable number of researchers have used the change in the natural frequencies for damage detection (Salawu 1997). From previous studies, it is observed that the effect on natural frequency when damage occurs in a structure is often of relatively low sensitivity. The alternative to using natural frequency as damage identification is by using mode shape, where modal assurance criteria (MAC) is used to determine the level of correlation between modes from the control beam and the modes from the damaged beam (Doebling *et al.* 1998). MAC was first used by West (1984) to locate the structural damage without the use of a prior finite element model. The concept of curvature mode shape was introduced by Pandey *et al.* (1991). It was demonstrated that the modal curvature was a much more sensitive damage indicator than the MAC or co-ordinate modal assurance criteria (COMAC) values. This approach was extended by Ratcliffe (1997) using both analytical and experimental results of the curvature of a damaged beam without need of a priori knowledge of the undamaged state. It found that the fundamental frequency is more sensitive the higher modes. Damage index method to locate the damage without the need to baseline data was developed by Stubbs and Kim (1996). Modal parameters of lower modes were found to have satisfactory precision in detecting the crack position and depth (Ruotolo, Surace 1997). The change in curvature of mode shape to locate the damage shows higher sensitivity compared to the mode shape itself (Wahab, De Roeck 1999).

Dynamic stiffness based on the experimental frequencies and mode shapes was used to detect the damage location and severity. It was found that at the ultimate damage state of the RC beam, the reduction in the stiffness was only 50%. On the other hand, it was found that in order to get higher sensitivity in locating the damage, dense measurement grid is required to calculate an accurate curvature for the higher modes (Maeck, De Roeck 1999). When the dynamic bending stiffness based on modal parameters was used to detect the damage position and severity, it was found that the frequencies reduced by 27% when full damage occurred, which is equivalent to dynamic bending stiffness reducing about 60%. The fundamental frequency was the more sensitive one and the third mode was the less sensitive one. It was found that the mode shapes need to be obtained with a sufficient accuracy in order to be used for calculating the curvature. The stiffness showed increase in some cases after damage was induced, which justified the tension stiffening and it thus could not be neglected (Maeck *et al.* 2000).

The natural frequencies were used to detect the crack location and depth and were found to be able to predict the crack size with error of 25% and the location with error of 12% (Lee, Chung 2000). Natural frequencies and mode shapes were found to be useful in detecting the existence of the damage, while MAC and COMAC were not useful for locating the damage (Alampalli 2000). The trend in the natural frequencies was found to be sensitive to the corrosion deterioration state of RC beams (Abdul Razak, Choi 2001), while damping changes were inconsistent (Kato, Shimada 1986; Salawu, Williams 1995). The increase in the number of cracks was found to reduce all natural frequencies (Khiem, Lien 2001). Mode shapes were used to locate the damage in 3-D type structures and it was found that the use of several modes could result in better sensitivity. The proposed method was found to be significantly affected by noise especially for the small damage cases (Park, Kim 2002).

Frequencies were found to be affected by the loading configuration (either symmetrical or asymmetrical), with odd modes more affected by the symmetrical configuration and the even modes more affected by the asymmetrical configuration. The MAC factor was found to be less sensitive than frequencies, but it gave an indication of the symmetrical or asymmetrical nature of damage. It was also found that there was a difficulty in locating the damage in RC beams due to the fact that in RC beams the cracks are not only limited in the zone where the load is applied but spreads over a certain distance on both sides of the loaded zone (Ndambi *et al.* 2002).

Modal parameters were used to detect damage severity and location and it was found that they had low sensitivity to detection of damage location or they would detect the wrong location. They also underestimated the damage severity compared to the actual damage size (Kim, Stubbs 2002). The case when few frequencies or mode shapes are available was investigated to detect the damage location and severity by the use of either frequency or mode shape and both parameters were found to be able to detect the damage location with small error and were accurate in detecting the damage severity when it was located at mid-span but less accurate for damage at quarter-span (Kim *et al.* 2003). Natural frequencies have been used for detecting locations and sizes of multi-cracks and they were found to be with an error of 15% compared to the actual locations and size (Patil, Maiti 2003). Mode shapes curvatures were found to be better in sensitivity to detect the damage location than the mode shape itself and lower modes had higher sensitivity than higher modes.

On the other hand, an adequate number of mode shapes are required to detect multi-cracks with higher accuracy (Dutta, Talukdar 2004). The investigation by Douka *et al.* (2004) found a shift in the anti-resonances of the cracked beam depending on the location and size of the cracks, which can be used as an additional information carrier for crack identification in double cracked beams. The intersection of the normalised frequency contours, in terms of normalised crack depth and location, with the constant natural frequencies planes was used to detect the crack location and depth, and it was found that both location and depth of the cracks have a significant effect on the first and second natural frequencies, and the effect decrease as the cracks get closer to the support. Moreover, higher modes can give better accuracy for locating the damage (Nahvi, Jabbari 2005). The number of required measured frequencies was found to be equal to twice the number of cracks and was seen to be adequate in predicting the location of the multi-cracks cases (Patil, Maiti 2005). The instantaneous frequency was found to oscillate between frequencies corresponding to the open and close of the crack. The variation of the instantaneous frequency increases with increasing crack depth following a polynomial law and consequently can be used for estimation of crack size (Loutridis *et al.* 2005). Time-domain method in which the parameters of a crack in a structural member were identified from strain or displacement measurement was proposed and the method was found to be effective for identifying the crack parameters with a certain degree of accuracy (Law, Lu 2005). The natural frequencies were found to decrease to a larger extent as the crack size increased and the change varied based on the location of the crack and the mode number (Choubey *et al.* 2006).

Local stiffness indicator was proposed to detect damage location and was obtained by applying the fourth order centred finite difference formula to the regressed mode shape data, with no baseline data required. The algorithm was found to have higher intensity at the location of the actual crack, while higher intensity was also detected always at the supports which implied that the algorithm could not be used for detecting damage located near the support (Ismail *et al.* 2006). The change in the natural frequencies is a function of the crack length and its location and also depends on the mode shapes (Choubey *et al.* 2006). The crack locations and sizes notably influence the natural frequencies and mode shapes of the cracked beams especially when the cracks are located at the step parts of the beams (Kisa, Gurel 2007). The structure becomes weaker than its previous condition when the crack size increases with time (Orhan 2007). The effect of the temperature variation on the natural frequencies was evident (Kim *et al.* 2007).

COMAC and flexibility methods were found to be able to detect some damage locations but they also made some false identification (Xia *et al.* 2007). It was also found that the accelerometer could detect the damage if it was placed within less than 300 mm from the actual damage location (Xia *et al.* 2007). Few natural frequencies and/or mode shapes were used to detect the damage location and severity, and it was found that the mode shapes are less sensitive for detecting damage while the modal damping is highly sensitive although inconsistent (Perera *et al.* 2008). The damping was found to be more sensitive to appearance of structural damage, while its statistical variations were more than that for natural frequencies (Guradelli *et al.* 2008). Lewandowski and Grzymisławska (2009) conducted experimental work to monitor the modal parameters to assess the use of the extra mass to reduce the vibration of the structures. Modal flexibility for which the curvature is calculated from the deflected shapes instead of using modal vectors were investigated, and it was found that calculating the curvature needs a very dense sensor resolution and the environmental effect on the dada has to be eliminated (Catbas *et al.* 2008). Crack position and size was detected using the peak values on the irregularity profile of mode shapes, with the method being easily calculable and not requiring the data of the structure. The only disadvantage was that it required use of many sensors in order to get high accuracy mode shapes (Wang, Qiao 2008). Investigation for some existing algorithm for location of damage based on mode shape curvature revealed that it was able to detect a single crack while failed in detecting multiple cracks. A modification was proposed and it was found that it gave reasonable sensitivity but still needed to be improved (Choi *et al.* 2008).

Measured natural frequencies were used in term of equal-eigenvalue-change contours plotting between pairs of different frequencies for damage detection, and it was found that the first and third nodes are sufficient to get information regarding the damage extent and magnitude (Lakshmanan *et al.* 2010). Modal identification errors influenced the sensitivity of the damage detection algorithms and it was found that when erroneous modals were used, it was better to use more than one algorithm for better sensitivity (Tomaszewska 2010). Kamiński *et al.* (2011) developed a finite element model and conducted experiments for calculating modal parameters for cracked RC beams. Erroneous conclusion of damage detection algorithms can be a result of the effect of environmental conditions on the structural perimeters (Limongelli 2010). The dynamic behaviour of damaged structural element was seen to change with the level of the excitation force, which could be used for damage detection, in case of fine frequency resolution and dense sensors resolution, without the need of the data (Kim, Lee 2010). A new damage detection method based on the natural frequencies and the mode shape, if available, was proposed and proved as good indicator that needed only the natural frequencies from the data (Radzieński *et al.* 2011). The slope of the first mode shape was used for damage detection and it showed good results, the only concern being that the error in identifying the mode shape could cause an error in the damage detection results (Zhua *et al.* 2011). Fundamental mode shape and static deflection were used for damage detection and were found to have good sensitivity (Cao *et al.* 2011).

4. Future directions

Based on the review of past studies regarding the use of modal testing for the assessment of RC structures, support conditions and damage detection, i.e. detection of damage location and severity, the following main conclusions and possible future directions can be derived:

(1) There have been many studies using natural frequencies as indicators of damage detection or health monitoring in structural elements. These studies mainly highlight the trend in natural frequencies due to element stiffness changes with different loading conditions and damage scenarios in the structural elements. Most of these studies were conducted on a homogeneous and isotropic material such as steel or aluminium. There have been some experimental studies on the overall behaviour of the RC structural elements. Ismail (2005) found that the first natural frequency increase occurred after damage was induced, the second frequency increase occurred only for the first loading cycle, while the subsequent frequency reductions occurred for all of the applied loading cycles. The reason for the distinct increase in natural frequency when damage was induced was attributed to the bond action, which was only initiated and activated once the steel was stressed, i.e. after applying the load. This made the stiffness higher than an uncracked condition. The stiffness increased in some cases after damage was induced, which justified the action of the tension stiffening, which could thus not be neglected (Maeck *et al.* 2000). These studies, however, did not consider the composite nature and action of having embedded steel bars in a concrete mass and subjecting it to loads which resemble the actual case of an RC structural element. Future studies must investigate and relate the effect of composite action on the dynamic characteristics of the RC structural elements. The composite action arises from bond action between steel bars and surrounding concrete depending on the steel bar stress levels, concrete softening at the tension zones due to tension stiffening and cracking, and concrete softening at the compression zones due to concrete crushing. These are the factors which will influence the natural frequencies and these factors are dependent on the steel properties, i.e. yield stress and concrete properties, namely the compressive strength and tensile stress. The phenomena of concrete softening in the tension and compression zones together with the bond action between the steel bars and the surrounding concrete occur in real RC structures. Conversely, the in-service are applicable to a majority of structures such as bridge girders, beams and slabs in framed buildings and other civil engineering structures;

(2) To date, no significant research has been undertaken to classify the damage source using the modal parameters. Structural elements can suffer deterioration due to either exposure to extreme loading conditions or due to the deterioration of the element materials over time. On the other hand, the supports may suffer loss in stiffness over time due to the effect of wear and tear in cases where the elastic bearing is used as isolation such as in bridge girders and tall buildings. Therefore, to identify the source of deterioration in overall stiffness, which is due either to the structural element itself or the support stiffness, is one of the future directions for investigations;

(3) Studies have shown that the existing damage severity algorithms based on natural frequencies and/or mode shapes, experience low

sensitivity, have different sensitivity for different modes, underestimate, require dense sensors grid, are erroneous, are affected by noise especially for small damage cases, affect loading configuration (either symmetrical or asymmetrical) and require an adequate number of modes. Based on the aforementioned conclusions, future studies must develop a new algorithm based on the mix between these two parameters (frequency as global indicator and mode shape vectors as local indicator). This new algorithm should have higher sensitivity, should consider the available number of modes, averages the considered set of modes by its own format, requires a number of sensors equal to the number of the carried modes and is sensitive to different damage configurations. The use of the modal parameter for damage detection is important in order to formulate a planned strategy for repair and maintenance works. Future studies must develop a more reliable weightage method to be used for the existing damage algorithms, which considers the different sensitivity of different modes and which is able to return with one stiffness deterioration value;

(4) Previous studies have shown that the mode shape vector and its second and fourth derivatives were used for detecting damage location and had some drawbacks regarding sensitivity and reliability such as mode shape curvature has higher sensitivity than the mode shape itself, dense sensor grids are required and a high accuracy is required for obtaining the mode shape in order to achieve reliable results. Besides, there are errors and failures of detection results, with the mode shape itself having low sensitivity and being affected by the noise. In addition, it is difficult for the mode shapes to locate damage in RC beams due to the fact that the cracks are not limited to the zone of applied load but spread over a certain distance on both zone sides. Mode shapes are also underestimated, have different sensitivity to the actual damage location, with different modes having different sensitivities. Additionally, adequate mode numbers are required for higher sensitivity. The fourth derivative experiences high intensity at the supports, which makes it unreliable for detecting damage close to the supports; the second derivative was less sensitive for multi cracks. Errors in calculating the algorithms can influence the sensitivity. Based on the aforementioned conclusions, future studies must (1) modify existing algorithms to improve its sensitivity; (2) develop a new algorithm based on the mode shape vector and its derivative, which is believed to overcome the drawback of the existing algorithms and increase the sensitivity to locate the damage regardless of location and level and (3) develop an elimination procedure to cut-off the anomalies which can appear as a result of the mathematical calculation of the algorithms.

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