DEVELOPMENT OF A FIELD METHOD TO MEASURE
OUT-OF-FLATNESS OF STRUCTURAL
STEEL PLATES

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DEVELOPMENT OF A FIELD METHOD TO MEASURE OUT-OF-FLATNESS OF STRUCTURAL STEEL PLATES

by

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THESIS

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CHAPTER ONE

INTRODUCTION

1.1 Background and Purpose Statement

The out-of-flatness of structural steel plates in bolted connections can prevent desired bolt tensions from being achieved, even when specified installation procedures are used. A bolt in a connection of out-of-flat plate elements will have a unique bolt-loosening response because of its relative position in the connection and its tightening order. Bolts tensioned adequately may lose a significant portion of their tension as the joint is completed, particularly those tightened early in the sequence.

In order to correlate the out-of-flatness of structural steel plates and its bolt-loosening effect, an efficient and accurate means of field measuring out-of-flatness is required. The purpose of this thesis is to detail and demonstrate the devices and methodology to field measure surface profiles of structural steel plates, like the webs and flanges of plate girders.

1.2 Summary and Organization of Thesis

This thesis is organized into six chapters. Chapter 2 defines out-of-flatness and establishes criteria for a method of field measuring out-of-flatness. Chapter 3 presents a method of measurement using a manual rotating beam laser level and precision leveling rod. Techniques for data reduction and presentation are also addressed. The method is demonstrated and validated on a number of specimens in

Chapter 4. A "step-by-step" procedure is formalized in Chapter 5. Chapter 6 presents a summary of work and conclusions.

CHAPTER TWO

PRELIMINARIES

2.1 Out-of-Flatness Defined

Surface measurement addresses the question of how a surface deviates from the ideal, perfectly smooth surface. The word generally used to describe deviation on a microscopic scale is "roughness". While specialized instrumentation exists to measure deviation on the sub-micron level, here the interest is in surface deviation on a greater scale, i.e. a surface's "out-of-flatness".

For the purposes of this study, "flatness" or "out-of-flatness" can be defined as the profile of the surface based on local height variations as measured across steel plates of common sizes, such as those found in the webs and flanges of plate girders.

2.2 Requirements for Method of Measuring Out-of-Flatness

Any field method for measuring out-of-flatness should satisfy the following requirements:

1. Simplicity - should be simple enough to allow an average measurer to obtain accurate, repeatable results.

2. Field Compatibility - should not involve ultrasensitive instrumentation suited only to the laboratory.

3. Horizontal and Vertical Surface Measurement Capability - must be capable of measuring nominally horizontal and vertical surfaces as these represent the most common situation.

4. Economy - must be as economical as possible.

5. Accuracy - must be as accurate as possible.

6. Typical In-Plane Dimensions - must be capable of measuring surface areas up to several square feet, i.e. typical connection areas found on the webs and flanges of plate girders.

CHAPTER THREE

MEASURING OUT-OF-FLATNESS: METHODOLOGY AND DEVICES

3.1 Methodology

3.1.1 Scheme of Measurement

The general scheme of measurement is shown in Figure 3.1. A manual rotating beam laser level of type used in conventional surveying applications is mounted to the steel surface to be measured with a magnetic base. The level emits a rotating laser beam providing

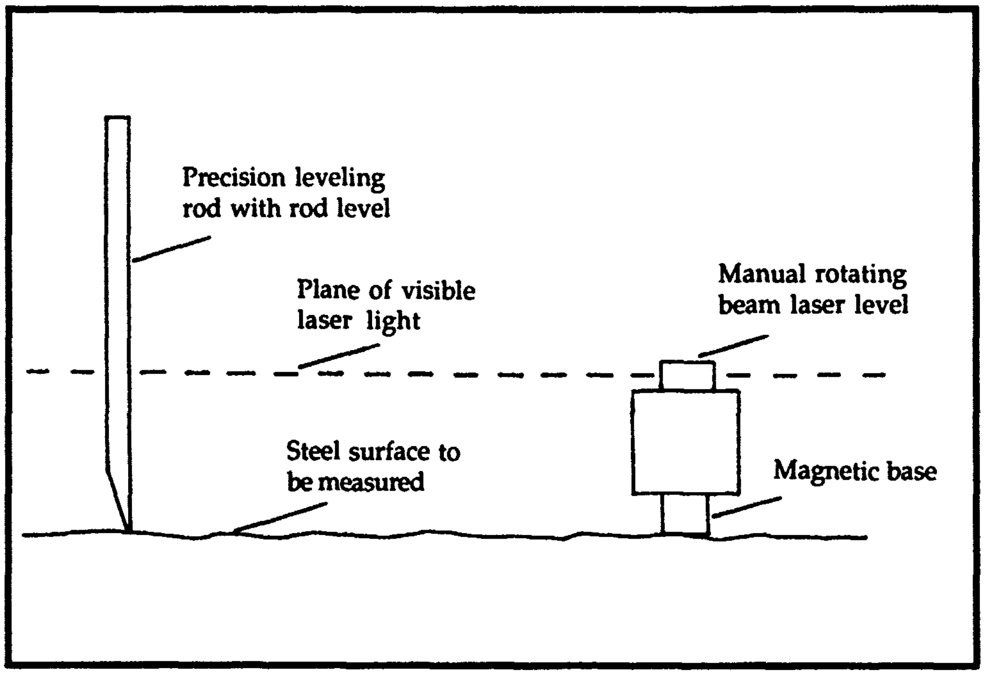


Figure 3.1 General scheme of measurement.

a plane of red laser light. The instrument is adjusted to orient the plane of light in the horizontal and a precision leveling rod is held vertical using an attached circular rod level. The laser light shows as a thin line across the rod and the surface height reading is taken. This procedure can be repeated over an area at any desired interval to establish the profile of the surface.

It is important that the leveling rod be held perpendicular to the plane of laser light to obtain the truest surface height reading. When the rod and laser plane are perpendicular, the rod reading will also be a minimum. Therefore, when measuring a nominally horizontal surface, the laser instrument is adjusted to provide a horizontal laser plane and the rod is held vertical using the attached rod level. When measuring a nominally vertical surface, the laser instrument is adjusted to provide a vertical laser plane and the rod is held horizontal using a common vial level along the longitudinal axis of the the rod. Measuring nominally vertical surfaces also requires "waving" the rod slightly through the horizontal plane to obtain the smallest and therefore truest rod reading. These procedures are discussed in further detail in Chapter Four.

3.1.2 Data Reduction

If the area or field of measurement is viewed in three-dimensional space as depicted in Figure 3.2, then each data point can be described by coordinates measured along three orthogonal axes X, Y and Z. A reference plane can then be established, and the deviation between each data point and the reference plane calculated.

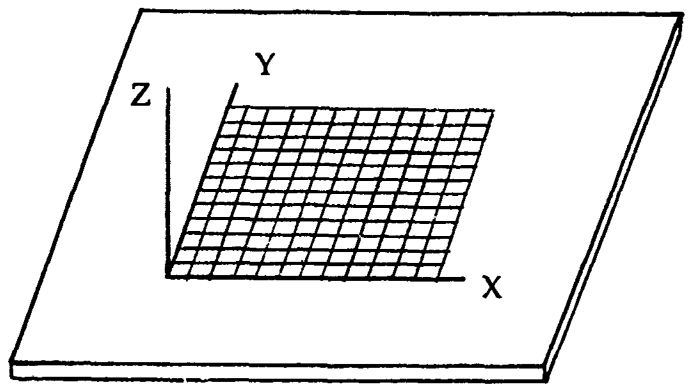


Figure 3.2 Field of measurement viewed in three-dimensional space with orthogonal axes X, Y and Z.

A reference plane can be defined by any three non-colinear data points (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3) using the following equation:

$$\begin{vmatrix} y_2 - y_1 & z_2 - z_1 \\ y_3 - y_1 & z_3 - z_1 \end{vmatrix}(x - x_1) + \begin{vmatrix} z_2 - z_1 & x_2 - x_1 \\ z_3 - z_1 & x_3 - x_1 \end{vmatrix}(y - y_1) + \begin{vmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{vmatrix}(z - z_1) = 0 \quad \textbf{3.1}$$

Equation 3.1 can be reduced to the following form where A, B, C and D are constants:

$$Ax + By + Cz + D = 0 \quad \textbf{3.2}$$

The perpendicular distance between a data point (x_0, y_0, z_0) and a reference plane of the form above is given by

$$\frac{Ax_0 + By_0 + Cz_0 + D}{-\sqrt{A^2 + B^2 + C^2}} \qquad 3.3$$

Equations 3.1 to 3.3 can be found in standard mathematics handbooks. (See, for example, reference 1.) The negative sign in the denominator is required to account for the fact that data points with the higher rod readings are actually the lower points on the surface. The sign of the result of Equation 3.3 indicates the distance "above" (positive) and "below" (negative) the reference plane.

Given the coordinates for all data points, a simple computer program can be written to determine a reference plane based on any three non-colinear points and the deviation of each point relative to the reference plane. Commercial spreadsheet programs can also be used to perform the required calculations. In this thesis, all spreadsheet calculations and graphical representations of data were accomplished using Microsoft Excel, Version 4.0.

3.1.3 Presentation of Results

There are commercial programs available that can graphically depict a three-dimensional surface profile. By magnifying the scale for deviation from a reference plane (Z axis direction) and using features such as grid lines, contour lines and color, the surface profile is visually illustrated. These capabilities are demonstrated in Chapter Four.

3.2 Devices

3.2.1 Manual Rotating Beam Laser Level

The laser instrument selected for measuring out-of flatness was the LB-5 Laser Beacon by Laser Alignment Inc., shown in Figure 3.3.

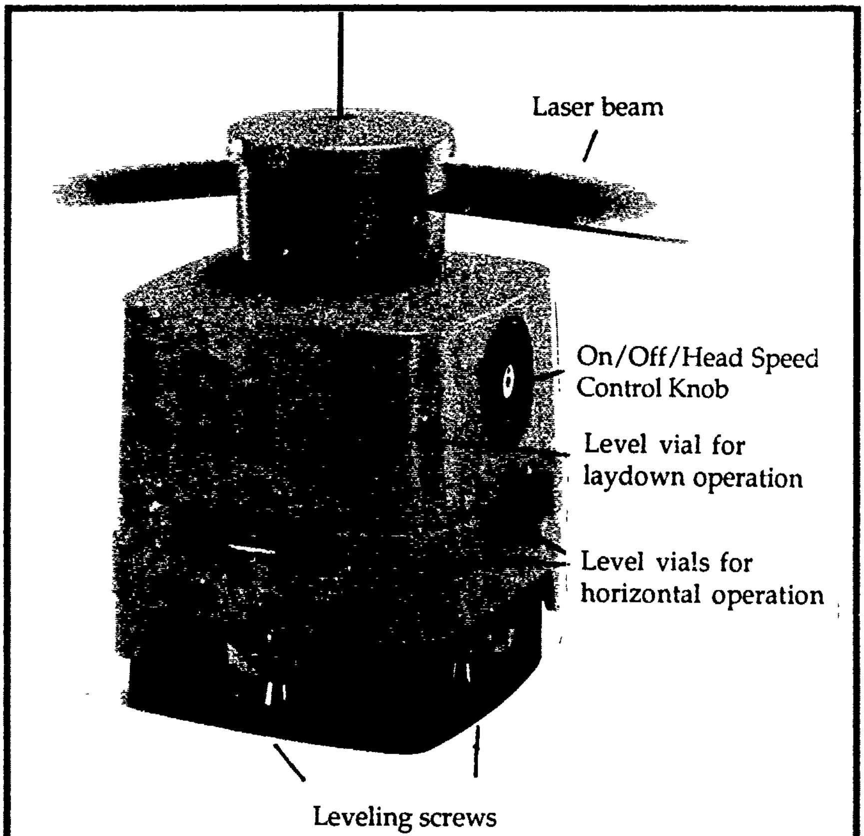


Figure 3.3 Laser Alignement LB-5 Laser Beacon. Shown 50% actual size.

The LB-5 was chosen because it possessed the following characteristics:

1. Manual leveling capability

2. Visible laser light

3. Compactness, durability and economy

Manual leveling capability enables the LB-5 to establish horizontal and vertical planes so nominally horizontal and vertical surfaces can be measured. To measure a nominally horizontal surface, a horizontal plane is established by adjusting the two leveling screws to center the two level vials for horizontal operation indicated in Figure 3.3. To measure a nominally vertical surface, the LB-5 is mounted with the vial for laydown operation facing up and a vertical plane is established by adjusting the top leveling screw to center the laydown vial.

The importance of manual leveling capability is seen in the fact that so-called automatic or "self-leveling" levels of the laser and optical type cannot establish planes outside the horizontal. They employ a gravity-referenced prism or mirror compensator to orient the beam or line-of-sight (LOS). The instrument is typically leveled using a circular spirit level; when the bubble is centered (or nearly so), the compensator takes over and maintains a horizontal beam or LOS, even if the instrument is slightly moved (3). If such an automatic level were tilted to achieve a plane out of the horizontal, the compensator would continue to maintain a horizontal reference to the limits of its stops. Beyond this point performance is completely unreliable and in most cases automatic laser levels will automatically shut down (3). In addition, automatic leveling capability adds cost, weight and bulkiness to the laser unit.

The LB-5 is called a visible beam instrument because it houses a visible Helium-Neon (HeNe) laser which produces a characteristic bright red beam. The ON/OFF/Head Speed Control Knob turns the laser on and off, and determines the rate of rotation. At operating speeds, the LB-5 produces a laser plane which appears on the leveling rod as a thin line of red light. This allows a single measurer to orient the instrument for horizontal or vertical operation, turn it on, and take readings directly off the rod.

It should be noted that many laser levels are classified as invisible beam instruments because the beam falls in the infra-red portion of the electro-magnetic spectrum. These beams can only be detected with the aid of a laser detector. While the LB-5 produces a visible beam, it also comes equipped with a laser detector since the beam can be electronically detected at far greater ranges than it can be seen on a leveling rod with the human eye. Over the short distances associated with out-of-flatness measurement, visual readings are easily taken off the rod. But the laser detector is evaluated as an alternative device for taking rod readings in Chapter Four.

Finally, the compactness, durability and economy of the LB-5 make it ideally suited to measuring out-of-flatness. With a 4"X4" base and 7" height, the unit can be used on small or congested surface areas. Self-contained power in the form of four "c" cell batteries adds to this flexibility. Weighing only 3.5 pounds, the LB-5 is safely mounted to steel surfaces with a magnetic base. The LB-5 is a purpose-built surveying instrument designed for use on everyday construction sites. It is shock and water resistant, and dustproof, but it is not indestructible. As with all surveying equipment, it must be handled with care to maximize performance and service life. Based on 1993 prices, the LB-5 has a manufacturer's suggested retail price of $1400 (2) which includes the accessory laser detector and laydown bracket. Admittedly, economy is always a relative term, but it should be noted that many conventional optical levels are more expensive. In addition, like most surveying equipment, the LB-5 can be rented for a reasonable fee from most distributors.

3.2.2 Precision Leveling Rod

A precision leveling rod was developed for measuring out-of-flatness and is shown in Figure 3.4. The rod was made from an 18" rigid steel rule. It has graduations in 10ths, 50ths and 100ths of an inch, allowing precise rod readings. The end of the rod is tapered to allow positioning at discrete points on the measured surface. An attached circular rod level is used to hold the rod vertical. A small pocket level, also shown, can be secured along the longitudinal axis of the rod to hold the rod horizontal.

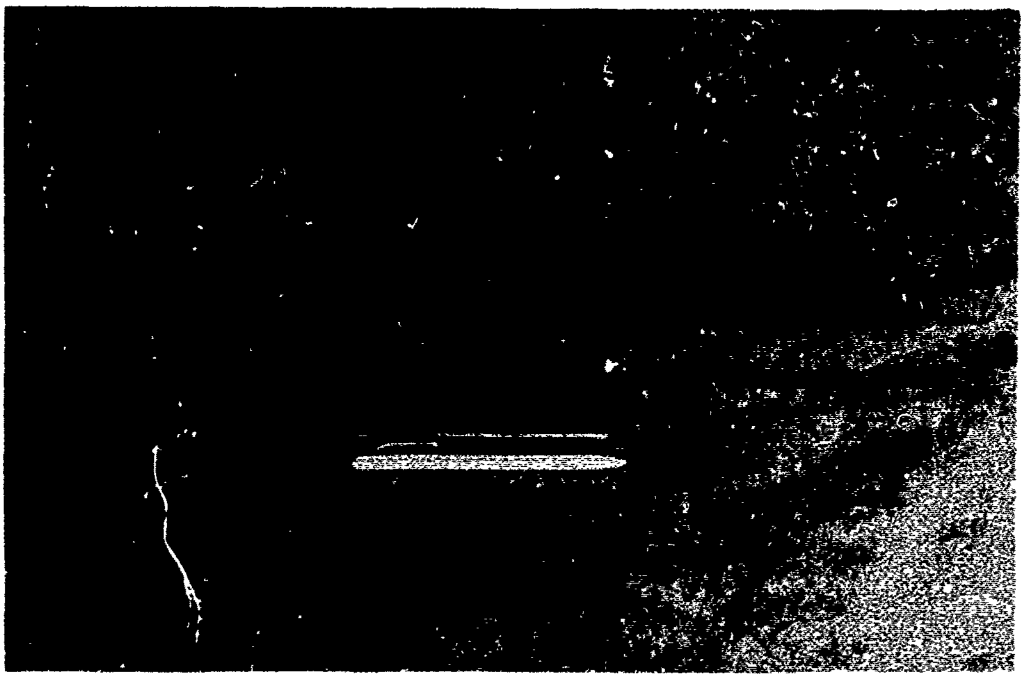


Figure 3.4 Precision leveling rod with pocket level.

CHAPTER FOUR

DEMONSTRATION AND VALIDATION

4.1 Preliminary Remarks

The laser method of measuring out-of-flatness outlined in Chapter Three was used on several specimens: a granite surface table, a plate specimen with noticeable curvature, and the top flange and web of a plate girder. Before a presentation of the results, a brief discussion of laser safety and instrument calibration are in order.

4.1.1 Laser Safety

Users of laser surveying equipment should be aware that even though the lasers being used are relatively low-powered, there is still a potential hazard of damage to the retina of the eye; if this damage takes place, no pain is necessarily felt and vision may not be severely impaired, although it will deteriorate with repeated exposures (3).

In the United States, the agency responsible for setting safety standards for the manufacturers of laser products is the Center for Devices and Radiological Health (CDRH) of the US Department of Health and Human Services (3). The CDRH produces a standard entitled "Performance Standard for Laser Products" (3), the last version of which was published in 1985. In accordance with this standard, the LB-5 is classified as a CLASS IIIa laser product based on the potential hazard of its emissions (4). Required certification and warning labels are also fixed to the unit (4). The safety instructions in the LB-5's Operation Manual read as follows:

> The LB-5 contains a semiconductor laser diode with a wavelength of 650 nanometers and is red in color. Its continuous output is 5 milliwatts or less. Never stare directly into the laser beam or view the beam with optical instruments. Whenever possible, set the unit above or below eye level. Turn the laser off when not in use. Do not point the laser unnecessarily at others.

Fortunately, accidents caused by misuse of the low-powered lasers used in construction surveying are virtually nil (3). Nevertheless, care must always be exercised when working with lasers. The bottom line is that safety instructions included with any laser product must be read and adhered to.

4.1.2 Instrument Calibration

Before measurements are made, the LB-5, like any surveying instrument, should be properly calibrated. Calibration is required to ensure the laser beam rotates through a true horizontal or vertical plane. Calibration instructions are included in the LB-5's Operation Manual. These instructions will not be included here as the procedure is simple to follow and should be done routinely as on any surveying instrument.

4.2 Measurement of a Granite Surface Table

4.2.1 General

The purpose of measuring a granite surface table was to see if the laser method of measurement would verify what was already known to be true — that the surface table is extremely flat. The LB-5's accompanying laser detector was evaluated as an alternative device to take rod readings. The effect of choosing a "best fit" reference plane for data reduction and presentation was also investigated.

4.2.2 Test Setup

The specimen measured was a Mitutoyo black granite surface table. The size of the plate was 18"X24" with a 4" thickness. Rated a "B" or "shop grade" surface table, its accuracy is guaranteed to 260 millionths of an inch or 0.0003" (5). The interpretation of this value is that all points on the surface of the table will be contained between two parallel planes 0.0003" apart (6).

A 12"X12" measuring field was drawn on the table's surface in removable china marker. Establishing an X and Y axis, and an interval of 1" along each, a grid of 169 points was created. The LB-5 was placed on the granite surface (without magnetic base), leveled in the horizontal, and turned on. The leveling rod was held vertical using the attached rod level. Surface height readings were taken at each grid point as shown in Figure 4.1(a).

Readings were also taken using the LB-5's laser detector, as shown in Figure 4.1(b). The laser detector was typical of detectors associated with laser surveying equipment. Both visual and audio indications of beam detection are provided. The detector was slowly slid down the rod so as to always approach the beam from the same direction. On first detection of the beam, the detector was clamped to the rod, and the reading taken off the rod.

(a)

(b)

Figure 4.1 Measuring the out-of-flatness of a granite surface table. (a) Direct reading of the rod; (b) Using a laser detector to obtain rod readings.

4.2.3 Results

4.2.3.1 Accuracy

The narrower the laser beam as it strikes the rod, the better the read. It was found that the beam could be narrowed by placing small strips of black electrical tape on the top and bottom edge of the laser's exit aperture. It was possible to narrow the beam's width to approximately 0.02". The center of the beam was estimated on the rod, and rod readings could be estimated to the nearest 0.01". It is necessary to estimate beam center on the rod rather than read the top or bottom edge of the beam as beam width varies slightly with range and ambient light conditions. Rod readings were easy to reproduce.

The accuracy of the laser method of measurement was within +/-0.009" as will be shown in Section 4.2.3.5.

4.2.3.2 Range

Narrowing the beam to obtain more accurate rod readings had the effect of reducing the range over which the laser beam could be read on the leveling rod. This range was also a function of the ambient light conditions. Under normal interior lighting conditions, the visible range of the laser on the rod was over ten feet. In direct bright sunlight, this range was reduced to about five feet. However, over the short ranges associated with out-of-flatness measurement, this reduction was determined to be inconsequential unless measuring extremely large fields.

4.2.3.3 Time

Time to measure a 12"X12" field (169 data points) was about 45 minutes or four readings and recordings per minute.

4.2.3.4 Laser Detector

Rod readings obtained with the laser detector were not repeatable and varied as much as +/-0.03". In addition, such meticulous attention was required to obtain readings with the laser detector so as to be completely impractical.

4.2.3.5 Data Reduction and Presentation

Data for the visual read of the surface table is shown on a spreadsheet in Table 4.1. The top portion of the table gives the X,Y,Z coordinates of each data point and represents the "raw" data. Note that the surface height readings from the rod (Z axis coordinates) are to the nearest 0.01". Three data points were arbitrarily chosen to establish a reference plane and are indicated by asterisks.The equation for the reference plane was calculated using equations 3.1 and 3.2. The deviation of each data point from the reference plane was calculated using equation 3.3. The deviations of each data point are shown in the bottom portion of Table 4.1 and represent the "reduced" data. Note that deviations were calculated to the nearest 0.001" and that deviations for the points used to establish the reference plane are zero, as expected.

It is important to understand that deviation of data points from an arbitrary reference plane does not in itself indicate an unflat surface. A close look at the reduced data in Table 4.1 shows that eight of 169 data points deviate from the reference plane by more than 0.01", with a maximum deviation of 0.013". But it is intuitive that the deviation of any data point will depend on the three data points chosen to establish the reference plane. The real indication of out-of-flatness is found in the patterns of deviation from a reference plane, and this is best shown by a graphical depiction of the data.

Table 4.1 Data for surface table. Data point coordinates and deviations from the reference plane are shown. Points used to establish the reference plane are indicated by asterisks.

SURFACE TABLE													
12"X12" FIELD													
LASER - VISUAL READ						Coordinates (in)							
12	5.71	5.71	5.70	5.69	5.68	5.68	5.67	5.66	5.65	5.64	5.63	5.63	5.62
11	5.71	5.70	5.70	5.69	5.68	5.67	5.66	5.65	5.65	5.64	5.63	5.62	5.61
10	5.70	5.70	5.69	5.69	5.67	* 5.66	5.66	5.65	5.64	5.63	5.63	5.62	5.61
9	5.70	5.69	5.68	5.68	5.67	5.66	5.65	5.64	5.63	5.63	5.62	5.61	5.60
8	5.69	5.69	5.68	5.67	5.66	5.65	5.65	5.64	5.63	5.62	5.61	5.60	5.60
7	5.69	5.68	5.67	5.66	5.66	5.65	5.64	5.63	5.63	5.62	5.61	5.60	5.59
6	5.68	5.68	5.67	5.66	5.66	5.64	5.64	5.63	5.62	5.61	5.60	5.60	5.59
5	5.68	5.67	5.66	5.65	5.65	5.64	5.63	5.62	5.61	5.60	5.60	5.59	5.58
4	5.68	5.67	5.66	5.65	5.64	5.63	5.63	5.62	5.61	5.60	5.60	5.58	5.58
3	5.67	5.66	5.65	5.64	5.64	5.63	5.62	5.61	5.60	5.60	5.59	5.58	* 5.57
2	5.66	* 5.66	5.65	5.64	5.63	5.62	5.61	5.60	5.60	5.59	5.58	5.57	5.56
1	5.66	5.65	5.64	5.64	5.63	5.62	5.61	5.60	5.59	5.58	5.57	5.56	5.56
0	5.65	5.64	5.64	5.63	5.62	5.61	5.60	5.60	5.59	5.58	5.57	5.56	5.55
	0	1	2	3	4	5	6	7	8	9	10	11	12
					Deviation from Reference Plane (in)								
12	0.001	-0.007	-0.006	-0.004	-0.003	-0.011	-0.010	-0.009	-0.007	-0.006	-0.004	-0.013	-0.011
11	-0.003	-0.001	-0.010	-0.009	-0.007	-0.006	-0.004	-0.003	-0.011	-0.010	-0.009	-0.007	-0.006
10	0.003	-0.006	-0.004	-0.013	-0.001	* 0.000	-0.009	-0.007	-0.006	-0.004	-0.013	-0.011	-0.010
9	-0.001	0.000	0.001	-0.007	-0.006	-0.004	-0.003	-0.001	0.000	-0.009	-0.007	-0.006	-0.004
8	0.004	-0.004	-0.003	-0.001	0.000	0.001	-0.007	-0.006	-0.004	-0.003	-0.001	0.000	-0.009
7	0.000	0.001	0.003	0.004	-0.004	-0.003	-0.001	0.000	-0.009	-0.007	-0.006	-0.004	-0.003
6	0.006	-0.003	-0.001	0.000	0.001	0.003	-0.006	-0.004	-0.003	-0.001	0.000	-0.009	-0.007
5	0.001	0.003	0.004	0.006	-0.003	-0.001	0.000	0.001	0.003	0.004	-0.004	-0.003	-0.001
4	-0.003	-0.001	0.000	0.001	0.003	0.004	-0.004	-0.003	-0.001	0.000	-0.009	0.003	-0.006
3	0.003	0.004	0.006	0.007	-0.001	0.000	0.001	0.003	0.004	-0.004	-0.003	-0.001	* 0.000
2	0.009	* 0.000	0.001	0.003	0.004	0.006	0.007	0.009	0.000	0.001	0.003	0.004	0.006
1	0.004	0.006	0.007	-0.001	0.000	0.001	0.003	0.004	0.006	0.007	0.009	0.010	0.001
0	0.010	0.011	0.003	0.004	0.006	0.007	0.009	0.000	0.001	0.003	0.004	0.006	0.007
	0	1	2	3	4	5	6	7	8	9	10	11	12

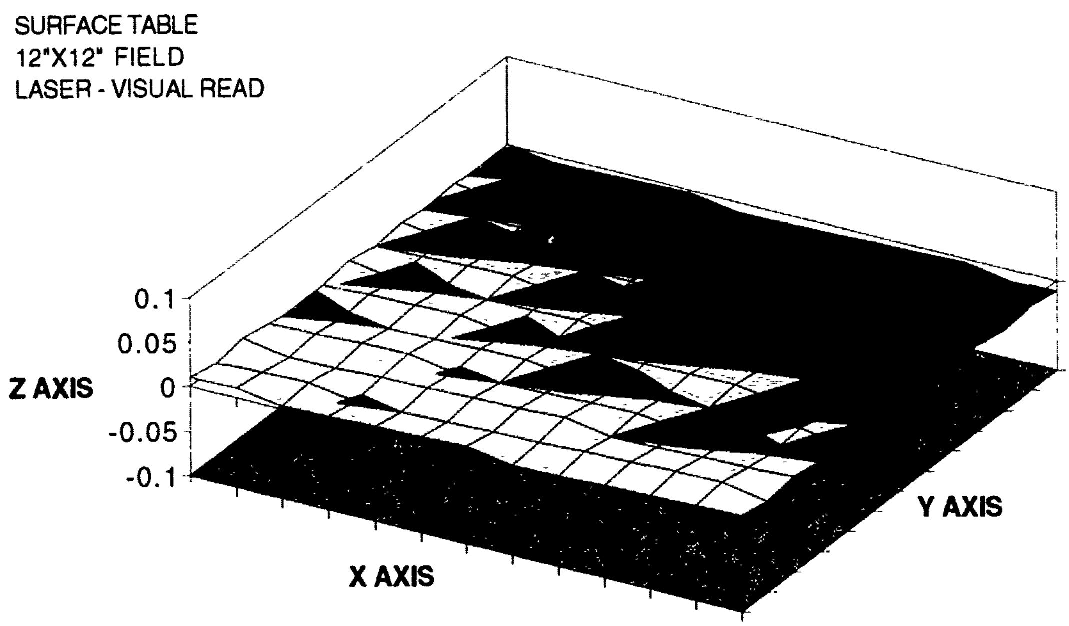


Figure 4.2 Surface table. (Based on data from Table 4.1.)

Using the graphing capabilities of Microsoft Excel, the profile of the surface table was graphically illustrated and is shown in Figure 4.2. This figure confirms the flatness of the surface table. The surface is shown to slope slightly downward toward the top right portion of the field due to the arbitrary selection or "tilting" of the reference plane. But the slope is uniform, indicating the flat nature of the measured surface. Note that the Z axis can be magnified to any desired scale to further scrutinize the surface. The use of color contouring to highlight areas above and below the reference plane is also helpful in understanding patterns of deviation relative to the selected plane.

It is possible to choose a reference plane that minimizes deviations. Using a least squares regression analysis, a "best fit" reference plane can be found and the deviation of data points calculated. Such a reference plane allows a more rational graphical depiction of the data by eliminating the "tilting" effect of an arbitrarily selected reference plane. For more information on regression analysis refer to *Linear Algebra and Its Applications* by Strang (7) or a similar linear algebra book.

To illustrate the selection of a "best fit" reference plane, the same raw data as in Table 4.1 was considered in Table 4.2. But a regression analysis was run on the data point coordinates to establish a "best fit" reference plane. A close look at the deviations in Table 4.2 shows a maximum deviation of 0.009" with an average deviation of 0.003". The graphical depiction of data in Table 4.2 is shown in Figure 4.3. Again, the flatness of the surface table is confirmed. However, the data and the figure show a surface with smaller deviations from the "best fit" reference plane.

Since the granite surface table is known to be extremely flat, the deviations in Table 4.2 represent error in the laser method's ability to measure out-of-flatness. Based on the deviations in Table 4.2, an accuracy within +/-0.009" can be expected using the laser method of measurement.

Table 4.2 Data for surface table with "best fit" reference plane selected. Data point coordinates are the same as in Table 4.1. Deviations are shown from a "best fit" reference plane established by regression analysis.

SURFACE TABLE													
12"X12" FIELD													
LASER - VISUAL READ						Coordinates (in.)							
12	5.71	5.71	5.70	5.69	5.68	5.68	5.67	5.66	5.65	5.64	5.63	5.63	5.62
11	5.71	5.70	5.70	5.69	5.68	5.67	5.66	5.65	5.65	5.64	5.63	5.62	5.61
10	5.70	5.70	5.69	5.69	5.67	5.66	5.66	5.65	5.64	5.63	5.63	5.62	5.61
9	5.70	5.69	5.68	5.68	5.67	5.66	5.65	5.64	5.63	5.63	5.62	5.61	5.60
8	5.69	5.69	5.68	5.67	5.66	5.65	5.66	5.64	5.63	5.62	5.61	5.60	5.60
7	5.69	5.68	5.67	5.66	5.66	5.65	5.64	5.63	5.63	5.62	5.61	5.60	5.59
6	5.68	5.68	5.67	5.66	5.65	5.64	5.64	5.63	5.62	5.61	5.60	5.60	5.59
5	5.68	5.67	5.66	5.65	5.65	5.64	5.63	5.62	5.61	5.60	5.60	5.59	5.58
4	5.68	5.67	5.66	5.65	5.64	5.63	5.63	5.62	5.61	5.60	5.60	5.58	5.58
3	5.67	5.66	5.65	5.64	5.64	5.63	5.62	5.61	5.60	5.60	5.59	5.58	5.57
2	5.66	5.66	5.65	5.64	5.63	5.62	5.61	5.60	5.60	5.59	5.58	5.57	5.56
1	5.66	5.65	5.64	5.64	5.63	5.62	5.61	5.60	5.59	5.58	5.57	5.56	5.56
0	5.65	5.64	5.64	5.63	5.62	5.61	5.60	5.60	5.59	5.58	5.57	5.56	5.55
	0	1	2	3	4	5	6	7	8	9	10	11	12
					Deviation from Reference Plane (in.)								
12	-0.007	0.002	0.000	-0.002	-0.004	0.004	0.003	0.001	-0.001	-0.003	-0.005	0.003	0.002
11	-0.001	-0.003	0.005	0.003	0.001	0.000	-0.002	-0.004	0.004	0.002	0.001	-0.001	-0.003
10	-0.006	0.002	0.000	0.009	-0.003	-0.006	0.003	0.001	0.000	-0.002	0.006	0.004	0.002
9	-0.001	-0.002	-0.004	0.004	0.002	0.000	-0.001	-0.003	-0.006	0.003	0.001	-0.001	-0.002
8	-0.006	0.003	0.001	-0.001	-0.003	-0.004	0.004	0.002	0.000	-0.002	-0.003	-0.005	0.003
7	0.000	-0.002	-0.004	-0.005	0.003	0.001	-0.001	-0.003	0.006	0.004	0.002	0.000	-0.002
6	-0.005	0.004	0.002	0.000	-0.002	-0.004	0.005	0.003	0.001	-0.001	-0.003	0.006	0.004
5	0.001	-0.001	-0.003	-0.005	0.004	0.002	0.000	-0.002	-0.004	-0.006	0.003	0.001	-0.001
4	0.006	0.004	0.002	0.001	-0.001	-0.003	0.005	0.003	0.002	0.000	0.008	-0.004	0.004
3	0.001	0.000	-0.002	-0.004	0.004	0.002	0.001	-0.001	-0.003	0.005	0.003	0.002	0.000
2	-0.003	0.006	0.003	0.001	0.000	-0.002	-0.004	-0.006	0.002	0.000	-0.001	-0.003	-0.006
1	0.002	0.000	-0.002	0.007	0.006	0.003	0.001	-0.001	-0.002	-0.004	-0.006	-0.008	0.000
0	-0.003	-0.004	0.004	0.002	0.000	-0.002	-0.003	0.006	0.003	0.001	-0.001	-0.002	-0.004
	0	1	2	3	4	5	6	7	8	9	10	11	12

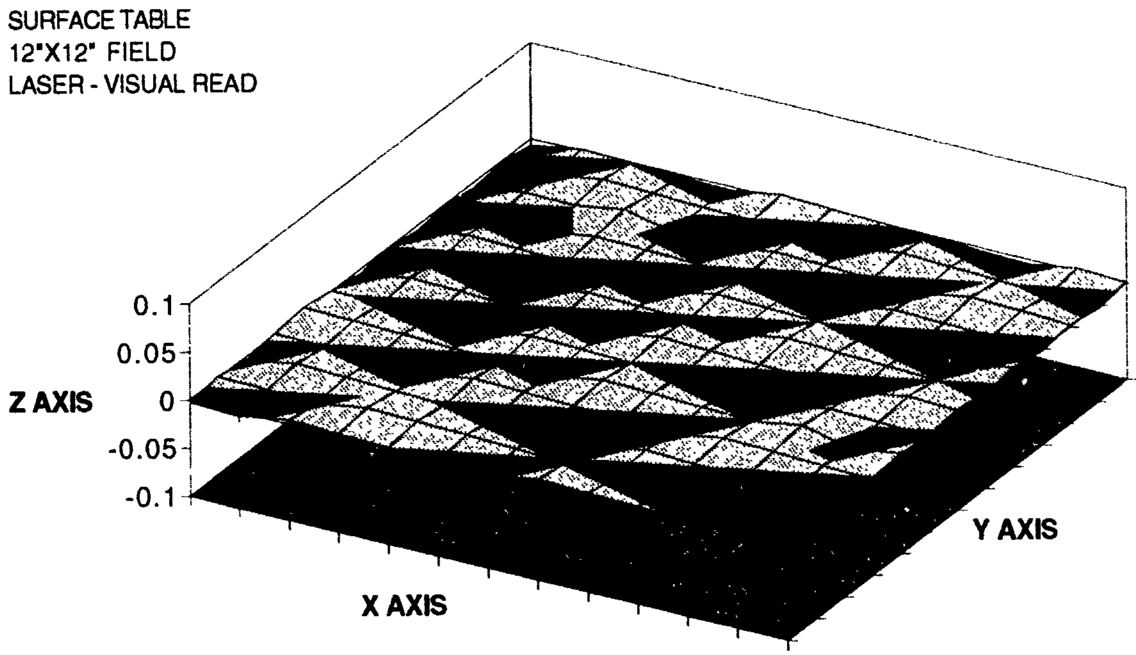


Figure 4.3 Surface table with "best fit" reference plane selected. (Based on data from Table 4.2.)

4.3 Measurement of a Plate Specimen with Noticeable Curvature

4.3.1 General

The purpose of measuring a plate specimen with noticeable curvature was to validate the measuring method on nominally vertical surfaces. The plate specimen was first measured in a horizontal orientation. Then it was measured in a vertical orientation to see how closely the results matched.

4.3.2 Test Setup

The surface of the plate specimen measured was noticeably concave. The steel plate's dimensions were 30"X36"X $^3/_8$".

The plate specimen was first measured in a horizontal orientation. Like the granite surface table, a 12"X12" measuring field with 1" grid was drawn on the plate's surface in china marker. Three large steel nuts were placed on a worktable in triangular fashion to provide stable support for the plate. The plate was laid on top of the nuts. The LB-5 was connected to the magnetic base using a $^5/_8$"-11 threaded adapter. The LB-5 was then mounted to the plate. Common to magnetic bases are on/off switches or buttons that allow easy placement and removal of the magnet. The LB-5 was leveled in the horizontal and turned on. The leveling rod was held vertical using the attached rod level. Surface height readings were taken at each grid point as shown in Figure 4.4(a).

To orient the plate for vertical measurement, the plate was positioned atop a pair of nuts bolted to the flange of a steel column as shown in Figure 4.4(b). Clamps were used to secure the plate against the column's flange. Care was taken to stabilize the plate without inducing deformation. The LB-5, since removed, was remounted to the plate's surface at a different location with the laydown vial facing up. Using the top leveling screw, the laydown vial was centered, leveling the instrument in the vertical. The LB-5 was turned on and the leveling rod was held horizontal with the aid of a pocket level secured along the longitudinal axis of the rod. Measuring a nominally vertical surface required waving the rod slightly in the horizontal plane in order to capture the lowest and therefore truest rod reading. Surface height readings were taken at each grid point as shown in Figure 4.4(b).

4.3.3 Results

4.3.3.1 Accuracy

By estimating beam center, it was still possible to estimate rod readings to the nearest 0.01" for the plate specimen in both the horizontal and vertical orientation. Again, the readings were easy to reproduce. Accuracy was within +/-0.009" as was shown in Section 4.2.3.5.

4.3.3.2 Time

Time required to measure the 12"X12" field (169 data points) with the plate nominally horizontal remained at approximately 45 minutes or four readings and recordings per minute. With the plate nominally vertical, time required increased to about 60 minutes or three readings and recordings per minute. This increase was attributed to the extra attention required to obtain readings on a nominally

(a)

(b)

Figure 4.4 Measuring the out-of-flatness of a plate specimen. (a) Measuring plate in horizontal orientation; (b) Measuring plate in vertical orientation.

vertical surface. As mentioned previously, the measurer must hold the rod horizontal and wave it slightly in the horizontal plane to obtain the lowest reading.

4.3.3.3 Data Reduction and Presentation

Data for the plate specimen measured in a horizontal orientation is shown in Table 4.3. The table gives the data point coordinates and the deviation of each data point from the reference plane, as in Section 4.2. The points used to establish the arbitrary reference plane are indicated by asterisks. The surface profile is graphically illustrated in Figure 4.5.

Similarly, data for the plate specimen measured in a vertical orientation is shown in Table 4.4. The data points used to establish the reference plane are the same as in Table 4.3 for the plate specimen in the horizontal orientation. Again, the surface profile is graphically illustrated in Figure 4.6.

A comparison of the surface profiles in Figures 4.5 and 4.6 shows an almost exact match. A close look at the data in Tables 4.3 and 4.4 gives further confirmation. Only 15 of 169 points showed a difference in deviation of greater than 0.01" with a maximum difference of 0.015". It should be noted that these differences in deviation may have been greater or smaller if a different reference plane had been selected. Nevertheless, the close match of the profiles together with the fact that rod readings for the vertical plate suffered no loss in accuracy, validates the measuring method on nominally vertical surfaces.

The profiles in Figures 4.5 and 4.6 demonstrate how graphics can make the magnitudes and patterns of deviation readily apparent. The use of grid lines and color contouring are extremely helpful in

Table 4.3 Data for plate specimen measured in horizontal orientation. Data point coordinates and deviations from the reference plane are shown. Points used to establish the reference plane are indicated by asterisks.

PLATE SPECIMEN													
12"X12" FIELD (HORIZONTAL)													
LASER - VISUAL READ					Coordinates (in.)								
12	8.28	8.30	8.31	8.32	8.33	8.33	8.33	8.33	8.32	8.32	8.31	8.30	8.29
11	8.30	8.31	8.32	8.33	8.34	8.34	8.34	8.34	8.34	8.33	8.33	8.32	8.30
10	8.31	8.32	* 8.34	8.35	8.35	8.35	8.36	8.36	8.35	8.35	8.34	8.33	8.31
9	8.32	8.34	8.35	8.36	8.36	8.36	8.36	8.36	8.36	8.36	8.35	8.34	8.32
8	8.33	8.34	8.35	8.36	8.36	8.37	8.37	8.37	8.36	8.36	8.35	8.34	8.33
7	8.34	8.35	8.36	8.36	8.37	8.38	8.38	8.38	8.37	8.36	* 8.35	8.34	8.33
6	8.33	8.35	8.35	8.36	8.37	8.37	8.37	8.37	8.36	8.36	8.35	8.34	8.32
5	8.33	8.34	8.35	8.35	8.36	8.36	8.37	8.36	8.36	8.35	8.34	8.33	8.31
4	8.31	8.33	8.34	8.34	8.35	8.35	8.35	8.35	8.35	8.34	8.33	8.32	8.30
3	8.30	8.31	8.32	8.33	8.33	8.34	8.34	8.34	8.33	8.33	8.32	8.31	8.30
2	8.28	8.29	8.30	* 8.30	8.31	8.31	8.32	8.31	8.31	8.31	8.30	8.29	8.27
1	8.25	8.26	8.27	8.28	8.29	8.29	8.30	8.30	8.29	8.29	8.28	8.27	8.25
0	8.22	8.23	8.24	8.25	8.25	8.26	8.26	8.26	8.26	8.25	8.25	8.24	8.23
	0	1	2	3	4	5	6	7	8	9	10	11	12
					Deviation from Reference Plane (in.)								
12	0.064	0.048	0.041	0.034	0.027	0.031	0.034	0.037	0.050	0.054	0.067	0.080	0.094
11	0.039	0.032	0.025	0.019	0.012	0.015	0.019	0.022	0.025	0.038	0.042	0.055	0.078
10	0.023	0.017	* 0.000	-0.007	-0.003	0.000	-0.007	-0.004	0.010	0.013	0.026	0.040	0.063
9	0.008	-0.009	-0.015	-0.022	-0.019	-0.016	-0.012	-0.009	-0.006	-0.002	0.011	0.024	0.047
8	-0.007	-0.014	-0.021	-0.028	-0.024	-0.031	-0.028	-0.024	-0.011	-0.008	0.005	0.019	0.032
7	-0.023	-0.030	-0.036	-0.033	-0.040	-0.046	-0.043	-0.040	-0.027	-0.013	* 0.000	0.013	0.027
6	-0.018	-0.035	-0.032	-0.038	-0.045	-0.042	-0.039	-0.035	-0.022	-0.019	-0.006	0.008	0.031
5	-0.024	-0.030	-0.037	-0.034	-0.040	-0.037	-0.044	-0.031	-0.027	-0.014	-0.001	0.012	0.036
4	-0.009	-0.026	-0.032	-0.029	-0.036	-0.033	-0.029	-0.026	-0.023	-0.010	0.004	0.017	0.040
3	-0.004	-0.011	-0.018	-0.025	-0.021	-0.028	-0.025	-0.021	-0.008	-0.005	0.008	0.022	0.035
2	0.010	0.003	-0.003	* 0.000	-0.007	-0.003	-0.010	0.003	0.006	0.010	0.023	0.036	0.060
1	0.035	0.028	0.021	0.015	0.008	0.011	0.004	0.008	0.021	0.024	0.038	0.051	0.074
0	0.059	0.053	0.046	0.039	0.042	0.036	0.039	0.042	0.046	0.059	0.062	0.075	0.089
	0	1	2	3	4	5	6	7	8	9	10	11	12

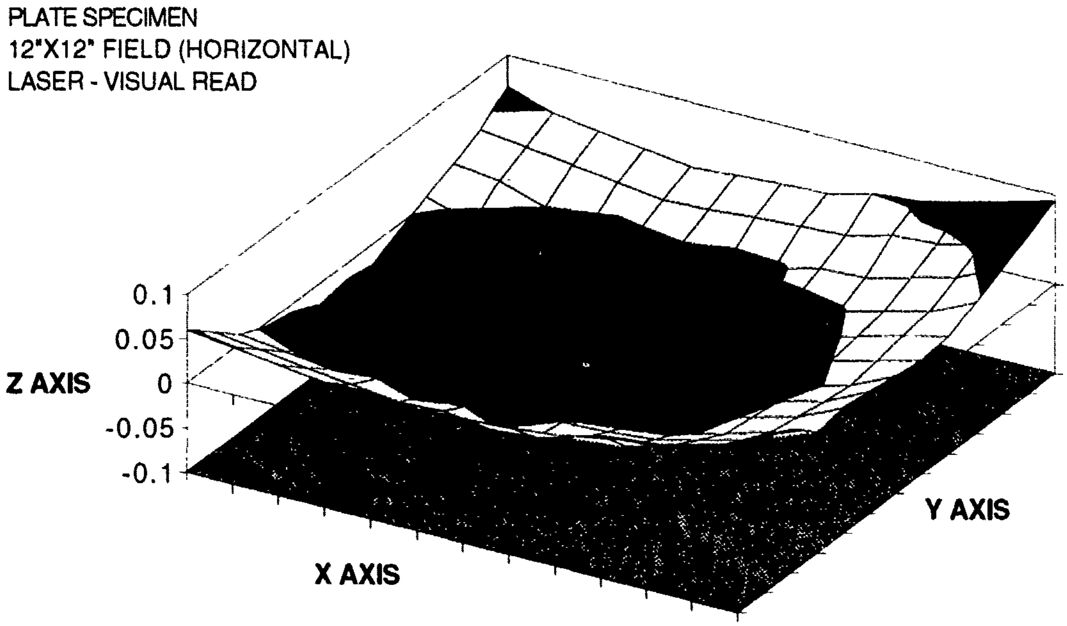


Figure 4.5 Plate specimen measured in horizontal orientation. (Based on data from Table 4.3.)

Table 4.4 Data for plate specimen measured in vertical orientation. Data point coordinates and deviations from the reference plane are shown. Points used to establish the reference plane are the same as in Table 4.3 for the plate specimen in a horizontal orientation, and are indicated by asterisks.

PLATE SPECIMEN													
12"X12" FIELD (VERTICAL)													
LASER - VISUAL READ						Coordinates (in)							
12	8.36	8.40	8.42	8.45	8.48	8.50	8.52	8.54	8.56	8.58	8.59	8.60	8.61
11	8.39	8.42	8.45	8.49	8.51	8.53	8.55	8.58	8.59	8.60	8.61	8.62	8.63
10	8.42	8.45	* 8.49	8.51	8.54	8.56	8.58	8.60	8.61	8.63	8.64	8.65	8.65
9	8.44	8.48	8.51	8.53	8.56	8.58	8.60	8.62	8.64	8.65	8.66	8.67	8.67
8	8.46	8.50	8.52	8.55	8.58	8.60	8.62	8.64	8.65	8.67	8.68	8.69	8.69
7	8.48	8.51	8.54	8.57	8.59	8.62	8.64	8.65	8.67	8.68	* 8.69	8.69	8.70
6	8.49	8.52	8.55	8.58	8.60	8.62	8.65	8.67	8.68	8.69	8.70	8.70	8.71
5	8.50	8.53	8.56	8.58	8.61	8.63	8.65	8.67	8.69	8.69	8.70	8.71	8.72
4	8.50	8.53	8.55	8.59	8.61	8.64	8.65	8.67	8.69	8.70	8.71	8.71	8.72
3	8.50	8.52	8.55	8.58	8.60	8.63	8.65	8.67	8.68	8.70	8.70	8.71	8.72
2	8.49	8.51	8.55	* 8.57	8.60	8.62	8.64	8.66	8.68	8.70	8.70	8.71	8.71
1	8.47	8.50	8.53	8.55	8.59	8.60	8.63	8.65	8.67	8.68	8.69	8.70	8.70
0	8.45	8.48	8.51	8.54	8.57	8.60	8.61	8.64	8.65	8.66	8.68	8.69	8.69
	0	1	2	3	4	5	6	7	8	9	10	11	12
					Deviation from Reference Plane (in)								
12	0.071	0.053	0.056	0.048	0.040	0.042	0.045	0.047	0.049	0.052	0.064	0.076	0.089
11	0.048	0.040	0.033	0.015	0.017	0.020	0.022	0.014	0.027	0.039	0.061	0.063	0.076
10	0.025	0.018	* 0.000	0.002	-0.005	-0.003	-0.001	0.001	0.014	0.016	0.028	0.041	0.063
9	0.013	-0.005	-0.013	-0.010	-0.018	-0.016	-0.014	-0.011	-0.009	0.003	0.016	0.028	0.050
8	0.000	-0.018	-0.016	-0.023	-0.031	-0.029	-0.026	-0.024	-0.012	-0.010	0.003	0.015	0.037
7	-0.013	-0.021	-0.028	-0.036	-0.034	-0.041	-0.039	-0.027	-0.025	-0.012	* 0.000	0.022	0.035
6	-0.016	-0.023	-0.031	-0.039	-0.037	-0.034	-0.042	-0.040	-0.027	-0.015	-0.003	0.020	0.032
5	-0.019	-0.026	-0.034	-0.032	-0.039	-0.037	-0.035	-0.032	-0.030	-0.008	0.004	0.017	0.029
4	-0.011	-0.019	-0.017	-0.034	-0.032	-0.040	-0.028	-0.025	-0.023	-0.011	0.002	0.024	0.036
3	-0.004	-0.002	-0.010	-0.017	-0.015	-0.023	-0.020	-0.018	-0.006	-0.003	0.019	0.031	0.043
2	0.013	0.015	-0.002	* 0.000	-0.008	-0.005	-0.003	-0.001	0.001	0.004	0.026	0.038	0.061
1	0.040	0.033	0.025	0.027	0.010	0.022	0.014	0.016	0.019	0.031	0.043	0.056	0.078
0	0.068	0.060	0.052	0.044	0.037	0.029	0.041	0.034	0.046	0.058	0.060	0.073	0.095
	0	1	2	3	4	5	6	7	8	9	10	11	12

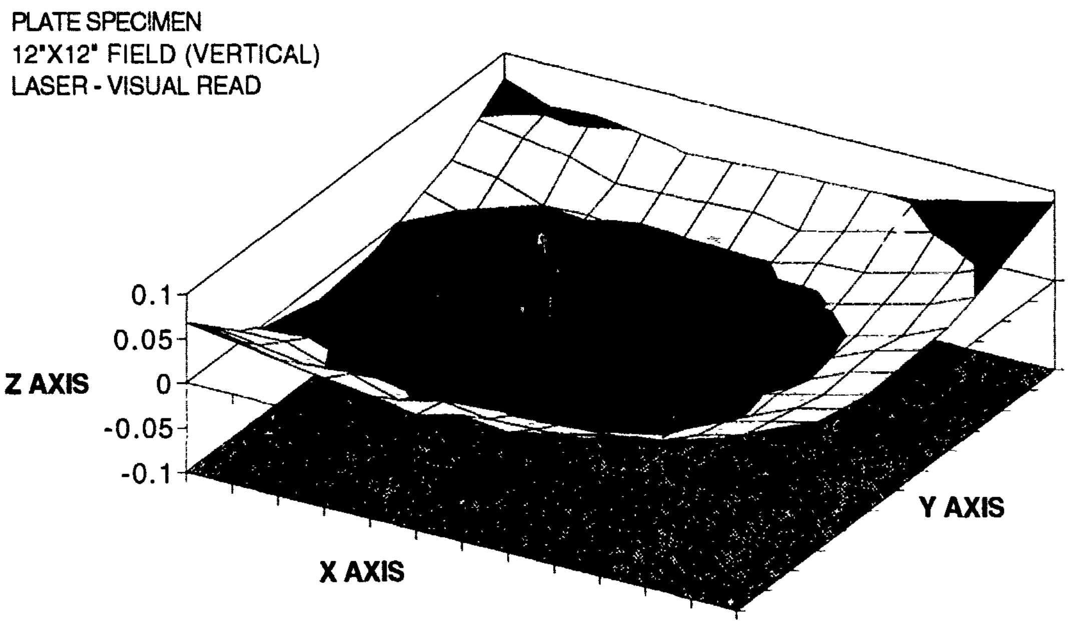


Figure 4.6 Plate specimen measured in vertical orientation. (Based on data from Table 4.4.)

understanding the deformed shape. And profiles of different specimens are easily compared.

4.4 Measurement of a Plate Girder Flange

4.4.1 General

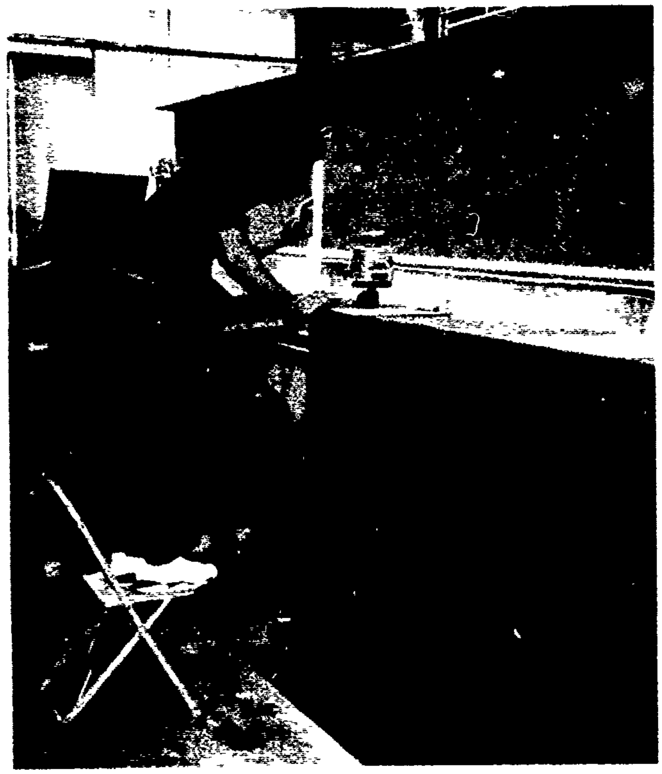
The purpose of measuring a plate girder flange was to demonstrate the laser method of measurement on a realistic, nominally horizontal specimen. Measurement of the flange was also done using an automatic optical level to evaluate its effectiveness in measuring nominally horizontal surfaces.

4.4.2 Test Setup

The specimen measured was the top flange of a plate girder. The flange had a width of 16" and a thickness of $1^1/_2$".

The flange was first measured using the laser method. A 10"X15" measuring field with 1" grid was drawn on the flange. The LB-5 was mounted to the flange with the magnetic base, leveled in the horizontal, and turned on. The leveling rod was held vertical using the attached rod level. Surface height readings were taken at each grid point as shown in Figure 4.7(a).

The flange was then measured using an automatic optical level. The optical level was mounted to the flange with the magnetic base, and the instrument was leveled. The leveling rod was held vertical by the rodperson while the level operator sighted on the rod. Surface height readings were taken at each grid point as shown in Figure 4.7(b)



(a)

(b)

Figure 4.7 Measuring the out-of-flatness of a plate girder flange. (a)Measurement using LB-5 laser level; (b) Measurement using automatic optical level.

4.4.3 Results

4.4.3.1 Accuracy

As previously mentioned, estimating beam center allows an estimated rod reading to the nearest 0.01". The accuracy of the laser method is within +/-0.009" as was shown in Section 4.2.3.5.

On the other hand, the magnification of the leveling rod graduations made possible by the automatic optical level allowed a clear rod reading to the nearest 0.01". The optical method was more accurate than the laser method. However, the coordination between the level operator and rodperson required by the optical method increased the likelihood of human errors.

4.4.3.2 Time

Time required to measure a 10"X15" field (176 data points) using the laser method was about 45 minutes or four readings and recordings per minute. Time required using the optical method was about 25 minutes but required two people.

4.4.3.3 Data Reduction and Presentation

Data for the plate girder flange measured using the laser method is shown in Table 4.5. The table gives the data point coordinates and the deviation of each data point from the reference plane, as in previous sections. The points used to establish the arbitrary reference plane are indicated by asterisks. The surface profile is graphically illustrated in Figure 4.8.

Similarly, data for the flange measured using the automatic optical level is shown in Table 4.6. The data points used to establish the reference plane are the same as in Table 4.5 for the flange measured using the laser method. The surface profile is graphically illustrated in Figure 4.9.

A comparison of the surface profiles in Figures 4.8 and 4.9 shows an almost exact match. A close look at the data in Tables 4.5 and 4.6 gives further confirmation. With the exception of 19 of 176 points, all deviations from the reference plane are exactly the same. The difference in deviation shown by the 19 points that did differ was exactly 0.01". This reflects the fact that estimating beam center on the rod gave an estimated rod reading to the nearest 0.01" that was wrong at only 19 points. And when the reading was wrong, it was simply a matter of rounding to the next higher 0.01" graduation instead of the next lower 0.01" graduation, or vice versa. In the great majority of cases, measurement with the laser level gave the same relative rod reading as measurement with the optical level.

Table 4.5 Data for plate girder flange measured using laser method. Data point coordinates and deviations from the reference plane are shown. Points used to establish the reference plane are indicated by asterisks.

PLATE GIRDER - FLANGE											
10"X15" FIELD											
LASER - VISUAL READ					Coordinates (in)						
15	8.26	8.27	8.27	8.27	8.28	8.28	8.28	8.28	8.28	8.28	8.28
14	8.25	* 8.26	8.26	8.27	8.27	8.27	8.27	8.27	8.27	8.27	8.27
13	8.25	8.25	8.25	8.26	8.26	8.26	8.26	8.26	8.27	8.26	8.26
12	8.24	8.24	8.25	8.25	8.25	8.25	8.26	8.26	8.26	8.26	8.26
11	8.23	8.23	8.24	8.24	8.25	8.25	8.25	8.25	8.25	8.25	8.25
10	8.23	8.23	8.23	8.23	8.24	8.24	8.24	8.25	8.25	* 8.25	8.25
9	8.22	8.22	8.23	8.23	8.23	8.23	8.24	8.24	8.24	8.24	8.24
8	8.21	8.21	8.22	8.22	8.22	8.23	8.23	8.23	8.23	8.24	8.24
7	8.21	8.21	8.21	8.21	8.22	8.22	8.22	8.23	8.23	8.23	8.23
6	8.21	8.21	8.21	8.21	8.21	8.22	8.22	8.22	8.23	8.23	8.23
5	8.20	8.20	8.21	8.21	8.21	8.21	8.21	8.22	8.22	8.22	8.22
4	8.20	8.20	8.20	8.21	8.21	8.21	8.21	8.21	8.22	8.22	8.22
3	8.20	8.20	8.20	* 8.20	8.21	8.21	8.21	8.21	8.21	8.22	8.22
2	8.20	8.20	8.20	8.20	8.21	8.21	8.21	8.21	8.21	8.21	8.21
1	8.20	8.20	8.20	8.20	8.20	8.21	8.21	8.21	8.21	8.21	8.21
0	8.20	8.20	8.20	8.20	8.20	8.21	8.21	8.21	8.21	8.21	8.21
	0	1	2	3	4	5	6	7	8	9	10
				Deviation from Reference Plane (in)							
15	0.004	-0.004	-0.003	-0.001	-0.009	-0.008	-0.006	-0.004	-0.003	-0.001	0.000
14	0.008	* 0.000	0.002	-0.007	-0.005	-0.003	-0.002	0.000	0.001	0.003	0.005
13	0.003	0.004	0.006	-0.002	-0.001	0.001	0.002	0.004	-0.004	0.007	0.009
12	0.007	0.008	0.000	0.002	0.003	0.005	-0.003	-0.002	0.000	0.001	0.003
11	0.011	0.013	0.004	0.006	-0.002	-0.001	0.001	0.002	0.004	0.006	0.007
10	0.005	0.007	0.009	0.010	0.002	0.003	0.005	-0.003	-0.002	* 0.000	0.002
9	0.010	0.011	0.003	0.004	0.006	0.008	-0.001	0.001	0.003	0.004	0.006
8	0.014	0.015	0.007	0.009	0.010	0.002	0.004	0.005	0.007	-0.001	0.000
7	0.008	0.010	0.011	0.013	0.005	0.006	0.008	0.000	0.001	0.003	0.004
6	0.002	0.004	0.006	0.007	0.009	0.000	0.002	0.004	-0.005	-0.003	-0.001
5	0.007	0.008	0.000	0.001	0.003	0.005	0.006	-0.002	0.000	0.001	0.003
4	0.001	0.002	0.004	-0.004	-0.003	-0.001	0.001	0.002	-0.006	-0.004	-0.003
3	-0.005	-0.003	-0.002	* 0.000	-0.008	-0.007	-0.005	-0.003	-0.002	-0.010	-0.009
2	-0.011	-0.009	-0.007	-0.006	-0.014	-0.012	-0.011	-0.009	-0.008	-0.006	-0.004
1	-0.016	-0.015	-0.013	-0.011	-0.010	-0.018	-0.017	-0.015	-0.013	-0.012	-0.010
0	-0.022	-0.020	-0.019	-0.017	-0.016	-0.024	-0.022	-0.021	-0.019	-0.017	-0.016
	0	1	2	3	4	5	6	7	8	9	10

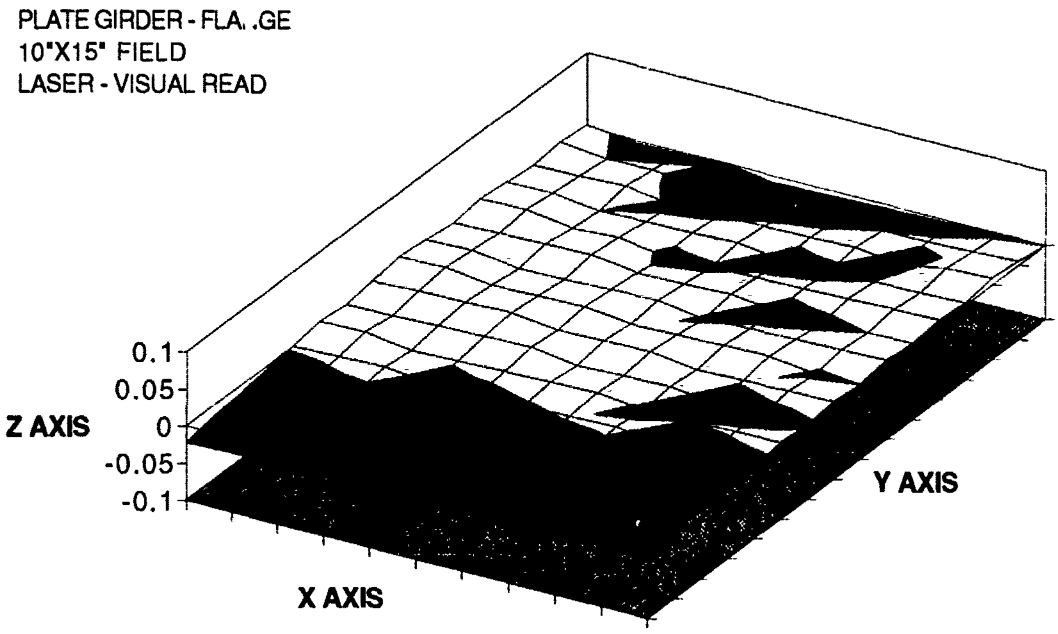


Figure 4.8 Plate girder flange measured using laser method. (Based on data from Table 4.5.)

Table 4.6 Data for plate girder flange measured using automatic optical level. Data point coordinates and deviations from the reference plane are shown. Points used to establish the reference plane are the same as in Table 4.5 for the flange measured using the laser method.

PLATE GIRDER - FLANGE											
10"X15" FIELD											
OPTICAL LEVEL					Coordinates (in)						
15	6.37	6.35	6.38	6.38	6.39	6.39	6.39	6.40	6.39	6.40	6.40
14	6.36	* 6.37	6.37	6.38	6.38	6.38	6.38	6.38	6.39	6.39	6.39
13	6.36	6.36	6.36	6.37	6.37	6.37	6.37	6.38	6.38	6.38	6.38
12	6.35	6.35	6.36	6.36	6.36	6.36	6.37	6.37	6.37	6.37	6.37
11	6.34	6.34	6.35	6.35	6.36	6.36	6.36	6.36	6.36	6.36	6.36
10	6.34	6.34	6.34	6.34	6.35	6.35	6.35	6.36	6.36	* 6.36	6.36
9	6.33	6.33	6.34	6.34	6.34	6.34	6.35	6.35	6.35	6.35	6.36
8	6.32	6.32	6.33	6.33	6.33	6.34	6.34	6.34	6.34	6.35	6.35
7	6.32	6.32	6.32	6.32	6.33	6.33	6.33	6.34	6.34	6.34	6.34
6	6.32	6.32	6.32	6.32	6.32	6.33	6.33	6.33	6.34	6.34	6.34
5	6.31	6.31	6.32	6.32	6.32	6.32	6.32	6.33	6.33	6.33	6.33
4	6.31	6.31	6.31	6.32	6.32	6.32	6.32	6.32	6.33	6.33	6.33
3	6.30	6.30	6.31	* 6.31	6.32	6.32	6.32	6.32	6.32	6.33	6.33
2	6.30	6.30	6.31	6.31	6.32	6.32	6.32	6.32	6.32	6.32	6.32
1	6.30	6.30	6.31	6.31	6.31	6.32	6.32	6.32	6.32	6.32	6.32
0	6.30	6.30	6.30	6.31	6.31	6.32	6.32	6.32	6.32	6.32	6.32
	0	1	2	3	4	5	6	7	8	9	10
				Deviation from Reference Plane (in)							
15	0.004	-0.004	-0.003	-0.001	-0.009	-0.008	-0.006	-0.014	-0.003	-0.011	-0.010
14	0.008	* 0.000	0.002	-0.007	-0.005	-0.003	-0.002	0.000	-0.009	-0.007	-0.005
13	0.003	0.004	0.006	-0.002	-0.001	0.001	0.002	-0.006	-0.004	-0.003	-0.001
12	0.007	0.008	0.000	0.002	0.003	0.005	-0.003	-0.002	0.000	0.001	0.003
11	0.011	0.013	0.004	0.006	-0.002	-0.001	0.001	0.002	0.004	0.006	0.007
10	0.005	0.007	0.009	0.010	0.002	0.003	0.005	-0.003	-0.002	* 0.000	0.002
9	0.010	0.011	0.003	0.004	0.006	0.008	-0.001	0.001	0.003	0.004	-0.004
8	0.014	0.015	0.007	0.009	0.010	0.002	0.004	0.005	0.007	-0.001	0.000
7	0.008	0.010	0.011	0.013	0.005	0.006	0.008	0.000	0.001	0.003	0.004
6	0.002	0.004	0.006	0.007	0.009	0.000	0.002	0.004	-0.005	-0.003	-0.001
5	0.007	0.008	0.000	0.001	0.003	0.005	0.006	-0.002	0.000	0.001	0.003
4	0.001	0.002	0.004	-0.004	-0.003	-0.001	0.001	0.002	-0.006	-0.004	-0.003
3	0.005	0.007	-0.002	* 0.000	-0.008	-0.007	-0.005	-0.003	-0.002	-0.010	-0.009
2	-0.001	0.001	-0.007	-0.006	-0.014	-0.012	-0.011	-0.009	-0.008	-0.006	-0.004
1	-0.006	-0.005	-0.013	-0.011	-0.010	-0.018	-0.017	-0.015	-0.013	-0.012	-0.010
0	-0.012	-0.010	-0.009	-0.017	-0.016	-0.024	-0.022	-0.021	-0.019	-0.017	-0.016
	0	1	2	3	4	5	6	7	8	9	10

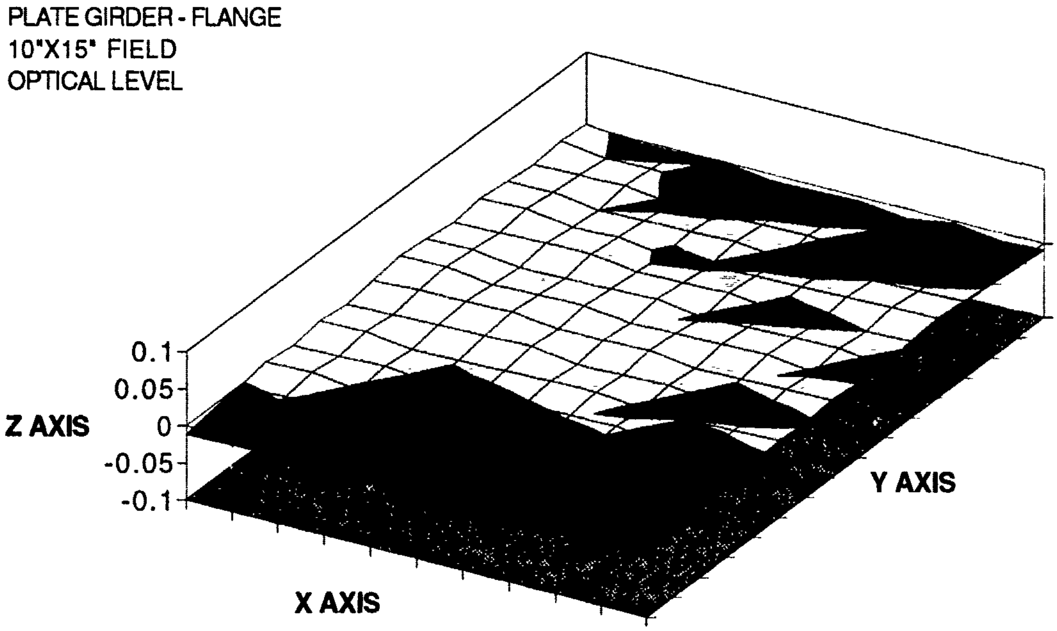


Figure 4.9 Plate girder flange measured using automatic optical level. (Based on data from Table 4.6.)

4.4.3.4 Measurement with the Automatic Optical Level

The automatic optical level will measure the out-of-flatness of nominally horizontal surfaces with greater accuracy and in less time than the laser level. Therefore the optical level can be considered when circumstances allow. However, the optical level is subject to a number of limitations that reduce its flexibility as a measuring device:

1. Measurement with the optical level requires two people: a level operator and a rodperson.

2. The coordination between the level operator and the rodperson increases the chance of human errors.

3. The automatic optical level can only establish a horizontal plane and is therefore only useful in measuring nominally horizontal surfaces.

4. The minimum focus range for optical levels can be as much as eight feet, limiting their use over the short ranges associated with out-of-flatness measurement. While optical levels are available with minimum focus ranges of less than three feet, these are the exception.

5. If the optical level is mounted on the surface to be measured, the level operator must assume rather awkward and difficult positions while sighting on the rod. A 90° eyepiece may help somewhat, but is a rare and suprisingly expensive accessory.

Thus, the automatic optical level can be used to measure out-of-flatness within the constraints of the foregoing limitations. However, the laser method is a one-person operation, gives the greatest ease and flexibility of measurement, and provides an accuracy of within +/- 0.009". Unless greater accuracy is required, the use of the optical level in out-of-flatness measurement is not recommended.

4.5 Measurement of a Plate Girder Web

4.5.1 General

The purpose of measuring a plate girder web was to demonstrate the laser method of measurement on a realistic, nominally vertical specimen.

4.5.2 Test Setup

The specimen measured was the web of the plate girder used in Section 4.4. The web had a depth of 48"and a thickness of $^1/_2$".

A 10"X30" measuring field with 1" grid was drawn on the web. The LB-5 was mounted to the web with the laydown vial facing up. Using the top leveling screw, the laydown vial was centered, leveling the instrument in the vertical. The LB-5 was turned on and the leveling rod was held horizontal with the aid of a pocket level secured along the longitudinal axis of the rod. Measuring the web required waving the rod slightly in the horizontal plane to capture the lowest and therefore truest rod reading. Surface height readings were taken at each grid point as shown in Figure 4.10.

4.5.3 Results

4.5.3.1 Accuracy

By estimating beam center, it was still possible to estimate rod readings to the nearest 0.01" for the web. The readings were easy to reproduce. Again, accuracy is within +/-0.009" as was previously shown.

Figure 4.10 Measuring the out-of-flatness of a plate girder web.

4.5.3.2 Time

The total time to measure the 10"X30" field (341 data points) was about three hours or two readings and recordings per minute. Measurements could be taken at the rate of three readings and recordings per minute, but fatigue of the measurer was a factor and required breaks in the work.

4.5.3.3 Data Reduction and Presentation

Data for the web is shown in Table 4.7. The table gives the data point coordinates and the deviation of each data point from the reference plane, as in previous sections. The points used to establish the arbitrary reference plane are indicated by asterisks. The surface profile is graphically illustrated in Figure 4.11. Patterns and severity of deviation from the reference plane are readily apparent.

Table 4.7 Data for plate girder web. Data point coordinates and deviations from the reference plane are shown. Points used to establish the reference plane are indicated by asterisks.

PLATE GIRDER - WEB											
10"X30" FIELD											
LASER - VISUAL READ					Coordinates (in.)						
30	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09	8.09
29	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10
28	8.11	8.11	8.10	8.10	8.10	8.10	* 8.10	8.10	8.10	8.10	8.10
27	8.11	8.11	8.11	8.11	8.11	8.11	8.11	8.11	8.11	8.11	8.11
26	8.12	8.13	8.13	8.12	8.12	8.12	8.12	8.12	8.12	8.12	8.12
25	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13
24	8.14	8.14	8.14	8.14	8.14	8.14	8.14	8.14	8.14	8.14	8.14
23	8.15	8.15	8.15	8.15	8.16	8.15	8.15	8.15	8.15	8.15	8.15
22	8.16	8.16	8.16	8.16	8.16	8.16	8.15	8.15	8.15	8.15	8.15
21	8.17	8.17	8.17	8.17	8.17	8.16	8.16	8.16	8.16	8.16	8.16
20	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17
19	8.18	8.18	8.18	8.18	8.18	8.17	8.17	8.17	8.17	8.17	8.17
18	8.19	8.19	8.19	8.19	8.19	8.19	8.18	8.18	8.18	8.18	8.18
17	8.20	8.20	8.20	8.19	8.19	8.19	8.19	8.19	8.19	8.19	8.19
16	8.21	8.20	8.20	8.20	8.20	8.20	8.20	8.19	8.19	8.19	8.19
15	8.21	8.21	8.21	8.21	8.20	8.20	8.20	8.20	8.20	8.20	8.20
14	8.21	8.21	8.21	8.21	8.21	8.21	8.21	8.20	8.20	8.20	8.20
13	8.22	8.22	8.22	8.22	8.21	8.21	8.21	8.21	8.21	8.21	8.21
12	8.23	8.23	8.23	8.22	8.22	8.22	8.21	8.21	8.21	8.21	8.21
11	8.23	8.23	8.23	8.23	8.23	8.22	8.22	8.22	8.22	8.21	8.21
10	8.24	8.24	8.23	8.23	8.23	8.23	8.23	8.23	8.22	8.22	8.22
9	8.24	* 8.24	8.24	8.24	8.24	8.23	8.23	8.23	8.23	8.22	8.22
8	8.25	8.25	8.24	8.24	8.24	8.24	8.24	8.23	8.23	8.23	8.23
7	8.25	8.25	8.25	8.24	8.24	8.24	8.24	8.24	8.23	8.23	8.23
6	8.25	8.25	8.25	8.25	8.24	8.24	8.24	8.24	8.24	8.24	8.24
5	8.26	8.26	8.25	8.25	8.25	8.25	8.24	8.24	8.24	8.24	8.24
4	8.26	8.26	8.26	8.25	8.25	8.25	8.24	8.24	* 8.24	8.24	8.24
3	8.26	8.26	8.26	8.26	8.25	8.25	8.25	8.25	8.24	8.24	8.24
2	8.27	8.27	8.26	8.26	8.26	8.25	8.25	8.25	8.25	8.25	8.25
1	8.27	8.27	8.27	8.27	8.26	8.26	8.25	8.25	8.25	8.25	8.25
0	8.27	8.27	8.27	8.27	8.26	8.26	8.26	8.25	8.25	8.25	8.25
	0	1	2	3	4	5	6	7	8	9	10
			Deviation from Reference Plane (in.)								
30	-0.024	-0.020	-0.015	-0.011	-0.006	-0.002	0.002	0.007	0.011	0.016	0.020
29	-0.020	-0.016	-0.012	-0.007	-0.003	0.002	0.006	0.011	0.015	0.019	0.024
28	-0.017	-0.012	-0.018	-0.013	-0.009	-0.004	* 0.000	0.004	0.009	0.013	0.018
27	-0.023	-0.018	-0.014	-0.009	-0.005	-0.001	0.004	0.008	0.013	0.017	0.022
26	-0.019	-0.005	0.000	-0.006	-0.001	0.003	0.008	0.012	0.016	0.021	0.025
25	-0.015	-0.011	-0.006	-0.002	0.003	0.007	0.011	0.016	0.020	0.025	0.029
24	-0.011	-0.007	-0.003	0.002	0.006	0.011	0.015	0.020	0.024	0.028	0.033
23	-0.008	-0.003	0.001	0.006	0.010	0.015	0.019	0.023	0.028	0.032	0.037
22	-0.004	0.001	0.005	0.009	0.014	0.018	0.013	0.017	0.022	0.026	0.031
21	0.000	0.004	0.009	0.013	0.018	0.012	0.017	0.021	0.025	0.030	0.034
20	-0.006	-0.002	0.003	0.007	0.012	0.016	0.020	0.025	0.029	0.034	0.038
19	-0.002	0.002	0.006	0.011	0.015	0.010	0.014	0.019	0.023	0.027	0.032
18	0.001	0.006	0.010	0.015	0.019	0.024	0.018	0.022	0.027	0.031	0.036
17	0.005	0.010	0.014	0.008	0.013	0.017	0.022	0.026	0.031	0.035	0.039
16	0.009	0.003	0.008	0.012	0.017	0.021	0.026	0.020	0.024	0.029	0.033
15	0.003	0.007	0.012	0.016	0.011	0.015	0.019	0.024	0.028	0.033	0.037
14	-0.003	0.001	0.005	0.010	0.014	0.019	0.023	0.018	0.022	0.026	0.031
13	0.000	0.005	0.009	0.014	0.008	0.013	0.017	0.021	0.026	0.030	0.035
12	0.004	0.009	0.013	0.007	0.012	0.016	0.011	0.015	0.020	0.024	0.028
11	-0.002	0.002	0.007	0.011	0.016	0.010	0.015	0.019	0.023	0.018	0.022
10	0.002	0.006	0.001	0.005	0.009	0.014	0.018	0.023	0.017	0.022	0.026
9	-0.004	* 0.000	0.004	0.009	0.013	0.008	0.012	0.017	0.021	0.015	0.020
8	-0.001	0.004	-0.002	0.003	0.007	0.012	0.016	0.010	0.015	0.019	0.024
7	-0.007	-0.002	0.002	-0.004	0.001	0.005	0.010	0.014	0.009	0.013	0.017
6	-0.013	-0.009	-0.004	0.000	-0.005	-0.001	0.004	0.008	0.012	0.017	0.021
5	-0.009	-0.005	-0.010	-0.006	-0.002	0.003	-0.003	0.002	0.006	0.011	0.015
4	-0.015	-0.011	-0.007	-0.012	-0.008	-0.003	-0.009	-0.004	* 0.000	0.004	0.009
3	-0.022	-0.017	-0.013	-0.008	-0.014	-0.009	-0.005	-0.001	-0.006	-0.002	0.003
2	-0.018	-0.013	-0.019	-0.015	-0.010	-0.016	-0.011	-0.007	-0.002	0.002	0.006
1	-0.024	-0.020	-0.015	-0.011	-0.016	-0.012	-0.017	-0.013	-0.009	-0.004	0.000
0	-0.030	-0.026	-0.021	-0.017	-0.023	-0.018	-0.014	-0.019	-0.015	-0.010	-0.006
	0	1	2	3	4	5	6	7	8	9	10

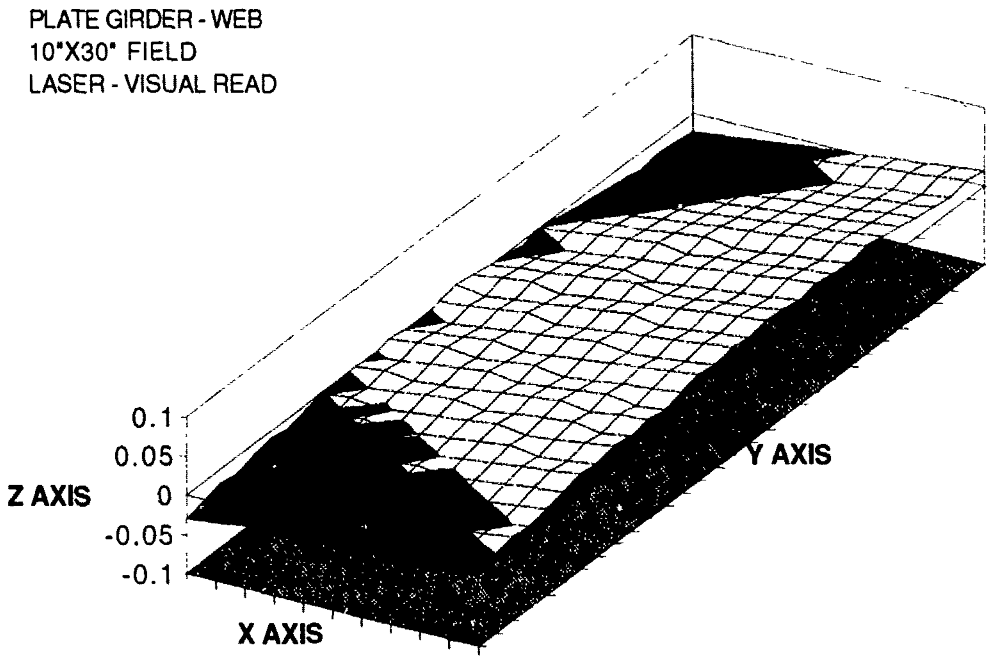


Figure 4.11 Plate girder web. (Based on data from Table 4.7.)

CHAPTER FIVE

MEASURING OUT-OF-FLATNESS: A "STEP-BY-STEP" PROCEDURE

A "step-by-step" procedure for field measuring the out-of-flatness of structural steel plates is presented below. The procedure is based on the development in preceding chapters. Familiarity with the Laser Alignment LB-5 Laser Beacon and precision leveling rod is assumed.

1. Read and follow all safety instructions included with the LB-5.

2. Calibrate the LB-5. Calibration instructions can be found in the Operation Manual.

3. Place a strip of electrical tape at the top and bottom edge of the laser beam's exit aperture to narrow the beam's width. Turn the LB-5 on and view the beam on the leveling rod. If necessary, further adjust the strips of tape to obtain a thin line of light on the rod. Narrowing the beam's width to approximately 0.02" works well.

4. Draw the measuring field on the surface to be measured. Removable china marker is useful for this purpose. Use of a 1" grid is recommended unless a smaller interval is needed or desired. Be sure to indicate an X and Y axis to "fix" the orientation of the field.

5. Horizontal surfaces. To measure nominally horizontal surfaces, mount the LB-5 near the measuring field with the magnetic base. Adjust the leveling screws to center the level vials for horizontal operation, and turn the instrument on. Hold the leveling rod vertical using the attached rod level. Take and record surface height readings at each grid point.

Vertical surfaces. To measure nominally vertical surfaces, mount the LB-5 near the measuring field with the laydown vial facing up. Use the top leveling screw to center the laydown vial, and turn the instrument on. Hold the leveling rod horizontal using a pocket level secured along the longitudinal axis of the rod. Wave the rod slightly in the horizontal plane to capture the lowest and therefore truest rod reading. Take and record surface height readings at each grid point.

Note: To take a rod reading, estimate the center of the beam as it appears on the rod. Then estimate the rod reading to the nearest 0.01". This procedure will give an accuracy within +/-0.009".

6. Data reduction. Define a reference plane using any three non-colinear data points (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3) using the following equation:

$$\begin{vmatrix} y_2 - y_1 & z_2 - z_1 \\ y_3 - y_1 & z_3 - z_1 \end{vmatrix}(x - x_1) + \begin{vmatrix} z_2 - z_1 & x_2 - x_1 \\ z_3 - z_1 & x_3 - x_1 \end{vmatrix}(y - y_1) + \begin{vmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{vmatrix}(z - z_1) = 0 \qquad \mathbf{6.1}$$

Reduce the above equation for a reference plane to the following form where A, B, C and D are constants:

$$Ax + By + Cz + D = 0 \qquad \mathbf{6.2}$$

Use a commercial spreadsheet program to calculate the perpendicular distance from the reference plane to each data point (x_0, y_0, z_0) by

$$\frac{Ax_0 + By_0 + Cz_0 + D}{-\sqrt{A^2 + B^2 + C^2}} \qquad \mathbf{6.3}$$

Note: If desired, a regression analysis can be performed on the data point coordinates to obtain a "best fit" reference plane (see reference 7).

7. Presentation. Use the graphing capabilities common to spreadsheet programs to graphically illustrate the surface profile. Use graphing features such as scale sizing, grid lines and color contouring to enhance the presentation.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

6.1 Summary of Work

The out-of-flatness of structural steel plates in bolted connections can prevent desired bolt tensions from being achieved, even when specified installation procedures are used. In order to correlate out-of-flatness and its bolt-loosening effect, an efficient and accurate means of field measuring out-of-flatness is required.

This thesis presents the development of a field method to measure the out-of-flatness of structural steel plates. First, out-of-flatness was defined and a list of measuring method requirements was established. Next, a method using a manual rotating beam laser level and a purpose-built precision leveling rod was presented. The methodology and devices were detailed to include techniques for data reduction and presentation. Finally, the measuring method was demonstrated and validated on a number of specimens: a granite surface table, a plate specimen with noticeable curvature, and the top flange and web of a plate girder.

6.2 Conclusions

The laser method of measuring out-of-flatness presented in this thesis provides a simple, economical means of measuring nominally horizontal and vertical surfaces in the field. The method requires only one measurer and will determine the surface profile of a plate to within +/-0.009". Time to measure a 12"X12" field with a 1" grid is about 45 minutes for a nominally horizontal surface. Time increases to about 60 minutes for a nominally vertical surface. The range over which measurements can be made varies from about five feet in direct bright sunlight to over ten feet in normal interior lighting conditions. Range is not a limiting factor over the short ranges associated with out-of-flatness measurement.

The laser detector is ineffective as an alternative device to take rod readings.

The automatic optical level can be used to measure nominally horizontal surfaces with greater accuracy and in less time than the laser method. However, the optical method requires two people, increases the chance of human errors, can only be used on nominally horizontal surfaces, and can require the level operator to assume difficult positions while sighting on the rod. The minimum focus range of the optical level may further limit its use on certain specimens. Unless greater accuracy is required, the use of an optical level in out-of-flatness measurement is not recommended.

Data reduction and presentation is greatly facilitated by the power of a spreadsheet program and its associated graphing capabilities. Graphing features like scale-sizing, grid lines and color contouring are effective in enhancing the presentation. Magnitudes and patterns of deviation from a selected reference plane are readily apparent. Immediate qualitative judgements can be made about the severity of out-of-flatness. Profiles of different specimens are easily compared.

Using an arbitrary reference plane will still allow an accurate depiction of the surface profile. However, a regression analysis can be run on the data point coordinates to obtain a "best fit" reference plane. A "best fit" plane will minimize deviations and provides a more rational reduction and presentation of data by eliminating the "tilting" effect of an arbitrarily selected reference plane.

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