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# Out-of-flatness of steel plate girder webs, part I: Tolerance review and measurements

Parfait M. Masungi [a,*], Maria E.M. Garlock [a], Spencer E. Quiel [b]

[a] Princeton University, Dept. of Civil and Environmental Engineering, 54 Olden Street, Princeton, NJ 08544, USA
[b] Lehigh University, Dept. of Civil and Environmental Engineering, 117 ATLSS Drive, Bethlehem, PA 18015, USA

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ABSTRACT

Slender webs in welded steel plate I-girders (often used for long spans or load transfer in bridges and buildings) develop initial out-of-flatness imperfections as a result of fabrication (e.g., rolling, forming, welding, and assembly). Previous research has suggested that these imperfections can reduce the shear strength of the web; therefore, various specifications since the 1960s have included out-of-flatness imperfection tolerance limits for webs in steel plate girders. The research presented in this paper (1) provides a comprehensive review of current web out-of-flatness tolerance limits and measurement approaches, (2) introduces an alternative measurement technique for the out-of-flatness of webs (which collects a wide array of equispaced measurements), and (3) presents field measurements of 23 web panels (bounded by transverse stiffeners) across 12 different girders (with depths ranging from 0.914 to 2.08 *m*) that were commercially fabricated for bridge applications. The peak value for the out-of-flatness of the web, averaged across all measurements for each panel, was $d/170$ (where $d$ represents the least panel dimension). However, the location of peak out-of-flatness is seldom at the middle of the panel and has a 'dimpled' shape, meaning that the peak out-of-plane bulge covers only a small portion of the panel. The measurements demonstrated in this paper provide significantly more data resolution, thus enabling a better evaluation of the true impact of realistically irregular imperfection shapes and magnitudes on the shear strength of the plate. Such an evaluation based on the measurements presented in this paper is documented in a companion paper and is performed via numerical finite element analysis.

## 1. Introduction

Built-up steel plate girders are typically composed of a thin web plate welded between flanges, thus producing an I-shape as shown in Fig. 1. A thin web plate, whose slenderness is defined as the ratio of depth-to-thickness ($D/t_w$), enables a weight reduction and increased separation between the flanges for increased flexural capacity and stiffness. These thin webs possess some shear strength but are typically limited by shear buckling (i.e. instability and loss of strength due to out-of-plane deformations) rather than by in-plane yielding. Intermediate vertical components (referred to as "transverse stiffeners," as shown in Fig. 1) are therefore shop welded to the web to (a) mitigate buckling, (b) enhance resistance to forces induced by shear and bending moment, (c) stabilize the web-to-flange interface against longitudinal rotation during handling and transport operations, and (d) resist direct bearing support forces [1–4].

When a girder section is fabricated, the web and flange plates will realistically have some geometric out-of-flatness imperfections (i.e. these plates will not be perfectly flat or perfectly orthogonal at their welded interface) [2]. Out-of-flatness imperfections can be exacerbated by unsymmetrical welding and are manifested in the web as small out-of-plane deformities (shaped as irregular bulges, waves, or ripples) or as minor flange-tilt about their longitudinal axis. The work presented herein focuses on the initial out-of-flatness imperfections of web plates, in particular post fabrication prior to erection. Large initial web out-of-flatness imperfections can have an adverse effect on their shear capacity and stiffness depending on their magnitudes and shapes [5,6]. The aesthetic quality of visible girders can also be negatively impacted by the appearance of web out-of-flatness imperfections, from which an uninformed observer may incorrectly assume that the girder is defective or damaged.

Since 1941, the fabrication of plate girders in US practice has adhered to the American Welding Society (AWS) specifications [7], and early steel specifications issued by the AWS such as AWS D2.0–66 [8]

* Corresponding author.
*E-mail addresses:* pmasungi@princeton.edu (P.M. Masungi), mgarlock@princeton.edu (M.E.M. Garlock), seq213@lehigh.edu (S.E. Quiel).

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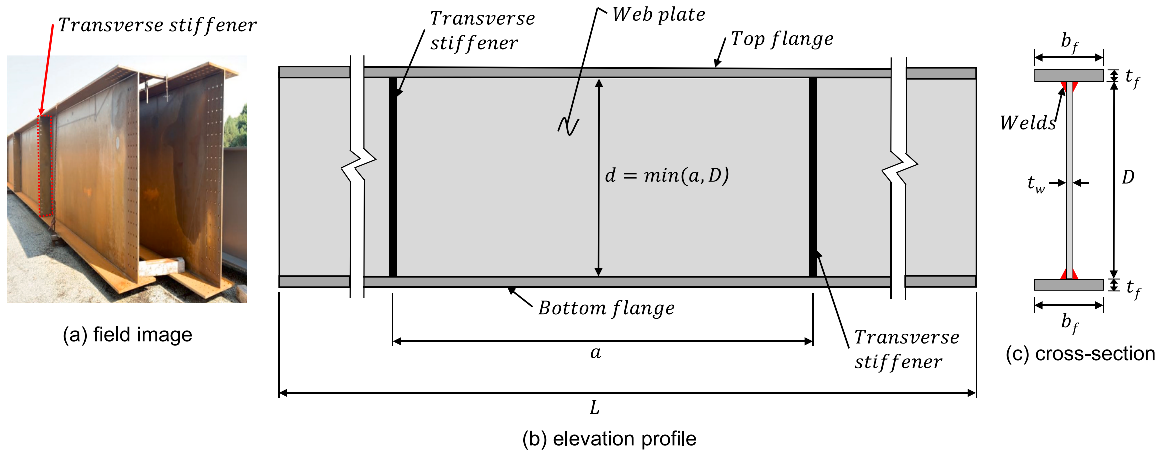


**Fig. 1.** Illustration of a typical welded steel plate girder.

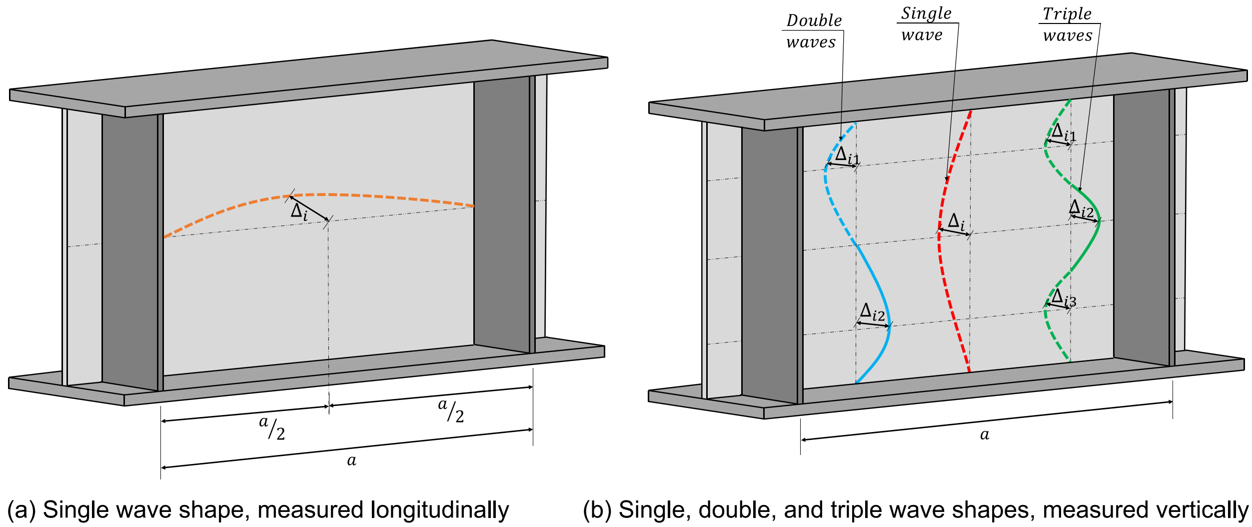


**Fig. 2.** General illustration of local out-of-flatness shapes.

provided acceptable tolerance limits for imperfections in the girder webs. However, early specifications did not specify a consistent approach nor standardized methods as to how the web out-of-flatness imperfections ought to be measured. The current AWS specifications (AASHTO/AWS D1.5) [2] and other steel design standards outside the US [9–17] now provide acceptable web out-of-flatness imperfection tolerance limits as well as simplified guidance on the measurement approach. However, there are numerous inconsistencies between these specifications, primarily regarding the tolerance limits, which can pose challenges to the design and fabrication of plate girders depending on the applicable regional standards. Following an extensive review of the published standards and their cited references, Zhang [18] concluded that these tolerance limits have little-to-no theoretical or engineering basis but are instead based on reasonable controls in plate girder fabrication production as well as balancing expectations between cost, aesthetics, and structural behavior.

Most design basis predictions for shear resistance of thin web plates in current plate girder practice [3,9,19] (based on previous research by Timoshenko [20], Basler et al. [21,22], Höglund [23], and others [24]) do not explicitly account for the influence of web out-of-flatness imperfections. To develop better scientific and engineering understanding of the influence of web out-of-flatness imperfections, Bergfelt [25] in 1979 studied the influence of four main factors on the shear resistance of thin webs in plate girders designed with transverse stiffeners: (1) web slenderness, (2) initial out-of-flatness imperfection shape, (3) initial out-of-flatness imperfection magnitude (which is characterized as a fractional ratio between the web depth or shortest panel length and the maximum measured out-of-flatness imperfection value), and (4) flange-to-web stiffness ratio. Bergfelt recognized that the shear strength of the plate would decrease if the initial out-of-flatness imperfection shape had the same shape as the buckling mode. Conversely, if the initial out-of-flatness imperfection shape deviated from that of the buckling mode, then the shear strength of the plate would likely increase since the plate would require additional force to "find" its buckled shape.

Following these studies, various strength reduction factors as a function of the web slenderness have been proposed [26,27] to address the gap that exists in most shear strength design equations by incorporating the influence of initial web out-of-flatness imperfections. Though useful, these factors are not based on field observations; they are derived by overlaying a perceived maximum out-of-plane imperfection magnitude (based on guidelines such as the aforementioned AWS standards) onto an idealized or theoretical web out-of-flatness imperfection shape. To date, there is no published work regarding the consistency of these idealized web imperfection shapes with field measurements in fabricated girders, both in terms of geometry and the resulting mechanical performance under shear loading. This study therefore meets a significant research need for integrating real field measurements (obtained via consistent and robust methodologies) of both the magnitude and shape

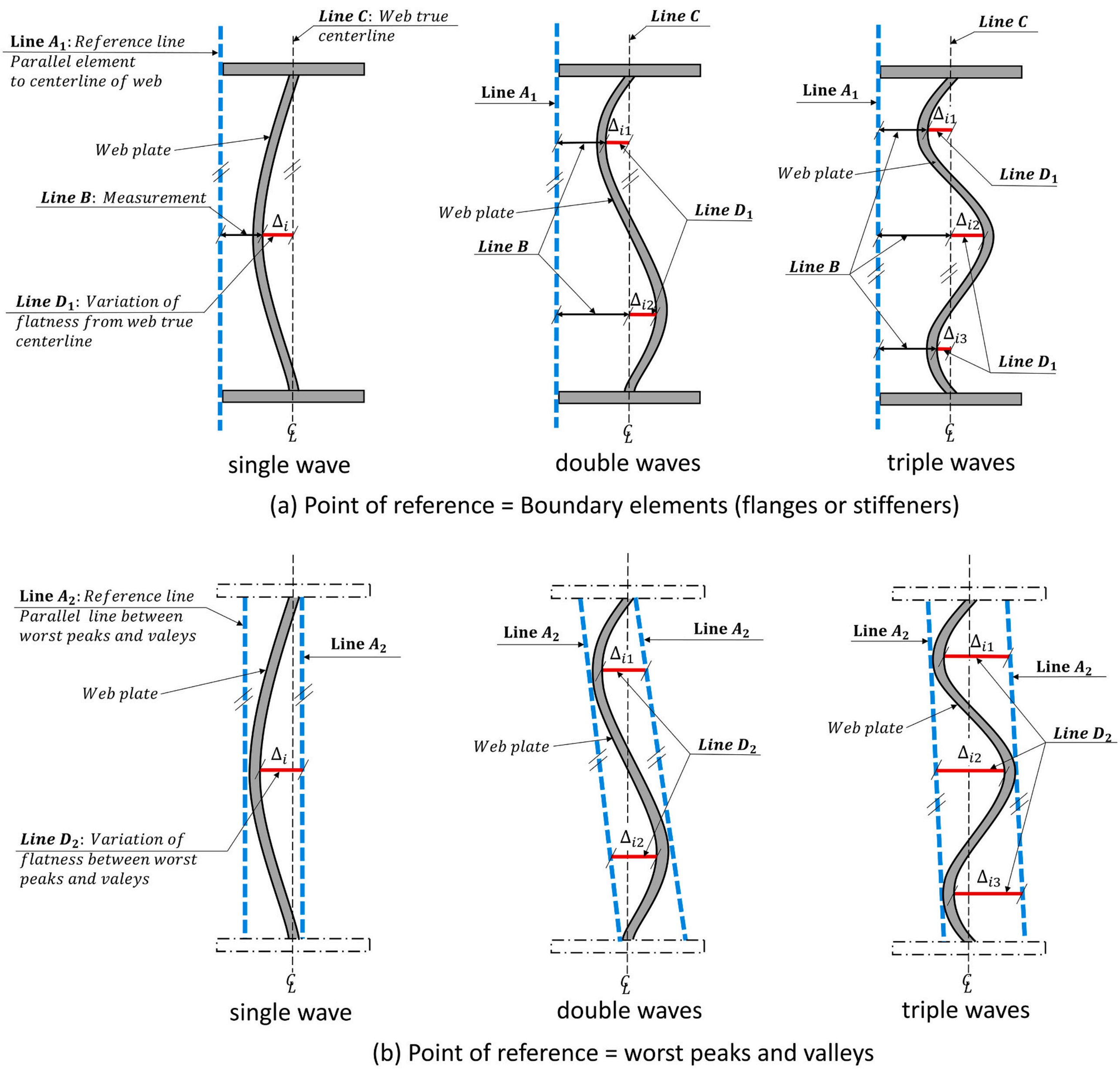


**Fig. 3.** Conventional out-of-flatness imperfection measurement approaches shown as single, double, and triple waves.

**Table 1**
Summary of code-based tolerance limits for web out-of-flatness imperfections.

| | Specification | General Tolerance Criteria | Commentary |
|---|---|---|---|
| US Specifications | ASTM A6/A6M, 2021 [29] | $\frac{7}{16}$ *in.* to 1 *in.* | For plates with tensile strength ≤60 *ksi*; specified thickness from $\frac{1}{2}$ in. to 1 in.; specified width from 36 in. to 144 in. |
| | AASHTO/AWS D1.5M/D1.5, 2020 [2] | $\frac{D}{150}$ | For unstiffened webs of all slenderness |
| | | $\frac{d}{67}$ to $\frac{d}{130}$ | For stiffened webs |
| Other specifications | AS/NZS 3678, Australia and New Zealand, 2016 [10] | $\frac{a}{375}$ or $\frac{D}{150}$ | For steel plates |
| | European Standard (Eurocode 2006) [41] | $\frac{a}{200}$ or $\frac{D}{200}$ | For steel plates |
| | NS 3472, Norway, 2001 | $\frac{D}{133}$ | For web plates |
| | British Standards (BS 5400), 1983 [11] | $\frac{a}{200}$ or $\frac{D}{165}$ | For web panels |
| | AS 1250, Australia, 1981 [17] | $\frac{D}{200}$ | For steel plates |
| | Japan Road Association, Specifications for Highway Bridges (JHSB), 1980 [13] | $\frac{D}{250}$ | For web panels |
| | DASt 012 Germany, 1980 [12] | $\frac{a}{250}$ or $\frac{D}{250}$ | For steel plates |
| | SIA-161, Switzerland, 1979 [15] | $\frac{D}{150}$ | For all webs |
| | European Recommendation for Steel Construction (ECCS), 1978 [14]. | $\frac{a}{500}$ or $\frac{d}{500}$ | For steel plates |
| | NBN B51–001, Belgium, 1977 [16] | $\frac{a}{250}$ or $\frac{D}{250}$ | For steel plates |
| | ÖNORM B4600, Austria, 1975 [42] | $\frac{a}{250}$ or $\frac{D}{250}$ | For steel plates |
| | BK-N1 \| BSK 99, Sweden, 1994 [43] | $\frac{D}{150}$ | For web plates |
| | CNR UNI 10011–88, Italy, 1988 [44] | $\frac{a}{400}$ or $\frac{D}{400}$ | For web panels |

"$a$" represents the web panel longitudinal length, and "$d$" represents the minimum of $(a, D)$ for AASHTO/AWS D1.5 or the web depth ($D$) for all other specifications.

of web out-of-flatness imperfections into the prediction of the shear response for conventional welded I-section plate girders. Specifically, this study has the following objectives:

(1) Conduct a synthesized review of existing measurement approaches and tolerance limits for initial out-of-flatness imperfections in welded plate girder webs.
(2) Introduce a new alternative field web out-of-flatness imperfection measurement technique to enhance current practice.
(3) Perform field studies with the new technique to examine realistic web out-of-flatness imperfection magnitudes and shapes and present some statistical data.

## 2. Review of current practice

To better understand the current out-of-flatness imperfection measurement techniques used by fabricators and highlight code-based imperfection tolerance limits, the authors conducted an extensive review by: (1) engaging steel fabricators to collect information on current practices, (2) performing a thorough observation on the initiation and progressive history of the US and international code-based out-of-flatness imperfection tolerance limits, and (3) synthesizing the contributions of out-of-flatness imperfection tolerance recommendations made by previous researchers. This section presents the results of this review.

### 2.1. Geometry and measurements for web out-of-flatness

The geometric imperfections of steel plates are generally classified as global or local out-of-flatness imperfections [18]. A global out-of-flatness imperfection is a change in out-of-plane position, similar to a sweep or camber. The geometry and measurements associated with global out-of-flatness imperfections are out of the scope of the work presented herein. Local out-of-flatness imperfections are measured between the edges of panel as shown in Fig. 2, where $\Delta_i$ denotes the out-of-flatness dimension. Henceforth, in this paper, the term "out-of-flatness" will specifically pertain to the local web out-of-flatness imperfection. Out-of-flatness shape classification is typically expressed as a single, double, triple, or more wave geometry as shown in Fig. 2b. Controlling or correcting the out-of-flatness shape during fabrication is extremely difficult because of the distortion and residual effects from rolling, forming, assembly, and welding [28].

Fig. 3 describes code-based out-of-flatness measurement approaches as recommended by various specifications [2,9,29]. Similar to Fig. 2, $\Delta_i$ represents the local out-of-flatness dimensions. For fully fabricated welded plate I-girders, the points of reference are the boundary elements (flanges or transverse stiffeners) that establish the reference line (*Line $A_1$*). One assumption here is that *Line $A_1$* is parallel to the true theoretical centerline of the web as described in AASHTO/AWS D1.5 [2]. Practically, the edges of the flanges or transverse stiffeners used as points of reference are not always parallel, and all measurements of $\Delta_i$ are not necessarily equal as shown in Fig. 3a. Alternatively, the point of reference can be established as a pair of parallel lines (*Line $A_2$*) that bracket the largest out-of-flatness peaks and valleys [29,30], as shown in Fig. 3b.

The quality control (QC) check conducted by steel fabricators in current US practice to measure web out-of-flatness typically utilizes the following conventional tools: a string to establish a straight line parallel to the theoretical centerline of the web, and a ruler to measure the perpendicular distance from that straight line to the web surface. During QC of plate girders, it is typical that only one web out-of-flatness measurement is taken near the end of the girder section where shear is high (i.e. near supports or at the location of joints, connections, or splices) [6]. However, this approach assumes that the largest out-of-flatness will occur at or near the center of the panel, which is not always the case (as will be shown later in this paper via field measurements). Also, the shape

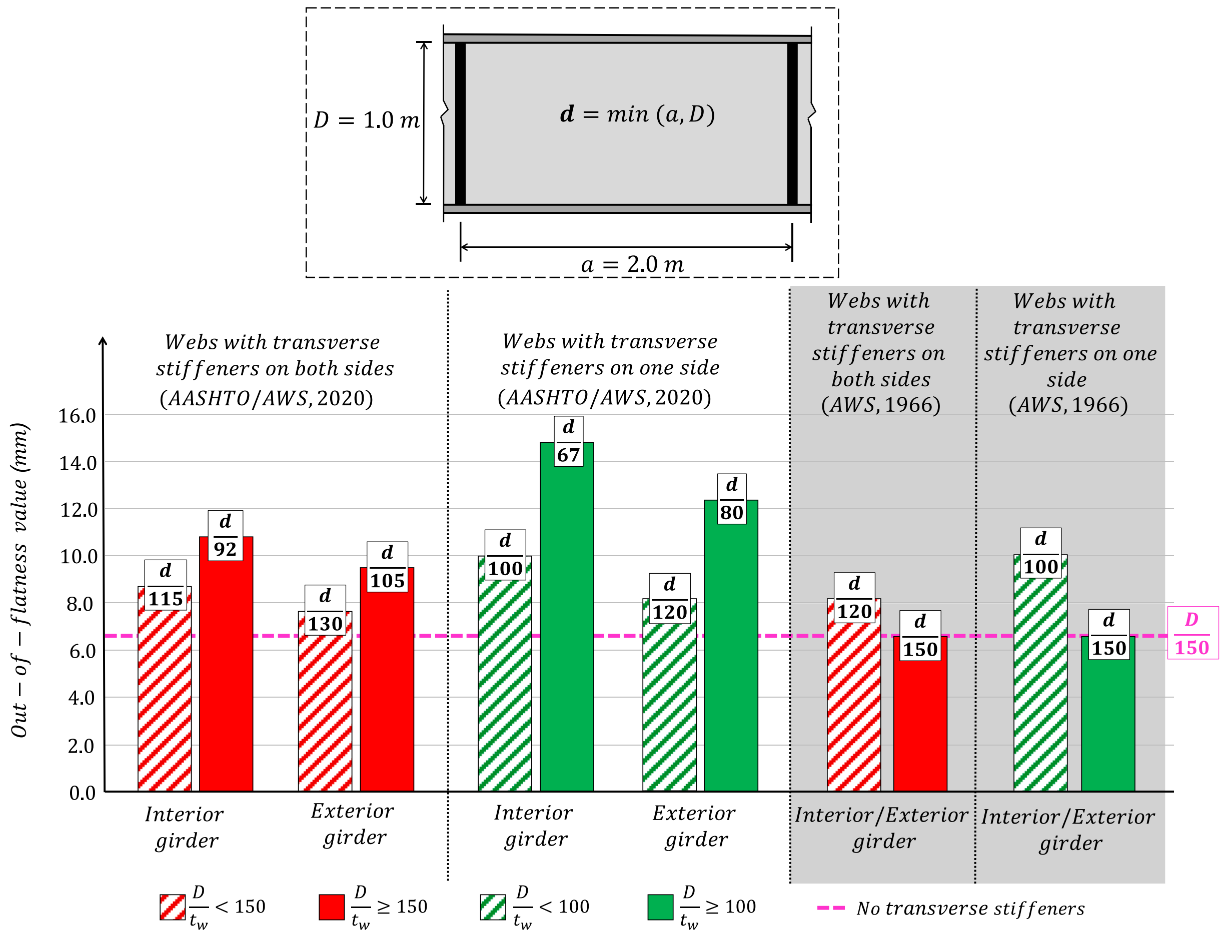


**Fig. 4.** Maximum out-of-flatness imperfection tolerance limits per AASHTO/AWS D1.5 (2020) vs AWS D2.0 (1966) for a plate girder where $d = D = 1.0\,m$.

of the out-of-flatness and the presence of multiple waves are neglected by taking only a single measurement. There are also several practical challenges with the string-and-ruler method itself. Since the scale of the measured out-of-flatness is typically small to the naked eye, the string-and-ruler technique may become somewhat subjective and can introduce systematic inaccuracies, biases, and undesired tilt angles during measurements [31]. For example, small tilt angles can impact the measurement results since there are no specified procedures for leveling. Consistency and repeatability in a series of measurements therefore becomes an added concern and can become heavily dependent on the skill and experience of the user. Thus, an alternative method for measuring web out-of-flatness with improved accuracy and consistency would enhance quality control.

### 2.2. Tolerance limits for web out-of-flatness

Table 1 highlights some of the current and historical code-based tolerance limits web for out-of-flatness per several US and international specifications. These limits are expressed as a function of the web panel geometry per Fig. 1. Fig. 4 summarizes the maximum out-of-flatness tolerance limits per AASHTO/AWS D1.5 (2020) versus AWS D2.0 (1966) for a plate girder where $d = D = 1.0\,m$. Collectively, Table 1, Table 2, and Fig. 4 show that out-of-flatness limits have generally evolved over the last 50 years as a function of the web slenderness and plate size. For unstiffened webs (with no intermediate stiffeners at regularly spaced intervals), the out-of-flatness tolerance limit of $d/150$ has remained unchanged, where "$d$" is the least panel dimension between two boundary elements (i.e. when $a > D$, then $d = D$; and when $a < D$, then $d = a$). For stiffened web panels (with intermediate stiffeners on one or both sides of the web at a given spacing), historical standards as shown in Fig. 4 and Table 1 imposed stricter limits with an increase in web slenderness, which is defined as $D/t_w$ per Fig. 1. This stricter limit is intended to mitigate the impact of out-of-flatness on plates with small $t_w$, which would presumably be more susceptible to reductions in shear strength. Recent standards have established stricter limits for exterior girders (primarily for aesthetic reasons since they are presumably visible) than interior girders. The recent standards also recognize that thinner web plates will invariably develop larger out-of-flatness during fabrication and therefore permit larger limits [2]. To date, the consequences of these limits and changes on the shear strength of thin web plates have not been examined in depth [18]. When a fabricated girder fails to meet these tolerance limits, corrective forming measures to straighten the web plate will typically involve localized heat treatment [32]. Correcting the web out-of-flatness will invariably result in fabrication cost increases, more labor, and construction delays [6].

As shown in Table 2, several previous research studies [28,30,33–40] have recommended additional out-of-flatness tolerance limits based on numerical studies and statistical approaches. Overall, these recommended limits for the maximum imperfection magnitude are similar to those prescribed by code-based specifications in Table 1, with some variance depending on the loading conditions. The results of these studies do not necessarily indicate how the out-of-flatness should be measured, nor do they consider the shape of the out-of-flatness and its resulting impact on the shear mechanics of the stiffened web panel.

**Table 2**
Summary of research-based tolerance limit recommendations for the maximum magnitude of web out-of-flatness imperfection.

| *Authors* | *Recommended Tolerances* | *Commentary* |
|---|---|---|
| Sadovsky, 1996 [33] | $\Delta_i \leq \frac{D}{250} * \frac{\lambda}{60}$ <br> $\lambda = \frac{D}{t_w} > 60$ | Mathematical approach by solving differential equations |
| Usami, 1993 [35] | $\Delta_i \leq \frac{D}{150}$ | For imperfect plates under compression or bending |
| Rangelov, 1992 [36] | $\Delta_i \leq \frac{D}{250}$ *for* $\lambda = \frac{D}{t_w} \leq 120$ <br> $\Delta_i \leq \frac{D}{250} * \frac{\lambda}{120}$ *for* $\lambda = \frac{D}{t_w} > 120$ | Built on Sadovsky's theory |
| Thimmhardy and Korol, 1988 [37] | $\Delta_i \leq \frac{D}{165}$ | For fabricated box girders |
| Komatsu et al., 1983 [39] | $\Delta_i \leq \frac{D}{250}$ | Statistical study |
| Carlsen and Czujko, 1978 [28] | $\Delta_i \leq \frac{D}{100}$ | Applicable for $\frac{D}{t_w} > 40$ and aspect ratio $1.5 < \frac{a}{D} < 3.3$ |
| Dowling, 1977 [40] | $\Delta_i \leq \frac{D}{200}$ | Applied with a strength reduction of <10% |
| Committee of Inquiry into the Basis of Design and Method of Erection of Steel Box-Girder Bridges, Scotland, 1973 [30] | $\Delta_i = G\frac{1+\frac{D}{5,000}}{30t_w}$ *for* $t_w \leq 25\ mm$ <br> equivalent to $\Delta_i \leq \frac{D}{375}$ <br> $\Delta_i = G\frac{1+\frac{D}{5,000}}{750}$ *for* $t_w > 25\ mm$ <br> equivalent to $\Delta_i \leq \frac{D}{200}$ | For steel plates with gauge length, $G = 2D$ for $a > 3D$ *or* $G = a$ for $a < 3D$ |

"$d$" denotes $min(a, D)$, and "$t_w$" denotes the web thickness.

## 3. Proposed field measurement technique

### 3.1. Plate girder descriptions

Field measurements were taken for web out-of-flatness in welded I-shaped plate girders that were recently fabricated and awaiting shipping at a major fabricator in the Northeast US. The measurements were collected on three different dates and are thus represented as three sets of data in Table 3, which lists the dimensions of each girder. The first, second and third sets of measurements were collected on July 26, 2021, June 20, 2023, and July 26, 2023, respectively. The results of this field study include measurements of 23 web panels (i.e. panels are bounded by vertical stiffeners) found within 12 girders that were to be used for roadway overpass bridges designed per design specifications published by the Pennsylvania Department of Transportation (PennDOT) [45] and AASHTO [46]. These results are therefore considered to be representative of plate girders used in current North American steel bridge construction practice. Because no large data set on web out-of-flatness can be found in the literature, additional field measurements of in-situ plate girders in a wider collection of existing bridges are needed to establish a more generalized assessment of initial web imperfections across the national steel girder bridge inventory in the US. The dataset herein, however, is sufficient to draw some conclusions as will be presented later.

The plate girders measured for this study were upright and rested on regularly spaced timber ties under the bottom flange. Table 3 summarizes the cross-section and longitudinal dimensions of the girders and their targeted web panel sections – webs are classified as compact ($D/t_w < 90.5$) or noncompact ($D/t_w > 90.5$) and slender ($D/t_w < 137$) by AISC [47] and AASHTO [46] standards. The web depth ($D$) ranged between 0.965 $m$ (38 $in.$) and 2.08 $m$ (82 $in.$), and web thickness ($t_w$) ranged from 14.4 $mm$ (0.57 $in.$) to 19.1 $mm$ (0.75 $in.$). All girders measured in this field study were destined for highway overpass bridge installations and are representative of current bridge design practice in the US, for which web slenderness ($D/t_w$) in I-shaped plate girders typically ranges from 60 to 118. The web panel aspect ratio ($a/D$) between transverse stiffeners varied from 0.89 to 7.69 and was tailored to meet the required shear strength of each girder based on its design loads and web thickness.

### 3.2. ALW out-of-flatness measurement technique

An enhanced technique called the adjustable laser widget (*ALW*) is used in this study to measure web out-of-flatness, with the goal of mitigating the potential for inaccuracies, systematic errors, lack of repeatability, and practical challenges that are associated with other methods in the current state of practice. Based on previous work by Zhang [18], the *ALW* technique for measuring web out-of-flatness (as illustrated in Fig. 5) utilizes the following components: (a) 7 laser

**Table 3**
Dimensions of plate girders measured in the field study.

| Set | Specimen Name | Web | | | Stiffened Panels | | | Flanges | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $D$ (m) | $t_w$ (mm) | $\frac{D}{t_w}$ | # of Panels | $a$ (m) | $\frac{a}{D}$ | $b_f$ (mm) | Top $t_{f1}$ (mm) | Bottom $t_{f2}$ (mm) |
| 1st | G1W | 1.78 | 19.1 | 93 | 4 | 1.58 | 0.89 | 610 | 31.8 | 44.5 |
| | G3W | 1.88 | 15.9 | 118 | 2 | 3.80 | 2.02 | 511 | 50.8 | 57.2 |
| | G4W | 2.08 | 19.1 | 109 | 2 | 4.77 | 2.29 | 511 | 38.1 | 44.5 |
| | G5W | 2.08 | 19.1 | 109 | 2 | 4.62 | 2.22 | 511 | 41.3 | 44.5 |
| | G6W | 2.08 | 19.1 | 109 | 1 | 4.62 | 2.22 | 514 | 38.1 | 44.5 |
| 2nd | G1-J6 | 0.965 | 16.1 | 60 | 2 | 6.09, 6.12 | 6.31, 6.34 | 508 | 39.0 | 38.4 |
| | G2-J6 | 0.965 | 16.2 | 60 | 2 | 4.47 | 4.63 | 508 | 38.1 | 51.7 |
| | G3-J6 | 0.914 | 14.4 | 64 | 1 | 7.03 | 7.69 | 635 | 31.8 | 44.7 |
| 3rd | G4-J7 | 1.52 | 19.1 | 80 | 2 | 7.63 | 3.2 | 565 | 31.8 | 50.8 |
| | G5-J7 | 1.75 | 19.1 | 92 | 2 | 7.63, 3.96 | 4.35, 2.26 | 508 | 38.1 | 38.1 |
| | G6-J7 | 1.52 | 19.1 | 80 | 2 | 4.88, 4.72 | 3.2 3.1 | 562 | 31.8 | 50.8 |
| | G7-J7 | 1.75 | 19.1 | 92 | 1 | 6.78 | 3.87 | 511 | 25.4 | 31.8 |

Note: The reported $b_f$ values represent the smallest flange width between the top and bottom flange.

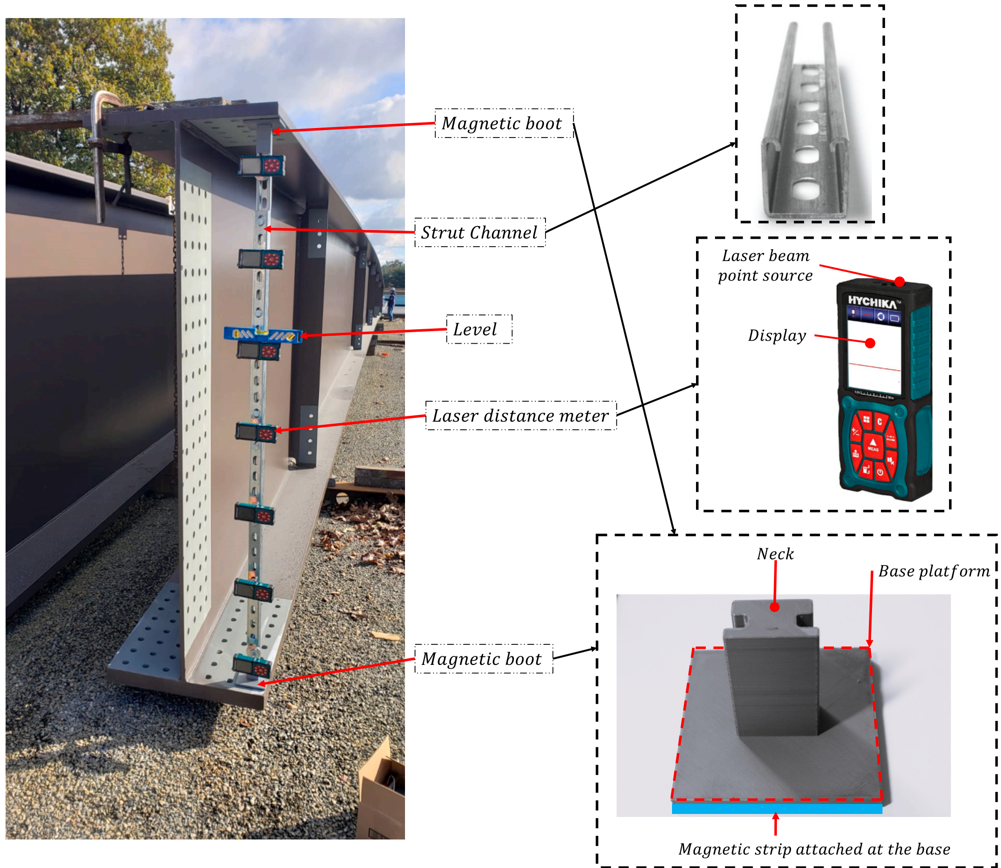


**Fig. 5.** Descriptive illustration of the adjustable laser widget (ALW) technique via the CLAW device.

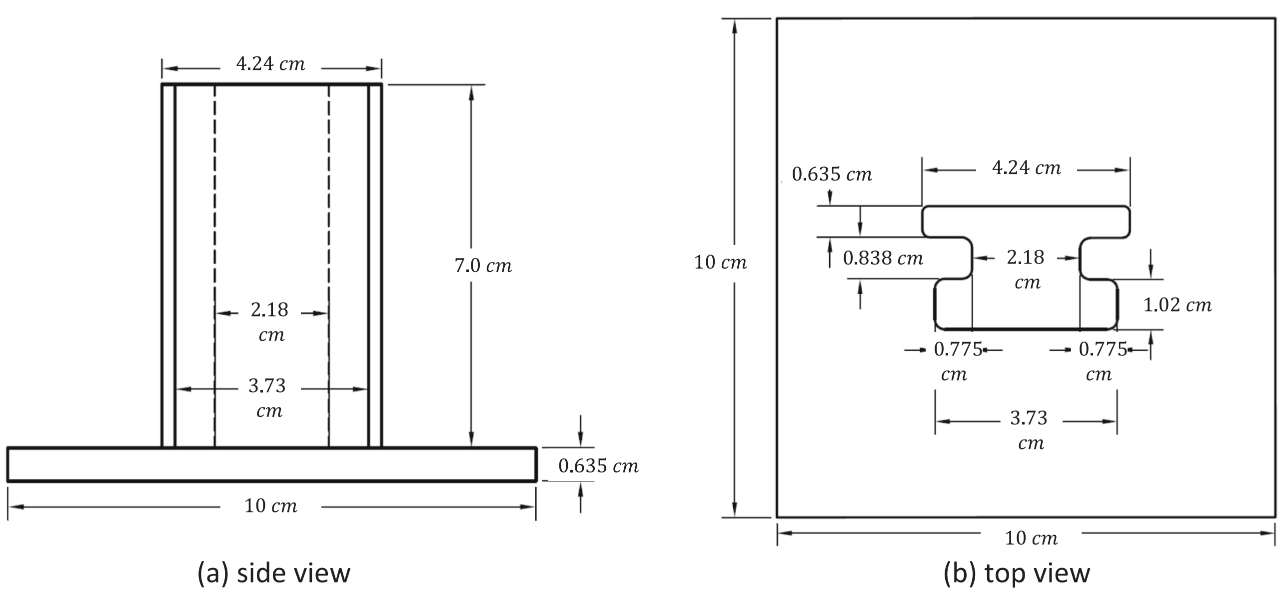


**Fig. 6.** Schematic of the 3D-printed magnetic boot grip at the top and bottom of the CLAW frame.

distance meter devices, (b) a leveling tool, (c) adjustable strut channels for framing (with slotted holes for mounting the laser meters), and (d) two 3D printed boots (see schematic in Fig. 6) at the top and bottom of the framing with magnetic strips to hold the apparatus in place during measurement. The name attributed to the assembly of these components as one measuring device is called the "CLAW" device [48]. When using the CLAW device, all 7 laser distance meters are leveled and vertically equidistant at $D/6$, thus collecting more than one data point across the web depth. The HYCHIKA laser distance meter LM-60C [49] was chosen for its 5.18 *mm* (2.04 *in.*) LCD screen, the ability to store a series of measurements, its manufactured rated tolerance of $+/-$ 1 *mm*, and because its laser pointer at the tip helped to mark the exact measurement location. By moving the CLAW device to several locations across the width of the web panel, enough data can be captured to identify the

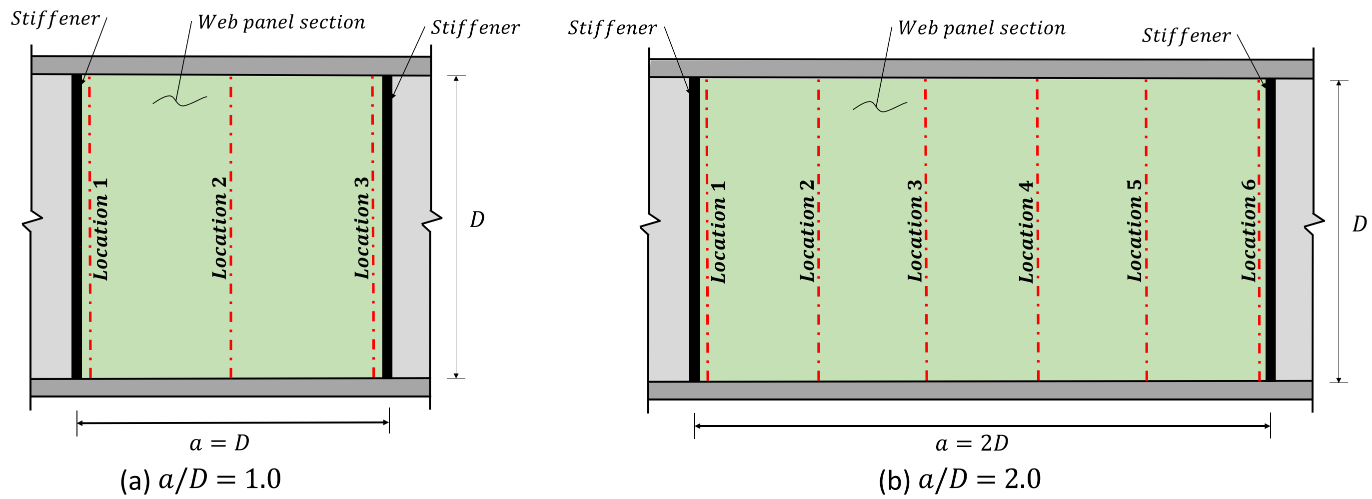


**Fig. 7.** Description measurement locations based on resolution factor ($r_p$). Red dash lines represent longitudinal locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

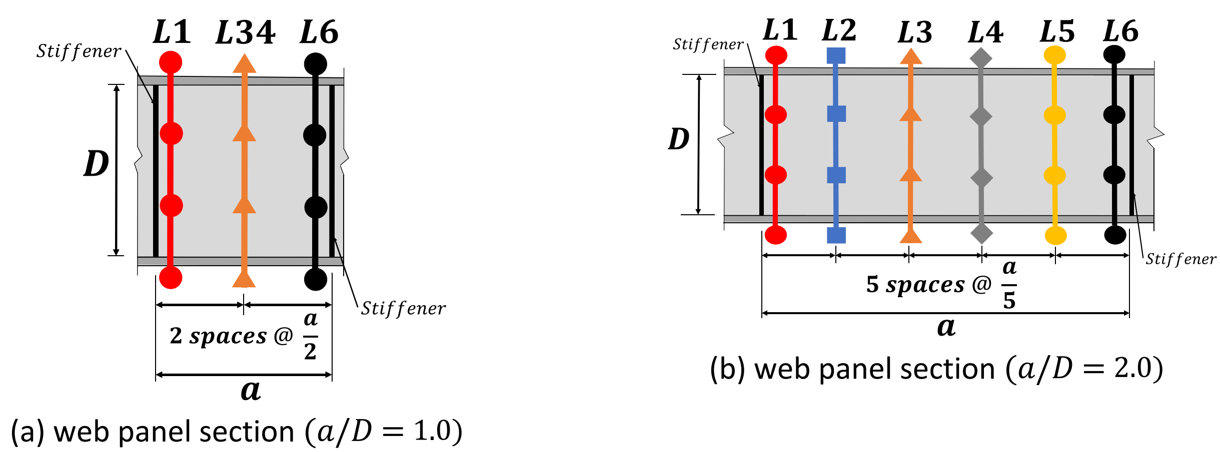


**Fig. 8.** Longitudinal measurement locations along a stiffened web panel section.

largest out-of-flatness magnitude and the true local out-of-flatness shape. In this study, the *ALW* technique is deployed per AASHTO/AWS D1.5 [2] by using the flanges as boundary elements to establish a straight parallel line to the theoretical true centerline of the web as shown in Fig. 3(a).

Compared to conventional string-and-ruler techniques, the *ALW* technique requires some additional preparation time (relatively 10 to 15 min) for setup and assembly before the first measurement is taken for a particular girder, since the adjustable frame and laser positions will need to be set for that depth geometry and boundary element. However, sequential *ALW* measurements on that girder take less than one minute per longitudinal location, at which all 7 laser measurements are simultaneously recorded. The *ALW* technique can therefore enable savings in time and labor, does not require specialized technical training or costly software for postprocessing, and provides a significant amount of data to identify the magnitude, location, and overall shape of the out-of-flatness of the web.

Based on the locations and maximum peak values of the out-of-flatness in the web, a resolution factor ($r_p$) is proposed as shown in Eq. (1), to define the number of minimum measurement locations necessary along the panel length for efficiently collecting the out-of-flatness measurements, while simultaneously capturing the appropriate shapes and magnitudes.

$$r_p = 3(a/D)\ \textit{for web panels where}\ D/t_w < 150 \tag{1}$$

Eq. (1) means that for a stiffened plate girder where $a/D$ of the widest panel section is equal to 1.0 or 2.0, the number of measurement locations for local web out-flatness imperfection as marked by the red dashed lines in Fig. 7 will equal to 3 or 6 respectively. For web panels where $D/t_w \geq 150$, a larger resolution should be considered. Using $r_p$ helps guide the minimum number of measurements necessary along a typical panel length by enhancing the current QC practices and capturing a broader array of measurement locations to better identify the maximum out-of-flatness magnitude. Additionally, this method provides fabricators and designers with higher confidence and accuracy in the field information and geometry to efficiently perform corrective measures when necessary.

As shown in Fig. 8, an example measurement of out-of-flatness for a selected web panel section where $a/D = 2.0$ were taken with the CLAW at six longitudinal locations with seven vertical points across the web depth. Only three longitudinal measurement locations were considered for shorter panel sections where $a/D \leq 1.0$. For targeted web panel sections where $a/D > 2.0$, additional measurements were taken proportionally as a function of the panel aspect ratio.

### 3.3. Out-of-flatness correction for the web

A key consideration when evaluating the results of field out-of-flatness measurements is the establishment of the original points of reference. The underlying assumptions are (1) the web plate is vertically

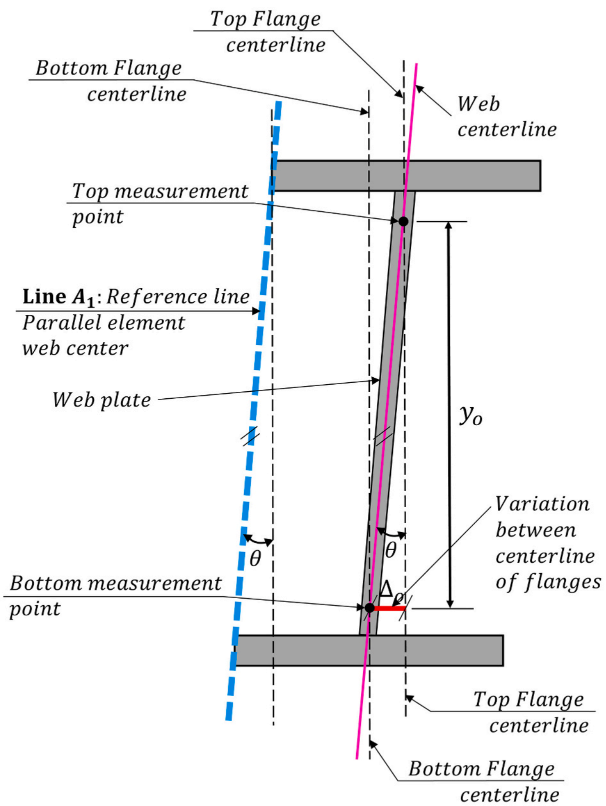


**Fig. 9.** Description of the tilt angle (θ) for a slightly asymmetric cross-section profile of a web plate girder.

leveled post fabrication at the time of measurements, and (2) the flange and web are perfectly symmetric and welded on center at 90° resulting in zero tilt ($\theta$) angle (see Fig. 9). However, these assumptions are not necessarily true; plate girders are permitted to have slightly asymmetric welded cross-sections and unleveled webs where $\theta > 0^\circ$, but within a given tolerance. $\theta$ can increase as a result of very small differential offset in fabrication tolerances. Although $\theta$ is very small, its influence on the out-of-flatness magnitude can be significant, and it must be accounted for to report accurate field measurements. In this study, a correction factor is defined based on the predetermined points of reference which helped define the reference line and vertical distances between the top and bottom measurement points as shown in Fig. 9. If a correction factor is not considered in the cases where $\theta > 0^\circ$, then field results will exhibit higher initial out-of-flatness magnitudes. To address this concern and other factors such as web leveling and slightly asymmetric welded cross-sections, a correction factor ($\Delta_o$) shown in Eq. (2) is computed for each point based on field measurements as a function of the true field $\theta$ and

**Table 4**
Summary of maximum measured out-of-flatness (OoF) for all web panels in the field study.

| Dataset | Specimen name | Panel | $\frac{D}{t_w}$ | $\frac{a}{D}$ | Maximum at each panel (M_P_23) | Center of each panel (C_P_23): |
|---|---|---|---|---|---|---|
| 1st | G1W | 1 | 93 | 0.89 | d/255 | d/445 |
| | | 2 | | | d/244 | d/593 |
| | | 3 | | | d/183 | d/1778 |
| | | 4 | | | d/507 | d/593 |
| | G3W | 1 | 118 | 2.02 | d/198 | d/470 |
| | | 2 | | | d/188 | d/940 |
| | G4W | 1 | 109 | 2.29 | d/241 | d/521 |
| | | 2 | | | d/190 | d/521 |
| | G5W | 1 | 109 | 2.22 | d/108 | d/417 |
| | | 2 | 109 | | d/96 | d/2083 |
| | G6W | 1 | 109 | 2.22 | d/120 | d/130 |
| 2nd | G1-J6 | 1 | 60 | 6.31 | d/50 | d/965 |
| | | 2 | | 6.34 | d/63 | d/483 |
| | G2-J6 | 1 | 60 | 4.63 | d/64 | d/161 |
| | | 2 | | | d/107 | d/965 |
| | G3-J6 | 1 | 64 | 7.69 | d/104 | d/914 |
| 3rd | G4-J7 | 1 | 80 | 3.2 | d/97 | d/1385 |
| | | 2 | | | d/102 | d/1524 |
| | G5-J7 | 1 | 92 | 4.35 | d/281 | d/1753 |
| | | 2 | | 2.26 | d/360 | d/1169 |
| | G6-J7 | 1 | 80 | 3.2 | d/126 | d/1524 |
| | | 2 | | 3.1 | d/99 | d/762 |
| | G7-J7 | 1 | 92 | 3.87 | d/137 | d/438 |
| | | | | Mean (μ) | d/170 | d/893 |
| | | | | St. Dev. (σ) | d/108 | d/549 |

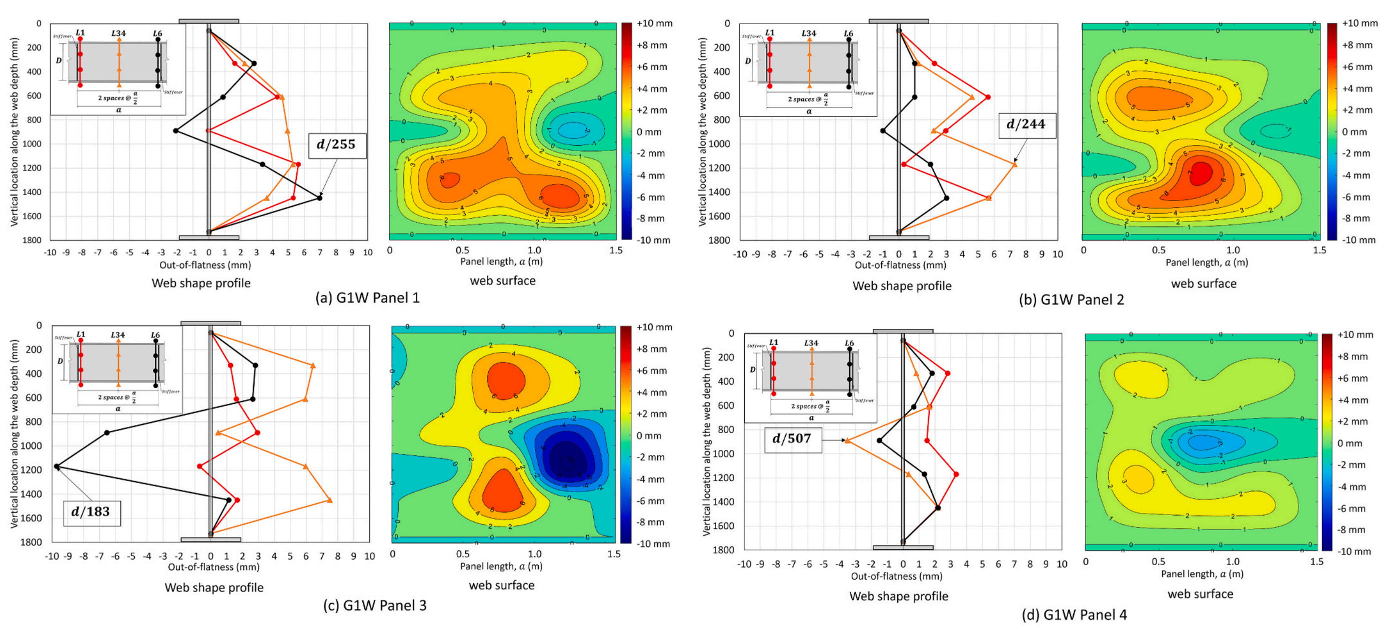


**Fig. 10.** Results of field measured web out-of-flatness for G1W plate girder: (a) web panel 1, (b) web panel 2, (c) web panel 3, and (d) web panel 4.

**Table 5**
Statistical summary of field measurements.

| Description | # of data point | Mean ($\mu$) | St. Dev. ($\sigma$) | Median | Min. | Max. |
|---|---|---|---|---|---|---|
| *Maximum at each panel (M_P_23)*: | 23 | $d/170$ | $d/108$ | $d/126$ | $d/50$ | $d/507$ |
| *Center of each panel (C_P_23)*: | 23 | $d/893$ | $d/549$ | $d/762$ | $d/130$ | $d/2083$ |
| *Max. of each longitudinal measurement (M_L_213)*: | 213 | $d/248$ | $d/144$ | $d/216$ | $d/50$ | $d/949$ |
| *All data points (A_1070)*: | 1070 | $d/835$ | $d/1060$ | $d/467$ | $d/50$ | $d/7455$ |

the distance between top and bottom measurement points $(y_o)$.

$$\Delta_o = y_o \tan(\theta) \quad (2)$$

Since $\theta$ is very small, current code-based out-of-flatness measurement approaches ignore the influence of $\theta$ in field measurements by assuming that the profile of all fabricated plate girders is perfectly symmetric and leveled, thereby indicating that $\theta = 0^{\circ}$ for all field measurements of out-of-flatness.

## 4. Field measurement results

### 4.1. Out-of-flatness magnitude and shape of webs

The web out-of-flatness results and surface contours of the 1st set, as described in Table 3, are plotted in Fig. 10 through Fig. 14. Additional surface contours obtained for the 2nd and 3rd set are similar in nature and shown in Figs. 15 and 16. The contour surfaces were generated using the "Modified Akima" (Makima) piecewise cubic Hermite interpolation in MATLAB [50] to help mitigate overshooting beyond the measured values within the web panel dimensions. In a companion paper, these surface contours were mapped to the mesh of finite element (FE) models, which were used for numerical evaluations of shear strength. The maximum out-of-flatness magnitudes are represented in the boxed values, where "*d*" denotes the least panel dimension between *a* or *D*.

Table 4 provides a summary of the maximum initial out-of-flatness magnitudes captured in the field for each panel, where panels are bounded by transverse stiffeners (see Fig. 8 for the number of measurements taken at each panel). Overall, the resulted mean ($\mu$) value of the maximum magnitude out-of-flatness is equal to $d/170$ with a standard deviation ($\sigma$) of $d/108$ for a normal distribution. For narrower web panel sections where $a/D \leq 1.0$ (i.e. girder G1W panels 1 through 4), the maximum out-of-flatness magnitudes ranged between $d/183$ and $d/507$ with both single and double wave surface shape profiles as shown in Fig. 10. For web panel sections where $a/D$ is close to two ($2.02 \leq a/D \leq 2.29$), meaning specimens G3W, G4W, G5W, G6W, and G5-J6 panel 2,

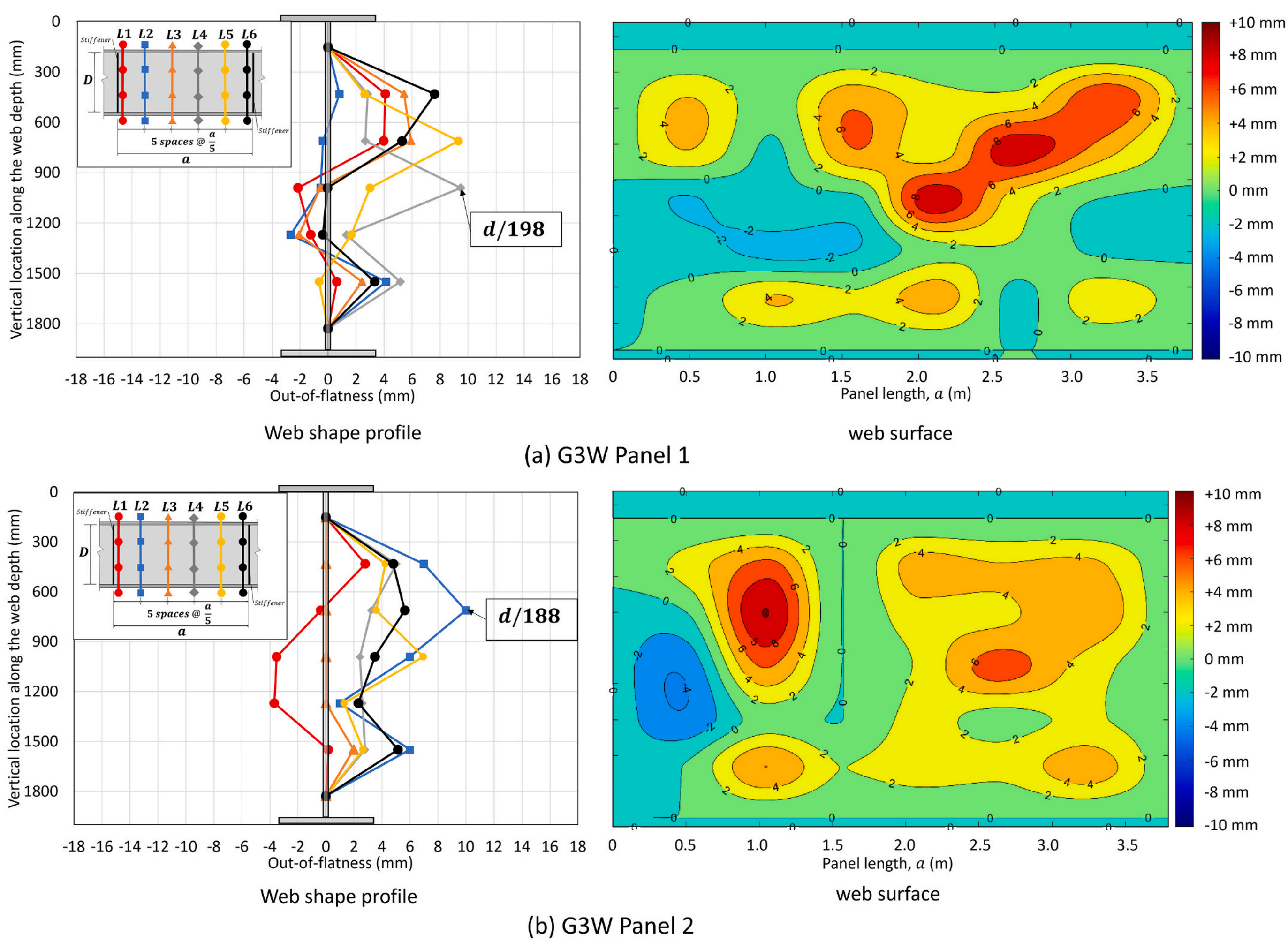


**Fig. 11.** Results of field measured web out-of-flatness for G3W plate girder. (a) web panel 1 and (b) web panel 2.

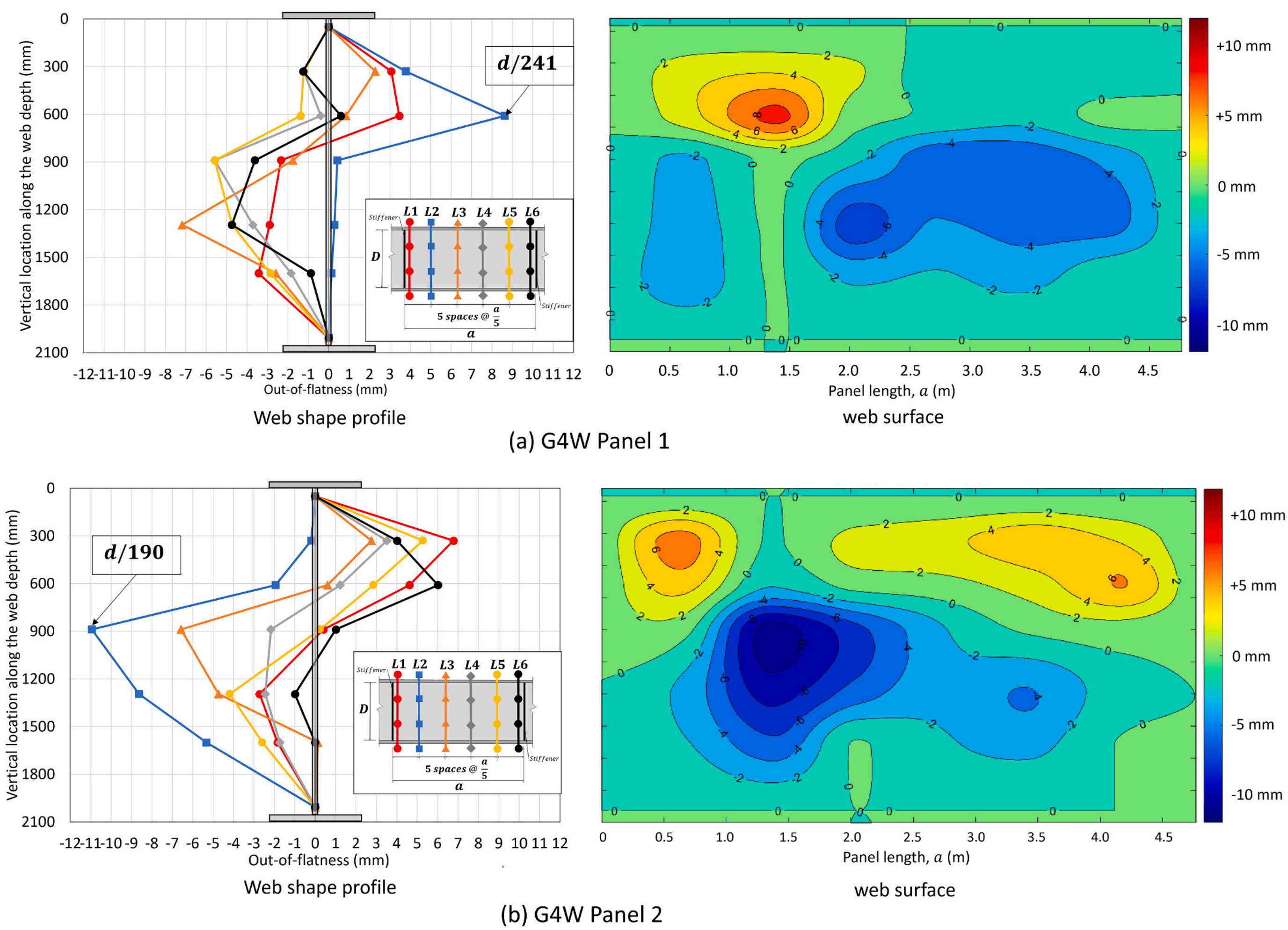


**Fig. 12.** Results of field measured web out-of-flatness for G4W plate girder. (a) web panel 1 and (b) web panel 2.

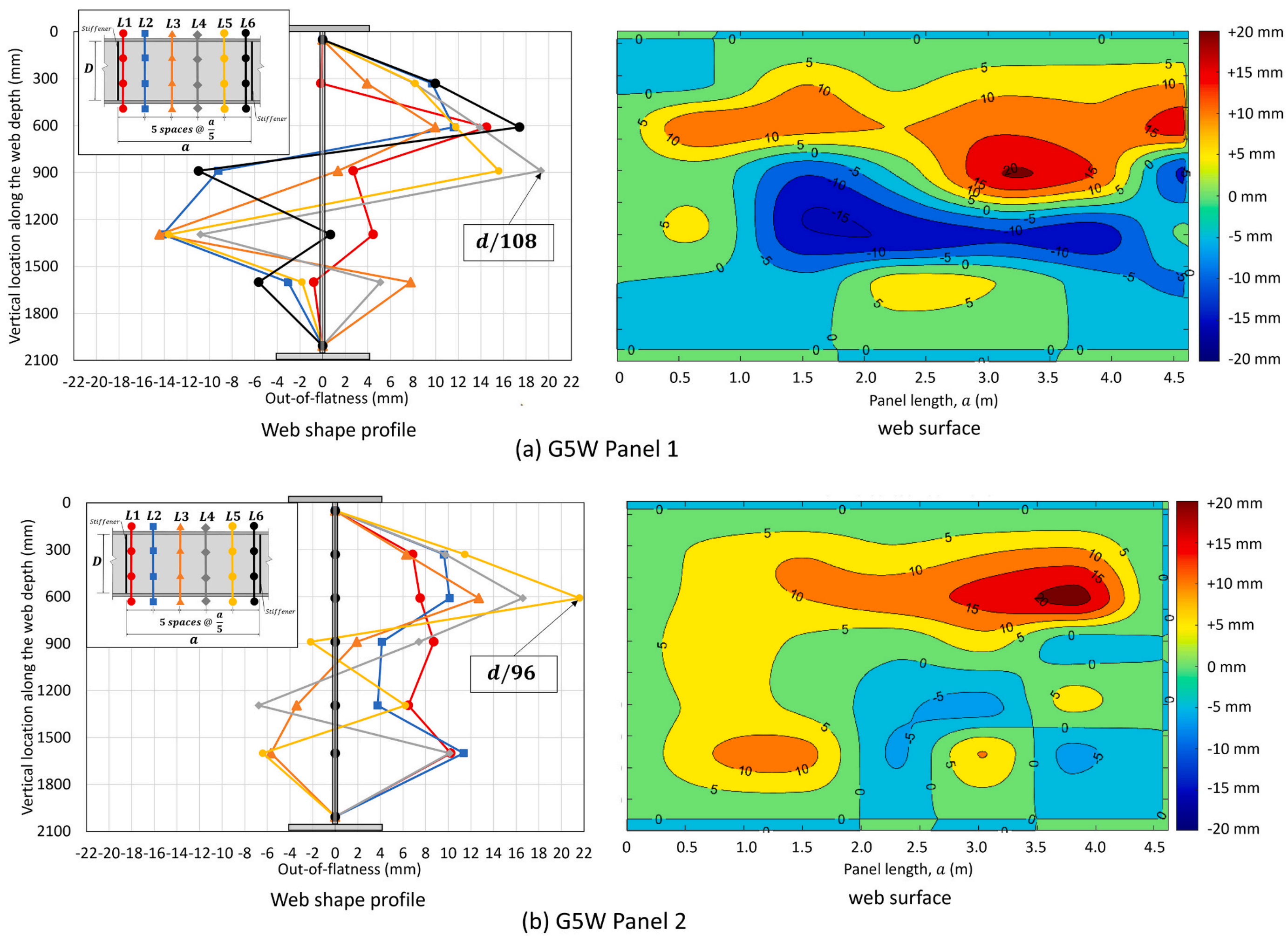


**Fig. 13.** Results of field measured web out-of-flatness for G5W plate girder. (a) web panel 1 and (b) web panel 2.

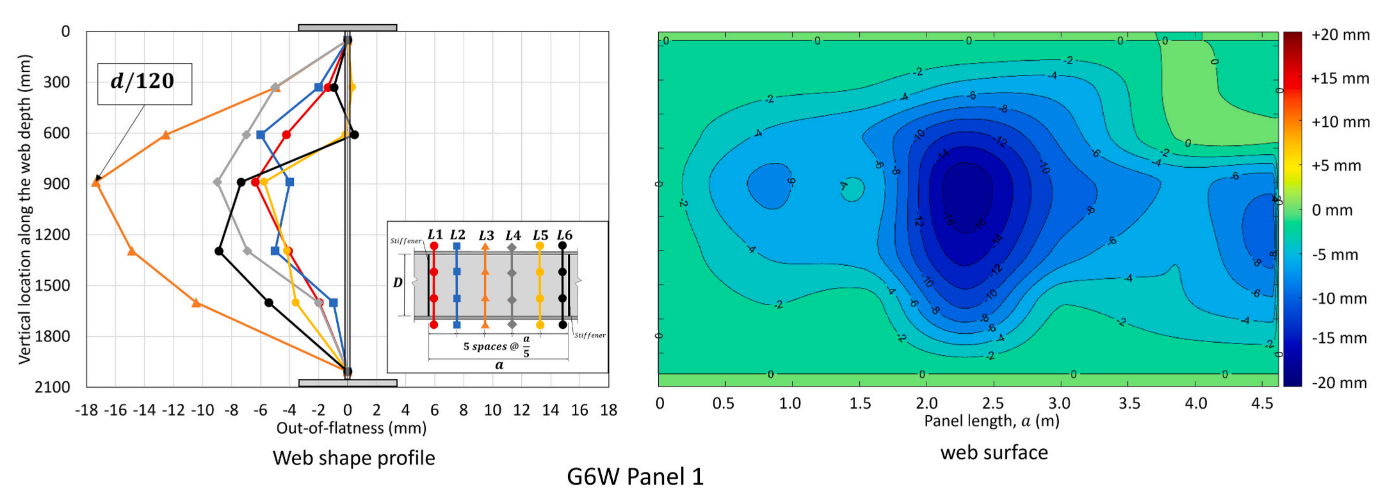


**Fig. 14.** Results of field measured web out-of-flatness for G6W plate girder, web panel 1.

the maximum out-of-flatness magnitudes ranged between $d/96$ and $d/360$ as shown in Fig. 13(b) and Fig. 16(d), respectively. Lastly, for longer web panel sections where $a/D \geq 3.0$ (i.e., most of sets 2 and 3), the maximum out-of-flatness magnitudes ranged between $d/50$ and $d/281$. A general trend observed in Table 4 is that the maximum out-of-flatness magnitude increases as the panel aspect ratio $a/D$ increases.

Field results show that there are no discernable patterns regarding the location of the maximum out-of-flatness magnitude along the panel length and across the web depth. Also, the maximum magnitude rarely coincides with the center of the web panel. Furthermore, the shape of out-of-flatness is somewhat random and loosely follows a single, double, or triple wave shape pattern as discussed in Section 3.1.

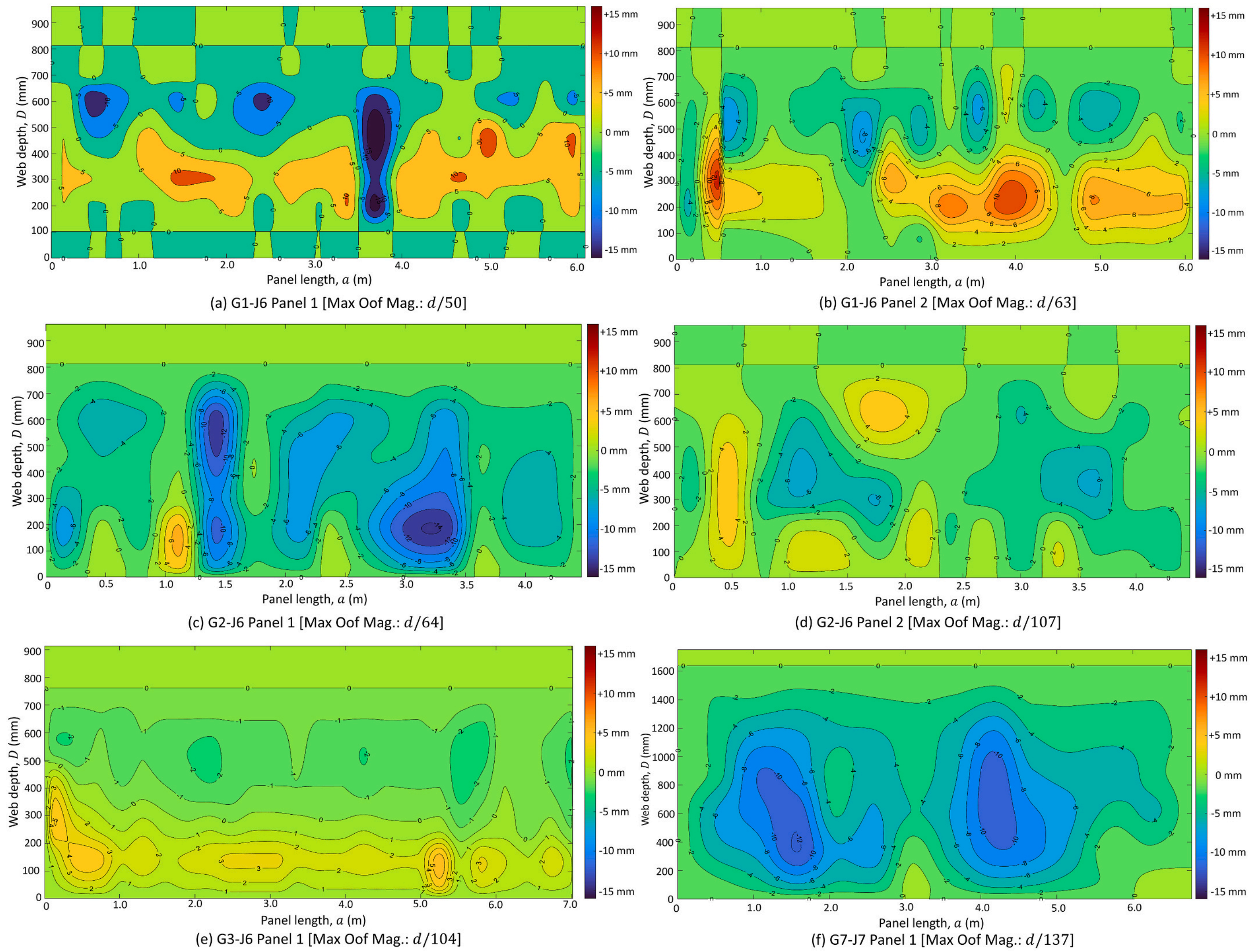


**Fig. 15.** Results of field measured web out-of-flatness surface contours (2nd data set) and G7-J7 web panel section.

### 4.2. Statistical evaluation

Each panel had several measurements as shown in Fig. 8, and the out-of-flatness data sets were grouped as follows:

- *Maximum at each panel (M_P_23)*: This data set represents the maximum out-of-flatness measured anywhere on each panel (as represented in Table 4), resulting in 23 data points.
- *Center of each panel (C_P_23)*: The out-of-flatness at the center of each panel was interpolated (as shown in the previous contour plots and Table 4), resulting in 23 data points.
- *Maximum of each longitudinal measurement line (M_L_213)*: Recall that Fig. 8(b) shows a schematic with six vertical lines for incremental longitudinal measurements on a panel (L1 through L6). This data set represents the maximum of each longitudinal set, resulting in 213 data points.
- *All data points (A_1070):* This data set includes all data points taken on every longitudinal line and every panel, resulting in 1070 data points.

Gaussian (normal) distributions were developed from each data set to obtain a corresponding Probabilistic Density Function (PDF) and Cumulative Density Distribution (CDF), which are plotted in Fig. 17. These plots include vertical dashed lines for the out-of-flatness tolerance limits of $d/67$, $d/115$ for webs with transverse stiffeners on one or both sides, as well as $d/150$ for webs with no transverse stiffeners (as summarized previously in Section 3.2 and prescribed by the bridge welding code [2]). Table 5 provides a summary of the statistical evaluation obtained from the PDF and CDF.

Fig. 17 and Tables 4 and 5 show that the maximum value data points (M_L_213 and M_P_23) have significantly larger out-of-flatness means, and smaller standard deviations compared to both the full data set (A_1070) and the measurements taken at the center of the panel (C_P_23). These results corroborate the following additional observations:

1. The maximum measured value does not represent the general, or overall, out-of-flatness configuration in a panel. Examining the contour plots in Figs. 10 through 16, it is observed that the maximum values are more like ‘dimples’, meaning that they cover only a small portion of the overall panel area.
2. The measurements at the center of the panel rarely capture the peak out-of-flatness location. Previous web-shear tests in the existing literature clearly show that the final deformed shape at shear failure resembles the shape of the lowest eigenmode [51–54], in which the peak out-of-plane deformation is near the center of the panel.

The implications of these results on the shear strength will be examined in a companion paper to present the results of numerical finite element analysis. Results of those analyses show that even if the peak

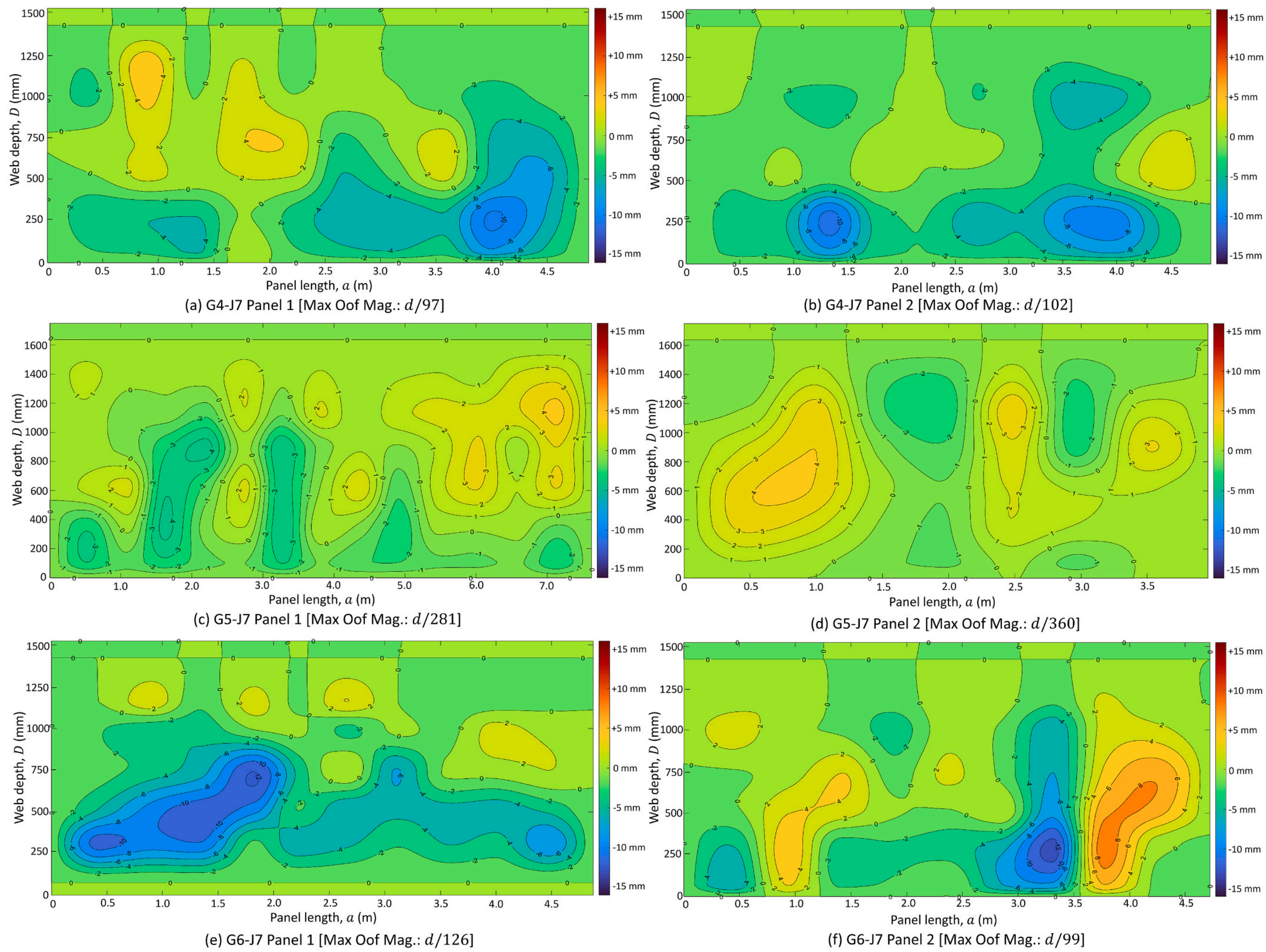


**Fig. 16.** Results of field measured web out-of-flatness surface contours (3rd data set).

value of the out-of-flatness exceeds the limit, a web plate with field measured imperfections will demonstrate up to 12% of 'reserve' shear capacity since the irregular realistic shape needs to be 'pushed' into its failure shape (which resembles the lowest eigenmode shape). These observations highlight the importance for further examining the current tolerance limits and measurement approaches. This examination can provide more confidence in current fabrication and QC procedures for welded plate girders and provide designers with valuable insight

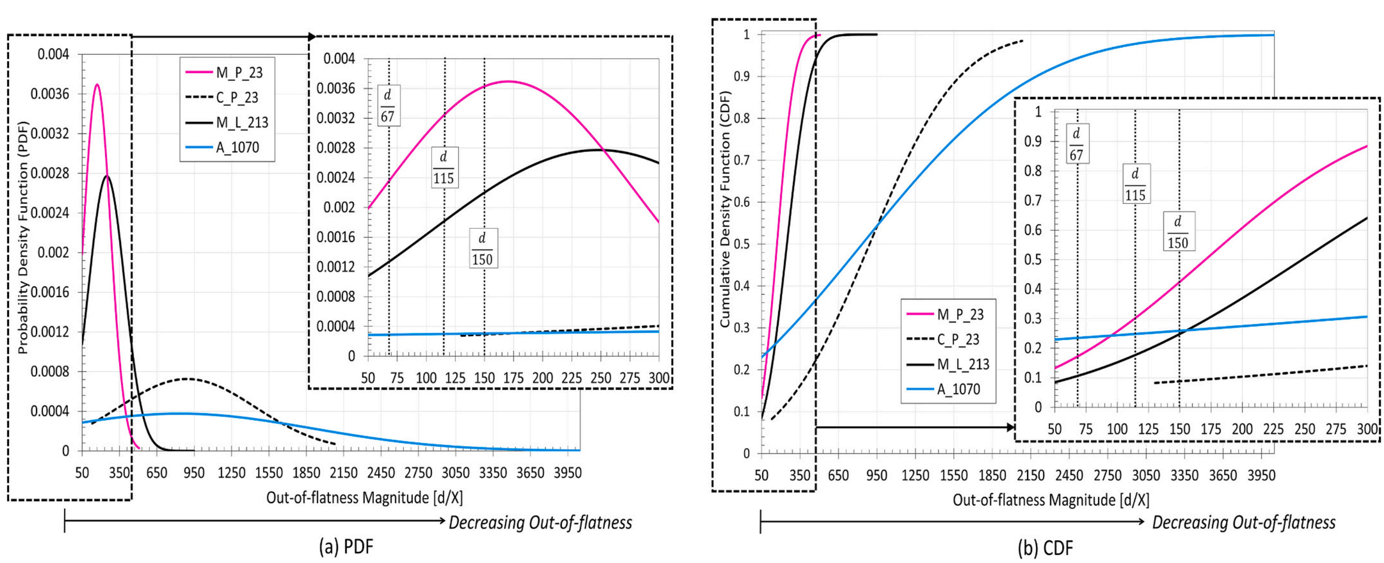


**Fig. 17.** Probability distribution functions for field measured web out-of-flatness magnitudes.

regarding the true mechanical impact of realistic out-of-flatness magnitudes and shapes.

## 5. Conclusions

This paper presented an extensive evaluation of initial out-of-flatness magnitudes and shapes for the slender webs of steel plate I-girders, with a specific focus on (a) state of practice as related to limits and measurement methods, and (b) actual out-of-flatness measurements in the field. A synthesized literature review examining the out-of-flatness limits imposed by US and international codes and standards in the last 50 years revealed that the more recent standards recognize that thinner web plates will develop larger out-of-flatness during fabrication; therefore, codes and standards now permit larger limits than earlier versions. The effects of these limits and changes on the shear strength of thin web plates had not been examined in great depth to date and they represented a significant knowledge gap which has been addressed by this study.

The authors introduced an alternative technique for measuring the out-of-flatness of webs called the "adjustable laser widget" (ALW). Twelve plate girders were measured with depths ranging from 0.914 to 2.08 $m$ at bridge fabricator facility in the US. It was found that the maximum magnitude for the out-of-flatness of webs varies with a mean value of $d/170$. This mean decreases to $d/835$ if all data points collected on the panel are used for the statistical evaluation. The maximums do not represent the general, or overall, out-of-flatness values in a panel and are more like 'dimples', meaning that they cover only a small area in comparison to the overall panel area. Further, the locations of the maximum out-of-flatness do not always correspond to be found at the center of the web panel section, and the shape follows either single, double, or triple waves out-of-plane. Measurements in the field that follow the proposed resolution factor ($r_p$) can assist in obtaining the shapes and magnitudes of out-of-flatness in a plate girder web.

A future companion paper will numerically investigate the influence of out-of-flatness magnitude and shape on the shear strength to provide further recommendations. Future work should consider both the web and flange out-of-flatness post the final erection of specimens to provide further insight on the current tolerance limits. The study presented herein, and future related work, can enable the development of appropriate tolerance limits and accurate shear strength models that provide mechanically pertinent fabrication assessments for plate girders.

## CRediT authorship contribution statement

**Parfait M. Masungi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria E.M. Garlock:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Spencer E. Quiel:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the research study and work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Appendix

Nomenclature and List of Symbols

| | |
|---|---|
| $a$ | longitudinal length of web panel section. Center-to-center spacing between transverse stiffeners |
| $b_f$ | width of flange plate |
| ALW | adjustable laser widget technique |
| $d$ | least panel dimension value as a function of web depth or longitudinal length of web panel |
| $D$ | web depth, clear distance between flanges |
| $a/D$ | aspect ratio of web panel section |
| $G$ | gauge length corresponding to the longitudinal length of the web section |
| $L$ | total longitudinal length of plate girder between supports |
| $r_p$ | resolution factor for the number of out-of-flatness measurement locations longitudinally |
| $t_{f1}$ | thickness of top flange plate |
| $t_{f2}$ | thickness of bottom flange plate |
| $t_w$ | thickness of web plate |
| $D/t_w$ | slenderness of web plate |
| Oof | out-of-flatness |
| QC | quality control |
| $y_o$ | vertical distance between the top and bottom most measurement points |
| $\mu$ | statistical mean (average) |
| $\sigma$ | standard deviation |
| λ | slenderness of web plate as described in code-based specifications |
| $\Delta_i$ | out-of-flatness value |

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