KRABO® sensorized bolts: an innovation for a safer future.

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Abstract

The sensorized bolt represents a recent innovation in the world of fasteners. A sensor embedded in the bolt allows real-time monitoring of the axial load, obtaining useful information to check the state of the bolted joints and increasing the safety of the structure. The bolts produced by Krabo, with its product "KRABO® Networking Bolts", are an example of this innovation, whose strong point is to be developed for mass production. This article discusses the operating principle of sensorized bolts and investigates their possible applications. The testing of the KRABO® bolt demonstrated a measurement accuracy greater than 95% on the axial load and functional interchangeability with equivalent non-sensorized bolts.

1. Introduction

Threaded fasteners are one of the most widely used solutions for joining multiple parts together; among these, screws, bolts, and studs are the most well-known. The integrity of the joint is ensured by the force applied by the threaded element on it. This force is called the clamp load, also known as axial load or preload, and it is of fundamental importance to ensure the stability and safety of the structure [1]. The clamp load is achieved by tightening the bolt with a wrench. This operation generates a force that elongates the screw section between the head and the nut, providing the preload needed to prevent separation of the joint components [2]. There are several methods to ensure that the correct preload is achieved. The simplest consists of tightening the bolt to a preset torque using a torque wrench. This method is approximate, as the relationship between applied torque and preload depends on the friction generated between the contact surfaces during the tightening rotation. The friction varies by many factors such as lubrication, surface roughness, contact area, and others [3]. A more accurate method involves performing a first torque-controlled tightening, also called "pre-torque", followed by a controlled angle tightening (torque plus angle), thereby partially reducing the effect of friction. For structural bolting, these methods are described in standard EN 1090-2 [4], which outlines the sequence of operations to be performed and the precautions to be taken to achieve the recommended preload. Also for structural fasteners, load-indicating washers are used, whose requirements are specified in standard EN 14399-9 [5]: these washers have protrusions that flatten during tightening, allowing visual inspection to verify that the minimum preload has been reached. A possible method to determine the tightening load is by measuring the elongation of the screw, which is directly proportional to the axial force according to Young's modulus [6]. The change in length of the screw due to tightening can be measured using various types of sensors. Among these are displacement sensors (LVDTs), which can measure the relative elongation between two points on the screw itself [7], and strain gauges, bonded to the shank of the screw [8] or

Figure 1. KRABO® Networking Bolt: sensorized bolt produced by Krabo.

embedded inside the screw body [9], whose deformation due to elongation is converted into a measurable electrical signal. A widely used method, thanks to its low invasiveness and relative simplicity, uses the sound wave generated by a piezoelectric transducer. With the ultrasonic technique, the time spent by the wave to travel through the screw is related to the screw's length via the speed of sound [10]. Direct measurement of the axial load not only verifies correct tightening but also detects preload loss due to service loads. Many applications require periodic inspection of bolted joints; these inspections are costly, often require plant shutdowns, and when performed manually, can be risky for the personnel involved. To date, the most common methods to detect bolt loosening involve visual inspection: bolts are marked with a marker or equipped with colored flags [11], so that any rotation from the initial position can be detected, signifying a complete preload loss. When partial preload loss is to be prevented, 100% re-tightening of the bolts to the design torque is carried out, using automatic or manual systems. To facilitate these maintenance operations, new technologies have recently been introduced that allow preload to be checked via color-changing elements on the bolt head [12] or level indicators [13]. The advantage of KRABO® bolts is the ability to remotely monitor the load [14]. The data transmitted from the bolt can be analyzed to plan maintenance only when necessary, reducing interventions to proven need. Monitoring load variations during the construction phase can help detect unforeseen settlements or failures early. Monitoring axial load over time also allows the detection of abnormal loads acting on the structure and the evaluation of its condition after events such as fires or earthquakes.

In this article, Section 2 illustrates the functioning of KRABO® bolts; Section 3 presents the results of an instrumented test that certifies their expected performance; Section 4 provides examples of possible applications; and finally, Section 5 discusses the conclusions.

2. KRABO® Networking Bolts

The sensor embedded into KRABO® bolts uses ultrasonic technology to measure the axial load on the bolt. Ultrasonic methods have been used for non-destructive testing since the mid-20th century [15]; ultrasonic technology was introduced into the bolted joints in the 1980s and has always been valued for its high measurement accuracy [16]. The sensor's operation is illustrated in the block diagram in Figure 2. A piezoelectric transducer is bonded to one end of the bolt and, when excited by the analog component controlled by the processor, generates an ultrasonic wave at a known frequency, in the MHz range. This wave travels through the shank and reflects off the opposite end of the bolt, producing a returning echo that strikes the transducer again. The processor measures the time interval, also known as time of flight, between the wave's emission and the echo, with microsecond-level precision. A wireless communication module transmits the data to the gateway. A battery

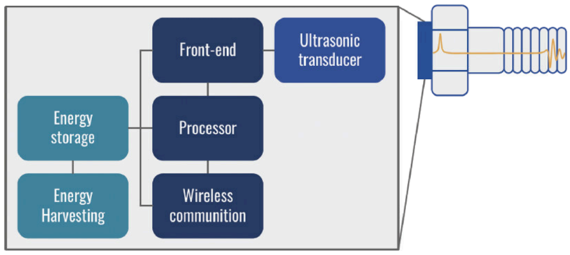

Figure 2. Block diagram of KRABO® bolt. The ultrasonic transducer is excited by the electronics, which are controlled by the processor to perform the measurement and transmit it wirelessly via the dedicated module. Published with permission from [14].

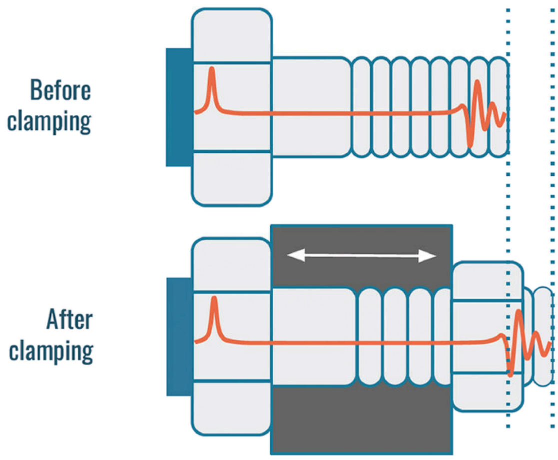

Figure 3. The ultrasonic method. It is possible to measure the axial load of the bolt because there is a proportional relationship between the bolt's elongation due to tightening and the axial load. Published with permission from [14].

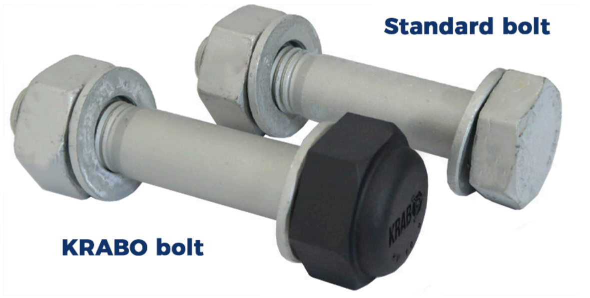

Figure 4. KRABO® Networking bolt comparison with respect to a conventional bolt. Published with permission from [14].

provides all the energy needed to power the electronics; an energy harvesting module can be added to extend battery life. Common energy harvesting examples include solar panels or RF charging antennas [17]. As shown in Figure 3, when the bolt is tightened, it elongates by an amount directly proportional to the axial load; therefore, the load can be measured by comparing the time of flight before and after tightening. All KRABO® bolts are supplied calibrated and ready to use: the relationship between the bolt's elongation and tightening load constitutes the calibration of the KRABO® sensor and it depends both on the intrinsic properties of the bolt and external factors, such as temperature and clamp length. The clamp length is the distance between the first free thread and the underside of the bolt head, equivalent to the thickness of the components of the joint being clamped. The geometric and physical properties of the bolt are relevant for sensor calibration and define a specific product code, associated with its calibration. Temperature is measured by a sensor integrated into the KRABO® electronics and the effect is compensated through proprietary algorithms; the grip length is the only input required from the end user and is also processed within these algorithms. The KRABO® bolt houses all necessary electronic components for measurement and data sharing via the internet within a small cavity in the bolt head. KRABO® technology allows retrofit installation on existing bolts by mechanically modifying the head and tip, in addition to purchasing a new native KRABO bolt from the manufacturer. Figure 4 shows a KRABO® bolt compared to the same bolt without a sensor: not only do they have comparable size, but also the same mechanical properties, making them fully interchangeable from a functional perspective. Figure 5 presents the infrastructure for KRABO® smart bolts. The sensor's measurement from within the bolt head is sent to a gateway using a wireless communication protocol (Zigbee), a widely adopted standard in home automation for its reliability and low power consumption [18]. The gateway, which can be strategically placed to receive signals from multiple bolts, sends all data to a server via a wired, WiFi®, or mobile network connection. Once powered and connected to the network, KRABO® bolts begin transmitting the axial load values to the proprietary KRABO® Cloud platform, available online [19]. Figure 6 shows the graphical interface, which allows users to view bolts installed on their structure, for example, on a bridge, divided by zones. Figure 7 shows the page for monitoring axial load over time for each bolt and configuring various parameters, including alerts that notify users when critical thresholds are overcome.

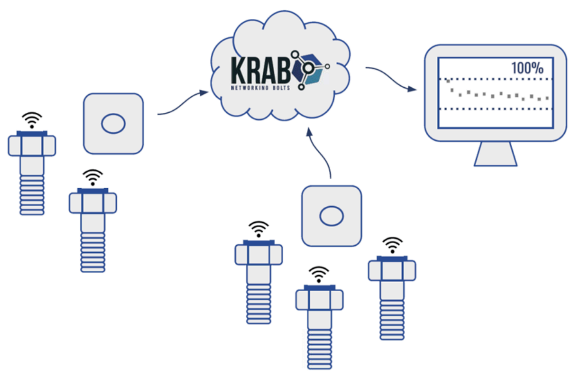

Figure 5: The communication infrastructure of KRABO® bolts. Published with permission from [14].

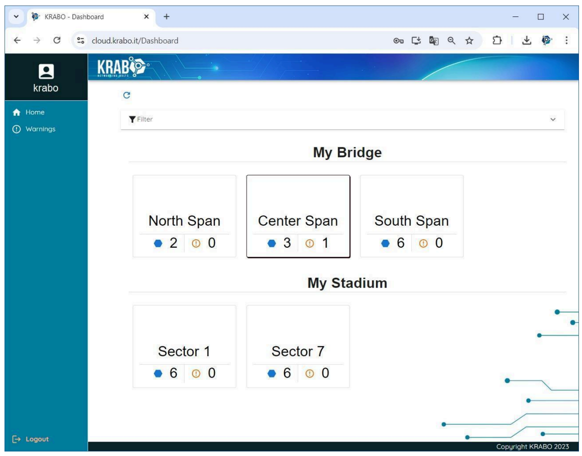

Figura 6. KRABO® Cloud homepage: each bolt can be organized into areas and sites at the customer's discretion.

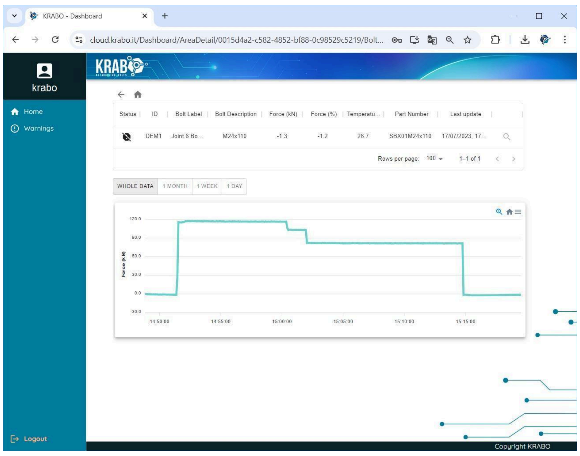

Figura 7. Detail page of a bolt showing the load trend over time on KRABO® Cloud.

3. Instrumental Test

The instrumental test aims to evaluate the accuracy of the KRABO® bolt. The test is conducted on KRABO® M24x115 bolts, class 10.9, on bolts produced according to ISO EN 14399-4 standard [20]. The functional characteristics of the KRABO® bolts are verified through a preload suitability test according to ISO EN 14399-2 [21], which involves a tightening test of the assembly. Figure 8 shows the result of the test: the KRABO® bolt meets the requirements of EN 14399-4 for the maximum force reached during the test (Fbi, max) and for the minimum value of the angular difference (ΔΘ2, min). Figure 8 also shows the result of the same test performed on an ISO EN 14399-4 bolt of the same size and demonstrates that the KRABO® bolt is interchangeable with a standard bolt. The accuracy verification is carried out according to ASTM-F2482 standard [22]. This standard applies to externally threaded elements capable of indicating the axial load during the tightening process and/or after installation. The ASTM F-2482 standard provides a method to certify the accuracy class: the sensorized bolt is tightened in increments from 0 kN up to the test load, which is considered the sensor's full scale, in steps of 25% of the test load. The value shown by the sensorized bolt is compared with a reference instrument capable of measuring the tension. The maximum error of the sensorized bolt compared to the full scale defines the accuracy class. A load cell with a full scale of 400 kN, connected to a TesT torque-tension testing machine, controlled by electronics that allow tightening the bolt to the desired load, is used as the reference. Three KRABO® M24x115 bolts with a grip length of 88.9 mm are tested; all measurements are performed between 22°C and 23°C. Three data points are sampled, two minutes apart, to verify the repeatability of the measurement; the full scale of the sensor is 293 kN. The value measured by the reference load cell is compared with the value recorded by the KRABO® system, as shown on KRABO® Cloud. Figure 9 presents the test result in a scatter plot; the KRABO® bolts are accurate and repeatable, always showing a value close to the reference. As detailed in Table 1, the KRABO® bolt shows a maximum error of 2.56% compared to the full scale. This result confirms that the KRABO® bolt falls within the LT 1 (±5%) accuracy class defined by the ASTM-F2482 standard.

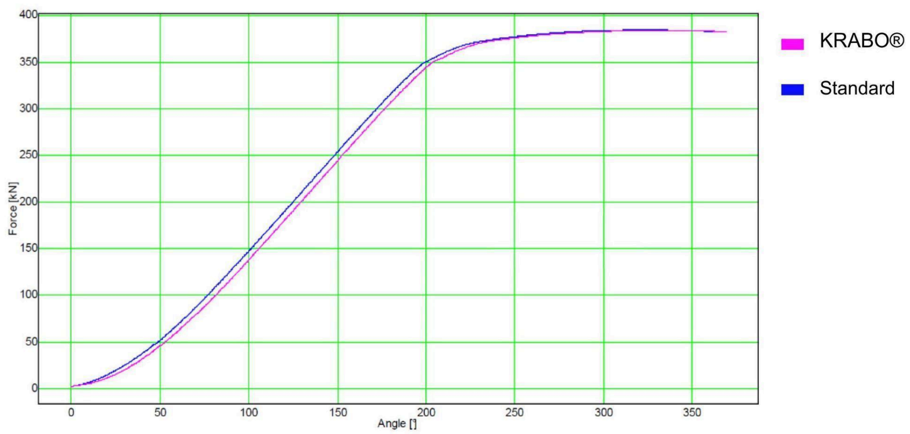

Figure 8. Preload suitability test: both the KRABO® bolt and the equivalent standard bolt comply with the requirements of the ISO EN 14399-2 standard.

Table 1. Evaluation of the accuracy of the KRABO® bolts compared to the reference load cell.

Sample	Step	Reference (kN)	KRABO® (kN)	Error (kN)	Error w.r.t. full scale
Bolt 1	25%	74,55	77,0	2,4	0,84%
	50%	146,2	145,8	-0,4	0,15%
	75%	219,1	214,8	-4,4	1,49%
	100%	292,3	284,8	-7,5	2,56%
Bolt 2	25%	76,2	77,0	0,8	0,29%
	50%	146,2	144,7	-1,5	0,52%
	75%	219,3	216,1	-3,2	1,10%
	100%	292	288,2	-3,8	1,31%
Bolt 3	25%	73,5	76,8	3,3	1,14%
	50%	148,5	150,9	2,4	0,81%
	75%	219,6	221,3	1,7	0,57%
	100%	293,4	294,4	1,0	0,33%

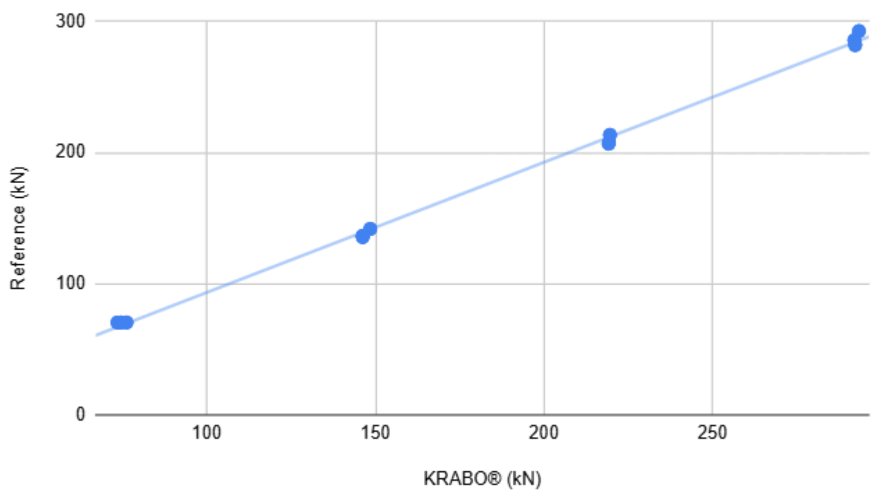

Figure 9. Scatter plot of the instrumental tests of the KRABO® bolts: the bolts consistently return a value very close to the value shown by the reference load cell.

4. Application examples

Sensorized bolts find applications in all fields where periodic inspection interventions are required, and can be used in situations where monitoring the axial load can enhance safety. Examples include rail transportation, renewable energy, earth-moving machinery, automobiles, civil engineering, and both large and small construction projects. In the railway sector, the British reference standard requires the inspection of all bolts on the track, with intervals of annual, quarterly, or monthly checks depending on traffic levels [23]. To perform these inspections, technologies based on cameras that photograph and check joints, identifying broken or loose bolts, are available, but they require a vehicle to travel along the track [24]. Wind turbine manufacturers typically require an inspection of bolt tightening load after the first 500 hours of operation [25], while 10% of bolts are inspected 2 to 4 times a year [26]. According to U.S. regulations, tower crane bolts must be checked annually [27]. In the earth-moving machinery sector, inspecting the undercarriage and bolts accounts for 50% of the total maintenance cost of an excavator [28], and truck manufacturers may require the inspection of chassis fasteners every 100,000 km [29]. In all these applications, using KRABO® bolts would not only limit periodic maintenance to necessary joints, reducing costs but also increase safety through continuous monitoring, allowing for the detection of load losses before complete loosening occurs. For structural bolting, pre- and post-tightening checks are defined in the EN 1090-2 standard, which specifies the requirements for steel and aluminum structures, regardless of their type and shape (e.g., buildings, bridges, plates, trusses), including structures subjected to fatigue or seismic actions. These inspections are based on partial checks (5 or 10% of bolts, depending on the case), to be carried out with different methods depending on the tightening strategy chosen, but they are still costly in terms of time and personnel [30]. The use of KRABO® bolts would eliminate the burden of these inspections and ensure greater tightening precision by directly measuring the load, increasing efficiency and safety. Many applications can be explored with sensorized bolts; for instance, using information obtained from sensorized bolts to monitor movements and degradation of structures such as bridges and buildings, or their extensive application in the automotive field, such as in wheel bolts, to enhance road safety.

5. Conclusion

KRABO® bolts are an innovative technology that, through a sensor integrated within the bolt itself, allows the measurement of axial load. The data, which is transmitted wirelessly to a control unit, is viewable and always available via a web interface. The instrumental test performed on KRABO® M24x115 bolt demonstrated an axial load accuracy exceeding 95%. The KRABO® technology allows retrofitting of already manufactured bolts, in addition to direct purchase from the manufacturer. The KRABO® M24x115 bolt, made from a standard ISO EN 14399-4 bolt, retained its functional characteristics, making it interchangeable with the original. The gradual adoption of this technology, both in new structures and in the recovery of existing buildings, represents a great opportunity to prevent the loosening of bolted joints, with benefits for safety.

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