Analysis of the Shear Angle in Corrugated Web Girders

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Abstract. The analysis of shear buckling resistance and the results of investigations into corrugated web girders indicate a substantial influence of rigid support stiffeners on shear buckling resistance of the corrugated web. In simply supported SIN girders, support stiffeners can be made from I-sections or T-sections. In cantilever girders, however, the role of support stiffener can be performed by end plate joint that connects the cantilever and span parts of the girder. This study reports investigations into a change in the shear angle in simply supported and cantilever girders with a corrugated web. Experimental investigations were conducted using WTA, WTB and WTC girders with the web height of 1000, 1250 and 1500 mm. The load-displacements paths (LDPs) of the shear angle $\gamma$ were analysed. It was demonstrated that rigid support stiffeners contribute to an increase in the linear range of changes in the shear angle in the LDP $P(\gamma)$. That is equivalent to an increase in the value of shear buckling resistance up to 42%. The buckling resistance, obtained on the basis of measurements of the shear angle $\gamma$, was compared with the results obtained from the measurements of the first buckling load, with the solution developed by the author, and also with a widely used computational model acc. Eurocode 3.

1. Introduction

Currently, plate girders with corrugated webs are commonly used in the load carrying structures of steel buildings and also public buildings. According to the manufacturer’ specifications [1], webs are made from thin hot rolled flat steel sheet 2, 2.5 and 3 mm in thickness. They utilize sinusoidal profile. Available girders range from 333 to 1500 mm in height.

Corrugated web girders are constructed in such a way that the load arising from shear forces is supported by the web, whereas flanges support the load produced by the action of bending moments. That leads to the occurrence of substantial shear force displacements and phenomena that contribute to a reduction in shear resistance of girders reported in studies [2 - 8]. The analysis of shear buckling resistance and the results of investigations into corrugated web girders indicate a substantial influence of rigid support stiffeners on shear buckling resistance of the corrugated web [9 – 11]. In simply supported SIN girders, support stiffeners can be made from I-sections or T-sections. In cantilever girders, however, the role of the support stiffener can be performed by end plate joint that connects the cantilever and span parts of the girder. The phenomena that affect the change in the value of the shear buckling resistance are directly reflected in a change in the shear angle $\gamma$ of SIN girders.

This study reports investigations into a change in the shear angle in simply supported and cantilever girders with a corrugated web. As regards simply supported girders, the analysis was performed for girders with semi-rigid and rigid support stiffeners. For cantilever girders, however, single cantilever girders were selected due to the significant effect of cantilever load $P$ on the girder...
span. Experimental tests were conducted on full-scale girders. The girders were assembled from prefabricated items connected by rigid end plates. The web heights were 1000, 1250 and 1500 mm. The load-displacements paths of the shear angle \( P(\gamma) \) were analysed. It was demonstrated that flexural stiffness of support stiffeners affects change in the shear angle value, which translates into changes in shear buckling resistance of SIN girders. The results of shear buckling resistance obtained on the basis of the analysis of load displacement paths of \( P(\gamma) \) were compared with the results from measurements of the first buckling load, the solution developed by the author acc. [12], and the computational model acc. Eurocode [13].

2. Experimental investigations
The experimental tests concerning changes in the shear angle were carried out on three groups of girders.

- **Group 1**: Four girders, namely M 1.21 (WTB1000/300x15), M 1.31 (WTB1000/300x20), M 1.41 (WTA 1250x300x15) and M 1.51 (WTA1500x300x15) with semi-rigid support stiffeners made from sheet metal 25 mm in thickness. Girders were assembled from prefabricated items with overall lengths of \( a = 3750 \) and \( b = 1500 \) mm. (Fig. 1 a).
- **Group 2**: Four girders M 2.21 (WTA1000/300x15), M 2.31 (WTB1000/300x15), M 2.41 (WTC1000/300x15) and M 2.51 (WTA1500/300x15) with reinforced support stiffeners. Flexural stiffness of support stiffeners was increased by tee bars bolted to end plates (Fig. 1 d). At the test stand, girders were assembled from prefabricated items of the lengths \( a = 2750 \) and \( b = 1500 \) mm. (Fig. 1 a). The second group included four girders M 2.21 (WTA1000/300x15), M 2.31 (WTB1000/300x15), M 2.41 (WTC1000/300x15) and M 2.51 (WTA1500/300x15) with reinforced support stiffeners. Flexural stiffness of support stiffeners was increased by tee bars bolted to end plates (Fig. 1 d). At the test stand, girders were assembled from prefabricated items of the lengths \( a = 2750 \) and \( b = 1500 \) mm.

![Figure 1](image-url). Girders with corrugated web a) with support stiffener 25x300; b) with support stiffener 25x300 + tee bar c) cantilever girders d); e); f) details

The first group comprised four girders, namely M 1.21 (WTB1000/300x15), M 1.31 (WTB1000/300x20), M 1.41 (WTA 1250x300x15) and M 1.51 (WTA1500x300x15) with semi-rigid support stiffeners made from sheet metal 25 mm in thickness. Girders were assembled from prefabricated items with overall lengths of \( a = 3750 \) and \( b = 1500 \) mm. (Fig. 1 a). The second group included four girders M 2.21 (WTA1000/300x15), M 2.31 (WTB1000/300x15), M 2.41 (WTC1000/300x15) and M 2.51 (WTA1500/300x15) with reinforced support stiffeners. Flexural stiffness of support stiffeners was increased by tee bars bolted to end plates (Fig. 1 d). At the test stand, girders were assembled from prefabricated items of the lengths \( a = 2750 \) and \( b = 1500 \) mm.
The third group of girders under consideration contained eight cantilever girders. They were assembled from a cantilever element \( w = 1500 \text{ mm} \) and two span elements of the length \( a = 3175 \text{ mm} \) for girders M 1.22 (WTA1000x300x15), M 1.32 (WTC1000/300x15), M 1.42 (WTA1250/300x15), M 1.52 (WTA1500/300x15), or the length \( a = 2175 \text{ mm} \) for girders M 2.22 (WTA1000x300x15), M 2.32 (WTB1000/300x15), M 2.42 (WTC1000/300x15) and M 2.52 (WTA1500/300x15) (Fig. 1 c). Two jointed together end plates, 2x25 mm in thickness, acted as support stiffeners in cantilever girders. All prefabricated elements of individual girders were connected with end plates using prestressed M24 bolts, Class 10.9, the resistance of which was greater than that of girders. Thus, it was possible to satisfy the requirement that the rotation at the connection should be treated as a linear function of rotational stiffness \( S_j \) [2, 14].

After assembly, the girders were mounted onto the test stand (Fig. 2). A steel frame (FR) was used to load the girders. As regards the first and the second group of girders, with simply supported beam loading diagram, the load was a pair of forces \( 2 \times P/2 \). The load was transferred by means of the actuator (1) via a dynamometer (2) onto the spreader boom (3), and then to the tested girder (4) at the site of middle stiffeners. Moveable (5) and fixed (6) bearings were placed between the spreader boom (3) and the girder (4). For cantilever girders, the load was transferred to the cantilever in the form of a single concentrated force \( P \) by means of the actuator (1) via a plate (7) to the cantilever end plate. Under the support stiffener, dynamometers (2) were located to measure reaction \( V \) to load \( P \). In the tests, the following were measured: force \( P \) loading beam girders, reaction \( V \) to load \( P \) in cantilever girder, total girder deflections \( y \), which was done using induction sensors (8), and also displacements of the diagonals and sides of the measurement frame (9) employed to determine the shear angle \( \gamma \).

Girder load \( P \) increased uniformly every 2 kN until non-linear displacements of the web were noted. Then, the load step was reduced. The loading rate was up to 20 kN/min.

![Figure 2. Girders on the test stand a) M 2.21 with stiffener 25x300 + tee bar, b) M 2.52 with stiffener 2x25x300 mm](image)

3. Load – displacements paths of the shear angle \( P(\gamma) \) in corrugated web girders
The shear angle \( \gamma \) in girders with corrugated web was determined using the measurement frame (9) (Fig. 2). Due to the dimensions of the web wave, measurement frame was square shaped. The square dimensions 310x310 mm corresponded to a double wave length in the SIN girder. The measurement frame was attached, at four points, to the convex web wave. The measurement frame centre was located in the girder horizontal axis near the strain gauge system used to mark strain. On each side and on two diagonals of the measurement frame, induction sensors S1 - S6 (PSx10) were installed. They were employed to measure changes in length. The sensitivity of the sensors was 0.001 mm.

The square measurement frame was chosen because of the web shape. In the frame, changes in the diagonal lengths indicate shear strain. Flexural strain is shown by means of changes in the lengths of
vertical and horizontal sides. In the tests, changes in the lengths of both vertical and horizontal sides of the frame were small compared with the changes in the diagonal lengths. Consequently, the effect of flexural strain on the determination of the shear angle in the girders of concern was marginal. In girders with the web height of 1000 mm, change in the side lengths compared with the change in diagonals was slightly greater than in girders with \( h_w = 1250 \) or 1500 mm.

The shear angle \( \gamma \) was determined on the basis of the diagonal length \( d \) shortening by \( \Delta d \) and the vertical side \( a_1 \) elongation by \( \Delta a_1 \) (Fig. 3). As a result, the shear angle \( \gamma \) was represented as the sum of the component angles:

\[
\gamma = \gamma_a + \gamma_b
\]  

The profile of the shear angle \( \gamma \) in the pre-buckling range was determined from the initial load \( P = 0 \text{ kN} \) to the onset of the web stability loss indicated by a bend in the curve \( P(\gamma) \). It should be added that in the post-buckling range, the shear angle changes into the shear deformation angle.

![Figure 3. Measurement frame for measuring the shear angle \( \gamma \)](image)

Figure 4 a and b show the comparison of two exemplary LDPs of the shear angle \( P(\gamma) \) in M 1.51 girders with the support stiffener 25x300 mm, and in M 2.51 with the support stiffener reinforced with a tee bar. Figure 5 a and b illustrate exemplary LDPs \( P(\gamma) \) in cantilever girders with the support stiffener 2x25x300 mm.

In Figures 4 and 5, load displacement paths in the pre-buckling behaviour are marked with a solid line. The range of post-buckling change in the shear deformation angle is indicated by a broken line. In LDPs \( P(\gamma) \) showing a change in the shear angle \( \gamma \), the coordinates of the characteristic points \( P_1(\gamma_1) \) and \( P_2(\gamma_2) \) are given. Characteristic points marked in LDPs \( P(\gamma) \) of girders refer to:
- \( P_1(\gamma_1) \) = girder buckling resistance corresponding to the first buckling load \( P_{cr} \). This point represents the onset of the stability loss of the girder web, which is signalled by the curve \( P(\gamma) \) transition from linear to non-linear form.
- \( P_2(\gamma_2) \) = girder limit load \( P_{uRd} \) corresponding to the corrugated web failure.

The coordinates of the characteristic points in LDPs \( P(\gamma) \) separate the following ranges: \( 0 - P_1(\gamma_1) \) - the range of the reversible change in the web shear angle \( \gamma \); the range ends with the web stability loss; \( P_1(\gamma_1) - P_2(\gamma_2) \) - the range of post-buckling resistance related to an increase in the shear deformation angle. In this range, tension fields in the corrugated web grow. That leads to the formation of the yield zone line in the corrugated web (1) at the final point (Fig. 6 a and b).

The range of shear angle changes in the pre-buckling behaviour in the first group comprising girders with semi-rigid support stiffener was up to 0.08°. Then, in the second group of girders with the support stiffener reinforced by a tee bar, the shear angle increased to 0.09°, which was congruent with an increase in the shear buckling resistance of the corrugated web [10, 12]. In cantilever girders with the support stiffener 2x25x300mm, the shear angle magnitude depended on the mode of the web stability loss that occurred in individual girders. As regards girders in which the web local stability
loss (L) decided the failure, the shear angle reached the values up to 0.1° in the pre-buckling range. Conversely, in girders with the interactive mode of the web stability loss, (I – local and global modes of stability loss combined), the shear angle value was reduced to 0.8°, which corresponded to a decrease in the shear buckling resistance. In the post-buckling range, the change in the shear deformation angle became non-linear.

![Figure 4](image4.png)

**Figure 4.** LDPs $P(\gamma)$ in girders with corrugated web a) with support stiffener 25x300mm M 1.51; b) with support stiffener 25x300mm + tee bar M 2.52

Additionally, the profile of load displacement paths of the shear angle LDPs $P(\gamma)$ is basically compliant with that of global displacement paths $P(\gamma)$. As a result, the characteristic coordinates coincide for both cases [11].

![Figure 5](image5.png)

**Figure 5.** LDPs $P(\gamma)$ in girders with corrugated web with support stiffener 2x25x300mm: a) M 1.52; b) M 2.52
4. Estimation of shear buckling resistance on the basis of the measured shear angle $\gamma$

The shear angle $\gamma$ determined on the basis of measurements made it possible to estimate shear buckling resistance that refers to the onset of the corrugated web stability loss at point $P_1(\gamma_1)$. The following dependence was employed:

$$\tau_{\gamma} = \gamma G$$

(2)

where: $\gamma$ – shear angle, $G = 80$ GPa – modulus of Kirchhoff.

Additionally, for the sake of comparison, shear buckling resistance was estimated on the basis of the determined buckling load per web $P_{cr}$. The following dependence was used:

$$\tau_n = \frac{0.5P_{cr}}{h_w t_w} ; \quad \tau_n = \frac{P_{cr}}{h_w t_w}$$

(3), (4)

where: $P_{cr}$ – first critical buckling load, $h_w$, $t_w$ – web height and thickness, (3) – for simply supported girders, (4) – for cantilever girders.

Table 1 summarizes the results of experimental investigations. The table gives the estimates of shear buckling resistance of the web in simply supported girders with semi-rigid and rigid support stiffeners and in cantilever girders. The estimation was based on measurements of the shear angle $\tau_{\gamma}$. The table also lists shear buckling resistance determined on the basis of the first buckling load $\tau_n$.

The graphs illustrate a change in shear buckling resistance as a function of the web height and thickness in simply supported girders with semi-rigid stiffeners (25x300mm), rigid stiffeners (25x300+ tee bar) and in cantilever girders (2x25x300).

Figure 7 compares graphs of shear buckling resistance estimated on the basis of measurements of the shear angle and the first buckling load.
Table 1. Experimental results of design shear buckling resistances.

| Girder | Web \( (h_w \times t_w) \) | Support Stiffener | \( P_{ult} \) | \( V_{cr} \) | \( \tau_n \) | \( \tau_{ny} \) |
|--------|----------------|------------------|--------|--------|-------|-------|
| M 1.21 | 1000x2.5 | 25x300 | 725 | 285 | 114.0 | 102.7 |
| M 1.31 | 1000x2.5 | 25x300 | 745 | 302.5 | 121.0 | 96.0 |
| M 1.41 | 1250x2 | 25x300 | 840 | 3000 | 120.0 | 112.3 |
| M 1.51 | 1500x2 | 25x300 | 828 | 300 | 100.0 | 90.2 |
| M 2.21 | 1000x2 | 25x300+tee bar | 621 | 285 | 142.5 | 119.3 |
| M 2.31 | 1000x2.5 | 25x300+tee bar | 894 | 370 | 148.0 | 145.9 |
| M 2.41 | 1000x3 | 25x300+tee bar | 1035 | 415 | 138.3 | 129.2 |
| M 2.51 | 1500x2 | 25x300+tee bar | 857 | 373 | 124.3 | 100.3 |
| M 1.22 | 1000x2 | 2x25x300 | 342 | 298 | 149.0 | 134.5 |
| M 2.22 | 1000x2 | 2x25x300 | 343 | 296 | 148.0 | 110.3 |
| M 1.32 | 1000x2.5 | 2x25x300 | 478 | 380 | 152.0 | 134.0 |
| M 2.32 | 1000x2.5 | 2x25x300 | 492 | 390 | 156.0 | 158.6 |
| M 2.42 | 1000x3 | 2x25x300 | 694 | 510 | 170.0 | 164.1 |
| M 1.42 | 1250x2 | 2x25x300 | 348 | 304 | 121.6 | 114.4 |
| M 1.52 | 1500x2 | 2x25x300 | 468 | 400 | 133.3 | 117.3 |
| M 2.52 | 1500x2 | 2x25x300 | 459 | 399 | 133.0 | 89.5 |

Figure 7. Comparison of the shear buckling resistance estimated on the basis of the measurement of the shear angle and the first buckling load.

5. Results and discussions
The results of shear buckling resistance based on the shear angle \( \gamma \) measurements were compared with those obtained using a widely applicable computational model acc. Eurocode 3 [13], and also with the solution proposed by the author acc. [12]. The solution, based on the computations of the interactive shear buckling resistance, concerned girders with semi-rigid and rigid support stiffeners:
\[ \tau_{n,BA} = \tau_y \left( \frac{2}{\lambda_{1,6}^6 + n} \right)^{1/6}, \]

where: \( n = 7 \) for semi-rigid stiffeners, \( n = 5 \) for rigid stiffeners \( \lambda_{1,6} = \sqrt{\frac{\tau_y}{\tau_{cry,I}}} \) - slenderness parameter, \( \tau_{cry,I} \) – interactive shear buckling resistance, \( \tau_y \) – shear yield strength.

Table 2 lists the results of normalized stress \( \tau/\tau_y \) in simply supported girders with semi-rigid (25x300mm) and rigid (25x300+ tee bar) stiffeners and in cantilever girders (2x25x300), based on the shear angle \( \gamma \) measurements \( \tau_\gamma/\tau_y \), Eurocode \( \tau_{n,EC}/\tau_y \), and also in accordance with the solution developed by the author \( \tau_{n,BA}/\tau_y \).

| Girder | Web \((h_w \times t_w)\) [mm] | Support Stiffener \([mm]\) | \( \tau_\gamma/\tau_y \) | \( \tau_{n,EC}/\tau_y \) | \( \tau_{n,BA}/\tau_y \) | \( \tau_{n,BA}/\tau_\gamma \) |
|--------|-------------------------------|--------------------------|-----------------|----------------|----------------|----------------|
| M 1.21 | 1000x2.5 25x300               | 0.70                     | 0.90            | 0.81           | 1.16           |                 |
| M 1.31 | 1000x2.5 25x300               | 0.70                     | 0.91            | 0.81           | 1.16           |                 |
| M 1.41 | 1250x2 25x300                | 0.66                     | 0.81            | 0.80           | 1.22           |                 |
| M 1.51 | 1500x2 25x300                | 0.66                     | 0.84            | 0.80           | 1.22           |                 |
| M 2.21 | 1000x2 25x300+tee bar         | 0.68                     | 0.87            | 0.86           | 1.26           |                 |
| M 2.31 | 1000x2.5 25x300+tee bar       | 0.82                     | 0.92            | 0.86           | 1.04           |                 |
| M 2.41 | 1000x3 25x300+tee bar         | 0.76                     | 0.81            | 0.86           | 1.14           |                 |
| M 2.51 | 1500x2 25x300+tee bar         | 0.66                     | 0.82            | 0.84           | 1.29           |                 |
| M 1.22 | 1000x2 2x25x300              | 0.71                     | 0.81            | 0.86           | 1.21           |                 |
| M 2.22 | 1000x2 2x25x300              | 0.61                     | 0.81            | 0.86           | 1.39           |                 |
| M 1.32 | 1000x2.5 2x25x300             | 0.80                     | 0.88            | 0.86           | 1.08           |                 |
| M 2.32 | 1000x2.5 2x25x300             | 0.94                     | 0.88            | 0.86           | 0.91           |                 |
| M 2.42 | 1000x3 2x25x300              | 0.72                     | 0.88            | 0.86           | 1.18           |                 |
| M 1.42 | 1250x2 2x25x300              | 0.81                     | 0.84            | 0.85           | 1.05           |                 |
| M 1.52 | 1500x2 2x25x300              | 0.72                     | 0.82            | 0.84           | 1.17           |                 |
| M 2.52 | 1500x2 2x25x300              | 0.59                     | 0.83            | 0.84           | 1.43           |                 |

Shear buckling resistance directly reflects changes in the shear angle. A strong correlation was found between shear buckling resistance and the web height \( h_w \) and thickness \( t_w \). Shear buckling resistance turned out to be the highest in the girders with the lowest and the thickest web. As the web height increased, the shear angle magnitude decreased, which automatically reduced the buckling resistance value. By contrast, the use of reinforced support stiffeners resulted in an increase in the linear range of shear angle changes, thus in the growth in the buckling resistance value up to 42%. However, all the results of shear buckling resistance determined based on shear angle turned out to be lower than the results obtained on the basis of the first buckling load. Yet, a drop or increment of the first buckling load in individual girders followed the behaviour of the shear angle.

The comparison of normalized shear resistances expressed as the function of slenderness, obtained from the tests on the basis of the shear angle \( (\tau_\gamma/\tau_y) \), EC 3 [13] \( (\tau_{n,EC}/\tau_y) \) and computed acc. the author’s proposed solution \( (\tau_{n,BA}/\tau_y) \), is shown in Fig. 8.
Figure 8. Normalized shear buckling resistance as a function of slenderness

The results of normalized shear buckling resistance from the tests $\tau_n/\tau_y$ on the basis of the shear angle turned out to be slightly lower than it was the case for the author’s solution acc. Eq. (4). The range of congruence between the solution and the experimental results for the shear angle was from 1.04 to 1.43. That follows from the fact that solution (5) corresponds to the results of shear buckling resistance obtained on the basis of the first buckling load. The solution acc. Eurocode [13] turned out to be slightly overestimated, especially for girders with semi-rigid support stiffeners.

6. Conclusions
In girders with corrugated web, the height and thickness of the web, and also the dimensions of flanges and support stiffeners affect changes in the shear angle, and accordingly shear buckling resistance of the corrugated web.

The mode of stability loss in the corrugated web (local stability loss – L, interactive stability loss – I) is strongly reflected in the measurements of the shear angle. The mode of stability loss directly affects the magnitude of the shear angle.

Rigid support stiffeners produce an increase in the range of linear changes in the shear angle. In LDPs $P(\gamma)$, the range is denoted as $0 - P_1(\gamma_1)$.

Increased rigidity of support stiffeners results in an increase in the shear angle, at the same time causing growth in the first buckling load and shear buckling resistance of the corrugated web.

The use of reinforced support stiffeners leads to an increase in the linear range of changes in the shear angle. Then, shear buckling resistance value grows up to 42%.

The results of the normalized buckling resistance determined on the basis of the shear angle measurements were compared with the results from the solution developed by the author acc. formula (5) [12]. The range of congruence between the solution relying on the interactive buckling resistance and the experimental results for the shear angle was from 1.04 to 1.43.

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