Monitoring of prestressing forces in prestressed concrete structures—An overview

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Summary
This paper presents an overview of currently available methods for monitoring prestressing forces in prestressed concrete structure. Structural health monitoring has become an increasingly important tool for assessment of structural performance. Additionally, the value of the prestressing force represents an important parameter in prestressed concrete structures. Thus, several methods for monitoring prestress forces have emerged. This paper aims to consolidate the work performed in the area of prestressing force monitoring by presenting the most important advances and the directions for future research. The methods presented in this paper are based on indirect monitoring of the prestressing force through monitoring of another relevant parameter. They are divided into five general classes based on the relevant parameter they monitor: (a) vibration-based methods (based on acceleration), (b) impedance-based methods (based on electrical impedance), (c) acoustoelastic methods (based on wave velocity), (d) elasto-magnetic methods (based on magnetic permeability), and (e) strain-based methods (based on strain). The paper presents a table summarizing the comparison between the methods based on defined criteria.

KEYWORDS
force monitoring, prestressed concrete, prestress loss, structural health monitoring

1 | INTRODUCTION
Since the introduction of prestressed concrete in the 1940s, there has been a significant increase in its use as a construction material due to its numerous advantages over traditional reinforced concrete, such as reduced member sizes, deflection control, and cracking control. For example, more than 45% of bridges built in the United States since 2010 have been made of prestressed concrete. Additionally, prestressed concrete is routinely used in the construction of several other types of important structures such as containment vessels of nuclear reactors, silos and tanks, posttensioned floor slabs, and prestressed and posttensioned concrete wind turbine towers. Due to the importance of these structures, extending their service life is of interest. This has led to several efforts in the monitoring of prestressed concrete to ensure structural integrity and performance through both long-term structural health monitoring (SHM) and intermittent nondestructive evaluation (NDE).

Prestress force levels are indicative of damage as both a precursor to certain types of damage (their loss can cause cracks) and a consequence of other types of damage (corrosion or rupture of strands). If force levels drop below a certain thresh-
old, tensile stresses can develop in the concrete, resulting in cracking or excessive deflections. Additionally, corrosion or rupture in prestressing strands result in local changes in the prestressing force levels, which can have a catastrophic effect on the structure. If a local change in prestressing force levels is detected, it can be indicative of such types of damage and maintenance can be scheduled to prevent propagation of this damage to a level that can threaten the safety of the structure.

Prestressing force levels are expected to decrease over the service life of a structure due to time-dependent losses that are caused by steel strand relaxation and concrete dimensional changes due to creep and shrinkage. These prestress losses are accounted for in the design process using empirical equations from design codes. However, these empirical equations are typically based on laboratory tests and may not truly represent the actual concrete mix and curing conditions. For example, prestress losses in prestressed high performance concrete have been shown to be significantly different from design predictions and dependent on the concrete mix.7 Overestimating prestress losses may result in conservative and possibly uneconomic designs. On the other hand, underestimating prestress losses can result in tensile stresses in the concrete and possibly cracking, which can affect durability by exposing reinforcement to the environment, and in some cases, combined with other mechanisms (e.g., corrosion), can lead to failure. Thus, evaluation of prestress forces and thus losses in prestressed concrete structures has become increasingly important.

The aim of this paper is to present and discuss the state of the art in monitoring prestressing force levels in prestressed concrete in laboratory and field applications. In particular, the aim is to summarize the progress made thus far in each of the fields of methods of monitoring of prestressing force and to identify their advantages and limitations with regard to specific application. Finally, this paper aims to identify challenges to the application of methods on real structures and to make recommendations to overcome said challenges.

This paper includes a representative but not exhaustive literature review due to the density of studies in the field of monitoring prestressing forces. To the best of the authors’ knowledge, the paper represents all active research areas in prestress force monitoring. Because the purpose is to present the state of the art of the field, and in the interest of brevity, literature included in this paper represents the progress milestone studies in each area in order to provide a complete perspective rather than a summary of every study performed.

Currently, directly measuring force levels in a structure in field applications is not feasible. Although forces can be monitored by means of a hydraulic force gauge, this would only provide information of the force near the anchorage (where the sensor is usually installed). Additionally, no literature has been found that demonstrates the durability and longevity of such force sensors in field applications. Instead, all technologies available and presented here rely on measuring a parameter that can be correlated with force levels. The paper is organized into five main sections, each of which discusses methods based on one parameter or a group of similar parameters. The methods presented are as follows: vibration methods (based on acceleration), impedance-based methods (based on electrical impedance), acoustoelastic methods (based on wave velocity), elasto-magnetic (EM) methods (based on magnetic permeability), and strain-based methods (based on strain). Each method is presented with considerable detail so that a less experienced reader can get sufficient information; however, a more experienced reader who might be less interested in details can move directly to a brief summary on the method included at the end of each section.

2 | EVALUATION CRITERIA

The methods presented in this paper consider general classes of NDE and SHM methods and not specific sensors or algorithms. Thus, they are evaluated based on their overall promise to provide stable and accurate long-term information on prestressing forces. The five criteria for evaluation include sensitivity to prestress force changes, imperviousness to other regularly changing factors such as environmental variables, ability to monitor the local distribution of the force along the strand, feasibility of instrumentation, and ease of applicability to different types of real-life structures. It should be noted that this paper examines methods pertaining mostly to strands in prestressed concrete structures and cable-stayed structures.

An ideal method should be highly sensitive to minor changes in prestressing force, while being completely unaffected by changes in other factors such as temperature and humidity, which are expected to vary periodically throughout the life of the structure. Prestress losses are typically less than 25% of the initial prestress force value, and the average based on more than forty studies was reported to be 21%.7 Although the variation of the prestress loss within several percent in general is not a concern for design as long as the loss stabilizes over time, steady evolution or sudden increase of the losses over time can be critical. In these cases, sensitivity of the method is very important because methods with higher sensitivity are more likely to detect evolution or increase of prestress losses at an early stage, which helps managers to plan preventive or repair actions.
Imperviousness to environmental factors, particularly temperature, is among the major challenges to on-site implementations of most long-term SHM and NDE techniques, regardless of the purpose of monitoring. Because no monitoring method or parameter is completely unaffected by temperature changes, the criterion in this case relates to the degree to which the influence of temperature on collected measurements, and thus results, is known and understood.

The force distribution along the strand provides important information regarding defects in the strand, which have been reported in the literature, as well as regarding immediate losses in prestressed concrete, such as those due to anchorage and friction. Significant change in the magnitude of the force along the strand can imply wire breakage, the effect of which is negligible as the distance from the breakage increases, and might be undetected if the force is only monitored near the anchorage. This criterion relates to the feasibility of instrumenting the strand or beam structure with multiple sensors along the longitudinal direction. Additionally, it relates to the localness of the monitored parameter, that is, the region in which it is valid and representative. For example, natural frequency is a global parameter that characterizes the entire structure, whereas strain is a local parameter representative of the behavior at the particular location at which it is measured.

The feasibility and potential for on-site implementations is another important criterion in the evaluation and comparison of the methods. This criterion is affected by the cost, size, and weight of sensors and equipment required for a monitoring technique. Thus, it strongly relates to the maturity of the monitoring technique. More mature techniques have more readily available commercial sensors of various sizes depending on the purpose of instrumentation, thereby reducing the cost of monitoring and providing good quality control of sensors, as opposed to those in the research phase.

Applicability to different types of structures is intrinsic to the method and is controlled by two aspects: (a) requirement for direct access to the prestressing strand and (b) need for a finite element model for data analysis. Both of these aspects limit the types of structures that can be monitored using a given method in different ways; the requirement for direct access limits the use of the method to structures with external prestressing tendons, whereas the need for a finite element model limits the application to less complex structures with known material properties. While overcoming the requirement for direct access is difficult, overcoming the need for a finite element model is often possible through calibration with known prestress force levels, which allows for creating an empirical relationship between the measured parameter and the prestress force level without the need for a finite element model. However, site conditions and requirements do not always allow for a calibration phase with known force levels, rendering this option more appropriate for laboratory applications.

### 3 | VIBRATION METHODS

Vibration methods encompass all methods of prestressing force identification that utilize the vibration properties of a structure. For the purposes of this study, presented methods will be limited to those involving natural frequencies as modal shapes or displacement measurements were shown to be unaffected by change in prestressing forces. The main principle is based on the dependence of natural frequencies on the stiffness of the structure, which in turn is dependably dependent on the prestressing force level. Such methods have been proven successful for cable-stayed structures where the force in the cable is directly related to the measured natural frequency using the tout-string theory. However, the relationship is more complicated in prestressed concrete structures. Although many researchers have developed relationships between the prestressing force and resulting natural frequencies of the structure, other researchers have shown that the prestressing force has no effect on natural frequencies. There are three different arguments for the relationship between prestressing forces and natural frequency.

First, some researchers argue that an increase in prestressing forces results in a decrease in natural frequencies, mainly due to the effect of “compression softening.” One of the first attempts to relate the vibration frequency of a structure to the prestress force level was an experimental study by Saiidi et al. The study first examined an analytical model for the relationship, given by Equation 1, which theorized that increasing prestress force levels would cause a decrease in natural frequencies.

\[
\omega_n^2 = \left(\frac{n\pi}{L}\right)^2 \frac{N}{m} + \left(\frac{n\pi}{L}\right)^4 \frac{EI}{m},
\]  

where \(\omega\) is the natural frequency of vibration, \(n\) is the mode number, \(L\) is the span length, \(N\) is the axial compressive force, that is, prestressing force, \(m\) is the beam mass per unit length, \(E\) is the modulus of elasticity of the concrete beam, and \(I\) is the moment of inertia for the beam section.

However, laboratory and field tests carried out in the study showed the opposite effect, where increasing prestress force levels caused increased natural frequencies, a result that was experimentally confirmed in other studies. Thus,
the second argument, mainly proven through experimental results, claims that an increase in prestress force causes an increase in natural frequencies. The discrepancy was explained by the stiffening effect due to closing of microcracks in the concrete as prestress force levels increase, thereby increasing the stiffness and natural frequencies of the structure, an effect not taken into account in the analytical model, given by Equation 1. The authors confirmed this effect by considering the change in effective flexural rigidity (i.e., flexural rigidity that would result in the measured natural frequencies) with the change in axial force. The positive correlation is presented in Figure 1.

Other researchers agree that increasing prestress forces in cracked beams results in crack closure that increases stiffness. Noble et al\textsuperscript{17} compared the natural frequencies of an uncracked and a cracked beam with varying levels of prestressing force. As shown in Figure 2, the study showed no statistically significant relationship between prestress force and natural frequencies for uncracked beam (Figure 2a) but a significant relationship for a cracked beam (Figure 2b). The researchers further explained the complicated relationship in Figure 2b, where there is a significant decrease in natural frequencies for prestressing force levels under 160 kN, followed by an increasing trend. The researchers attributed the decrease to the complex dynamic behavior of the cracked beam causing it to behave as a series of independent beams with lengths that increase as closure of cracks occurs. The increasing span lengths cause a decrease in the stiffness and thus natural frequencies of the structure. However, as cracks continue to gradually close due to the increasing prestressing force, the

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FIGURE 1  Variation of flexural rigidity with axial (prestressing) force\textsuperscript{14}

FIGURE 2  Regression analysis of the fundamental frequency with posttensioning load for (a) an uncracked beam and (b) a cracked beam\textsuperscript{17}
beam begins to behave monolithically at a certain force threshold (160 kN in this experiment), resulting in an increase in stiffness and natural frequencies as prestressing force increases.

Other researchers have reported a positive correlation between crack closure and natural frequencies, further contributing to the second argument. Grace and Ross experimentally showed a decrease in natural frequencies of posttensioned concrete beams caused by a decrease in stiffness due to fatigue cracking.18 Hop experimentally showed similar results.19 Hamed and Frostig analytically showed a reduction in natural frequencies with increased cracking, but no model for the relationship to prestress force levels was developed.20 De Roeck agrees with the researchers and argues that loss of prestress can only be detected by vibration methods if accompanied by cracking.21

The discrepancy gave rise to the third argument that, if cracking is neglected, prestressing forces do not affect natural frequencies.22-24 Dall’Asta and Dezi present a simplified but accurate analytical model for the natural frequencies of a prestressed concrete beam that accounts for the fact that the prestressing force is internal to the system, given by Equation 2 (as opposed to Equation 1 that assumes the prestressing force to be external).22

\[ \omega_n^2 = \frac{n^4\pi^4}{mL^4} \left( E_b - \frac{N}{A_b} \right) I_b + \left( E_c + \frac{N}{A_c} \right) I_c \]  

where \( E_b, A_b, \) and \( I_b \) are the elastic modulus, cross-sectional area, and moment of inertia of the concrete beam, respectively, and \( E_c, A_c, \) and \( I_c \) are the same quantities for the steel strand.

Based on typical values for a prestressed concrete beam, the terms \( N/A_b \) and \( N/A_c \) are negligible compared to the terms \( E_b \) and \( E_c \), respectively. Furthermore, \( I_c \) is negligible compared to \( I_b \), reducing the equation to that of a simply supported beam and implying that prestressing forces do not have a significant impact on natural frequencies of the beam.

The other two discussions of the study by Saiidi et al similarly support that prestressing forces should not be treated as an external force in the system and thus do not cause compression softening or a frequency change, except due to closing of microcracks.23,24 This was confirmed by another study where researchers compared the effect of posttensioning steel hollow beams and externally axially loading them to test the theory of compression softening without the interference of microcracks.25 The conclusion was that posttensioning and external axial loads do not affect beams in the same manner, with only the latter causing compression softening in slender beams. Sample results from the study are presented in Figure 3. The labels Beam 1 and Beam 2 refer to a slender beam and a stocky beam, respectively, to test the theory that compression softening affects beams susceptible to buckling (slender beam only), whereas the labels Case 1 and Case 2 refer to an externally axially loaded beam and a posttensioned beam, respectively. As shown in Figure 3a, in the case of a slender beam, increasing external axial load causes behavior that complies with the compression softening theory, whereas increasing prestress force causes a statistically significant decrease in the fundamental bending frequency, but that behavior does not comply with the compression softening theory. In Figure 3b, neither the externally axially loaded nor the posttensioned beam show behavior that agrees with compression softening theory; an externally axially loaded beam shows a significant increase in bending frequency, whereas a posttensioned beam shows a statistically significant decrease in bending frequency with increasing force.

Furthermore, a rigorous analytical model derived by Hamed and Frostig26 using the variational principle of virtual work shows that there is no dependence of natural frequencies on prestressing forces. Moreover, another extensive experimental

**FIGURE 3** Means of dynamic test data with varying load for (a) a slender beam and (b) a stocky beam25
program on uncracked prestressed concrete beams showed that there is no statistically significant change in natural frequencies due to change in prestress force for six of the nine tested beams,\textsuperscript{27} with the authors additionally arguing that any observed changes are due to chance and not systematic change.

The contradicting arguments show that prestress force identification based on vibration methods has not been achieved. However, the following conclusions can be drawn from the presented studies:

1. The compression softening theory for prestressed concrete beams has been debunked based on analytical work, as given in Equation 2 and experimental studies, as shown in Figure 3.
2. In the case of uncracked beams, changes in prestress forces have no effect on natural frequencies, as shown in Figure 2a and discussed in other studies.
3. In the case of cracked beams, an increase in prestress forces causes closure of microcracks, which stiffens the structure and causes an increase in natural frequencies. The increase in rigidity has been reported in multiple studies as shown in Figures 1 and 2b.

Based on the studies and above conclusions, detection of prestress loss using changes in natural frequencies is not possible in uncracked beams. Additionally, even in the case of cracked beams, there is no developed relation between the level of prestressing and the natural frequencies because it is dependent on the level of cracking. This is further complicated by the global nature of vibration monitoring because other types of damage and change of boundary conditions can result in changes in natural frequencies. Moreover, natural frequencies can vary significantly due to environmental changes\textsuperscript{28} and lack of ideal supports; one study reports a 6\% change,\textsuperscript{29} whereas another reports up to 18\% change.\textsuperscript{30} In comparison, changes in frequency due to prestress losses are insignificant and may not be detected.\textsuperscript{27}

4 | IMPEDANCE-BASED METHODS

Impedance-based SHM methods exploit properties of piezoelectric materials for SHM purposes. In piezoelectric materials, electrical and mechanical responses are coupled; mechanical stress produces electrical charge and vice versa.\textsuperscript{31} This is known as the piezoelectric effect and both the direct and converse versions are used in sensing applications, thereby allowing a piezoelectric material to function as both an actuator and sensor, typically by means of a piezoceramic material, such as PZT (Lead Zirconate Titanate). A PZT patch is affixed to a structural element and an alternating electrical field is applied to it. Due to the converse piezoelectric effect, a deformation is induced in the PZT patch and consequently the host structure. This engages the direct piezoelectric effect, and the induced deformation causes an electric charge. Liang et al.\textsuperscript{32} first showed that the resulting electrical impedance of the PZT is related to the mechanical impedance of the host structure. As given in Equation 3, the electrical admittance, $Y(\omega)$, (inverse of electrical impedance) of the PZT actuator is a function of the mechanical impedance of both the PZT actuator, $Z(\omega)$, and the host structure, $Z_a(\omega)$.

$$Y(\omega) = I/V = i\omega a \left( \varepsilon_{33}^{T} - \frac{Z(\omega)}{Z(\omega) + Z_a(\omega)} d_{33}^2 Y_{\omega}^{E} \right)$$

where $V$ is the input voltage to the PZT actuator, $I$ is the output current from the PZT sensor, and $a, d_{33}^2, Y_{\omega}^{E}$, and $\varepsilon_{33}^{T}$ are the geometry constant, piezoelectric coupling constant, Young's modulus, and the complex dielectric constant of the PZT at zero stress, respectively.

Assuming the mechanical properties of the PZT sensor do not change, changes in the electrical impedance signature reflect changes in the mechanical properties of the host structure, thereby allowing PZT sensors to be used for damage detection purposes. Due to their small size and negligible effects on the properties and behavior of the structure, as shown in Figure 4b, PZT sensors offer an advantage over other sensing technologies.

Several applications of PZT impedance-based SHM have emerged including detection of cracks\textsuperscript{35-37} and delamination.\textsuperscript{38,39} The first attempt to monitor prestressed concrete structures by PZT sensors was carried out by Abe et al.,\textsuperscript{40} where the researchers developed the analytical relationship between stress and the wave propagation (directly related to electrical admittance) for both the one-dimensional case (bar under axial stress) and two-dimensional case (plate under axial stress). Based on measured impedance and the analytical relationship, the absolute stress state of the elements was estimated,\textsuperscript{40} but the estimates were lower than measurements made by strain gauges due to stress transfer at the interface of the PZT and the structural element.

Subsequent studies focused on the detection of changes in the prestressing force, rather than the absolute force or stress due to the difficulty of analytically relating the stress to the PZT measurements, as illustrated by the aforementioned...
Kim et al. combined a global vibration-based method with a local impedance-based method to achieve three-step SHM: (a) damage detection using a damage index based on global frequency responses, that is, detection of prestress loss, (b) characterization of prestress loss using impedance signals, that is, confirming that the change to the damage index is due to prestress loss and not changes to boundary conditions, and (c) prestress loss estimation using modal parameters. The method was applied to a 6-m prestressed concrete girder in the laboratory instrumented with seven equally spaced accelerometers along the span, as well as a load cell on the jacking end and a PZT patch on the dead end. Five different levels of prestress force were applied to the beam, simulating four prestress loss stages, each of which constituted 17% loss of the initial prestressing force. Prestress loss was characterized using the frequency shift in the impedance signal, shown in Figure 5a, and quantified using changes in natural frequencies. As shown in Figure 5, as prestressing force levels were decreased, the peak frequency of the impedance signal shifted to the right. The sensitivity and accurate prediction of smaller changes in the prestressing force value were not demonstrated.

A subsequent study extended the algorithm to additionally identify a second type of damage, added mass to the beam to simulate stiffness change. It was shown that impedance signatures did not significantly change due to stiffness change, as shown in Figure 5b, indicating that the method is robust to other changes to the structure that do not impact the prestress force. Despite a demonstration of the capability of impedance-based methods to characterize prestress loss damage demonstrated in the previous two studies, the studies feature two limitations: (a) the necessity of the use of vibration characteristics for quantification of prestress loss, which is not a simple task as discussed in the previous section (vibration-based methods) and (b) the requirement for high resonant frequency range to establish sensitivity to changes in prestressing forces. In both of the studies, the frequency range required for achieving impedance signatures sensitive to prestress loss change was determined through trial and error to be 880–980 kHz, as shown in Figure 5a. Such a high
frequency range is disadvantageous for two reasons: (a) It requires the use of a high performance impedance analyzer that is both heavy and expensive, making it unsuitable for typical site deployment, and (b) it does not allow for wireless deployment because the frequency range of wireless sensors is less than 100 kHz.41

To lower the frequency range, researchers investigated the possibility of installing an aluminum plate between the bearing plate and the anchor block and affixing the PZT patch to the plate,41,42 as shown in Figure 6. Because the stiffness of the aluminum plate is lower than that of the bearing plate and the anchor block, the resonant frequency range is reduced. Additionally, Nguyen and Kim42 extended the study to analytically determine the frequency range before the experiment to overcome the difficulty of the trial-and-error method in field applications, which is often not feasible. In both applications, laboratory experiments were performed and the change in impedance due to changes in prestress force was detected using wireless sensors with significant frequency range reduction compared to previous studies (20–30 kHz in this case), as shown in Figure 7a.41,42 Empirical relationships were derived between prestress loss and frequency shift, shown in Figure 7b, as well as between prestress loss and a damage index. However, the relationships are only applicable to the structure and environmental conditions for which they were derived and cannot be generalized.42 It is worth noting that because PZT sensors measure local effects, prestress loss levels detected and quantified reflect changes at the anchorage only and not necessarily throughout the length of the beam structure.

Huynh and Kim43 recognized that the installation of a plate between the bearing plate and the anchor block reduces the stiffness of the connection due to the low stiffness of the plate and also limits the application of the method to new structures. To extend the method to existing structures, they designed a portable PZT interface consisting of a thin-walled
beam-like element with a PZT patch. The results show that damage indices from acquired impedance signals can detect prestress loss, but quantification of losses was not investigated. Although impedance-based methods have shown promising short-term results, a main issue that needs to be considered before successful implementation in on-site conditions is sensitivity to varying temperature. It has been shown that temperature can significantly impact impedance signal leading to false positive alarms in damage detection. Figure 8a shows impedance signature under varying prestress force levels with a constant temperature, whereas Figure 8b shows impedance signatures under a constant prestress force and varying temperatures. As shown, it is difficult to discern one effect from the other visually. Park et al proposed a modified damage index to address temperature influence. This was successfully applied in a study proposed by Huynh and Kim. However, it requires measurements at several different temperatures in the healthy state in order to establish a baseline healthy impedance signal insensitive to temperature changes. Additionally, its success largely depends on the frequency range used; Huynh et al showed that a narrower frequency range provides better results but that could limit sensitivity to prestress loss.

Based on the above studies, the following conclusions can be made regarding impedance-based methods for prestress force measurement:

1. Detection of prestress losses using impedance-based methods is possible and has been achieved, as shown in Figures 5a and 7a. Quantification of losses is only possible through calibration to develop empirical relationships as shown in Figure 7b. Impedance signatures near the anchorage have also been shown to be insensitive to other types of damage such as change in stiffness at locations farther away from the anchorage, which shows robustness for detection of prestress losses.

2. Advances in sensor configuration have allowed for the reduction of the frequency range sensitive to prestress loss from above 800 kHz (Figures 4 and 5) to under 50 kHz (Figures 6 and 7). This allows for wireless deployment of sensors and overcomes the need for an expensive high performance impedance analyzer.

3. Temperature effects can cause changes in impedance signals that must be compensated for to accurately establish a relationship between impedance and prestress force levels. Currently, this can only be performed through calibration at constant force for different temperatures and using a modified damage index to account for temperature. This allows for detection of prestress loss, but quantification is yet to be achieved.

4. The previous studies all consider prestress force change near the anchorage due to the local nature of PZT sensors. More sensors would be required along the beam structure in order to evaluate the distribution of the prestressing force. However, there are no examples in the literature of attachment of PZT patches to the concrete surface or embedment along the prestressed concrete structure for the purpose of monitoring the prestress force distribution. Thus, the possibility of monitoring the distribution of the force has not been explored.

5 | ELASTO-MAGNETIC METHODS

The EM methods are based on the dependence of magnetic properties of ferromagnetic materials, such as steel, on mechanical stress. When a ferromagnetic material is exposed to a magnetic field, a magnetic flux is induced in a process known as magnetization. Every ferromagnetic material has a unique magnetization curve (relationship between the
applied magnetic field and the magnetic flux density). The ratio of the two quantities that define the magnetic curve at any point is referred to as magnetic permeability, as given in Equation 4.47

$$\Delta B = \mu \Delta H,$$

(4)

where $B$ is the magnetic flux density, $H$ is the applied magnetic field strength, and $\mu$ is the magnetic permeability.

A typical magnetization curve for a ferromagnetic material is given in Figure 9. As shown, the curve is nonlinear, hysteretic, and dependent on mechanical stress. EM sensors take advantage of this nonlinearity and dependence on stress; the value of permeability changes depending on the stress, thereby allowing for determination of stress through measurement of magnetic permeability. To measure magnetic permeability, sensors are composed of two solenoid coils that are installed around a steel wire or bar, thereby enclosing it without contact, that is, as a sleeve. The interrogation unit charges the inner primary coil, which serves as the charging element and applies a magnetic field to the steel wire or bar under consideration. The resulting magnetic flux produces an electric current measured by the outer secondary coil, which serves as the sensing element. Relative permeability can then be calculated using the output voltage, as given in Equation 5.51

$$\bar{\mu} = \frac{\mu}{\mu_0} = 1 + \frac{A_0}{A_f} \left( \frac{V_{out}}{V_0} - 1 \right),$$

(5)

where $\bar{\mu}$ is the relative magnetic permeability of the ferromagnetic material to vacuum, $\mu_0$ is the magnetic permeability of vacuum, $A_0$ and $A_f$ are the cross-sectional areas of the secondary coil and the steel, respectively, and $V_{out}$ and $V_0$ are the induced voltage with and without the ferromagnetic material, respectively.

Because relative permeability is a property of the ferromagnetic material, steel bars or wires under consideration can be tested in the laboratory to establish a relationship between magnetic permeability and the stress in the strand. EM sensors show unique promise to provide measurements of absolute stress rather than relative stress even when structures have not been instrumented during construction. The sensor was first proposed in Slovakia by Kvasnica and Fabo and by Jarosevic, then further developed into a prototype by Sumitro et al. In the investigation by Kvasnica and Fabo, the dependence of permeability on temperature was discussed and shown to be linear but also dependent on stress and the strength of the magnetic field applied, as given in Figure 10. Sumitro et al performed laboratory tests using the developed
Fabo et al first used EM sensors in several civil engineering SHM applications, including monitoring prestressing force in unbonded tendons in a nuclear reactor envelope in Czech Republic over 5 years and monitoring the replacement of external prestressing tendons on a bridge. Force determination was achieved, although comparison to other estimates was not possible in the applications. The researchers concluded that an accurate determination of the magnetic properties of the steel elements is necessary and that temperature influences on measurements can be significant. They recommended the use of a differential sensor for temperature compensation, although details were not provided.

Wang et al further studied the relationship between magnetic permeability and stress during the prestressing of tendons on a prestressed concrete bridge and showed that relative permeability varies linearly with stress. The researchers confirmed the effect of temperature changes that have previously been discussed in depth in the study of Chen by conducting a laboratory test where temperature was varied and relative permeability of steel strands was measured under zero stress. The effects of temperature variations were shown to be linear and compensated for using empirical relationships derived from the tests. Similar implementation and results were obtained by Yim et al through implementation...
on a cable-stayed bridge. A typical in situ instrumentation is shown in Figure 12. The results from the on-site calibrations performed in the two studies are presented in Figure 13.

Another extensive calibration study was carried out by Zonta et al.\textsuperscript{57} prior to the installation of EM sensors on an in-service cable-stayed bridge. The calibration procedure was performed in two stages: laboratory calibration and on-site calibration. The results from the laboratory calibration under constant temperature indicated that the relationship between permeability and force is not strictly linear but better approximated by a polynomial of the third degree. However, the researchers observed that the relationship is “virtually linear” for loads above 4000 kN.\textsuperscript{57} Calibration at different temperature confirmed the effect shown in Figure 10, where the temperature constant depends on stress. The researchers additionally tested the repeatability of the sensor, which is particularly important for sensors assembled in situ. The results, shown in Figure 14, indicated that although the slope of the relationship remains unchanged, the intercept varies with different sensors. Thus, site calibration was required to ensure the correct intercept value is used. This was performed in this study using vibration tests and the natural frequencies of the strand. However, this method yields uncertainties that affect the accuracy of the EM sensor results.

FIGURE 12 In situ installation procedure of elasto-magnetic sensor\textsuperscript{51}

FIGURE 13 On-site calibration of elasto-magnetic sensors using load cell measurements indicating (a) linear relationship between magnetic permeability and stress for a strand that is comparable to relationships for a single wire and a strand tested in the laboratory\textsuperscript{56} and (b) linear relationship between effective relative permeability and force\textsuperscript{51}
The previous studies focused on external prestressing tendons or strands in cable-stayed bridges. There have, however, been experiments on prestressed concrete beams, where sensors were embedded in the concrete and prestressing forces were estimated relatively accurately for laboratory experiments. An example of such installation is presented in Figure 15. Nevertheless, the literature lacks examples of implementation in prestressed concrete beams in field conditions, possibly due to the bulky nature of the sensors and concerns regarding loss of concrete area in the vicinity of the sensor and effects on bonding between the prestressing strands and concrete at EM sensor locations.

Based on the previous studies involving EM sensors, the following conclusions can be made:

1. EM sensors provide high sensitivity to stress via a linear relationship (as shown in Figures 13 and 14) and show promise for absolute stress measurements, as shown in Figure 11, rather than relative stress, thereby allowing for determination of stress levels even when sensors are installed after construction.

2. Magnetic permeability is sensitive to stress, which allows for stress measurements using EM sensors, but it is also sensitive to temperature. As shown in Figure 10, the dependence of magnetic permeability on temperature is linear, which simplifies analysis, but the constant varies based on the stress level. This can complicate analysis as calibration is required at different stress levels.

3. EM sensors require calibration at known load levels. This can be performed in the laboratory on a similar steel sample or in situ. For sensors assembled on site, in situ calibration is necessary because whereas the slope of the linear relationship is repeatable, the intercept is not, as shown in Figure 14. In situ calibration can be challenging in cases when the structure is already constructed and loaded.

4. Due to their bulky size (see Figures 12 and 15), EM sensors seem better suited for applications on suspension bridges and cable-stayed bridges due to the external nature of strands. Concrete embedment has not been extensively studied and may be challenging.

5. Although there have not been studies on the distribution of prestressing forces along a strand, magnetic permeability appears to be a local parameter. Thus, measurement of local force changes, that is, the distribution of the force, along a steel strand or a prestressed concrete structure would require the installation of multiple sensors along the structure.
6 | ACOUSTOELASTIC METHODS

Acoustoelastic methods rely on the principle of acoustoelasticity to relate the properties of ultrasonic wave propagation, mainly wave velocity, in steel wires and strands to applied stress.\textsuperscript{59} The dependence of the change in wave velocity on stress changes has been utilized in several applications in civil engineering including measurement of residual stress\textsuperscript{60,61} and of bolt stress.\textsuperscript{62,63}

The first attempt to study elastic wave propagation in prestressed steel strands was an experimental study conducted by Kwun et al in 1998, where the researchers tested specimens of prestressing strands instrumented with magnetostrictive sensors, to emit and detect elastic waves, under different stress levels.\textsuperscript{64} The main finding from the testing was that the presence of tensile load on the specimens caused significant attenuation in a specific portion of the frequency components of the wave, which resulted in the disappearance of this portion. The center frequency of the portion (notch frequency) was found to be linearly dependent on the logarithm of the applied load, as shown in Figure 16. Despite the absence of a theoretical basis for this result, it indicated promise in the use of longitudinal wave properties for the determination of prestress forces.

Several future attempts focused on the time of flight of waves (or the wave velocity) between an input and output transducer to quantify changes in stress, based on theoretical analysis of the wave velocity. In a homogeneous isotropic material under uniform axial stress, the bulk longitudinal plane wave velocity can be written in the first-order approximation as given in Equation 6.\textsuperscript{59,62,65,66}

\[
V_\sigma = \sqrt{\frac{\lambda + 2\mu}{\rho}} \left[ 1 + \frac{\sigma}{2(\lambda + 2\mu)(3\lambda + 2\mu)} \left( \frac{\lambda + \mu}{\mu} (4\lambda + 10\mu + 4m) + \lambda + 2l \right) \right],
\]

where \(\rho\) is the mass density, \(\sigma\) is the tensile stress, \(\lambda\) and \(\mu\) are Lame’s elastic constants, and \(m\) and \(l\) are Murnaghan’s third order elastic constants. Equation 6 can be rewritten as follows:

\[
V_\sigma = V_0 (1 + K\sigma),
\]

where \(V_0 = \sqrt{\frac{\lambda + 2\mu}{\rho}}\) is the longitudinal wave velocity under zero stress, and \(K = \frac{1}{2(\lambda + 2\mu)(3\lambda + 2\mu)} \left( \frac{\lambda + \mu}{\mu} (4\lambda + 10\mu + 4m) + \lambda + 2l \right)\).

\[\text{FIGURE 16} \quad \text{Linear relationship between notch frequency and applied tensile load}\textsuperscript{64}\]
A study was conducted by Chen and Wissawapaisal to estimate the wave velocity of a 4.76-m long prestressing strand.\textsuperscript{67,68} The instrumentation employed in the studies consisted of one AE transducer at each end of the prestressing strand, as shown in Figure 17. Sample results are presented in Figure 18 and indicate a linear increase in the time of flight for stress levels between 18\% and 70\% of the ultimate tensile strength (UTS) of the strand. Outside of this range, the dependence of wave velocity on stress levels tends to be nonlinear. Figure 18 also shows good agreement between experimental and analytical results obtained using Equation 6. Another important finding from the two studies is the detection of waveforms for longer steel strands (up to 83.94 m), indicating the possibility of applying the method to full-scale prestressed concrete structures with ungrouted tendons.\textsuperscript{68}

Other researchers recognized the difficulty in estimating the parameters required to determine the acoustoelastic factor, \( K \), but were interested in experimentally quantifying the parameter as an indication of the sensitivity of the wave velocity for stress measurements. If incremental stress changes are considered instead of absolute stress, the incremental velocity change as a percentage of the velocity at a known reference stress, \( V_{\sigma_R} \), is given by Equation 8, and \( K \) denotes the sensitivity of the relation.\textsuperscript{69}

\[
\frac{\Delta V_{\sigma}}{V_{\sigma_R}} = K \Delta \sigma.
\]

\textbf{FIGURE 17} Instrumentation of an ungrouted tendon in prestressed concrete beam with AE transducers, (a) schematic illustration,\textsuperscript{67} and (b) laboratory deployment\textsuperscript{68}

\textbf{FIGURE 18} Time shift comparison between experimental (dotted lines) and analytical results (solid lines) for the fourth cycle waveform\textsuperscript{67}
Washer et al. performed tests on strands and center wires from decomposed strands to experimentally determine the acoustoelastic factor. The tests indicated that the relationship is not linear throughout the full range of tensile stresses. It is, however, linear for stress ranges with lower bounds between 30% and 50% of UTS and upper bounds between 70% and 80%, which is acceptable for typical stress level in strands in prestressed concrete structures. The constant $K$ in this range was determined to be less than 1% per GPa of stress for all tested specimens, as shown in Table 1. Additionally, the tests indicated that the constant is different even for strands that meet the same specifications but manufactured at different times, as shown in Figure 19, indicating the need for calibration on the same strands used in a project prior to implementation on site. The low sensitivity observed in the study raises doubts regarding monitoring relatively low prestress losses throughout the service life of a structure. One subsequent study showed that the change in the wave velocity as a function of applied stress was nonlinear in stress levels below 20% of UTS of the strand, but linear throughout the entire range for a single core wire, whereas another showed nonlinearity at low stress levels even in the single wire. The acoustoelastic coefficient was different in the studies but still under 1% per GPa. Additionally, the previous three studies all discuss the potential of increasing the sensitivity of the method by including the effect of the elongation of the strand under stress, that is, by clamping the sensors to the strand and allowing the distance between them to increase with increasing stress. Although the elongation effect increases sensitivity, as shown in Figure 20, it remains under 1% per GPa.

Besides wave velocity, researchers have studied other properties of wave propagation, such as the transmitted ultrasonic energy in terms of the amplitude of the frequency peak and the area under the energy spectrum. The relationships of these properties with load are shown in Figure 21 for a laboratory test performed by Rizzo on a core wire. Both parameters were found to linearly decrease with increasing tensile stress for a single wire, with a significant decrease in the area under the energy spectrum of 45% per GPa. When applied to an assembled strand, the results did not show linear behavior, leading the author to recommend instrumentation of the core wire only. It should be noted that the sensing mechanism requires direct access to the ends of the strands, thereby limiting the application to shorter strands due to attenuation concerns, up to a few meters long. Further investigations or site implementations of this method have not been reported.

All the aforementioned studies have been on ungrouted strands or wires due to the effect of grouting material on attenuation, thereby restricting the applications for prestressed concrete to unbonded tendons. Additionally, studies have not investigated the effect of temperature on measurements, as well as the possibility of embedding sensors in the concrete.

### Table 1

| Material designation | Stress range (GPa) | Phase velocity (m/s) | Group velocity (m/s) | $k_p$ (%/GPa) | $k_g$ (%/GPa) |
|----------------------|-------------------|----------------------|----------------------|---------------|---------------|
| C1                   | 0.90–1.58         | 5,061                | 4,892                | -0.68         | -0.69         |
| C2                   | 5,119             |                      |                      | -0.50         | -0.52         |
| C3                   | 0.90–1.58         | 5,060                | 4,715                | -0.59         | -0.62         |
| C4                   | 5,006             |                      |                      | -0.62         | -0.65         |
| R1                   | 0.5–1.23          | 4,937                | 4,596                | -0.74         | -0.69         |

**FIGURE 19** Change in velocity with change in stress for two center wires manufactured at different times with the same specifications
Based on the previous studies, the following conclusions can be made regarding acoustoelastic methods for measuring prestress forces:

1. Velocity of stress waves in prestressing strands is linearly dependent on stress for typical stress levels in prestressing strands, enabling measurement using the acoustoelastic effect. However, change in velocity shows inherently low sensitivity to stress changes, less than 1% per GPa, as shown in Table 1. While including the effect of strand elongation can improve sensitivity, as shown in Figure 20, it remains low compared with other methods.
2. Absolute measurement of stress is possible as shown in Figure 18 but requires approximating the parameters in Equation 6, which can be challenging. Instead, relative or absolute stress can be determined through laboratory calibration and Equation 8, as shown in Table 1 and Figure 19.

3. Issues such as the effect of temperature on measurements, as well as attenuation due to the presence of grouting material, challenge the application of the methods in field settings.

4. The nature of wave propagation methods is global; wave velocities reflect the global behavior of a strand, rather than behavior in the vicinity of the transducer. Therefore, monitoring the distribution of the prestressing force along a prestressed concrete structure is currently not achievable using acoustoelastic methods.

7 | STRAIN-BASED METHODS

Due to the well-established relationship between strain and stress in the linear elastic range, strain monitoring is regarded as the closest to direct monitoring of stress. Recent advances in the development of durable and stable strain sensors have led to the increasing popularity and use of strain-based methods for prestress force monitoring. In fact, the ACI 423 Guide to Estimating Prestress Loss lists measured prestress loss values in laboratory or field setting from more than 40 studies, all of which are conducted using types of strain sensors.

If structures are instrumented with sensors during construction, either through attaching them to prestressing strands or embedding them in the concrete, long-term strain changes can be monitored. Additionally, instrumentation during construction allows for measuring strain changes during prestress force transfer, thereby enabling calculation of the initial stress in the prestressing strands. If the strain change at the location of the prestressing strands is determined, the stress change can be calculated using Hooke’s law, given by Equation 9.

$$\Delta \sigma_p = E \Delta \varepsilon_p,$$

where \(\Delta \sigma_p\) is the average stress change in the prestressing strand, \(E\) is the modulus of elasticity of the prestressing steel, and \(\Delta \varepsilon_p\) is the strain change at the location of the center of gravity of the prestressing strands.

In cases where the location of the prestressing strand is not known with accuracy or where there is concerns regarding separating the effects of bending due operational load on the structure from the effects of prestress loss, strain changes at the centroid of stiffness of the concrete cross-section can be monitored instead of strain changes at the center of gravity of prestressing strands. Because strain at the centroid of stiffness is minimally affected by bending due to load and temperature changes, the effect of long-term prestress losses can be isolated.

In applications where the strain sensors are embedded in the concrete, at least two strain sensors are commonly embedded in every instrumented cross section. Assuming a linear strain distribution, the strain at the center of gravity of the prestressing strand can be determined. Assuming a perfect bond between the prestressing strands and surrounding concrete, the strain changes measured in the concrete can be assumed to be equal to the strain changes in the prestressing strands at the same location, and Equation 9 can be used to estimate the stress change, as illustrated in Figure 22. This type of instrumentation has been used by many researchers employing vibrating wire strain gauges, demountable mechanical gauges, electrical strain gauges, or fiber optic sensors (see Figure 23a, 23b, 23c).

Alternatively, strain sensors can be placed at the location of the centroid of the prestressing strands or attached directly to prestressing strands to reduce the number of required sensors and directly measure the strain changes at or in the steel strand. Such applications have utilized similar types of sensors such as electrical resistance strain gauges, distributed fiber optic sensors (see Figure 23d), and discrete fiber optic sensors. However, attaching strain sensors directly to strands exposes them to large tensile strains during prestressing, which can cause damage to the sensors. Some researchers attempted to overcome the issue by embedding the sensors into metal packaging prior to attaching them. This approach, shown in Figure 23d, has only been tested in the laboratory and some sensors were damaged in the process regardless of the packaging, indicating that the packaging needs to be improved.

Two examples of results are presented in Figure 24. Figure 24a shows results from a 60-day laboratory experiment where prestress loss in the tendons is measured using strain sensors and compared with design code estimates. Figure 24b shows results from a field instrumentation on a posttensioned pedestrian bridge, where prestress loss is measured over a period of seven years, confirming the longevity of sensors in field conditions. Additionally, using a set of discrete sensors along the length of a structure or a distributed sensor, the distribution of the prestressing force along the structure at a given point in time can be determined, as shown in Figure 25.
Although the instrumentation approaches discussed above have been applied extensively in field settings, newer approaches are still in the laboratory-testing phase. One such approach is replacing the core wire of a seven-wire prestressing strand by a fiber-reinforced polymer where an optical fiber can be embedded during manufacturing for sensing purposes, as shown in Figure 26. Although laboratory tests indicate that the embedded sensor can provide accurate strain measurements, the application in field settings is yet to be explored.
FIGURE 24  Example of prestress loss measured using strain sensors from (a) laboratory experiment lasting 60 days\textsuperscript{86} and (b) field measurements collected over seven years\textsuperscript{73}

FIGURE 25  Distribution of prestressing force along a structure using (a) distributed fiber optic sensor\textsuperscript{87} and (b) set of discrete fiber optic sensors

FIGURE 26  Smart prestressing strand with a carbon core wire and embedded fiber optic sensor\textsuperscript{89}
A common challenge in strain-based monitoring is the sensitivity of strain measurements to temperature changes in terms of the thermal effects on both the sensor and the structure. However, several commercial sensors currently exist on the market, which have been tested for temperature influences and manufacturers provide calibrated constants for temperature compensation. As for thermal effects on the structure, they can be sufficiently accurately compensated for using Equation 10.

$$\varepsilon_{\text{compensated}} = \varepsilon_{\text{measured}} - \alpha_T \Delta T,$$

(10)

where $\varepsilon_{\text{compensated}}$ is the thermally compensated strain, $\varepsilon_{\text{measured}}$ is the measured strain, $\alpha_T$ is the thermal expansion coefficient of the steel or the concrete (depending on the material the sensor is attached to), and $\Delta T$ is the temperature change.

Thus, temperature monitoring is required in field conditions. The thermal expansion coefficient can be determined in the field or during laboratory testing.

Strain-based methods show promise for monitoring prestressing losses as demonstrated above if structures are instrumented during construction because estimation of stress changes is based on changes in strain and not absolute measurement of stress. However, if structures are not instrumented during construction, semidestructive or destructive strain-based methods can be used to determine the remaining prestress force as demonstrated by some studies. Tabatabai and Dickson\(^91\) performed extensive testing on a 34-year old posttensioned concrete girder acquired after dismantling of a bridge. First, they loaded the beam until the first crack occurred then unloaded it and instrumented the crack with a crack gauge. By reloading the beam until the crack width began to increase, they were able to determine the bending moment at which decompression occurred. This allowed for back-calculating the prestress force. This technique has been used on several older beams that were tested to failure.\(^92\)-\(^94\) A less invasive method was used by other researchers, which involves instrumenting wires from prestressing strands with strain sensors and cutting the wires to observe the strain release, shown in Figure 27, which can be used to infer the stress in the wire prior to cutting, using Equation 9.\(^81,95\) Remennikov and Kaewunruen reported that less than 5% of the concrete along a beam structure needs to be removed to expose the prestressing strands and allow for such testing.\(^81\) Additionally, due to the friction between wires, this will only have a minor effect on the prestressing force locally.

Based on the above studies utilizing strain measurements, the following conclusions can be made regarding strain-based assessment of prestressing forces:

1. Strain monitoring is a mature sensing field with a well-defined relationship with stress, given by Equation 9, which allows for monitoring prestressing forces in field applications. However, instrumentation during construction is required because measured changes are relative and not absolute.
2. Several applications of strain-based monitoring of prestressing forces have been reported utilizing different types of strain sensors, as shown in Figure 23. Newer technologies involve smart strands that provide the required strength, as well as sensing capabilities, as shown in Figure 26, are currently in the laboratory development phase.

![FIGURE 27](image-url)  
Semidestructive strain-based determination of prestressing force: (a) cutting of wires in prestressed concrete beam and (b) strain change during cutting process\(^81\)
3. Sufficiently accurate temperature compensation for strain measurements is well developed, as given by Equation 10 and has allowed for field monitoring, even under varying temperatures.

4. Because strain is a local parameter, it measures effects in the vicinity of the sensor, thereby allowing for the measurement of the distribution of the prestressing force along a structure using multiple discrete sensors (Figure 25b), or a distributed sensor (Figure 25a).

5. Destructive or semidestructive techniques can be used to determine prestressing forces in structures that have not been instrumented during construction, as shown in Figure 27. This is more applicable in laboratory settings for research purposes or in rehabilitation projects.

In addition to the numerous applications of strain-based monitoring of prestressing forces, a formalized method for design of the sensor network, analysis of collected data, and assessment of uncertainties was proposed in the study of Abdel-Jaber and Glisic96 and applied to a structure instrumented during construction. The resulting prestressing force distribution and associated uncertainties are presented in Figure 25b.

8 | CONCLUSIONS AND RECOMMENDATIONS

Five different classes of methods for monitoring prestress losses were presented and discussed in the previous five sections. Each section ends with concise conclusions about corresponding techniques written in form of bullet points. These conclusions are summarized and compared in this section, and complemented with identified potential directions for future research. The following conclusions, also summarized in Table 2, can be made regarding the promise of each class of methods for monitoring prestressed concrete structures:

1. Vibration methods do not show promise for monitoring prestressed concrete structures due to the contradicting arguments regarding the effect of the prestressing force change on natural frequencies, particularly in uncracked beams. Additionally, the global nature of vibration monitoring further limits their applicability; other factors such as changes in boundary conditions, environmental conditions, and other types of damage can cause significant changes in natural frequencies, making it difficult to discern or separate the effects of prestress losses, if they are detected. The authors could not immediately identify future research in vibration methods that could be helpful for reliable detection and quantification of prestress losses.

2. Impedance-based methods show promise for detecting local changes in prestressing forces. They do, however, require calibration and are sensitive to temperature changes, which might necessitate further calibration under varying temperatures. Due to the local nature of the sensors and methods, current applications only provide information about the prestressing force near the anchorage, where the sensor is typically installed. Future research in impedance-based methods could focus on methods for reliable quantification of prestress losses, methods for implementation on concrete, if possible, (surface or embedded), and enabling monitoring of force distribution along the structure, that is, at multiple points along the structure (as opposed to a limited number of points at anchorage locations).

3. EM methods tend to be more suitable for external tendons due to the bulkiness of sensors, which complicates embedment in concrete structures where the density of reinforcement can affect sensor placement. They do, however, show
promise for assessment of absolute force levels in external tendons, even when structures are not instrumented during construction. In theory, although calibration is required, it can be performed on a sample of prestressing strand in the laboratory and does not need to be performed on site. However, repeatability of sensors built in situ requires knowledge of the initial stress in the strand for calibration. Future research in EM methods could focus on packaging and methodology for embedding the sensors in concrete, which would enable monitoring distribution of the force along the structure.

4. Acoustoelastic methods show low sensitivity to prestressing force changes. The issue is compounded by attenuation of stress waves, which limits their application to ungrouted, shorter tendons because access to both ends of a tendon is required. Future research could focus on increasing the sensitivity of the method in grouted tendons, evaluating and compensating temperature effects, and creating an embeddable sensor, which would enable monitoring the distribution of the force along the structure.

5. Strain-based methods show the most promise with regard to monitoring prestressing forces due to the maturity of the sensing technologies and the well-established relationship between strain and stress. The only limitation is the requirement for instrumentation at construction because strain changes are relative and not absolute. Given that the strain-based methods are relatively mature both in terms of sensors and algorithms, future research could focus on pervasive implementation of strain sensors, for example, by using distributed fiber optic sensors, self-sensitive (nano-) materials, large-area electronics, and so on, and algorithms that combine mathematical/numerical models with monitoring results, to more accurately discern prestress losses from other unusual behaviors.

Despite the existence of a wide variety of methods for monitoring of prestressing forces in prestressed concrete structures, only strain-based methods are extensively used in field applications. Additionally, with the exception of a few studies, the literature lacks guidelines for the design of sensor networks or assessment of uncertainties. Such guidelines are required to establish comparisons between results from different studies, as well as to effectively assess results from the monitoring systems.

Applications of the other classes of methods need to be extended to field conditions in conjunction with reliable strain-based methods to validate such sensors and methods. As demonstrated previously, impedance-based and EM methods show promise to overcome the shortcomings of the widely used strain-based methods, such as the requirement for installation during construction. Thus, their extension to field applications can provide assessment for existing prestressed concrete infrastructure elements. Aspects of their application, such as longevity in field settings, and accurate calibration are yet to be investigated in detail with respect to prestressed concrete structures, as opposed to strands in suspension and cable-stayed bridges.

Other directions for future research include implementing current strain-based methods, such as smart strands discussed in strain-based methods, in field settings and comparing their performance to steel tendons. Research should investigate the cost of using such technologies in the field, their robustness to harsh site conditions, and their long-term performance.

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