by D.R. Rammer and S.L. Zelinka

OPTICAL METHOD FOR MEASURING THE SURFACE AREA OF A THREADED FASTENER

Voluntary withdrawal of wood treated with chromated copper arsenate (CCA) for residential construction in 2004 has highlighted the need for an effective and rapid corrosion test to measure the performance of fasteners in contact with wood treated with new preservatives.[1] Experience has shown that to be meaningful, the corrosion test should be run on real fasteners as opposed to coupons with a simple geometry and smooth surface.[2] For controlled experiments where uniform corrosion is typically observed,[3] the corrosion rate (μm/year), R, can be determined by the equation:

$$R = K\frac{\Delta m}{A\rho\Delta t} \quad (1)$$

where Δm (g) is the change in mass, Δt is the change in time (h), A is the surface area (cm^2), ρ is the density (g cm^{-3}), and K is a constant (87,600 mm cm^{-1} h year^{-1}).

Electrochemical techniques can also be used to rapidly determine corrosion rates. The corrosion rate for electrochemical measurements is determined by the equation:

$$R = C\frac{E_w I_{\mathrm{corr}}}{A\rho} \quad (2)$$

where E_w is the equivalent weight (grams equivalent^{-1}), I_{corr} is the corrosion current (Amps), A is the surface area (cm^2), ρ is the density (g cm^{-3}), and C is a constant (3272 mm year^{-1}). For both expressions, an accurate calculation of the corrosion rate requires an accurate determination of the surface area.[4,5] For axially symmetric fasteners, such as dowels or nails, the determination of the surface area is straightforward, but for more complex geometries, such as screws, the task becomes more complicated.

This article highlights major aspects of a new optical technique to determine the surface area of a threaded fastener; the theoretical framework has been reported elsewhere.[6] Specifically, this article describes general surface area expressions used in the analysis, details of image acquisition system, and major image processing steps contained within the measurement system. In short, the general approach is to acquire a high contrast image, break the complicated fastener geometry into smaller defined segments with known analytical solutions, calculate the surface area of each individual segment, and add the individual segments to determine the total surface area of the threaded fastener. This method has been successfully used to determine the surface area of threaded fasteners used in recent corrosion experiments.[3,7]

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THREAD SURFACE AREA

From the acquired images, the entire fastener is divided into segments from which known analytical solutions can be used to calculate the surface area of the segment. Axially symmetric fasteners can be idealized as an infinite number of disks of negligible width, but difficulty arises for threaded fasteners because the threads are not axially symmetric and the thread geometry can vary along the fastener length. Rammer and Zelinka[6] have developed analytical expressions for the surface area of threaded fasteners to overcome these difficulties.

The following expression was developed to determine the thread surface area (Γ) as it varies along the length of the fastener:

$$\Gamma = \iint \sqrt{Tr^2 + \Psi_i^2}\, dr d\theta \quad (3)$$

where T is a function of the thread flank angle while Ψ represents how the upper and lower thread flank surface are affected by the change of the crest diameter. Upper and lower flank Ψs were developed for the three possible fastener geometry conditions: (1) where both the thread root and crest diameters changing linearly (e.g., fastener tip), (2) where both the thread crest and root diameters are constant (e.g., fastener body), and (3) where the thread root diameter is constant but the thread crest diameter is linearly changing (e.g., fastener body near head). These three regions are highlighted in Fig. 1a. Transitions between the possible fastener conditions are handled through the limits of integration for expression 3.

IMAGE ACQUISITION

Image acquisition, image analysis, and surface area calculations were conducted within a custom developed LabView® software program (National Instruments, Austin, TX). Fasteners are placed on a stage with light sources placed on all sides of the fastener with the goal to develop enough contrast to define the fastener edges and minimize shadows while not sacrificing the details of the thread surface detail (Fig. 1b). Backlighting, which defined the fastener edges, was provided through a diffused opaque glass. The fastener thread features were illuminated by top lighting with a 3-inch diameter ring light attached to the front of the camera lens and regulated by a Schott ACE 1–150-W power source (SCHOTT AG, Mainz, Germany). Additionally, three lights provided low angle light to soften shadows on the fastener edges.

A Pulnix® 1320 CL CCD mounted with a tele-centric lens (Jai Inc., San Jose, CA) was used to acquire calibrated images (1020 × 1396 pixels 8-bit grayscale). A certified glass distortion target was used to calibrate the systems optics. While in a live stream image acquisition mode, the lighting

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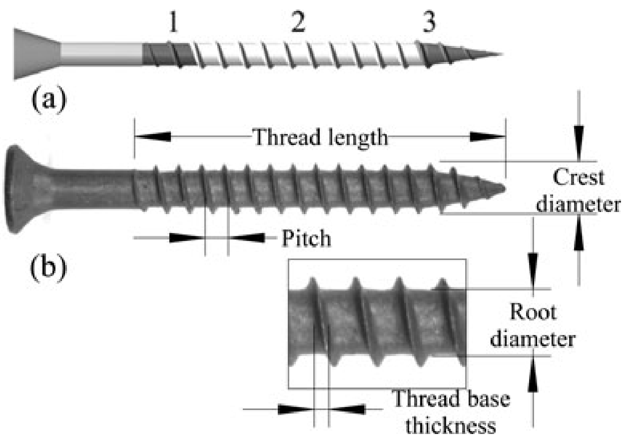

Fig. 1: Threaded fastener (a) highlighting the three regions to calculate the surface area and (b) a photographed fastener, with key characteristics identified, showing appropriate lighting for image analysis with the custom developed LabView software

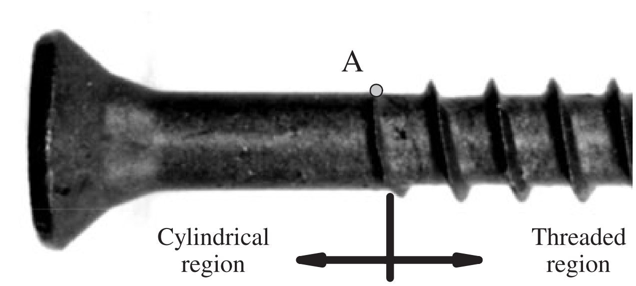

Fig. 2: The user must select the point at which the cylindrical (axially symmetric) region meets the threaded region (Point A)

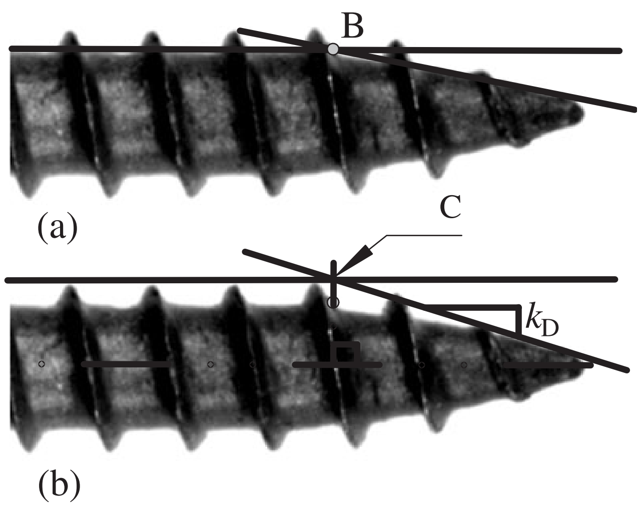

Fig. 3: The user then selects (a) Point B, where the fastener transitions from a constant diameter to a decreasing diameter and (b) computer program determines point C and k_D

could be adjusted by the operator until sufficient contrast was obtained. After the contrast was properly adjusted, the image was acquired in LabView, (National Instruments, Austin, TX) saved as a bitmap file, and used to determine the surface area.

IMAGE PROCESSING

For threaded fasteners, the key characteristics that are needed to determine the surface area from the acquired images are: root diameter, thread crest diameter, thread length, thread width at the root diameter, and thread transitions (i.e., location between fastener tip and constant shank region). Figure 1b highlights these key fastener characteristics. Image acquisition, image analysis, and surface area calculation were carried out in an interactive program developed using LabView, which took advantage of the subroutines contained within the LabView vision development module. One of the goals of the program was to minimize the level of human interaction within the image analysis procedure to decrease the variability of results due to user judgment. However, four key user interactions are still required to assist with the image processing. All image analysis is carried out using a local coordinate system that is established at the middle of the fastener head and runs along the axis of the fastener.

The first user interaction locates the transition between the smooth shank and threaded shank region (Point A in Fig. 2). Using this location, an algorithm calculates the surface area of the smooth shank region using pixel wide cylinders, while a separate algorithm determines the root diameter edge and creates lines defining the upper and lower crest diameter locations within the threaded region.

The second user interaction locates the transition between the straight threaded region and the cone-shaped tip region (Point B in Fig. 3a). Using this location, the coordinate of intersection between a line perpendicular to the fastener axis through this point and the line representing the crest diameters are determined (Point C in Fig. 3b). Using this coordinate and the coordinate of the fastener tip, the slope of the threaded crest with the fastener tip, k_D, is determined.

The third user interaction determines the thread base thickness at the root diameter, t_w. Using the fastener axis as a reference line, the user draws a line whose endpoints are defined by the intersection between the thread flank and the root diameter of this reference line (Fig. 4).

The final user interaction locates where the thread crest diameter starts to decrease into the smooth shank diameter and the rate of crest diameter decrease. To determine these parameters, the user selects the apex of a thread in the transition region (Point E in Fig. 5). Using point E, a line through point A (determined from the first user interface) is determined and this slope is the rate of crest diameter decrease. The intersection of this line with the line defining the crest diameter is the point where the crest diameter starts to decrease (Point F). Using these

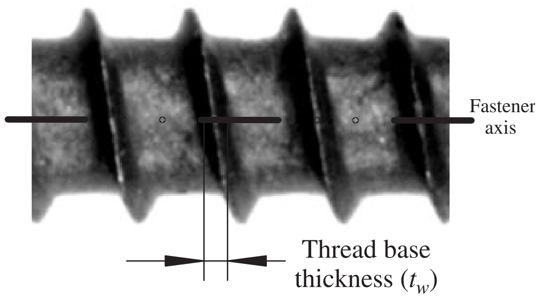

Fig. 4: The user draws line along fastener axis to measure thread base thickness

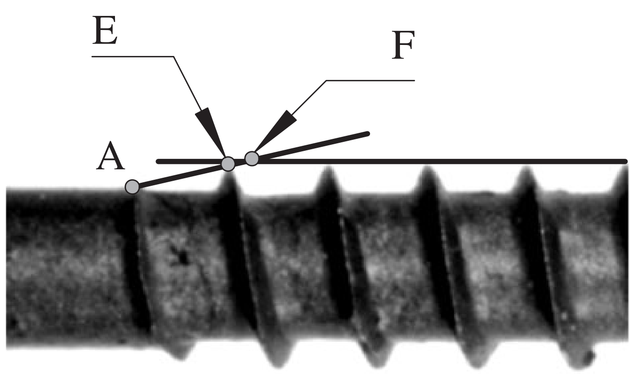

Fig. 5: By selecting the height of a thread in the region where the thread height varies but not the root diameter (Point E), a line is generated through point A. The intersection of this line with the height of the thread in the constant region determines Point F, the beginning of Region 1 in Fig. 1

four user interaction parameters, machine vision-detected parameters, and the analytical expressions,[6] the surface area of threaded fasteners may be determined.

EXAMPLE

To demonstrate the efficacy of the surface area algorithms, the surface area of a No. 10 (2.54 cm) wood screw was calculated. The parameters of the No.10 wood screw are specified by ASME,[8] and these parameters were used to generate a geometric model to test the algorithm (Fig. 6).

The surface area of this geometric model was then calculated numerically by sectioning the model into squares, taking the norm of the cross products of the vectors of each one of these squares, and summing the results over the entire mode.[6] Figure 7 shows the results of the numerical analysis along with the analytical solutions. As Fig. 7 shows, the numerical solution converges to the analytic solution as the number of grids increases, which validates the general analytical expression for surface area.

Fig. 6: Actual No. 10 wood screw and mathematical model

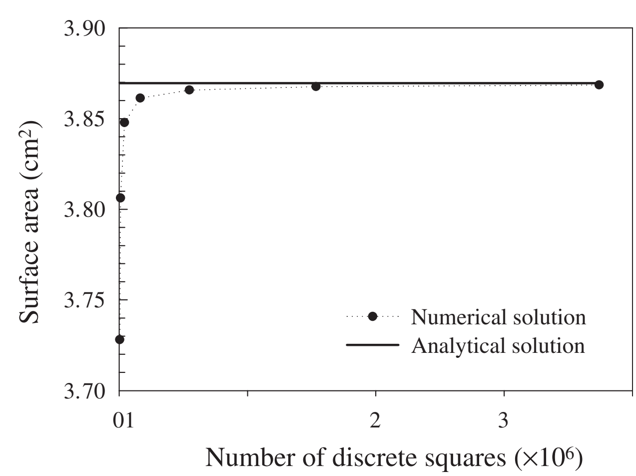

Fig. 7: Comparison of analytical and numerical surface area calculations for No. 10, 2.54-cm- (1-in.-) long wood screw

APPLICATION

Before this algorithm, fastener corrosion was reported in terms of a percent weight loss because it could be calculated without knowing the surface area. However, it is impossible to compare the percent weight loss between different size fasteners because in addition to mass loss, the corrosion rate depends on surface area and density of the specimen (Eq. 1).

Baker[9] conducted a corrosion test on 11 different types of fasteners exposed to CCA-treated wood for 17 years in two different environments, and reported his data as percent mass loss. These data represent a significant baseline upon which to compare new wood preservatives, but were limited because they were presented as percent mass loss. Using photographs from Baker's[9] laboratory notebook, we were able to use the current method to calculate surface areas for the fasteners tested, convert his data into corrosion rates, and establish a historical baseline for corrosion rate of metal fasteners in wood preservatives.[3]

SUMMARY

Quantifying the surface area of a threaded fastener is essential to properly calculating an accurate corrosion rate. The method proposed here determines the surface area by acquiring a digital image of the fasteners and applying specific algorithms to identify key features of the fasteners to extract appropriate dimensions that can be used in analytical expressions to determine the total surface area of a threaded fastener. This method was then validated by correctly calculating the surface area of a #10 wood screw. By applying this method to historic corrosion data, the true corrosion rates were calculated for comparison with other studies.[3]

References

1. Zelinka, S.L., and Rammer, D.R., *"Review of Test Method Used to Determine the Corrosion Rate of Metals in Contact with Treated Wood"*, General Technical Report, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, FPL-GTR-156 (2005).
2. Zelinka, S.L., Rammer, D.R., Stone, D.S., and Gilbertson, J.T., "Direct Current Testing to Measure Corrosiveness of Wood Preservatives," *Corrosion Science* **49:**1673–1685 (2007).
3. Zelinka, S.L., and Rammer, D.R., "Corrosion Rates of Fasteners Inserted into ACQ, ACA, and CCA Treated Wood Exposed to a 100% Relative Humidity Environment," *ASCE Journal of Materials in Civil Engineering* (Accepted for publication).
4. Zelinka, S.L., "Uncertainties in Corrosion Rate Measurements of Fasteners Exposed to Treated Wood at 100% Relative Humidity," *ASTM Journal of Testing and Evaluation* **35:**106–109 (2007).
5. Freeman, R.A., and Silverman, D.C., "Error Propagation in Coupon Immersion Tests," *Corrosion* **48:**463–466 (1992).
6. Rammer, D.R., and Zelinka, S.L., "Determination of the Surface Area of a Threaded Fastener," *ASTM Journal of Testing and Evaluation* **36:**80–88 (2008).
7. Zelinka, S.L. Rammer, D.R., and Stone, D.S., "Electrochemical Corrosion Testing of Fasteners in Wood Extract," *Corrosion Science* **50**(5):1251–1257 (2008).
8. ANSI/ASME. *Wood Screws (Inch Series), B18.6.1–1981*, American Society of Mechanical Engineering, New York, NY (1997).
9. Baker, A.J., "Corrosion of Nails in CCA- and ACA-Treated Wood in Two Environments," *Forest Products Journal* **42:**39–41 (1992). ■

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