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DIAGNOSTIC PROCEDURES FOR ASSESSMENT OF STRUCTURES

Abstract

The evaluation and verification of the actual loads, load carrying capacity and prediction of the remaining life are often required for existing structures. The objective of the paper is to present some of diagnostic techniques and examples of their practical applications. Diagnostic equipment such as strain measurement devices, deflection measurement equipment, optical and laser devises, accelerometers, tiltmeters, acoustic emission and crack control equipment as well as diagnostic procedures have been described.

Keywords: assessment of structures, diagnostic procedures

1. Introduction

Existing structures often require evaluation and verification of the actual loads and load carrying capacity as well as prediction of the remaining life. There are questions about the distribution of load on structural components, degree of deterioration and degradation of members and materials, assessment of deformations and displacements, occurrence and width of cracks, accumulation of fatigue load cycles, and so on. The analytical procedures are as accurate as the input data, i.e. assumptions about the boundary conditions, load and load distribution parameters, material behavior, redundancy and load sharing, contribution of nonstructural members, loss of section due to corrosion and other factors. It is a common practice to make conservative assumptions to account for uncertainties in quantification of these parameters in the analysis. However, the consequences of structural evaluation can call for an expensive repair, rehabilitation or replacement. Therefore, there is often a need for either a more detailed analysis and/or experimental verification of analytical assumptions using diagnostic procedures. Field tests confirm that the actual behavior of structures and its components is often very different than what is analytically predicted. For example, Bakht and Jaeger (1990) observed that the actual load capacity of bridges is considerably higher than what is predicted by analytical methods. In certain cases, this extra safety reserve in the load capacity can be used to prove that the bridge is adequate and thus to avoid or delay expensive repair or replacement. On the other hand, although diagnostic tests are useful tools in structural evaluation, they cannot ensure that the part subjected to testing will not fail or malfunction. That is because every non-destructive test (NDT) has limitations and evaluation techniques should not be applied on a routine basis because of the difficulty of using the equipment and in the interpretation of the results due to lack of standardization (Hellier 2001; Abudayyeh et al. 2004).

The objective of this paper is to present some of diagnostic techniques and examples of practical applications.

2. Needs for diagnostic techniques

Diagnostic techniques are mostly used for verification of analytical models and the selection of equipment and methodology depends on the actual needs. The major questions relate to the loads and load carrying capacity. The needs can concern short-term or long-term parameters. Knowledge of the actual loads and load effects may require surveys and on-site measurements, for example:

- Natural loads such as wind, snow, ice, earthquake, temperature are recorded and the accumulated database can be used in prediction of structural load and load combinations. The required information includes magnitude and frequency of occurrence. Very important is simultaneous occurrence of loads and correlation between them. For each time-varying load, the statistical parameters include magnitude, return period, duration and coefficient of correlation with other loads.
- Live load in buildings. There is a need for recording the extreme load effects in various types, depending on function (apartments, offices, hotels, hospitals).
- Truck loads on highway bridges. The available techniques include weigh-in-motion (WIM) measurements with the objective to record all moving vehicles, with axle loads and spacing, lane position, speed, multiple presence with other vehicles.
- Fatigue load spectra. The measurements are focused on recording the strains in critical (fatigue-prone) components or connections, caused by load cycles, e.g. moving crane or vehicles.
- Dynamic loads. In structures designed for static and dynamic load components, there can be a need for verification of the extreme total load effect.
- Load distribution factors. This is verification of the structural analysis methods, to determine how is the load distributed on the load sharing members.
- Construction loads. Instrumentation can help monitor progressive changes in the loads and displacements/deformations during construction.
- Displacements and deformations. Structural performance can be unacceptable due to excessive deflection and/or vibration, or horizontal sway.
- Strain and stress. Load effect can be measured in terms on moments and shears, but the local effects are strains and stresses.
- Cracking in concrete. Brittle materials such as concrete can crack when in tension. The presence of crack can be unacceptable for various reasons (aesthetics, limited functionality, gradual deterioration). For example, in prestressed concrete beams exposed to the elements, multiple opening of cracks can lead to corrosion of strands.
- Fatigue cracks in steel. Occurrence and propagation of cracks can lead to collapse. Therefore, it is important to know when a crack initiated and if it keeps growing.
- Minimum load carrying capacity. Some structures are difficult to model analytically (e.g. complex geometry, unknown material properties, partially damaged, deteriorated, repaired) and there is a need to verify if they are adequate for normal use or operation.

3. Diagnostics equipment

3.1. Strain measurement devices

The strain transducer, shown in Figure 1, is one of the most important tools for the measurement of micro-displacements. They are used for the measurement of strain caused by an external influence or an internal effect such as forces, pressures, moments, heat, structural changes of the material, and the like. A strain transducer is a sensor whose resistance varies with applied force. It converts force, pressure, tension, weight, etc., into a change in electrical resistance which can then be measured. When it is stretched by applied force its resistance increases. Strain transducer should be installed in the same direction as the strain.

Experimental stress analysis uses the strain values measured on the surface of a specimen or structural part to state the stress in the material and also to predict its safety and endurance. Strain transducers are used to record the induced strains as a most direct approach to quantifying stress in a structural member. The transducer generally contains a pressure sensitive diaphragm with strain gages bonded to it.

Fig. 1. Reusable strain transducer mounted to the lower flange of a beam

When a load is applied to the surface, the resulting change in surface length is communicated to the resistor and the corresponding strain is measured in terms of the electrical resistance of the foil wire, which varies linearly with strain. The foil diaphragm and the adhesive bonding agent must work together in transmitting the strain, while the adhesive must also serve as an electrical insulator between the foil grid and the surface. When selecting a strain transducer, one must consider not only the strain characteristics of the sensor, but also its stability and temperature sensitivity. Unfortunately, the most desirable strain gage materials are also sensitive to temperature variations and tend to change resistance as they age. For tests of short duration, this may not be a serious concern, but for continuous industrial measurement, one must include temperature and drift compensation.

In the past, strain transducer required a careful surface preparation and soldering to install. Now, most field strain gage installations can be replaced with a highly accurate new type strain transducer. These units are rugged and can be installed in any weather. Since they are pre-wired and easy to mount, they drastically reduce the field installation time.

The strain gages can be disposable or reusable. A new generation of these devices is wireless. It is important to note that strain measuring equipment requires power supply which is usually not available on the bridge. Then, power has to be provided by a generator or battery.

3.2. Deflection measurement equipment

The linear variable differential transformer (LVDT) is a type of electrical transformer used for measuring linear displacement. The transformer has three solenoid coils placed end-to-end around a tube. The center coil is the primary, and the two outer coils are the secondary. A cylindrical ferromagnetic core, attached to the object whose position is to be measured, slides along the axis of the tube. An alternating current is driven through the primary, causing a voltage to be induced in each secondary proportional to its mutual inductance with the primary. The frequency is usually in the range 1 to 10 kHz.

As the core moves, these mutual inductances change, causing the voltages induced in the secondary to change. The coils are connected in reverse series, so that the output voltage is the difference (hence "differential") between the two secondary voltages. When the core is in its central position, equidistant between the two secondary, equal but opposite voltages are induced in these two coils, so the output voltage is zero.

When the core is displaced in one direction, the voltage in one coil increases as the other decreases, cause the output voltage to increase from zero to a maximum. This voltage is in phase with the primary voltage. When the core moves in the other direction, the output voltage also increases from zero to a maximum, but its phase is opposite to that of the primary. The magnitude of the output voltage is proportional to the distance moved by the core (up to its limit of travel), which is why the device is described as "linear". The phase of the voltage indicates the direction of the displacement.

Because the sliding core does not touch the inside of the tube, it can move without friction, making the LVDT a highly reliable device. The absence of any sliding or rotating contacts allows the LVDT to be completely sealed against the environment.

LVDTs are commonly used for measuring deflection in jointed reinforced concrete pavements, deflection of the deck under testing load and fatigue load.

Fig. 2. The linear variable differential transformer (LVDT)

3.3. Optical and laser devises

In the past decade, developing new nondestructive methods for bridge diagnosis has attracted serious attention. These techniques are used for bridge management to help enhance the cost-effectiveness of diagnosing bridges.

High-resolution images can be used to global diagnosis as a relatively new approach. These images can be provided using a couple current devices (CCD) or CCD camera. A typical camera has a sensor to receive light signals to be processed to form digital images. High-resolution images devices have many advantages in term of global diagnosis. One of them is no sensors required to attach to the bridge which significantly reduce a cost. Moreover, a large number of points can be covered for which measurement data are to be obtained. The large number of pixels offer unprecedented amount of spatially intensive data for effective diagnosis.

CCD image data can be effectively used for diagnosing structural stiffness loss. Laboratory experiments show that this method can detect structural damage as small as a 3 percent stiffness reduction.

High-resolution monitoring system can be used for bridges and also for buildings. This is very good solution for monitoring structural movement over the long-term such as: motion of bridge piers or building walls, the status of cracks in concrete and masonry, and strain levels induced during construction.

An additional contemporary method of NDT is Impact – Echo. This method base on an acoustic signal sends into the test specimen and record reflection from internal flaws, material layers or other interface. By analysis the reflected signal, conclusions about the depth of the reflecting surface can be show on graph. Impact – Echo method is commonly used in tunnel construction to check the required limiting thicknesses.

Total station is modern solution for measurement of deflection with accuracy up to 0.2 millimeters. This monitoring system is easier to set up and use, reducing labor and time requirements. The total station obtained three-dimensional coordinates of every target by measuring a horizontal angle, vertical angle, and distance between points. It automatically recorded the coordinates with a point number, point description, date, time, and atmospheric conditions [Merkle and Myers].

a)


b)


Fig. 3. Total station set up for load testing (a) and reference point (b)

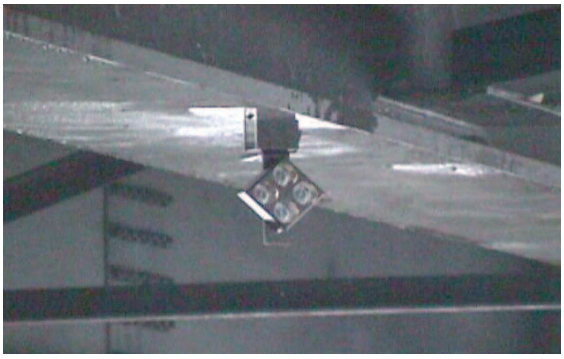

Fig. 4. Target (prism) on a structural component

3.4. Accelerometers

An accelerometer is a device that measures the vibration, or acceleration of motion of a structure. The force caused by vibration or a change in motion (acceleration) causes the mass to "squeeze" the piezoelectric material which produces an electrical charge that is proportional to the force exerted upon it. Since the charge is proportional to the force, and the mass is a constant, then the charge is also proportional to the acceleration.

There are two types of piezoelectric accelerometers (vibration sensors). The first type is a "high impedance" charge output accelerometer. In this type of accelerometer the piezoelectric crystal produces an electrical charge which is connected directly to the measurement instruments. The charge output requires special accommodations and instrumentation most commonly found in research facilities. This type of accelerometer is also used in high temperature applications (> 120^{o}C) where low impedance models can not be used.

The second type of accelerometer is a low impedance output accelerometer. A low impedance accelerometer has a charge accelerometer as its front end but has a tiny built-in micro-circuit and FET transistor that converts that charge into a low impedance voltage that can easily interface with standard instrumentation. This type of accelerometer is commonly used in industry. An accelerometer power supply like the ACC-PS1, provides the proper power to the microcircuit 18 to 24 V ≅ 2 mA constant current and removes the DC bias level, they typically produces a zero based output signal up to +/- 5V depending upon the mV/g rating of the accelerometer. All OMEGA(R) accelerometers are this low impedance type.

3.5. Tiltmeters

A tiltmeter is an instrument designed to measure very small changes from horizontal level (angle of rotation). The most frequently it used for monitoring the response of structures to various influences such as loading and foundation settlement. Typical applications for tiltmeters include:

– Monitoring stabilization measures, such as pressure grouting and underpinning.
– Monitoring structures for the effects of tunneling and excavating.
– Monitoring the deflection and deformation of retaining walls.
– Monitoring convergence and other movements in tunnels.
– Providing early warning of threatening deformations, allowing time for corrective action to be taken.

The very first tiltmeter was a long-length stationary pendulum. These were used in the very first large concrete dams, and are still in use today, improved with newer technology such as laser reflectors. The modern electronic tiltmeter uses a simple bubble level principle, as used in the common carpenter level. An arrangement of electrodes senses the exact position of the bubble in the electrolytic solution, to a high degree of precision. Any small changes in the level are recorded using a standard catalogER. This arrangement is quite insensitive to temperature, and can be fully compensated, using built-in thermal electronics. Tiltmeters have also been extensively applied in the area of monitoring volcano and volcanic eruption prediction.

3.6. Acoustic emission

Acoustic Emission (AE) refers to the generation of transient elastic waves produced by a sudden redistribution of stress in a material or a small surface displacement. When a structure is subjected to an external stimulus (change in pressure, load, or temperature), localized sources trigger the release of energy, in the form of stress waves, which propagate to the surface and are recorded by sensors. Earthquakes and rock bursts to the initiation and growth of cracks, slip and dislocation movements, melting, twinning, and phase transformations in metals are natural sources of AE. In composites, matrix cracking and fiber breakage and deboning contribute to acoustic emissions. AE's have also been measured and recorded in polymers, wood, and concrete, among other materials.

Detection and analysis of AE signals can supply valuable information regarding the origin and importance of a discontinuity in a material. Because of the versatility of Acoustic Emission Testing (AET), it has industrial applications in nondestructive testing and is used extensively as a research tool.

The application of AE to non-destructive testing of materials in the ultrasonic regime, typically takes place between 100 kHz and 1 MHz. Unlike conventional ultrasonic testing, AE tools are designed for monitoring acoustic emissions produced within the material during failure, rather than actively transmitting waves then collecting them after they have traveled through the material [Blitz and Simpson 1991]. Part failure can be documented during unattended monitoring. The monitoring of the level of AE activity during multiple load cycles forms the basis for many AE safety inspection methods that allow the parts undergoing inspection to remain in service.

The technique is used, for example, to study the formation of cracks during the welding process, as opposed to locating them after the weld has been formed with the more familiar ultrasonic testing technique [Blitz and Simpson 1991]. In a material under active stress, such as some components of an airplane during flight, transducers mounted in an area can detect the formation of a crack at the moment it begins propagating [Blitz and Simpson 1991]. A group of transducers can be used to record signals then locate the precise area of their origin by measuring the time for the sound to reach different transducers [Blitz and Simpson 1991].The technique is also valuable for detecting cracks forming in pipelines transporting liquids under high pressures [Blitz and Simpson 1991].

3.7. Crack control equipment

The most frequently applied method for examining cracks uses a transducer on either side of a crack opening and the wave speed of the facial material replaces that of the interior wave speed according to ASTM C 1383 regulations [ASTM 1998]. However, after generating a stress wave, the front of a P wave must arrive first. Because the first transducer, A, is closer to the wave source, S, the first transducer, A, may sense that P, S, and R waves are mixed, whereas the second transducer, B, located farther from S has an energy loss problem and cannot effectively measure the arriving waves. What is most significant is that almost all bridges have been given a surface finish, and consequently it is very hard to obtain the correct surface P wave speed for a structure whose surface has been weathered or has many cracks. Hence, using the wave speed as a replacement for speed of the interior material is likely inappropriate. Additionally, the cracks are typically with in the area of tensile steels. Thus in practical applications, the ASTM methods are quite limited [Ming-Cheng Chen at all 2007].

Fatigue crack detection may be enhanced for visual examination by the unaided eye by using liquids to penetrate fatigue cracks. One method (liquid penetrate testing) involves using dyes, fluorescent or non-fluorescing, in fluids for non-magnetic materials, usually metals. Another commonly used method for magnetic materials involves using a liquid suspension of fine iron particles applied to a part while it is in an externally applied magnetic field (magnetic-particle testing).

4. Diagnostic procedures

4.1. Weigh-in-motion truck measurement

Weigh-in-motion (WIM) devices are designed to capture and record truck axle weights and gross vehicle weights as they drive over a sensor. Unlike older static weigh stations, current WIM systems do not require the subject trucks to stop making them much more efficient. Gross vehicle and axle weight monitoring is useful in an array of applications including: Pavement design, monitoring, and research; Bridge design, monitoring, and research; Size and weight enforcement; Legislation and regulation; Administration and planning.

The most widely accepted and utilized WIM contemporary devises in North America are: piezoelectric sensor, bending plate and single load cell.

Piezoelectric Sensors are the most common WIM device. The sensor is embedded in the pavement and produces a charge that is equivalent to the deformation induced by the tire loads on the pavement's surface. It is common to install two inductive loops and two piezoelectric sensors in each monitored lane. A properly installed and calibrated Piezoelectric WIM system can provide gross vehicle weights that are within 15% of the actual vehicle weight for 95% of the measured trucks.

The bending scale consists of two steel platforms that are 0.6 x 2 m (2 ft. x 6 ft.), adjacently placed to cover a 3.65 m (12 ft.) lane. The plates are instrumented with strain gages, which measures tire load induced plate strains. The measured strains are then analyzed to determine the tire load. A properly installed and calibrated bending plate WIM system can provide gross vehicle weights that are within 10% of the actual vehicle weight for 95% of the measured trucks.

Single Load Cell device consists of two 3 x 3 m (6 ft. x 6 ft.) platforms placed adjacently to cover the 3.65 m (12 ft.) monitored lane. The scale mechanism incorporates patented load transfer torque tubes which effectively transfer all loading on the weighing surface to the load cell, which is mounted centrally in the scale. The system consists of two (2) steel frames (per lane) which are installed into existing or new asphalt or concrete pavement, and weigh pads which are bolted to the installation frame.

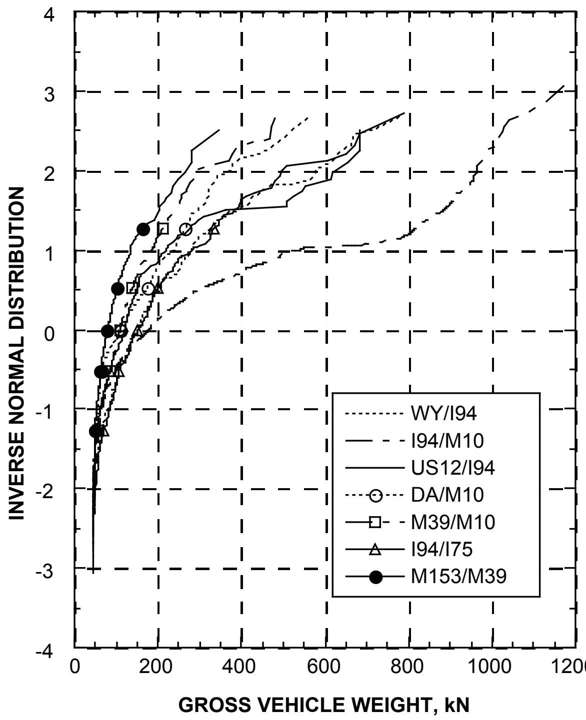

Fig. 5. CDF's of gross vehicle weight for different bridges

4.2. Verification of load distribution

Although modern computer techniques can provide detailed information about the load distribution in a bridge, the American Association of State Highway and Transportation Officials [AASHTO1998] Bridge Design Specifications provide a simple method for determining live load distribution, such that the bridge can be designed and analyzed as a series of beams, rather than a more complex three-dimensional structure. This makes routine design easy and provides a simple and quick way to evaluate a bridge.

Field testing is an increasingly important topic in an effort to deal with the deteriorating infrastructure. There is a need for accurate inexpensive methods for diagnostics, verification of load distribution, and determination of the actual load-carrying capacity. A considerable number of bridges in Michigan were constructed in the 1950s and 1960s [Eom and Nowak 2001]. Many of them show signs of deterioration. In particular, there is severe corrosion on many steel and concrete structures. By analytical methods, some of these bridges are not adequate to carry the normal highway traffic. However, the actual load-carrying capacity is often much higher than what can be determined by analysis [Bakht and Jaeger 1990], due to more favorable load sharing, effect of nonstructural components (parapets, railing, and sidewalks), and other difficult to quantify factors. Field testing can reveal the hidden strength reserve and thus verify the adequacy of the bridge.

Previous research was presented by Kim and Nowak (1997) and Nowak et al. (1999, 2000). About 20 structures were selected as representative for the bridge inventory in the state of Michigan. For each structure, field tests and analysis were performed. The girders were instrumented, and strains and stresses were measured due to heavy trucks (up to 761 kN). GDFs were then calculated for one truck (one lane loaded) and two trucks side-by-side (two lanes loaded). The GDFs were also determined by the advanced structural analysis, based on the finite-element method (FEM). The currently available computer procedures allow for a very high degree of mathematical accuracy. However, the limitation, even for the latest generation of FEM programs, is the accuracy of input data, in particular, material properties and boundary conditions. The actual support conditions are difficult to represent analytically. Hinge-roller supports can be partially fixed (frozen) due to corrosion, accumulation of debris, and presence of a heavy diaphragm over the support. Nonstructural components such as sidewalks, curbs, and parapets contribute to the overall stiffness, and it is difficult to estimate this contribution analytically.

Loading uses in field test is chosen based on WIM data. For example, in Michigan, the maximum mid-span moment in medium span bridges is caused by 11-axle trucks, with gross vehicle weight (GVW) up to 730 kN depending the axle configuration [Eom and Nowak 2001]. This is almost twice the allowable legal load in other states. Most states allow a maximum GVW of 356 kN only with up to 5 axles per vehicle. The vehicles used in the analysis in Michigan were fully loaded, three-unit, 11-axle trucks. A typical side-view of a truck used in the tests is shown in Figure 7. Analysis was performed under side-by-side truck loading condition.

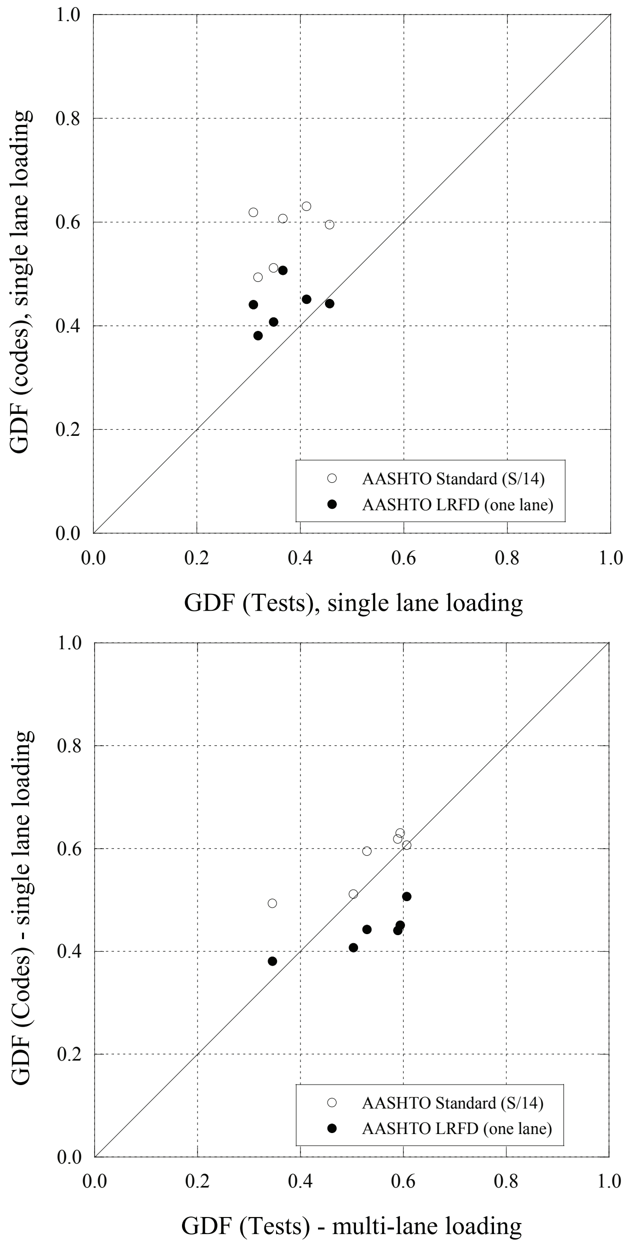

Fig. 6. Comparison of code specified vs. measured GDF's

Fig. 7. Truck used in diagnostic test

4.3. Verification of dynamic load

The dynamic load is time variant and random in nature and it depends on the vehicle type, vehicle weight, axle configuration, bridge span length, road roughness, and transverse position of a truck on the bridge. The dynamic load is usually considered as an equivalent static live load and is expressed in terms of dynamic load factor (DLF) [Nassif and Nowak 1995]. DLF is taken as a ratio of dynamic and static responses. In the AASHTO Standard (2002), dynamic load factors DLF are specified as a function of span length only (maximum 30 percent). In the AASHTO LRFD (2007), the dynamic load factor is equal to 0.33 of the truck effect, with no dynamic load applied to the uniform loading.

Field measurements are performed to determine the actual truck load effects and to verify the available analytical models [Nassif and Nowak 1995]. Measurements are taken using a system with strain transducers. For each truck passage, the dynamic response is monitored by recording strain data. The field measurements confirmed the results of analytical studies. The strain/stress due to dynamic load is nearly constant and is not dependant on static strain/stress. Therefore, the dynamic load factor is reduced for heavier trucks.

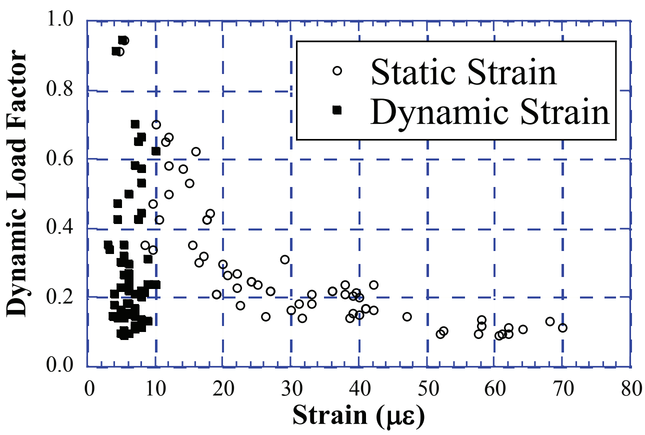

Fig. 8. Strain vs. dynamic load factor

To verify dynamic load the fallow measurement should be done on the bridge: dynamic load amplification, corresponding truck weight, in particular axle loads and axle spacing. The measurements should be taken simultaneously by two systems: the weight-in-motion (WIM) system and dynamic system (accelerations). The WIM system is purpose to measure and record all relevant truck information in addition to the strain response in each girder. The dynamic system is set up to measure accelerations simultaneously in this same location, where the strain gauges (close to maximum moment) [Nassif and Nowak 1995].

These measurements carry out static and dynamic stresses for each girder. The test results are showing that dynamic component of stresses is practically independent of static component. Therefore, verification of dynamic load on existing bridges is very important.

4.4. Fatigue load spectra

Fatigue is an important consideration in the design and analysis of steel bridge structures. Multiple passages of heavy trucks can lead to cracking and premature failure. Analysis of fatigue performance involves the determination of loads and material strength. Material response has been studied by many researchers. Fisher (1983) developed S-N curves for categories of details in steel structures. Fisher's work demonstrated the importance of load level, particularly magnitude and frequency of occurrence. For example, many fatigue load tests for girder bridges were conducted by Laman and Nowak (1996).

The objective of fatigue load research has largely been to establish an equivalent fatigue truck that will cause the same cumulative fatigue damage as the normal traffic distribution. A single, equivalent fatigue truck is a very attractive and useful tool for the practicing engineer. Schilling (1984), Raju et al (1990), and AASHTO (1989) suggest that the accuracy of the fatigue truck model is improved by adjusting the fatigue truck axle weights in proportion to an equivalent total weight, calculated from the specific site load distribution. In addition to the equivalent total weight, the equivalent lane moment has been calculated for each bridge in the study, which may be a more accurate indication of Miner's equivalent stress for use in fatigue calculations, particularly for shorter (< 20 m) spans. The equivalent lane moment does not, however, include the effects of intermediate smaller cycles caused by long vehicles crossing the bridge or dynamic effects. Greater accuracy is achieved when these intermediate cycles are included in the fatigue analysis.

In test conducted by Jeffrey and Nowak in 1996, a fatigue load model was developed from weigh-in-motion (WIM) measurements [Laman 1995]. Statistical parameters of stress were calculated for girder bridges. The results indicated that magnitude and frequency of truck loading were strongly site-specific and component-specific. Based on the WIM data, a design fatigue truck was developed. The model was calibrated against measured dynamic strains to achieve uniform reliability against fatigue failure.

The tests show that live load stress spectra are strongly component-specific. Each component experiences a very different distribution of strain cycle ranges. The girder that is nearest the left wheel track of vehicles traveling in the right lane experiences the highest stresses in the stress spectra and decreases as a function of the distance from this location. This information can be useful to target bridge inspection efforts to the critical members.

Example of the results of measurements taken on the bridge with 9 girders is presented in Figure 9. The cumulative distribution functions are shown for each girder. For this bridge, the response of each girder to the live load varies considerably.

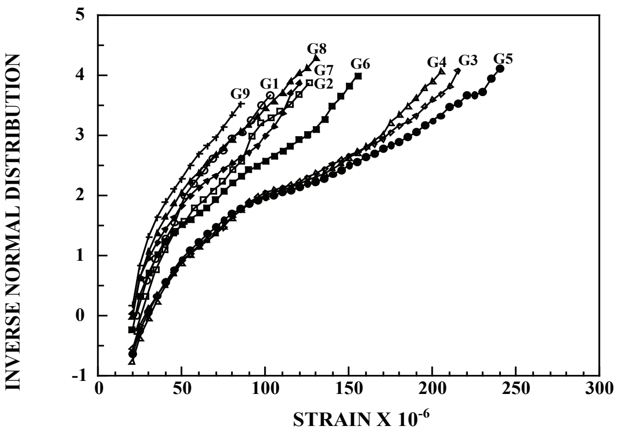

Fig. 9. CDF's of strain for different girders

A vehicle type that dominates the distribution of vehicle types does not necessarily dominate the fatigue damage of the particular component. A vehicle type that dominates the distribution of lane moments will likely dominate the fatigue analysis. This has been demonstrated in this study by the ten and eleven axle vehicles at each bridge and for several span lengths. Eleven axle vehicles dominate the extreme values of the load spectra. Distributions of lane moment demonstrate that eleven axle vehicles, although longer with more even load distribution, produce lane moments that are much greater than 5 axle vehicles.

The fatigue load models based on a three axle truck may overestimate the fatigue damage for bridges with a simple span shorter than 12 to 18 m and underestimate the fatigue damage for longer spans. The proposed fatigue load model more accurately predicts the fatigue damage caused by normal truck traffic passing over a bridge. The model is site-specific and is characterized by the load spectra of the bridge.

4.5. Proof load testing

To estimate the inherent extra capacities of bridges, several nondestructive load tests have been in use for many years. In general, nondestructive load test can be divided in two categories: diagnostic tests and proof load tests. Diagnostic tests are performed to get a better understanding of the bridge behavior, whereas proof load tests are used to obtain the actual live load capacity or to check the ability of the bridge to carry a certain live load with a factor of safety [Saraf, Sokolik and Nowak 1997].

Diagnostic tests involve a lower load level such as small trucks or normal traffic, and are used to calibrate or verify analytical models. These analytical models are then used to calculate the rating factors. However, several important parameters influencing the bridge behavior at lower load levels, such as the unintended composite action, bearing restraints, and effect of parapets, may disappear at higher load levels. Alternatively, proof load testing can be used for accurate evaluation of load-carrying capacity [Saraf and Nowak 1998].

Proof load testing can be used either to find the yield capacity of the structure, or to check its ability to carry a specified live load. Usually, the yield capacity of a bridge is very high and requires exceptionally heavy loads. In study [Saraf and Nowak 1998], proof load tests were carried out to verify if the bridge can safely carry the maximum allowable lega1 load. In Michigan, the maximum midspan moment in medium span bridges is caused by two-unit 11-axle trucks [Michigan Bridge Analysis Guide 1983]. For such an 11-axle truck, GVW can be up to 685 kN, which is almost twice the allowable legal load in other states (most states allow a maximum GVW of only 356 kN), more than five times the H15 design load, and more than twice the HS20 design load.

The proof load level should be sufficiently higher than that from a two-unit 11-axle truck to ensure the desired level of safety [Lin and Nowak 1984]. Until recently, the calculation of the appropriate proof load level was left to the judgment of researchers conducting the test. The final draft report by Lichtenstein (1993) provides guidelines for calculating the target proof load level. It suggests that the maximum allowable legal load should be multiplied by a factor X_p, which represents the live load factor needed to bring the bridge to an operating rating factor of 1.0.The report recommends that X_p should be 1.4. It also recommends several adjustments to X_p, which should be considered in selecting a target live load magnitude. According to the report, testing load should cause twice bigger effect than allowable legal load.

Fig. 10. Proof load test of a bridge using military tanks

5. Conclusions

Experimental procedures can be used as an efficient tool in evaluation of structures in particular when combined with analytical methods. There is a variety of equipment of techniques available for a wide spectrum of applications. The major selection criteria depend on what is to be measured, observed or monitored. The requirements and considerations include:

- Accuracy. Strain in steel and concrete is typically measured in terms of 0.001 or less, while deflection in 0.1 inch (or less). Higher accuracy can be costly.
- Ease of installation. This is an important consideration, as installation can be time-consuming, costly and disruptive to normal operation of the structure.
- Ease of operation. The equipment that runs without any operator is preferred, but it has to be reliable as frequent repairs can be costly.
- Time frame for operation of equipment. There is considerable difference between a short-term (seconds, minutes, hours, days, weeks) and long-term (weeks, months, years).
- Economics. Application of diagnostic procedures is viable when their cost is below the expected cost of repairs or replacement.
- On-site power supply. Availability of power supply can be detrimental in particular in case of long-term measurements. Renewable sources (e.g. solar or wind) can be considered as alternative solutions.
- Environmental effects. There are two groups issues. One is the effect of ambient conditions (weather, temperature, rain, snow, ice, wind, water) on functioning of the diagnostic equipment. The other is environmental protection restrictions which can impact the practical applicability of a procedure.
- Days and hours of operation. The availability of equipment and/or access to the structural components can be restricted to certain time periods, e.g. nights or after work hours only.
- Closure, limited operation and traffic control. In transportation projects, a major consideration is avoidance of any traffic disturbance such as lane closure, bridge closure or detour. Otherwise, there is an inconvenience to the public and increased risk of traffic accidents. Traffic control is also an additional cost that is added to the budget of diagnostic procedures.
- Security issues. Diagnostic procedures can make the structure vulnerable to vandalism or terrorist attack. Therefore, it is safe to consider the security issues when planning diagnostic testing.
- New developments. The new devices and techniques become available and it is important to keep track of the new developments that need to be checked for structural monitoring and diagnostics {note: this is obvious, so the suggestion}.

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