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

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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 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.

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^{0}_{c}). For stresses beyond this point, there is a gradual increase in curvature up to about 0.75f^{0}_{c}_0.9f^{0}_{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, o_{u}, (Karsan, Jirsa 1969). The stress level of about 30% of f^{0}_{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).

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).

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