Designation: C1651 – 11

Standard Test Method for Measurement of Roll Wave Optical Distortion in Heat-Treated Flat Glass[1]

This standard is issued under the fixed designation C1651; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method is applicable to the determination of the peak-to-valley depth and peak-to-peak distances of the out-of-plane deformation referred to as roll wave which occurs in flat, heat-treated architectural glass substrates processed in a heat processing continuous or oscillating conveyance oven.

1.2 This test method does not address other flatness issues like edge kink, ream, pocket distortion, bow, or other distortions outside of roll wave as defined in this test method.

1.3 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 Reference to these documents shall be the latest issue unless otherwise specified by the authority applying this test method.

2.2 *ASTM Standards:*[2]
C162 Terminology of Glass and Glass Products
C1036 Specification for Flat Glass
C1048 Specification for Heat-Strengthened and Fully Tempered Flat Glass

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *peak-to-valley depth of roll wave*—characteristic depth, *W*, of roll wave as illustrated in Fig. 1.

3.1.2 *peak-to-peak wavelength of roll wave*—characteristic length, *L*, of roll wave shown as a sine-wave representing the deformed surface section as illustrated in Fig. 1.

3.1.3 *roll wave*—A repetitive wave-like departure from flatness in glass that results from heat treating the glass in a horizontal roller hearth furnace. Roll wave excludes edge effects such as edge kink and distortion influenced by assembly or installation.

3.1.4 *roll wave optical distortion*—visual distortion, *D*, that results from roll wave and expressed as lens power as in Eq 1.

3.1.5 *valley-to-valley wavelength of roll wave*—characteristic length, *L*, of roll wave shown as a sine-wave representing the deformed surface section as illustrated in Fig. 1.

4. Summary of Test Method

4.1 This test consists of moving an instrument across the glass surface in a direction parallel to the direction that the glass substrate traveled during heat processing. The instrument will primarily measure the out-of-plane deformation of the glass surface which is characteristic of the glass and known as "roll wave". The peak-to-valley depths of the roll waves, *W*, and the peak-to-peak distances, *L*, are measured. (See Fig. 1.)

4.1.1 Other out-of-plane deformations of the glass surface may also be present which do not have the same peak and valley wave character of the roll wave, but which also result in the appearance of optical distortion in the glass.

4.1.2 The optical distortion due to the out-of-plane deformation of the surface is measured as an optical power, similar to the optical power of a cylindrical mirror or lens.

4.1.3 For those deformations that do have a wave character, the distortion can be calculated using the following formula. From the measured roll wave depth, *W* and the measured peak-to-peak or valley to valley wavelength of the roll wave, *L*, the optical roll wave distortion *D* is:

$$D = 4\pi^2 W/L^2 \quad (1)$$

where *W* and *L* are in metres and *D* is in diopters. The dimensions of diopters (dpt) is m^{-1}. The more usual unit of

[1] This test method is under the jurisdiction of ASTM Committee C14 on Glass and Glass Products and is the direct responsibility of Subcommittee C14.11 on Optical Properties.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

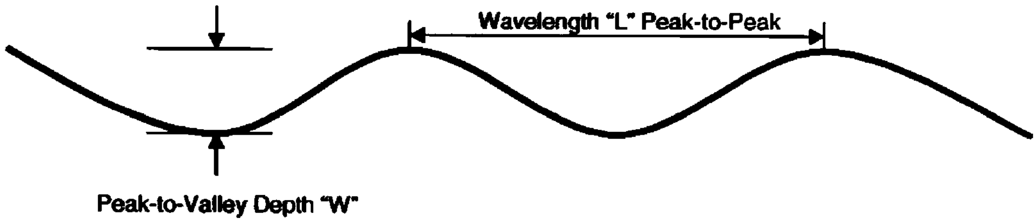

FIG. 1 Representative Roll Wave Showing *"W"* and *"L"*

optical distortion is millidiopters which are obtained by multiplying the value in diopters by 1 000.

4.2 Appendix X1 and references show the relationship between *W*, *L*, the measured radius of curvature *R* and the optical distortion of a reflecting surface, *D*.

5. Significance and Use

5.1 This test method is a procedure for determining the peak-to-valley depth and the wavelength of roll wave in flat glass and then calculating the optical distortion resulting from that roll wave. Peak-to-valley measurements provide a means of monitoring the roll wave distortion in a heat processed glass product.

5.2 Measured peak-to-valley depth provides information required by some specifiers of heat-treated glass products.

5.3 Roll wave is inherent in flat glass which has been heat treated in a furnace in which rollers are used to convey the glass.

5.4 Consult Specifications C1036 and C1048 for additional glass characteristics and quality information.

6. Apparatus

6.1 Optical distortion in flat glass can be characterized by determining the out-of-plane deformation of the glass by use of an instrument to measure the peak-to-valley depth of the deformations. Two such instruments are the so-called "Flat Bottom" Gauge and the "Three Point Contact" Gauge. (As stated in 10.1 a Round Robin Interlaboratory Study (ILS) will be carried out to establish, among other things, the comparative precision and bias of measurement made with the "Flat Bottom" Gauge and the "Three Point Contact" Gauge.)

6.2 The "Flat Bottom" Gauge consists of a flat plate which is a minimum of 12 in. (305 mm) long. (The flat plate shall be equal to or greater in length than the circumference of the furnace roller and less than twice the circumference of the roller) It shall be no less than 2 in. (50.8 mm) wide, with a smooth, low-coefficient of friction surface and have a depth measuring gauge equipped with a dial indicator, digital micrometre, or linear variable differential transformer (LVDT) with a protruding ball-end spring loaded plunger. This indicator, micrometre, or LVDT is used to measure the out-of-plane depth, *W*, of valleys and is located at the center of the bar. Such a gauge is shown in Fig. 2.

6.3 The "Three Point Contact" Gauge has three contact points, one at each end of the gauge and equally spaced from a center contact point at which position the depth of the roll wave is measured. The distance between the outboard contact points of the "Three Point Contact" Gauge must be adjustable to permit setting the outside contact points apart by a distance equal to the wavelength, *L*, of the roll wave. The center contact point is a depth measuring gauge which can be either a dial indicator, a digital micrometre, or a spring loaded LVDT plunger. Such a gauge is shown in Fig. 3 and Fig. 4.

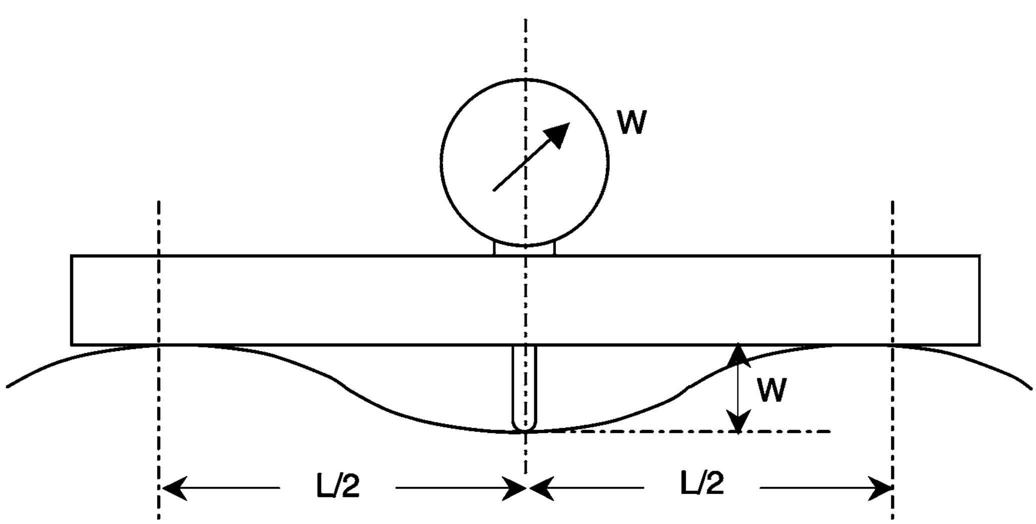

FIG. 2 "Flat Bottom" Roll Wave Gauge with Dial Indicator

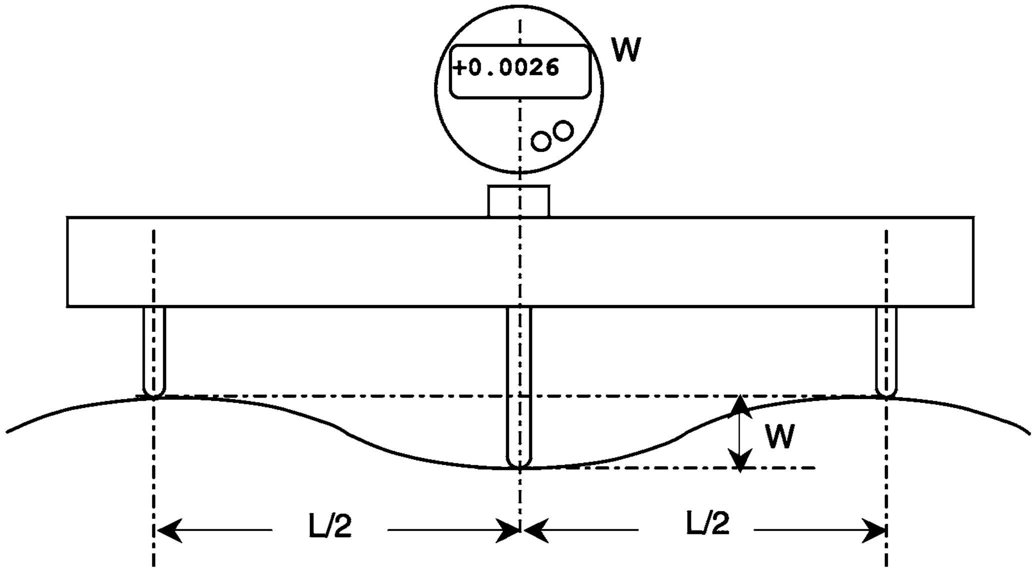

FIG. 3 "Three-Point Contact" Gauge on Valley

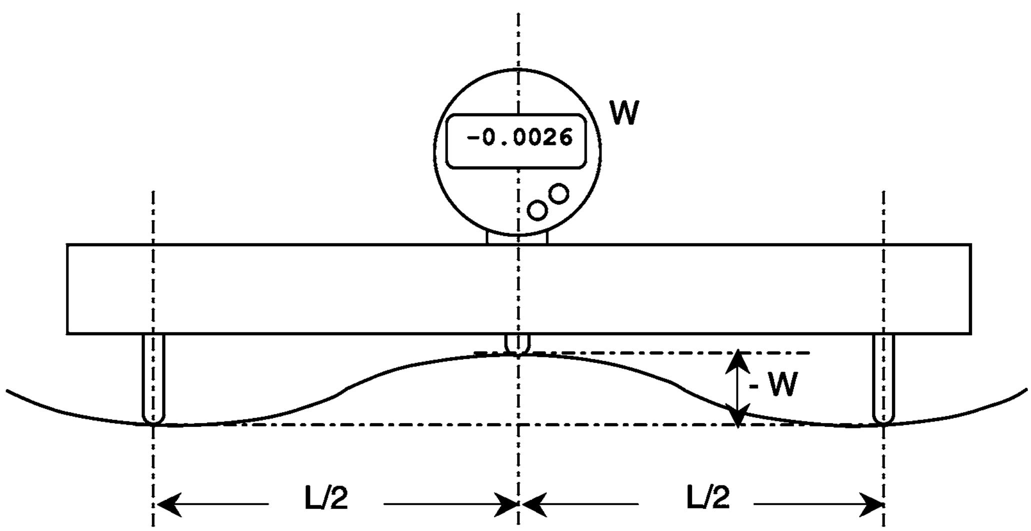

FIG. 4 "Three Point Contact" Gauge on Peak

NOTE 1—The wavelength of the roll wave is often, but not always equal to the circumference of the conveyor rolls in the tempering furnace.

NOTE 2—Surface distortions apart from roll wave are likely present and should not be considered when calculating the average wavelength (L_{ave}) in 8.1. These invalid wavelengths include: (*1*) any peak-to-peak or valley-to-valley distance that is not within ± 1 inch (± 25.4 millimetres) of roll circumference (if known), or (*2*) any peak or valley measurement that does not repeat at equal intervals.

NOTE 3—If the measured roll wave wavelength is not within ± 1 inch (± 25.4 millimetres) of roll circumference, or when the circumference of the furnace roll is not known, the Flat Bottom Gauge should be used to measure roll wave since its use does not depend on knowing the average wavelength of the roll wave.

6.4 These instruments can be manually conveyed across the glass or fitted with a trolley system for pulling it across the glass and plotting depth, *W*, versus position as described in the literature.(**1**, **2**, **3**)[3]

[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.

6.5 The glass to be measured shall be placed on a flat supporting surface with any edge/end kink facing upward. The direction of the edge/end kink may be determined by using visual or optical inspection techniques (such as the reflection of a Zebra board) or production documentation, or both. The supporting surface should have dimensions equal to or exceeding the dimensions the specimen to be tested. The departure from flatness of the supporting surface shall be less than the depth of the out-of-plane roll wave deformations if the measurement is to be accurate. The table or surface must be free of debris and any other surface condition that might affect the reading.

6.6 This test method is appropriate principally for in-plant or laboratory measurement of roll wave distortion. The test method can be adapted to on-site measurements of roll wave only after removal of the glass from its frame and supporting it in accordance with 6.5. This would automatically exclude insulating glass units and laminated glass lites from measurement under this test method.

7. Procedure

7.1 Place the clean test lite on a flat supporting surface in accordance with 6.5.

7.1.1 Prior to using the roll wave gauge for measurement, place it on a rigid flat surface, such as a granite plate, or on a piece of annealed float glass which is greater than or equal to ⅜ in. (10 mm) in thickness and which is larger than the gauge. The depth of measuring plunger must be depressed by some amount when the gauge is resting on the flat surface. Adjust the gauge meter to read zero, following the gauge manufacturer's instructions.

7.1.2 Determine the direction of the roll waves using visual or optical inspection (such as the reflection of a Zebra board) or production documentation, or both. Place a measuring tape on the glass surface perpendicular to the roll waves. The measuring tape shall extend from leading or trailing edge and extend the entire length of the substrate where the roll wave peaks and valleys will be determined.

7.2 *Procedure A: Measuring with a Flat Bottom Gauge:*

7.2.1 Place the gauge on the surface of the glass as shown in Fig. 2 at the approximate centerline of the glass dimension perpendicular to the roll wave and near one end of the expected scan. To eliminate the influence of the end-effects on the computation of Optical Distortion, the first peak or valley used for computation of optical distortion shall be no less than 12 in. (305 mm), or one wavelength, whichever is larger, from the edge of the glass.

7.2.2 Without pressing down on the gauge, push or pull it along the centerline, parallel to the measuring tape and observe the depth measuring gauge oscillating between peaks and valleys.

7.2.3 Determine the reading of the depth measuring gauge, p_i or v_i, at each peak and valley as you push or pull the gauge along the centerline. These readings along with the locations of the peaks $P_1, P_2, P_3,\ldots P_n$ and valleys $V_1, V_2, V_3,\ldots. V_m$ can be marked on the glass using a washable marking pen. Transfer these numbers to a table similar to Table 1.

7.2.4 While the above specifies only a single traverse of the glass, it is obvious that several traverses will better represent the distortion over the face of the glass. It is common practice, for instance, to make three to five traverses across the glass in order to better represent the distortion of the entire glass surface.

TABLE 1 Example of Data Table for Roll Wave Measurements from a "Flat Bottom" Gauge

	Peak 1	Valley 1	Peak 2	Valley 2	Peak 3	Valley 3	Peak 4
Distance P_i or V_i to Peak or Valley in inches (mm)	12.0 (305)	16.5 (419)	20.4 (517)	24.4 (616)	29.0 (736)	33.3 (844)	37.0 (940)
Depth Reading p_i or v_i of Peak or Valley in inches (mm)	0 (0)	0.0015 (0.038)	0 (0)	0.0033 (0.084)	0 (0)	0.0022 (0.056)	0 (0)

7.2.5 Calculate the distortion, *D*, using section 8.2.

7.3 *Procedure B: Measuring with a "Three Point Contact" Gauge:*

7.3.1 The procedure previously described for using the flat bottom type roll wave gauge generally applies to the "Three Point Contact" Gauge. However, the test method differs as follows:

7.3.2 Whenever the wavelength, *L*, is not known from prior test results, make a preliminary run, following steps described in 7.2.1 and 7.2.2. Then use 8.1 to establish the average wavelength, *L*. If necessary, change the contact points of the gauge so that the distance between the end contact points is equal to *L*, and the contact points are equidistant from the dial or indicator in the center of the gauge.

7.3.3 Check that the dial or digital gauge still reads zero on a flat surface as stated in 7.1.1. When the end contact points are located at peaks and the plunger is located in the valley, the gauge will indicate the peak-to-valley depth. With end contact point located at the bottom of a valley, the plunger is forced upward, and will show peak-to-valley with the opposite sign. (See Fig. 3 and Fig. 4.)

7.3.4 Follow the same procedure for obtaining data as described in 7.2.2 and 7.2.3 and which is shown in Fig. 3 and Fig. 4.

7.3.5 Calculate the distortion using section 8.2.

8. Calculation

8.1 *Calculating the Average Wavelength of the Roll Wave:*

8.1.1 Required only for use of the "Three Point Contact" Gauge.

8.1.2 In the example given in Table 1, the distance between Peak 1 and Peak 4 (three waves) is 25.0 in. (635 mm) and the distance between Valley 1 and Valley 3 (two waves) is 16.8 in. (425 mm).

8.1.3 With the distance to the first peak equal to P_1, to the second peak equal to P_2, and to the *n*th peak equal to P_n; and the distance to the first valley equal to V_1, to the second valley equal to V2 and to the *m*th valley equal to V_m, the following yields the average wavelength of the roll wave:

$$L_{ave} = [(P_n - P_1)/(n-1) + (V_m - V_1)/(m-1)]/2 \quad (2)$$

where *n* is the number of peaks and *m* is the number of valleys. In the example shown in Table 1, *n* = 4 and *m* = 3 so that

$$L_{ave} = (25.0/3 + 16.8/2)/2 = 8.4\ in. \quad (3)$$

or

$$L_{ave} = (635/3 + 425/2)/2 = 213\ mm \quad (4)$$

8.2 *Calculating the Optical Distortion:*

8.2.1 The Optical Distortion can be calculated at each peak and valley except for the first and last peak or valley for which there is no "previous" or "next" peak or valley, respectively. The distortion values, D_{pi} or D_{vi} obtained for peaks and valleys will only be accurate if the gauge is evenly supported on the glass. If the gauge is not fully supported at a peak or valley, a D_{pi} or D_{vi} value should not be calculated for that point and no value should be reported.

8.2.2 The following formulae pertain if the first data point is a peak. These formulae are slightly different when the first data point is a valley. The formulae for valley first data are in Note 4.

8.2.3 The optical distortion values, D_{pi} (in millidiopters or mdpt) in the case that the first data point is a peak and for the peaks p_i, are arrived at using the following formulae (as mentioned in 8.2.1, calculation is not possible at the last data point):

$$D_{pi} = [4\pi^2 \times 10^3]\ (p_i - v_{i-1})/[V_i - V_{i-1}]^2 \text{ for } v_i, p_i \text{ and } V_i \text{ in metres} \quad (5)$$

or

$$D_{pi} = [(4\pi^2/25.4) \times 10^6]\ (p_i - v_{i-1})/[V_i - V_{i-1}]^2 \text{ for } v_i, p_i \text{ and } V_i \text{ in inches} \quad (6)$$

or

$$D_{pi} = [4\pi^2 \times 10^6]\ (p_i - v_{i-1})/[V_i - V_{i-1}]^2 \text{ for } v_i, p_i \text{ and } V_i \text{ in millimetres} \quad (7)$$

8.2.4 The optical distortion values, D_{vi} (in millidiopters or mdpt) for the valleys (still excluding the last data point if it is a peak), are arrived at using the following similar formulae:

$$D_{vi} = [4\pi^2 \times 10^3]\ (v_i - p_{i-1})/[P_i - P_{i-1}]^2 \text{ for } v_i, p_i \text{ and } P_i \text{ in metres} \quad (8)$$

or

$$D_{vi} = [(4\pi^2/25.4) \times 10^6]\ (v_i - p_{i-1})/[P_i - P_{i-1}]^2 \text{ for } v_i, p_i \text{ and } P_i \text{ in inches} \quad (9)$$

or

$$D_{vi} = [4\pi^2 \times 10^6]\ (v_i - p_{i-1})/[P_i - P_{i-1}]^2 \text{ for } v_i, p_i \text{ and } P_i \text{ in millimetres} \quad (10)$$

8.2.5 Values calculated using formulae 4, 5, 7, and 8 are tabulated in Table 2.

8.2.6 The optical distortion of a part may then be characterized by its average value or by its maximum value. In the above example these are respectively:

$$D_{avg} = 54 \text{ mdpt}$$

$$D_{max} = 69 \text{ mdpt}$$

NOTE 4—The following formulae are used when the first data point is a valley:

$$D_{pi} = [4\pi^2 \times 10^3]\ (p_i - v_i)/[V_{i+1} - V_i]^2 \text{ for } v_i, p_i, \text{ and } V_i \text{ in metres} \quad (11)$$

$$D_{vi} = [4\pi^2 \times 10^3]\ (v_i - p_{i-1})/[P_i - P_{i-1}]^2 \text{ for } v_i, p_i, \text{ and } P_i \text{ in metres} \quad (12)$$

TABLE 2 Example of Data Table for Reporting Optical Distortion Using a "Flat Bottom" Gauge

	Peak 1	Valley 1	Peak 2	Valley 2	Peak 3	Valley 3	Peak 4
Distance P_i or V_i, to Peak or Valley in inches (mm)	12.0 (305)	16.5 (419)	20.4 (517)	24.4 (616)	29.0 (736)	33.3 (844)	37.0 (940)
Depth Reading p_i or v_i of Peak or Valley in inches (mm)	0 (0)	0.0015 (0.038)	0 (0)	0.0033 (0.084)	0 (0)	0.0022 (0.056)	0 (0)
Calculated Distortion, D_{pi} or D_{vi}, in millidiopters (mdpt)	NA	33	62	69	53	53	NA

9. Report

9.1 A report shall be generated providing the following information:

9.1.1 Date of Measurement,

9.1.2 Operator Name,

9.1.3 Type of gauge used,

9.1.4 Specimen ID,

9.1.5 Average wavelength, L_{ave} (Optional for "Flat Bottom" Gauge),

9.2 The report shall also contain one or more of the following:

9.2.1 Maximum, minimum, and average peak-to-valley depth, W_{max} W_{min}, W_{avg},

9.2.2 Maximum and average optical distortion, D_{max}, D_{avg}, and

9.2.3 Comments on departure of distortion from repetitive wave like behavior.

10. Precision and Bias

10.1 Subcommittee C14.11 is planning to conduct a Round Robin Inter-Laboratory Study (ILS) using tempered glass samples to establish the precision and bias of this method.

11. Keywords

11.1 flat glass; heat-treated glass; optical distortion; roll wave

APPENDIX

(Nonmandatory Information)

X1. Definitions and Computation of Optical Distortion of Reflected Scenery

X1.1 The focal length, *F*, of light rays reflected from a surface can be shown to be related to the radius of curvature of that surface:

$$F = R/2 \quad (X1.1)$$

X1.2 The Optical Power or Optical Distortion, D, is defined as:

$$D = 1/F = 2/R \quad (X1.2)$$

X1.3 Assuming that the roll wave surface is of sinusoidal contour with amplitude of W/2 (half of the peak-to-valley depth) and a wavelength of *L*, we write the surface equation of the roll wave as:

$$Y(x) = W/2\ (\ sin\ (2\pi x/L)) \quad (X1.3)$$

Where Y(x) is the half height of the roll wave at any point along a line, x, which is perpendicular to the roll wave. W is the peak-to-valley depth of the roll wave and L is the wavelength of the roll wave.

X1.4 Now, the radius of curvature of a surface at any point can be shown to be equal to the inverse of the second derivative of the surface equation, so we can calculate 1/R as follows:

$$1/R = \left[d^2/dx^2\ Y(x)\right] \quad (X1.4)$$

or:

$$1/R = \left[d^2/dx^2\ (W/2sin(2\pi x/L))\right]^{x=L/4} = 2\pi^2 W/L^2 \quad (X1.5)$$

X1.5 The second derivative at is evaluated at x = L/4 because the smallest radius of curvature and thus the maximum distortion occurs where the sinusoidal Roll Wave is at its peak at x = L/4 and where sin (2πx/L) = 1.

Therefore, since D = 2/R, we get the equation for roll wave distortion:

$$D = 4\pi^2 W/L^2 \quad (X1.6)$$

REFERENCES

(1) "Maintenance and Use of RWG Roller Wave Gage Instruction Manual", *Strainoptic Technologies Inc.*, July 2001.

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(6) "Road Vehicles-Safety Glazing Materials - Test Methods for Optical Properties," ISO 3538 International Standard.