Controlling Measure for Distortional Buckling of Cold-formed Thin-walled Steel Lipped Channel Members

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Abstract. This paper proposed a structural measure according to add batten sheets between two lips to controlling distortional buckling of cold-formed thin-walled steel members with lipped channel section, and the effectiveness was verified through existing tests. At the same time, the stiffness requirements of batten sheets were presented. The structural measures of adding batten sheets between two lips can effectively prevent the rotation of partially stiffened elements, and the distortional buckling load and bearing capacity of the members have been greatly improved. The test shows that the batten sheets with a certain distance and stiffness can improve the bearing capacity of the member or avoid the occurrence of distortional buckling.

Keywords. Cold-formed thin-walled steel member, batten sheet, partially stiffened element, distortional buckling.

1. Introduction

Cold-formed lipped channel sections have been widely used in light gauge steel construction. These channel members may buckle in one and several modes including local buckling, distortional buckling, and overall buckling based on different boundary conditions, sections, and the effective length. Distortional buckling involves distortion of the cross section with rotation and translation occurring at interior fold lines. Distortional buckling occurs at a wavelength intermediate to the two other modes. Chinese code Technical code of cold-formed thin-walled steel structures (GB50018-2002) [1] gives detailed consideration to local buckling and overall buckling of cold-formed thin-walled steel with lipped channel section members, but relatively insufficient consideration is given to distortional buckling, and the existing analysis methods are complex. At the same time, relevant experimental and theoretical analysis [2-5] shows that the distortional buckling of some sections is the main factor controlling the bearing capacity. Silvestre [6] studied the Non-linear behavior and load-carrying capacity of CFRP-strengthened lipped channel steel columns when distortional buckling occurs. Yao and his research team [7-10] analyzed the behavior of distortional buckling of cold-formed steel lipped channel members with connecting bars and diaphragms between lips and given the requirement of the connecting bars and diaphragm. These researches are not adequate for using battens between lips to increase the distortional buckling strength of cold-formed steel channel members.

This paper presents a countermeasure to restrain the occurrence of distortional buckling of cold-formed thin-walled steel members with lipped channel section by setting batten sheets between two lips was suggested. A series of axially-compressed members’ tests was conducted to verify the validity of countermeasure and the stiffness requirement of the batten sheet is proposed.
2. Controlled Countermeasure of Distortional Buckling
The distortional buckling is easy to occur for cold-formed thin-walled lipped channel members, especially for members that the maximum stress acts at the partially stiffener edge. The distortional buckling can decrease the load-carrying capacities of members and utilized efficiency of elements. The distortional buckling strength will decrease with the increase of the distortional buckling wave length which affected by the increase of dimension of lips [11]. The lip is easy to buckle in plane and decrease the supported act for the partially stiffened element when lip has bigger width because the lip is a unstiffened plate. The increased effect of lip on distortional buckling strength is limited. The simple and direct method to restrain the occurrence of distortional buckling is that batten sheets are set between two lips to increase the nominal effective length for distortional buckling. The distortional buckling wave length can assign the distance of batten sheet when the distance of batten sheets is less than the distortional buckling wave length and the batten sheet can prevent the in-plane buckling of lips.

2.1. Stiffness Requirement of Batten Sheet
The controlled countermeasure to restrain the occurrence of distortional buckling and the analytical model for supporting stiffness are shown in figure 1.

It is that the batten sheet should satisfy the minimum stiffness that can prevent the in-plane buckling of lips when the distortional buckling occur if the batten sheet between lips can decrease the wave length of distortional buckling. The stiffness requirement can be analyzed based on the applied force which the lip and the partially stiffened plate act on the batten sheet and the analytical model is shown in figure 2. The stiffness requirement of the batten sheet is that the lateral buckling strength of the lip and the partially stiffened plate should be minimum than the buckling strength of the batten sheet.

\[ w = B \cos \frac{\pi x}{\lambda} y \]  
\[ N_{lip} = -\int_{-\lambda/2}^{\lambda/2} \sigma_{lip} \frac{\partial^2 \omega}{\partial^2 x} \, t \, dx \bigm|_{y=b} = -2\sigma_{lip} \omega \left( \frac{\pi}{\lambda} \right) Bb \]  

![Figure 1. Arrangement of batten sheets between lips.](image1)

![Figure 2. Analytical model for supporting stiffness for batten sheet.](image2)
where is the distortional buckling stress. The lateral force of the partially stiffened plate is

\[ N_f = \int_{-A/2}^{A/2} \int_0^b \sigma_y \frac{\partial^2 w}{\partial x^2} dx dy \]

\[ = \int_{-A/2}^{A/2} \int_0^b \sigma_{st} (1 - \alpha + \alpha y / b) \frac{\partial^2 w}{\partial x^2} dx dy \]

\[ = -\sigma_{st} (1 - \alpha) \left( \frac{\pi}{\lambda} \right) B^2 + 2\sigma_{st} \alpha \left( \frac{\pi}{\lambda} \right) b^2 / 3B \]

where, is the maximum compressed stress of the the partially stiffened plate and is the stress of the other edge of the partially stiffened plate in which the compressed stress is taken as positive value and the tension stress is negative value.

The flexural load-carrying capacity of the lip is

\[ N_{lip} = EI \int_{-A/2}^{A/2} \frac{\partial^4 w}{\partial x^4} t dx \bigg|_{x=0} = EI \left( \frac{\pi}{\lambda} \right)^3 B^2 \]

where \( I \) is the moment of inertia of the lip.

The equilibrium equation of the batten sheets is

\[ N_b = \phi A_s f = \phi A_s E \frac{b_s B}{h_s} = -N_f - N_{lip} + N_{lipb} \]

where \( \phi, A_s, f, h_s, b_s \) are the overall buckling stability coefficient, the sectional area, design stress, length, the width of the batten sheet, respectively.

The minimum width of the batten sheet can be obtained as equation (6) from the expression (5) if the thickness of the batten sheet equals that of the member.

\[ b_s = \sigma_{st} \left( 2at / b + (1 - \alpha) + 2\alpha / 3 \right) - EI \left( \frac{\pi}{\lambda} \right)^2 \]

\[ \phi E t / h_s / \left( \frac{\pi}{\lambda} \right) \]

The minimum width of the batten sheet can be given as follows if the maximum stress acts at the stiffened edge using the same method as the maximum stress acts at the partially stiffened edge.

\[ b_s = \sigma_u \left( 2(1 - \alpha)at + 1 - 2ab / 3 \right) - EI \left( \frac{\pi}{\lambda} \right)^2 b \]

\[ \phi E t / h_s / \left( \frac{\pi}{\lambda} \right) \]

3. Test for Controlled Countermeasure of Distortional Buckling

3.1. Axially-compressed Member

Test specimens conducted are cold-formed steel lipped channel members with two stiffeners in the web. Section of specimens is shown in figure 3, and set-up of batten sheets is shown in figure 4.

The nominal thickness is 1 mm. The dimension of the batten sheet is \( h_s \times b_s \times t = 100 \times 40 \times 1 \) mm. The nominal length, actual dimension of specimens and the interval of the batten sheet are shown in table 1. The specified yield stress is 550 MPa and the coupon test results were 615 MPa. Complete details of the test, including the definition of the sectional dimension, member dimensions, material properties, and boundary conditions, are summarized in Yao (2012) [12]. Material properties of specimens are shown in table 2.
Figure 3. Section of specimens.  

Figure 4. Set-up of batten sheets.

Table 1. Section sizes of specimens.

| Sections          | Nominal length/ mm | specimen length/ mm | h  | h₁/ mm | h₂/ mm | b  | b₁/ mm | b₂/ mm | a  | a₁/ mm | a₂/ mm | Intervals of batten sheets |
|-------------------|--------------------|---------------------|----|---------|---------|----|---------|---------|----|---------|---------|---------------------------|
| SS1010-20-AC-D    | 400                | 400                 | 100.95 | 101.72 | 52.60  | 49.79 | 11.69  | 13.43  |    |         |         | No batten sheets           |
| SS1010-20-AC-D    | 400                | 400                 | 99.73  | 97.05  | 53.34  | 49.48 | 12.59  | 11.78  |    |         |         | No batten sheets           |
| SS1010-20-AC-D    | 400                | 401                 | 99.80  | 97.54  | 53.38  | 49.31 | 12.97  | 11.83  |    |         |         | 150 mm                    |
| SS1010-20-AC-D    | 400                | 399                 | 101.05 | 101.97 | 53.22  | 50.03 | 11.37  | 13.55  |    |         |         | 300 mm                    |
| SS1010-30-AC-D    | 600                | 600                 | 100.02 | 97.50  | 53.47  | 49.49 | 12.95  | 11.79  |    |         |         | No batten sheets           |
| SS1010-30-AC-D    | 600                | 600                 | 99.75  | 97.34  | 53.43  | 49.34 | 12.98  | 11.93  |    |         |         | No batten sheets           |
| SS1010-30-AC-D    | 600                | 602                 | 100.31 | 100.16 | 52.76  | 49.52 | 12.35  | 13.14  |    |         |         | 150 mm                    |
| SS1010-30-AC-D    | 600                | 600                 | 100.86 | 101.50 | 52.75  | 49.43 | 12.15  | 13.23  |    |         |         | 300 mm                    |
| SS1010-40-AC-D    | 800                | 799                 | 101.10 | 101.63 | 53.04  | 49.73 | 12.57  | 13.11  |    |         |         | No batten sheets           |
| SS1010-40-AC-D    | 800                | 800                 | 99.74  | 99.27  | 53.42  | 49.41 | 13.17  | 11.70  |    |         |         | No batten sheets           |
| SS1010-40-AC-D    | 800                | 800                 | 99.85  | 98.24  | 53.41  | 49.37 | 13.11  | 11.89  |    |         |         | 150 mm                    |
Table 2. Material properties of specimens.

| specimens  | \( f_{0.2} \) (MPa) | E (MPa)   | \( \delta \) /% |
|------------|----------------------|-----------|-----------------|
| SS1001     | 613                  | 2.02×10⁵  | 11.7            |
| SS1002     | 617                  | 2.14×10⁵  | 10.7            |
| SS1003     | 615                  | 1.98×10⁵  | 11.1            |

3.2. Comparison on Load-carrying Capacities between Test and Calculated Results

Five methods are used to predict the load-carrying capacities of test specimens. \( P_{c1} \) is predicted using Chinese technical code technical code of cold-formed thin-walled steel structures\(^{[1]}\) and considering the interaction of plates. \( P_{c2} \) is calculated using Chinese code\(^{[1]}\) and not considering the interaction of plates. \( P_{cr1} \) is obtained using Chinese code\(^{[1]}\) and considering the interaction of plates, and the effect of batten sheet. \( P_{cr2} \) is given using Chinese code\(^{[1]}\) and the affect of batten sheet but not considering the interaction of plates. \( P_t \) is predicted using direct strength method in the AISI S100 (2007) which is the minimum of the overall buckling strength, local buckling strength and the distortional buckling.

The test results and calculated load-carrying capacities are shown in table 3, where \( P_t \) is the test results. The increase of load-carrying capacities of specimens because of the batten sheets also are given in table 3.

As shown in Table 3, there is no increase for load-carrying capacities when the interval of batten sheet is longer than the distortional buckling half-wave length of members, but the load-carrying capacities increase gradually with the decrease of interval of batten sheet when the interval of batten sheet is shorter than the distortional buckling half-wave length of members. The load-carrying capacities can increase 20 percent if the interval of batten sheet is shorter than the half of distortional buckling half-wave length of members. The test results and predicted results all indicate that the controlled measure for distortional buckling by setting the batten sheet between lips is reasonable and can crease the ultimate...
strength of lipped channel members.

**Table 3.** Comparison on load-carrying capacities of members between the test and calculated results.

| Sections       | $L_0$/mm | $\lambda$/mm | Intervals of batten sheets | $P_1$/kN | $P_{c1}$/kN | $P_2$/kN | $P_{c2}$/kN | $P_N$/kN | $\Delta P_1$ | $\Delta P_2$ | $P_{c1}$/% | $P_{c2}$/% | $P}$/% | $k$ |
|----------------|----------|---------------|-----------------------------|----------|-------------|----------|-------------|----------|-------------|-------------|-----------|-----------|--------|------|
| SS1010-20      | 400      | 517.9         | No                          | 77.5     | 61          | 61.3     | 67.14       | 65.90    | 60          | /           | /         | /        | /      | 1    |
| -AC-D-1        |          |               | Batten sheets               |          |             |          |             |          |             |             |           |           |        | 26   |
| SS1010-20      | 400      | 517.9         | No                          | 75.9     | 62          | 61.8     | 67.34       | 66.11    | 60          | /           | /         | /        | /      | 1    |
| -AC-D-2        |          |               | Batten sheets               |          |             |          |             |          |             |             |           |           |        | 24   |
| SS1010-20      | 400      | 517.9         | 150 mm                      | 77.1     | /           | /        | 79.60       | 77.95    | 67          | 0.5        | 1         | 18.1%    | 1%      | 4    |
| -AC-D-3        |          |               |                              | 1        |             |          |             |          |             |             |           |           |        | 3    |
| SS1010-20      | 400      | 517.9         | 300 mm                      | 70.9     | /           | /        | 70.53       | 68.78    | 66          | /           | /         | /        | /      | 1    |
| -AC-D-4        |          |               |                              | 9        |             |          |             |          |             |             |           |           |        | 27   |
| SS1010-30      | 600      | 517.9         | No                          | 66.5     | 59          | 59.4     | 62.61       | 62.29    | 58          | /           | /         | /        | /      | 1    |
| -AC-D-1        |          |               | Batten sheets               | 5        | 98          | 46       | 61.24       | 29.30    |             |             |           |           |        | 26   |
| SS1010-30      | 600      | 517.9         | No                          | 64.4     | 60          | 59.5     | 62.56       | 71.50    | 58          | /           | /         | /        | /      | 1    |
| -AC-D-2        |          |               | Batten sheets               | 4        | 98          | 56       | 71.50       | 50.42    |             |             |           |           |        | 26   |
| SS1010-30      | 600      | 517.9         | 150 mm                      | 77.7     | /           | /        | 78.05       | 76.37    | 66          | 17.2        | 2         | 22.7%    | 4%      | 3    |
| -AC-D-3        |          |               |                              | 2        |             |          |             |          |             |             |           |           |        | 0.00 |
| SS1010-30      | 600      | 517.9         | 300 mm                      | 75.0     | /           | /        | 68.28       | 67.97    | 66          | 14.6        | 9         | 8.9%     | 1%      | 1    |
| -AC-D-4        |          |               |                              | 0        |             |          |             |          |             |             |           |           |        | 9    |
| SS1010-40      | 800      | 517.9         | No                          | 63.6     | 57          | 57.6     | 60.60       | 60.14    | 58          | /           | /         | /        | /      | 1    |
| -AC-D-1        |          |               | Batten sheets               | 6        | 98          | 66       | 68.14       | 14.26    |             |             |           |           |        | 28   |
| SS1010-40      | 800      | 517.9         | No                          | 60.6     | 57          | 57.6     | 60.59       | 59.42    | 58          | /           | /         | /        | /      | 1    |
| -AC-D-2        |          |               | Batten sheets               | 6        | 98          | 66       | 68.14       | 14.26    |             |             |           |           |        | 26   |
| SS1010-40      | 800      | 517.9         | 150 mm                      | 77.4     | /           | /        | 74.04       | 70.91    | 65          | 25.2        | 2         | 18.1%    | 5%      | 2    |
| -AC-D-3        |          |               |                              | 7        |             |          |             |          |             |             |           |           |        | 0    |
| SS1010-40      | 800      | 517.9         | 300 mm                      | 70.0     | /           | /        | 65.42       | 62.62    | 65          | 12.8        | 8         | 4.7%     | 4%      | 2    |
| -AC-D-4        |          |               |                              | 0        |             |          |             |          |             |             |           |           |        | 64   |
| SS1010-40      | 800      | 517.9         | 600 mm                      | 62.1     | /           | /        | 61.60       | 60.58    | 58          | 0.1%        | 1         | 1.8%     | 0%      | 1    |
| -AC-D-5        |          |               |                              | 1        |             |          |             |          |             |             |           |           |        | 28   |
4. Conclusion

This paper presents a countermeasure to restrain the occurrence of distortional buckling by setting batten sheets between two lips. The conclusions are following:

(1) A series of tests verify the validity of countermeasure for increasing the distortional buckling strength and the stiffness requirement of the batten sheets is proposed.

(2) With different layout spacing of batten sheets, the increase range of bearing capacity of members is obviously different. Generally, the spacing is smaller, increase of load-carrying capacities is higher.

(3) Comparison on load-carrying capacities with experimental results and calculated results predicted with North America specification and Chinese code indicates that the increase of load-carrying capacity for the cold-formed thin-walled lipped channel members is obvious with the decrease of intervals of batten sheets.

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