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"THE DEVELOPMENT, INSTALLATION AND MONITORING OF SMART BOLTS FOR BRIDGES"

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The Development, Installation, and Monitoring of Smart Bolts for Bridges

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Abstract

North American bridge specifications require that all bolts be installed such that their tension, or preload, is greater than a specified minimum. One of five bolt installation methods must be used: calibrated wrench (torque), turn-of-nut, direct tension indicators, "other" (twist-off bolts usually), and lock-pin-and-collar bolts. During service, it is expected that bolts installed in bridges will maintain their high level of tension.

"Smart bolts" are regular heavy hex high strength bolts with an ultrasonic transducer embedded into their head. When coupled to an ultrasonic extensometer, or Bolt Gage, the performance of the bolt(s) can be easily and reliably monitored through the installation process, through seismic events, overloads, movable bridge cycles, etc., and remedial measures quantified if the bolt tension is shown to deteriorate.

Applied Bolting Technology has collaborated with Raymond Engineering in the development of the "ULTRA-BOLT", and in its application to the structural bolting industry. Several bridges and other structures have been chosen for demonstrating the "smart bolt" technology.

Introduction

Bolts clamp things together - usually extremely well when tightened properly and in a correctly designed joint. But when a clamped joint gets "loose", slip occurs, the bolt preload relaxes, and anything can happen. To correctly renovate such connections, it must be known whether the bolts have lost preload, and how much. If it can be demonstrated that the bolts have stretched more, they may be near fracture. For example, if an earthquake subjects a bridge to low frequency high amplitude (seismic)

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loads (Ghobarah, 1990), have the connections been weakened, and do they need retensioning? If a movable bridge operates for a season or two, and the maintenance engineers notice a few dozen broken bolts, how many other bolts are loose and ready to fracture under the full effect of service loads?

In November of 1991, the Advanced Technology Laboratory for Large Structural Systems at Lehigh University (ATLSS Report No. 92-05) sponsored a forum where fifty-five influential practicing structural engineers met by invitation to identify the technologies that were needed to improve and economize connections of the future. This forum indicated the need for a "smart" high strength bolt "...that showed when it has been tightened to the required tension and when it has lost sufficient tension to require retightening...." This same forum mentioned "...connection damage evaluation...", and "...verification of performance and design effectiveness..." as aspects of bolted connection technology which warranted some national prioritization in order to make happen.

At this forum these experts simply stated what we already knew -

> ***What the bolting industry needs is a bolt that knows what it is doing. It needs a bolt that knows it's preload during installation. It needs a bolt that is smart enough to decide when it needs retensioning.***

Do Bridge Bolts Loose Tension?

Evidence of bolts which loosen in (and even fall out of) aircraft, aircraft hangars, bridges, towers, sign supports, arena roofs, power plants, crane girders, amusement rides, etc. has proven disquieting (Wallace, 1993). Loss of life has resulted. Involved and expensive bolt retensioning procedures have been written for many applications like truck frames, crane slewing rings, movable bridge parts, and even entire building frames. These retensioning procedures have usually been based on torque or part turn because better technology did not exist.

Bolts "loosen" when some or all their preload disappears. The precise mechanism whereby bolts loose preload is not well understood in all applications, but some of the following could be involved:

1. Insufficient preload during initial installation.
2. External loads which are more severe than anticipated by the designer, which cause slip of the clamped material.
3. Relaxation of the bolt or thread form under high initial stress.
4. "Seating in" of the nut or bolt head into the clamped surfaces.
5. High amplitude low cycle tensile fatigue, as in earthquakes, for example.

6. Poor initial fit-up resulting in deformation of the clamped material.
7. High frequency lateral vibration which causes the mating helical thread forms to unwind.
8. Stripping or "incipient stripping" of the threads on the bolt or in the nut.

In a recent field test by this author , privately reported, of a Louisiana through truss bridge constructed with hex head bolts installed in 1968 and tested in 1993 showed the following profile of bolt tensions remaining (Figure 1). These bolts, while probably originally installed to very high tensions as was the anecdotal evidence from the bridge owner, showed signs of embedment losses caused by fretting of the bolt head and nut against the steel plates.

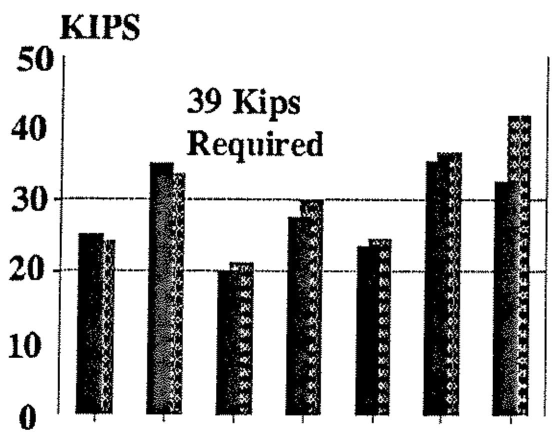

FIG. 1 RED RIVER BRIDGE BOLT TENSIONS

Even in new bridges, ultrasonic tests have shown that bolt tensions sometimes vary widely. In a 1994 test of a new bridge in Denver (Wallace, 1994), ultrasonic release stretch measurements showed that half the newly installed bolts were undertensioned (Figure 2).

This unacceptable situation was found despite the owner of the bridge taking all currently mandated FHWA and material samples, and their state-controlled meticulous care in the inspection of bolt hardware and the installation procedure.

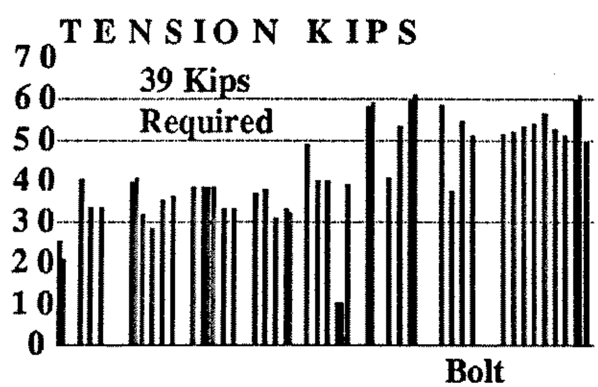

FIG. 2 - 23RD ST. BRIDGE DENVER

The Ultrasonic Release Stretch Method

No accurate direct method has been available for checking the adequacy of bolt tensions achieved by the installation process until ultrasonics came along. The "ultrasonic release stretch" length measurement technique, has a demonstrated field accuracy of +/- 5 percent or less, versus the +/- 30 percent or more for the torque wrench inspection method. Moreover, the equipment and technique involved have now become practical and economical for field inspection crews.

Recognizing this, the Research Council on Structural Connections (RCSC) bolt installation committee, at their 1993 annual meeting, has inserted a more accurate wording of the clause on ultrasonic measurement of bolt preload as a quality assurance procedure. Their new wording is as follows:

Verification of bolt preload after installation by using an ultrasonic extensometer can also be done on some bolts considered representative of the others. The ultrasonic equipment is made specifically for this purpose and is considered very accurate. The method involves measurement of the bolt length change during release of the nut, and either theoretical or actual calibration of this "release stretch" length change against a known standard. Reinstallation of the released bolt or installation of a new (replacement) bolt and nut must be done.

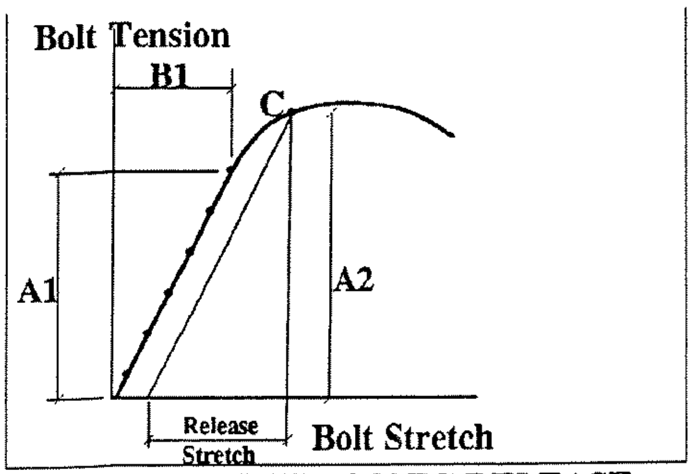

FIG.3 - ULTRASONIC RELEASE STRETCH METHOD

As Figure 3 shows, a bolt may be sitting at point C on its tension/elongation curve, and this point may be beyond the proportional limit of the bolt. To measure its tension, the length of the bolt is measured as-installed, then the nut is released, and by so doing the "release stretch" of the bolt is measured. Note that the unloading line of the bolt is parallel to the elastic portion of the loading curve. Then the bolt is either removed from the hole and calibrated to the same release stretch in (say) a Tinius-Olsen tensile tester, or, more simply, the bolt's stiffness is calculated from simple formulas. By one of these methods, the tension in the bolt before release is determined. In the case of the Raymond equipment, bolt stretch formulas are built into the machine, making reading the bolt tension extremely easy.

ULTRA-BOLTS Use This Technology, But Make It Easy

Using the Raymond Bolt Gage, either the stretch or the tension can be read very accurately, either during installation, as the bolt is "released" after installation, or as the bolt sits in the connection and experiences external loads. For every bolt to be examined in this way, the end of the bolt must be ground smooth to accept a magnetic transducer, the transducer has to be connected ultrasonically to the bolt by using a liquid couplant (such as glycerin), and the Bolt Gage signal characteristics must be set up for that particular bolt. All this takes time and a certain threshold level of competence achieved only through practice.

While this external transducer technique is ten times (at least) more accurate than measuring torque, it is not without difficulty, and is difficult to perform reliably under adverse conditions such as hanging over the side of a bridge.

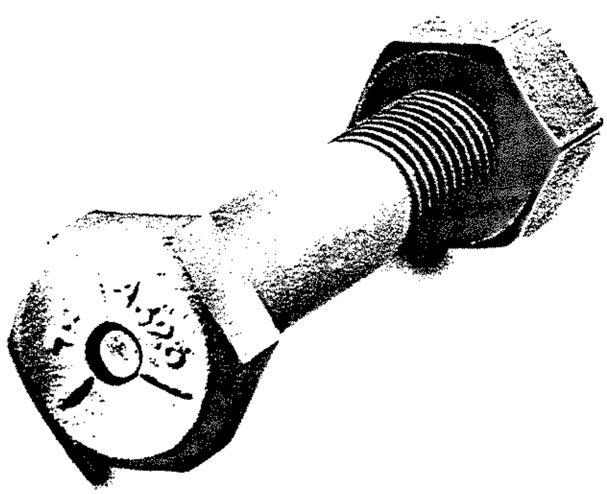

FIG.4 - ULTRA-BOLT

ULTRA-BOLTS make the whole process user-friendly and reliable, because the thin-film ultrasonic transducer, only about 3 mm thick, has been bonded into a shallow milled boss in the head of the bolt. The transducer is, therefore, permanently coupled to the bolt. Note that the stiffness and torsional strength of the bolt is unchanged by the presence of the transducer. This distinguishes the ULTRA-BOLT from all other of internal strain gage devices currently available in bolts. The ULTRA-BOLTS are calibrated at the manufacturing plant, either singly or by lot samples, and with the bolts comes a electronic data card containing all of the set-up parameters necessary to enable the Bolt Gage to instantly connect to the bolt and read its tension. If the installed grip (the dimension from the underside of the bolt head to the face of the nut) in the bridge is different to that with which it was calibrated, a small correction factor must be manually done by the operator.

The procedure to read the ULTRA-BOLT's tension is extremely simple - just insert the data card into the Bolt Gage, enter the bolt's signature number found on the side of the bolt head, attach a temperature probe, and read the tension or stretch. Bolts as short as 50 mm and as long as 9000 mm can be read accurately (+/- 5 percent or better).

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Installation of ULTRA-BOLTS in Bridges

There are currently four bridges with ULTRA-BOLTS either installed or specified to be installed in trials (the fifth, the monumental Akashi Bridge in Japan, is using the identical technology supplied from the USA to monitor the cable clamp bolt tension changes during assembly of the main span structure, although it is not called by the ULTRA name):

- The Navajo Bridge in Arizona
- The Richmond Bridge in Vermont
- The East Haddam railroad bridge in Connecticut
- The Tomlinson lift span in Connecticut
- The Akashi Bridge (6000 M span) in Japan

In all cases the owners of the bridges are using a number of ULTRA-BOLTS to allow their own staffs to economically monitor the changes in bolt tensions over time. Construction loads and their influence on connection forces, construction sequence loading as in the Akashi Bridge in Japan, and as an indicator of bolt tension losses during operation of movable spans are only a few of the reasons for their selection. Their low cost (around $25.00 per bolt in quantities of a few hundred) attracts bridge owners who have experienced the high cost of field renovation of suspected low tension bolts.

Because the data from these bridges is still proprietary to the bridge owners, it cannot be specifically outlined in this report at the time of writing. Consequently, an example situation will be used for this paper which illustrates the principles and type of data that is being collected.

The example is as follows: a number of 108 mm (4.25 in) long grip M22 ASTM A490 ULTRA-BOLTS are to be installed in a special bridge connection. Calibration of this lot of bolts shows the "stiffness" (tension divided by stretch) to be 986 kN/mm (5,630,000 lb/in) at a grip of 70mm (2.75 in). The installation requires a 174 kN (39,000 lb) preload or a little higher, and the bolt's real proof load is about 196 kN (44,000 lb). The calibrated stiffness of the ULTRA-BOLT indicates that, at 174 kN tension, a stretch of .1753 mm (.0069 in) should have been induced into this bolt. The Bolt Gage will read either tension or elongation of the ULTRA-BOLT directly up to the proof load or proportional limit of the bolt. Beyond the proof load (the intersection of A1, B1 on Figure 3) the BOLT GAGE will still read stretch accurately, but its own internal translation of stretch into tension will overstate the tension reading because of the bolt's inelastic behavior in this region. For this reason, it is important to originally install the ULTRA-BOLTS to the proof load or lower so the starting tension is always accurately known.

Our example bolt is one of many similar bolts which are going to be installed in a bridge connection where the designer is using A490 bolts because he doesn't have room to use the more conventional A325 bolts. (Although uncommon, many states including Pennsylvania, Florida, and West Virginia have used A490 bolts in bridges. The ULTRA-BOLT can be any grade, however.) In addition, the designer is using the A490 bolts in direct tension, not shear, prompting him to require very careful installation. The entire connection, we're told, requires fifty bolts, and the owner has decided to install ten ULTRA-BOLTS spotted among the other forty. All the bolts will be installed by the same method - turn of nut, DTI's, torque, whatever. The owner's personnel are going to check the stretch in the ULTRA-BOLTS after installation by connecting a Bolt Gage, punching in the individual ULTRA-BOLTS' calibration codes which are marked on the sides of their heads. The Bolt Gage will then prompt them to make a correction for grip variation between the grip as installed and the calibration grip. Bolt tension or elongation can be directly read.

In our example the bridge owner wants his field staff to come back after the bridge deck is cast and cured, after adjacent connections have been made, and after the passage of specific heavy loads, to check the ULTRA-BOLTS for changes in stretch and tension. Because the transducers are bonded to the bolts, and because the calibration data for them has already been embedded in the Bolt Gage's removable data card (owned and archived by the bridge owner), reading the ten bolts will only take a few minutes. They simply connect the bolt to the BOLT GAGE, punch in a code number which identifies the bolt, read the load and stretch, and store the data. The data from this and previous checks are stored on the separate and secure data card, which can be read by ANY Bolt Gage, and which can be downloaded to any PC using the simple software provided.

<u>Interpretation of ULTRA-BOLT Data</u>

All installations must begin with the operator knowing the originally installed tension and elongation, which should preferably be in the elastic region of the bolts' tension-elongation curve (that is, somewhere below proof load). If the installation of the ULTRA-BOLT cannot be monitored to make this possible, then it is best to have them installed carefully using a DTI so that it is clear that their tension must have been brought up to somewhere just a little above minimum specified proof load as is the intended practice in structural applications. After installation, the ULTRA-BOLT can be easily read again by connecting to a Bolt Gage, and if the elongation is clearly more than that it would be at a little above proof load, it is best to re-zero the Bolt Gage at that point. In this case, from that point on only the *change* in elongation will be known from the re-zero point, but this is extremely useful knowledge.

When reading the ULTRA-BOLT data after installation, one of two scenarios will be found:

1. That elongation and therefore tension has dropped off in the ULTRA-BOLTS. While it is theoretically possible that the bolt could have seen an excursion far into the inelastic region and then unloaded so that the residual elongation is less than the original or last reading, this is unlikely in most circumstances. Reducing elongation (the bolt is getting shorter) will indicate the tension is also reducing.

2. The elongation has increased. This is far more serious. In this case, the bolt has clearly been stretched further, so the Bolt Gage will not give a reliable indication of tension, but will provide useful data on bolt stretch. More careful attention must be paid to what is occurring structurally in the bolt. Assuming the ULTRA-BOLTS were all uniformly installed to the bolt's proof load (about 70% of minimum UTS), then the additional stretch means the bolt is taking load excursions which the designer or owner will probably want to monitor more closely. Reading the bolts at more frequent intervals could be warranted. Bringing a lead wire from the bolt to a central monitoring panel located in (say) the bridge operators control house is possible and economical

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