Automatic System for Accurate Elongation Measurement in Post-Tensioning Meethod

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A system digitizes and automates measurement for elongation and prestressing force in the post-tensioning method using Internet of Things (IoT) technology. The system is designed to improve accuracy and efficiency in the post-tensioning process by using advanced technologies to monitor tension forces in tendons. The system accurately determines the final elongation of the tendon by analyzing real-time data from sensors, including elongation and pressure measurements. The system also provides a solution for recording construction data by saving it to an internet server. This paper presents the system and highlights its practicality and accuracy in terms of site application.

INTRODUCTION

In single-strand tendon systems, post-tensioning (PT) forces are individually applied to single-strand tendons using monostrand hydraulic jacks and pressure pumps. It is important to apply the intended prestress to the tendon and accurately measure the applied stress. Codes and specifications provide tendon installation methods to minimize errors between the intended and actual stresses. Table 1 summarizes general working procedures for stressing and field measurement of the tendon system.

REQUIREMENTS AND FIELD MEASUREMENT

Requirements for measuring tendon elongation

Once the forces are applied and the wedges are seated, it is challenging to directly measure the actual stress in the tendons without special measuring methods. Accordingly, the field measurement of tendon elongations has been carried out to assess the forces inside PT tendons after the wedges are seated.

Section R26.10.2(e) of ACI 318-19 (ACI Committee 318 2019) requires that prestressing force and friction losses shall be verified by (1) and (2).

1. Measured elongation of prestressed reinforcement compared with elongation calculated using the modulus of elasticity determined from tests or as reported by the manufacturer.
2. Jacking force measured using calibrated equipment such as a hydraulic pressure gauge, load cell, or dynamometer.

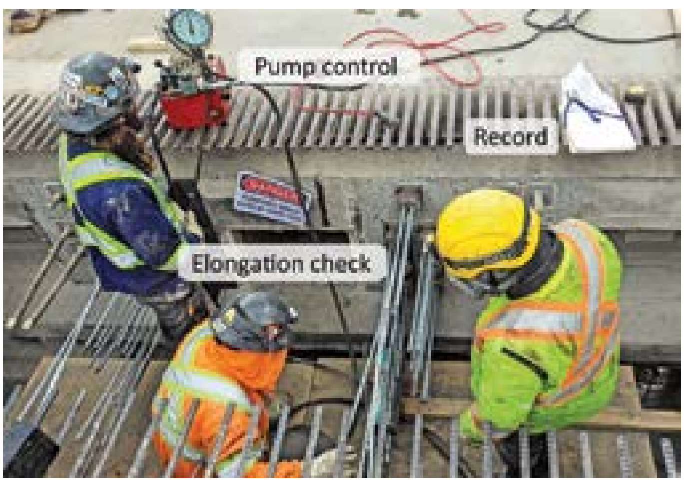
Table 1—Working procedures for stressing operation and field measurement of tendons

Working procedures	Multistrand tendons	Encapsulated unbonded single-strand tendons
Preparation for stressing	Make sure strands are clean of concrete slurry, debris, and so on	
Placing of anchor head and wedges or wedge	Strand is marked with paint or grease pen at both ends	Strand is marked with paint at stressing end(s)
Positioning of jack	Initial stress is applied to grip the strand	
Stressing	Pressure and/or elongation values are measured and/or recorded at critical points	
Anchor set and load transfer	By releasing the jack, the load is transferred to the anchorage, and the wedge is seated. Elongation is measured and recorded	
Cutting of strands	Once the stressing operation has been completed and approved	
Capping of anchorages	Grout caps or flexible filler caps	Permanent protection cap filled with grease
Grouting	Grouting of the tendon or injecting flexible filler	—

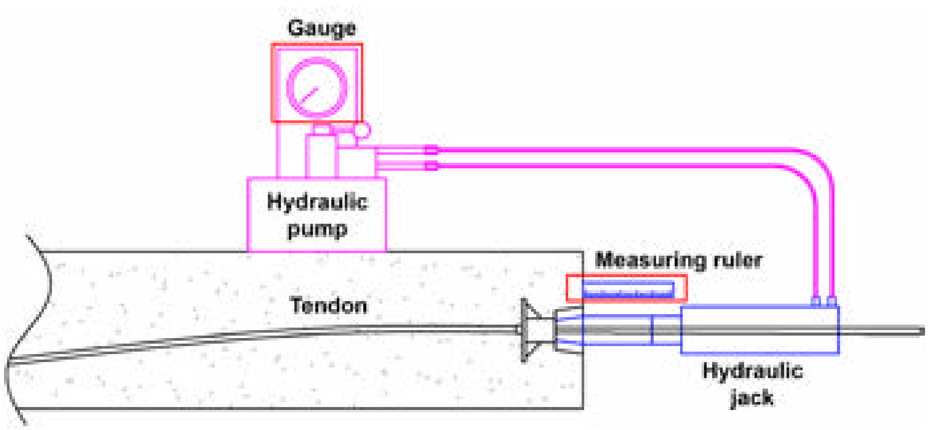
Field measurement method for elongation

Field measurements of elongations have been performed by visually observing the piston movement during stressing, often using analog/dial gauges and/or measuring the elongation length of the tendon after anchor set. Jacking forces have been measured by reading the pressure gauge of the pressure pump and using the calibration chart. Figure 1 shows the conventional practice for stressing tendons and measuring elongations in post-tensioning. Often, the strands are marked with paint or a grease pen to measure the elongations, but inaccuracies are introduced due to the thickness of the mark being made. Measurements before and after stressing are sometimes done by different people. Depending on the people, the front, back, or an estimated middle point of the mark is read.

An operator controls the hydraulic pump to reach the required pressure on the pressure gauge and sets the anchor by releasing the hydraulic jack. When the wedge is seated and PT loss occurs, the corresponding elongation length decreases; this is referred to as wedge slip. A typical value for the wedge slip is 6 mm (0.25 in.) when using stressing equipment with a power seating device. After removing the jack, the operator manually measures the tendon elongation using a tape measure or a ruler. Elongation length and pressure gauge readings are recorded on the construction site, often using manual methods such as pen and paper. The conventional measurement and management have been carried out in an analog way, undesirably needing extra labor and time.



(a) Conventional practice of stressing tendons



(b) Elongation measurement

Fig. 1—Conventional practice and equipment for stressing tendons and measuring elongations.

To verify applied forces, the measured tendon elongation is compared with the theoretical elongation. The theoretical elongation is a value expected in advance. However, there may be inevitable discrepancies between the expected and measured elongations. The friction along prestressing reinforcement may vary due to tolerances and tendon profile irregularities. Friction coefficients between prestressing reinforcement and the duct are also variable. A slightly higher tolerance is permitted for PT construction than in pretensioned construction. Codes specify a maximum elongation tolerance of 7% for post-tensioning (Table 2).

In concrete slab systems, multiple tendons are individually stressed using monostrand jacks. Measurement uncertainties increase the deviation of individual strand forces. Accurate measurement of actual forces in the tendons is necessary for uniform tension control. Additionally, efficient management with reduced labor is preferred.

The second author developed an Internet of Things (IoT) system for the measurement of prestressing force in the PT method in 2015. This system also serves as an alternate method for recording PT construction data by saving it to an internet server. Building upon the initial study, the system has been developed. This paper presents the system and highlights its practicality and accuracy in terms of the site application. The system uses advanced technologies to measure the tension forces of tendons by multiplying the hydraulic pressure by the jack piston area. The manufactured system accurately determines the final elongation of the tendon by analyzing

Table 2—Acceptance tolerances between expected and measured elongations in selected codes

Code/ Specification	Entire tendon		Individual/ particular strand in multistrand tendons	
ACI 318-19	±7%		—	
AASHTO (2010)	≤15 m (49 ft)	>15 m (49 ft)	—	
	±7%	±5%	—	
fib Model Code (2013)	≤15 m (49 ft)	>15 m (49 ft)	≤15 m (49 ft)	>15 m (49 ft)
	±7%	±5%	±15%	±10%

real-time data from sensors, including elongation and pressure measurements.

AUTOMATIC SYSTEM FOR MEASUREMENT IN POST-TENSIONING METHOD

System plan

The purpose of the system is to automate real-time measurement for elongation and pressure and accurately determine the final elongation of strand(s). Figure 2 shows a side view of the smart system applied to a PT member and a mobile terminal for data transmission. The system comprises a hydraulic jack; a hydraulic pump; a digital elongation-length measurement sensor; a digital pressure-measurement sensor; and a measurement unit consisting of a data logger, battery, and wireless near-field communication module (for example, Bluetooth®) for transmitting the collected data to the control module.

The hydraulic jack stretches the strand directly by moving a piston forward to apply tension force. Installed on the hydraulic jack, the digital elongation-length measurement sensor measures the elongation length of the strand. Although it actually measures the movement length of the piston, determining its movement length is equivalent to measuring the elongation length of the strand because the piston grips the strand. The digital pressure-measurement sensor is installed on the pressure supply pipe to measure the pressure applied to the jack. The measurement unit receives real-time data from the digital elongation-length measurement sensor and the digital pressure-measurement sensor, forwarding it to the control module in real time. The prestressing force is obtained from the measured pressure times the jack piston area. Automatically, the system determines the final elongation based on the elongation and pressure data. The system directly measures the distance the jack piston retracts when the wedge is seated to obtain the value of the wedge slip. The processed final elongation and wedge-slip value are also sent to the control module after the tensioning work is done. The relationship that the prestressing force is equal to the pressure times the piston area would remain the same regardless of the piston size or hydraulic jack capacity.

For multistrand tendons, to exclude the initial slack, the elastic modulus is obtained by measuring the stress and strain at a relatively low stress (for example, at a pump pressure of 100 bar [1450 psi]) and at the peak (refer to Fig. 3). The final effective elongation is

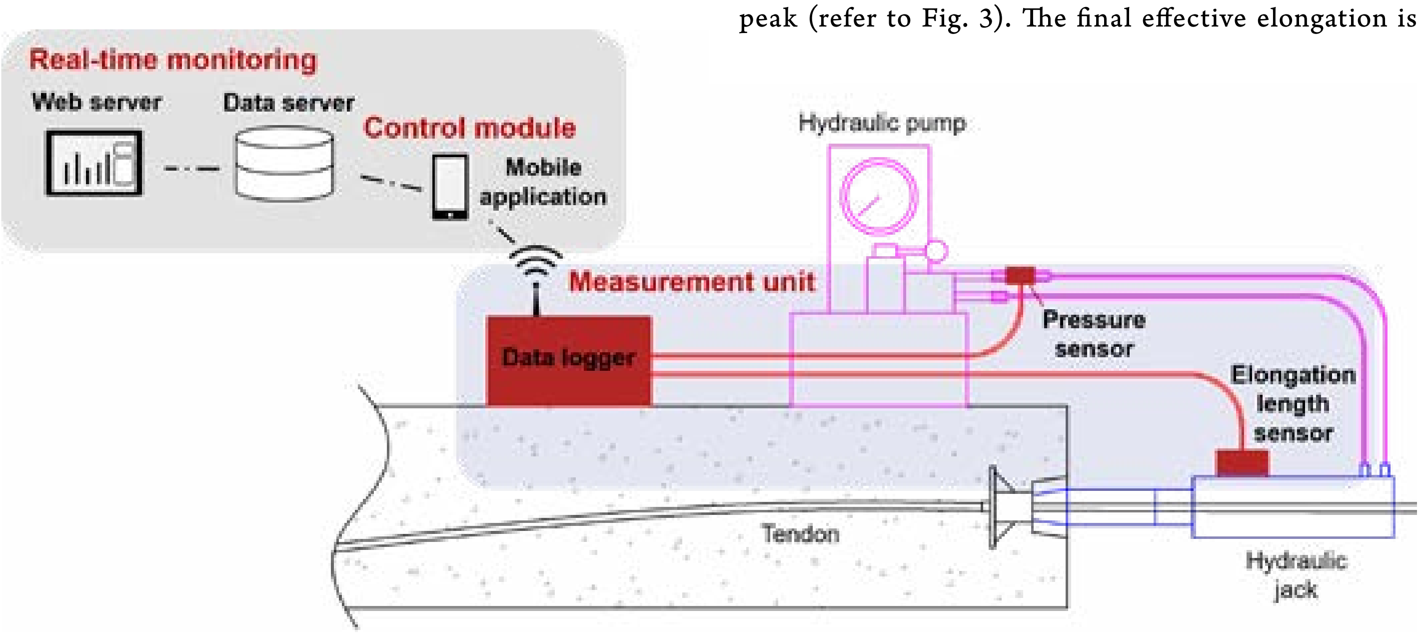


Fig. 2—Side view of smart post-tensioning system.

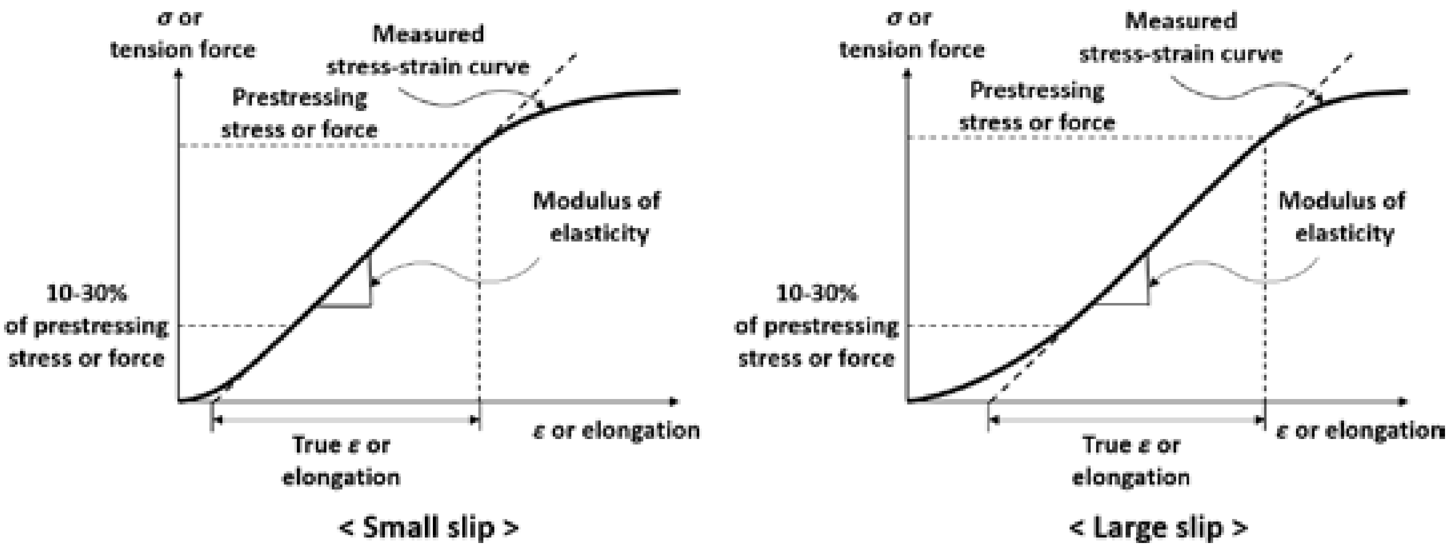


Fig. 3—Measured force-elongation relations for strands with initial slack.

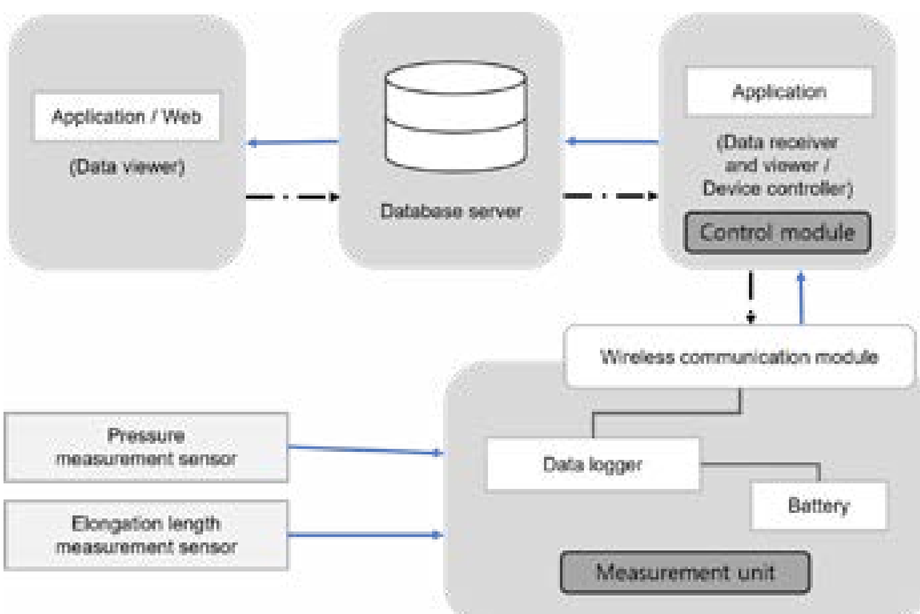


Fig. 4—System plan.

Fig. 5—(Left) Prototype digital elongation-length measurement sensor; (center) measurement unit; and (right) digital pressure-measurement sensor.

determined by multiplying the peak stress by the elastic modulus. It is common practice, and the developed system just simplifies this conventional process digitally. Even for unbonded single-strand tendons of slabs-on-ground, there is a slack by the wedge slip at the dead end (no hydraulic pull-seating or push-seating), which should not be included in the final elongation either.

Figure 4 illustrates the system layout. The measurement data are transmitted to the data logger, which is directly connected to the sensors (Fig. 5). Using the collected data, the data logger employs an internal algorithm to determine the elastic modulus of each strand. Once the algorithm detects the completion of the tensioning operation, it determines the final elongation by considering factors such as initial slacks, anchor set, and correction values from any errors in the stressing equipment.

Figures 6 and 7 show the interface of the control module (mobile application) and the main server, respectively. The control module serves as both a data receiver and a device controller. It provides a visual display for workers to review the measured data and facilitates communication with the measurement unit. Additionally, the control module transfers the measured data to the main server through an internet connection, where it is accumulated in a database.

Resolving uncertainties: system's advantage

Initial slack—There is always a certain amount of initial slack present in a strand, particularly for multi-strand tendons. Initial slack is not a valid value for final elongation. Accurate elongation measurement should be performed after removing the initial slack, if it is not negligible like single-strand tendons. The length of the initial slack affects the measured elongation, as depicted in Fig. 3. For instance, if two identical tendons are subjected to the same pressure, but one has a larger initial slack length than the other, the one with the larger slack will exhibit a greater total elongation despite having the same material properties and length. Consequently, AFCEN (2012) mandates the removal of initial slack using an equitension jack (low-force jack) prior to actual stressing.

In case of not using an equitension jack (low-force jack), the smart PT system automatically and accurately determines the final elongation, with the need for procedures to identify initial slack, saving significant time, especially for multistrand tendons. Further details regarding this process can be found later in this paper.

Modulus of elasticity—The computation of the tension force involves multiplying the measured elongation by the modulus of elasticity. It should be noted that the modulus of elasticity within each strand is uncertain. On-site values can range from 185,000 to 205,000 MPa (26,830 to 29,733 ksi). Consequently, accurately determining the actual tension in tendons based solely on the measured elongation becomes challenging.

Fig. 6—Mobile application interface design (Portuguese version).

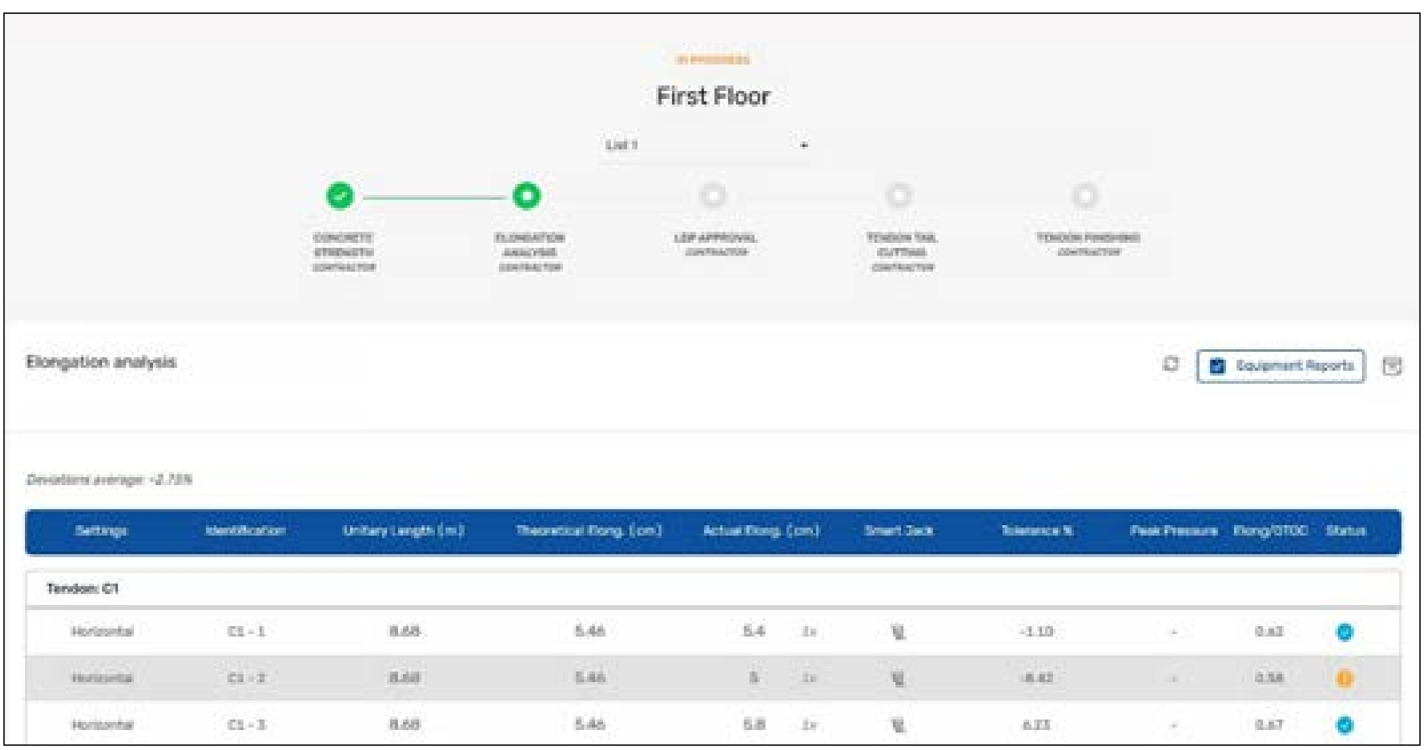


Fig. 7—Main server interface design (elongation analysis).

However, due to the system's ability to record all strains and forces during the tensioning process, it becomes possible to obtain precise modulus of elasticity values for each strand.

Wedge slip—Figure 8 illustrates the stress distribution in a strand immediately after anchor set when stressed from one end. Friction and anchor set contribute to initial stress loss during the stressing process. Once the jacking force reaches its target value, the wedges are inserted, then the strand is released, or the jack is reversed. As the strand retracts and draws the wedges into a conical wedge cavity in the anchor or a wedge plate, seating loss occurs, and the total elongation is reduced as much as the wedge seats. The seating loss is also dependent on jobsite conditions (cleanliness of the wedge cavity). The contractor can determine the appropriate value for each project based on the manufacturer's data and/or recommendations. A typical value is 6 mm (1/4 in.) when stressing equipment with a power seating device is used, but it can vary between 3 and 13 mm (1/8 and 1/2 in.). The smart system measures the exact length of the anchor set and determines the final elongation.

Accurate measurements—In terms of pressure, once the target pressure is reached, the operator or the presetting reverses the pump (Fig. 9), seats the wedges, and releases the tendon. However, several physical factors contribute to the challenge of accurately measuring the tension force. The pump is controlled manually, and the accuracy depends on the skill of a record-taker to record the gauge pressure at lock-off. As for the tendon elongation measurement, analog measurement using a tape measure or a ruler is also dependent on the measurer. The smart system incorporates sensors that accurately measure pressure and elongation. More accurate values are obtained, and automated measurements are more convenient.

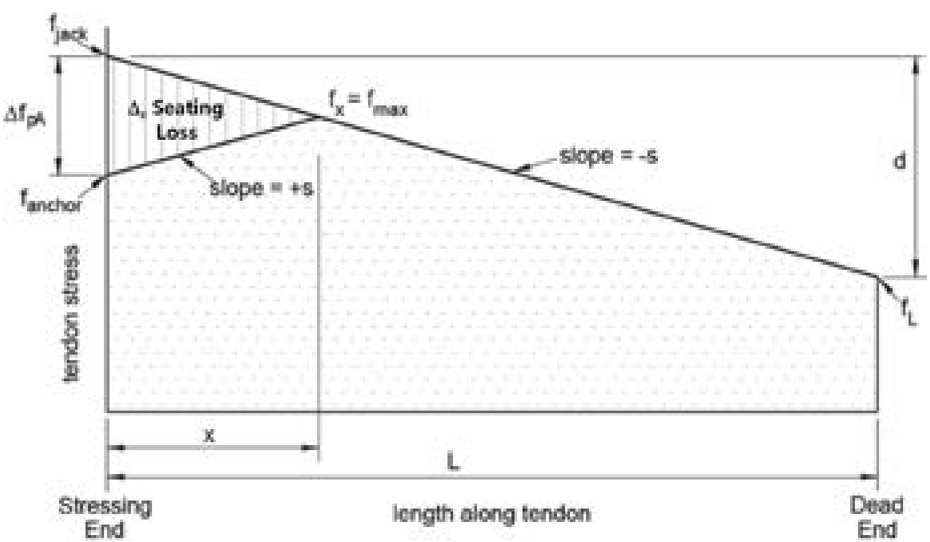


Fig. 8—Stress distribution in strand with one stressing end (ACI 423.10R-16 [Joint ACI-ASCE Committee 423 2016]).

Fig. 9—General hydraulic pump gauge and control on site.

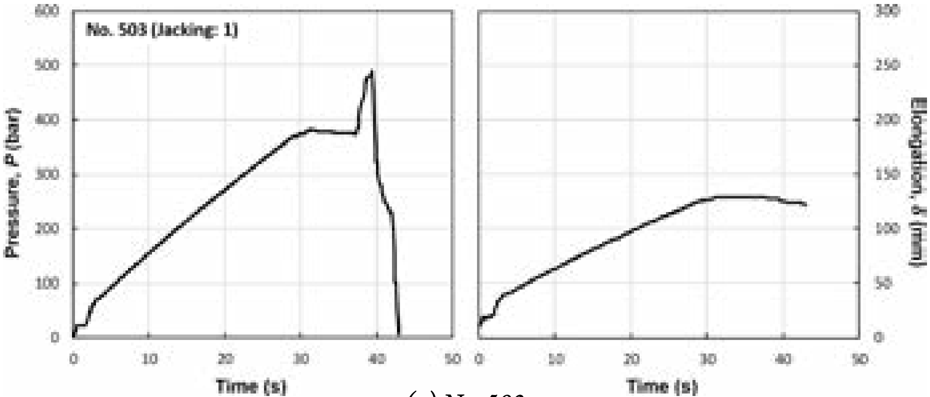
Internal algorithm for final elongation

Hurst (1998) indicated that the actual elongation in a prestressed tendon is determined by considering both the pressure applied to the jack and the tendon elongation during tensioning. The usual procedure is to apply a small force P', approximately 10 to 20% of the final prestress force, and to measure the total elongation from the initial elongation due to this small force. The total elongation δ_t when the tendon is tensioned to its full force is then given by

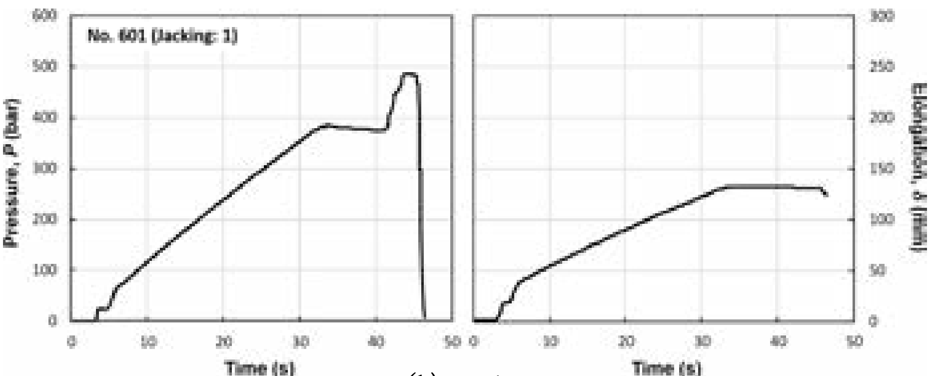
$$\delta_t = [(P_o - P')/P_o]\delta_e$$

where P_o is the full prestressing force applied to a member; and δ_e is the expected elongation when a steel strand is tensioned gradually from zero tension up to the full force without any friction.

The smart PT system measured actual data on a construction site (Fig. 10). The graph shows elongation and pressure data over time, from applying pressure to a jack to setting an anchor. In Fig. 10(a) and (b), the hydraulic pump applied pressure gradually, reaching a maximum tension pressure value of 383 and 385 bar (5555 and 5584 psi), respectively. The elongations were 129 and 132 mm (5.08 and 5.19 in.), respectively. This

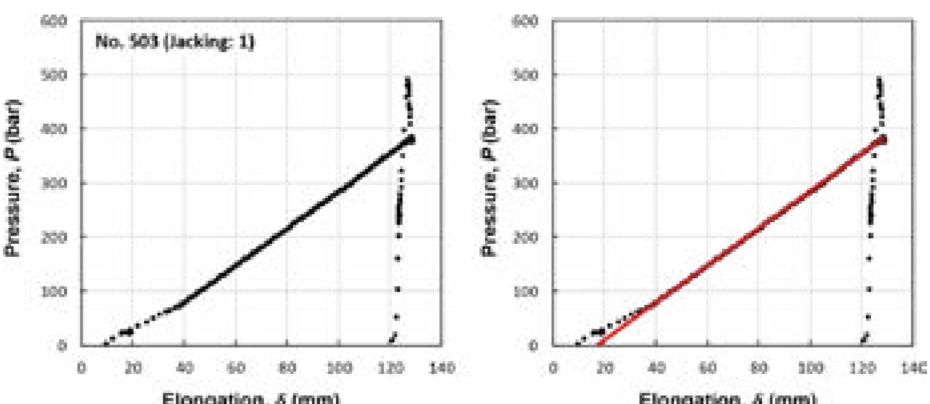


(a) No. 503



(b) No. 601

Fig. 10—Real-time pressure and elongation data measured on construction site in Korea.



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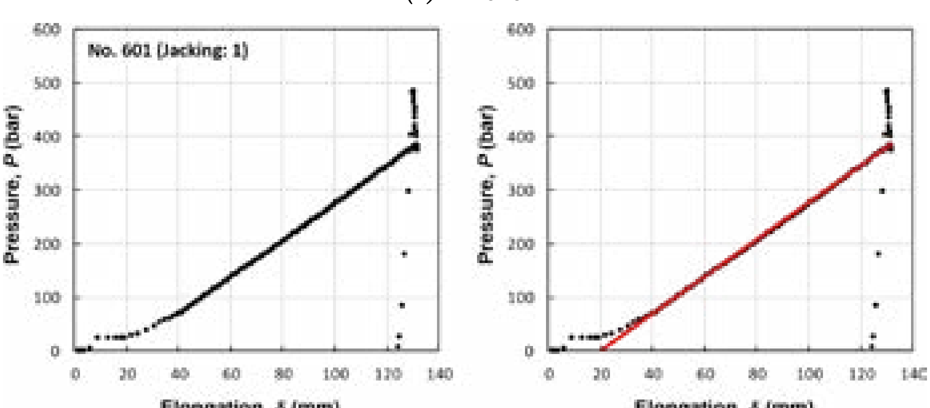


(b) No. 601

Fig. 11—Scatter diagrams of elongation and pressure data points and elongation-pressure relationship determined from algorithm.

maximum elongation occurs when the pressure reaches its peak value. Subsequently, the pump is reversed, causing a sharp increase in pressure for hydraulic blocking (that is, power seating). However, because the higher pressure is not used for tendon tensioning, it is not considered in the effective value. Finally, once the jack is released, the wedge is slipped at the jacking end, and the stressing operation is done. The reduced wedge slip due to power seating can still be monitored, and the slip value is used to determine the final elongation.

Figures 11(a) and (b) present scatter diagrams of elongation and pressure data points from Fig. 10(a) and (b), respectively. As discussed in the previous section and Fig. 3, there is always the initial slack in strand(s) of multistrand and single-strand tendons without pull-seating or push-seating at the dead end. Due to the initial slack, the elongation increases significantly during early stressing, but the rate of increase is not consistent. After the slack removal, the elongation rises in almost direct proportion to the pressure increase up to the points where the effective maximum pressure and elongation occur. This increase can be approximated by a line with a constant slope. The red line in Fig. 11 represents this slope, which is influenced by factors such as the elastic modulus, length, section area of the prestressing steel, and friction losses. The elastic modulus and length of the steel are assumed to be constant, and the section area of the steel and friction losses also have an almost constant value. Thus, the constant slope is obtained for each tendon.

When effective maximum pressure P_{max} is applied to the single-strand tendon, the true elongation Δ excluding the initial slack can be calculated by

$$\Delta = P_{max} / Slope$$

In Fig. 11, the pressure steeply decreases after the hydraulic jack is released. At this time, due to the anchor set, the elongation also decreases slightly as much as the wedges are slipped (Δ_s) and seating losses occur. As a result, the final elongation Δ_t of the single-strand tendon is given by

$$\Delta_t = \Delta - \Delta_s$$

This system measures the backward movement of the jack piston and the pressure of the hydraulic pump to determine the wedge slip (Δ_s). Because sensors are used for the measurements, it has the advantage of being automated and accurate. The system automatically determines final elongation by excluding loss in seating. Alternatively, a fixed wedge-slip value can be used as a default value if an engineer chooses to use that mode in the system.

Additionally, repetitive discrepancies can occur in the stressing process, depending on the jacking equipment. To simplify matters in the construction field, workers occasionally use the default correction value as a practical solution. This involves compensating for the discrepancy between the measured piston movement and strand movement that consistently occurs in the same equipment system. This is usually a small value (for example, 2.5 to 7.5 mm [0.1 to 0.3 in.]) and thus is often ignored.

In conventional multistrand PT construction practices, operators manually read the piston or strand movement using a ruler, dial gauge, or tape measure and the pressure gauge of the pressure pump by eye to calculate the constant slope in the elongation-pressure relationship for each tendon. However, this method is tedious and may be prone to inaccurate readings. To improve the manual method, the smart PT system digitizes and automates all measurements and determines the final elongation using the internal algorithm according to the description in this paper.

In two-end jacking practices, the system automatically determines the effective elongation (of the strand) by excluding the slack that occurs initially, including the slippage at the dead end, during the first jacking at one end. Therefore, no manual procedures such as paint marking and subsequent hand calculations are necessary.

Also, the system is designed to function with multiple jack pulls when tensioning long tendons. Figure 12 illustrates pressure and elongation data measured during tensioning when performing jack pulls two times. After setting the system to the mode of "jacking twice" and performing tensioning, the internal algorithm automatically measures the elongation at the first tensioning. Then, at the second tensioning, it measures the effective elongation that occurs after the maximum pressure in the first tensioning. After tensioning up to the target pressure and releasing the pressure, it measures the loss of wedge seating and determines the final elongation by combing two elongation values minus the measured slip.

FIELD APPLICATION AND RESULTS

The system is applied to the construction site to verify the system operation and field applicability. Figure 13 shows system installation at an outdoor laboratory in Brazil. The pressure-measurement sensor (in the red box in Fig. 13) is installed on the hydraulic pressure pipe of the hydraulic pump, the elongation measurement sensor (in the blue box in Fig. 13) is installed on the hydraulic jack, and the measurement unit (in the green box in Fig. 13) is attached to the hydraulic pump.

Figure 14 shows a steel beam with an unbonded tendon as the test member. Tensioning the tendon in the test member, the hydraulic jack moves in a direction away from the surface. Figure 15 illustrates the movement of the hydraulic jack after the tendon reaches the target pressure. Before releasing the

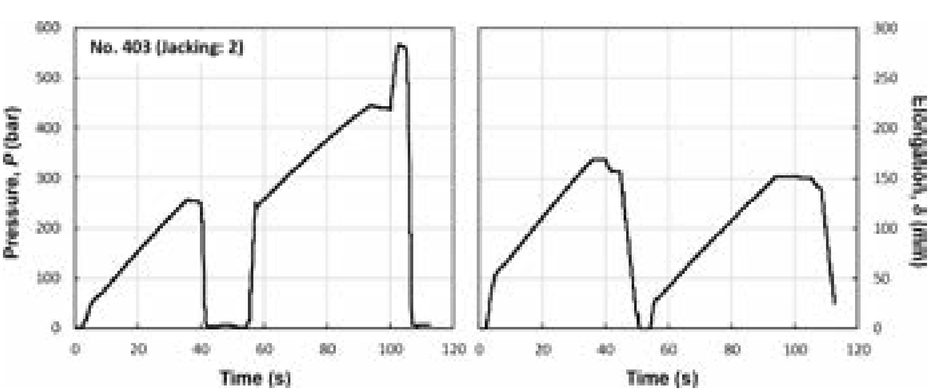


Fig. 12—Real-time pressure and elongation data recorded on construction site in Korea (jacking twice).

Fig. 13—Device setting at outdoor laboratory in Brazil.

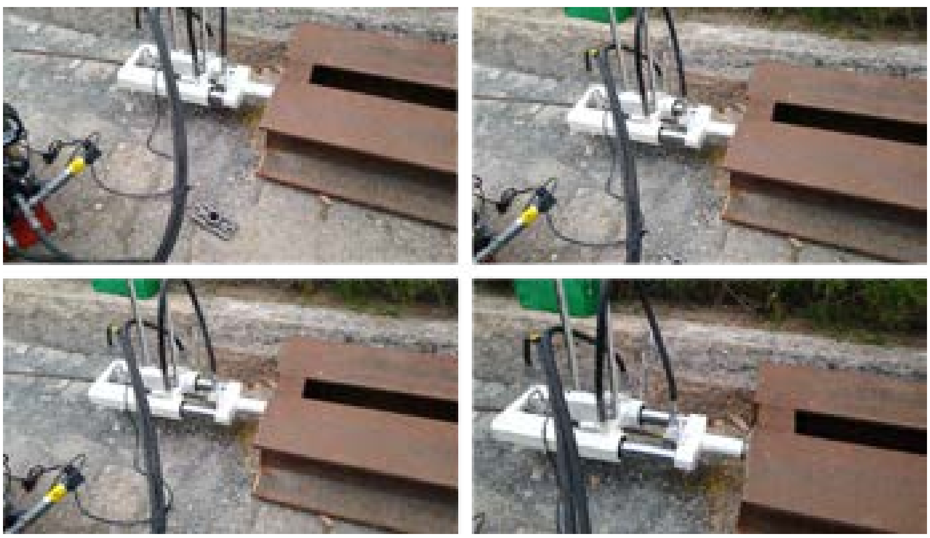
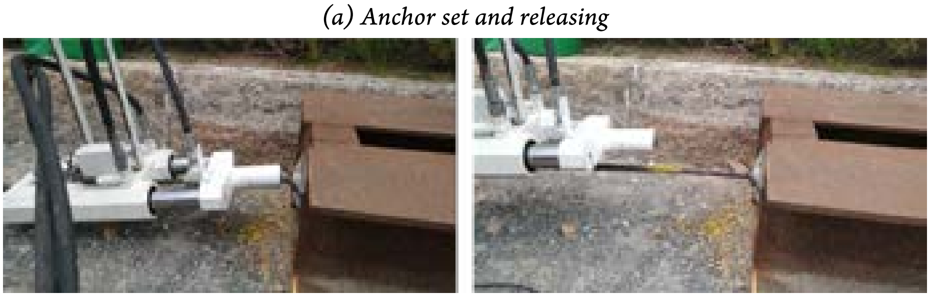


Fig. 14—Hydraulic jack movement during tensioning of test tendon.

(a) Anchor set and releasing



(b) Removal of hydraulic jack

Fig. 15—Hydraulic jack movement after tendon has reached target pressure.

hydraulic jack, pressure is applied in the opposite direction to the forward direction to draw the wedge in the anchor. Right after the hydraulic jack is released, the wedge slips, and the elongation sensor measures the length. To ensure the accuracy of the final elongation measurement from the system, the initial slack in the tendon is eliminated before the test. This means that the directly measured elongation length following tensioning represents the actual elongation of the tendon. Consequently, the system's accuracy is validated by comparing the manually measured elongation with the final elongation obtained from the system.

In Fig. 16, the manually measured elongation is 85 mm (3.35 in.). When the system determines the elongation based on the sensor data, it gives 92 mm (3.62 in.) without correction. As mentioned earlier, a repeated equipment-related error always occurs. Empirically, each hydraulic jack produces constant errors, and there was an equipment error of 7 mm (0.28 in.) in this test. To address this, the system algorithm is designed to receive the correction value in advance. The system algorithm excludes the correction value to determine the final elongation. Consequently, Table 3 shows that the smart system can measure the final elongation with greater accuracy, bringing it closer to the conventionally measured value.

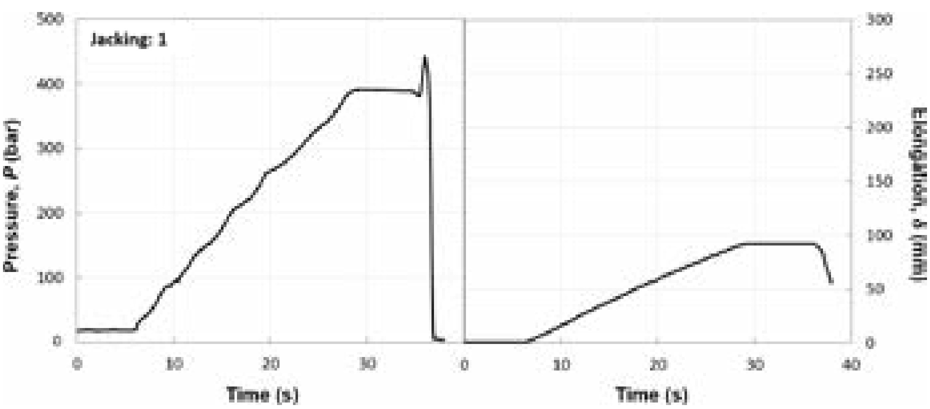
Figure 17 displays the measured pressure and elongation data during the tensioning of the test tendon. Upon manual analysis of the raw data, it is observed that the maximum tension pressure reaches 391 bar (5671 psi), the maximum elongation is recorded as 92 mm (3.62 in.), and the wedge slip is measured to be 6 mm (0.24 in.). It is confirmed that the internal algorithm of the system accurately detects the critical values from the raw data and finally automatically determines the final elongation.

Fig. 16—Manually measured elongation of test tendon.

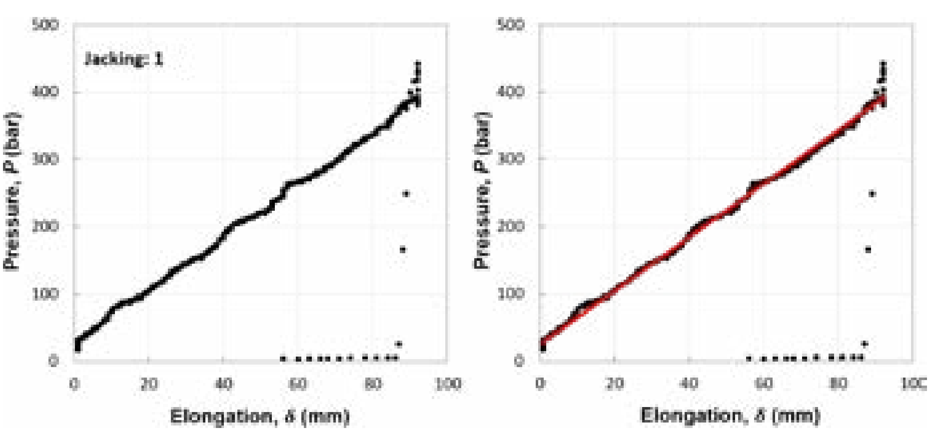
Additional tests were carried out for single-strand tendons of 7.55 and 8.15 m (297 and 321 in.) (Table 4). The correction value for the test equipment was determined to be 9 mm (0.35 in.) before the tests. Over the course of 13 tests, differences between the final elongation processed by the system and the manually measured elongation were observed in the range of –5.6% to 3.8%. The mean absolute error was approximately 2.7%, confirming the successful operation of the automated system in the field with this level of accuracy.

Table 3—Comparison of manually measured final elongation and final elongation by smart system for test tendon

Test ID	Correction value, mm (in.)	Measured wedge slip, mm (in.)	Final elongation		Results comparison	
			Processed elongation *A*, mm (in.)	Direct method check *B*, mm (in.)	*D* = *A* – *B*	*D*/*B* × 100, %
C 1.1	7 (0.275)	6 (0.235)	85 (3.35)	85 (3.35)	0	0.0



(a) Real-time pressure and elongation data



(b) Elongation-pressure relationship computed by data logger

Fig. 17—Digitally measured elongation-pressure relationship of test tendon.

CONCLUSIONS

The smart post-tensioning (PT) system digitizes and automates the final elongation measurement process in construction. By using digital sensors, the system ensures accurate measurements while reducing human error. It provides reliable final elongation with precise wedge slip and maximum pressure data. Field tests confirm its stable operation, and additional tests are being conducted internationally. Overall, the system offers a promising solution for automated final elongation measurements in the PT method.

The authors' expectation is that the system can significantly reduce the labor and time required to measure and manage the final elongation of the PT tendon. The reason can be summarized as follows. First, the system performs accurate measurements with sensors, so there is no need to manually measure prestressing force and/or elongation that may be affected by human errors. Second, based on the measurement data, the internal algorithm automatically figures out the initial slack and wedge slip, which takes considerable time and effort, particularly for multistrand tendons. Finally, the system sends and stores all data measured during tensioning work to a main server that engineers, including the field

Table 4—Additional test results in Brazil on accuracy of final elongation determined by smart system

Test ID	Length, m (in.)	Target pressure, bar (psi)	Correction value, mm (in.)	Measured wedge slip, mm (in.)	Final elongation		Results comparison	
					Processed elongation *A*, mm (in.)	Direct method check *B*, mm (in.)	*D* = (*A* – *B*), mm (in.)	*D*/*B* × 100, %
D11.1	7.55 (297)	400 (5801)	9 (0.35)	7 (0.275)	54 (2.13)	52 (2.05)	2 (0.08)	3.8
D12.1	7.55 (297)	400 (5801)	9 (0.35)	7 (0.275)	50 (1.97)	52 (2.05)	–2 (–0.08)	–3.8
D13.1	7.55 (297)	400 (5801)	9 (0.35)	6 (0.235)	54 (2.13)	53 (2.09)	1 (0.04)	1.9
D14.1	7.55 (297)	400 (5801)	9 (0.35)	7 (0.275)	51 (2.01)	54 (2.09)	–3 (–0.12)	–5.6
D15.1	7.55 (297)	400 (5801)	9 (0.35)	6 (0.235)	54 (2.13)	54 (2.13)	0 (0)	0.0
D16.1	7.55 (297)	400 (5801)	9 (0.35)	6 (0.235)	53 (2.09)	53 (2.09)	0 (0)	0.0
D17.1	7.55 (297)	400 (5801)	9 (0.35)	7 (0.275)	50 (1.97)	50 (1.97)	0 (0)	0.0
D18.1	8.15 (321)	400 (5801)	9 (0.35)	9 (0.35)	52 (2.05)	55 (2.17)	–3 (–0.12)	–5.5
D19.1	8.15 (321)	400 (5801)	9 (0.35)	7 (0.275)	56 (2.20)	55 (2.17)	1 (0.04)	1.8
D20.1	8.15 (321)	400 (5801)	9 (0.35)	7 (0.275)	52 (2.05)	55 (2.17)	–3 (–0.12)	–5.5
D21.1	8.15 (321)	400 (5801)	9 (0.35)	8 (0.315)	53 (2.09)	55 (2.17)	–2 (–0.08)	–3.6
D22.1	8.15 (321)	400 (5801)	9 (0.35)	8 (0.315)	55 (2.17)	55 (2.17)	0 (0)	0.0
D23.1	8.15 (321)	400 (5801)	9 (0.35)	7 (0.275)	54 (2.13)	56 (2.20)	–2 (–0.08)	–3.6

inspector, can access remotely in real time through a mobile application.

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