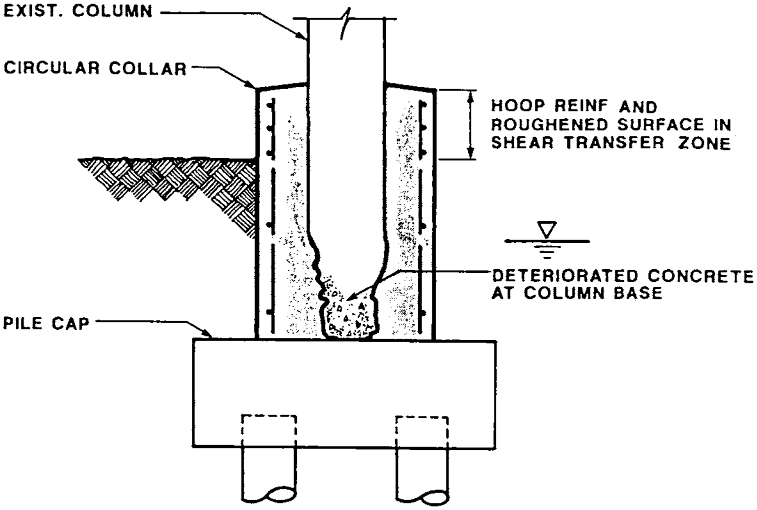

Fig. 9--"Shear" collar used to repair columns

SP 128-30

Improved Determination of the Locations and Sizes of Steel Rebars in Concrete

by S. Popovics and J. S. Popovics

Synopsis: According to the trade literature, the determinations of location, direction, and the cover thickness over a single steel bar in concrete are relatively easy and reliable from a magnetic measurement if the bar diameter is known. The estimation of the bar diameter is also possible if the cover thickness is known, although these results are less reliable. Only recent publications suggest double measurements from which both the cover thickness and the bar diameter can be estimated without previous knowledge of either of them. Unfortunately, the accuracy of diameter determination remains unimproved even with these methods.

In this paper an attempt is presented for the further improvement of the magnetic determination of bar characteristics. The basic idea is to combine a magnetic device with a computer that calculates, without any previous knowledge about the bar,

1. the thickness of the concrete cover above the bar; and
2. the diameter of the bar.

Preliminary data also indicate that distinction can be made whether the tested area is above a single bar or multiple bars, although this is not discussed in this paper.

Experimental data obtained on laboratory specimens illustrate the new method.

Keywords: Computers; cover; magnetic tests; nondestructive tests; reinforced concrete; reinforcing steels

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THE NEED FOR TESTING THE REINFORCEMENT

It is evident that the behavior of a reinforced concrete structure is determined by the material propereties of the selected steel and concrete, the geometry of the structure, as well as the location and size of the steel within the concrete. Therefore, in order to nondestructively assess an existing reinforced concrete structure, it is critical to determine the size, direction, location and depth of the reinforcing steel in a reliable manner.

The writers concluded, after a literature review, that although the location, orientation, and depth of the embedded steel bars can be estimated quite well with some of the present magnetic devices, these methods are not reliable enough for nondestructive in-place determination of steel rebar size. Therefore, there is an obvious need to develop a more accurate nondestructive method for such a purpose.

PROPERTIES OF STEEL REINFORCEMENT

Steel reinforcement in concrete may consist of bars, fibers, welded wire fabric, and prestressing wire. This paper deals only with steel reinforcing bars.

The sizes of bars in the U. S. are indicated by numbers. For sizes #3 through #8, they are based on the number of eighths of an inch included in the nominal diameter of the bar. Bars of designation #9 through #11 are round bars corresponding to the former 1 in. square, 1 1/8 in. (28.6 mm) square, and 1 1/4 in. (31.8 mm) square sizes. Bars designated #14 and #18 are round bars having a cross-sectional area equal to those of 1 1/2 in. (38.1 mm)and 2 in. (50.8 mm) square bars, respectively. The nominal diameter of a deformed bar is equivalent to the diameter of a plain bar having the same weight per foot as the deformed bar. (1)

Reinforcing steel may be of several types, or grades.(2) The magnetic properties of these may differ, for instance, the disturbance capacity increases usually with decreasing steel strength. This effect can be 5 percent for #5 and larger bars but it is usually negligible for smaller bars. Nevertheless, calibration of the equipment is recommended for a given steel when a magnetic device is used.

EXISTING TESTING EQUIPMENT AND METHOD

Since the determination of the location and size of steel bars embedded in concrete has been a frequently occuring problem in condition surveys of structures, several test methods have been offered for such measurements. The most reliable among these is X-ray image analysis. This method, however, is not used because it is not practical in the field; it is too complicated, expensive and hazardous.

The most widely used practical method is based on magnetism of the steel. Various magnetic devices have been commercially available both in the USA and abroad to estimate the location and/or diameter of a steel bar embedded in concrete.

Typically, a magnetic device is portable. Many of them measure the disturbance in the existing magnetic field caused by the presence of a ferrous metal, such as steel, in its vicinity. The magnitude of this disturbance is a function of both the mass of the steel and the distance from it. Such a device

- measures and shows on a dial or digitally or, preferably, in both ways, the amplitude of the perturbation field with or without indicating automatically the location of the maximum intensity;
- may print out the reading.

The usual measurement procedure is, as follows:

The Device is placed on the surface of the reinforced concrete element and moved as well rotated. The direction of motion of the Probe is perpendicular to the axis of the poles of the Probe.(3,4) The position of the Probe at maximum reading on the dial, or a signal, indicates the direction and location of the steel bar. From this reading

- the thickness of the concrete cover, that is, the depth of the reinforcing bar, can be estimated with the help of a preestablished calibration curve or scale, if the size of the bar is known; or
- the size of the bar can be estimated with the help of a calibration curve or scale, if its depth is known.

If neither the depth nor the size of the bar are known double measurement is recommended.(5,6) In our experiments the first measurement was performed while the Device rested on the surface of the concrete above the bar; this reading was used for the estimation of the bar depth. The second measurement was performed in the same bar position but the Device raised above the surface; this measurement was used for the estimation of the bar size. There is another procedure in the practice, the so-called spacer technique, that requires a series of calibration curves, and the dual measurement is used to find the bar size first, then the cover thickness is determined from the calibration curve for that bar. In any case, double measurements can provide both data sought but not with the needed accuracy. This is so because a first measurement is influenced both by the depth as well as by the size of the bar, and so is the second measurement. The generally used procedure, described above, cannot separate the two influences; thus, both estimated values are biased.

Two groups of measurements are used mostly at present for testing of hidden magnetic materials. One is based on electromagnetic measurements. These methods have been successfully used in geophysical applications where the measurement of a magnetically inducted current in a material can be interpreted to give information about subsurface geologic structures. This method has also been expanded to construction materials applications for the measurement of steel fiber content in concrete.(7) However, there is no evidence to indicate that this method has been used for steel rebar location and size determinations in concrete.

Another method is the measurement of the magnitude of the disturbance of the magnetic field caused by reinforcement with an appropriate meter. Since the magnetic device used in our experiments was based on this principle, a brief description of the method is in order.

MAGNETIC EQUIPMENT

The equipment used in our experiments is a commercially available cover meter that is a battery operated, portable unit, rugged and field-worthy. It consists of the meter with analog display in a carrying case along with a magnetic probe. The display gives the option of describing the magnetic disturbance in terms of depth of a bar with known diameter, or the diameter of a bar with known depth, or simply reading a linear output scale for a given measured disturbance of the magnetic firld. Also, the meter has a zeroing function. The equipment is also available with digital display.

In order to test the reliability of the equipment, two series of tests were conducted. In the first series, a disturbance measurement of a single sample, a #3 bar at a depth of 9/16" (14.3 mm), was performed 20 times in the same spot so that the meter was adjusted to zero after every reading. 17 of the 20 readings were 7.20, 3 were 7.25. This means a coefficient of variation of 0.26%. This process was repeated but the meter was not zeroed repeatedly. Here 16 readings were 7.30, 3 were 7.31, and 1 was 7.32 providing a coefficient of variation of 0.08%. In another repetition, the same sample was measured with the probe alternating 180^{o} of rotation each time. In each case the axis of the probe was parallel to the axis of the steel bar. No variation was found in meter readings with rotation. In the second series a different bar sample was used. Here the variability in readings along the length of the bar was measured; in other words, the effect of the end of the bar was measured. This test was done at two depths, 1.5 and 2.25 in (37.6 and 57.2 mm) depths. It was found that readings moving along the the axis approaching the end of the bar were very constant at both depths. This would seem to suggest that the length of the tested bar has little effect on the readings when the length of the bar is longer than the distance between pole faces.

Thus, it can be concluded that the test equipment and associated test method are reliable enough to give repeatable test results.

THEORY OF MAGNETIC FIELD

The magnetic field extends between the two pole faces of the Device, and is shaped like half of a doughnut. To a reasonable approximation, the intensity of the magnetic field is inversely proportional to the cube of the distance from the pole faces. Hence the amplitude of perturbation in the field is also inversely proportional to the cube of its distance from the pole faces. A further factor is that it is more difficult for a magnetic field to propagate in non-magnetic space than in magnetic material. Therefore, when magnetic material is placed in the field of the Probe, all of the lines of magnetic force, which can find a shorter distance from one pole face to the other by going through the rebar rather than going through non-magnetic space, will pass through the rebar. These disturbances can make the Probe pole faces highly directional. The consequence of this is that there is a sharp maximum when the long axis is parallel to the bar and/or when the Probe is directly above the rebar. Also, the magnitude of the maximum readings can be interpreted as either steel bar diameter at known depth, or steel depth with known diameter of a single bar.

APPLICATION IN GEOPHYSICS

Magnetic measurements have also been used succesfully in the past in geophysical applications. There, variations in the intensity of the Earth's magnetic field are interpreted to give approximations of the type, size, depth, and orientation of subsurface magnetic bodies such as ore deposits.(8) In particular, it is known that the vertical component of the Earth's magnetic field over an infinite subsurface horizontal cylinder varies according to the equation (9):

$$V = (6.25 \times 10^5)\ (R^2 I/Z^2)\ ((1-X^2/Z^2)/(1+X^2/Z^2)) \qquad 1)$$

where,

V = vertical component of the magnetic field, oe
R = radius of subsurface bar, cm
Z = depth of subsurface bar, cm
X = offset from centerline of subsurface rod, cm
I = intensity of magnetization, oe.

A typical lateral response of magnetic intensity based on the above equation is shown in Figure 1. If Eq. 1 is applicable, it is clear that the determination of the subsurface bar depth and diameter is a relatively straight-forward procedure once various magnetic field disturbance measurements have been taken. Therefore, it seems reasonable to approach the problem of nondestructive evaluation of reinforced concrete in the same manner, that is, with various repetitive measurements.

PROBLEMS OF THE EXISTING METHODS

The difficulty with the presently used devices and procedures is that they are not reliable enough. Single measurements can provide the approximate value of either the bar depth or the size, but only when the other is known with adequate accuracy. In practice, however, usually neither the depth nor the size of the bar are known. In such cases double measurements are performed at each bar location. Double measurements can provide both data sought but not with the needed accuracy, as was discussed earlier.

Another difficulty with the present methods is that they do not distinguish between single and multiple bar arrangements in many cases. In other words, the readings cannot always reveal adequately whether the Probe is above a single bar or two or more bars.

The new method presented below intends to eliminate, or at least reduce, the above difficulties. The essence of the new method is the use of multiple measurements performed in a systematic two-dimensional manner for each bar determination.

DEVELOPMENT OF THE SYSTEM OF MULTIPLE MEASUREMENTS

Initially, centerline meter readings for several different size bars at different depths were obtained in the following way:

The steel bar in question is secured in place by plywood blocks. A 1/2" (12.7 mm) thick plywood shim is placed over the bar; this is taken to represent a reinforced concrete element with 1/2" (12.7 mm) cover over the steel. Since the induced magnetic perturbance of most concretes are in the order of the perturbance of woods, this assumption is valid.(8) The axis of the probe is placed parallel directly over the bar but resting on the plywood shim. A centerline reading can now be taken using the linear scale on the instrument. This reading, as described above, can be interpreted as bar depth with known diameter, bar diameter with known depth, or just a scaled output. Once this centerline measurement was completed, a second 1/2" (12.7 mm) plywood shim was added and the measurements were repeated. This procedure was repeated for bar depths of 1/2", 1", 1 1/2", 2", 2 1/2", 3", 3 1/2", and 4" (12.7, 25.4, 38.1, 50.8, 63.5, 76.2, 88.9, and 101.6 mm).

An example for the results of these centerline measurements is shown in Figure 2 for known cover depths. This confirms that the depth of cover has a significant influence on the meter reading. Analysis of the data reveals that for depths of cover greater than 1 inch, the measurement values decrease roughly with the third power of the cover thickness. For depths of cover of 1 inch or less, however, the third order relation does not apply; a first order relation appears more appropriate. It can also be seen that there is not much sensitivity to bar diameter; the data for the bars of widely varying diameters are clumped together at each depth of cover. That is, it is very difficult to make reliable estimates of bar diameters based on center line readings. The results that were experimentally obtained can be compared with the "expected response" taken from the scale of the meter. This response, shown in Figure 3, is the readings based on manufacturer's tests of amplitude versus cover depth for known cover depths. It can be seen that although the expected response is more uniform and less "clumped," the meter cannot make confident estimates of bar diameter based on centerline reading alone, particularly for bars of larger diameter, even when the cover depth is known.

Because of the apparent insensitivity of centerline measurements to bar diameter, offset readings were included in the analysis in two dimensions, as follows:

Keeping the 1/2" (12.7 mm) depth of the bar constant and the probe parallel to the longitudinal axis of the bar, five offset readings were taken on each side of the bar at 1/2" (12.7 mm) spacings to improve the reliability of the measurements. Once the 10 offset measurements and the centerline measurements were completed, a second 1/2" (12.7 mm) plywood shim was added and the measurements are repeated at a new apparent depth. This procedure was repeated for bar depths of 1/2", 1", 1 1/2", 2", 2 1/2", 3", 3 1/2", and 4" (12.7, 25.4, 38.1, 50.8, 63.5, 76.2, 88.9, and 101.6 mm). With all of the readings, the lateral response of a bar could be plotted at various depths of cover. A typical lateral response is shown in Figure 4. The center line meter reading (R max) is at 0 inch offset. If the theoretical formula used in geophysical prospecting, that is (Eq. 1), is compared with the experimentally obtained lateral response in Figure 4, we can see that the measured response is much less peaked. Therefore, it seems that Eq. 1 is not suitable for our purposes. Figure 5 shows the obtained lateral response for rebars with different diameters at the same depth. It can be seen that the offset measurements are able to distinguish between bar sizes better than those taken directly over the axis of the bar.

It is clear that the shapes of the curves representing the lateral responses for specific bars change as depth of cover and/or bar diameter change. For instance, the peakedness of the response decreases as depth of cover increases for all specimens. Mathematical characteristics of these changes were used for the development of formulas for the estimation of concrete cover and bar diameter from the results of these offset measurements. The specific formulas are not presented here because it is likely that these would not be valid for another magnetic probe of a different brand. It may be noted, however, that (a) the correlation coefficient associated with our formula for the concrete cover estimation from lateral measurements is 0.978 with a standard error of 0.174 in. (4.42 mm); and (b) the correlation coefficient associated with the bar size estimation is 0.941 with a standard error of 0.06 in. (1.52 mm). There is every reason to believe that similar good approximation can be achieved with formulas developed for other magnetic probes.

Although the approximations of our formulas are quite good, better than those of the existing methods, further improvement in the estimations can be achieved by a combination of the two formulas into an algorithm. The formulas as well as the algorithm could be used without a computer but this would be cumbersome and time consuming. Therefore, computerization, that is a combination of the Device with a small computer, is desirable both for the collection and storage of the intensity data as well as for the calculations.

Computerization would make the performance of the new method as quick and simple to use as the presently available methods.

The above procedure is considered only as a first step in the development of a reliable method for steel reinforcing bar size and depth determination. Refinements in the method should be made resulting from further research. Such refinements could be:

- development of more accurate predictive equations for concrete cover and, especially, for bar size, based on repeated magnetic measurements;
- establishment of a method that can be used for the whole practical range of depth of cover;
- simplification of the measurement procedure;
- development of a procedure for cases where steel bars are placed closely together;
- utilization of supplementary nondestructive techniques.

CONCLUSIONS

The concept of a new procedure is presented for the improved determination of bar locations and diameters from multiple magnetic measurements in two dimensions without any previous knowledge about the structure. This new procedure is comprised of the following elements:

- a suitable magnetic device;
- multiple measurements in two dimensions;
- special formulas organized into an algorithm for the improved calculation of the bar locations and diameters;
- a small computer that records and stores the obtained data and makes the use of the algorithm.

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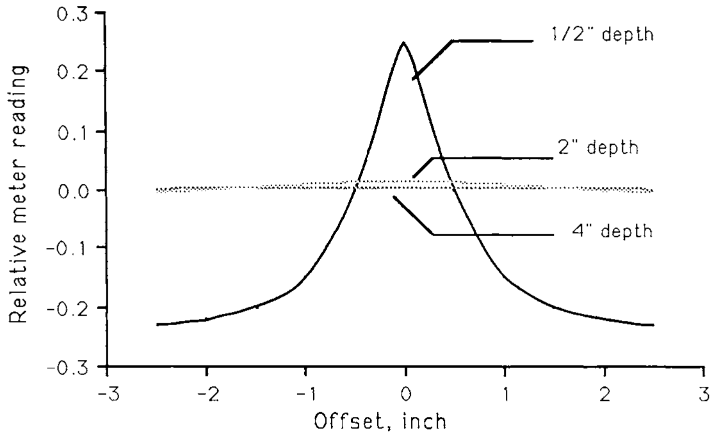

Fig. 1--Theoretical lateral response of the vertical component of the magnetic field according to Eq. 1