

A simplified test method to estimate the relative rib area of rebar

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ABSTRACT:

An alternative formula to the current standard is proposed for the calculation of the relative rib area of concrete reinforcing bar (rebar). The relative rib area is an important geometrical feature of rebar, as it facilitates distributed load transfer between concrete and reinforcement. The proposed formula and concomitant method are mathematically simple and easily implemented in practice. The proposed formula is based on the proposition that the projected outline of both the ribbed and un-ribbed rebar can be accurately approximated by elliptical curves, such that the net projected area of the ribs only is calculated as the difference between the areas of the two ellipses thus constructed. In contrast, the standard formula assumes a quadratic relationship between the rib height and the un-ribbed bar surface. Three available rebar specimens are evaluated against both formulae. The specimens are geometrically measured in three dimensions by a laser scanning system, the data of which are projected onto the plane perpendicular to the longitudinal axis of the rebar, and numerically integrated to calculate the actual projected area of the ribs. The standard formula accurately estimates the projected rib area in one out of three cases, while it overestimates (thus being nonconservative) for the balance. The proposed formula accurately estimates the projected area in two out of three cases, while it underestimates (thus being conservative) for the balance.

Nomenclature

Roman

- a_m Rib height at the rib mid-point [m]
 A_r Projected rib area [m²]
 c Longitudinal rib spacing [m]
 d Rebar nominal diameter [m]
 d_e Rebar "diameter" across rib peaks [m]
 d_i Rebar "diameter" across rib valleys [m]
 e Average gap between adjacent rib rows [m]
 f_R Relative rib area [-]
 x Horizontal distance from rebar cross-section centre point [m]
 y Vertical distance from rebar cross-section centre point [m]

Subscripts

- e External
 i Internal
 m Middle

1. INTRODUCTION

An alternative simplified formula is proposed for the calculation of the relative rib area of concrete reinforcing bar (rebar). The proposed formula yields test results that are superior to the existing simplified parabola formula that is listed in the testing standard ISO 15630-1 ^[1] and is easy to implement in a laboratory test method.

The proposed formula is based on the proposition that the projected outline of both the ribbed and un-ribbed rebar can be accurately approximated by elliptical curves, such that the net projected area of the ribs only is calculated as the difference between the areas of the two ellipses thus constructed. The plane of the projection is perpendicular to the longitudinal axis of the rebar specimen.

The proposed formula (and method) requires only two types of measurement by means of a dial-, vernier- or digital callipers. The distance from peak-to-peak of two opposing ribs on opposite sides of the rebar is measured (d_e), as well as the distance from valley-to-valley (d_i). Measurements are taken at a few locations, say five, along the length of a rebar specimen, the values of which are subsequently averaged.

Let d represent the nominal diameter of the rebar. Typically, the rib peak-to-peak distance is larger than the nominal diameter ($d_e > d$), while the rib valley-to-valley measurement is less than the nominal diameter ($d_i < d$). The value of d_e therefore represents the major axis of the ellipse whose minor axis is d , while d_i represents the minor axis of the ellipse whose major axis is d . This arrangement is graphically displayed in Figure 1 but take care that the nominal diameter (d) is not a measurable quantity as implied in the drawing, but instead a nominal quantity.

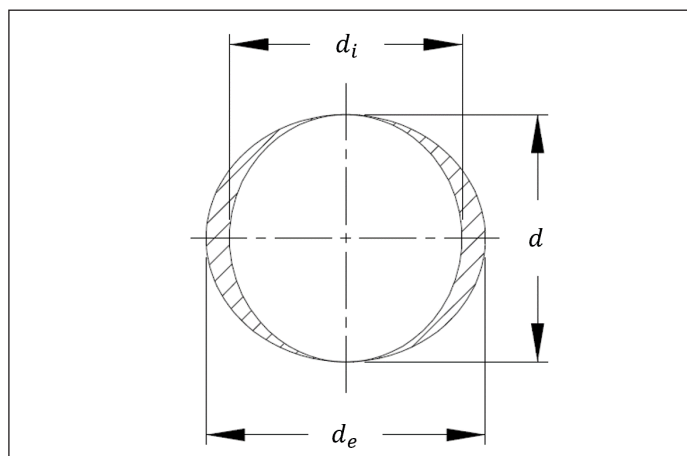


Figure 1: Rebar transverse cross section

The projected rib area, which is required to calculate the relative rib area, is identified by the cross-hatched region in Figure 1.

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2. BACKGROUND

Concrete is the predominant material used in construction today due to its many advantages such as economical cost, on-site fabricability and durability [2]. World production of Portland cement reached 4.4 billion metric tons in 2021 (statista.com). Typical engineering properties of structural concrete are listed in Table 1.

Table 1: Engineering properties of structural concrete [2]

Compressive strength	35 [MPa]
Flexural strength	6 [MPa]
Tensile strength	3 [MPa]
Modulus of elasticity	28 [GPa]
Poisson's ratio	0.18
Tensile strain at failure	0.001
Coefficient of thermal expansion	10×10^{-6} [1/°C]

Because the low flexural and tensile strength of concrete limit its application in construction severely, the practice of reinforcement of concrete with steel has developed over the course of history. A French engineer named Francois Hennebique reportedly reinforced concrete floor slabs in 1879, and progressed to a complete building system, which was patented in 1892 [3]. Not only is the tensile strength of steel high, but an important advantage of steel is that its coefficient of thermal expansion is very nearly equal to that of concrete. The typical requirement for the minimum yield strength of reinforcing steel bar is 500 [MPa] [4].

Although many materials could conceivably be utilised as reinforcement in concrete, steel is widely used today. Of the 1.95 billion metric tons of steel produced in 2021 (worldsteel.org), 52% were used in buildings and infrastructure, of which 44% was rebar. This means that about 23% of steel production (that is 446 million metric tons) ends up as rebar.

Steel reinforced concrete is a composite building material. The systematic or structured composition of steel and concrete allows for the preferential utilisation of steel – with its superior tensile properties – in regions where the concrete alone would not be able to withstand the tensile stresses caused by the loading of the overall structure, while the balance of the structure consists of concrete only. Since the steel reinforcing is embedded in the concrete, there is physical interaction between the steel and concrete as internal loads are transferred between the two types of materials. The ability to transfer such loads may be described as the bond strength between the rebar and the concrete, which is defined as the maximum measured load in a tensile bond test of a steel reinforcing bar [5]. In order to improve the bonding performance between the steel and the concrete, transverse ribs were introduced to the surfaces of rebar with a view to cause mechanical interlocking between steel and concrete. In this regard, several patents were filed with the United States patent office since the early twentieth century, a few of which are highlighted below.

J. M. Dudley filed a patent application in 1907 [6] which described the object of his invention “to produce a reinforcing bar which shall, as a whole, possess the maximum strength for its weight in metal and which shall be so designed that it may be readily and cheaply rolled into the desired conformation which will be such as to form a rigid mechanical bond with the material in which it is embedded.” A drawing of the proposed bar is displayed below in Figure 2.

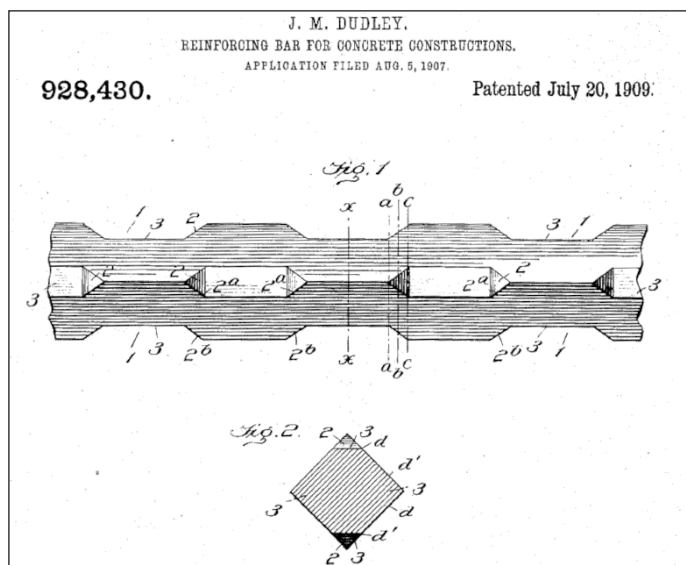


Figure 2: 1909 reinforcing bar patent [6]

W. P. Witherow filed a patent application in 1916 [7] which describes one object of his invention “to provide a reinforcing bar which has on the surface of a regularly formed central body projections which form a mechanical bond with the concrete in which the bar is embedded, thereby decreasing the likelihood of relative movement between the bar and concrete and increasing the strength of the structure.” Drawings of the proposed bar are displayed in Figure 3.

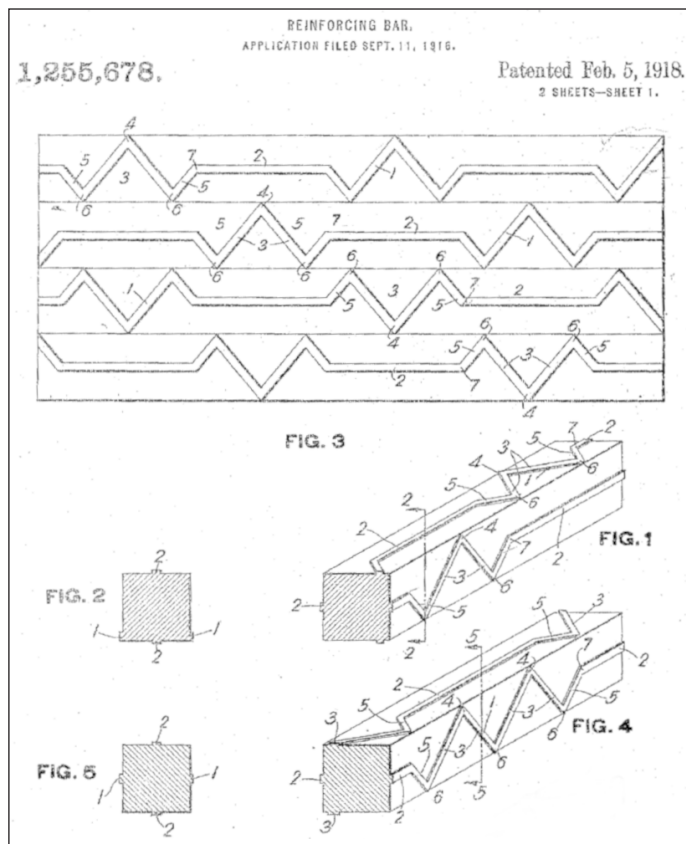


Figure 3: 1918 reinforcing bar patent [7]

V. M. Surerus filed a patent application in 1944 [8] which describes his invention of reinforcing bar “of such form that it may be produced very economically and present very high bond value.” The application also stated that “Another object is to provide a reinforcing bar of such form

that any tendency to rotation of the bar in either direction by the forces exerted against it under load will be counteracted." Some of the patent drawings are displayed in Figure 4.

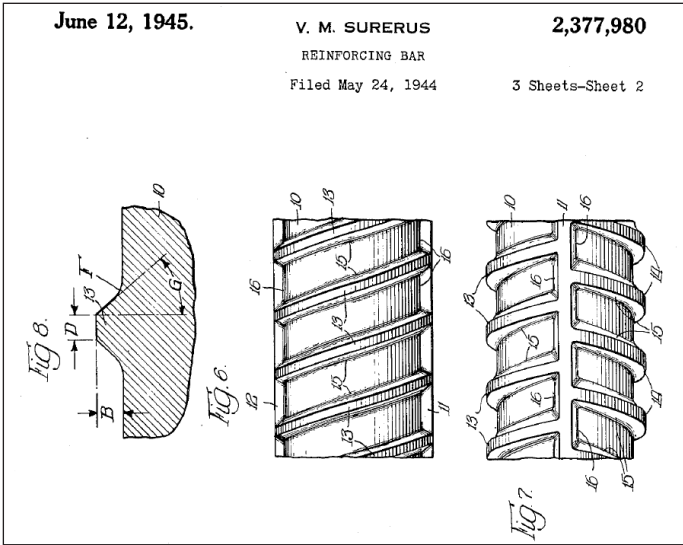


Figure 4: 1945 rebar patent [8]

This invention strongly resembles the geometry of typical rebar encountered today. The development of ribs on rebar led to the need to define and specify surface geometry requirements for rebar, such as the relative rib area. Metelli and Plizzari [9] reported that they reviewed various previous studies, all of which showed that the main rib parameter influencing bond strength and stiffness is the relative rib area (f_R), also referred to as the bond index. So instead of conducting bond strength tests, which require casting of rebar specimens in concrete sections, simple tensile tests in combination with the assessment of the surface geometry of the rebar, are an acceptable proxy.

The relative rib area is the ratio of projected rib area (perpendicular to the axis of the rebar) to the outside surface area between consecutive ribs of a particular specimen of rebar on a nominal basis. The numerator of the fraction is the projected rib area in units of length squared [L²], while the denominator is the outside surface area of the rebar (calculated for the nominal diameter) between consecutive ribs, also with units of length squared [L²]. The longitudinal distance between consecutive ribs is called the rib spacing.

Determination of the numerator, which is the projected rib area, is really the most difficult part of evaluating the relative rib area of a rebar specimen, and our attention is focused on this characteristic.

3. PROJECTED RIB AREA

3.1 Testing standard

The international testing standard ISO 15630-1 [1] states in its paragraph 11.3 that the relative rib area is defined by the following formula (which we have simplified here by assuming only a single type of rib per row, as well as two identical rows per rebar on either side):

$$f_R = \frac{2}{\pi d} \frac{F_R \sin \beta}{c} \quad (4)$$

where (with reference to Figure 5 below):

F_R is the area of the longitudinal section of one rib,

calculated as $F_R = \sum_{i=1}^p (a_{s,i} \Delta l)$;

β is the angle of inclination of the ribs;

d is the nominal diameter of the rebar;

c is the longitudinal rib spacing or pitch.

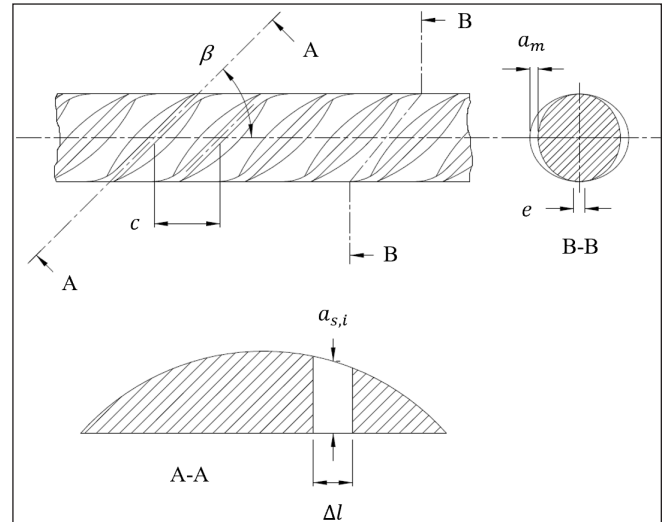


Figure 5: Rebar rib layout definitions as per [1]

A few additional symbols are defined in Figure 5, namely:

e is the circumferential distance between adjacent rib rows, the value of which is employed to account for those areas on the rebar (outside of rib rows) where ribs are not present;

$a_{s,i}$ is the average height of a portion (i) of a rib which is subdivided into (p) parts of equal length Δl .

Application of Eq. (1) in practice appears to be nearly impossible, even though the standard goes so far as to state it as a definition of the relative rib area. The standard, however, allows for the utilisation of so-called simplified formulae, which follows below.

a.) Trapezium formula:

$$f_R = (a_{1/4} + a_m + a_{3/4}) (\pi d - \Sigma e_i) \frac{1}{4\pi d c} \quad (2)$$

b.) Simpson's Rule formula:

$$f_R = (2a_{1/4} + a_m + 2a_{3/4}) (\pi d - \Sigma e_i) \frac{1}{6\pi d c} \quad (3)$$

c.) Parabola formula:

$$f_R = \frac{2a_m}{3\pi d c} (\pi d - \Sigma e_i) \quad (4)$$

The values of $a_{1/4}$, a_m , and $a_{3/4}$ are the measured rib height at the quarter-point, mid-point, and three-quarters point along the length of the rib. These quantities are utilised by the first two formulas listed above.

The third simplified formula, the parabola equation defined in Eq. (4), requires only two quantities to be measured and appears to present the simplest method for practical implementation.

3.1.1 Parabola approximation to rib height

The parabola formula assumes that the rib height, as a function of distance along the circumference of the rebar, can be approximated by a second order curve. This notion is visually displayed in Figure 6.

Due to assumed symmetry, only one quarter of the geometry needs to be solved, and subsequently multiplied by four (two rib rows with two symmetrical half-ribs per row). If we denote the distance along the circumference by the symbol s , and the rib height as $y(s)$, then we need to solve for the coefficient b in the general equation for a parabola

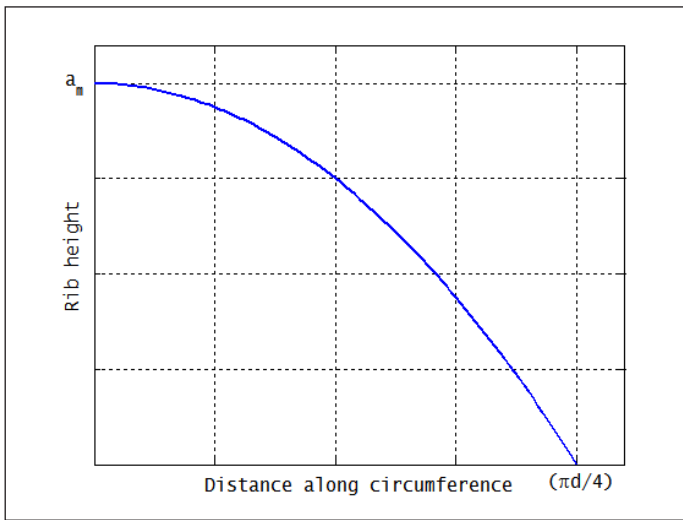


Figure 6: Parabolic shape of rib height

(where the intersect with the vertical axis, that is a_m , has already been substituted):

$$y(s) = -b \cdot s^2 + a_m \quad (5)$$

That is easily done by substituting the value of zero rib height at $s = (\pi d)/4$, that is $y((\pi d)/4) = 0$, into Eq.(5)

$$0 = -b \cdot \left(\frac{\pi d}{4}\right)^2 + a_m \quad (6)$$

$$\therefore b = a_m \left(\frac{4}{\pi d}\right)^2$$

Substitution back into Eq.(5) yields

$$y = -a_m \left(\frac{4}{\pi d}\right)^2 \cdot s^2 + a_m \quad (7)$$

If we now denote the total projected rib area by A_R , this enables one to calculate for this quantity by integrating along the length of the circumferential curve of the quarter-rib, as follows:

$$\frac{1}{4} A_R = \int_0^{\frac{\pi d}{4}} a_m \left(1 - \left(\frac{4}{\pi d}\right)^2 \cdot s^2\right) ds$$

$$\therefore A_R = 4a_m \left(s - \frac{1}{3} \left(\frac{4}{\pi d}\right)^2 s^3\right) \Big|_0^{\frac{\pi d}{4}} \quad (8)$$

$$= 4a_m \left(\frac{\pi d}{4} - \frac{1}{3} \left(\frac{4}{\pi d}\right)^2 \left(\frac{\pi d}{4}\right)^3\right)$$

$$= 4a_m \left(\frac{\pi d}{4} - \frac{1}{3} \frac{\pi d}{4}\right)$$

$$= 4a_m \frac{\pi d}{4} \left(1 - \frac{1}{3}\right)$$

$$= \frac{2}{3} a_m (\pi d)$$

The end-result is identical with Eq. (4) if we divide by the factor $(\pi d c)$ to obtain the relative rib area (and also, for the moment, neglecting for the circumferential distance between adjacent rib rows, e , which has a negligible effect).

The parabolic approximation is next compared against the proposed elliptical approximation.

3.2 Elliptical approximation

With the proposed elliptical approximation, the rib height is not explicitly assumed to follow a particular curve (although it is elliptical); instead, the projected rib area is directly approximated as the difference between two primary surface areas, both of which are assumed to resemble an elliptical shape in the projected plane.

The larger ellipse is the projected area of the rebar (ribs and all), while the smaller ellipse is the projected area of the same rebar excluding the ribs. The rib height can subsequently be calculated, with a typical result shown in Figure 7.

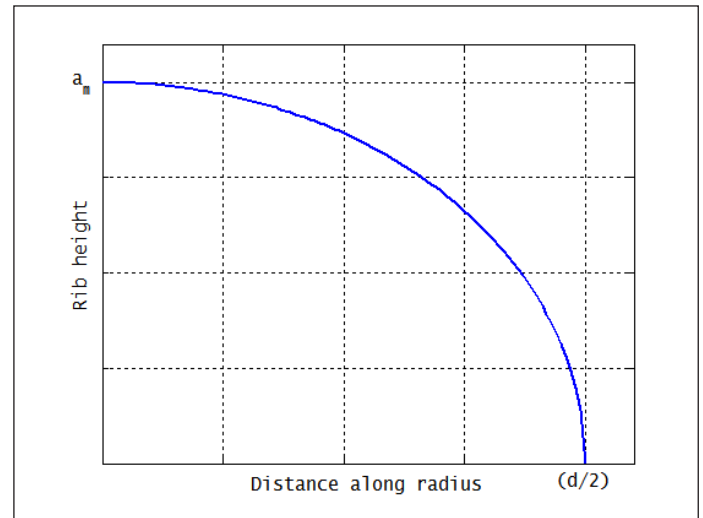


Figure 7: Elliptical depiction of rib height

It is important to note that the rib height is plotted against radius, and not circumference as in the case of the parabolic approximation. The equation for projected rib area is simply the difference between the outer and inner ellipses, as follows:

$$A_R = A_e - A_i$$

where

$$A_e = \pi \left(\frac{d_e}{2}\right) \left(\frac{d}{2}\right) = \frac{1}{4} \pi d d_e \quad (9)$$

$$A_i = \pi \left(\frac{d}{2}\right) \left(\frac{d_i}{2}\right) = \frac{1}{4} \pi d d_i$$

The projected areas of the outer and inner ellipses are calculated from the quantities defined in Figure 1, which is expanded below in Figure 8 for easy reference.

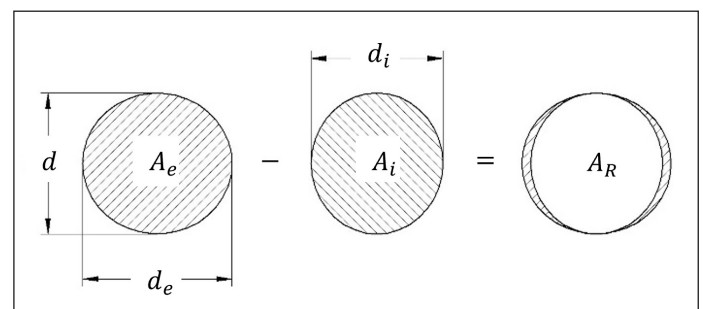


Figure 8: Schematic calculation of rebar projected rib area

The elliptical formula for the projected rib area is further developed below.

$$\begin{aligned}
 A_R &= (1/4) \pi d d_e - (1/4) \pi d d_i \\
 &= (1/4) \pi d (d_e - d_i) \\
 &= (1/4) \pi d (2a_m) \\
 &= \frac{1}{2} a_m (\pi d)
 \end{aligned}
 \tag{10}$$

The rib height at rib mid-point is taken as half the difference between the quantities d_e and d_i , that is $a_m = 1/2(d_e - d_i)$.

The result of Eq. (10) is substantially less than the result obtained in Eq. (8), that is $A_R = 2/3 a_m (\pi d)$. In fact, should Eq. (8) be nearly correct, then Eq. (10) underestimates the projected rib area by a quarter (25%); conversely, should Eq. (10) be nearly correct, then Eq. (8) overestimates the projected rib area by a third (33%).

The picture in Figure 9 provides a visual comparison between the two approximation schemes for rebar of nominal diameter 32 [mm]. The difference in areas is quite prominent, where one witnesses the additional rib area attributed by the parabola formula towards the edge of the rib. It is worth noting that this fact could not reasonably be gleaned from the depictions in Figure 6 and Figure 7, which in fact creates quite the opposite visual impression.

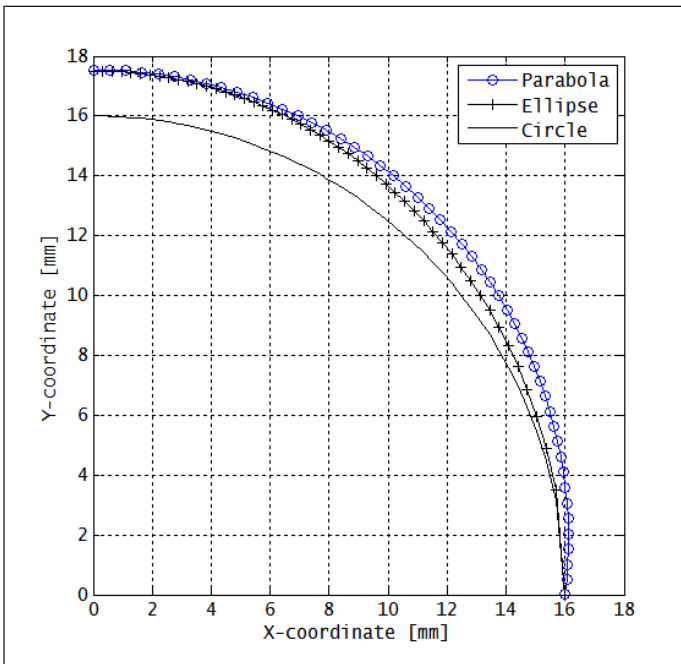


Figure 9: Comparison between parabola and ellipse formulae

The prediction performances of the two approximation schemes are now evaluated against geometric data of actual rebar specimens (as obtained from a three-dimensional scanning system) below.

3.3 Actual test specimens

Rebar test specimens of nominal diameter 32 [mm], from three different manufacturers, are available for evaluation. Photographs of the specimens appear in Figure 10.

The important measurements, as defined in Figure 1, Figure 5 and Figure 8 are taken from the specimens by a calibrated digital calliper and listed in Table 2.

The corresponding calculations for the projected rib area, as per Eq. (8) and Eq. (10), are listed in Table 3.



Figure 10: Photographs of rebar specimens

Table 2: Measurements taken from rebar specimens

Specimen	d_e	d_i	c
1	35.20	31.77	15.4
2	34.75	30.06	20.9
3	35.50	30.50	23.6

Table 3: Projected rib area calculations for rebar specimens

Specimen	Rib height a_m [mm]	A_R [mm ²]	
		Parabolic $2/3 a_m (\pi d)$	Elliptical $1/2 a_m (\pi d)$
1	1.72	114.9	86.2
2	2.35	157.2	117.9
3	2.50	167.6	125.7

The large differences in values between the parabolic and elliptical estimates are compared against the results from three-dimensional laser scanning of the rebar specimens.

3.4 3D laser scanning of rebar geometry

The rebar specimens are geometrically scanned with the aid of a three-dimensional metrology system (MetraScan750 optical elite CMM system; scanning software: Vxmodel and Vinspect; design software: Inventor 2020). The resultant CAD models of the specimens are displayed in Figure 11.

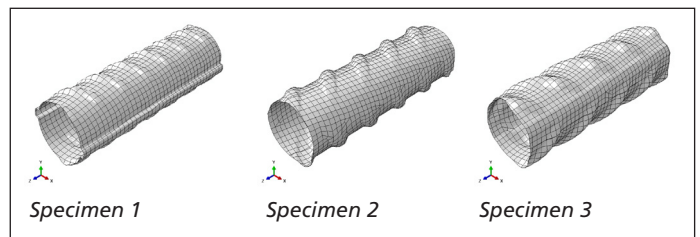


Figure 11: Three-dimensional CAD models of rebar specimens

The coordinates of the CAD models are processed and numerically integrated across their cross-sections (that is in the X-Y plane, with reference to Figure 11) to obtain a value for the projected rib area.

3.4.1 Rebar Specimen 1

Every recorded three-dimensional coordinate of the outside surface of Specimen 1 is plotted in the X-Y plane, the cloud of which is displayed in Figure 12. The regions of highest density of course represent more points, such as the un-ribbed outer surface of the rebar.

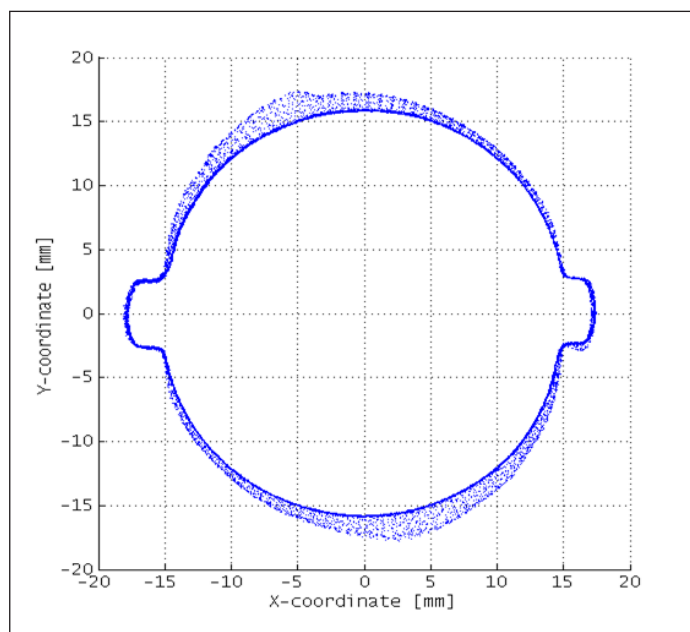


Figure 12: Specimen 1 projected coordinate cloud

The two approximations under consideration, namely the parabola and ellipse formulae, are subsequently superimposed onto the scanned data. The result can be visually assessed in Figure 13.

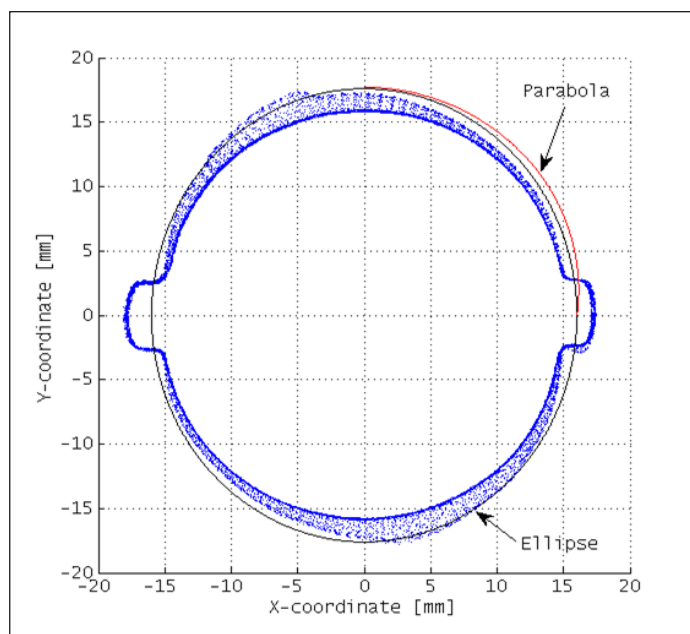


Figure 13: Specimen 1 coordinate cloud with parabola and ellipse curves superimposed

The projected rib area is calculated by numerically integrating over the region of interest. The X-dimension is discretised into many small lengths of equal size so that the surface area of the resultant rectangle is easily calculated as width multiplied by height. The total projected area is then the sum of the many individual rectangles as one progresses from, say, left to right across the X-axis. The calculated areas for reducing step sizes are reported in Table 4.

Table 4: Specimen 1 numerically integrated rib projected area

Step size [mm]	Top half A_{R1}	Bottom half A_{R2}	Total projected area $A_R = A_{R1} + A_{R2}$
1.000	69.1	69.7	138.7
0.500	56.6	56.8	113.4
0.250	49.9	49.4	99.4
0.125	44.4	44.6	89.0
0.0625	38.7	38.4	77.1

The results in Table 4 are plotted in Figure 14. It is noted that the step size cannot be arbitrarily reduced with a view to improve the accuracy of the integration result, as we are not working with a continuous function. Because of a lack of sufficient resolution in data points, one soon finds "empty" zones where no data points exist as the step size is reduced, resulting in an erroneous calculation of zero surface area for that particular step in distance. The values of 89.0 and 77.1 [mm²] for step sizes 0.125 and 0.0625 [mm], respectively, appear to worsen the result instead of improving it.

Since one expects convergence of the finite sum (integration), it is proposed that a least-squares line is fitted through the data points of the first three steps (that is, step sizes equal to 1.0, 0.5, and 0.25 [mm]) as shown in Figure 14. The function value where the x-value equals zero, which is equivalent to an integration step size of zero, is then taken as the best estimate of the projected rib area. For Specimen 1, this value equals 86.8 [mm²].

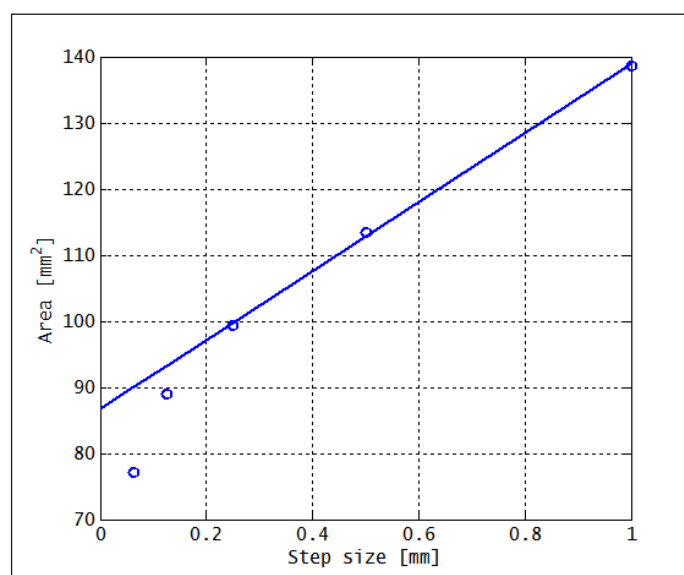


Figure 14: Specimen 1 convergence of numerically integrated rib projected area

3.4.2 Rebar Specimen 2

The three-dimensional coordinates of Specimen 2 are plotted in the X-Y plane displayed in Figure 15 overleaf. The calculated projected area for the various step sizes are reported in Table 5 overleaf.

The results in Table 5 are reproduced in graphical format in Figure 16. Once again, the least-squares line is fitted through the data of the three largest steps, and the best estimate for the projected area taken as the function value of the straight line where the x-value equals zero (equivalent to a step size of zero). This value is 120.2 [mm²].

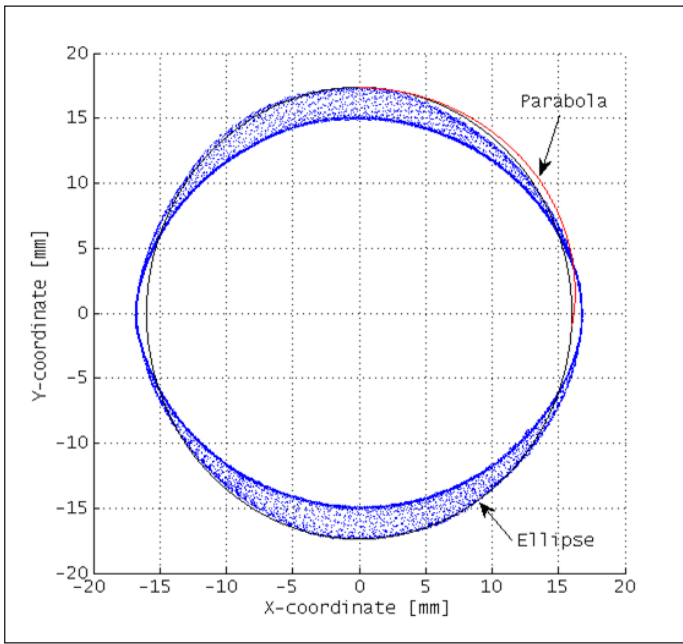


Figure 15: Specimen 2 coordinate cloud with parabola and ellipse curves superimposed

Table 5: Specimen 2 numerically integrated rib projected area

Step size [mm]	Top half A_{R1}	Bottom half A_{R2}	Total projected area $A_R = A_{R1} + A_{R2}$
1.000	82.9	85.1	168.0
0.500	71.1	73.2	144.3
0.250	64.9	67.0	132.0
0.125	61.5	63.5	125.0
0.0625	55.5	59.1	114.5

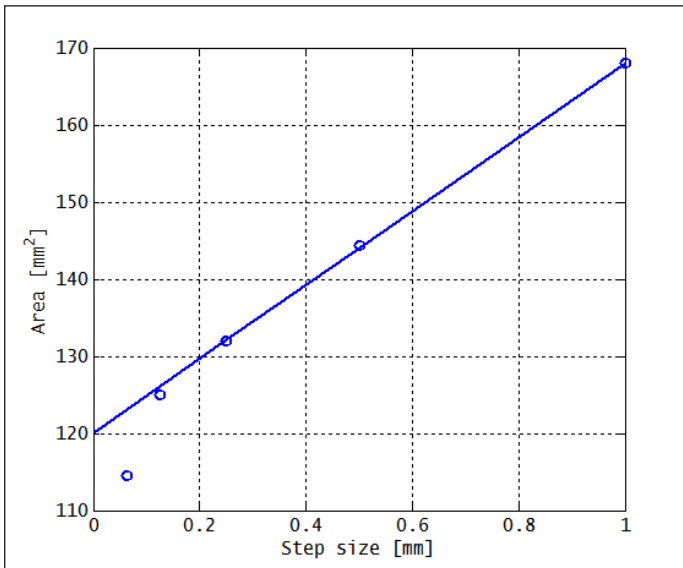


Figure 16: Specimen 2 convergence of numerically integrated rib projected area

3.4.3 Rebar Specimen 3

The three-dimensional coordinates of Specimen 3 are plotted in the X-Y plane displayed in Figure 17.

The calculated projected area for the various step sizes are reported in Table 6.

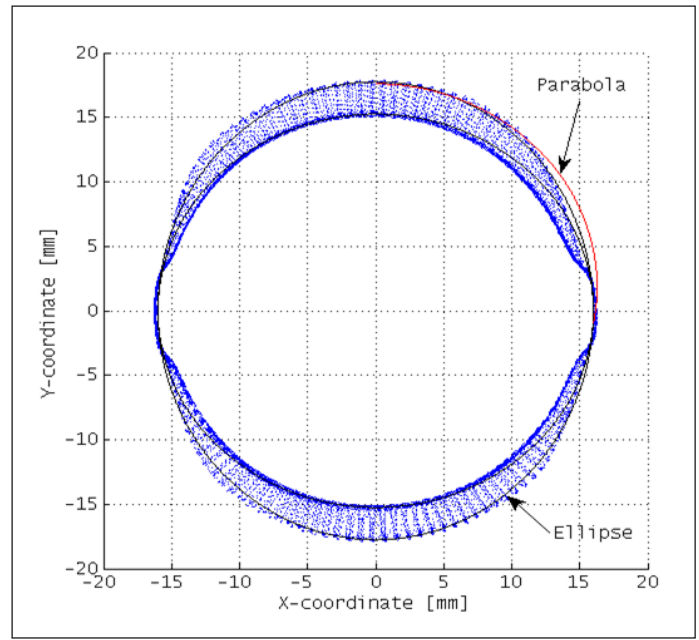


Figure 17: Specimen 3 coordinate cloud with parabola and ellipse curves superimposed

Table 6: Specimen 3 numerically integrated rib projected area

Step size [mm]	Top half A_{R1}	Bottom half A_{R2}	Total projected area $A_R = A_{R1} + A_{R2}$
1.000	115.9	113.0	228.9
0.500	102.6	99.6	202.2
0.250	94.8	91.8	186.6
0.125	90.3	85.7	176.0
0.0625	83.8	77.4	161.2

The results in Table 6 are reproduced in graphical format in Figure 18. Once again, the least-squares line is fitted through the data of the three largest step sizes, and the best estimate for the projected area taken as the function value of the straight line where the x-value equals zero (equivalent to a step size of zero). This value is 173.2 [mm²].

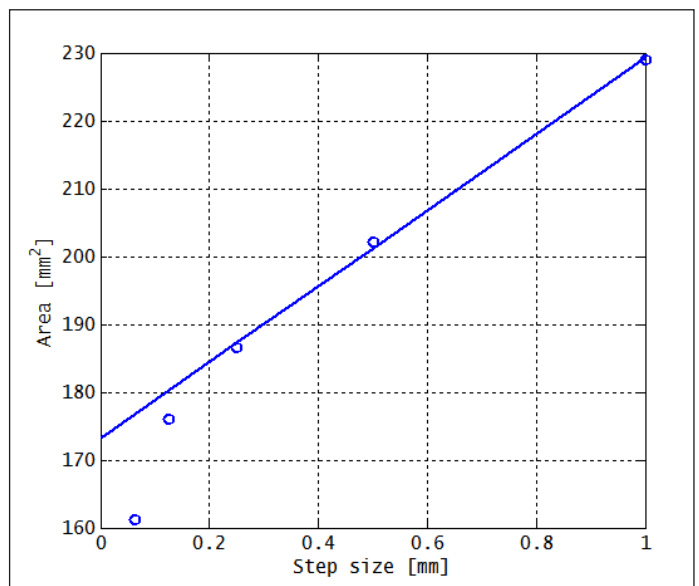


Figure 18: Specimen 3 convergence of numerically integrated rib projected area

3.5 Summary of geometric evaluation

The results of the preceding sections are summarised below in Table 7.

Table 7: Updated projected area calculations for rebar specimens

Specimen	Rib height a_m [mm]	A_R [mm ²]		
		Parabola $2/3 a_m (\pi d)$	Elliptical $1/2 a_m (\pi d)$	Numerical integration CAD model
1	1.72	114.9	86.2	86.8
2	2.35	157.2	117.9	120.2
3	2.50	167.6	125.7	173.2

4. RELATIVE RIB AREA

4.1 Minimum requirement

Progression from the projected rib area towards the relative rib area is trivial. The projected rib area is simply divided by the rebar outside surface area (calculated for the nominal diameter) between consecutive ribs. The denominator is therefore equal to the value of πdc .

The values thus obtained for relative rib area are compared against the minimum requirements specified in the applicable standard^[4], which are reproduced in Table 8. Since the specimens under consideration have a nominal diameter of 32 [mm], the value of interest to us is of course $f_R \geq 0.056$.

Table 8: Characteristic relative rib area

Nominal rebar size, d [mm]	Relative rib area, f_R
$d \leq 6$	0.035
$6 < d \leq 12$	0.040
$d > 12$	0.056

4.2 Final comparison

The calculated values for the relative rib area of the three rebar specimens under evaluation are listed for the two simplified formulae, as well as for the numerically integrated model data.

Table 9: Relative rib area calculations for rebar specimens

Specimen	$f_R = A_R / (\pi dc)$		
	Parabola	Elliptical	Numerical integration
1	0.074	0.056	0.056
2	0.075	0.056	0.057
3	0.071	0.053	0.073



JOHANNES JORDAAN is a mechanical engineer that enjoys numerical modelling of dynamic systems, especially those where an optimization algorithm (aka artificial intelligence) is integral to the reliable performance of the system. At present, his focus is finite element analysis of mechanical systems, and the value-add that can be inferred by its close interaction with mechanical testing.

CONCLUSION

A new test method that can be employed to evaluate the relative rib area of rebar is described and demonstrated on three rebar specimens.

The primary objective of the proposed method is to offer a simplified alternative to the current standard formulae. The test results show that the proposed elliptical formula yields values that are approximately equal to those obtained by numerical integration of the geometric data of the specimens in two of the three specimens, while it underestimates the relative rib area in one case, thus being too conservative in its estimation.

A secondary objective of the work is to assess the accuracy and suitability of the parabola formula, which is one of the simplified options available in the testing standard. In this regard, the test results show that the parabola formula yields values for the relative rib area of the specimens that are significantly higher than the same values obtained by numerical integration of the geometric data of the specimens, thus being too liberal or nonconservative in its estimation for two of the three specimens. The parabola formula gives an accurate estimation in one case, Specimen 3, for which the ribs exhibit prominent height away from the centre of the ribs.

A third and final objective of the work is to demonstrate the utilisation of modern technology such as laser scanning techniques, employed in conjunction with automated numerical programming which could be utilised in a fully automatic and computerised method to measure the relative rib area of rebar on an individual basis. **CB**

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