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Monitoring structural responses during proof load testing of reinforced concrete bridges: A review

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ABSTRACT: Proof load testing can be an interesting method to assess existing bridges for which analytical methods are unable to provide an accurate assessment. In a proof load test, a load representative of the factored live load is applied to the bridge. If the bridge can carry this load without distress, the proof load test is successful, and the bridge proves it fulfils the code requirements. Since large loads are applied, the structure or element that is tested needs to be carefully monitored during the test. This paper reviews the literature on reported load tests and the measurement techniques used during these tests. It also includes the test goals these techniques can address, and the advantages and disadvantages of the contact and non-contact techniques. The result of this review is guidance for the selection of appropriate monitoring and measurement techniques during load tests. This practical recommendation can serve engineers during the preparation of a load test, and will be extended in the future with stop criteria validated with experimental results.

1 INTRODUCTION

Since the early days load testing has been used to evaluate the performance of bridges (Lantsoght et al., 2017b). Currently, new and existing bridges can be load tested. There are two types of load tests: diagnostic tests and proof load tests.

A diagnostic load test is used to gather direct information about the behavior of the bridge from the field test and update analytical models.

Proof load tests are used to evaluate the structural safety of existing bridges. In this test, a high percentage of the live load is applied to a bridge. If the bridge carries the load without any signs of distress or nonlinearity, the test is considered successful, and the bridge proves that it meets the required safety level for the existing structure. In contrast to a diagnostic test, a proof load test involves large loads, so one of the main concerns is the high risk of causing irreversible damage or even the collapse of the structure. To minimize this risk, the structural response of the bridge needs to be monitored in real-time during the test with various sensors. These measurements are used to define stop criteria that indicate that the test needs to be stopped. Stop criteria are usually based on measurements of structural responses like deflections, crack width, strains, and the development of the cracks(Deutscher Ausschuss für Stahlbeton, 2000, Lantsoght et al., 2019).

Currently, instrumenting a bridge that will be load tested can be time-consuming (Lantsoght, 2019). Most of the measurement techniques are based on contact sensors, which need to be calibrated, installed and wired. Moreover, these traditional measurement techniques, such as linear variable displacement transformers (LVDTs) or strain gauges, can only capture the structural response at one given position and require further interpretation to correlate the output to the structural behavior of the bridge.

In order to prepare a proof load test faster and improve the efficiency of the measurements taken during the test, non-contact measuring techniques can be incorporated to the sensor plan. These techniques have the advantage that they are applied without physical contact with the structure, and they require no cables or reference measurements. These types of measurement methods, such as digital image correlation, have already been used successfully (Schmidt et al., 2018). In addition, the sensor plan could include methods like acoustic emissions and fiber optic sensors that can measure over larger distances or areas in a distributed way so that a minimum number of sensors is used.

One of the challenges that engineers face is choosing the optimal measuring technique from a large variety of options. Currently, there is no guideline that includes up to date recommendations on the selection of a sensor plan. This paper reviews the literature on reported load tests and the measurement techniques used during these tests. It also includes the methodology, advantages, and disadvantages of contact and non-contact measuring techniques. Finally, recommendations for the development of the sensor plan are given. The goal is to guide engineers in the selection of the appropriate measuring technique during load tests which can help them save time during the preparation of a proof load test.

2 STATE-OF-THE-PRACTICE OF LOAD TESTING AND INVOLVED MEASURING TECHNIQUES

The current state of the practice for load testing includes diagnostic and proof load tests, as well as failure tests. Successful load tests on concrete bridges have been widely reported in the literature. The next sections present examples of load tests on concrete bridges and the measuring techniques or sensors used during these tests.

2.1 *Diagnostic load tests*

Diagnostic load test are the most common type of load tests and they are used to check design assumptions and analytical models. For example, diagnostic load tests have been used to determine the transverse flexural distribution by measuring the strains over the width of the bridge and the deflections. Examples have been reported in the USA (Saraf, 1998, Arockiasamy and Amer, 1998, Velázquez et al., 2000, Catbas et al., 2005, Jones, 2011, Sanayei et al., 2016, Diaz Arancibia and Okumus, 2018) and Australia (Al-Mahaidi et al., 2000). The strain measurements were obtained using strain gauges, clip gauges, wire vibrating strain gauges, and LVDTs. The sensors were mounted to the underside of the concrete slabs using frames or scaffolding.

The deflections are usually recorded with LVDTs or deflection gauges. These measurements can be used to assess the overall stiffness of a bridge as reported by Aktan et al. (1992).

In addition, strain measurements over the height of the beams can determine if the element is cracked or uncracked by finding the position of the neutral axis. Strain gauges were adhesively bonded over the height of girders (Hag-Elsafi and Kunnin, 2006, Jeffrey et al., 2009, Jáuregui et al., 2010).

For new bridges, diagnostic tests can be used to demonstrate the behavior of the bridge or to confirm assumptions made in the analytical models. For example, a high-performance concrete bridge in the USA (Yang and Myers, 2003) was instrumented to verify the design. Vibrating wire strain gauges, electrical resistant strain gauges, and thermocouples were used to monitor concrete strains. The deflections were measured with LVDTs and total station, however the readings were too small to be recorded with the land surveying system. In addition, inclinometers were placed on the deck to measure the slope deformation.

2.2 *Proof load tests*

Proof load tests evaluate the strength of existing bridges. For example, in the USA (Shahawy, 1995), displacement transducers were used to obtain strain readings, the acceleration response was measured with acceleration and vibration transducers and the vertical deflections were measured using LVDTs. The deflections, strains and accelerations were monitored in real-time during the test.

Proof load testing is also used when the uncertainties on the bridge are large. An old bridge (Juntunen and Isola, 1995) was proof load tested to estimate the amount of degradation in the USA. The deflection measurements were recorded using LVDTs and monitored in real-time during the experiment. A spotting scope was used to observe the fascia beams to monitor the development of cracks. Deflection measurements were also taken with an electronic level however the accuracy was not adequate and the results were not interpreted.

Four reinforced concrete slab bridges were proof loaded and one bridge was tested to collapse in the Netherlands (Lantsoght et al., 2017a). The objective of the tests was to provide recommendations for the preparation, execution, and analysis of proof loading. These bridges were instrumented with LVDTs to measure the support deflections, crack widths and strains on the bottom of the slab. Laser distance sensors recorded the mid-span deflections. Acoustic emission sensors tracked the cracking active areas and load cells measured the applied load.

Four concrete bridges were proof load tested in Denmark (Schmidt et al., 2018). The initial goal was to develop a fast testing method that involved advanced monitoring systems. LVDTs, a total station, and laser distance sensors recorded the deflections to evaluate the load distribution and degree of fixation at the supports. Load cells measured the applied loads. In addition, DIC technique was applied using a wide-angle lens camera. Photographs were taken of the bottom of the deck without applying an artificial pattern which allowed to register the crack initiation, deformations and strains. Finally, a 3D laser scanner was used to reproduce the test environment in virtual reality, which helped to measure the distances and check strains.

2.3 *Collapse tests*

Collapse tests provide information about the onset of nonlinear behavior and the ultimate capacity of structures. Recently, a prestressed concrete bridge was tested to failure in Germany (Gehrlein et al., 2018). In addition to the conventional measuring techniques, such as LVDTs, load cells, and electrical strain gauges, a camera-based system and fiber optical measurements were applied. More than 750 m of fiber optical sensors were bonded to the sides of the beams and on the surface of the slab. The objective was to monitor and compare the strain measurements. The crack development was monitored with the camera-based system.

3 REVIEW OF MEASURING TECHNIQUES

Several types of measuring techniques and sensors are available to monitor the structural response of a bridge. They are usually classified based on the behavior or mechanisms and the purpose. However, in this paper, the measuring techniques are divided into two categories: contact and non-contact. In the former, the sensor has physical contact with the structure, which usually complicates and slows down the preparation of a proof load test.

In order to select from the large variety of options, the basic principles and applications should be known.

3.1 *Non-contact*

3.1.1 *Digital Image Correlation*

Digital Image Correlation (DIC) is a non-contact technique that provides full-field displacement measurements of an entire specimen surface by comparing a reference image in an undeformed state to a series of deformed images by tracking points or patterns between them. The specimen requires that its surface must have a random speckle pattern, which can be its natural texture or made by applying white and black paint. The accuracy is highly dependent on the quality of the pattern, the resolution of the camera and the lens. Algorithms may be needed to correct the distortion, the amount of light or the out of plane movements.

The application of DIC in concrete structures has been continuously increasing due to the evolution of technology. DIC has been used to measure bridge deflections by mounting targets at the bottom of girders (Jáuregui et al., 2003, Alipour et al., 2019).

3.1.2 *Virtual Visual sensor*

This technique proposes that every pixel in a digital video taken from a structure represents a candidate of a virtual visual sensor (VVS). The methodology uses an Eulerian specification where a pixel is selected and its intensity is monitored over time and analyzed using the Fast Fourier Transform (FFT), to reveal the fundamental frequency of vibration (Schumacher and Shariati, 2013). The displacement amplitudes can also be estimated using targets.

3.1.3 *Microwave interferometer radar*

The microwave radar measures the static deflections of several points on a large structure as well as vibrations to identify resonant frequencies and mode shapes. Every discontinuity on the structure is a potential reflecting target. The implementation of the radar involves two steps. First, several consecutive radar images are acquired. Then, the displacements of the targets are evaluated with the backscattered microwaves. The latest version of the radar provides real-time monitoring of the displacements. The equipment consists of the sensor module that is mounted on a tripod, the control unit, and the power supply. The preparation includes the set-up of the radar below or near the structure and the possible installations of metallic reflectors. The radar was used on the Manhattan Bridge in New York (Mayer et al., 2010) to measure deflections and resonant frequencies.

3.1.4 *Laser distance sensors*

The laser triangulation sensors determine the position of a target by measuring the reflected light from the surface. The operating principle consists on projecting a laser beam on a measuring target. Then a part of the beam is reflected via focusing optics onto a detector. The equipment consists of the laser, cable, amplifier and A/D converter. A mounting system is required to attach the laser.

3.1.5 *Total station*

The total station is an equipment that combines the use of an electronic distance measuring device (EDM) with an electronic theodolite. The theodolite measures the vertical and horizontal angle, while the EDM uses electromagnetic energy to measure the slope distance to the target or prism. The EDM sends a light signal which reflects from the prism. The time interval that the light takes to travel is measured and used to calculate the distance. The robotic total stations (RTS) are provided with an automatic target recognition system. The total station needs to be set on stable ground with an unobstructed view to the field targets as reported in Merkle and Myers (2004).

3.2 *Contact*

3.2.1 *Fiber optic sensors*

An optical fiber consists of a cylindrical central core surrounded by a cladding that has a lower refractive index. The cladding traps the light being carried by the core by reflecting the light waves. Fiber optic sensors (FOS) measure the change of some property of the guided light. The fiber Bragg grating (FBG) sensors monitor changes in the wavelength of the light, which is affected by strains, temperature, and vibration. The distributed sensors (DOFS) are based on the interaction between the emitted light and the backscattering caused by changes in strain and temperature. The usual equipment of a fiber optic system consists of the fiber optic cable, amplifier, splicer and A/D converter. Fiber optic sensors can be embedded in the structure during the concrete casting or adhesively bonded to the element.

3.2.2 *Linear variable differential transformers*

Linear variable differential transformers (LVDTs) are a type of electromechanical transducer used to measure linear displacements. The transducer detects the displacement between the central core and the electrical coils. The core movement causes the mutual inductance between the coils to vary. This varies the output voltage proportional to the position. The equipment consists of the LVDT that needs to be calibrated, cable, amplifier, A/D converter and the mounting system.

3.2.3 *Electrical resistance strain gauge*

An electrical resistance strain gauge consists of a thin metallic film deposited on a non-conducting plastic film (Aktan et al., 2003). The operating principle relies on the relationship that the resistance of a conductor will change directly proportional to a change in its length and this change in electrical resistance is related to strain. A Wheatstone bridge circuit converts the change in resistance to voltage.

3.2.4 *Vibrating wire strain gauge*

Vibrating wire strain gauges (VWSG) use the principle that a wire vibrates when held in tension and a force is applied (Ettouney and Alampalli, 2012). These types of gauges consist of two end blocks with a wire fixed in between them. The blocks are fixed to the surface and the relative displacement between them causes a change in the natural frequency of the wire, which is translated into a measurement of deformation.

3.2.5 *Strain transducers*

Demountable strain gauges or strain transducers consist of a full Wheatstone bridge foil strain gauge mounted inside a flexible proving ring. The strain transducer is attached to the structure in two ends with a known distance between them. The change in the length gage is related to the strain.

3.2.6 *Inclinometer*

Inclinometers measure the inclination of a structural element. An electrically-based inclinometer requires DC input in the range of 5-15 volts and gives outputs in the same range (Ettouney and Alampalli, 2012). The measured voltages are then converted to inclinations using their sensitivity. There are several types of inclinometers for instance: the hydrostatically based inclinometers, the fiber optic tiltmeter (which operates using a beam light, a shield and a sensor), the vibrating wire-based and the pendulum.

3.2.7 *Acoustic emission*

Acoustic emission (AE) sensors are typically made of piezoelectric elements like lead zirconate titanate (PZT) protected by metal housings, which are mounted to the surface of the specimen. The sensors detect the mechanical waves and convert them into electric signals. Since the signals are of low magnitude, preamplifiers are needed to convert them into usable signals, which will then be recorded and processed by the data acquisition system (Grosse and Ohtsu, 2008). AE sensors detect passive phenomenon in reinforced concrete structures like cracking (Schechinger and Vogel, 2007), hydrating (Lura et al., 2009), or bond slip of steel bars (Van Steen et al., 2019).

3.2.8 *Smart aggregates*

Smart aggregate (SA) is a new type of sensor (Song et al., 2008) that consists of a PZT patch placed in between two marble elements. The PZT is covered by epoxy for water proof. The piezoelectric property of the PZT patch allows the sensor to act as both an actuator (source) of ultrasonic elastic waves and receiver (sensor). Since the mechanical properties are comparable to the aggregates in normal concrete, SA can be embedded inside the concrete. Concrete protects them from environmental influences. Therefore, SA can perform stably over time. SA provides information about crack distribution (Du et al., 2018), strain and stress level (Kevinly et al., to be published).

3.2.9 *RFID sensor*

Radio frequency identification (RFID) uses electromagnetic fields (EM) to automatically identify and track tags. Passive RFID is an emerging technique where the RFID reader first transmits continuous waves (CW) to the tag to wirelessly power the chip, and then receives the modulated RF commands from the tag. This type of sensor can measure displacement, strains and can monitor environmental conditions such as moisture, humidity and temperature. In laboratory environments (Cazeca et al., 2013, Ozbey et al., 2016), the method has been used to measure displacements with an accuracy of the order of millimeters and strains in the order of microstrains. With respect to crack detection, an RFID antenna for detection of surface cracks was introduced by Kalansuriya et al. (2013), which also proposed a 2-D grid of tags to improve spatial coverage.

3.2.10 *Accelerometer*

Accelerometers are sensors that measure the acceleration of a structure. There are different types: force-balance, capacitive, piezoresistive and piezoelectric. Piezoelectric accelerometers are the most common type. They are designed to produce an electrical signal proportional to the forces induced by the vibration of the structure. Quartz and PZT are common materials.

3.3 *Environmental sensors*

There are several types of sensors to measure the temperature effects. For example thermocouples, thermistors, vibrating wire strain gauges and fiber optic sensors. Relative humidity is usually measured using a thin film principle that consists of the change of dielectric properties due to the changes in the water content. Wind speed and direction are traditionally measured with a cup anemometer and a wind vane or using an ultrasonic anemometer.

4 COMPARISON OF MEASURING TECHNIQUES

Table 1 provides a general comparison of the measuring techniques found in the literature with the overall advantages and disadvantages. For instance, measuring the deflection of a structural member can be performed with a variety of techniques. While contact sensors provide high accuracy measurements, the drawback that hinders its application in the field is the necessity to be fixed. Non-contact techniques provide the advantage that the measurements can be obtained from a remote location, however, most of them need a speckle pattern or a target attached to the surface which can increase the set-up time.

Strains are usually measured with electrical strain gauges which can only be used as discrete or punctual sensors and require long connecting cables. On the other hand, fiber optic sensors present the advantage that large lengths of a structure can be monitored with both strain and temperature measurements in a distributed way using one cable. Additionally, these sensors are immune to electromagnetic interference and provide high sensitivity and accuracy.

Acoustic emission and Digital Image Correlation can be used to monitor and detect the location of the cracks during a load test. Some commercial DIC systems are able to display real-time results, but the cameras need to be connected to a computer and the correlation algorithm can be time consuming. AE can be monitored in real time and detect the internal micro cracking, which provides an insight on the initiation and propagation of cracks.

Dynamic response parameters such as natural frequencies, mode shapes and vibration amplitudes can predict structural damage since they are a measurement of the stiffness and the elastic properties of the structure(Casas and Moughty, 2017). These parameters are usually recorded with accelerometers.

5 SENSOR SELECTION

An important aspect of the planning and preparation of a load tests is the designing of a sensor plan. This plan should include details such as the position, type, range, sampling rate, data acquisition system, required installation and wiring as well as a justification of the selection of the sensors.

The first step in developing a sensor plan is the selection of the sensors or measuring techniques. This selection should be based on several important criteria:

1. The variable or structural response that will be measured. It is also important to understand the correlation between the measured variable, the structural components and the specific loading case.
2. The preliminary calculations which provide an insight of the expected magnitudes. These calculations will help with the selection of range, sensitivity, and accuracy.
3. The spatial properties and the accessibility
4. The environmental conditions in which the measurements will be made.

For proof loading, the current codes and guidelines (Deutscher Ausschuss für Stahlbeton, 2000, ACI Committee 437, 2013) as well as the recommendations formulated in the Netherlands (Lantsoght et al., 2016, Lantsoght et al., 2019) define the stop criteria on the measurements of the concrete strains, deflections and crack widths. The recommended measurements during a proof load test are:

a) Concrete strains.
b) Applied load.
c) Deflection.
d) Deflection of the supports to obtain the net deflection.
e) Rotations at the supports provide an indication of the degree of fixation.
f) Crack widths of existing and new cracks.
g) Crack development.
h) Reference strains to measure the effect of temperature and humidity and correct the readings.
i) Environmental conditions such as ambient, temperature, wind speed and humidity. Some sensors have a range of temperatures in which they can operate successfully.
j) Joint displacements and settlements.

The steps in the process of selecting a sensor or measuring technique are summarized in Figure 1. The first step is to identify the variables or structural responses that need to be monitored. Next, the accessibility to the site must be considered. This can determine the possibility of using a non-contact technique. Then, a choice must be made between monitoring at a given position or in a distributed way.

Table 1. Summary of available techniques and sensors

Technique	Parameter	Mechanism	Range of accuracy	Advantages	Disadvantages	Wireless
LVDT	Displacements	Electromechanical	μm	Very reliable, high accuracy, simple, light and easy to maintain	Sensible to temperature, setup can be difficult on-site, operating range	No[i]
DIC	Displacement, strains and crack development	Photogrammetry	pixel	Non-contact, full-field measurements and no fixed reference	Noise, calibration, durability and cost of equipment	Yes
Laser distance sensor	Displacement	Optical	μm	Installation of the laser (Frame to attach the laser)	Highly sensitive, clean from dirt, raindrops and foreign materials, sensitive to temperature	No
Interferometric radar	Displacement	Microwave	mm	Remote sensing, suitable for day and night and all weather conditions, several targets can be monitored	Location of measurement points, relative displacements, careful planning	Yes
Total station	Displacement	EDM with electronic theodolite	mm	Rugged, widely available	Data gathering time consuming, sensitive to vibrations and environmental conditions	Yes
Fiber optic sensors	Strains due to load and temperature	Optical	με	High sensitivity, no reference, cover long distances, immune to electromagnetism	Installation, sensitive to temperature, careful handling	No
Strain gauge	Strain	Electrical resistance	με	Integral part of the structure, light, available in different sizes	Tedious to install, not reusable, sensitive to temperature	No[i]
VWSG	Strain	Frequency of vibration	με	Immune to electrical noise, can be embedded	No dynamic measurements, data analysis, bigger size	No[i]
Strain transducers	Strain	Electrical resistance	με	No need of surface preparation, reusable, waterproof, commercialized	Not an integral part of the structure, short term, issues with temperature	No[i]
RFID sensor	Displacement, strain, crack location	Electromagnetic fields	με	Remote sensing, no need of power supply, inexpensive, several tags can monitor larger areas	Calibration, sensitive to ambient environment and electromagnetic radiation, noise, not commercialized	Yes
Inclinometers	Inclination	Several	0.001°-0.1°	Very sensitive	Installation can be difficult	Yes
Accelerometer	Acceleration	Several	g	Widely commercialized and relatively easy to install	Requires experienced personal, maintenance for long term	No[i]
VVS	Frequency of vibration	Photogrammetry/ FFT	Pixel/Hz	Non-contact, multiple objects can be monitored simultaneously	Noise, dependent of the equipment and distance to the ROI	Yes
Acoustic emission	Crack location	Electric wave	cm	Real time measurements of fracture process, very sensitive	Material heterogeneity, signal attenuation, noise, smooth and dry surface	No

Smart aggregates	Crack location and strain change	Electric wave	με	Installation is not limited to the surface, less influence by environmental changes	Hole drilling, sensors are not commercialized	No

[i] A wireless transmitter is commercially available. The transmitter connects to the sensors and collects the data. Then via Bluetooth, the readings are sent to the electronic device

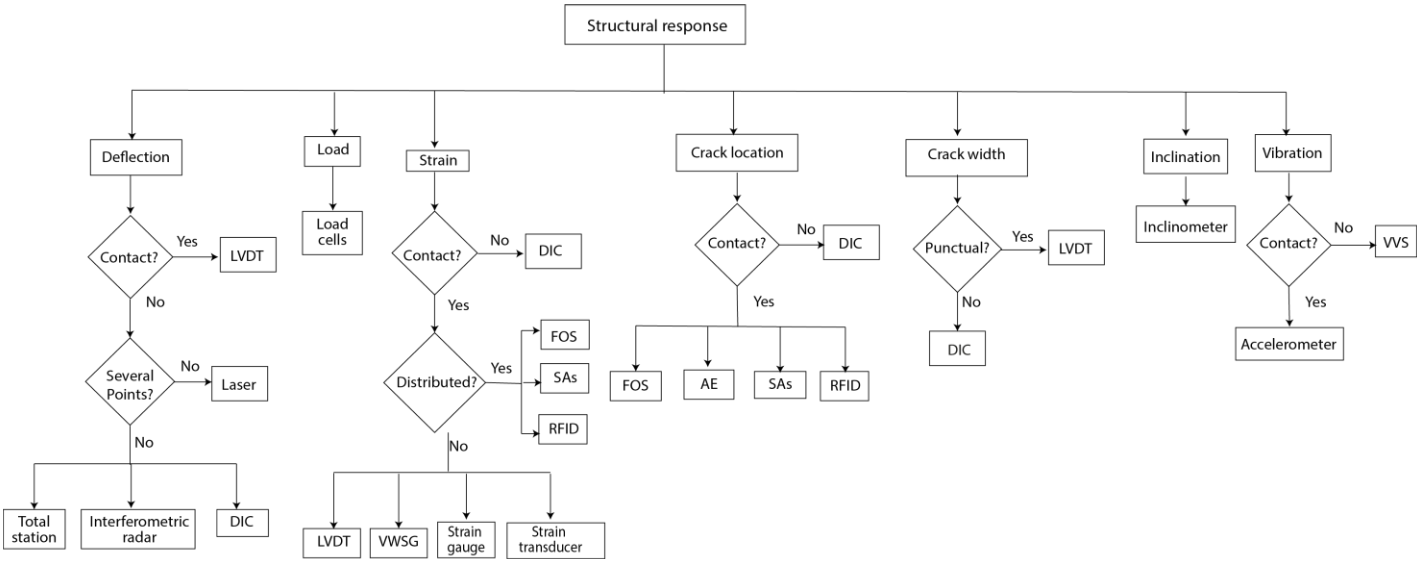

Figure 1. Sensor or measuring technique selection

6 CONCLUSIONS AND RECOMMENDATIONS

This paper has reviewed various sensors and measuring techniques that are applicable to proof load testing of concrete bridges. The applications, the methodology, advantages and disadvantages of contact and non-contact methods have been presented. The following are some of the important recommendations:

- Non-contact techniques are the better choice for bridges that are difficult to access. The deflections can be measured with a total station, interferometric radar or DIC from a remote location.
- The load-deflection diagram provides information on the overall stiffness of the bridge. This diagram should be monitored during the experiment as it can provide an indication of the onset of nonlinear behavior. If the deflections are measured at different positions along the transversal and longitudinal direction, deflection profiles can be developed
- Sensors should be selected depending on the expected measuring values to choose an appropriate accuracy and range.
- For proof load testing of reinforced concrete slabs, strains at the bottom of the cross-section can be followed for the verification of stop criteria. The strains can be monitored with FOS to cover larger lengths in a distributed way.
- During a proof load test, the development of cracks should be monitored in real-time. AE, SAs, and DIC provide advantages over other traditional methods. In particular, DIC can monitor larger areas in cases where it is difficult to predict the exact point of the initiation of the crack. On the other hand, SAs and AE can monitor the internal cracking and provide insight into the initiation and propagation of the cracks earlier than other techniques.

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