Study on the Local Stability of Unidirectional Buckling Members of a New Type of Section Steel

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Abstract. The paper investigates the unidirectional buckling performance of lipped thin-walled U-shaped steel using numerical simulation with the finite strip program CUFSM. The local stability of the steel under compression at the opening side is studied. 33 different members are selected, each with a length of 2.5 m. All the members are divided into four series, and each series is used to investigate the influence of one parameter: the ratio of web height-to-upper flange width, the ratio of lipped height-to-upper flange width, the ratio of lower flange width-to-web height and the thickness of the plate. The laws of buckling stress, buckling mode and half-wave length of the member are analyzed. Finally, this paper gives a reasonable value range for these four parameters, according to which a reasonable cross section can be designed in the actual project, so that it can meet the needs of the actual project and has a certain economic index.

1. Introduction

The lipped thin-walled U-shaped steel (Figure 1) is a new type of section steel that has just come into view in recent years. Experts and scholars have little research on it, and its mechanical properties are not clear. The lipped thin-walled U-shaped steel is the cold-formed thin-walled steel, whose stability is a core issue. Generally speaking, the greater the width-to-thickness ratio of cold-formed thin-walled steel plate is, the better its economic benefits will be, but the large width-to-thickness ratio will lead to premature destabilization failure of the member. Therefore, it is necessary to take measures to limit the buckling of the plate, such as setting the stiffening ribs or limiting the width-to-thickness ratio of the plate. Increasing the width-to-thickness ratio of the plate can increase the buckling capacity of the member and prevent the member from premature destabilization failure. However, increasing the width-to-thickness ratio of the plate will inevitably increase the amount of steel used in the plate, so a reasonable section design is particularly important for cold-formed thin-walled steel. The reasonable section should not only meet the bearing capacity requirements, but also meet economic requirements. Due to the lack of research on the lipped thin-walled U-shaped steel, the design of its section is still in the exploratory stage, so how to design a reasonable section of lipped thin-walled U-shaped steel is an urgent issue to be resolved.
2. Verification of the finite strip program

In this paper, the validity of the CUFSM program is verified by an example chosen from the literature. Example: Choose the example in Figure 1 from literature [3]. The yield strength of steel is $f_y=235\,\text{MPa}$, the elastic modulus is $E=203400\,\text{N/mm}^2$, the shear modulus is $G=77900\,\text{N/mm}^2$, and the Poisson's ratio is $\nu=0.3$. The member is simply supported at both ends and is subject to axial pressure.

According to the formula in the literature [3], the stress obtained by calculating local buckling is $\sigma_{lcl}=121.1\,\text{N/mm}^2$, and the stress obtained by calculating distortional buckling is $\sigma_{dcl}=213.6\,\text{N/mm}^2$.

The elastic buckling loads of the members in the example are calculated using the finite strip program CUFSM and the results are shown in the following figure.

![Figure 2 The curve of CUFSM analysis results](image)

The critical elastic buckling load of local buckling of the member is $=116.53\,\text{N/mm}^2$, while the result obtained in the literature [3] is $\sigma_{el}=121.1\,\text{N/mm}^2$, with a difference of 3.77%. The critical elastic buckling load of distortional buckling of the member is $\sigma_{edl}=207.76\,\text{N/mm}^2$, while the result obtained in the literature [3] is $\sigma_{edl}=213.6\,\text{N/mm}^2$, with a difference of 2.73%.

From the analysis of the above example, it can be seen that it is feasible to use the finite strip program CUFSM to calculate the elastic buckling load of the members with a difference of 5% from the theoretical value, which is within the acceptable error range.

3. Specimen design and simplification of calculation model simplification

As shown in Figure 1, b is the lower flange, h is the web, b1 is the upper flange, and a is the lip. In this paper, the section size of the basic member is: $h=160\,\text{mm}$, $b=140\,\text{mm}$, $b_1=25\,\text{mm}$, $a=10\,\text{mm}$ and $t=1.6\,\text{mm}$, and the corresponding specimen number is h160b140b125a10t1.6. A total of 33 specimens are set in this paper, and the specific specimen types are shown in Table 1-4.

![Figure 1. Cross-section of lipped thin-walled U-shaped steel](image)
All the specimens in this paper are Q345 steel, with the yield strength of $f_y=345$MPa, the elastic modulus of $E=20600$ $N/mm^2$, the shear modulus of $G=79000$ $N/mm^2$ and the Poisson's ratio of $\nu=0.3$. Combined with the engineering practice, the length of the specimen studied in this paper is taken as 2.5m, assuming that the two ends of the member are simply supported.

4. Finite strip method analysis of lipped thin-walled U-shaped steel under compression at the opening side.

The finite strip program CUFSM is used to analyze four series of specimens, and the following results are obtained:

Table 1. The calculation results of the ratio of web-to-upper flange ($h/b_1$) of specimens

| Specimen number | $h/b_1$ | Buckling mode | Buckling stress | Half-wave length | Global buckling | Distortional buckling | Local buckling | Others |
|-----------------|---------|---------------|----------------|------------------|----------------|-----------------------|----------------|--------|
| h100b140b;25a10b1.6 | 4.00 | distortional | 343.44 | 1330 | 0.2% | 99.2% | 0.6% | 0.0% |
| h110b140b;25a10b1.6 | 4.40 | distortional | 298.55 | 1410 | 0.1% | 99.4% | 0.4% | 0.0% |
| h120b140b;25a10b1.6 | 4.80 | distortional | 262.42 | 1490 | 0.1% | 99.6% | 0.3% | 0.0% |
| h130b140b;25a10b1.6 | 5.20 | distortional | 232.73 | 1570 | 0.1% | 99.7% | 0.2% | 0.0% |
| h140b140b;25a10b1.6 | 5.60 | distortional | 207.98 | 1650 | 0.1% | 99.8% | 0.1% | 0.0% |
| h150b140b;25a10b1.6 | 6.00 | distortional | 187.14 | 1720 | 0.1% | 99.8% | 0.1% | 0.0% |
| h160b140b;25a10b1.6 | 6.40 | distortional | 169.28 | 1800 | 0.1% | 99.8% | 0.1% | 0.1% |
| h170b140b;25a10b1.6 | 6.80 | distortional | 153.96 | 1870 | 0.1% | 99.8% | 0.1% | 0.0% |
| h180b140b;25a10b1.6 | 7.20 | distortional | 140.6 | 1940 | 0.0% | 99.8% | 0.2% | 0.0% |

Table 2. The calculation results of the ratio of lip-to-upper flange ($a/b_1$) of specimens

| Specimen number | $a/b_1$ | Buckling mode | Buckling stress | Half-wave length | Global buckling | Distortional buckling | Local buckling | Others |
|-----------------|---------|---------------|----------------|------------------|----------------|-----------------------|----------------|--------|
| h160b140b;25a5b1.6 | 0.20 | distortional | 156.79 | 1670 | 0.0% | 99.8% | 0.1% | 0.0% |
| h160b140b;25a10b1.6 | 0.40 | distortional | 169.28 | 1800 | 0.0% | 99.8% | 0.1% | 0.0% |
| h160b140b;25a15b1.6 | 0.60 | distortional | 179.37 | 1900 | 0.0% | 99.8% | 0.1% | 0.0% |
| h160b140b;25a20b1.6 | 0.80 | distortional | 188.33 | 2000 | 0.0% | 99.9% | 0.1% | 0.0% |
| h160b140b;25a25b1.6 | 1.00 | distortional | 196.93 | 2080 | 0.0% | 99.9% | 0.1% | 0.0% |
| h160b140b;25a30b1.6 | 1.20 | distortional | 205.53 | 2150 | 0.0% | 99.8% | 0.1% | 0.0% |
| h160b140b;25a35b1.6 | 1.40 | distortional | 214.51 | 2220 | 0.0% | 99.8% | 0.1% | 0.0% |
| h160b140b;25a40b1.6 | 1.60 | distortional | 223.83 | 2290 | 0.0% | 99.8% | 0.2% | 0.0% |
| h160b140b;25a45b1.6 | 1.80 | distortional | 233.57 | 2350 | 0.0% | 99.8% | 0.2% | 0.0% |

Table 3. The calculation results of the ratio of lower flange-to-web ($b/h$) of specimens

| Specimen number | $b/h$ | Buckling mode | Buckling stress | Half-wave length | Global buckling | Distortional buckling | Local buckling | Others |
|-----------------|-------|---------------|----------------|------------------|----------------|-----------------------|----------------|--------|
| h160b100b;25a10b1.6 | 0.63 | distortional | 186.5 | 1720 | 0.1% | 99.8% | 0.2% | 0.0% |
| h160b110b;25a10b1.6 | 0.69 | distortional | 181.62 | 1740 | 0.0% | 99.8% | 0.1% | 0.0% |
| h160b120b;25a10b1.6 | 0.75 | distortional | 177.12 | 1760 | 0.0% | 99.8% | 0.1% | 0.0% |
| h160b130b;25a10b1.6 | 0.81 | distortional | 173.05 | 1780 | 0.0% | 99.8% | 0.1% | 0.0% |
| h160b140b;25a10b1.6 | 0.88 | distortional | 169.28 | 1800 | 0.0% | 99.8% | 0.1% | 0.0% |
| h160b150b;25a10b1.6 | 0.94 | distortional | 165.84 | 1820 | 0.1% | 99.8% | 0.2% | 0.0% |
| h160b160b;25a10b1.6 | 1.00 | distortional | 162.67 | 1830 | 0.1% | 99.7% | 0.2% | 0.0% |
| h160b170b;25a10b1.6 | 1.06 | distortional | 159.77 | 1850 | 0.1% | 99.7% | 0.2% | 0.0% |
| h160b180b;25a10b1.6 | 1.13 | distortional | 157.10 | 1870 | 0.1% | 99.6% | 0.2% | 0.0% |
| Specimen number | t   | Buckling mode | Buckling stress | Half-wave length | Global buckling | Distortional buckling | Local buckling | Others |
|-----------------|-----|---------------|----------------|-----------------|----------------|----------------------|----------------|--------|
| h160b140b25a10t1.2 | 1.2 | distortional  | 125.3          | 2080            | 0.0%           | 99.8%                | 0.1%           | 0.0%   |
| h160b140b25a10t1.4 | 1.4 | distortional  | 147.15         | 1920            | 0.0%           | 99.8%                | 0.1%           | 0.0%   |
| h160b140b25a10t1.6 | 1.6 | distortional  | 169.28         | 1800            | 0.0%           | 99.8%                | 0.1%           | 0.0%   |
| h160b140b25a10t1.8 | 1.8 | distortional  | 191.68         | 1690            | 0.0%           | 99.8%                | 0.1%           | 0.0%   |
| h160b140b25a10t2.0 | 2   | distortional  | 214.37         | 1610            | 0.0%           | 99.8%                | 0.1%           | 0.0%   |
| h160b140b25a10t2.2 | 2.2 | distortional  | 237.35         | 1530            | 0.0%           | 99.8%                | 0.1%           | 0.0%   |
| h160b140b25a10t2.4 | 2.4 | distortional  | 260.61         | 1470            | 0.0%           | 99.8%                | 0.1%           | 0.0%   |
| h160b140b25a10t2.6 | 2.6 | distortional  | 284.15         | 1410            | 0.0%           | 99.8%                | 0.1%           | 0.0%   |
| h160b140b25a10t2.8 | 2.8 | distortional  | 367.99         | 1300            | 0.0%           | 99.8%                | 0.1%           | 0.0%   |

Note: The unit of buckling stress in the above tables is MPa, and the unit of half-wave length and thickness is mm.

It can be seen from Table 1 that the distortional buckling occurs in the specimen. As the ratio of web-to-upper flange of the specimen increases, the buckling stress of the specimen decreases and the decreasing rate of the buckling stress gradually slows down. On the one hand, because the opening side of the specimen is compressed, that is, the part above the neutral axis of the web, the upper flange of the specimen and the lip are compressed, the height of the web increases, that is, the height-to-thickness ratio of the web itself also increases, so the height-to-thickness ratio of the web in the compression area also increases, resulting in the reduction of the buckling stress. On the other hand, with the increase of the web height, the restraint effect of the upper flange on the web will be weakened, which will also lead to the reduction of the buckling stress of the specimen.

It can be seen from Table 2 that the distortional buckling occurs in the specimen. As the ratio of lip-to-upper flange of the specimen increases, the buckling stress of the specimen increases. When the ratio of lip-to-upper flange is greater than 0.4, the growth of the buckling load slows down. With the increase of the ratio of height-to-thickness of the lip, the constraint of the lip on the upper flange increases gradually, so the upper flange will get closer to the stiffening plate, which will also increase the buckling stress of the upper flange, thus increasing the buckling stress of the whole specimen. However, if the height-to-thickness ratio of the lip is too large, its own stability will be reduced, which will also lead to the decrease of the buckling load of the whole specimen. Therefore, it is suggested that the ratio of lip-to-upper flange of lipped thin-walled U-shaped steel should be set at the range of 0.4-0.5 in the actual project.

It can be seen from Table 3 that the distortional buckling occurs in the specimen. The buckling load of the specimen decreases with the increase of the ratio of lower flange-to-web, and when the ratio exceeds 0.8, the decrease of the buckling stress tends to slow down. Increasing the width of the lower flange will reduce the stability of the lower flange, but the stability of the lower flange has little effect on the overall stability performance because the lower flange is located in the tension zone. Similarly, the increase of the width of the lower flange can also increase the constraint on the tension edge of web, resulting in the increase of the buckling stress of the specimen, but the increase of the constraint on the tension edge has little effect on the overall stability. Combined with the above analysis, the real reason for the decrease of the buckling stress of the specimen is that the increase of the width of the lower flange will lead to the decrease of the neutral axis of the section, which will increase the height of the compression part of the web and decrease the height of the tension part, resulting in the decrease of the stability of the web and the decrease of the buckling stress.

It can be seen from Table 4 that the distortional buckling occurs in the specimen. The buckling stress of the specimen increases with the increase of the thickness of the specimen, and the buckling stress is approximately proportional to the thickness of the specimen. The increase of the thickness of the specimen will increase the width-to-thickness ratio of all the plates in the specimen, especially in the compression zone. Increasing the thickness of the plate is the most direct way to improve the stability of this series of specimens, which can effectively prevent the specimens from buckling failure.
In the actual project, the buckling bearing capacity of the specimen can be increased by increasing the thickness of the plate, which is not economical because the impact of the increase of the thickness of the specimen on the buckling capacity of the whole specimen is not significant.

5. Conclusion
This paper investigates the local stability of unidirectional buckling members of the lipped thin-walled U-shaped steel under compression at the opening side and draws the following conclusions.

1. When the lipped thin-walled U-shaped steel member is compressed at the opening side, its stability is determined by distortional buckling, that is to say, there is only distortional buckling when the member is buckled.
2. As the ratio of web-to-upper flange of the specimen increases, the buckling stress of the specimen decreases and the decreasing rate of the buckling stress gradually slows down. That is to say, the smaller the ratio of web-to-upper flange, the greater the increase of buckling load of the specimen. In practice, the ratio of web-to-upper flange of the lipped thin-walled U-shaped steel should be minimized, and it is recommended to keep it below five to achieve higher benefits.
3. As the ratio of lip-to-upper flange of the specimen increases, the buckling stress of the specimen increases. When the ratio of lip-to-upper flange is greater than 0.4, the growth of the buckling load slows down. Therefore, the ratio of lip-to-upper flange should be set at the range of 0.4-0.5 in the actual project to achieve higher benefits.
4. The buckling stress of the specimen decreases with the increase of the ratio of lower flange-to-web, and when the ratio exceeds 0.8, the decrease of the buckling stress tends to slow down. In other words, when the ratio of lower flange-to-web is less than 0.8, the increase of buckling stress is greater in the actual project. Therefore, in the engineering design, the ratio of lower flange-to-web should be controlled below 0.8 to achieve higher benefits.
5. The buckling stress of the specimen increases with the increase of the thickness of the specimen, and the buckling stress is approximately proportional to the thickness of the specimen. Increasing the thickness of the plate is the most direct way to improve the stability of this series of specimens, which can effectively prevent the specimens from buckling failure. In the actual project, the buckling bearing capacity of the specimen can be increased by increasing the thickness of the plate, which is not economical because the impact of the increase of the thickness of the specimen on the buckling capacity of the whole specimen is not significant.
6. The half-wave length is essentially related to the width-to-thickness ratio of the plate when the distortional buckling occurs. The larger the width-to-thickness ratio is, the larger the half-wave length is; the smaller the width-to-thickness ratio is, the smaller the half-wave length is. The influence of the width-to-thickness ratio of the plate in the compression zone on the half-wave length is greater than that of the plate in the tension zone.

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