Review of full-scale dynamic testing of bridge structures

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Full-scale dynamic testing of structures can provide valuable information on the service behaviour and performance of structures. With the growing interest in the structural condition of highway bridges, dynamic testing can be used as a tool for assessing the integrity of bridges. From the measured dynamic response, induced by ambient or forced excitation, modal parameters (natural frequencies, mode shapes and modal damping values) and system parameters (stiffness, mass and damping matrices) can be obtained. These identified parameters can then be used to characterize and monitor the performance of the structure. Analytical models of the structure can also be validated using these parameters. Reasons for conducting full-scale tests are given, and a discussion of the types of excitation devices used in forced vibration testing of large civil engineering structures is also included in the paper. A detailed review of published full-scale dynamic tests conducted on bridge structures is also given.

Keywords: bridge structures, full-scale testing, dynamic testing, ambient vibration testing, forced vibration testing, vibrators

Dynamic field tests have been carried out on bridges since the late 19th century[1]. Many of the early tests were conducted as part of safety inspection (of railway bridges) and involved monitoring bridge vibrations. Modern test methods are sophisticated extensions of these early investigations. Most of the more recent tests reported have been concerned with improving analysis and design procedures, assessment of bridge design code provisions and monitoring the in-service behaviour of bridges. These test objectives underline the importance of vibration testing.

For effective utilization of any method or process, it is important to understand and appreciate the techniques involved. Periodic evaluation of the procedures adopted, and results obtained, by previous researchers help to identify the benefits and limitations of the method. Awareness of the techniques will also be improved. To this end, this paper has been written with the aim of providing a relatively broad background and literature base on the subject of full-scale dynamic testing of bridges so that understanding of the subject is enhanced. This contribution will provide a valuable introduction to dynamic testing of bridges for both newcomers and experienced practitioners.

A simple view of dynamic testing is to consider it as a procedure for determining the resonance (natural) frequencies of a structure. The identified vibration mode shape for each natural frequency corresponds to the deflected shape when the structure is vibrating at that frequency. Each vibration mode is associated with a damping value which is a measure of energy dissipation. The natural frequency, vibration mode shape and damping value of a mode are sometimes referred to as the modal parameters of the particular mode. In the literature, dynamic tests involving identification of modal parameters are also termed modal tests or modal surveys. The basic stages involved in dynamic testing are illustrated in *Figure 1*. Although the stages have been shown as distinct phases, it should be noted that modern test configurations usually incorporate a number of processes within a single device.

Reasons for full-scale dynamic testing

There are various reasons for conducting full-scale dynamic testing. Some of these are

(1) Dynamic measurements on a full-scale structure serve to increase the database on dynamic behaviour of similar structures. This database can then be used in predicting the response of new structures. Since full-scale tests could be expensive, this database becomes invaluable in procedures utilizing test data to evaluate and improve current analytical methods.
(2) To determine the integrity of a structure after the occurrence of an overload such as a military manoeuvre on a bridge. If the nature of loading causing

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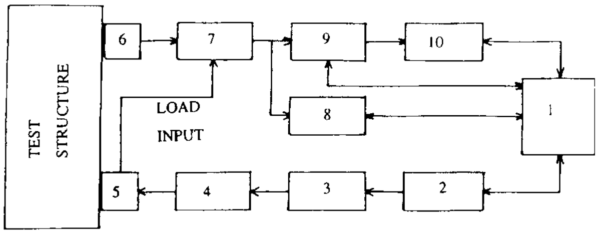

1 Test control unit (micro-computer)
2 Excitation signal generation
3 Power amplification
4 Excitation mechanism
5 Force transducer
6 Motion/response transducers
7 Signal conditioning
8 Signal monitoring
9 Signal recording
10 Signal/data processing and analysis

Figure 1 Stages involved in vibration testing

the overload is unknown, results of the dynamic tests can be used to determine the type of loading[2]. The same approach can also be used to assess the effectiveness of remedial works[3,4].

(3) To validate theoretical models of structures. Mathematical models of real structures usually involve significant assumptions especially with regard to boundary conditions. Moreover, as the structural system becomes more complex and sophisticated, it becomes more difficult to understand its mechanisms, and, therefore, to develop an appropriate model which will give a good prediction of its dynamic response[5]. Comparison and correlation of theoretical predictions with measured response will lead to a better understanding of the structure, well-defined safety margins, less conservative assumptions and hence, more economical designs.

(4) To assess the integrity of a structure when higher loading levels are envisaged either due to a change of use, higher environmental loading or an increase in allowable loading. An example of such application is the current assessment of some highway bridges in the UK to check their ability to withstand 40 tonne trucks to be introduced in 1999. According to Proulx *et al.*[6], dynamic testing is more reliable than other methods to evaluate the dynamic amplification factor since it (dynamic testing) yields information, on the dynamic properties of the structure, that can be used in structural assessment and design of repair work.

(5) The overall condition of a structure can be monitored by regular measurement of its dynamic response. Changes, as a result of deterioration, in the system parameters – mass, stiffness and damping – lead to changes in the vibrational response and these can be measured using standard dynamic testing techniques. Results of tests have shown that the size of damage is proportional to the magnitudes of observed changes in identified system parameters[7].

(6) As a trouble shooting tool to verify that the behaviour of a given system conforms to that expected. This provides performance information on the completed structure and also yields useful data for future designs. Dynamic testing has historically been used by engineers to study structural vibration problems.

Types of tests

The basis of the classification adopted here is the degree of control over the input excitation. Dynamic testing methods without any control on the input are classified as ambient vibration testing. Thus, stages 2 – 5 in *Figure 1* will not be present in the test set-up. Forced vibration testing incorporates those methods where the vibration is artificially induced. Methods where the excitation is artifically induced but is not and/or cannot be measured are also categorized under forced vibration testing. Examples of these are excitation by explosions and vehicle impact.

Ambient vibration testing

In ambient vibration testing, the input excitation is not under the control of the test engineer. The increasing popularity of this method is probably due to the convenience of measuring the vibration response while the structure is under service loading and the increasing availability of robust data acquisition and storage systems. The loading could be from either wind, waves, vehicular or pedestrian traffic or any other service loading. Since the input is unknown, certain assumptions have to be made about its nature. The basic assumption of the method is that the excitation forces are a stationary random process, having an acceptably flat frequency spectrum[8]. If this assumption holds, then the vibration response of any structure subjected to such effects will contain all the normal modes. Ambient vibration testing implicity assumes response data alone could be used to estimate vibration parameters[4,9].

In most cases, the nature of the input excitation can only be approximated by statistical descriptions (for example wind loading) or by assuming the excitation spectrum to be concentrated within a frequency range (for example, 2–4 Hz for vehicular excitation of bridges[10]). If the loading spectrum is limited to a narrow band of frequencies, only a limited picture of the dynamics of the structure can be monitored[4]. Inadequate knowledge of the input force also implies generalized mass and stiffness cannot be derived. A theoretical justification of ambient vibration testing has been proposed by James *et al.*[11].

Although reliable frequency and mode shape data can be obtained[12], estimated damping values are prone to errors. The errors in the damping estimates are due to a combination of factors such as the (possible) nonstationarity of the excitation process, signal processing and data analysis procedures necessary to extract modal parameters and the insufficient excitation of some modes[13–17]. Brownjohn[18] has discussed the problems of obtaining reliable damping estimates from ambient vibration testing.

The frequency response function changes depending on the amplitude of the input excitation. This leads to variation in damping estimates since damping depends on vibration amplitudes. Hence, results from low level excitation might not be appropriate to predict the dynamic response to high level excitation[19]. Coupled with this is the considerable degree of nonlinearity exhibited by many real-life structures.

To achieve better results, it is necessary to use higher energy excitation techniques which approximate the dynamic load levels likely to be encountered in the operating environment. Thus, the only alternative to ambient vibration testing is to conduct forced vibration testing using properly designed excitation systems which can produce desired loading spectra. Tests on offshore structures[20] using both ambient and forced vibration methods have shown that damping and frequencies can be measured more accurately with forced vibration and that the higher modes can only be excited to measurable levels by artifical excitation.

Forced vibration testing

This involves application of input excitation of known force levels at known frequencies. The input is thus under the control of the experimentalist. Forced vibration tests have the advantage of suppressing effects of extraneous noise in the measured structural response. The input loading can be altered to suit test requirements. Also included in this category are tests in which the input is controlled but not measured. The physical means through which the excitation is realized may be termed a vibrator, vibrator exciter, exciter or shaker. It is a device used for transmitting a vibratory force into the structure. Forced vibration testing is based on the classical fact that if the loads on a structure are known and the resulting motion can be measured, then it should be possible to estimate the structural properties.

In full-scale testing of large structures, vibrators are generally of the contacting type i.e. the exciter stays in contact with the test structure throughout the testing period. In such applications, they are physically mounted onto the structure. However, noncontacting devices such as impactors have also been successfully used on some large structures. Appropriate contacting vibrators are usually of the eccentric rotating mass or electrohydraulic type. A brief description of the general characteristics of eccentric rotating mass vibrators, electrohydraulic vibrators and impactors is given below. Further details on the configuration and operating principles of these machines can be found in Unholtz[21] and Clements *et al.*[22]. Some other types of excitation mechanisms in which the input force is not measured are also discussed.

Eccentric rotating mass vibrators An early form of contacting vibrator is the eccentric rotating mass vibrator which is a reaction type mechanical vibration machine. These vibrators have been used for some years to excite large civil engineering structures[23,24]. The eccentric mass vibrator generates vibratory force by using a rotating shaft carrying a mass whose centre-of-mass is displaced from the centre-of-rotation of the shaft. The motion generating the force can be circular or rectilinear. The magnitude of the applied force is constant for a particular setting of mass, rotational speed and the out of balance displacement.

The machine can be operated at different frequencies by changing the rotational speed of the shaft. Adequate shaft speed control is necessary in order to have satisfactory results. The simplest reaction type machine uses a single rotating mass. Machines with more than one rotating mass are also available[24]. An example is shown in *Figure 2*. These have the advantage of generating forces in more than one direction. These exciters are capable of delivering only sinusoidally varying forces that are proportional to the square of the rotational speed so that reliable excitation can only be achieved above 1 Hz[18].

Details of the design, construction and operation of some eccentric rotating mass exciters which have been built are available in the literature[25–27]. Field application of such exciters to the full-scale testing of a highway bridge has been described by Ohlsson[28].

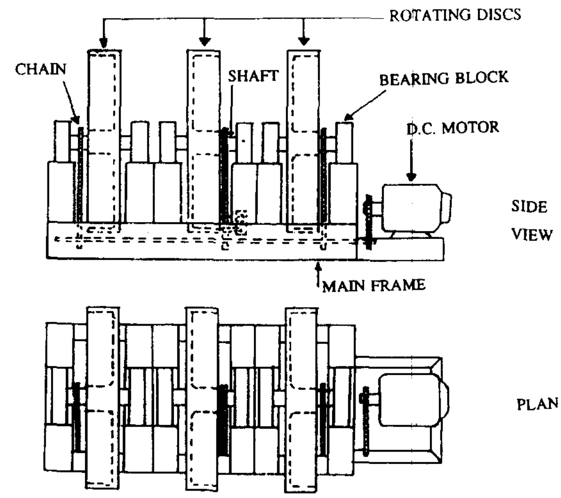

Figure 2 Rotating mass vibrator (after Reference 26)

Electrohydraulic vibrators The electrohydraulic vibrators can generate higher forces than the other types. The force is generated through the (reciprocating) motion induced by the high-pressure flow of a liquid. The pressure is provided by one or more pump units. In operation, the system usually consists of a servocontrolled hydraulic actuator which drives an attached mass. The weight of the mass can be varied to obtain varying force magnitudes. The vibrators provide relatively high vibration strokes and allow accurate excitation at different frequencies in bending or torsion. They also have the advantage of being able to apply a static preload and complex waveforms to the test structure. However, the attainable stroke reduces with increasing frequency.

Electrohydraulic vibrators are less common than the eccentric rotating mass types. Leonard[29] has described an inertial excitation system consisting of four masses, each driven by an electrohydraulic actuator, mounted on a mobile axle. Utilization of similar exciters has been reported[3,30–33]. The vibrator (shown in *Figure 3*) used at the University of Plymouth for full-scale tests is of the electrohydraulic type. Details of the design, construction and operation of the vibrator have been described by Salawu[34].

Impactors The simplest means of applying an impact to a structure is by using an instrumented hammer or a suspended mass to deliver blows to the structure. A simple impact device is shown in *Figure 4*. The impulse delivered to the structure can be varied by changing the mass of the impact device. The impact frequency range can also be varied by changing the hammer head type. The impulse function consists of a short duration broad-band spectrum. The width of the function determines the frequency content while the height and shape control the energy level of the spectrum[35]. Impulse testing is susceptible to input noise since the input force is applied over a short period compared to the record length (of the measured response).

A 5.4 kg instrumented sledge hammer was used by Maguire and Severn[36] to test four 40 tonne bridge beams. The hammer was reported to have a maximum impact force of 22 kN. A cylindrical steel hammer, having a mass of 840 kg, was also used as the excitation device during the dynamic tests reported by Lee *et al.*[37]. Green and Cebon[38]

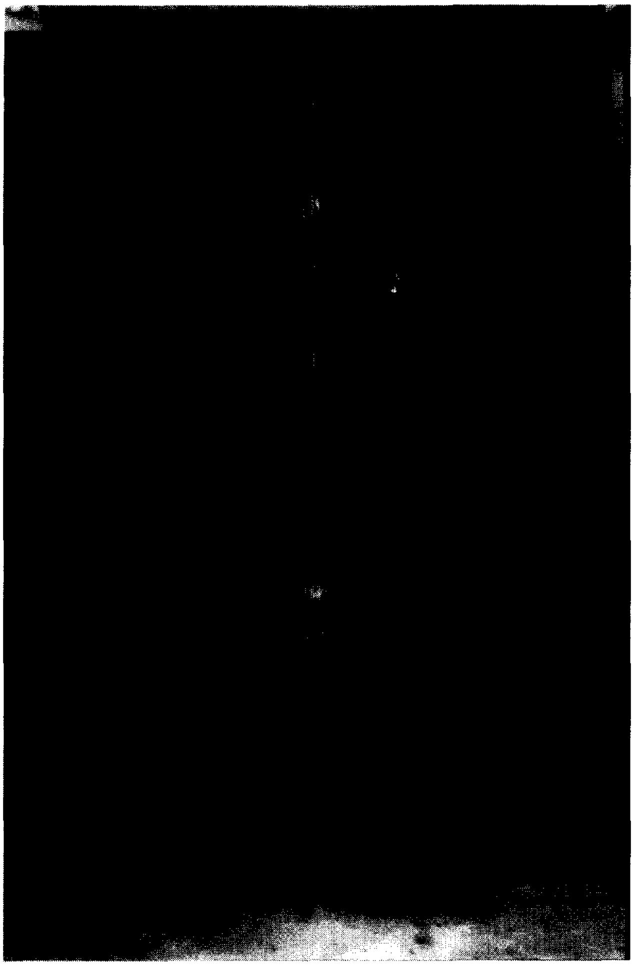

Figure 3 Electrohydraulic vibrator

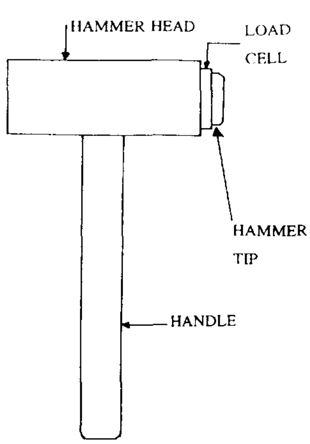

Figure 4 Simple impact device

have reported successful utilization of an instrumented hammer during the modal identification of two highway bridges. Despite these published tests, an instrumented hammer is rarely used on large structures because of the large mass of the latter and the risk of local damage, at the point of contact, to the structure when high force levels are applied.

Other special impact devices have been developed to excite large structures. One such device was called a sand drop impactor[39]. It consisted of a weight dropped onto a sand bed that was, in turn, mounted on a load cell. The device has been reported to have successfully excited a number of both steel and concrete structures. More recently, the use of a 'bolt-gun' to excite large structures has been reported[40].

Other excitation mechanisms The other means of forced excitation can generally be classed under transient testing. For these other methods, the input force is not usually measured. They take one of two forms – impulse testing or step relaxation. In impulse testing, the impulsive force is applied to a structure initially at rest by vehicle impact, a vehicle driven over an uneven surface, a dropped weight, rocket impact, the controlled jumping of people or a hammer. The same comments made in the previous section apply to this type of excitation.

In step relaxation testing, excitation is achieved by releasing the structure from a statically deformed position. The initial static deformation is achieved by either loading the structure with a wire or cable[41,42], hydraulic rams[43,44] or by continuous thrust from rocket motors. An example of transient excitation is shown in *Figure 5*. The response of the structure to this form of excitation is strongly dominated by those modes whose deformed shapes best resemble the statically deformed configuration of the structure. Step relaxation is seldom used because it can be mechanically difficult to implement[16]. However, it is possibly the simplest and most effective method of determining damping[18].

Full-scale ambient vibration testing

Most of the published works on full-scale dynamic testing have used the ambient vibration testing method. This is due, among other factors, to the ease of measuring the vibration response while the structure is still in service, elimination of the need for special excitation devices and the possibility of correlating structural vibration response with the normal service loading. The literature on ambient vibration testing of highway bridges is extensive. Some of the reported tests are presented in this section. The list is by no means exhaustive but the papers reviewed are meant to illustrate the different test approaches employed and the main results obtained.

Ambient vibration testing of the Tamar suspension bridge has been reported by Williams[45]. The dynamic response was monitored when the bridge was excited by a wind of between 7 m/s and 12 m/s speed and a fairly continuous flow of traffic. Seismometers were used at 17 locations for the measurements. Ten natural frequencies in the range of 0.3 Hz – 2.75 Hz were identified. Although analytical mode shapes were given, experimentally determined mode shapes and damping values were not reported. Seismometers were also used to measure the wind induced oscillations of the Špilje lake bridge, Yugoslavia[8]. The problem of traffic induced noise[46] was encountered during the tests.

Preliminary vibration tests were conducted on the 866 m long Foyle bridge (Northern Ireland)[47,48]. The vibration

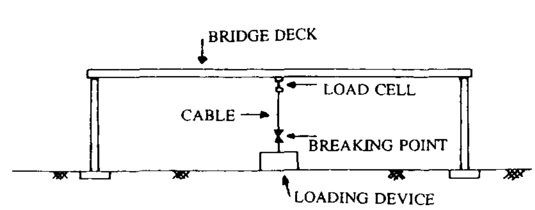

Figure 5 Transient excitation

monitoring system employed was automated and could be programmed to gather data either to a preset timetable or when certain environmental conditions were fulfilled. The results showed that the lower frequency end (<0.2 Hz) of the relative displacement spectrum was caused by traffic crossing the bridge. Thus, the analysis could be refined by filtering out the traffic noise. Such filtering procedures could also have reduced some of the difficulties encountered during testing of the Špilje lake bridge[8].

Dynamic response monitoring during normal bridge traffic was carried out by Creed[49] on a six-span concrete motorway bridge. Eight vertical accelerometers were used in pairs to assess mode shapes and check bearing motion at the supports. The measured natural frequencies for a given span were found to be repeatable to within 2.5% though the mode shape ratios were only repeatable to within 35 – 40%. The measured natural frequencies also showed good agreement (within 3.5%) with finite element analysis predictions. Ambient vibration testing was also used by Pardon *et al.*[50] to study the dynamic behaviour of a steel truss bridge.

The Golden Gate suspension bridge, California, has been the subject of a number of investigations to monitor the structural dynamic behaviour and give warning of any impending disaster[51]. Recently, extensive experimental investigations have been conducted[19,52] on the bridge to determine effective damping, three-dimensional mode shapes and resonant frequencies. Excitation was from wind, ocean waves and vehicular traffic. 20 vertical, 18 torsional, 33 lateral and 20 longitudinal modes were identified (frequency range 0 – 1.5 Hz) from simultaneous measurement of vertical, lateral and longitudinal vibration of the suspended structure. The measured mode shapes and frequencies showed good agreement with the results of both two- and three-dimensional finite element analyses. McLamore *et al.*[53] also studied the dynamic characteristics of two suspension bridges using ambient vibration methods.

During the 1970s, the Transport Research Laboratory, England, conducted series of full-scale vibration tests on motorway bridges to re-assess bridge loading rules and to gain a better understanding of the dynamic behaviour of bridges. As part of the series, Eyre and Smith[54] measured the dynamic response of Tinsley viaduct due to excitation from normal vehicular traffic and a 30 tonne control vehicle. The viaduct is a two-level, 20-span steel structure with a total length of 1032 m. The measurements were made on the 18th span of the upper level using cantilever deflection gauges. It was found that the superstructure deflected as a continuous beam and that the principal bending and torsional vibration frequencies were in the range 1.80 – 3.60 Hz and 1.31 – 1.84 Hz, respectively.

Eyre and Smith[54] also measured the wind oscillations of the seven-span Cleddau bridge. The main 213 m river span of the bridge has a 136.5 m length of simply suspended section. Accelerometers were positioned at the centre of the span and at quarter points close to the joints between the cantilevers and the suspended section. The measured maximum oscillations were lower than the predictions from wind tunnel tests. A peak value of ±28 mm was measured compared with ±150 mm obtained from turbulent wind tests.

The traffic induced vibration of some 18 bridges were studied by Ward[55]. Vertical vibrations were recorded on the ground approaches to the bridges and at locations close to the midspan. The approach measurements were made to provide an estimate of the energy input to the bridge and to unambiguously identify the natural frequencies of the bridge. Estimates of the damping values were obtained by treating the time histories as a series of transient vibration records associated with the passage of each vehicle across the bridge. It was found that most of the energy associated with the traffic loading was confined within the frequency range 0 – 30 Hz.

Ambient vibration tests have been conducted on the Humber suspension bridge to determine vertical, lateral and torsional vibrational characteristics of the deck and towers[13]. It was found that while many vertical and lateral modes occurred at close frequencies, they were not related. Though there were relatively few predominantly longitudinal modes, there was significant longitudinal participation in most main span vertical modes. This interaction between different vibration modes was also observed on the Golden Gate suspension bridge[19]. From the correlation between wind speed and modal amplitude, Brownjohn *et al.*[13] suggested that low frequency excitation is mainly wind induced while response upwards of about 2 Hz is mainly traffic induced. Although reliable frequency values were obtained, the modal damping values were believed to be over-estimated due to signal processing errors involved in analysing the response from ambient vibration. Similar conclusions about damping estimates were also expressed by Mazurek and DeWolf[56].

Using a different data acquisition method, Littler and Ellis[57] also conducted vibration tests on the Humber bridge. The estimated natural frequencies and mode shapes were in agreement with the results of Brownjohn *et al.*[13]. Detailed discussions of a number of modal surveys, using ambient excitation, that were conducted on suspension and cable stayed bridges are given elsewhere[18].

Full-scale forced vibration testing

The number of reported forced vibration tests is less than that reported for ambient vibration testing. A factor contributing to this is the difficulty in constructing suitable excitation systems that can generate sufficient excitation forces at low frequencies, especially for long-span slender bridges. The papers reviewed form a subset of the published literature and have been chosen to highlight types of excitation systems used, the main conclusions from the tests and the various test procedures adopted.

Rotating eccentric mass exciters were used to generate excitation forces during the tests on the Bosporus suspension bridge[18]. The tests had only partial success because the exciters were unable to supply adequate force at frequencies much below 1 Hz, which is the range of interest for suspension bridges. During modal testing of the Pöinja river bridge, Yugoslavia[8], two electromechanical vibration generators were used to generate harmonic vibrations in the frequency range 0.5 – 9.0 Hz.

Okauchi *et al.*[58] successfully conducted forced vibration tests on the Ohnaruto suspension bridge. Excitation of the bridge was by a pair of 200 kN vertically acting reciprocating mass exciters operating at a constant amplitude of 140 mm. This was sufficient to give reasonably accurate damping estimates. A damping value of 0.53% of critical damping was obtained for the first vertical mode. Ohlsson[28] conducted swept sine tests on the 366 m cable stayed Tjorn bridge, Sweden, with a special type of reciprocating mass exciter. Four vibrational modes were identified in the frequency range 0.4 –1.6 Hz.

Cantieni and Pietrzko[59] conducted tests on a three-span 108 m long wooden footbridge to verify design assumptions and check if pedestrian induced vibration was excessive. Excitation of the bridge was by a servohydraulic vibrator which was capable of generating a maximum force amplitude of ±5 kN at frequencies ≥2.3 Hz. The bridge response was measured in three orthogonal directions at 77 points using accelerometers. The accumulated spectrum over all 231 measured frequency response functions was used to identify prominent modes. Using a burst random excitation signal was found to reduce the measurement time and eliminate leakage errors during spectral computations. However, utilization of specialized software and signal conditioning equipment was necessary. Results obtained from the tests showed that the bridge was not susceptible to excessive vibration by walking pedestrians.

Forced vibration tests, in addition to fatigue tests, were conducted on a full-scale in-situ composite three-span highway bridge in order to evaluate the effectiveness of using changes in dynamic properties as a means of detecting structural deterioration[30]. A closed loop electrohydraulic actuator system was used to generate the excitation forces. Four types of forced vibration testing techniques – transient, stepped-sine, slow sine sweep and steady-state normal mode – were utilized. For the transient tests, the damping values for all three spans in each of the three modes reported were consistent. For the stepped-sine tests, the damping values obtained varied from span to span although the range was consistently between 1 and 3%.

Techniques and instrumentation used in full-scale forced vibration tests by the Transport Research Laboratory to determine characteristics of highway bridges have been discussed by Leonard[29]. A special mobile inertial excitation system (mentioned earlier in the section on forced vibration testing), called the energy input device, was used to apply sinusoidal forces over the frequency range 1.5 Hz to 30 Hz at force levels of up to ±16 kN. The device, which is a form of electrohydraulic actuator, was used on bridges with individual spans up to 50 m[46,60,61].

Results of damping measurements on 23 steel and composite bridges (spans between 17 m and 213 m) were discussed by Eyre and Tilly[61]. The damping was measured from decays of response obtained for the first bending mode though it was acknowledged that higher bending and torsional modes could be significant for bridges having low natural frequencies which coincide with those for the suspension of heavy vehicles. It was found that damping increased with amplitude of vibration and stabilized at an upper level which was about four times higher than the level at small amplitudes. The lower level of damping was associated with the behaviour of the superstructure while the higher level included contributions from joints and substructure and was more relevant to unduly 'lively' behaviour. A tendency for damping to increase with frequency was also noted. Tilly[46] and Eyre and Tilly[61] have presented damping values for steel, composite and concrete bridges and the intrinsic material values for steel and concrete.

Raimer and Pernici[62] have reported sinusoidal forced vibration tests on a three-span prestressed concrete bridge. Salane and Baldwin[63] also conducted steady-state sinusoidal tests on a three-span highway bridge using an electrohydraulic actuator. The bridge had a composite deck supported on four steel girders. Three resonant modes, two bending and one torsional, were identified. A modal damping ratio of 0.0134 was obtained for the first bending mode.

Several bridges were studied in Japan to obtain their modal parameters by using mechanical shakers or impulsively fired rocket engines[64]. Rocket engines were also used for excitation during tests on a Scandinavian suspension bridge[65].

An instrumented hammer was used during the dynamic tests reported by Green and Cebon[38]. The repeatability of the testing procedure was demonstrated by dropping the hammer several times at one position while the linearity of the measured dynamic response was ascertained by dropping the hammer at three different positions on the bridge. Sun and Hardy[66] have stated that linearity of the structural system could be assumed in impact testing if the impact level is limited to a certain range. The estimated damping ratios, from the tests by Green and Cebon, varied from 1.4% to 8.8% of critical damping. Although the authors did not give any reason for the high damping values, they (high damping values) could have been due to high impact energy during excitation. This raises the question of uniformity of 'blows' when using instrumented hammers. During the tests reported by Biswas *et al.*[67], a soft tipped head was used on the 53.4 N hammer employed as the exciter. This enabled elimination of local damage to the bridge and allowed sufficient bridge response at low frequencies.

The pull back and quick release testing method was used by Douglas and Reid[64] and Douglas and Richard[68] to determine the modal parameters of some highway bridges. The dynamic excitations were produced by pulling (using cables) the bridges with two crawler tractors and simultaneously quick-releasing the loading cables. Marecos *et al.*[69] had previously used a similar technique on the Tagus bridge. The same method was used in the full-scale tests reported by Richardson and Douglas[44] to investigate the dynamic response of a 277 m long reinforced concrete bridge. However, the initial deformation of the bridge was obtained by using steel rams and hydraulic jacks. Five of the possible six deck acceleration components were measured at each of 47 measurement locations on the bridge deck. The authors used novel presentation methods, power spectral density surfaces and power spectral density contour plots, to display power spectral density curves from different stations on the same plot. Eyre[41] obtained the dynamic response of the seven-span Cleddau bridge by suddenly releasing a 32.7 tonne mass from the centre of the main span.

Douglas *et al.*[43] have proposed a baseline correction procedure to improve the results obtained from the normal quick release method. The modified procedure was tested on a series of data obtained during field tests on a two-span reinforced concrete box girder bridge. The procedure enhanced the use of the quick release dynamic testing method and also produced detailed static response of the structure as a by-product of the dynamic investigation.

Several full-scale dynamic tests have been conducted in Ontario, Canada, to investigate the effects of traffic and road characteristics on bridge dynamic behaviour. Results from a series of such tests conducted between 1956 and 1971 have been reported by Green[70]. The results indicated that the dynamic deflection can be in excess of values suggested by design specifications. It was found that for superstructures having a (fundamental) longitudinal flexural frequency between 2 Hz and 5 Hz, the dynamic interaction between vehicle and bridge systems appeared to be present and gave rise to higher dynamic deflections. Values of damping were found to range from 0.64% to 0.15% of critical damping for simple and continuous spans having lengths up to 75 m. For structures with a total length in excess of 125 m, damping values of 0.64% to 0.95% were found to be representative.

More recently, Billing[10] has reported dynamic tests on 27 bridges of various configurations, of steel, timber and concrete construction to obtain data to support the Ontario Highway Bridge Design Code (OHBDC) provisions. Excitation of the bridges was by passing trucks and scheduled runs, at known speeds, by test vehicles of various weights. Further details of instrumentation layout, test and data processing procedures adopted are given by Billing[71]. The number of modes found depended upon the particular characteristics of a bridge. Interaction between the vibration modes of the individual spans was also noticed. The damping ratios of the first flexural modes of steel and concrete bridges were found to be 0.4% – 0.7% and 0.8% – 3.8% of critical damping, respectively. These values are consistent with other damping measurements[46,72].

Williams[3,4] has reported dynamic tests on the three-span Axmouth bridge, which is believed to be the oldest concrete bridge in England. Excitation was by a 7.5 tonne lorry crossing the bridge. A system of three Willmore seismomters were used to monitor vibration levels in three orthogonal directions at eight locations on the bridge. The vibration monitoring was used to assess the effects of piling work on one of the bridge's piers. Proulx *et al.*[6] also used vehicular-crossing as the source of excitation during dynamic tests on a steel arch bridge. Pressure tubes were used to estimate the total excitation time of the structure and the speed of the test vehicles. Results of the tests were used to estimate the bridge's dynamic amplification factor and dynamic properties. However, the accuracy of some of the computed power spectral density curves is doubtful since the frequency resolution was poor and the sampling period shorter than would be expected.

Dynamic tests were conducted on a three-span reinforced concrete bridge to determine vibrational parameters[37]. From the results, it appeared that the transverse torsional flexibility of a bridge deck has little effect on the lower modes of vibration of the deck. The experimental results were compared with analytical procedures which modelled the bridge deck as a beam. It was concluded that using the concrete dynamic modulus in the dynamic analysis produced results that compared more favourably with field measurements. Kohoutek[73] used a 40 kg mass and a 50 tonne truck to excite a five-span bridge during full-scale dynamic and modal tests. The test results were correlated with theoretical predictions and used to assess the structural condition of the bridge.

Conclusions

Of the two main types of dynamic testing, ambient vibration testing is easier to conduct since the structural response can be measured while the structure is still in service. Artifical excitation systems, which could sometimes be complex and expensive, are not required. A disadvantage of the method is that some of the estimated dynamic parameters, especially damping, could be in error since their values may depend on the (uncontrolled) unknown excitation level. Structural response measured under a given operating condition would give a true picture of the behaviour of the structure for that particular service environment. However, use of the model derived from such data may not be reliable in predicting response under a different operating environment. For tests involving normal vehicular traffic as the means of excitation, the natural frequencies of the bridge could be accompanied by some harmonics due to the motion of the vehicles. Despite these shortcomings, the ease and convenience of the method would continue to make it a popular option.

Forced vibration testing produces data from which more accurate system and modal parameters can be obtained especially if the input load is measured. Of the forced vibration test methods, impact testing is the easiest to conduct but probably produces less reliable data compared to tests using rotating mass and electrohydraulic vibrators. However, the latter types of excitation devices are more difficult to develop. Although the concept of transient testing is quite straightforward, devising and applying suitable transient excitation could be difficult. It is also possible that not all the vibration modes of interest will be sufficiently manifested by transient excitation. Both impact and transient testing have the disadvantage of potentially inducing localized damage on the test structure.

Selection of an appropriate excitation mechanism is one of the main problems encountered in full-scale forced vibration testing of large structures. The system chosen should be robust and be able to generate sufficient force levels while not causing localized damage to the structure. The papers reviewed have illustrated the various types of devices that have been employed. Selection of a particular system will depend on, among other things, the type of structure to be tested, information required from the test and available resources.

Results from the reported tests indicate that vibration testing is a useful tool for obtaining information on the condition of structural systems. The review has shown that forced vibration testing produces better parameter estimates than ambient testing. However, ambient testing will continue to be more popular as it is relatively easier to conduct. Most of the reported work was concerned with validating analytical models, characterization of the dynamic behaviour of the test bridges and investigating relationships between vehicular/cyclist/pedestrian traffic (loading) and dynamic response of bridges. Only a few of the published tests dealt with integrity assessment/damage detection despite the potential of using vibration testing for these purposes.

References

1 Kato, M and Shimada, S. 'Methods of field vibration tests on bridges', *J. Japan Soc. Civ. Engrs*, 1981, **66**(2), 28–42 (in Japanese)

2 Tsang, W. F. and Rider, E. 'Modelling of structures using experimental forced vibration data with a particular application in force prediction', *RNEC Research Report RNEC-RP-88023*, Royal Naval Engineering College, Plymouth, UK, 1988

3 Williams, C. 'The effects of vibration on large structures and the determination of dynamic characteristics', *Int. Conf. on Engineering Integrity through Testing*, Birmingham, UK, 1990, 441–452

4 Williams, C. 'Testing of large structures using vibration techniques', in *Structural integrity assessment*, Elsevier Applied Science, London, UK, 1992, 290–229

5 Nalitolela, N. G., Penny, J. E. T. and Friswell, M. I. 'Updating structural parameters of a finite element model by adding mass or stiffness to the system', *Proc. 8th Int. Modal Analysis Conf.*, Kissimme, FL, USA, 1990, 836–842

6 Proulx, J., Hébert, D. and Paultre, P. 'Evaluation of the dynamic properties of a steel arch bridge', *Proc. 10th Int. Modal Analysis Conf.*, San Diego, CA, USA, 1992, **2**, 1025–1031

7 Tsai, W. H. and Yang, J. C. S. 'Nondestructive evaluation of composite structures using system identification technique', *J. Eng. Mat. Technol. Trans. ASME*, 1988, **110**(2), 134–139

8 Taškov, L. A. 'Dynamic testing of bridge structures applying forced and ambient vibration methods', *Proc. Conf. on Civil Engineering Dynamics*, Society for Earthquakes and Civil Engineering Dynamics, London, UK, 1988, Paper 6

9 Bendat, J. S. and Piersol, A. G. *Engineering applications of correlation and spectral analysis.* John Wiley, New York, USA, 1980

10 Billing, J. R. 'Dynamic loading and testing of bridges in Ontario', *Can. J. Civ. Engng*, 1984, **11**(4), 833–843

11 James, G. H., Carne, T. G., Lauffer, J. P. and Nord, A. R. 'Modal testing using natural excitation', *Proc. 10th Int. Modal Analysis Conf.*, San Diego, CA, USA, 1992, **2**, 1209–1216

12 Srinivasan, M. G., Kot, C. A. and Hsieh, B. S. 'Dynamic testing of as-built civil engineering structures – a review and evaluation', *Report NUREC/CR 3649*, Office of Nuclear Regulatory Commission, 1984

13 Brownjohn, J. M. W., Dumangolu, A. A., Severn, R. T. and Taylor, C. A. 'Ambient vibration measurements of the Humber suspension bridge and comparison with calculated characteristics' *Proc. Inst Civ. Engrs: Part 2*, 1987, **83**, 561–600

14 Littler, J. D. 'Discussion of "Ambient vibration measurements of the Humber suspension bridge and comparison with calculated characteristics" by Brownjohn *et al.*' *Proc. Instn Civ. Engrs: Part 2*, 1988, **85**, 725–730

15 Jeary, A. P. 'Establishing non-linear damping characteristics of structures from non-stationary response time-histories', *Struct. Engr*, 1992, **70**(4), 61–66

16 Carne, T. G., Lauffer, J. P., Gomez, A. J. and Benjannet, H. 'Modal testing an immense flexible structure using natural and artifical excitation', *Int. J. Analytical Experimental Modal Analysis*, 1988 **3**(4), 117–122

17 Bendat, J. S. and Piersol, A. G. *Random data: analysis and measurement procedures* (2nd edn) John Wiley, New York, USA, 1986

18 Brownjohn, J. M. W. *'Assessment of structural integrity by dynamic measurements' PhD thesis,* Department of Civil Engineering, University of Bristol, Bristol, UK, 1988

19 Abdel-Ghaffar, A. M. and Scanlan, R. H. Ambient vibration studies of Golden Gate bridge: I - Suspended structure', *J. Engng Mech., ASCE*, 1985, **111**(4), 463–482

20 Gundy, W. T., Scharton, T. D. and Thomas, R. L. 'Damping measurements on an offshore platform', *Proc. 12th Offshore Technology Conf.*, Houston, TX, USA, 1980, 4

21 Unholtz, K. 'Vibration testing machines', in *Shock and vibration handbook* (Harris, C. M. Ed) (3rd edn) McGraw-Hill, New York, USA, 1988, 25:1–25:26

22 Clements, E. W., Sullivan, J. R. and Vigness, I. 'Shock testing machines', In: *Shock and vibration handbook* (Harris, C. M. Ed) (3rd edn) McGraw-Hill, New York, USA, 1988, 26:1–26:20

23 Jeary, A. P. and Sparks, P. R. 'Some observations on the sway characteristics of concrete structures', *Symp. on Vibrations in Concrete Structures*, New Orleans, USA, 1977

24 Ellis, B. R., Jeary, A. P. and Sparks, P. R. 'Full scale and model scale studies of the dynamic behaviour of an offshore structure', *Proc. Int. Conf. on the Behaviour of Slender Structures*, City University, London, UK, 1977, III.1.1–III.1.13

25 Hudson, D. E. 'Synchronized vibration generators for dynamic tests of full scale structures', Research Report, Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, CA, USA, 1962

26 Shepherd, R. and Reay, A. M. 'Some apparatus for the small amplitude dynamic testing of multistorey buildings', *J. British Soc. for Strain Measurements*, 1967 **4**, 16–21

27 Severn, R. T., Jeary, A. P. and Ellis, B. R. 'Forced vibration tests and theoretical studies on dams', *Proc. Instn Civ. Engrs.: Part 2*, 1980, **69**, 605–634

28 Ohlson, S. 'Modal testing of the Tjorn bridge', *Proc. 4th Int. Modal Analysis Conf.*, Los Angeles, CA, USA, 1986, 1, 599–605

29 Leonard, D. R. 'Dynamic tests on highway bridges – test procedures and equipment', *TRRL Laboratory Report* 654, Transport and Road Research Laboratory, Berkshire, UK, 1974

30 Salane, H. J., Baldwin, J. W. and Duffield, R. C. 'Dynamics approach for monitoring bridge deterioration', *Transp. Res. Record*, 1987, **832**, 21–28

31 Galambos, T. and Mayes, R. 'Lessons from dynamic tests of an eleven storey building', *Engng Struct.* 1979

32 Kennedy, J. B. and Grace, N. F. 'Prestressed continuous composite bridges under dynamic loading', *J. Struct. Engng, ASCE*, 1990, **116**(6), 1660–1678

33 Tsang, W. F. and Williams, C. 'Application of experimental modal analysis to full-scale civil engineering structures', *3rd Int. Conf. on Recent Advances in Structural Dynamics*, University of Southampton, Southampton, UK, 1988, Paper 88

34 Salawu, O. S. 'Design and calibration of equipment for forced vibration testing: test rig and actuator', *Research Report* SCSE 92-009, School of Civil and Structural Engineering, University of Plymouth, Plymouth, UK, 1992

35 Allemang, R. J. and Brown, D. L. 'Experimental modal analysis,' in *Shock and vibration handbook*, (Harris, C. M., Ed) (3rd edn) McGraw-Hill, New York, USA, 1988, 21:1–21:34

36 Maguire, J. R. and Severn, R. T. 'Assessing the dynamic properties of prototype structures by hammer testing', *Proc. Instn Civ. Engrs.: Part 2*, 1987, **83**, 769–784

37 Lee, P. K. K., Ho, D. and Chung, H. W. 'Static and dynamic tests of concrete bridges', *J. Struct. Engng, ASCE*, 1987, **113**(1), 61–73

38 Green, M. F. and Cebon, D. 'Modal testing of two highway bridges', *Proc. 11th Int. Modal Analysis Conf.*, Kissimme, FL, USA, 1993, 2, 838–844

39 Morgan, B. J. and Oesterle, R. G. 'On-site modal analysis - a new powerful inspection technique', *Proc. 2nd Int. Bridge Conf.*, Pittsburg, PA, USA, 1985, 108–114

40 Wood, M. G., Friswell, M. I. and Penny, J. E. T. 'Exciting large structures using a bolt-gun', *Proc. 10th Int. Modal Analysis Conf.*, San Diego, CA, USA, 1992, 1, 233–238

41 Eyre, R. 'Dynamic tests on the Cleddau bridge at Milford Haven', *TRRL Rep.* SR200 UC, Transport and Road Research Laboratory, Crowthorne, Berkshire, UK, 1976

42 Chasteau, V. A. L. 'The use of tuned vibration absorbers to reduce wind excited oscillations of a steel foot bridge', *Civ. Engr. in South Africa*, 1973, **15**(6), 147–154

43 Douglas, B. M., Maragakis, E. A. and Nath, B. 'Static deformations of bridges from quick release dynamic experiments', *J. Struct. Engng, ASCE*, 1990, **116**(8), 2201–2213

44 Richardson, J. A. and Douglas, B. M. 'Identifying frequencies and three-dimensional mode shapes from a full scale bridge test', *Proc. 5th Int. Modal Analysis Conf.*, London, UK, 1987, 1, 160–165

45 Williams, C. 'Vibration monitoring of some civil engineering structures', *B.S.S.M./I.Mech.E. Joint Conf. Measurement in the Vibration Environment*, British Society for Strain Measurement, Durham, UK, 1983

46 Tilly, G. P. 'Damping of highway bridges: a review', *Symp. on Dynamic Behaviour of Bridges*, Transport and Road Research Laboratory, Crowthorne, Berkshire, UK, 1977, 1–9

47 Leitch, J., Long, A. E., Thompson, A. and Sloan, T. D. 'Monitoring the behaviour of a major box girder bridge', *Joint Inst. Struct. Eng./B.R.E. Seminar on Structural Assessment Based on Full and Large Scale Testing*, Building Research Establishment, Garston, Watford, UK, 1987, Paper 27

48 Sloan, T. D., Kirkpatrick, J., Boyd, J. W. and Thompson, A. 'Monitoring the in-service behaviour of the Foyle bridge', *Struct. Engr*, 1992, **70**(7), 130–134

49 Creed, S. G. 'Assessment of large engineering structures using data collected during in-service loading', *Structural Assessment Conf.* Building Research Establishment, Garston, UK, 1987, Paper 7

50 Pardeon, G. C., Carr, A. J. and Moss, P. J. 'Bridge modal identification problems', *Proc., 2nd ASCE Engineering Mechanical Division Specialty Conf. on the Dynamic Response of Structures: Experimentation, Observation, Prediction and Control*, Atlanta, USA, 1981, 29–45

51 Vincent, G. S. 'Golden Gate bridge vibration studies', *J. Struct. Div., ASCE*, 1958, **84**(ST6)

52 Abdel-Ghaffar, A. M. and Scanlan, R. H. 'Ambient vibration studies of Golden Gate bridge: II – Pier-Tower structure', *J. Engng Mech., ASCE*, 1985, **111**(4), 483–499

53 McLamore, V. R., Hart, G. C. and Stubbs, I. R. 'Ambient vibration of two suspension bridges', *J. Struct. Div., ASCE*, 1971, **97**(ST10), 2567–2582

54 Eyre, R. and Smith, I. J. 'Wind and traffic induced dynamic behaviour of some steel box girder bridges', *Symp. on Dynamic Behaviour of Bridges*, Transport and Road Research Laboratory, Crowthorne, UK, 1977, 56–69

55 Ward, H. S. 'Traffic generated vibrations and bridge integrity', *J. Struct. Engng, ASCE*, 1984, **110**(10), 2487–2498

56 Mazurek, D. F. and DeWolf, J. T. 'Experimental study of bridge monitoring technique', *J. Struct. Engng., ASCE*, 1990, **116**(9), 2532–2549

57 Littler, J. D. and Ellis, B. R. 'Ambient vibration measurements of the

Humber bridge', *Int. Conf. on Flow Induced Vibrations*, Bowness-on-Windermere, UK, 1987

58 Okauchi, I., Tanaka, A., Iwaya, K. and Furuyan, N. 'Vibration test of Ohnaruto bridge to confirm wind proofness', *IABSE Symp*, Tokyo, Japan, 1986

59 Cantieni, R. and Pietrzko, S. 'Modal testing of a wooden footbridge using random excitation', *Proc., 11th Int. Modal Analysis Conf.*, Kissimme, FL, USA, 1993, 2, 1230–1236

60 Wills, J. 'Correlation of calculated and measured dynamic behaviour of bridges', *Symp. on Dynamic Behaviour of Bridges*, Transport and Road Research Laboratory, Crowthorne, UK, 1977, 70–89

61 Eyre, R. and Tilly, G. P. 'Damping measurements on steel and composite bridges', *Symp. on Dynamic Behaviour of Bridges*, Transport and Road Research Laboratory, Crowthorne, UK, 1977, 22–39

62 Raimer, J. H. and Pernici, G. 'Dynamic testing of a modern concrete bridge', *Can. J. Civ. Engng.*, 1979, **6**(3)

63 Salane, H. J. and Baldwin, J. W. 'Identification of modal properties of bridges', *J. Struct. Engng, ASCE*, 1990, **116**(7), 2008–2021

64 Douglas, B. M. and Reid, W. H. 'Dynamic tests and system identification of bridges', *J. Struct. Div., ASCE*, 1982, **108**(ST10), 2295–2312

65 Selberg, H. E. 'Aerodynamic stability and related aspects of suspension bridges', *Symp. on Suspension Bridges*, Lisbon, Portugal, 1966

66 Sun, X. and Hardy, H. R. 'An investigation of applicability of modal analysis as nondestructive evaluation method in geotechnical engineering', *Proc. 10th Int. Modal Analysis Conf.*, San Diego, CA, USA, 1992, 1, 9–19

67 Biswas, M., Pandey, A. K. and Samman, M. M. 'Diagnostic experimental spectral/modal analysis of a highway bridge', *Int. J. Anal. Experimental Modal Analysis*, 1990, **5**(1), 33–42

68 Douglas, B. M. and Richard, J. 'Maximum amplitude tests of a highway bridge', *Proc., 8th World Conf. on Earthquake Engineering*, Earthquake Engineering Research Institute and International Association for Earthquake Engineering, 1984

69 Mareco, J. Catanheta, M. and Trigo, J. T. 'Field observations of Tagus River suspension bridge', *J. Struct. Div., ASCE*, 1969, **95**(ST4)

70 Green, R. 'Dynamic response of bridge superstructures – Ontario observations', *Symp. on Dynamic Behaviour of Bridges*, Transport and Road Research Laboratory, Crowthorne, UK, 1977, 40–55

71 Billing, J. R. 'Dynamic test of bridges in Ontario, 1980: data capture, test procedures and data processing', *MTC Research and Development Report SRR-82-02*, Ontario Ministry of Transportation and Communications, Downsview, Ontario, Canada, 1982

72 Cantieni, R. 'Dynamic load tests on highway bridges in Switzerland', *Report 211*, Eidgenossische Material-prufungs-und Versuchsantalt (EMPA), Dubendorf, Switzerland, 1983

73 Kohoutek, R. 'Tests on bridge over Talbragar river at Dubbo', *Proc., 11th Int. Modal Analysis Conf.*, Kissimme, FL, USA, 1993, 2, 1168–1174